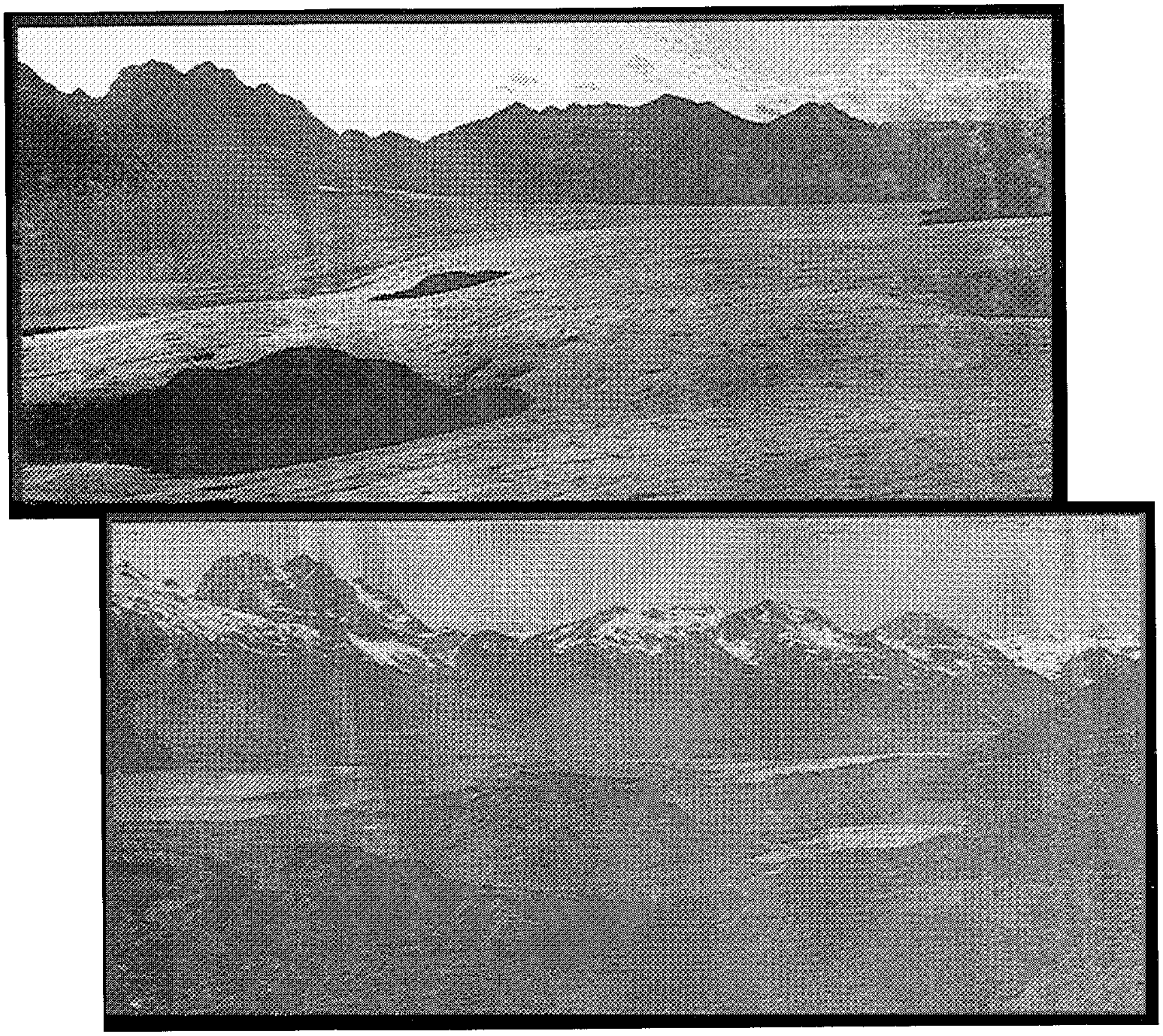
Proceedings
of the Third Glacier Bay Science Symposium, 1993



September 15-18
Glacier Bay Lodge
Glacier Bay National Park and Preserve, Alaska

Editor: Daniel R. Engstrom

MARCH 3, 1849

As the nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all. The department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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Sponsored by:
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Cover photo

Thirty-six years of landscape change in the Wachusett Inlet area. During this period nunataks appeared in Burroughs Glacier, a new landscape was revealed as ice melted, and plants colonized the area. The view is north from W.O. Field's photo station 7. From D.B. Lawrence et al. (this volume).

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FOREWORD

The Third Glacier Bay Science Symposium was held at Glacier Bay Lodge in Glacier Bay National Park and Preserve, Alaska, on September 15-18, 1993. Like its predecessors, this meeting was jointly sponsored by the National Park Service, Friends of Glacier Bay, and the Glacier Bay Science Board. The symposium theme, *Creating Glacier Bay's research role within park, regional and global contexts -- A Plan for Action,"* built upon the two previous Glacier Bay symposia: the first a retrospective tribute to Glacier Bay's pioneer scientists, the second an overview of the current status of Glacier Bay science and research. The third symposium's goal was twofold: (i) to review scientific research efforts in Glacier Bay and the contiguous biosphere of Southeast Alaska since the last symposium (1988), and (ii) to develop an action plan for Glacier Bay to implement recommendations of the National Academy of Sciences (NAS) report on *Science and the National Parks.*

The meeting was attended by 135 registered participants encompassing local interests, state agencies, the National Park Service and other federal agencies, and university scientists from across the country. Forty-one scientific papers were presented in a series of five technical sessions covering physical, biological, and cultural elements of the Glacier Bay ecosystem. A lead-off panel discussion and four concurrent evening workshops were also held to provide an open forum for exchanging views among park managers, policy experts, and independent scientists on what the organizational and physical infrastructure of the Glacier Bay science plan should be. A concurrent poster session and a special evening presentation by elders of the Huna Traditional Tribal Council on the oral history of Tlingit use and habitation of Glacier Bay complimented this diverse and full agenda.

Attendees were greeted by several days of exceptional fall weather, with the Fairweather range in full and glorious view. The indoor events were made tolerable by early morning field trips to explore the marine, intertidal, and rainforest environs of Bartlett Cove. Fortunately, the weather held for the traditional 'up bay' excursion aboard the MV *Spirit of Adventure* to sites of scenic and scientific wonder, guided by the running commentary of scientific experts on board. This all-day event was followed by a banquet and evening presentation by author, Judith Aftergut, and a tribute and dedication to Richard P. Goldthwait by Dave Mickelson. A not-to-be-missed replay of Sandy Milner's recollections of his early research days in Glacier Bay along with other humorous stories continued informally into the wee hours.

By most counts the symposium was a great success. The presentations were consistently good, being at the same time of high scientific quality and accessible to the diverse audience in attendance. The discussions and workshops focusing on science policy in the National Parks, although open-ended, provided much impetus for subsequent selection of Glacier Bay as a candidate ecosystem-based research center for the National Biological Service. The social events, informal discussions, and scenic splendor were probably without equal. Closure for this symposium, however, comes with publication of a proceedings of the presented papers. This volume, following tradition from two previous symposia, contains 40 peer-reviewed chapters that summarize the oral and poster presentations; only a few of the technical papers were not prepared for publication. These *Proceedings* also include Superintendent Jensen's welcoming address, the dedication to Richard Goldthwait, and excerpts from the keynote address by Roland Wauer and evening lecture by Judith Aftergut. A closing note by Bill Brown of the Friends of Glacier Bay assesses what the meeting accomplished, what it did not, and the task ahead.

The publication of these *Proceedings* would not have been possible without the editorial assistance of session chairs, Rob Bosworth, Dave Brew, Chris Fastie, Brendan Kelly, Gordon Kruse, Sandy Milner, and Ross Powell, and layout editor, Thetus Smith of the Alaska System Support Office, National Park Service.

Daniel R. Engstrom
Editor

OPENING REMARKS

Daniel R. Engstrom
Program Chairman

On behalf of the organizing committee, the Friends of Glacier Bay, and the Glacier Bay Science Board, I welcome all of you to the Third Glacier Bay Science Symposium. It is a personal pleasure for me to be here in Glacier Bay for yet another science gathering and to greet many old friends -- some not seen since our previous meeting five years ago. It seems like a very short time since the second symposium ... or even the first, as I have such clear memories of those earlier events.

I arrived in Glacier Bay for the first time in 1983 to begin my research on newly formed lakes in recently deglaciated terrain. Days before the first symposium, I joined Bill Field and Don Lawrence for a trip 'up bay' aboard the MV *Nunatak.* I must say, it was a tremendous opportunity to first experience this dynamic landscape in the company of pioneering scientists, who had during their lifetimes personally witnessed a half century of glacial retreat and vegetational succession. I clearly recall pouring over volumes of Bill's glacier photos in the *Nunatak's* steamy galley as Bill and Don recounted the great expanses of ice and barren moraines where I could see only deep fjords and impenetrable thickets of green.

Unfortunately, Bill Field has not been back to Glacier Bay since the first symposium, and we will miss him again this year[1] Bill sends his best wishes for our success. Another of the early science giants of Glacier Bay, Dick Goldthwait, will not be returning. Dick passed away last year, and it is to his memory that we dedicate these proceedings. We are very fortunate, however, that Don and Lib Lawrence are able to join us at this gathering. They have attended every one of these events and indeed have played a pivotal role in the creation of the symposium idea as well as supporting in many ways each of the past meetings.

As program chair, I am greatly indebted to many others for making this meeting possible. Organizing such a complex event from a half continent away would have been an insurmountable task were it not for the guidance and support of a truly dedicated organizing committee. I especially want to acknowledge a handful of individuals whose efforts certainly exceed mine -- Carolyn Elder, Lynn Jensen, and John Scheerens for logistics and Jim Taggart and Mary Beth Moss for program. I also want to thank the sponsoring organizations: the Friends of Glacier Bay and Glacier Bay Science Board -- the primary force behind this year's and all past science symposia; the National Park Service -- especially Marv Jensen, for dedicating much staff time to this event; and Northern Illinois University -- registrar for the meeting, courtesy of Ross Powell. I would also like to thank Glacier Bay Lodge and owner Bob Geirsdorf for hosting our event and generously providing the opening reception last night.

Now regarding the substance of our program over the next few days, I would like to emphasize one important point. This Glacier Bay symposium, like its predecessors, has more than a single agenda: (i) We will, of course, be reviewing past and ongoing scientific research in the park and surrounding region -- a process familiar to most in this room; (ii) Our other purpose springs from the theme of this meeting, which is spelled out in the introduction to the program. Our symposium comes at a time when science policy in the National Park System and Department of Interior is in much ferment. We have through our actions here the potential to influence how future science is conducted in this park and elsewhere in the NPS system. Hence, we have scheduled into this symposium a key panel discussion and a series of evening workshops, the goals of which are to develop a draft action response to Interior's Science Advisory Board telling them how we would like to see science conducted in Glacier Bay. I want to strongly encourage everyone to participate fully in this part of the program as well as the technical sessions. Our success depends in a major way on your input to this process.

I would now like to ask Superintendent Marvin Jensen to formally open the meeting.

WELCOME TO SCIENCE PAST AND FUTURE

by

Marvin O. Jensen

Superintendent
Glacier Bay National Park and Preserve
P.O. Box 140
Gustavus, Alaska 99826

September 14, 1993
Gustavus, Alaska

Welcome to the Glacier Bay National Park and Preserve for the 1993 Science Symposium. This is the third in a series of science symposia and is sponsored by the Friends of Glacier Bay, the Glacier Bay Science Board and the National Park Service.

Many people have spent long hours in arranging for this symposium. I would like to thank especially Dan Engstrom for his work as chairman of the symposium, Jim Taggart and his staff, Ross Powell and the members of the science board. I would also like to thank Bob Giersdorf, Gary Sorrels and the Glacier Bay Lodge staff for staying open for the symposium.

I believe that science began in Glacier Bay before European man first came to the area. Science at Glacier Bay began with the Tlingit people, who studied seasons and cycles of the species of food sources and other needs.

The Tlingits' technical reports were the oral histories and instructions from elder to young people on how to provide for themselves and how to treat or interact and live with nature.

Modern science began with John Muir's visit to study the glaciers for comparison with canyons in the Sierra Nevada and other places. William Cooper and the Ecological Society of America followed, seeing the qualities of the place as a science refugium and the need for it to be protected as a national monument for science and other purposes.

Bill Field, Don Lawrence, Richard Goldthwaite and many others capitalized on the protected status of Glacier Bay for studies in a protected area. Many of the basic principles of biology and ecology that are known and taught today came from the work done by these and other scientists working at Glacier Bay.

Considerable amounts of excellent contemporary science continue today on a wide variety of topics of nature and natural forces. Many of you have contributed much to the existing body of knowledge about this place and of natural phenomenon.

As in the natural world, the general nature and approach to science continues in an evolutionary process. There are many forces that shape the what, how, why, who, when and where of studies.

There have been many forces over the last five years since our last symposium that have shaped and continue to shape the science program at Glacier Bay. They are:

- statements and recommendations from the last science symposium.
- the Alaska National Park Service Science Initiative.
- issues associated with the use and protection of the park.
- National Biological Survey (renamed National Biological Service).
- world heritage status.

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I want to touch briefly on each of these forces and issue a challenge to you for this symposium.

Recommendations from the Last Science Symposium

In my introduction at the last science symposium I mentioned that I believed the park should increase emphasis on marine studies because most of the use and activities are in or on the marine systems within the park. I'm even more convinced of that today.

I also mentioned that the Alaska Region of the National Park Service was working on a science initiative. The purpose of that science initiative was to obtain funding for a staff of scientists to study in each park the species, ecosystems, and processes and learn as much as possible so that decisions to be made would be made from a base of knowledge. About one-fourth of the science initiative for Alaska was funded in 1990 and 1991. That funding gave Glacier Bay a scientist and a fledgling science program along with other parks in the region. That scientist has a marine background and so the fledgling science program was oriented in that direction. And not a moment too soon. Because several issues surfaced or resurfaced about that same time.

Issues

The issue of allowing commercial fishing arose at about the same time funding for and hiring of a marine scientist took place. Our approach to the question of whether commercial fishing should continue in the non-wilderness parts of park waters is that the effects on and relationships with this use **must be studied and evaluated before a final decision is made.**

The question of relationships between vessels, whales and other concerns has been going on for more than a decade and was resurfacing at the same time commercial fishing and the science initiative were evolving.

Scientific evaluation of known information relative to these issues was essential to our efforts to update the vessel management program.

World Heritage

In December 1992 another change occurred at Glacier Bay that has relevance to its science program. Glacier Bay was designated a world heritage site by action of the World Heritage Committee. In that action Glacier Bay was joined with Wrangell-St. Elias and Kluane national parks and together became the largest joint, international world heritage site in the world.

Just this past summer on June 22 the Tatshenshini-Alsek Wilderness Provincial Park was established by Premier Mike Harcourt of British Columbia. By common boundaries this new provincial park links Glacier Bay to Kluane and Wrangell-St. Elias national parks. Mr. Harcourt, in announcing the new park designation, said that he would pursue world heritage nomination for the new park. We reviewed and made comments on the world heritage nomination paper for the new park just about a week ago. Adding the new provincial park would be the capstone to the existing joint world heritage trio - joining together some 25,000,000 acres of some of the most incredibly diverse land forms and ecosystems in the world.

International Biosphere

Glacier Bay is already a joint international biosphere reserve with Admiralty Island National Monument, which is administered by the National Forest Service.

NAS & NBS

Just as the Glacier Bay science program started to blossom, events occurred that are changing the entire approach to science in the national park system.

The National Academy of Science published its report on science in the national parks. From my reading of the report, I concluded that it was saying that the NPS had

- not done enough science,
- not done a quality job of science and that
- managers had not listened to or used information from science reports as a basis for NPS decisions.

Just as the NPS was reviewing and deciding what to do about the NAS report, national elections changed the administration and the new secretary of Interior announced that there would be a new agency to do science for all of the Interior Department's land management agencies. Thus was launched the National Biological Service. And, thus was Glacier Bay National Park's blossoming science program suddenly moved out of our immediate grasp.

However, all is not lost. The two scientists, their research technicians, equipment and materials -- all remain at Glacier Bay and, most importantly, their emphasis to do science at Glacier Bay continues. It will simply be done under a different name and by a different process.

Now What?

These areas are protected in a joint international park system. We have a science program under a new agency beginning October 1.

We have many issues demanding information as a basis for decision-making.

Do we simply hang our respective plaques and certificates on the wall and go our own separate ways? I admit having done so about our joint biosphere reserve status with Admiralty Island. But I believe that the time is ripe for joining together all of these interests and forces.

I think we need to join together to

- identify management issues.
- develop research strategies to learn about resources and values associated with those issues.
- share information, study and management programs among the managers of the various protected sites and with the public groups that have interest in these areas.
- work with each other in deciding courses to follow based on sound information.
- pursue coordinated approaches to managing uses.

I challenge you to consider these developments and questions during the symposium.

There are workshops scheduled for these purposes that will provide a forum for discussion on these matters. I am hopeful that recommendations will come from you during these workshops.

I look forward to sharing this week with you and to the reports and discussions that are planned.

R.P. Goldthwait (back, third from left) and former students in Muir Inlet, 1986

In Memoriam

Richard P. Goldthwait was born on June 6, 1911, in Hanover, New Hampshire.
He died on July 7, 1992, at Wolfeboro, New Hampshire.

Comments at Glacier Bay Science Symposium on Richard P. Goldthwait's Activities in Glacier Bay

September 16, 1993
David M. Mickelson

As we gather for the third Glacier Bay Science Symposium, we are without a prominent scientist and friend of Glacier Bay. Richard P. Goldthwait died of a stroke on July 7, 1992, while collecting water samples in New Hampshire. I wish to spend a few minutes commenting on Dick's career and in particular his contributions to our understanding of glacial history in Glacier Bay National Park, as well as to remember our visits here together. Dick, or "Doc G" as he was known to many of his students, first worked in Glacier Bay in 1931. At that time he was part of the Dartmouth-Harvard Crillon expedition and did seismic profiles on the South Crillon Glacier. This was the first glacier bed profiling using seismic methods, and this technology then developed rapidly before and during World War II. As his career developed, his interests were directed more toward glacial geology and glacial history; but he retained a strong interest in meteorology, climatology, and glaciology as well. He did research in the Antarctic, Greenland, Baffin Island, New Zealand, and of course Alaska during his career as a faculty member between 1939 and 1943 at Brown University, and from 1946 until his retirement in 1978 at Ohio State University. It was there that he founded the Institute of Polar Studies, which is now known as the Byrd Polar Research Center.

Dick spent parts of at least 30 field seasons in Glacier Bay during his professional career. After his initial work on the Crillon Glacier, he did field work on the outer coast, the lower bay, and particularly in Muir Inlet. He occupied photo stations with Bill Field, he collected many buried wood samples that were dated and which led him to believe that Muir, Adams, and Wachusett Inlets were gravel filled to well above sea level during the Mid- Holocene.

In my opinion, a landmark in his contributions to Glacier Bay was the leadership role he took in Institute of Polar Studies Report 20 entitled, "Soil Development and Ecological Succession in a Deglaciated Area of Muir Inlet, Southeast Alaska." Although ideas and approaches have changed in the nearly 30 years since its publication, it was an early example of interdisciplinary research done by people in fields ranging from meteorology, biological science, soil science, and geology and serves as a good model as we approach the task of developing a Glacier Bay Science Plan. Another major contribution of Dick's was the student research that he initiated. I count eight former students that did theses in Glacier Bay. All of these have continued productive careers and several of us, including Ross Powell and I, are still actively doing research in the park. In fact, another generation of our students, several of whom are here today, carry on the tradition. In addition, there were countless others who worked as members of field parties without actually doing a thesis, but who were exposed to the breathtaking scenery and soul-searching terrain and climate of Glacier Bay. My fondest memories of Doc G are from Glacier Bay. I remember lying in the tent along Wachusett Inlet, trying to think of puns in an attempt to keep up with the unending flow of puns that came from him. Greg Streveler mentioned one this week as we came over from Gustavus. He remembers Dick stumbling out of thick alder, face scratched, glasses awry, and mentioning that he'd had a "slight aldercation."

He was also a great teacher. Never one to criticize, he let his students critically examine their ideas by questioning. In my first field season in Glacier Bay I found a winding ridge of silt several meters high and about 300m long. It sat on what the geologists here recognize as "Middle Van Horn Formation," lake sediment very similar to what was in the ridge. I hypothesized that this ridge had formed by erosion in this strange pattern. I showed it to him, and he began to ask questions. By evening I realized that it was an esker composed of silt -- something I'd never heard about. By prodding with questions, he had let me discover its origin myself.

Dick received many awards and honors during his career, and I will not take time to list them. I should point out, however, that in 1983 he received an award of merit from the National Park Service for his work in Glacier Bay. His culminating achievement in Glacier Bay was to lead a group of U.S. and European glacial geologists on a field trip to Glacier Bay in 1986. This fulfilled his longtime dream of having an opportunity to demonstrate many glacier processes to others not fortunate enough to have worked in Glacier Bay.

As well as being a great teacher and researcher, Dick was also an environmentalist for as long as I knew him. He was concerned about the future of this planet and in particular areas like Glacier Bay. He approached his concern for the environment, as he did most other things, with reason and with an understanding that there are always tradeoffs to be made, but that a concern for the environment should be a major factor in decision-making.

Finally, I think many of you knew Dick and his wife Kay as friends. Kay wishes to be remembered to many of you with whom they became friends both here and in Gustavus.

VOICES FROM GLACIER BAY: SCIENCE AND THE SENSE OF WONDER

by

Judith B. Aftergut

At the symposium banquet, Judith Aftergut, a writer, read sections from her manuscript *Voices from Glacier Bay.* The book is a combination of commentary, personal experiences, and interviews with people who know Glacier Bay well. One focus of the book is how people see from varying perspectives, how the strict lines break down between "science" and "poetry." Judith has been visiting the Glacier Bay area (mostly in summer or fall) since 1974.

The following sections from the book include interviews with Dr. Field, Dr. Lawrence, Dr. Goldthwait, and Carol Janda. Not all of these specific excerpts were read at the symposium. In the sections which follow, the arrangement of time is not linear and connections are made intuitively. As was not the case at the symposium, the factual base for this material has been reviewed by Dr. Lawrence.

> June 1976. Well-equipped, but not brave, I took five days to build the courage to camp overnight alone in Reid Inlet. I had never camped by myself. The tour boat traveled the West Arm because of thick ice that year in Muir Inlet, when Muir Glacier was in a period of major retreat. As we rode north, the vegetation became gradually different, with a predominance of spruce forest near Bartlett Cove, cottonwoods farther north, alders and willows, then finally bare rock, gravel and ice at Reid Glacier's face.
>
> A crew member rowed me ashore. I placed my gear high on the rocks. It was hard to tell where the tide line was, with so little vegetation and less experience.[1]
>
> The glacier calved often that year. In 24 hours, the entire face of Reid Glacier changed.
>
> I lost my binoculars and camera in their black leather cases among rocks. My search for them was successful. A thought came to my mind, an earlier bit of advice given by Chuck Jurasz, who was conducting research on humpback whales in Glacier Bay. I ignored it.
>
> I hiked to the Ibachs' cabin and back along the beach. Joe Ibach was a miner, hunting guide, homesteader. He and his wife Muz had a reputation for independence. Although the Ibachs were no longer alive and swallows nested inside their cabin, I felt their presence. I set up my tent and ate dinner about 11 PM. I fell asleep at sunset. All night Reid glacier moaned and creaked.
>
> In the morning, I explored a stream bed beneath late spring melting snow arches, then met the tour boat on the beach. A humpback whale surfaced at the entrance to Reid Inlet as we left.

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[1] On the coast of Alaska, after the earthquake of 1964, a line of white barnacles on the rocks was used to measure the previous tide line. Sea level on the coast had shifted in the range of seven feet. Dr. Lawrence, personal communication.

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When the film from my camera was developed and returned, I learned that the roll of film contained 20 pictures, not 36. My extensive photographic efforts had been useless.

The advice I had ignored was, "See for yourself."

July 1976. Dr. William O. Field spoke to park staff in Bartlett Cove on the 50th anniversary of his first Glacier Bay trip. He had returned again to Glacier Bay to see, photograph and measure the glaciers' positions rather than to celebrate.

On this July evening, Field discussed a specific phenomenon which interested him. Some glaciers in Glacier Bay were advancing while others were in retreat. He was searching for possible reasons. Field referred to an explanation proposed by Austin Post of the U.S. Geological Survey. The basis for the advances, he asserted, was not climatic. Post proposed that, when tidewater glaciers laid down sufficient outwash deposits, the inlet became shallow, particularly on the resulting beach at the glacier's face. Such glaciers then began an advance as the ice slid forward over the outwash. The glacier's advance would depend not necessarily upon colder temperatures or larger snow deposits at higher elevations but upon a slowing of the glacier's retreat and the shape of the inlet.

After Field's presentation, I asked him a more personal question: "What is it like to see these glaciers over so many years?" Bill Field was a tall man with a shock of white hair and a quiet voice, extremely dignified, almost patrician. He smiled and said, "It's like visiting old friends."

In September of 1979, Don and Lib Lawrence came to Glacier Bay to celebrate the 100th anniversary of John Muir's first visit. Don Lawrence showed slides of trips to Glacier Bay in the 1940s and '50s, when Muir and McBride glaciers had just separated.

One surprise for Don Lawrence during his summer 1952 visit to Glacier Bay was that *Dryas* plants have growth layers in their stems (rings). He "discovered" this one night in a dream, then saw it to be true when he looked, and later he found it described in a scientific journal.

Lawrence said, "It was exciting to have the dream come true."

That night Don Lawrence showed a sequence of slides and described experiments he and Lib performed in the early 1950s on a research site located between Goose Cove and Nunatak Cove. They called it their "farm," although they planted no crops and did no cultivation. The nickname was invented by Lib. They did fertilize a few circular millacre plots (disks of 1/1000th of an acre each). Natural accumulations of nitrogen are not present in raw glacial till. The objective was to see to what extent this absence inhibited the growth of pioneers in the succession process. To discover how added nitrogen might enhance the growth rate of cottonwood saplings already well established in the area, within the test plots they planted alder seedlings near some cottonwood saplings. They mulched some cottonwoods with alder leaves, placed NPK fertilizer on the ground around other cottonwood saplings, and left some saplings growing with nothing added. Those cottonwoods treated with some source of nitrogen grew faster than usual. This demonstrated the great importance of nitrogen to the growth process.

As the Lawrences measured growth of the undisturbed test cottonwoods over the years, they made an unexpected discovery. One single cottonwood growing with no visible added nitrogenous material from alders and without fertilizer containing alder leaves grew at a faster rate than the others. Don Lawrence had no explanation, until he found cottonwood roots reaching out to nearby *Dryas* plants. At that time plants of the genus *Dryas* were not known to fix nitrogen. Later Don noticed that *Dryas drummondii* plants, which grow in expanding circles, were increasing their coverage faster than one would expect and that these pioneering plants were a dark blue green in color. He found they were fixing nitrogen from nodules inhabited by actinomycetes, an order of filamentous bacteria on their roots. The resulting root nodules resembled clusters of coral. This was the first discovery of nitrogen fixing in any member of the rose family. Since the time of Dr. Lawrence's discovery, five genera of the rose family, mostly pioneering plants in environments from desert to alpine, have been found to fix nitrogen.[2]

In 1952, Lib recorded indicators of annual vertical height growth of cottonwoods as measured between alternate sets of bud scale scars, formed when winter bud scales fell off the cottonwood branches each spring. "The cottonwood is a very accurate, faithful, obliging, external (!) timekeeper," according to Don. "You don't have to cut down a cottonwood to count the growth layers or rings. This was the ideal place to learn exciting things about process and early stages of ecosystem development."

The Lawrences' slides from 30-40 years earlier impressed the audience of Gustavus residents, park staff members and others with long connections to the area. The room was filled with their exclamations. Don Lawrence did not seem to note this surprise. He continued calmly his presentation.

A few days later, Don and Lib traveled up Muir Inlet. It was reported that Don stood on deck for nearly the whole trip, coming into the cabin only briefly to warm up.

Since the early 1950s, Don and Lib Lawrence had never gone farther up Muir Inlet than their "farm." Muir Glacier had receded 11 miles in the intervening years.

In September 1983, at the First Glacier Bay Science Symposium, Dr. Richard P. Goldthwait, professor of geology at The Ohio State University, wore his "Friends of the Pleistocene" t-shirt. I asked him about his perspective on time and change through the lens of geology and glaciology.

JA: I suppose geologists must have a sense of time and the process of change that most people don't have. Most people don't look at a landscape in order to decipher history in the same way that a geologist would.

RG: We have to. We have to think of this as just the end product of a whole several billion years of physiographic or geophysical activity on the earth. My own field is mainly geomorphology or glaciology. I study the last two- or 2-1/2 million years. I leave the rest to someone else.

Spring 1979. Seattle. The poet Robert Bly quoted Carl Gustav Jung at the seminar I attended. Bly said as we reach our twenties, a few events in our lives may stand out like rocks in a sea of perceptions.

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[2] Kohls, Steven J. et al. *Plant and Soil*, 1994. Volume 162, pp. 229-239.

These initial events begin a sense of our personal knowing. Bly went on to say that, in our thirties, we gain more awareness, and the "rocks" of perception become "islands." In our forties, these thoughts may coalesce. We have a different sense of ourselves. "Islands" of thought connect, expand and begin to form "continents."

Dr. Goldthwait studied land depressed by the weight of ice and rebounding in Glacier Bay over centuries. Glacier Bay islands have risen literally, three centimeters on average per year near the mouth of the Bay, three meters per century.

Geologists study the processes by which the earth forms and is shaped. This process occurs with the sudden devastation of earthquakes, the explosiveness of volcanoes, the power of glaciers, with gentle deposits of dust, mud or ash, and from the movement of tectonic plates. Geologists find a history of these processes in the layers of deposits, unraveling a history of constant change where everything, above or below the earth's surface, changes form sooner or later.

They don't speak much of the resulting sense of impermanence. Most people live in an illusion that the earth is stable. Geologists are not trained to speak of the poetic and the mystic. Most of us do not pay attention to the earth's daily alchemy, to transformation and metamorphosis.

Geologists prefer to deal in facts. Yet, buried beneath their own personal surface may also be a deeper story. They delight in discovery. Unspoken layers of realization may be revealed by a sparkle in the eye and a shift in voice tone. Their lives are concerned with specific events, processes unnoticed by most people, and in seeing the "truths" of existence over a million year time frame.

Geologists develop a different sense of time from most people. They know they measure only minute fractions of the earth's activity, yet a scientist is constrained by the need to appear to know something. It must be difficult to live in a discipline which, by its very nature, makes it clear that everything changes, when the objective of so much science is to find certainty and definitive explanations.

Geologists are at the mercy of time, weather and wind, of accidents of nature, of being (with luck) at the right place at the right time, at the whims of their engines and winches. They learn to read a landscape as a parent might read a child's face. They live in a combination of what is obvious -- layers of rock offering clear indications of the earth's motion -- and of the world's mysteries. They make up stories about their "findings," based upon radiocarbon dates, rates of erosion and deposition, weathering and other earth transitions.

They are detectives, filled often with a hidden sense of wonder. Geologists are a bit shy. They're used to understatement. Not everyone understands their language or shares their interests. Most people look on the surface. They search beneath as well.

Geology can be intrusive, requiring extraction of core samples from deep in the earth, preparation for mines and oil drilling, yet geologists may have a quiet intensity -- observing, questioning, conducting a love affair with the land. Rocks don't shout out their history. It takes subtlety to notice. You have to dig for it.

November 1978. On a greyhound bus traveling between Seattle and Portland, I met a poet and former TV reporter who had grown up in Harlem and Jamaica. I spoke of Glacier Bay and how ice carved the land's surface, with the resulting alternation from sea and fjord to river valley. I said I had learned there to be careful of my own impacts on the landscape -- to leave few reminders of my presence, for example, by building a fire, (where there is wood) low on the beach, beneath the high tide line, so the incoming tide washed away the remains.

He said, "What about people's impacts on other people?"

I wondered if he thought it less important to care so much for land when people in the world are in need. I did not give him enough credit. Although my new friend had not seen Glacier Bay, he said, " It's a wonder, a marvel, like a cloud chamber in physics, where you can see things that aren't theoretical. It demonstrates the truth of the theory."

Carol Janda spent 14 years at Glacier Bay while her husband served as chief ranger for the National Park Service. I spoke with her in the spring of 1978 at Coulee Dam, Washington, where they had moved after leaving Glacier Bay. Carol Janda was an artist, a potter and painter. Her comments about Glacier Bay were often stated in visual terms.

CJ: If you think about it, you begin to realize immediately that it's the quality and length of the sun's rays that make the difference in the light in that part of the country. If you're thinking about painting or photography, it's one of the reasons the area is so photogenic.

JA: Sometimes after I've been to Glacier Bay, I feel that I see things more clearly. I'm not sure if I really do.

CJ: I think you do. Partly it's because you've got your own head together more, but you can do that anywhere. You don't have to go to Glacier Bay. You can do that in Coulee Dam or Seattle or wherever, but the opportunity for interruption is much greater where there are more neighbors and television and shopping and the movies and other people.

It takes time, quiet time in Glacier Bay or anywhere. That's what contemplation is. That's probably what meditation is. Without the opportunity to meditate, meaning a lack of distractions, you don't meditate. At Glacier Bay, you did have the opportunity to meditate. In fact, it's forced upon you, and if you took it, then you ended up doing this intensity thing to yourself, where you were very intense about certain topics or in certain ways. Then you had to take a little dose of "Don't take yourself too seriously."

It's irrelevant whether that intensity is healthy or unhealthy. It is what it is. Probably there are many people who lived at Glacier Bay who didn't feel that intensity -- who didn't recognize it or didn't want to recognize it or who weren't interested, and I think they were probably perfectly happy -- happier than I was, perhaps. I don't know what good it's going to do me. Maybe no good, but it's there.

The trouble is, we're all separate. We're all alone, whether we like it or not. I think probably the sooner you learn that, the more able you are to cope with it. It doesn't make you any happier to know it, but it's wise to know it. You're stuck with making your own decisions because it's your own life.

JA: Do you think with experience around Glacier Bay, in living with that long span of time, a person can develop a sense of where we fit in the world in terms of history?

CJ: The school kids in Gustavus did a timeline -- "Where was the glacier in 1492, and where was the glacier in 1776?" You realized that 200 or 300 or 400 years ago, there was no Bartlett Cove. Perhaps the islands stuck up a bit, but basically they were not even there. To visualize the glacier moving back in that period of time makes you more appreciative of the actual speed with which some of these things happen in glaciated country, as opposed to the wearing down of the Appalachians, for instance, where you have evidence that it happened but you can't see it daily or even yearly.

Bill Field's work relates totally to that. As far as placing ourselves in the time frame of mankind is concerned, I don't think I ever quite achieved that. I don't think I had enough input to decide where I was. I think you could decide, and you could decide better in Glacier Bay than you could, for instance, in Seattle. I definitely believe that, because in Seattle, or here in Coulee Dam, you don't get to thinking about it.

- KEYNOTE ADDRESS -

CAN SCIENCE REALLY FUNCTION IN THE NATIONAL PARKS?

by

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In consideration of our immediate task - "Creating Glacier Bay's Research Role within Park, Regional and Global Contexts ... A Plan for Action" - can we utilize a systematic method of decision-making to arrive at a "fundamental metamorphosis" to benefit Glacier Bay resources? We most assuredly can. The question is not if we can, but do we have the will and capacity to follow through.

I was one of 12 members of the National Research Council Committee (NRC) on "Improving the Science and Technology Programs of the National Park Service." It was a fascinating exercise, to say the least. My associates included two retired NPS employees, one a planner and the other from management; one Forest Service bioadministrator and one Forest Service researcher and seven academicians: two sociologists, an architect, a botanist, a mammalogist, and two administrators. All seven of the academicians either depended upon NPS support or were in a position to benefit from NPS contracts.

I began my task with considerable enthusiasm, a born optimist. Mid-way through I was still optimistic, although by then I had a few misgivings. Toward the end, I decided to submit a minority report. But the process dragged on and on, with changes in our approach occurring with each draft. Finally, because of the press of other projects and the lateness of the hour, I did not submit a minority report. I regret that decision.

The NRC process, in itself, was adequate, in my view. But the design and report were still left to 12 personalities, several with more persuasive ability than others. And a few unwilling to comprehend facts or to change their original position. For example, in spite of the fact that I discussed the difference between research and resource management in the Park Service on at least two occasions, and we agreed to include related recommendations about the separation and retention of a resource management program, the concept still did not get through to most of the group and was left out of the final report.

Additionally, at the last meeting of the NRC Committee, we agreed on the necessity of a Science Advisory Board that would report to Congress or an independent entity, that would include members of pertinent non-governmental organizations and have legislative authority to assess all aspects of the NP science program. The published report mysteriously excluded that recommendation and, instead, recommended an advisory board that "should report to the director annually." The proverbial fox watching over the chickens.

The published report included a set of recommendations that, in my view, were good and necessary, but did not go far enough and address necessary organizational changes. The management-type members of the committee won the day with the theme "Don't rock the boat." I believe that we missed a great opportunity to lay out a strategy that could have made a real difference. And now, since the NPS has still not been able to get its act together, much

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of its science program is being removed by the new Secretary of Interior's revival of the National Biological Survey (Service). Change will undoubtedly be severe. But for the first time it may get the attention of park management. I am convinced, however, that if the Park Service had taken action earlier, as was recommended when the opportunity arose in the context of the State of the Parks Report in 1980 and 1981, such drastic action would not now be necessary.

Only time will tell how effective the National Biological Survey (Service) changes will be. I suspect that the NBS will enhance the more global issues, such as Global Climate Change, Inventory and Monitoring, and Information Transfer. Thinking people recognize that we are facing a global environmental crisis - that requires widescale action. A wiser man than I said that "it is time we steered by the stars, not by the lights of each passing ship." Let's hope that the NBS provides the organization to address that requirement.

But what about the more day-to-day national park issues? Those will continue to require an NPS response. In my view, a systematic process is still essential to reach certain objectives. And many of our parks, in spite of being part of a global research network of one type or another, must still get their act together if the problems are to be resolved. We must include an inner ecology in all that we do - recognizing that we cannot be our best unless we are no longer part of the problem.

Defining objectives remains the logical place to begin. But it isn't always easy to determine the true objectives. In truth, we enter an exercise with our own perceptions, and more often than not, with our own priorities. It, therefore, requires a measure of performance. A highway system can be measured by a certain throughput. But we are dealing with ice, rock, trees, flowers, birds, and bugs - the components. The ultimate objective may be the long-term perpetuation of a healthy ecosystem.

Fixed constraints must be considered. These include such things as congressional mandates: enabling legislation, Antiquities Act, NEPA, Endangered Species Act, and so on. The scientific expertise required to do the job must be included, as well as management that must be dealt with in a practical and mature fashion.

As we progress with the process we must be ever wary to not jump to early conclusions. I am reminded of a group of city fathers, when confronted with multiple automobile accidents along the main road into their town. That route ran along the top of a cliff before descending into town via a winding, dangerous road. People drove off the cliff or missed the turns. The city fathers met and identified the problem: dead and injured people at the base of the cliff. After much deliberation, the town purchased an ambulance and stationed it at the bottom of the cliff. They felt very civic minded, but accidents continued. Their solution only resolved part of the problem, not the reason for the problem.

Most of the NRC recommendations are still valid, even with the advent of NBS. They include, in my order of priorities:

1. Separate funding and autonomy and improving the budget environment. This requires a complete reorganization of the way funds are allocated to science. It will require line-item funding and tracking, along with multi-year expenditures to assure the continuation of projects. The process must be fixed so science allocations cannot be moved elsewhere at the discretion of a regional director or superintendent. How does this relate to Glacier Bay?

2. NPS still needs an explicit legislative mandate for science. This would not be necessary in the best of worlds. But so long as the parks are being managed by non-scientists, in a few cases anti-scientists, or those who have sold their souls to the bureaucracy to get where they are, we need a mandate for separate funding and autonomy.

3. NPS still must build greater credibility in science. This should begin with elevating the role of the Chief Scientist, encouraging external science, and the establishment of an external Science Advisory Board.

I also want to take a few minutes to defend the value of a separate natural resources management program at the park and regional levels. Natural Resource Management Specialists perform the liaison between science and management and coordinate the implementation. Scientists should not need to concern themselves with the interpretation of their reports (so long as the reports are written in an articulate manner) except to assure themselves that the interpretation for management is correct. Scientists should not need to concern themselves with the implementation of their recommendations except to assess the success of the implementation. Scientists should not need to concern themselves with preparing resource management plans, EIS documents, and a host of other management documents, but only to review them to assure their scientific integrity.

The Resource Management Specialist should get away from the computer long enough to interface with the scientist to make sure the direction and purpose of the research complies with the work orders, and that all new, pertinent data is incrementally incorporated into management decisions. Park management should never be surprised with any of the research findings that appear in the annual or final reports.

My principal concern today is about the resolve at the park and regional levels. How to address the myriad of issues that are not yet of global concern, but are of immediate and vital importance if we are going to protect the whales, or the unique forest ecosystem, or the bald eagles.

How can scientists function amid the changes, the constraints, the ever-increasing requirements that seem to have little relation to the overriding issues of the day?

Although many components of our world are changing, there also is much that stays the same, and perhaps we can begin to deal more effectively with that. An often-heard complaint is that there is just too much paperwork. There is no doubt that requests for reports and other paper have accelerated in recent years. But Park Scientists are often to blame for their own inaction. I have just completed three years of visiting national parks all across the continent, from Forillon on Canada's Gaspe Peninsula to the Everglades, and from Jasper and Banff to Chiricahua, Big Bend, and Jean Lafitte. Over and over I discovered that the scientists, resource specialists, and interpreters that complained most were those individuals that spent most of their time in front of a computer screen doing things of minimal importance.

Funding has seriously declined throughout the park system, and yet some parks have found a way. They seem to find dollars in mysterious ways. What too often is missing is will and tenacity. So much depends upon your own set of priorities, and your resolve to get on with it.

The field scientist is often the first to note an impending problem, and he or she cannot always wait for the mechanics of bureaucracy to swing into action. It may be necessary to strike out on your own, to stick your neck out in the process. It has been my experience that nothing truly worthwhile is achieved without significant risk and effort.

Where to begin? Can science really function in the national parks?

The answer must be an overwhelming yes! The Glacier Bay, the Alaska Region, the NPS science program must go forward. It is time to evoke powerful images and establish sound objectives. Take advantage of those visions that already are a reality: World Heritage Site and Biosphere Reserve status, and the many scientists, both from NPS and external institutions, who are willing and eager to continue their work here because of the mystique of this place, which is also the workplace. It seems to me that the greatly expanded World Heritage Site designation can be utilized as a powerful tool to benefit all the areas concerned. But don't concentrate your efforts. Take advantage of every conceivable opportunity.

Where must the Glacier Bay science program be in 20 years? How can that program most benefit the multiple resources?

Develop a systematic process to reach a stated goal in a practical timeframe. Design a strategy that evokes all the elements possible, and attack each phase with vigor. Utilize each of the NRC recommendations that might benefit Glacier Bay.

Also, there are some basic truths that must be included. For instance, don't stop making your point about Glacier Bay's being the best possible site for the Arctic System Science Program. Make sure that all requests pound out the fact that this park's enabling legislation, unlike most national park units, created Glacier Bay as a research park in recognition that it is one of the world's premier natural laboratories for studying ecological interactions between glaciers and terrestrial and marine ecosystems. That Glacier Bay represents the very best model anywhere for addressing those kinds of issues. Perhaps Senator Murkowski needs to introduce legislation that identifies Glacier Bay as America's National Laboratory for Arctic Research, including line-item funding to support that program.

It is vitally important that you take advantage of the new NBS and not let it stall your efforts or enthusiasm. Think through the new circumstances and determine how best to proceed with the additional **opportunities,** not constraints, provided.

Some additional thoughts: 1) Know the park resources first-hand. A completed, award-winning GIS is not a substitute for real knowledge - it is only a tool for perceiving that knowledge. Another way of stating the obvious is if you spend more time at the computer than you do in the field, you will lose touch with the real issues and not be able to speak for nature when necessary. 2) Knowledge is power. Take advantage of your knowledge about the area in a subtle, caring way so that you, a representative of park science, will be held in respect, not as an antagonist. 3) Keep in mind that the squeaky wheel gets the most grease. And 4), don't ignore or lose sight of aesthetics. One of our most powerful arguments is our park's scenic attributes - the uncontested wilderness - nature in the raw - our moral responsibility for its long-term perpetuation.

Let's not tread water while waiting for assistance from NBS. The viability of the park resources, the Glacier Bay ecosystem, is up to you. Their very survival may depend upon what occurs during the next few days of this symposium.

Role of Physical Sciences in Global Change Research at Glacier Bay National Park and Preserve

by

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Abstract

Glacier Bay National Park and Preserve (GBNPP) is uniquely situated to provide significant data to the world's global change research initiatives. Its past glacial and climatic records and its present physical and biological environments allow collection and analysis of some unique data sets, unobtainable elsewhere in the world, that could have important repercussions for global change modelling. This paper describes what data need to be collected, and by what means, in atmospheric, glaciological, glacial geological, hydrological, marine geological and oceanographic sciences.

KEY WORDS: Global change, national parks, pyhsical sciences (atmospheric, glaciology, glacial geology, hydrology, marine geology, oceanography).

While glaciers in the rest of the world advanced only several hundred meters during the Little Ice Age, those in the Glacier Bay Ice Field (GBIF) system experienced at least 80 km of terminus advance, as documented from old sediments exposed on the fjord walls. Tlingit oral narratives suggest that the advance was extremely fast, and was perhaps a surge. I quote two Tlingit narratives directly from Dauenhauer and Dauenhauer (1987).

"Gatheeni, the bay where the glacier was... It was while people were living there, the houses: maybe as many as five houses stood there... It was said you could clearly see up the bay; it [the glacier] was only a tiny piece, it was hanging there up the bay. Hunters would go up there by boat. Suddenly people said, 'What's wrong with the glacier? It's growing so much!' They used to see it way up bay. But now it was near, getting closer, the way it was moving, people said...[i]t was now growing fast. They said the way it was moving, the way it was growing, was faster than a running dog. Then people became afraid. It was when the year was becoming full...'Little Black Glacier that was there from long ago...is already disappearing into the new one' is what people said... At the same time Glacier Bay was murky... It was churning up from the bottom of the bay. Whirlpools churned over to the surface like the tide. Where the glacier was moving, it behaved that way... The clay there was like diluted milk. '[T]hat glacier...[is] nearly on top of us...the way its going...like a running dog...there's no way to get away from it' [is what they said]. How swiftly it was growing. It was even faster than anything" (Susie James, p. 245-260).

"Now this is the way...things happened to us in Glacier Bay... At that time the ice didn't begin advancing from the top. It began advancing from the bottom. That is why no one knew... All of a sudden it struck the middle of the land people were living on. Why was the land shaking? People thought it was an earthquake; it didn't bother anyone. Why didn't it quit? Here it was, the ice crushing against itself and moving in... 'It wasn't an earthquake was it? It's becoming stronger.' The people forgot about it again... [Before] there was no glacier to be seen...[then] the house was already falling over on its side from how strong the ice was getting. It was behaving like it was crushing against itself, how strong the ice was. And they knew. It was the ice pushing the people, wasn't it? It was pushing the village along. 'It isn't right... Quick! Let's pack...' On that side of the village people were packing; it was already like a whirlpool. The village was trembling constantly... When they were all seated in their canoes they just drifted... Only when they were drifting out they saw. The house was rolling over... It fell over sideways...it was sliding

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downward...to the bottom of the sea before their eyes" (Amy Marvin, p. 261-291).

After this rapid advance to beyond the mouth of Glacier Bay, the GBIF system experienced a rapid retreat; the largest documented in human history. During retreat, the GBIF system first divided into the Russell System and Muir System glaciers and then into the smaller glaciers we see today. The retreat is very well documented, although many of the data evaluating specific driving forces are yet to be collected.

While some glacier termini in GBNPP were still retreating, others reversed their movement and started to readvance. Consequently, the area is a prime site in which to evaluate the driving mechanisms of marine-ending glaciers. That is, determining the relative importance of climate versus self-regulating mechanisms such as subglacial conditions, or the effect of sediment supply changing water depth at grounding lines. Such data are directly relevant to our understanding of glacier behavior during a global climate change.

A compilation of world temperature data shows that southern and southeastern Alaska have experienced warming up to 2° C in the recent past (e.g. Jones and Wigley, 1990). If that trend continues, then the glacial behavior needs to be predicted in order to plan appropriate responses to local and regional environmental changes. The National Park Service (NPS) may need to consider such changes in management plans.

On a longer time scale, documenting the fluctuations of the GBIF system through the Quaternary will aid in interpreting the past climatic history of the northern hemisphere, and specifically, the timing of glaciation and the response to climate change of the Laurentide Ice Sheet (LIS). The Gulf of Alaska is the major moisture source of the LIS and the GBIF, and their behavior is, therefore, directly linked to changes in circulation patterns and moisture contents of air masses originating in the Gulf of Alaska. GBIF is closer to the source as well as being a documented rapid-response system to external forcing. Consequently, GBIF will predictably show a more rapid response to climatic change than the LIS, and the record of that response will be best preserved in the glacimarine record. We need to document the older marine record and relate it to climate change using models that are constructed from studies of the more recent behavior of the glaciers.

The last example I use in documenting the utility of the Glacier Bay area is its internationally recognized status as a prime site for successional studies in terrestrial, freshwater and marine systems. The physical environment and changes in it are primary controls on the ecology and its development and changes. Thus, physical science studies in GBNPP are essential to understanding the factors controlling ecological succession.

Atmospheric Sciences

The major atmospheric science data needed are meteorological; they are required to characterize the regional setting and provide the background for comprehensive glacial mass balance studies. Instrumentation required for data collection consists of meteorological stations placed at strategic locations in the bay. An additional series of sites should include high elevation snow accumulation areas on both the west and east sides of the Fairweather Range, and in the Takhinsha Mountains for glaciers feeding Muir Inlet. Mid-elevation sites in the same areas should be established at equilibrium line altitudes. The fourth group of stations are coastal and within areas where higher elevation data are collected as well as in transects down major fjords of the bay. This arrangement would account for changes in meteorological conditions with elevation and also it would be able to define different sources of weather (especially moisture).

The NPS and university scientists should ideally collaborate in monitoring and data analysis; however, there must be a commitment to long-term maintenance, which would be best done by the NPS.

Glaciology

Given that the region was created and is still dominated by glaciers, the paucity of glaciological data is alarming. Two major aspects of glaciological data are a priority at the present time. The first is glacial mass balance, both past and present, which is critical for any predictive models of glacial behavior. The second is subglacial condition information which is also important for predicting glacial stability in terms of flow velocity and sediment delivery to grounding lines. Subglacial streams are extremely important in creating water column structure in fjords as they affect salinity and sediment concentrations and ultimately influence productivity in fjords.

Types of data required for documenting mass balance are those from ice cores, snow pits, ablation stake grids, and remote sensing (aerial photography, synthetic aperture radar, radio-echosounding). Glacier calving mechanisms are also very important to the total mass balance for marine-ending glaciers, since most of their ice loss is by calving. Actual mechanisms controlling calving speed are not understood. Documenting flow velocities for total ice flux needs to be done for calving flux rates and mass balance studies. Determining subglacial conditions over broad areas is best achieved by use of ground-penetrating radar.

Glacial Geology

Studies documenting past glacial fluctuations are needed in upper Muir Inlet and throughout the west arm to extend the excellent data base available from lower Muir Inlet. It appears that the Russell and Muir systems behaved differently and perhaps independently. Consequently, a reliable past record of glacial fluctuations from all around GBNPP is required for providing models on which future glacial behavior can be predicted. Some excellent records may be retained in preserved lake sediments.

Processes at modern glaciers should also be studied in order to provide models for interpreting past glacier behavior as well as predicting future changes.

Hydrology

The monitoring of outwash and runoff streams has not been done systematically in the past, although some very discontinuous measurements have been made by individual researchers for short periods of time. Selected streams should be gauged for both water and sediment discharge, and rating curves for each should be constructed. These data are needed as baseline information for the glacial, marine and lacustrine studies as described elsewhere in this paper, as well as for freshwater and marine ecology and successional studies.

Marine Geology

Two aspects of marine geology currently require investigation: modern processes, especially near tidewater termini, and past glacial movements as recorded in marine sediments. In a similar way to glaciers ending on land, documenting modern process at tidewater termini enables construction of models that can be used to interpret older marine sediments, as well as predicting future glacial behavior. Standard marine geological techniques such as sediment trapping, echosounding, side-scan sonar records, and using a submersible ROV, can be used at tidewater termini to document the processes.

High resolution seismic reflection and acoustic profiling should be combined with gravity and piston coring to document past glacier behavior. However, ultimately, drilling of sediment cores must be undertaken to verify longer histories inferred from the total thickness of sediment recorded in the acoustic profiles. Long cores are required to reach the deeply buried deposits that hold the best pre-Little Ice Age and Little Ice Age advance glacial record. These programs of acoustic profiling and sediment sampling should be conducted in the fjords and on the continental shelf of the Gulf of Alaska.

In addition to the sediment record, paleoecological and paleobiogeographical analyses should be conducted in order to fully characterize the older environments recorded in the sedimentary record.

Oceanography

All aspects of oceanography, geological, physical, chemical, and biological are urgently needed for the data base in GBNPP. Very little oceanographic monitoring has been carried out in the park. Data need to be collected to document such things as glacier-seawater interactions, suspended particulate transport and deposition, fjord water mixing, tidal currents and velocities, fjord water circulation dynamics and models, marine ecology relative to glaciers and fjord maturity, organic carbon characterization and sources, and phytoplankton blooms and productivity. Combined, these data would contribute to resolving problems such as glacier melting rates and calving speeds, paths of sediment transport and settling and its accumulation rates, annual productivity and food web strength and characteristics, and differences in sediments and biology relative glaciers and fjord maturity.

These data should be obtained using long-term moorings in transects down-bay (which should be established and monitored by government agencies) and seasonal moorings and transects closer to glaciers (to be carried out by university and government researchers). Remote sensing images and analyses should be used to extend that data base aerially and spatially.

Recommendations

A large range of data from GBNPP is required to create a reliable base for global change research. Consequently, a variety of scientists are needed from different government agencies as well as from universities. Ideally, a physical scientist should be located in the bay to coordinate the extensive efforts required to do a thorough job. The NPS needs to accept the responsibility to conduct or ensure implementation of long-term studies that can outlast individual research projects and investigators. Long-term monitoring projects should include aerial photography of GBNPP, glacier terminus photography, meteorological stations and oceanographic moorings.

These cooperative studies will require both a variety and increased number of scientists; the NPS needs to evaluate the "carrying capacity" of scientists in the park and provide guidelines for researchers to follow in relation to field operations. Scientific facilities within the park need to be improved by construction of a science center that would include laboratories, library facilities, gear storage, and sleeping quarters. Ideally, local and regional school children should be involved in the research and the science center.

The Glacier Bay Science Board has an important role to play in future initiatives. The board should attempt to communicate with all scientists as well with the NPS and NBS personnel at the park; it should stimulate interdisciplinary interaction during periods between Science Symposia by using newsletters. It should encourage current Glacier Bay researchers to attract other experts into the bay to do additional research.

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Bedrock-Geologic and Geophysical Research in Glacier Bay National Park and Preserve:
Unique Opportunities of Local-to-Global Significance

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Contribution from the Geological Survey of Canada No. 27394

Abstract

Bedrock-geologic- and geophysical-research opportunities exist in Glacier Bay National Park and Preserve that would contribute both to "Science for the Park" and to "the Park for Science." The geoscience research topics are classified into 10 major categories, which, in turn, are loosely grouped into (1) presently active phenomena and (2) those recorded in the older rocks. The topics concerned with presently active phenomena are of global significance, are unique to the Glacier Bay region, and cannot be studied in any way elsewhere in the world; they are thus the primary topics of this paper. The other topics are of regional and local significance, and can only be studied in the park but are only briefly summarized here. Presently active phenomena include (1) uplift and lateral fault motion, including current vertical uplift centered on Bartlett Cove (which probably has the highest uplift rate in North America), differential warping of uplifted ancient sea terraces on the outer coast south of Lituya Bay, and movements on the Fairweather Fault; (2) seismicity, including activity on the Fairweather Fault, on a "cryptic" seismic zone that appears to span the gap between the Denali and Fairweather Faults through the upper part of Glacier Bay, and on the Fairweather Fault; (3) mass wasting, including rockfalls and resulting giant waves in Lituya Bay and the large developing detachment on the north side of Tidal Inlet; and (4) possible dynamic causes of the very large, positive gravity anomaly that is associated with the Fairweather Range.

KEY WORDS. Glacier Bay, regional uplift, faults, seismicity, mass wasting, future geoscience research.

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This introduction to this paper lists the geoscience-research studies that, in our collective opinion, should be undertaken in Glacier Bay National Park and its environs. The backgrounds for the most important of these topics are discussed in the other sections of the article. We do not propose specific detailed programs for these studies here, but we do urge the park staff and the concerned scientific community to cooperate in developing and supporting the appropriate research. We consider the Glacier Bay region to be a unique field laboratory for studies of large-scale crustal geodynamics and for the assessment of earthquake risk. We also hypothesize that complex but understandable relations exist between present seismic patterns and regional uplift, and that these relations are both direct and indirect continuations of the faulting history which extend back to at least 25 million years ago. We believe that such studies should be the future focus of integrated bedrock-geoscience research in Glacier Bay National Park and Preserve and in adjacent regions (see Hunter and Powell, this volume, for index map).

Present-day seismicity is concentrated on the Denali Fault, on a "cryptic" (that is, poorly understood) seismic zone that connects the Denali Fault with the Fairweather and Transition Faults, and on the Fairweather and Transition Faults (Figs. 1 and 2). Regional uplift is apparently centered on Glacier Bay proper but extends more than 200 km to the south and 100 km to the east (Fig. 3). Faults recognized in the Glacier Bay region are parts of the dominantly north-northwest-striking mosaic that characterizes all of southeastern Alaska and adjacent regions (Figs. 1 and 2); that mosaic is inferred to have first developed during early Tertiary time, and the faults have ten's to hundreds's of kilometers of post-Oligocene lateral offsets and as much as 10 km or more of vertical offset. The long-term development of these faults surely was accompanied by significant seismicity, and so we view the current seismicity as the present-day manifestation of a long-lived tectonic history.

Other factors have combined to produce the largest isostatic-gravity anomaly in North America beneath the Fairweather Range (Fig. 4). All of these factors have also produced the exceedingly steep and high topography that not only has allowed the development of late Tertiary and Quaternary glaciers but also has created an environment wherein earthquake-induced major mass-wasting events occur. We discuss below the present-day seismic patterns, fault motions, regional uplift, and mass-wasting followed by discussions of past fault motions and the geophysical anomalies.

Research opportunities afforded by the older rocks and not discussed further here are (1) geomorphology of the different parts of the park and preserve (to our knowledge, no systematic research has considered this topic since the early physiographic analyses); (2) vertical and horizontal petrologic and chemical variations in volcanic, granitic, and gabbroic rock bodies throughout the park, including volcanic and granitic units of various ages and the LaPerouse, Mount Wilbur, and Mount Fairweather layered gabbro bodies (the most recent research on these rocks is by D.A. Brew and others written commun., 1994, for the composition and geochronology of the granitic units; and by Loney and Himmelberg, 1983, for the layered gabbros); (3) textural and mineralogic variations in metamorphic rocks, especially those in the high part of the Fairweather Range west of Johns Hopkins Inlet, at Dundas Bay and in the Inian Islands, and in the anomalously low-grade zone that crosses Fairweather Glacier (the most recent research on these rocks is by Dusel-Bacon and others, 1991); (4) biostratigraphic analysis of Permian and older fossiliferous rocks, including those near White Glacier and in the Muir Inlet/Sitth-gha-ee Peak area (the most recent synthesis on this topic is by D.A. Brew and others, written commun., 1994); (5) sedimentary-facies analysis of Silurian turbidites, specifically those of the Point Augusta Formation in the southeastern part of the park (the most recent research on these rocks is by Karl and Giffen, 1992); and (6) tectonic and geologic synthesis of the Glacier Bay region in its regional context (the most recent reports on this topic are by Brew, 1990, Brew and others, 1991, and Mihalynuk and others, 1993).

Although this paper is concerned with bedrock-geologic features, we note that close ties exist between all of the above-mentioned topics and the glacial and surficial geology discussed elsewhere in this volume and by Powell (1984, 1991). Similarly, the bedrock-uplift interpretation is closely related to oceanographic and geodetic tidal-gauge and leveling data.

Much, but not all, of the research opportunities listed above would be in extremely difficult terrain and would require either extended-climbing-expedition or helicopter access. The seismic and neotectonic research would require the repetitive temporary installation of instruments at different places in the park. Some of this research could be accomplished at sea level from small boats.

All of the proposed studies would contribute to establishing Glacier Bay National Park and Preserve as a prototype for successful implementation of the symbiotic concepts of "Science for the Park" and "the Park for Science".

Present-Day Uplift

One feature unique to the Glacier Bay region is the ongoing uplift of the land; it is invisible because it is too slow for us to perceive directly. However, comparison of tidal-gage records taken during the 20th century in various parts of southeastern Alaska (Hicks and Shofnos, 1965) define a broad area of uplift, at least 200 km north-south by

100 km east-west. The maximum rate of uplift is 4 cm/yr, as measured at Bartlett Cove between 1938 and 1959--probably the highest uplift rate yet recorded in North America. The data set did not include measurements on the outer coast between Yakutat Bay and Sitka, and so the seaward extent of the uplift is unknown. Landward, a 1944 repeat of a 1910 leveling line between Skagway and Takhini (north of Whitehorse, Yukon Territory) had earlier shown downward tilt to the north (Small and Wharton, 1969), but the eastward vertical movement is still unknown. Computer contours of the rate of elevation change obtained from these tidal-gage and leveling data sets are plotted in figure 3.

Although the existence and magnitudes of the vertical movements seem well established, much more needs to be learned about their spatial and temporal variations and their possible mechanisms. Hudson and others (1982) provided evidence that the vertical movements are continuing and that the center of uplift may have moved northward from Bartlett Cove. Isostatic rebound after retreat of the glacial ice was initially assumed to be the cause of this uplift (Hicks and Shofnos, 1965). Clark (1978) assumed such a process in inverse calculations of the ice loads and glacial history needed to cause the sea-level changes recorded in southeastern Alaska, but his calculations did not explain the Bartlett Cove maximum rate of uplift and did not consider the subsidence recorded near Whitehorse. Increased knowledge of the seismicity (Horner, 1983, 1990) has recently emphasized the importance of tectonic processes as a cause of the vertical movements. The uplift of the Glacier Bay region has been rapid enough to cause gravity changes that should be measurable. Barnes (1990, 1991) compared the gravity changes predicted from the uplift with repeated measurements over a 31-yr period; the measurements recorded no change. From this and other evidence, Barnes (1990, 1991) concluded that the uplift process probably involves elastic compression and accumulating stress.

Better understanding of the uplift will require continued study of tidal-gage data to determine the areal extent and possible temporal changes in sea level. A permanent, continuously recording tidal gage at Bartlett Cove is badly needed, and all other tidal-gage stations and bench marks should be routinely reoccupied. Additional measurements of vertical and horizontal movements should be obtained with a network of reoccupiable Global Positioning System (GPS) and (or) very long baseline interferometry (VLBI) stations. An absolute gravity measurement should be made at the Bartlett Cove park headquarters, and this measurement should be routinely tied to other gravity base stations in the uplift area.

Present-Day Seismic Patterns

Present-day seismicity is concentrated on the Denali Fault northwest of Haines, Alaska (15 km southwest of Skagway, on Figs. 1 and 2); on the diffuse "cryptic" zone that extends from the Denali Fault to the Fairweather Fault and beyond to the Transition Fault; and on the Fairweather and Transition Faults (Figs. 1 and 2). In addition, two other northeast-striking cryptic zones occur in the Coast Mountains south and east of Haines (Fig. 2). All of this activity is in general interpreted to result from the interaction and slight convergence of the 6 cm/yr north-northwest-moving Pacific Plate with the North American Plate (Horner, 1990).

The Denali Fault Zone (Fig. 1) in the Glacier Bay region actually consists of two segments, the Dalton Fault to the north and the Chatham Strait Fault to the south. Only the active Dalton Fault part is shown in figures 1 and 2; the inactive Chatham Strait Fault extends southward from the Dalton segment beneath the conspicuous fiord shown in these figures. (The northern section of the Chatham Strait Fault is referred to in some reports as the Chilkat River or Lynn Canal Fault.) M (Richter magnitude) ≥ 4.0 seismic events occur on the Denali Fault Zone north of a point about 35 km south of Skagway (Fig. 2) (Horner, 1990). Horner (1983) calculated that $M \geq 6.0$ events recur about every 30 yr in the Yukon Territory to the north, including this segment of the Denali Fault. The southern section of the active Denali Fault is almost joins the northeast end of the cryptic zone described below, but a 10- to 15-km-wide gap may exist between the two zones. The Denali Fault at this latitude separates Wrangellia (*sensu stricto*) lithotectonic terrane rocks on the east from Alexander and Wrangellia terrane rocks on the west (Brew, 1990).

On the northeast-striking Denali-to-Transition-Fault diffuse cryptic zone (Fig. 2), an $M = 6.0$ event occurred in 1952 and a $M = 5.9$ event in 1985. A fault-plane solution for an $M = 5.8$ event in July 1990 (R.B. Horner, written commun., 1992) indicated a shallow thrust fault with uplift to the southwest or northeast. The National Earthquake Information Center (1990) published a nearly identical solution. Activity on such a thrust fault would contribute to the observed vertical movements. Horner (1990) calculated that $M \geq 6.0$ events recur about every 30 years in this zone, similar to the recurrence rate noted above for the Denali Fault in the Yukon Territory. Overall, the Denali-to-Transition-Fault cryptic zone is about 200 km long by 70 km wide. It trends at a high angle to the dominantly northwest-striking structures in the Wrangellia, Alexander, Chugach, and Yakutat Lithotectonic Terranes (Brew, 1990), and no faults or other structures exposed at the surface follow the long axis of the zone (Brew and others, 1978).

The north-northwest-striking Fairweather Fault is part of a major transform plate boundary that lies along the coast of southeastern Alaska; another part is the northwest-striking Transition Fault (Figs. 1 and 2). The Fairweather and Transition Faults are inferred to join to the south in the Queen Charlotte Fault System. This transform boundary has been the locus of four $M \geq 7.0$ earthquakes during the 20th century, and its present low level of activity suggests that most accumulated strain is released episodically in major earthquakes. In this regard, both the 50-km-long aseismic segment centered on the Alsek River (Fig. 2) and the segment south of Cross Sound are of particular interest because they may be small seismic "gaps" wherein near-term activity should be anticipated. As summarized by Horner (1990), the recurrence interval on the whole transform system for $M \geq 7.9$ events is about 120 yr, and for $M \geq 6.0$ about 5 yr. On the Fairweather Fault alone, the recurrence interval for an $M = 7.9$ event is 60 to 85 yr. The on-land Fairweather Fault separates the Chugach Lithotectonic Terrane on the east from the Yakutat Block or Terrane on the west. The offshore Transition Fault separates the Yakutat Block or Terrane on the east from the Pacific Plate on the west (Plafker, 1987).

Present-Day Fault Motions

Present-day movement on the Fairweather Fault is predominantly right lateral. During the 1958 $M = 7.9$ earthquake, ground breakage occurred along almost all of the outer coast (from Palma Bay on the south to Nunatak Fiord on the north). Maximum displacement was measured near Crillon Lake, where rocks on the southwest side of the fault moved 3.5 m to the northwest and 1.0 m upward relative to those on the east (G. Plafker, written commun., 1993). As summarized by Horner (1990), the convergence between the Pacific and North American Plates is partitioned between the Transition and Fairweather Faults, with the Transition Fault accommodating about 10 mm/yr and the Fairweather Fault accommodating 10 to 20 mm per yr. No known ground breakage was found to be associated with any of the other recent seismic events described in the above section.

Past Fault Motions

As noted above, the present patterns of seismicity and fault motions are mostly related to recognized large-scale faults (Figs. 1 and 2). Offsets of Tertiary volcanic fields and intrusive bodies establish that most of the measurable separations have occurred during the past 25 million years (Brew, 1990; Brew and others, 1991), although the possibility of earlier movements cannot be eliminated. The long history of both lateral and vertical movements and the even-earlier history of terrane juxtaposition (Brew and others, 1991) indicate that southeastern Alaska has been the site of tectonic deformation, probably with accompanying seismicity for at least the past 200 million years.

Four faults in the Glacier Bay region have significant lateral separations (summarized in part by Brew and others, 1991): (1) The Denali Fault System has about 150 km of right-lateral separation (that is, the opposite side of the fault has moved to the observer's right), and different blocks on both sides have moved vertically by amounts that range from 0 to as much as 8 km; (2) the Tarr Inlet Suture Zone, which is the local segment of the Border Ranges Fault, has an unmeasured amount of right-lateral movement that probably occurred between about 120 and 60 million years ago (Pavlis and others, 1989), and the rocks on the west side of this zone have been uplifted as much as 8 km relative to the block to the east; (3) the Peril Strait Fault, which is an inactive splay to the southeast of the Fairweather Fault, has about 20 km of right-lateral separation and, possibly, 2 km of uplift of its west side; and (4) the Fairweather Fault has been the locus of large-scale right-lateral movement since 25 million years ago, such that the Yakutat Block or Terrane to the west has moved about 600 km northward (Plafker, 1987); because the amount of northward movement of the Chugach terrane (on the east side of the fault) is uncertain, the net separation is likewise uncertain.

Present-Day Mass-Wasting

The most important mass-wasting events in the Glacier Bay region are directly linked to large magnitude earthquakes. The best known of these events is the rockfall in Lituya Bay associated with the M=7.9 earthquake on the Fairweather Fault in 1958. This rockfall dropped approximately 30 million m^3 of debris into the North Arm of Lituya Bay and caused a giant wave that ran up about 530 m across the shoulder between the North Arm and the main part of the Bay and up to 60 m throughout most of the rest of the bay (Miller, 1960). Trimlines and dendrochronology were used to establish the occurrence of similar, but somewhat smaller, waves in Lituya Bay in 1853-1854, 1874(?), and 1936 (Miller, 1960). Miller also inferred a submarine slide in Beartrack Cove within Glacier Bay proper at the time of that same earthquake; Powell (1991) discussed similar submarine events. The seismic events that were large enough to cause these rockfalls probably also triggered numerous small rockfalls, landslides, and glacier calving elsewhere in the vicinity of the park.

Lituya Bay will probably be the scene of similar rockfalls and giant waves in the future because deep fissures have been observed above the slide scar (G. Plafker, written commun., 1993). In addition, D.A. Brew (written commun., 1976) suggested that a large semidetached mass of rock on the north side of Tidal Inlet poses a similar threat. There is no evidence of past rockfalls at this locality, and the east-striking faults that control the orientation of the inlet (Brew and others, 1978) are not known to be seismically active.

Fairweather Range Isostatic-Gravity Anomaly

The isostatic-gravity map of the Glacier Bay region (Fig. 4; Barnes, 1990) shows a very large, positive high on the west side of the park, as well as other, lesser highs and three small lows. One low is along the outer coast, and two lows are in the upper Muir Inlet area. Barnes (1990) pointed out that the latter two lows are too small to represent isostatic depressions at the base of the earth's crust as might be expected if they were caused by glacial loading. The very large positive high is greater than any other in the United States (with the possible exception of the Aleutian Arc). It is interpreted to be caused primarily by a buried gabbroic body that crops out at the surface as the Mount Fairweather, Mount Wilbur, La Perouse, and Astrolabe Peninsula stocks. Such an anomaly should be reduced by isostatic-adjustment processes, such as crustal thickening or surface subsidence, and so we surmise that some tectonic process is acting to maintain the anomaly.

Conclusions

Glacier Bay National Park and Preserve and adjacent areas afford unique opportunities for geoscience research. Although many topics deserve study, the most important and exciting topic is geotectonic study of the present-day regional uplift, seismic patterns, strain rates, and lateral fault movements. Such an integrated study would not only contribute to our understanding of northeastern Pacific crustal geodynamics and the analysis of large earthquake risk but also facilitate testing the hypothesis that the present patterns of seismicity and regional uplift are both direct and indirect continuations of the faulting history which extends back at least 25 million years. Altogether, these research opportunities provide an exceptional situation for the joint development of the concepts of "Science for the Park" and "the Park for Science".

Acknowledgments

U.S. Geological Survey and Geological Survey of Canada studies in Glacier Bay region started soon after the turn of the century, well before present Park units were established, and continue to the present day. The geologists and geophysicists who have done the field studies deserve the credit for the information used in this article. The superindents and staff of Glacier Bay National Monument and subsequently of Glacier Bay National Park and Preserve deserve credit for recognizing the importance of bedrock geoscience studies for interpretative, management, and scientific purposes and for supporting and facilitating those studies for so many years.

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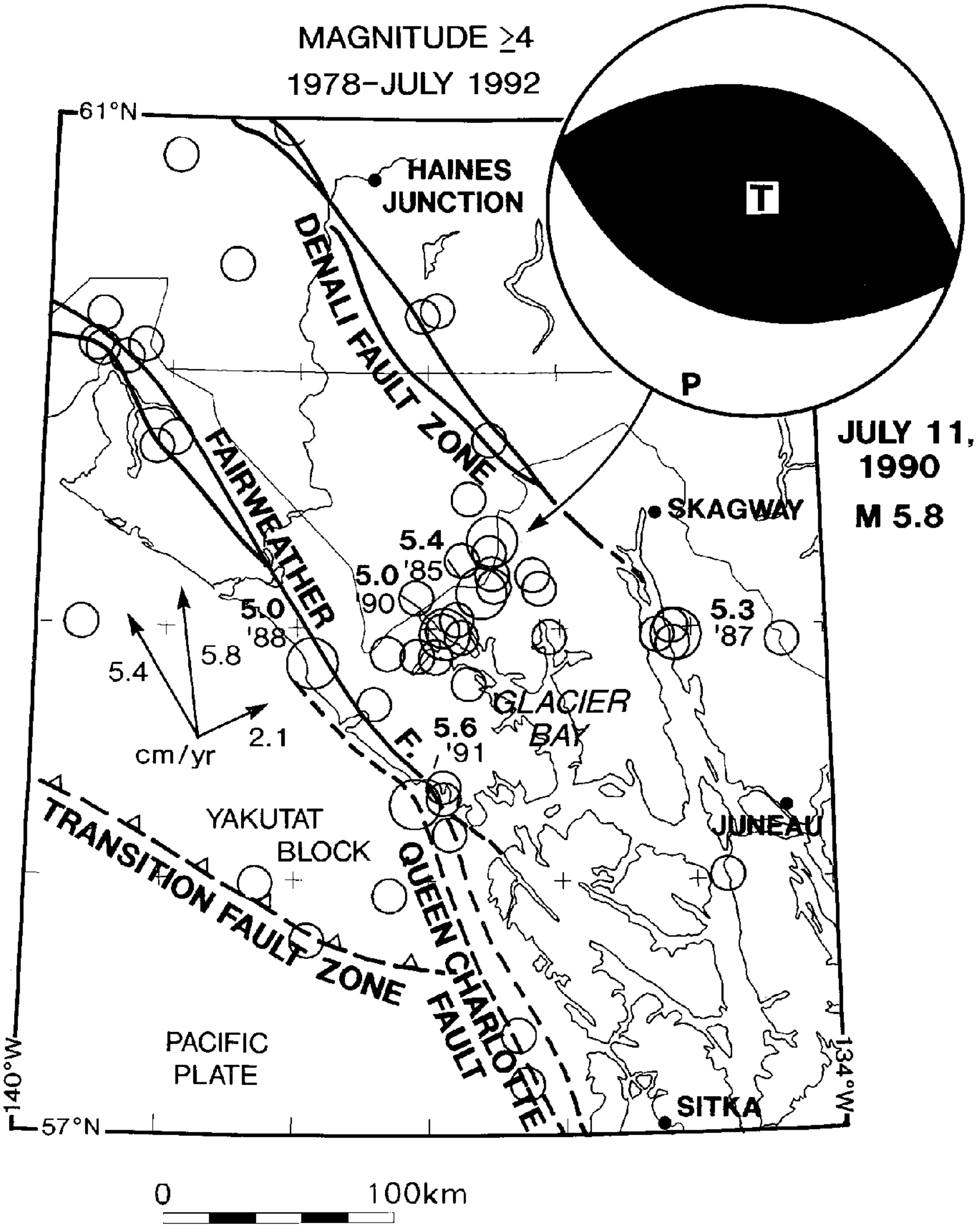

Fig. 1. Glacier Bay region of southeastern Alaska and adjacent areas of British Columbia and the Yukon Territory, Canada, showing locations of $M \geq 4$ earthquakes from 1978 to July 1992. Superposed are major, currently active fault zones. Motion-vector diagram superposed on the Yakutat block indicates movement of the Pacific Plate relative to the North American plate. Smaller circles, $4<M<5$ seismic events; larger circles, $M>5$ events, with magnitude and year indicated by, for example, **5.4**, '85, except for the $M=5.8$ 1990 earthquake, whose location is shown at end of arrow leading from thrust-mechanism diagram in the upper right-hand corner. Thrust mechanism is based on data of R.B. Horner (written commun., 1992) but is nearly identical to that determined by National Earthquake Information Center (1990, EDR 90-7). Long axis of black part of thrust-mechanism diagram is strike of fault movement plane. Analysis of seismic waves shows that movement was on a shallow thrust fault, with uplift to the southwest or northeast, within black area on lower hemisphere stereographic projection. Epicenters from Geological Survey of Canada's Earthquake Epicentre File.

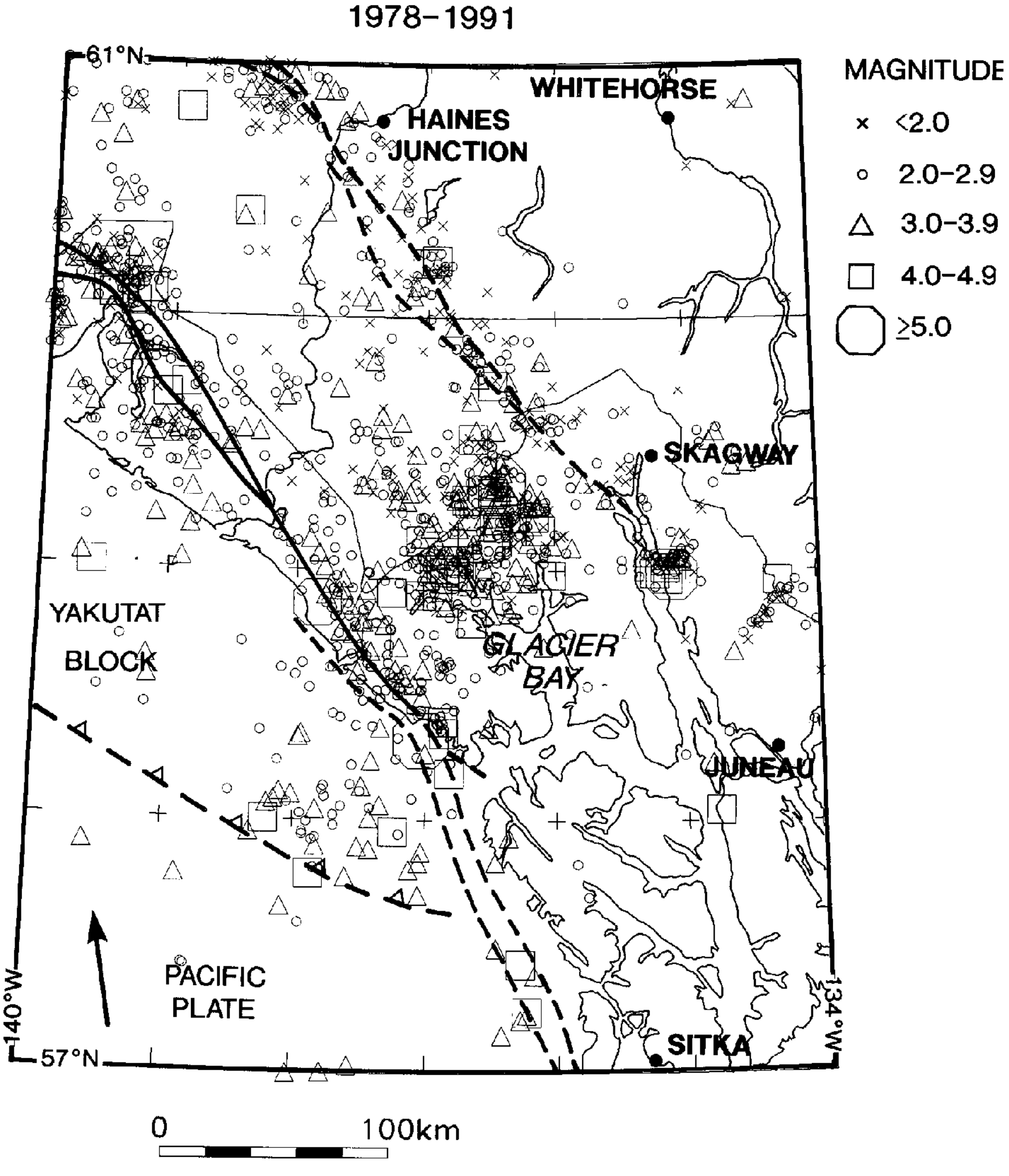

Fig. 2. Glacier Bay region of southeastern Alaska and adjacent areas of British Columbia and the Yukon Territory, Canada, showing locations of all earthquakes from 1978 to 1991, superposed on major currently active fault zones that are also shown on figure 1. Magnitude thresholds are M~2.5 onshore and M~3.0 offshore. Epicenters from Geological Survey of Canada's Earthquake Epicentre File.

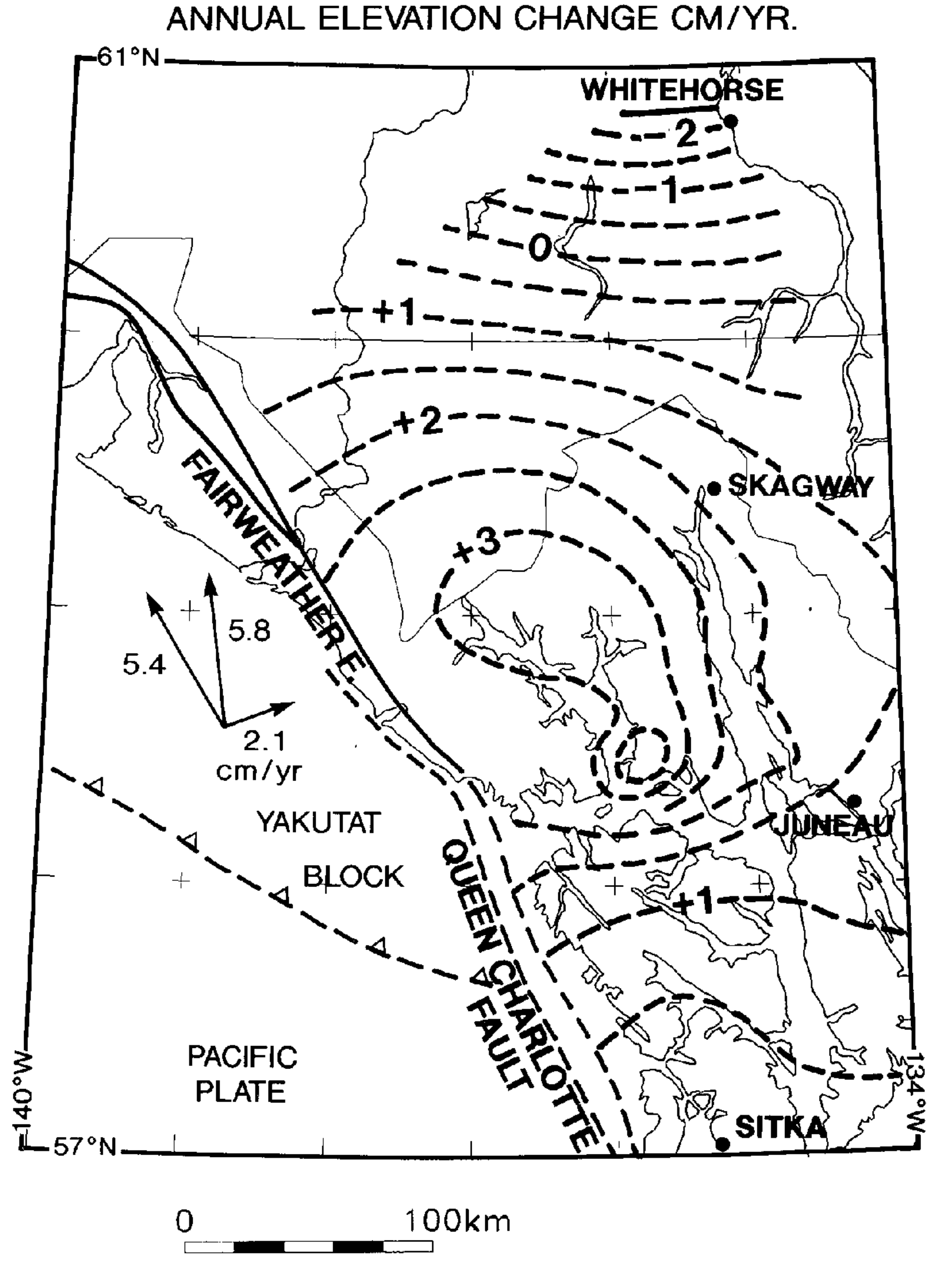

Fig. 3. Glacier Bay region of southeastern Alaska and adjacent areas of British Columbia and the Yukon Territory, Canada, showing contours of uplift and subsidence rates (from Barnes (1991) based on tidal-gage data of Hicks and Shofnos (1965) for 1939-59 and Hudson and others (1982) for 1960-80; and on leveling differences observed along the White Pass and Yukon Railroad between 1910 and 1944 as reported by Smith and Wharton (1969). Current plate margin is also shown, along with motion vectors from figure 1. Note component of convergence across the Fairweather Fault. Negative rates shown between the 0 isopleth and Whitehorse indicate subsidence of the Earth's surface.

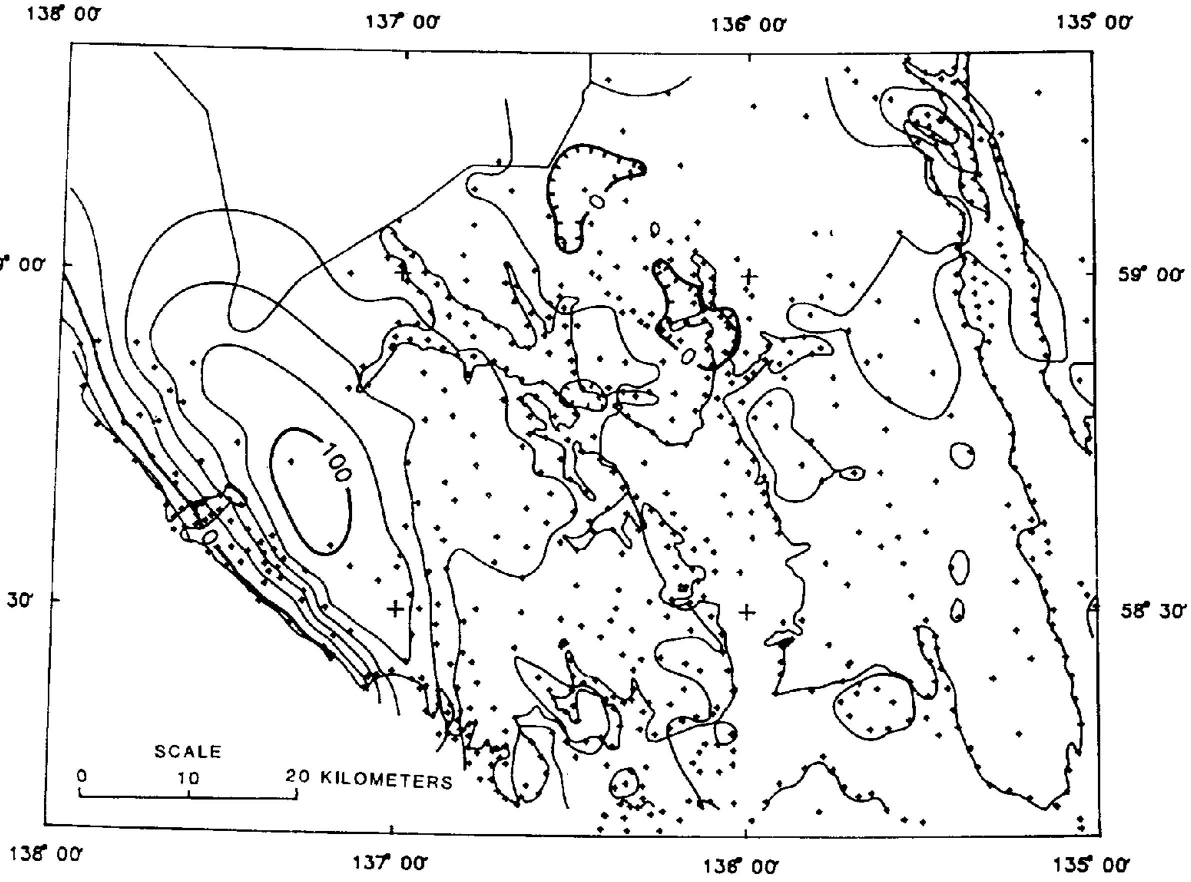

Fig. 4. Isostatic-gravity map of Glacier Bay National Park and vicinity, southeastern Alaska. Crosses, locations of measurements; contour interval, 20 mgals; hachured lines, gravity lows (From Barnes, 1990, Fig. 2).

Glacier Fluctuations and Sediment Yields Interpreted from Seismic-Reflection Profiles in Johns Hopkins Inlet, Glacier Bay, Alaska

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Abstract

Seismic facies and sequence analyses of single-channel, seismic-reflection profiles of the sediment fill within Johns Hopkins Inlet, Glacier Bay, Alaska, allow the interpretation of three seismic facies and four lithofacies. Four old morainal banks, which were deposited during glacial terminus quasi-stabilities, are recognized by seismic facies and stratigraphic analyses of the deposit in the inlet. These old morainal banks separate the fjord into different basins and range from 120 to 200 m high and from 700 to 2500 m wide near their bases. Two of the banks are now buried by younger glacimarine deposits, and the other two are still 20 and 150 m ridges above the present flat fjord floor. Calculations from seismic-reflection profiles indicate that these morainal banks have forebank slopes (8-16°) steeper than backbank slopes (3.5-7.5°). The estimated slope of the fjord floor beyond the present morainal bank is less than 1°.

A large volume of glacimarine sediment has accumulated in Johns Hopkins Inlet since the last deglaciation. Between 1899-1926, Johns Hopkins Glacier retreated discontinuously and relatively fast at an average rate of about 670 m/a. The periods of fast glacial retreat between glacial quasi-stable periods opened up deep basins along the fjord. The deepest basin in the fjord had been filled with about 200 m of glacimarine sediment by 1979. The highest sedimentation rate was between 1917-1942 at about 4 m/a. A total of about 1.6×10^9 m^3 sediment, estimated from seismic profiles, had been accumulated in the fjord, with about 44% of the sediment (7×10^8 m^3) accumulated as morainal banks. The average sediment accumulation rate throughout the fjord during 1892-1979 is about 1.8 - 2.0×10^7 m^3/a, which is comparable with that in Tarr Inlet ($2.5\text{-}3.0 \times 10^7$ m^3/a) for the same time period.

KEY WORDS: Seismic facies analysis, glacimarine sedimentation, sediment yields, terminus fluctuations, morainal-bank deposits, basin-fill deposits.

In the last two decades, many kilometers of high-resolution seismic-reflection data have been collected from the Gulf of Alaska and adjacent fjords, including Glacier Bay (e.g. Carlson & Molnia, 1978; Carlson et al., 1979, 1980). It has been documented that seismic-reflection configurations reveal the gross stratification patterns of deposits (e.g. Payton, 1977). Interpretation of seismic facies including stratigraphic analysis of high-resolution profiles have advanced our understanding of modern sedimentary processes and lithofacies produced in different depositional environments, and have aided our understanding of recent basin fill histories. However, few such studies have been conducted in modern glacial fjords. This paper presents results of seismic facies and stratigraphic analyses of high-resolution seismic-reflection profiles from sediment fill in Johns Hopkins Inlet, Glacier Bay, Alaska, and demonstrates further the utility of such analyses for estimating sediment accumulation rates in glacial fjords and for reconstructing tidewater terminus fluctuations.

Study Area

Johns Hopkins Inlet is about 15 km long and 1.5-3.0 km wide (Fig. 1). The inlet has two major tidewater termini, Johns Hopkins Glacier at the head, and Lamplugh Glacier at

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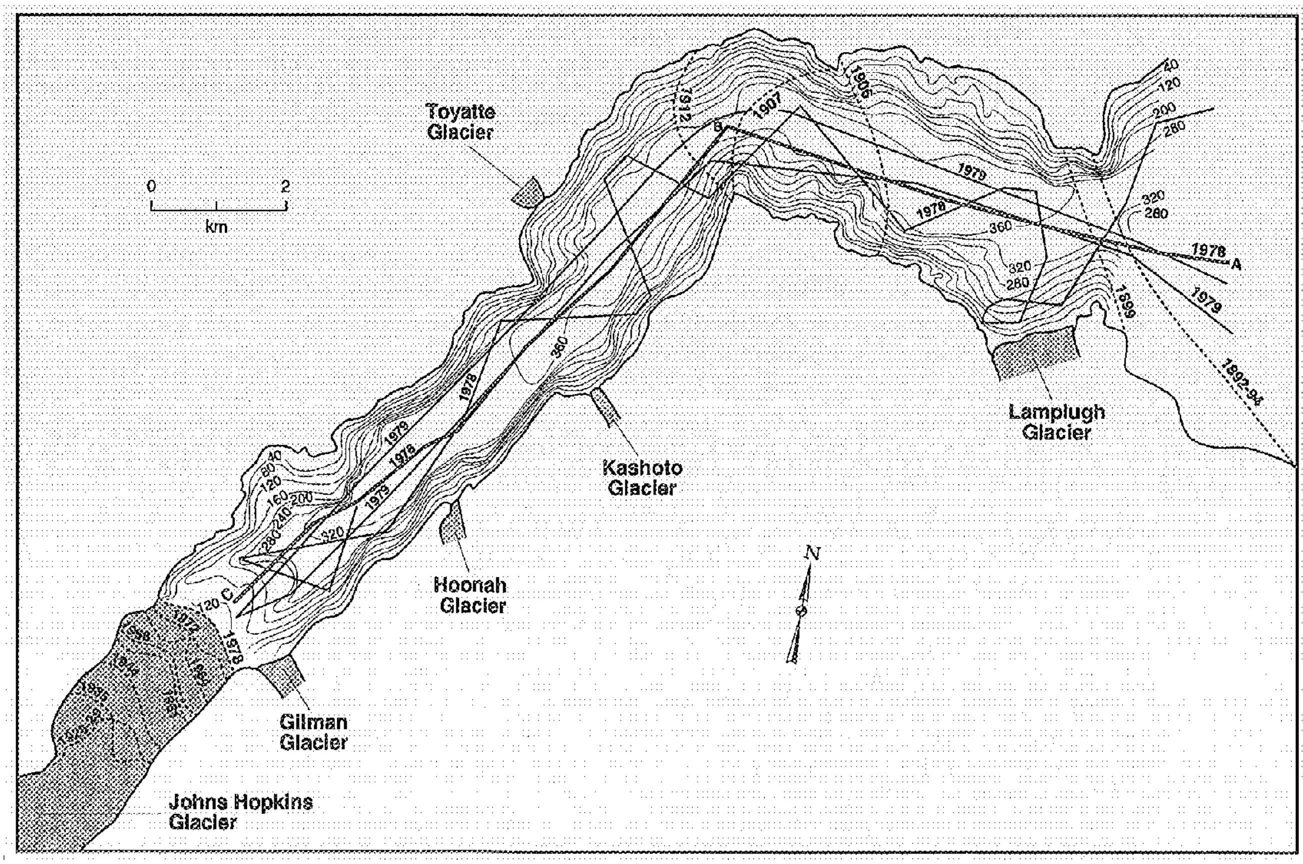

Fig. 1. Bathymetric map of Johns Hopkins Inlet with known terminus positions (bold dashed lines) and tracklines of seismic-reflection profiles. Bathymetric data are from N O.A A , National Ocean Survey, 1972 (unpublished) The contour-line interval is 40 m Terminus positions (bold dashed lines) are from Field (1964) and Powell (1980). Seismic-reflection profiles were collected by U.S. Geological Survey (Menlo Park, CA) during 1978 and 1979. Seismic profiling systems used to collected the data are a minisparker system (1978) and a 800 J scar uniboom system (1979) Bold line A-B-C shows the profile locations for Figure 2 and Figure 3

the south side of the fjord near the entrance. Modern morainal banks are building at the grounding lines of both glaciers. The bathymetry of Johns Hopkins Inlet (Fig. 1) shows that the fjord with steep side walls and a relatively flat floor has two ridges across the fjord floor. The larger ridge occurs at the fjord entrance with a topographic relief of about 150 m above the present fjord floor (Fig. 2). The smaller ridge, with a topographic relief of only about 20 m, occurs at about 1/3 way from the fjord elbow to the terminus of Johns Hopkins Glacier (Fig. 3). The maximum water depth is about 380 m in the center of the fjord (Fig. 2, 3).

Methods

Seismic facies units are determined in this study by analyzing acoustic characteristics such as internal configuration, reflection continuity, amplitude, frequency, external form and type of bounding surface. Five major types of data are used for lithofacies interpretations. These data include: (a) seismic-reflection profiles; (b) historical records of glacial terminus positions; (c) fjord bathymetry, geometry, and paleotopograhpy; (d) modern analogs at or near present tidewater termini; and (e) depositional facies models.

Depositional modelling of temperate glacimarine environments has documented that different stability conditions of tidewater termini create different sedimentary environments with specific depositional processes, and produce distinctive lithofacies associations (e.g. Powell, 1980, 1981, 1988). Inversely, a specific lithofacies association may be an indicator of a particular glacimarine environment and glacier stability condition. Interpretations of seismic profiles in this study were aided by modern depositional models because they provide examples of sedimentary processes active in proximal glacimarine environments and the models illustrate how the processes control sediment distribution. Known historical terminus positions in the fjord allow sediment accumulation rates to be estimated, and terminus fluctuation history to be reconstructed.

Seismic-reflection data used in this study are single-channel, high-resolution profiles collected by U.S. Geological Survey (Menlo Park, California) during 1978 and 1979 (Carlson et al., 1979; Fig. 1). The profiling systems used to collected the data were a 500 J minisparker system (1978) and a 800 J scar uniboom system (1979). The velocity of sound in seawater, approximately 1,500 m/s, is used to calculate sediment thickness in this study.

Results

Studies of modern glacimarine sedimentation have indicated that grounding-line systems where termini are quasi-stable, form sediment accumulations of positive topographic relief in the form of morainal banks and ice-contact deltas, however, sheet-like grounding-line deposits are produced during rapid terminus retreat (Powell, 1991).

Sediments of morainal banks are usually coarse-grained and often poorly stratified. Deposits produced in ice-distal regions are usually fine-grained and commonly consist of mud layers interstratified or interlaminated with sand or silt layers (e.g. Powell, 1988; Mackiewicz et al., 1984; Cowan, 1988; Cowan & Powell, 1990). With the knowledge of the characteristics of modern glacimarine deposits, seismic-reflection profiles of the sediment fill within Johns Hopkins Inlet are interpreted as having three distinct seismic facies and four lithofacies. The lithofacies include (1) chaotic bedrock, (2) chaotic morainal bank sediment, (3) discontinuously stratified ice-proximal glacimarine sediment, and (4) continuously stratified ice-distal glacimarine sediment (Fig. 2, 3).

Morainal Bank Deposits

Four old morainal banks are interpreted from seismic stratigraphic analysis in Johns Hopkins Inlet (Fig.2, 3). The first (oldest and largest) bank is located at the fjord entrance, and occurs as a ridge about 150 m above the present fjord

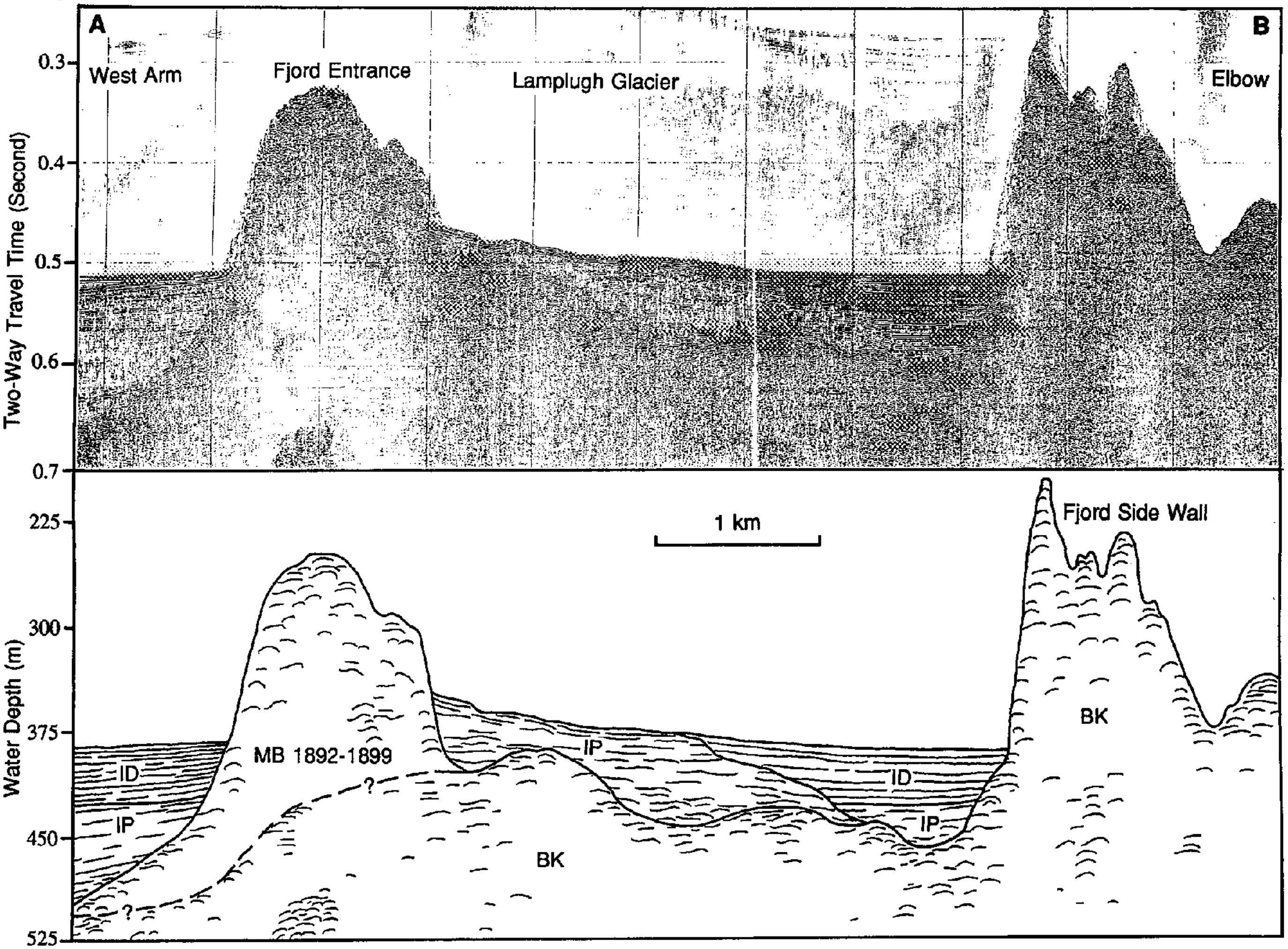

Fig. 2. Seismic-reflection profile A-B (minisparker) and its interpretive line-drawing. MB - morainal bank deposit; IP - ice-proximal glacimarine deposit; ID - ice-distal glacimarine deposit; BK - bedrock. See Figure 1 for the location.

floor (Fig. 1, 2). The second bank occurring around the fjord elbow is mostly buried by younger glacimarine sediment, with only a small portion on the fjord sides above the present flat fjord floor (Fig. 3). The third bank occurs at about 1/3 way from fjord elbow to the present glacier terminus. This bank also shows a ridge-like feature on the fjord floor, but only about 20 m above the present fjord floor (Fig. 1, 3). The fourth bank located about 3 km from the present terminus of Johns Hopkins Glacier is now completely buried by later ice-proximal and ice-distal glacimarine sediments (Fig. 3). These old morainal banks range from about 120 to 200 m high, 700 to 2500 m wide near the bases, and are made up of about $8.3x10^7$ to $1.8x10^8$ m^3 of sediment.

Morainal banks formed in Johns Hopkins Inlet, including the present morainal bank, have relatively steep slopes, and the forebank slopes (8.1°-16.0°) are steeper than backbank slopes (3.5°-7.5°) (Table 1). These slope angles are similar to those estimated from echosounding profiles for modern morainal banks of Muir, Grand Pacific and Margerie Glaciers (Hunter & Powell, 1993), as well as those of older morainal banks in Disenchantment Bay (Carlson et al., 1992) and older push moraines in Muir Inlet (Seramur, 1989). However, the slopes are steeper than those of stratified moraines in Muir Inlet (Seramur, 1989) and those of morainal banks in lower Glacier Bay (Cai, 1994; see Table 1). The present morainal bank of Johns Hopkins Glacier (Fig. 3), high above the present fjord floor, has a forebank slope of 8.1° to 13.1° The steep forebank slope, and hummocky, convex bank-front surface (Fig. 3) indicate that the present morainal bank is probably pushed from behind by the slowly advancing Johns Hopkins Glacier. The forebank deposits probably have been reworked due to the pushing.

Powell (1980, 1984) described sediment on the present morainal bank of Johns Hopkins Glacier as varying in texture from gravel, to sandy mud, to diamicton with minor mud on the morainal bank in the central fjord. Sediment adjacent to the ice cliff is fine- to coarse-grained sand which is occasionally muddy. Coarse-grained deposits (up to boulders) with a very thin draping of mud over some clasts are reported on the morainal banks of Lamplugh Glacier (Powell, 1980, 1984). Sand and gravel deposited on this bank were probably contributed from subglacial streams and from melting out of basal and englacial debris at the ice-water interface (Powell, 1980). Surface textures of morainal banks that exhibit poorly sorted gravel and rubble in mounds and ridges with muddy drape were also observed with a Phantom ROV submersible on the older bank downfjord from the present terminus of Lamplugh Glacier (Powell et al., 1991). Sediments in the old morainal banks interpreted from seismic profiles in this study are believed to be similar to those modern morainal bank deposits, which consist of poorly sorted and poorly stratified sediment with various textures from rubble to sandy mud to diamicton.

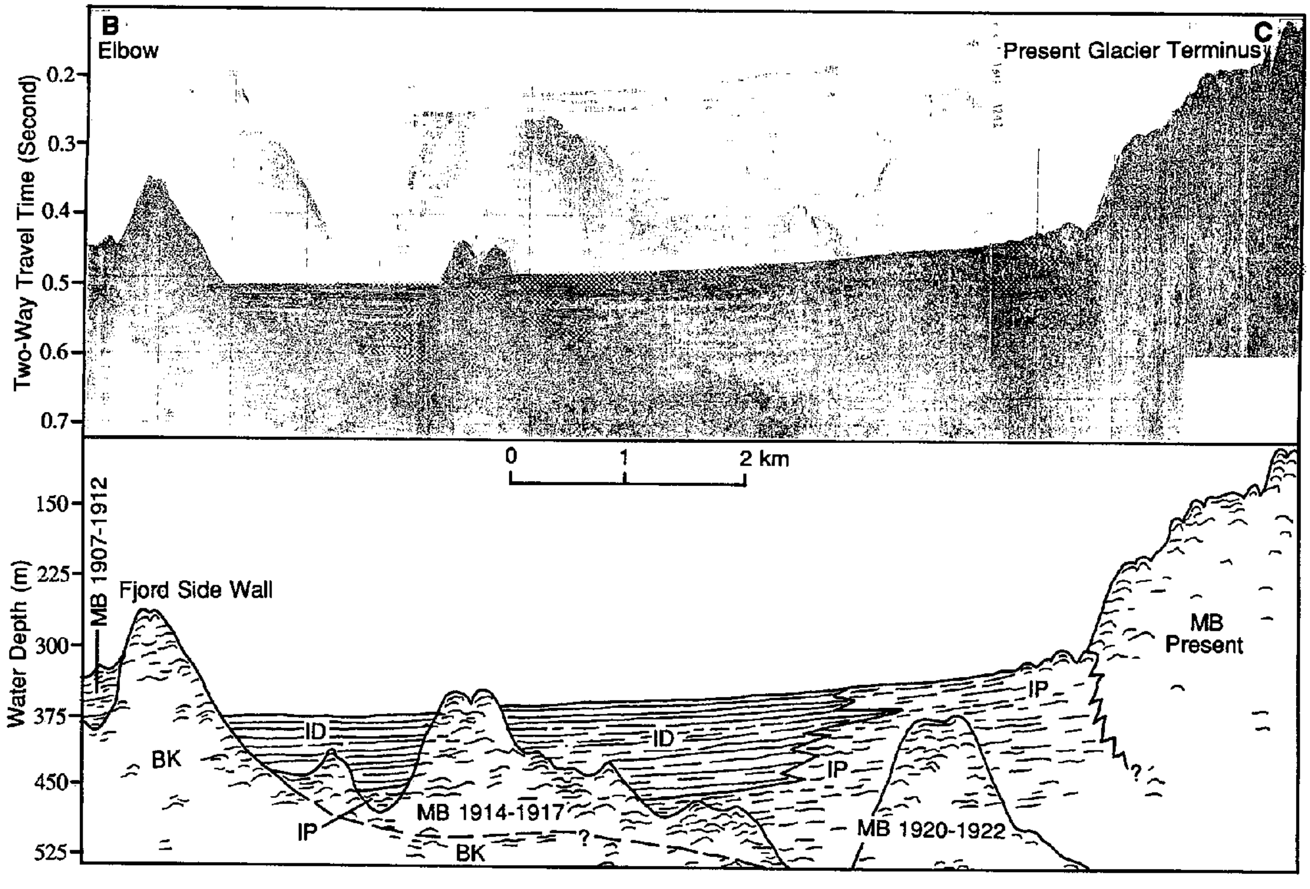

Fig. 3. Seismic-reflection profile B-C (minisparker) and its interpretive line-drawing. MB - morainal bank deposit; IP - ice-proximal glacimarine deposit; ID - ice-distal glacimarine deposit; BK - bedrock. See Figure 1 for the location.

Table 1 Morainal Bank Slopes

Location	Forebank	Backbank	Distal	Source
Modern Morainal Banks				
Muir Glacier	8.1-25.6°	----	5.3-8.5°	Hunter & Powell
Margerie Glacier	9.9-31.0°	----	----	(1993)
Grand Pacific Gla.	8.5-25.0°	----	0.6-1.6°	
Older Morainal Banks				
Tarr Inlet	2.3-4.6°	----	----	Carlson et al. (1983)
West Arm	6.5-11.5°*	----	----	Cai (1994)
Lower Glacier Bay	0.5-1.0°	1.2-3.8°	----	
	2.8-6.9°	3.4-4.9°	----	
Muir Inlet				
Stratified Moraines	3.0°	1.7°	----	Seramur (1989)
Push Moraines				
Entrance	6.0-17.0°*	----	----	Seramur (1989)
Upper Fjord	3.0-17.0°*	----	----	
Disenchantment Bay	14.0-14.5°*	----	----	Carlson et al. (1992)
Johns Hopkins Inlet				
Entrance (1892-99)	11.7-16.0°	3.6°	----	this study
M. Fjord (1914-17)	11.3°	3.5°	----	
Up Fjord (1920-22)	15.0°	7.5°	----	
Present (1926-79)	8.1-13.1°	----	0.2-0.8°	

* Forebank and backbank were not distinguished.

Basin Fill Deposits

The four old morainal banks separated Johns Hopkins Inlet into four sedimentary basins (Fig. 4). Sediment fill within these basins between morainal banks is thick, and varies from near 100 m in the lower middle-fjord basin to more than 200 m in the upper middle-fjord basin. The seismic facies of these basin fill sediments are mainly discontinuously stratified ice-proximal facies and relatively continuously stratified ice-distal facies (Fig. 2, 3).

The slope of the fjord floor within the fjord basin between the present morainal bank and the small morainal bank ridge is downfjord and very gentle (Fig. 3), changing from about 1.5° between 2 to 3 km from the present terminus of the Johns Hopkins Glacier to about 0.4° near the distal end of the basin about 6 km away (an overall average of about 0.8°). The fjord floor within the basin between the small morainal bank ridge and the fjord elbow has downfjord slope of only about 0.2°. The fjord floor within the lower fjord basin also has a gentle slope of about 0.8° (0.7-1.0°); however, the floor of this basin slopes upfjord instead of downfjord (Fig. 2). This change of slope direction indicates that the main sediment sources for basins on both sides of the fjord elbow are different. The main source for the upper fjord basins is primarily Johns Hopkins Glacier, whereas the main source for the lower fjord basin is probably Lamplugh Glacier at least at present. The slope reversal and the stepping changes in water depth from upfjord to downfjord side of both morainal bank ridges (Fig. 2, 3) clearly demonstrate that the presence of morainal banks not only can separate the fjord into basins, but may also creates sediment "traps". As long as the morainal bank is still above the fjord floor as continuous ridges across the fjord, the majority of sediment supplied by the glacier may be trapped within the basin dammed by that bank. Most of the sediment supplied from Lamplugh Glacier spreads out in the upfjord instead of downfjord direction because of the blockage by the morainal bank at the entrance to Johns Hopkins Inlet.

Sediment cores collected in Johns Hopkins Inlet showed that sediment several meters below the fjord floor is basically homogeneous silty mud with only occasional thin silt to fine sand layers (Powell, 1980). Basin fill sediments of ice-distal glacimarine deposits identified from seismic-reflection profiles probably have similar lithological features to the sediment cores.

Sedimentation Rates and Sediment Yields

Between 1899-1926, Johns Hopkins Glacier retreated discontinuously and relatively fast at an average rate of about 670 m/a. Periods of relatively fast glacial retreat during 1912-1926 (average about 890 m/a), opened up deep fjord basins, probably about 550 m deep. The water depth of about 450 m in the center of the fjord was recorded in 1942 (Field, 1964). This bathymetric change suggests an average sedimentation rate at the fjord center line between 1912-1942 was about 3-4 m/a. By 1979, the water depth in the fjord center had decreased to about 380 m, showing that the fjord center had been infilling at an average rate of about 1.89 m/a between 1942-1979 (about 70 meters in 37 years).

A large volume of glacimarine sediment has accumulated in Johns Hopkins Inlet during and since the last deglaciation. About 200 m thick glacimarine sediment fills the deepest basin within the inlet (Fig. 4). Calculations from seismic-reflection profiles show that the total volume of sediment in the fjord is about 1.6×10^9 m^3, and about 7.0×10^8 m^3 (about 44% of the total) was deposited as morainal banks. The average sediment accumulation rate during 1892-1979 was approximately 1.8×10^7 to 2.0×10^7 m^3/a, which is very similar to that estimated in Tarr Inlet (2.5-3.0×10^7 m^3/a) during the same time interval (Cai & Powell, 1993; Cai, 1994), and to that in Muir Inlet during 1860-1980 (2.1×10^7 m^3/a; see Table 2; Seramur, 1989).

Historical records of terminus positions (Scidmore, 1896; Cooper, 1937; Field, 1964; Powell, 1980), indicate that the fjord-entrance morainal bank was formed between 1892-1899 (Fig. 4). The estimate of sediment volume for this morainal bank is about 1.8×10^8 m^3, with an average accumulation rate of about 2.6×10^7 m^3/a. The morainal bank near the fjord elbow was probably formed during 1907-1912

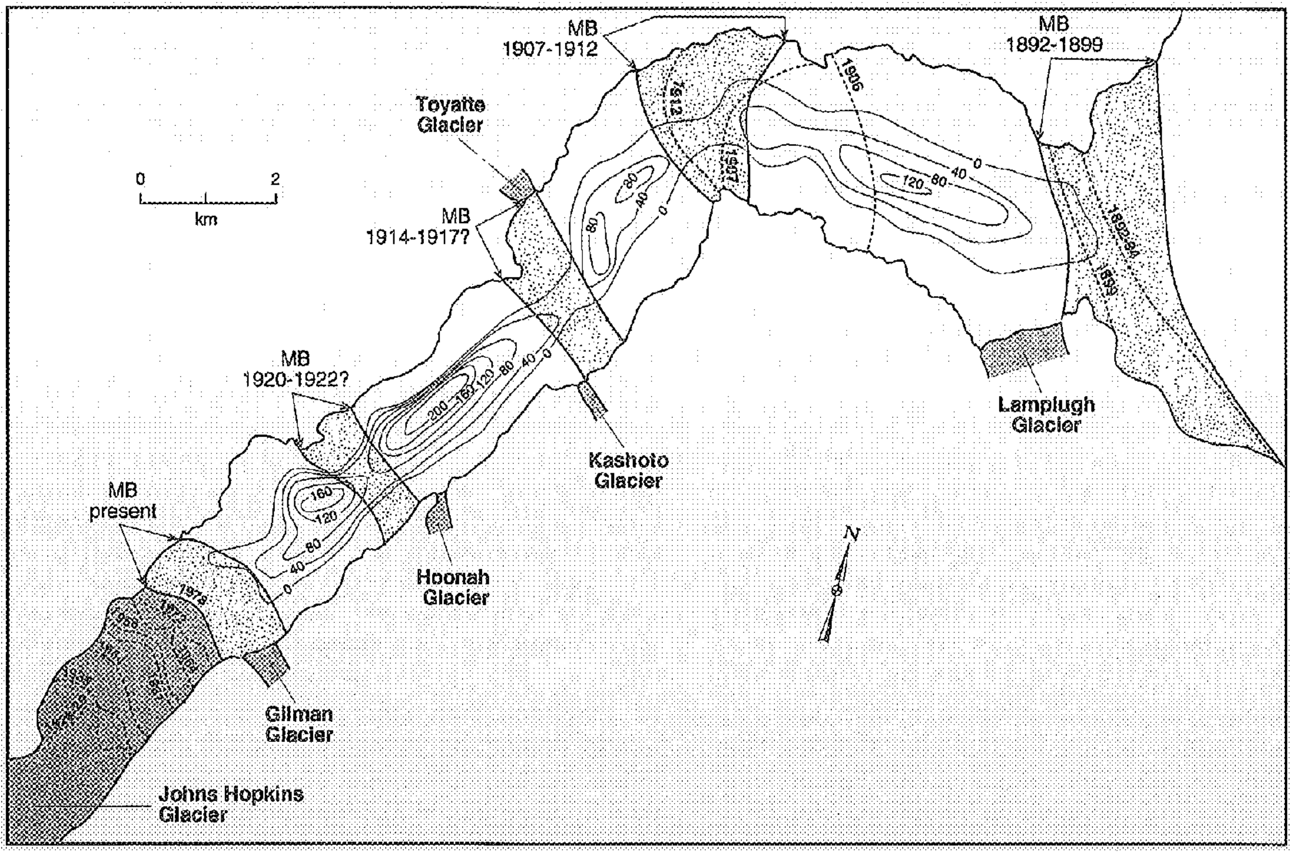

Fig. 4. Isopach map of glacimarine sediment (morainal bank deposits excluded) with known terminus positions (dashed bold lines) and the positions of four older morainal banks interpreted from seismic-reflection profiles (dotted areas) Isopach contour interval is 40 m Terminus positions are from Field (1964) and Powell (1980)

(Fig.4). The total volume of sediment for this morainal bank is at least about 8.3×10^7 m^3 (perhaps underestimated due to the poor coverage of seismic profiles at that area), which gives a minimum average accumulation rate of about 1.7×10^7 m^3/a. Compared to the estimates of other quasi-stable grounding-line systems in Glacier Bay (Table 2; Cowan, 1988; Seramur, 1989; Powell, 1991), sediment accumulation rates of morainal banks in Johns Hopkins Inlet are very similar to those of morainal bank complexes in Muir Inlet and those of Carroll Glacier deltas. However, the rates are about one order of magnitude lower than that of the morainal bank near Glacier Bay entrance (Cai, 1994) and at least one order of magnitude higher than those of most deltas in other inlets and morainal banks in McBride Inlet. If our interpretation of the seismic profiles is correct, the difference among estimated rates of sediment accumulation can be explained by the actual variations of sediment supply from different sizes of glacial drainage basins during different time periods (Powell, 1991).

The third and fourth morainal banks located in the middle and upper parts of Johns Hopkins Inlet have sediment volumes estimated from seismic-reflection profiles of about 1.0×10^8 and 7.6×10^7 m^3, respectively. Unfortunately, there is no historical record of terminus positions between 1912 and 1926 when these two morainal banks are believed to have been formed. If the accumulation rates of morainal banks (2.6×10^7 m^3/a) has not significantly changed in Johns Hopkins Inlet, it would have taken about 4 and 3 years for the third and fourth morainal banks to accumulate, respectively.

Between 1912 and 1926, Johns Hopkins Glacier retreated for about 12.5 km at an average rate of about 890 m/a (Fig. 4). If the terminus did spend a total of 7 years in quasi-stability to produce the third and fourth morainal banks, the actual terminus average retreat-rate during 1912-1926 would be about 1800 m/a. If this is true, it would have taken only about 2 years for the terminus to retreat from the elbow to the third morainal bank position, and about another 2-3 years to the fourth morainal bank position. Thus, we can infer that the third and fourth morainal banks probably formed during 1914-1917, and 1920-1922, respectively.

Table 2 Sediment Accumulation Rates Estimated in Glacier Bay

Location & Feature	Period	Rates (m^3/a)	Source
Adams River Delta	1948-1977	6.8×10^5	Powell (1991)
Carroll Glacier Delta			
Queen Inlet	1920-1948	2.8×10^7	
Wachusett Inlet	1980-1984	4.1×10^7	
Crillon Glacier Delta	1926-1961	1.6×10^6	
Rendu Glacier Delta	1892-1964	1.6×10^4	
Riggs Glacier Delta	1979-1985	2.8×10^6	
McBride Inlet			
Morainal Bank	1978-1981	4.0×10^5	Cowan (1988)
Ice-Contact Basin	1985-1987	2.0×10^6	
Ice-Proximal	1984-1987	3.1×10^6	
Muir Morainal Bank Complex	1860-1880	4.1×10^7	Seramur (1989)
	1860-1899	2.3×10^7	
Muir Inlet Basins	1899-1980	2.1×10^7	
Muir Glacier			
Push-Morainal Banks	1880-1899	4.4×10^7	
	1965-1974	2.7×10^6	Powell (1991)
Grounding-Line Fan	1987-1988	3.3×10^6	
Tarr Inlet Basin	1892-1979	$2.5\text{-}3 \times 10^7$	Cai & Powell (1993)
Glacier Bay Entrance Bank	1700-1750?	1.5×10^8	Cai (1994)
Johns Hopkins Inlet			
Entrance Bank	1892-1899	5.0×10^7	this study
Elbow Bank	1906-1912	8.3×10^7	
Fjord Basin	1892-1979	$2.3\text{-}2.5 \times 10^7$	

Terminus Fluctuation History

The terminus of Johns Hopkins Glacier was near the fjord entrance during 1892-1899 (Fig. 4; Scidmore, 1896; Cooper, 1937), and was at its first quasi-stability when the entrance morainal bank was deposited. From 1892 to 1899, the terminus position retreated less than 0.5 km, at an average rate of only 70 m/a. After 1899, Johns Hopkins Glacier started to retreat, and separated from Lamplugh Glacier. By 1906-1907, Johns Hopkins Glacier retreated to near the elbow (Field, 1964) where a quasi-stability was established and a morainal bank was deposited. It took about 5-6 years for the terminus to make the turn around the elbow. Beginning in 1912, Johns Hopkins Glacier started its relatively rapid retreat at an average rate of about 1800 m/a. With at least two short quasi-stabilities around 1914-1917 and 1920-1922, the terminus retreated for about 12.5 km by 1926 when the retreat ended. The terminus was stable during 1926-1929 (Field, 1964), then slowly advanced over about 2-3 km after 1929 (Field, 1964; Powell, 1980), but has recently retreated slightly over the last 2-3 years.

Lamplugh Glacier, located on the south side of Johns Hopkins Inlet near its mouth, was a tributary of Johns Hopkins Glacier until 1899 (Field, 1964). It has experienced very small fluctuations (less than 2 km) since it became independent, and was relatively stable for several decades at the position back only about 200 m from its former junction with Johns Hopkins Glacier (Cooper, 1937; Field, 1964; Powell, 1980). Similar to Johns Hopkins Glacier, Lamplugh Glacier has also retreated slightly over the past 2-3 years.

Summary

The last deglaciation in Johns Hopkins Inlet started only about 100 years ago. During the last 100 years, the terminus of Johns Hopkins Glacier, near the fjord mouth during 1892-1899, has experienced two major fluctuation periods: a relatively fast retreat and a slow advance. The average retreat rate is at least 10 times faster than the average advance rate. The terminus retreated for about 18 km in about 34 years between 1892 and 1926, with an average retreat rate of about 530 m/a. However, retreat rates vary from about 70 m/a during 1892-1899 to about 1800 m/a during 1912-1926. Between 1892 and 1926, the terminus of Johns Hopkins Glacier had reached at least four quasi-stabilities, when four morainal banks were deposited in 1892-1899, 1907-1912, 1914-1917, and 1920-1922, respectively. The glacier was relatively stable during 1926-1929. Beginning in 1929, the terminus slowly advanced over about 2-3 km at an average rate of less than 50 m/a, and appears to be at its most advanced position around 1990.

Calculations from seismic reflection profiles indicate that morainal banks in Johns Hopkins Inlet have similar slopes to most banks in Glacier Bay. The forebank slopes in Johns Hopkins Inlet (8-16°) are steeper than backbank slopes (3.5-7.5°). The slope of ice-distal fjord floor is less than 1°.

The relatively fast terminus retreat from the fjord between terminus quasi-stabilities, especially during 1912-1926 (average more than 890 m/a) has opened up deep fjord basins (up to about 550 m deep) along its course. However, these deep basins have been filled with up to 200 m of glacimarine sediment, with a total sediment volume of about 1.6×10^9 m^3. The average sedimentation rates were about 4 m/a between 1917-1942 and about 1.9 m/a between 1942-1979. The sediment accumulation rate averaged about 1.8 - 2.0×10^7 m^3/a between 1892-1979. About 44% of the total sediment in the fjord (7×10^9 m^3) was accumulated as morainal banks, with 1.8×10^8 m^3 of sediment in the largest old bank and 7.6×10^7 m^3 in the smallest, and overall the old morainal banks had an average accumulation rate of 1.7 - 2.6×10^7 m^3/a.

Results of this study indicate that seismic facies analysis of high-resolution seismic-reflection profiles can be used not only for interpreting glacimarine depositional processes and sediment lithofacies, but also for estimating sediment accumulation rates and reconstructing terminus fluctuation history, to provide important information for predictions of the future terminus fluctuations.

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Characteristics of Suspended Particulate Matter and Sedimentation of Organic Carbon in Glacier Bay Fjords

by

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Abstract

Suspended particulate matter has been examined *in situ* using video cameras attached to a submersible Remote Observation Vehicle (ROV) and by Scanning Electron Microscopy (SEM) of filtered water samples. The ROV system provides the opportunity to observe the true composition and size of suspended particles and SEM allows for identification of particle constituents and measurement of aggregate sizes.

Glacial meltwater streams that discharge into the fjords form thick, sediment-laden plumes that spread laterally downfjord. Particles that settle through the overflow are generally small, discrete grains. Below the surface layer, marine snow, discrete suspended grains and stringers were observed. The size and settling rate of most small particles is increased by flocculation of clay minerals and the incorporation of phytoplankton and non-clay mineral matter into flocs and fecal pellets.

Measurements of total organic carbon in bottom sediment collected from 4 fjords in Glacier Bay range from 0.16 to 0.30%. Samples from Tarr Inlet and Rendu Inlet were at the lower end of the range and those from Queen Inlet and Reid Inlet were above 0.24%. The source of the organic carbon buried in fjord sediment has not yet been investigated but the abundance and rapid settling rates of marine phytoplankton suggest that it may be a major source.

KEY WORDS. suspended sediment, organic carbon, flocculation, fecal pellet, phytoplankton.

Fjords in Glacier Bay National Park receive large volumes of suspended sediment from meltwater stream discharge. Upon entering the fjord, this sediment settles rapidly accumulating at rates up to 13 m/yr in basins adjacent to the glacier (Cowan and Powell 1991). Small particles, such as silt and clay settle more rapidly through the water column than is predicted by Stokes' Law resulting in deposition of glacimarine mud even in high energy areas such as near glaciers. The diameter of small particles can be increased by flocculation of mineral grains or by aggregation by organisms. The resulting flocs and fecal pellets have a higher settling rate than the discrete small particles. The concentration of a large number of fine particles into fewer large ones will also increase the transparency of water allowing sunlight to penetrate deeper into the water column, enhancing primary productivity (Eisma 1993). The incorporation of phytoplankton into rapidly settling particles may also bury organic carbon in modern glacimarine sediments. The fjords may be a sink for organic carbon along with the rapidly accumulating sediment.

Methods and Study Area

Two methods were used to evaluate the characteristics of suspended particulate matter from the fjords of Glacier Bay: 1) *in situ* observation using video cameras attached to a submersible ROV and 2) Scanning Electron Microscopy (SEM) of filtered water samples. The ROV system provides the opportunity to observe the true composition and size of suspended particles while collecting continuous salinity, temperature and optical backscatter profiles (a proxy for suspended sediment concentration) through the water column. Particles were observed during periods when the submersible was held steady within the water column.

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The SEM allows for identification of particle constituents and measurement of aggregate sizes. Subsamples of approximately 21 ml of fjord water were gently filtered using 0.8 micron filters for examination under the SEM. Small sample sizes kept particle aggregates from overlapping on the filter paper.

Sediment from the fjord floor was collected with an Ekman box dredge during April 1993 for total organic carbon analysis. Bulk samples were collected from beneath the sediment surface (>10 cm) to ensure that they represented deposition during the previous summer when organic carbon content should be higher than in winter. Six sediment samples and one water sample were collected in this pilot project. The samples were analyzed by a commercial laboratory using standard acidification and combustion techniques.

Submersible dives were made in Tarr, Muir, and Queen Inlets (Fig. 1). Water samples were collected from these fjords as well as from McBride Inlet. Grab samples were collected to analyze the organic carbon content of sediment from Tarr, Reid, Rendu and Queen Inlets (Fig. 1).

Results

Particle Characteristics

The shape, size and composition of suspended particulate matter in Glacier Bay fjords is similar to that from Arctic fjords described by Winters and Syvitski (1992). However, the number of particles are greatly increased in the temperate fjords of Glacier Bay because of the higher sediment discharge. Particles are transported downfjord in a brackish (>5 ppt) overflow plume that can be up to 20 m thick. The overflow appears as a haze in video observations because the dense cloud of particles in transport reflects the light from the ROV. These particles are generally small and rounded with few attached clays. Under the SEM, individual silt grains from the overflow plume show evidence of crushing by the glacier during transport to the fjord (Fig. 2a).

A complete range of particle sizes are released from the overflow plume during slack low tide when turbulence is at a minimum (Cowan and Powell 1990). The particles begin to sink vertically as discrete turbid layers separated by layers of less turbid water. Video images show separation of sand grains from silt and clay because the sand settles past smaller particles to the bottom of the turbid layer. Particles within the turbid layer become larger and their composition more complex with depth. Stringers or filamentous particles up to several centimeters long occur within turbid layers. These thread-like particles are weighted on one or both ends by larger spherical flocs. The stringers are fragile and break apart when exposed to the turbulence caused by the moving ROV. The nature of the filament is unknown because they do not survive water sampling and filtration.

The most common particles observed with the ROV within turbid layers appear as "fluffy" equidimensional flocs and are described in the literature as marine snow (Syvitski et al. 1983). These particles are formed during settling by flocculation of mineral grains or by aggregation resulting from organic interaction. There is a high probability that particles within turbid layers will collide because of the high concentrations and range of particle sizes. Larger particles or those with higher specific gravity settle faster and overtake the smaller lower density ones thus increasing the collision rate. Colliding particles can then be held together by electrostatic forces. Figure 2b is a sand-size particle composed of hundreds of densely packed clay to silt size mineral grains. This compact particle may settle up to 70 times faster than the single silt grains that formed it (Officer 1981).

The most common flocs within turbid layers are in the medium to coarse silt range. They are formed from mineral grains and have compact semi-spherical shapes (Fig. 3). Flocculation of plate-shaped minerals show edge-to-edge and edge-to-face contacts which produce a firm structure that persists until deposition (Eisma 1993).

Interaction of particles with organisms is less common than inorganic flocculation but is important in Glacier Bay fjords. Organisms excreting fecal pellets produce streamlined aggregates of small particles (Fig. 2c). Of the several shapes and sizes of fecal pellets observed with the SEM, all have been made of only mineral material. Most diatoms that have settled below the surface layer are coated with small particles or are attached to large flocs (Fig 2d). Alldredge and McGillivary (1991) suggest that sticky secretions from bacteria and algae increase the probability of attachment of particles on diatoms.

Organic Carbon

Six sediment samples and one water sample were analyzed for total organic carbon (TOC) content (Table 1). The water sample collected from above the fjord bottom in Tarr Inlet contained <1 mg/L TOC. This low value can be explained by low primary productivity in the water column in April (Burrell 1983). Particle size distributions were measured for 5 of the sediment samples to determine if particle size affected the organic carbon content (Table 1).

The highest values for TOC occurred in samples from Queen and Reid Inlets. Both of these fjords receive meltwater discharge from deltas and have vegetated fjord walls. Rendu and Tarr Inlets have comparatively low TOC. Rendu Inlet has a moderate amount of vegetation and Tarr Inlet has the least. Tarr Inlet samples had the most sand which is expected since they were collected within 2 km of

Grand Pacific and Marjorie Glaciers (Fig. 1). Organic carbon generally increases with clay content (Syvitski et al. 1990) which would explain the lower TOC in these samples.

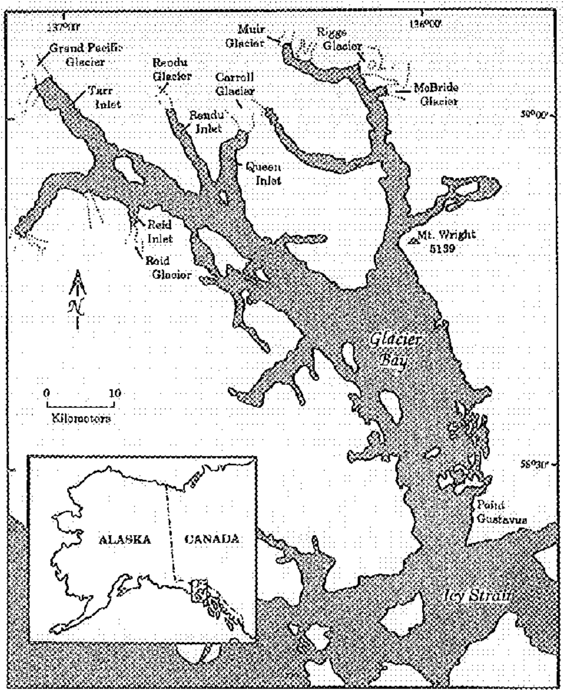

Fig. 1. Map of Glacier Bay National Park showing the locations of Tarr, Reid, Rendu, Queen, McBride, and Muir Inlets discussed in this paper.

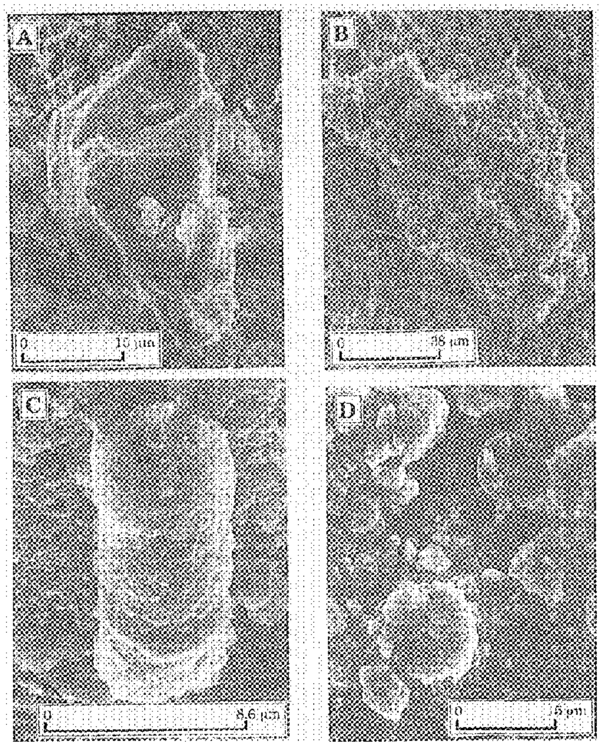

Fig. 2. SEM micrographs of particles from Glacier Bay fjords. a) A coarse silt size particle from 5 m depth showing conchoidal fracture and high relief which according to Krinsley and Doornkamp (1973) are features typical of glacial environments. b) A complex sand size aggregate collected from 66 m depth. The filter appears in the background of each photograph. c) This fecal pellet aggregated clay size particles into a silt size streamlined shape. d) These diatoms from 140 m depth are coated with attached clay size particles.

TABLE 1. Organic Carbon and Particle Size Distributions of Bottom Sediment Samples from Four Fjords.

PARAMETER	TARR INLET	TARR INLET	QUEEN INLET	REID INLET	RENDU INLET (top of sampler)	RENDU INLET (bottom of sampler)
% TOTAL CARBON	0.31	0.34	2.21	2.01	1.51	1.49
% CO_3 AS CARBON	0.13	0.17	1.91	1.77	1.35	1.30
% TOTAL ORGANIC CARBON	0.18	0.17	0.30	0.24	0.16	0.19
% SAND	20.4	5.4	0.7	1.4	0.2	- -
% SILT	63.5	71.6	70.0	65.3	69.8	- -
% CLAY	16.1	23.0	29.3	33.3	30.0	- -

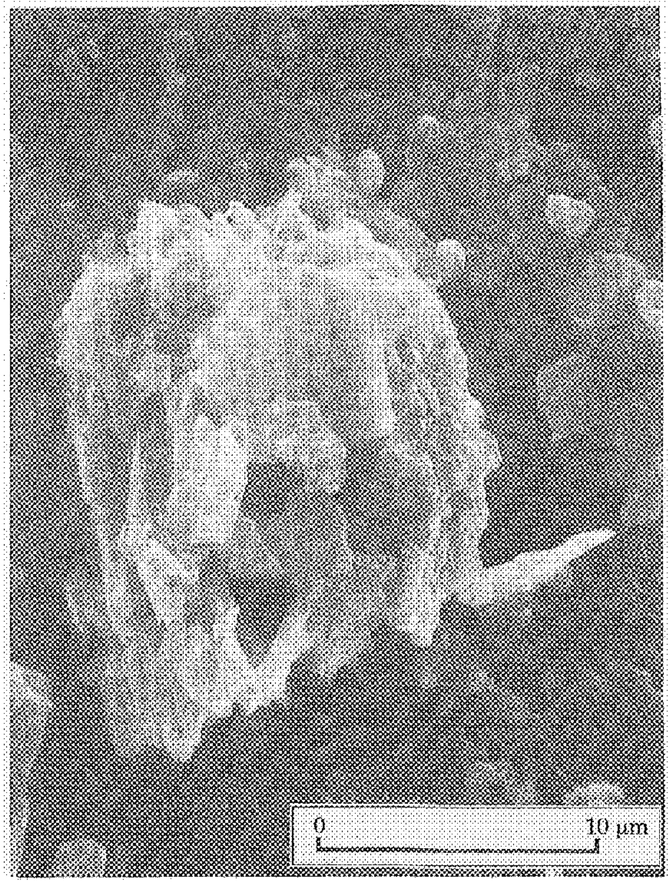

Fig. 3. SEM micrograph of a medium silt size floc collected from 48 m depth in Tarr Inlet. Mineral grains form a compact particle with edge-to-face attachments of grains.

Discussion

Flocculation and organic aggregation of fine particles greatly increase the downward flux of suspended sediment by increasing the settling velocity. Flocculated particles along with weak estuarine circulation (Cowan 1992) result in most sediment accumulating in basins proximal to the glacier. The ROV submersible is an excellent tool for identification of large fragile particles such as stringers that cannot be preserved during the collection of water samples. The observation of stringers below 20 m, the depth of the surface layer in Tarr, Queen and Muir Inlets suggests that the fjord water column was stable at the time of these observations because turbulence would cause the break up of these delicate aggregates. SEM photomicrographs suggest that most marine snow in these fjords is composed of mineral flocs ranging in size from medium to coarse silt. Aggregation of particles is also caused by the adherence of clays to the remains of phytoplankton and by the formation of fecal pellets by zooplankton.

The organic carbon content of bottom sediment in Glacier Bay fjords is similar to that of glacial dominated fjords in Arctic Canada (Syvitski et al. 1990) and slightly less than that from Antarctic fjords (Domack and Ishman 1993). Coronation Fiord, a tidewater glacial fjord on Baffin Island has a range of TOC from 0.1% near the glacier to 0.5%, 40 km downfjord (Syvitski et al. 1990). In the Antarctic fjords, TOC ranges from 0.20% near the fjord head increasing up to 1.5% by 20 km downfjord (Domack and Ishman 1993). In the Canadian fjords, marine snow and phytodetritus were the greatest source of particulate organic carbon to the fjord. The abundance and rapid settling rates of marine phytoplankton in Glacier Bay fjords suggest that it may be a major source here. Once deposited, organic carbon may become remineralized and available to organisms or be buried and preserved. Remineralization is mediated by bacteria in the bottom sediment and reduces the TOC concentration by half within 10 cm of the sediment surface (Alperin et al. 1992). In Glacier Bay, burial of the remaining TOC will be aided by rapid sediment accumulation and low bioturbation. The samples collected for this pilot study do not allow evaluation of seasonal changes in organic carbon input or calculation of the organic carbon deposition rate. These questions and the TOC distribution within the Glacier Bay fjord system are the subjects for future study. Glacier Bay may provide a modern analog for high organic carbon accumulation in marine sediments during the last glacial maximum. During this time the increased rate of organic matter accumulation is believed to have played a major role in carbon burial (Calvert and Pedersen 1992).

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Effects of Ice-proximal Sediment Dynamics on the Stability of Muir Glacier, Glacier Bay, Alaska

by

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Abstract

Recent studies have shown that water depth at tidewater termini affects calving rates and, therefore, glacier mass balance and terminus stability. If sediment dynamics at tidewater termini influence grounding-line water depth, they may also moderate glacier dynamics. Grounding-line water depths are governed by glacial and marine processes that interact during the formation of morainal bank depocenters. Morainal banks can fluctuate 10s of meters in height within a few weeks. Such rapid changes are important when interpreting glacier behavior where termini fluctuations may represent a dynamic response to sedimentary processes that are independent of climatic forcing.

Sedimentologic investigations in upper Muir Inlet have focused on quantitatively assessing sediment budgets in the ice-proximal environment. Monitoring of Muir Glacier morainal bank has included repeated bathymetric mapping, sediment trap studies, bottom grab sampling, and glacier and iceberg sampling. These investigations provide detailed information on process dynamics and sediment budgets in order to determine the complex relationships between ice-proximal marine processes and glacier response.

These relationships must be understood to interpret recent changes in the dynamics of Muir Glacier, where a century of retreat has been succeeded by quasi-stability as calving rates declined in response to rapid grounding-line deposition. Grounding-line fans aggraded to sea level forming deltas that reduced the length of the calving margin from 900 m to 290 m between 1988 and 1991. Ice flow velocities decreased 45% in response to a reduction in the calving flux as the width exposed to tidewater decreased. Annual morainal bank growth ranged from 10^6 to 10^7 m^3/yr and is the result of glacifluvial dumping, suspension settling from turbid overflow plumes, debris dumping from ice-cliff and iceberg melting, glacier squeezing and pushing of morainal bank sediment, and sediment gravity flow processes. Each of these processes is an integral facet of the morainal bank dynamics and glacier response. These studies of Muir Glacier indicate that glacier response to sediment dynamics needs to be addressed before climatic implications are made.

KEY WORDS: Glacier Bay, glacier, glacimarine, grounding-line, morainal bank, tidewater termini.

A study of the relationships between sediment dynamics and terminus stability has been conducted within Glacier Bay National Park and Preserve (GBNPP) as part of an ongoing program to monitor ice-proximal glacimarine processes. Recent studies have demonstrated that the response of glaciers with tidewater termini is not straight foreword and

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often asynchronous to climatic forcing (e.g., Warren, 1990; Powell, 1991). The relationship between climate and termini fluctuations is closely related to iceberg calving dynamics (Meier and Post, 1987; Mayo, 1988) controlled by water depth (Brown et al., 1982) and basin configuration (Powell, 1983). Several workers (Goldthwait et al., 1963; Post, 1975; Powell, 1984; Mayo, 1988) have suggested that sediment accumulation at the grounding line can increase terminus stability by reducing water depth. One of the main goals of this study is to monitor grounding-line sediment dynamics in order to assess their effect on terminus stability.

Data used to document ice-proximal sediment dynamics includes suspended sediment trapping, glacier/iceberg sampling, stream sampling, bottom grab sampling, and echo-sounding profiling. Sediment trapping and glacier/iceberg sampling were performed between July 23 and August 15, 1991 in upper Muir Inlet (Figure 1) near the terminus of Muir Glacier while bathymetric data have been collected since 1979 with an increase in the occurrence of echo-sounding profiling since 1989 to emphasize short-term sediment dynamics. These data sets are integrated to provide estimates on the growth rate of an active morainal bank, to determine the total glacier sediment budget, and to assess the response of the glacier to sediment dynamics. The latter is addressed by correlating observed glacier behavior with sediment dynamics. Recent glacier behavior has been recorded using aerial photographs collected by Austin Post and Robert Krimmel of the U.S. Geological Survey taken near the end of the ablation season in 1978-1981, 1986-1988, and 1990, radar mapping in 1984 by Jim Luthy (National Park Service), and field observations in 1991.

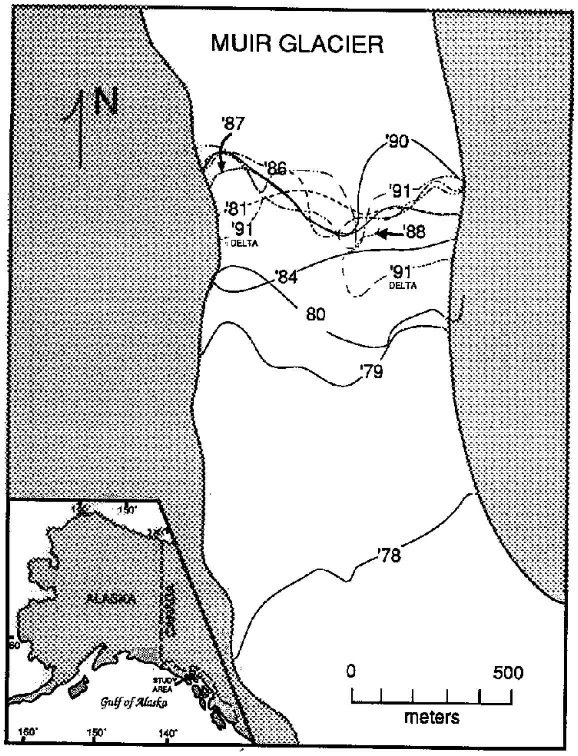

Fig. 1. Map of upper Muir Inlet showing terminus retreat positions between 1978 and 1991.

Changes in the Muir Glacier Terminus

Retreat of Muir Glacier has been well documented during the past 100 years (e.g., Reid, 1896; Field, 1947; Powell, 1984; Goldthwait, 1986) with an average retreat rate of 0.39 km/yr (Powell, 1991) and a maximum rate of 2.7 km/yr between 1976 and 1977. Retreat has been generally rapid, but punctuated by short-term stillstands and readvances where the fjord narrows and/or bathymetric highs are encountered. Rapid retreat of the terminus continued until the 1980s when a position of quasi-stability was reached in 1981 (Figures 1 & 2) and eventually maintained after 1986. Shortly after this position was first reached in 1981 there was a 100 to 250 m (175 m average) readvance to the 1984 position as the glacier attempted to establish a new equilibrium at the head of the fjord. Since 1986, terminus fluctuations have been localized within a narrow zone where the largest fluctuations are attributable to the temporal and spatial development of calving embayments and morainal bank depocenters.

Terminus configuration during the period of quasi-stability is characterized by a promontory at the fjord center, bounded by calving embayments (Figure 1). Between 1986 and 1990 the promontory remained in one place and coincident with a morainal bank that aggraded from a grounding-line fan (Figure 2D-E) to an ice-contact delta (Figure 2F-G). Aggradation of the morainal bank occurred where stream conduits dumped glacifluvial sediment between 1988 and 1989. Concomitant with fan aggradation and the stabilizing of the promontory, the two lateral embayments became increasingly pronounced as calving continued. In the 1990-1991 winter, the morainal bank collapsed on the west side of the promontory (Figure 2L), and the consequent terminus retreat created a central embayment bounded by two promontories which were the flanks of the old single promontory. The flanks were preserved because two lateral deltas that aggraded to sea level between 1988 and 1989 had then prograded across the base of the ice cliff so that less than 50% of the glacier terminus was tidewater. The embayment that developed was approximately 290 m wide with 440 m perimeter which actively calved into Muir Inlet during the 1991 summer. Delta progradation continued to eventually cause the aggradation of the grounding-line to sea level during 1993.

Ice-Proximal Bathymetry and Morainal Bank Dynamics

Annual bathymetric data of upper Muir Inlet are shown in Figure 2 with the corresponding isopach maps that show the changes in fjord floor bathymetry that occurred between echo-sounding periods. Changes in morainal bank morphology are summarized in Table 1 where the magnitude of change indicates that the ice-proximal environment is one of the most dynamic environments in the world. Annual changes in the morainal bank ranged from a collapse of 50m with the volumetric loss of 5.6 x 10^6 m^3 between 1988-1989 to more than 80 m of grounding-line fan aggradation and 3.3 x 10^6 m^3 of growth between 1987-1988. The greatest annual growth of the morainal bank was 7.8 x 10^6 m^3 between 1989 and 1990.

Isopach maps were developed to obtain quantitative measurements of process dynamics. The maximum observed growth was 1.1 x 10^6 m^3 over a 10 day interval in 1991 (Table 1) whereas summer changes were commonly lower (e.g. 0.4 x 10^6 m^3 over the 1990 summer) indicating that sediment is rapidly redistributed in the morainal bank environment. Collapse of sediment along the morainal bank towards the grounding line is associated with zones of ice cliff retreat where up to 1.1 x 10^6 m^3 of sediment collapsed over a 30 day interval in 1990. The down fjord diffusion of sediment from the morainal bank is attributed to mass movement processes of the order of 1.06 x 10^6 m^3 in a 16 day interval.

The Morainal Bank

Two profiles of the Muir Glacier morainal bank are shown in Figure 3. The 1989 profile (A-B) is a topographic profile drawn from the 6/18/89 bathymetric map while the 1991 profile (C-D) depicts the echo-sounding record from 8/15/91 reduced to a 1:1 scale. Profile A-B represents the condition of the morainal bank following retreat of the terminus promontory off of the morainal bank early in the ablation season. The morainal bank is characterized by a relatively gentle, slightly hummocky slope of about 8° following the terminus retreat during winter while glacifluvial discharge was low (see Hunter, 1994). Profile C-D records the morainal bank late in the ablation season and exhibits the crest that records the position of the 1990 terminus (Figure 1). The average slope of the morainal bank at the end of the summer was 18°. Slope angles up to 25.6° were observed,

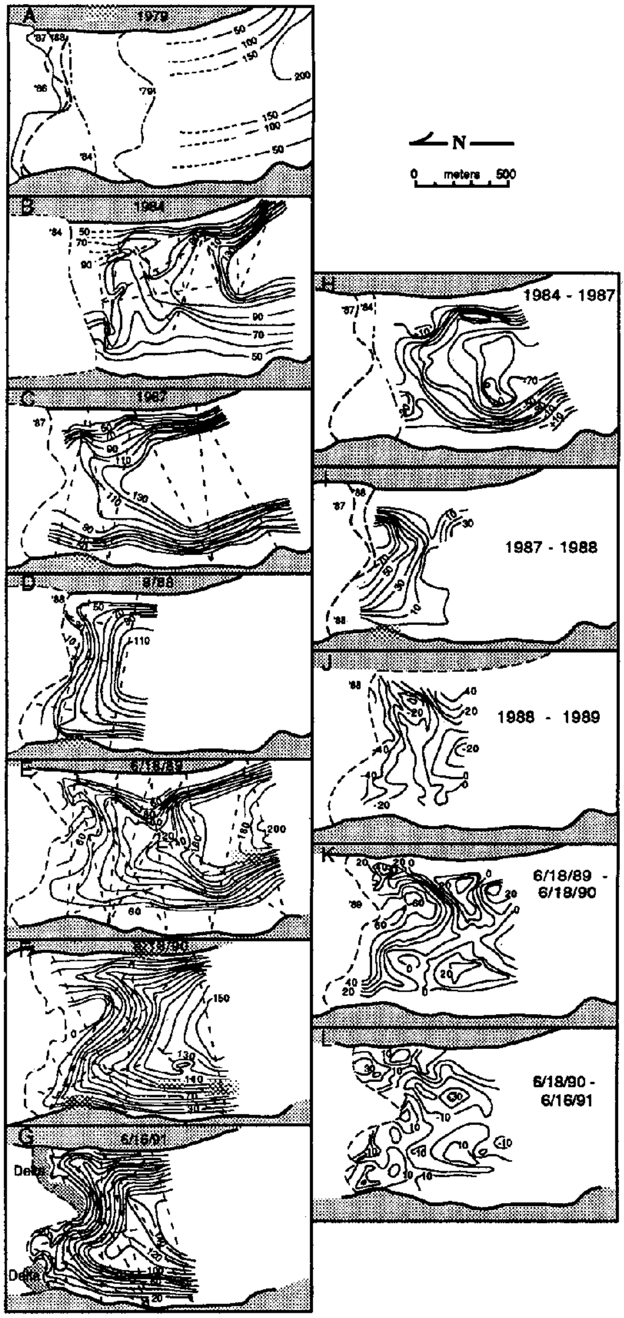

Fig. 2. Annual bathymetric maps (A-G) and annual isopach maps (H-L) for upper Muir Inlet between 1979 and 1991. Isopach maps show bathymetric changes that occurred over a known time interval (e.g., map H represents changes in sea floor morphology between bathymetric profiling periods B and C) and are used to document morainal bank sediment dynamics.

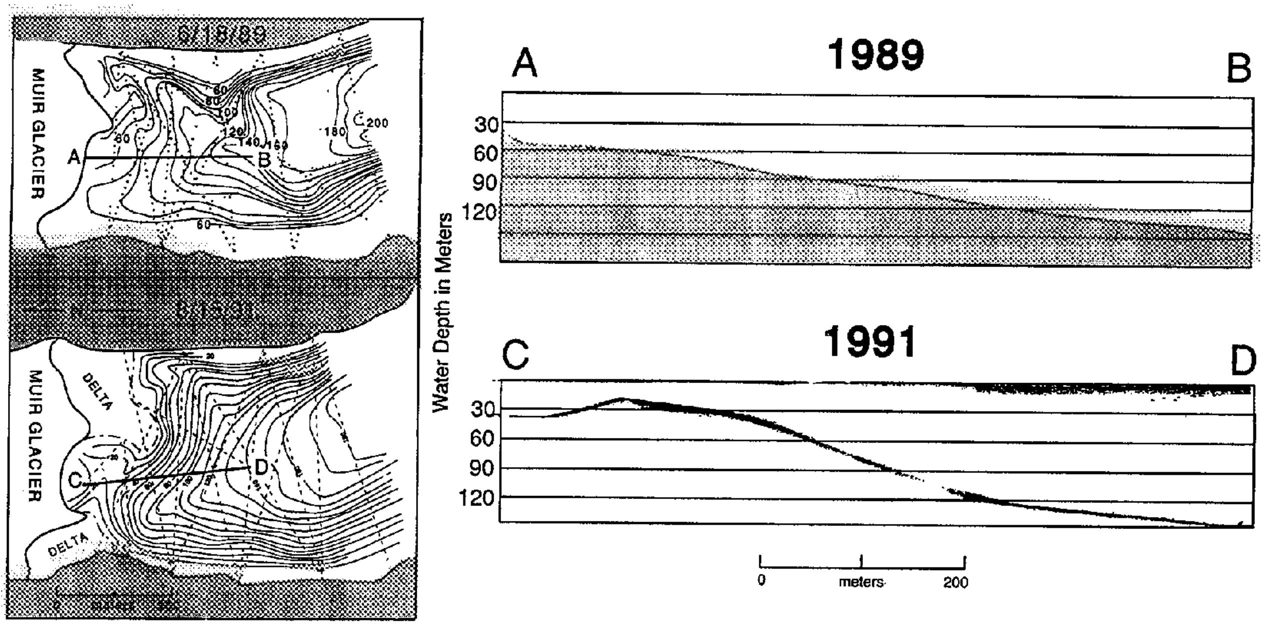

Fig. 3. Location map (left) and morainal bank profiles (right) from bathymetric profiling in June 1989 (line A-B) and August 1991 (line C-D). Reconstructed slope angles of 8° observed in 1989 (line A-B) developed as the terminus retreated and sediment was redistributed down fiord. Higher slope angles (line C-D) were maintained while the glacier advanced on to the morainal bank. Glacier activity both pushed and supports the sediment pile while outwash streams provided a constant sediment supply.

with an average of 22.8° being common for the Muir morainal bank. Higher slope angles are maintained when the glacier terminus was advancing or stable because of two processes: (1) back pressure caused by glacier push on the proximal slope of the moraonal bank and (2) rapid glacifluvial deposition during summer. Sediment gravity flow processes, slides and slumps appear to rapidly remove sediment from the grounding line to reduce the slope angle when back pressure by the glacier and sediment influx are not maintained.

Glacier Debris Flux

Debris flux through the glacier was determined by systematic sampling of icebergs whose locations were noted as they calved from the tidewater ice cliff, and by sampling ice along the terrestrial margin as described by Hunter 1994. Samples are grouped (Table 2) using a classification scheme modified from Lawson (1979) and Gottler (1992). All ice samples can be classified into three categories: (1) englacial, (2) morainal, and (3) basal. Englacial ice is divided into three facies: i) bubbly diffuse ice that has a low debris content (average 0.5 % by volume), ii) diffuse stratified with an average debris concentration of 1.4 % by volume, and iii) banded ice that is characterized by thin debris layers (average debris concentration 0.9 % by volume) and comprised less than 1 % of the ice cliff. Morainal and basal ice facies are not differentiated by Lawson but have been separated in this study based on stratigraphic position in the ice cliff. Lawson (1979) divided basal ice into either dispersed or stratified facies. Dispersed facies is absent in the morainal sections but 7 to 10 m thick sequences have been observed at the top of basal sections. This facies is characterized by deep blue, bubble free ice with an average debris concentration of 0.5 % by volume. This ice facies is a transitional phase between englacial diffuse ice and basal ice and appears to represent a change in the ice dynamics near the glacier sole.

Basal stratified ice is subdivided into: suspended, discontinuous, and solid subfacies (Lawson, 1979). Suspended subfacies is generally bubble free and contains debris suspended within the ice with an average concentration of 2.7 % by volume (Table 2). The solid subfacies is absent from Muir Glacier, and the remaining discontinuous subfacies has high debris concentrations (15.3 % by volume) and is characterized by debris with only interstitial ice or thin (~1-3 mm thick) debris layers separated by thin ice layers. An additional basal subfacies observed at the terminus of Muir Glacier is that described as a basal freeze-on layer. Samples of this facies at Muir

Glacier average 47 % by volume (up to 68%) but have been measure at about 70 % by volume at Grand Pacific and Johns Hopkins Glaciers, and Gottler (1992) estimated approximately 100 % by volume at McBride Glacier. These layers represent debris frozen onto the sole near the terminus and are cemented by interstitial ice. Freeze-on layers occur at the sole of the glacier where individual layers may exceed 1 m in thickness.

Sediment Budget

The sediment budget for Muir Glacier is determined by combining glacial debris flux data with monitored sedimentation rates. Glacifluvial output of suspended sediment has been calculated from 36 sediment traps moored within 4 km of the terminus (Hunter, 1994). Bottom traps (located 2 and 5 m above bottom) provide the best proxy for sediment accumulating at the sea floor. Sea floor sedimentation rates ranged from 477 mm/d near the mouth of the east delta to 0.6 mm/d approximately 4 km down fjord from the terminus of Muir Glacier. Oceanographic monitoring of fjord salinity stratification by Cowan (1988) has been used to estimate the peak discharge periods from McBride Glacier, 18 km southeast of Muir Glacier. Cowan observed that peak discharge lasted approximately 52 days and used this time interval to extrapolate daily sedimentation rates in order to calculate seasonal glacifluvial discharge. By assuming a 52 day peak discharge period for Muir Glacier during the 1991 field season, a value of 2.1 x 10^6 m^3 is calculated for suspension settling within 5 km of the terminus. This value is closely corroborated by extrapolating suspended sediment concentration data from 21 stream samples collected on both the east and west deltas near Muir Glacier. Streams of the east and west deltas transported 6.0 and 4.0 kg/m^3, respectively, with stream velocities measured at 3.5 m s^{-1} at the east delta and 3.9 m s^{-1} at the west delta. The total suspended sediment discharge calculated for these stream is 2.0 x 10^6 m^3/yr.

Bedload dumping at the mouths of the ice-contact deltas can be calculated by monitoring the growth of depocenters near stream mouths using bathymetric mapping techniques (Hunter, 1994). Daily rates are determined by summing the contributions from the east, central, and west deltas and then dividing by the number of days between successive echo sounding intervals. An average daily sedimentation rate of 9.3 x 10^4 m^3 calculated by this method, extrapolates to 5.0 x 10^6 m^3 for 52 days. Of this value, 1.1 x 10^6 m^3 is attributed to proximal suspension settling; so that 4.5 x 10^6 m^3 is attributed to bedload dumping.

Total glacial debris flux is determined knowing the debris concentration and facies distribution in the ice cliff (Table 2). Where the glacier has a terminus width of 880 m, an average estimated height of 90 m (60 m above tidewater and an average grounding-line water depth of 30 m in 1991), and a velocity of 1,700 m/yr, there is an calculated ice flux of 1.35 x 10^8 m^3/yr across the grounding line (Hunter, 1994). Using the ice flux (F), debris concentration in volume percent (V_d), and relative percentage of each ice facies (I_f), the total volume of debris transported to the terminus in year (V) is calculated by:

$$V = V_d \times I_f \times F$$

The sum of all ice facies volumes indicates that 1.3 x 10^6 m^3 of debris is transported within the glacier each year (Table 2). An additional 1.4 x 10^4 m^3 of debris is transported supraglacially where moraines have a total width of 110 m and a thickness of 0.08 m (Gottler, 1992). If the basal freeze-on layer averages 1 m thick (cf. Gottler, 1992) across the terminus, then an additional 7.2 x 10^5 m^3 of debris may be transported to the grounding line through local recycling.

Discussion

Morainal banks are an important component of ice-proximal glacimarine environments which develop as ice-contact depocenters that control grounding-line water depths. Sediment delivered to grounding lines as glacial debris and glacifluvial sediment is affected by varying oceanic conditions in the ice-proximal environment. The rate that these banks grow is a function of how rapidly debris can be introduced to the grounding line and how efficient oceanic and gravity flow processes are at removing sediment. The recent behavior of Muir Glacier demonstrates how a tidewater terminus can have its behavior mediated by proximal sediment dynamics.

A comparison of recent glacier dynamics by Hunter (1994) indicates that in a 14 year period Muir Glacier's surface area decreased 10%. Surface velocities slowed by 45% as the calving speed was reduced by 52%. The reduction in calving speed is more dramatic if one considers the change in total ice volume lost to calving per year. The width of the calving terminus was 900 m in 1978 (Brown et al., 1982) when 5.3 x 10^8 m^3 of ice ablated through calving. By 1991, the calving margin was approximately 440 m long around the periphery of a 290 m wide embayment. The average calving speed in the embayment was approximately 2,000 m/yr resulting in 7.5 x 10^7 m^3 of ice loss to calving, an 86% reduction since 1978.

Dramatic changes in the dynamics of Muir Glacier have occurred as the grounding line retreated and later aggraded in response to rapid morainal bank growth. Average water depths along the grounding line have aggraded from 100 m in 1978 (Brown et al., 1982) to 30 m in 1991. As the

Table 1: Ice-proximal sediment dynamics in upper Muir Inlet.

Annual:

Period	Volumetric Changes w/in 0.7 km (10^6 m^3)	Morainal Bank Change Change (10^6 m^3)	Maximum Aggradation (m)	Maximum Loss (m)
1984-1987*	-9.90	NA	NA	30
1987-1988*	NA	3.30	80	NA
1988-1989	-8.12	-5.15	NA	50
1989-1990	8.18	7.76	60	20
1990-1991	2.28	0.08	30	20

* (From Powell 1991)

Short-term Dynamics:

Period:	East Delta (10^6 m^3)	West Delta (10^6 m^3)	Central Delta (10^6 m^3)	Back Collapse (10^6 m^3)	Proglacial Mass Movements (10^6 m^3)
Annual:					
Summer 1990	NA	0.66	NA	0.53	1.08
Summer 1991	1.13	0.48	1.82	0.27	0.71
Short Term:					
6/2-6/18/90	0.15	1.02	1.81	0.15	1.39
6/18-8/17/90	1.06	1.30	NA	1.05	0.55
6/16-7/22/91	1.61	0.81	NA*	0.40	0.84
7/22-8/5/91	0.54	0.63	NA*	0.24	0.07
8/5-8/15/91	1.05	0.17	NA*	0.17	0.20

* Only east and west deltas active during these periods

Table 2: Summary of Average Debris Concentrations used in Debris Flux Calculations.[*]

Ice Flux: 1.35 x 10^8 m^3/yr

Ice Facies	%	C_o	Vol %	Q_{dt}[†]	D_m[†]	D_c[†]	D_Δ[†]
Englacial							
Diffused	83.0	16.8	0.6	6.50	0.39	3.52	2.59
]Stratified	2.0	42.5	1.4	0.38	<0.01	0.21	0.17
Banded	0.7	12.1	0.4	0.04	TR	0.02	0.02
Morainal							
Dispersed	--	--	--	--	--	--	--
Suspended	0.8	116.7	3.9	0.42	<0.01	0.24	0.18
Discontinuous/ Solid	0.6	509.4	17.0	1.38	0.01	0.77	0.60
Basal							
Dispersed	10.0	20.1	0.7	0.90	<0.01	0.51	0.39
Suspended	1.8	116.7	3.9	0.95	<0.01	0.53	0.41
Discontinuous/ Solid	1.1	509.4	17.0	2.53	0.16	1.42	0.95
Total[†]				13.1	0.58	7.22	5.32
Freeze-on	NA	1433	47.82	7.2 x 10^5 m^3/yr			
Supraglacial				1.4 x 10^4 m^3/yr			

[*] (% = Representative Percentage of Each Ice Facies in Ice Cliff;
C_o = Debris Concentration in kg/m^3; Vol % = Percent by Volume Debris Concentration)

[†] Values in 10^5 m^3/yr unless otherwise indicated

grounding line aggraded and ice-contact deltas prograded laterally across the base of the ice cliff, back pressure from the glacier pushing the morainal bank resulted in reduction of the ice flow velocity. Tensional stresses near the terminus were replaced by compressional stresses producing shearing and thrusting of terminal ice while also causing deformation of ice-contact sediments.

It has long been realized that the calving mechanism of a tidewater glacier strongly effects the mass balance of the glacier (Mercer, 1961). Where calving dominates glacier ablation processes, fluctuation in the calving speed will influence terminus behavior. This study has demonstrated that between 1978 and 1991, calving was dramatically reduced at Muir Glacier while the terminus established itself in a regime of quasi-stability. Bathymetric mapping and sediment budget studies have documented growth of the morainal bank at the Muir grounding line and demonstrated a dynamic control on terminus behavior.

Sedimentation rates reported in this paper are among the highest recorded in GBNPP (cf. Cowan, 1988; Powell, 1991). High rates of sedimentation reflect the rapid transfer rates of Alaskan temperate glaciers with their high debris concentrations. Glacial abrasion and debris entrainment in Muir Inlet is enhanced by the friable nature of deformed and metasomatized bedrock of the Alexander Terrane in the region. Previous estimates for denudation rates in the Muir Glacier basin are between 0.5 cm/yr and 1.9 cm/yr (see review by Hunter, 1994), whereas, a denudation rate of 4.1 cm/yr is calculated by this study. These denudation rates show a general agreement in order of magnitude, being about two orders of magnitude greater than estimated denudation rates across the United States and one order greater than most mountainous regions (see review by Chorley et al., 1984).

The close comparison of sediment volumes calculated using sediment traps and stream samples suggest that these volumes of sediment flux by suspension settling are reasonable. Reid (1896) observed high sediment concentration (up to 13 g/L) at the time when Muir Glacier terminated on a morainal bank near the mouth of Muir Inlet. These concentrations were higher than those observed by Cowan (1988) in McBride Inlet suggesting that anomolously high sedimentation rates develop when a glacier advances onto a morainal bank. Therefore, the high denudation rate may be partly explained by sediment recycling as the glacier overrides the morainal bank and large volumes of sediment are pumped out of the glacier through stream conduits. Some of the difference in denudation rates may also be due to different types of measurement. This study measured the recent sediment dynamics while Powell and Molnia (1989) measured sediment fill volumes from high resolution seismic profiles. A main difference may be compaction and longer time intervals over which the sedimentation rates were averaged (i.e., Powell and Molnia, 1989) whereas this study uses data from sediment traps collected over a relatively short-time period.

Significance of Study

1) This paper has demonstrated the dynamic nature of active morainal banks developed at grounding lines of temperate tidewater termini in southeast Alaska. The dynamics are characterized by extremely high rates of sediment delivery and rapid sediment remobilization.

2) Glacifluvial sedimentation (6.0×10^6 m^3) is nearly a factor of five higher than glacial debris flux (1.31×10^6 m^3). Glacifluvial sedimentation within 5 km of the terminus is characterized by 35% suspension settling and 65% bedload dumping.

3) Bedload dumping is restricted to delta fronts and point sources at outwash conduits along the ice cliff where depocenters become sites of morainal bank aggradation. Glacifluvial sedimentation is augmented by debris meltout from the tidewater ice cliff and debris release from basal freeze-on layers; although, these processes are two orders of magnitude lower than bedload dumping.

4) Rapid ice-proximal sedimentation is compounded by sediment pushing by a glacier, resulting in high slope angles (up to 25°) of morainal banks and large bathymetric changes of -50 m to +80 m. During periods of glacier retreat, morainal bank slopes approach 10° following sediment collapse associated with the release of support by the glacier.

5) Recognition of high angles of paleoslopes in Quaternary ice-proximal glacimarine sequences may be useful indicators of paleoglacier dynamics and terminus proximity.

6) Morainal bank sediment dynamics impose a first-order control on the water depth of the grounding-line that affects calving speeds and glacier mass balance.

7) Marine-ending glaciers (ice shelves and tidewater termini) have been considered important indicators of global climate trends because they are inherently unstable, but their behavior has demonstrated that they can fluctuate independent of climate. In order to accurately model the response of marine glaciers to recent climate trends, a more comprehensive understanding of their dynamics needs to be achieved, and in particular, the affects of sedimentation at grounding lines need to be addressed.

8) Ancient glacial deposits are strongly biased towards the glacimarine environment. These deposits have been used to make climatic inferences for the geologic past that may be oversimplified in light of greater understanding of the dynamics of these glaciers.

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Influence of Sedimentation, Accumulation to Total Area Ratio, and Channel Geometry on the Advance of a Fjord-type Glacier

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Abstract

The Taku Glacier has advanced 7.25 km since 1890 in contrast to neighboring glaciers, which have all been retreating. We consider this advance to be linked to the tidewater glacier cycle of periodic rapid-calving retreat followed by gradual readvance. However, the rate of advance of the Taku Glacier has been up to two to three times greater than observed for other fjord-type glaciers that are currently in the advance mode of their respective cycles. The rate of advance of the Taku averaged 76 m/yr between 1890 and 1929, increased to 158 m/yr during 1929-1937, then declined to 64 m/yr by 1963. We attribute these high rates of advance to (1) the rapid filling of the Taku recessional fjord with sediments derived from adjacent Taku River and from glacier erosion, (2) the high accumulation to total area ratio (AAR ~ 0.88), and (3) channel geometry. In 1890, the Taku Glacier calved icebergs into a 100 m deep tidal basin. By 1929 a shoal moraine had developed along parts of the terminus and by 1937 water depth at the terminus was only 7 m. The rate of advance since 1963 steadily declined to 14 m/yr (1979-88) as the glacier terminus and its distributary lobe, Hole-in-the-Wall Glacier, spread out over tidal outwash flats, and as the AAR decreased to ~0.83. The terminus has been essentially stationary since 1988 despite its still relatively high AAR. The positive net balance may be presently thickening the glacier rather than expanding its area. Surface elevations in the ablation zone increased 40-90 m between 1948-1989. Radio echo soundings show the glacier in the lower ablation zone has displaced sediments to 210 m below sea level, 110 m lower than the 1890 soundings. The glacier currently terminates 1.5 km across the Taku River from Taku Point. Continued advance of the Taku Glacier could impact and perhaps block the Taku River, as it did as recently as 1750 AD.

KEY WORDS. Tidewater glacier, glacier advance, glacier erosion and sedimentation, glacier depth.

The Taku Glacier is a temperate, maritime, valley glacier that covers an area of about 700 km^2. It is the largest glacier draining the Juneau Icefield which mantles the Coast Mountains on the border between Alaska and Canada, north and northeast of Juneau. The Taku Glacier has advanced 7.25 km since the turn of the century while all other glaciers radiating from the Juneau Icefield have been retreating This contrasting behavior, which has attracted considerable

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scientific attention, has been termed the "Taku Anomaly" (Heusser et al., 1954). We consider the Taku Glacier to be a fjord-type glacier and interpret its advance as linked to the tidewater glacier cycle of periodic rapid calving retreat followed by gradual readvance. The terminus currently lies about 1.5 km across the Taku River from Taku Point (Fig. 1). The Taku River extends into Canada for some 200 km and drains a vast intermountane region, estimated at 17,000 km^2. Continued advance of the Taku Glacier may impact the Taku River and perhaps block it, creating a glacier-dammed lake as it did as recently as 1750 AD (Lawrence, 1950). Closure of this river could eliminate major salmon runs which are now important economic resources for Alaska and Canada. Even partial blockage of the river could seriously impact use of the river as a transportation corridor and also affect plans to use the Taku River valley for a road connecting Juneau, Alaska to Canada. These concerns prompted our investigations of the Taku Glacier. We discuss here how the glacier's rate of advance has been influenced by sedimentation, the accumulation to total area ratio (AAR), and channel geometry.

The Advance of the Taku Glacier

We measured the advance of the Taku Glacier by using charts and bathymetric data from the U.S. Coast & Geodetic Survey (USC&GS) (now National Oceanic and Atmospheric Administration (NOAA)), surveys of the International Boundary Commission, vertical aerial photography, and our own more recent surveys (Motyka, 1989; R.J. Motyka and D.C. Trabant, unpublished data). The principal tools for plotting and comparing terminus positions were a stereozoom transfer scope and a photogrammetric digital stereo plotter. The results are shown in Figure 1. Historic positions and rates of advance of the glacier terminus have also been reported by Lawrence (1950), Field (1967), and Pelto and Miller (1990). Our study includes additional historic positions and more recent positions based on our surveys and vertical aerial photography. Our study also differs in that we not only determined the rates of linear advance (in our case, averaged across the terminus between respective dates) but also the rates of areal expansion in the lower part of the ablation zone (Table 1). Areas and terminus lengths were measured with a compensating polar planimeter. Comparing changes in rates of area expansion to rates of linear down-channel advance provides a means of assessing the influence of geometry on the rate of advance. Data on lateral boundaries above the terminus for 1890 and 1929 is lacking. The value for areal expansion per year (A/yr in Table 1) for this period is a minimum and pertains only to the areal expansion between the 1890 and 1929 terminus positions.

Using data collected between 1946 and 1986, Pelto and Miller (1990) calculated the mean annual equilibrium line altitude (ELA) of the Taku Glacier at 910 m. We used this ELA to measure the accumulation zone from 1:63,360 scale U.S. Geological Survey topographic maps using a polar planimeter. The glacier's total area was also measured with a polar planimeter. The position of the ELA in relation to glacier geometry (below the confluence of tributary glaciers and at the head of the distributary valley), makes the AAR at Taku Glacier relatively insensitive to small changes in ELA. Growth of accumulation zone area has been minor and changes in AAR have been mainly due to the expansion of the ablation zone as the glacier steadily advanced down valley. Although the ELA is likely to have been at a lower elevation at the turn of the century when the climate was cooler (Motyka and Beget, in press), for simplicity we assumed the mean annual ELA was at 910 m for all our measurements. Our estimates of the glacier's AAR (Table 1) are least accurate for earlier periods where glacier boundaries are not well known and the ELA may have been lower and most accurate for more recent periods for which we have good vertical aerial photo coverage and the mean annual ELA is well defined.

The earliest survey of the Taku Glacier terminus was made during a bathymetric survey of Taku Inlet by the USC&GS in 1890. The chart shows the glacier terminated at the head of a 100 m deep tidal basin, labeled "Taku Fjord" in Figure 2. The calving terminus became a popular tourist attraction during the early part of this century. The terminus advanced at an average linear rate of 76 m/yr between 1890 and 1929, the date of a U.S. Navy aerial photo of the terminus. The advance accelerated to 158 m/yr, averaged between 1929 and 1937, then slowed to 90 m/yr between 1937 and 1952, and 53 m/yr by 1973. The rate of advance continued to decline, averaging 34 m/yr between 1973 and 1979 and 14 m/yr between 1979 and 1988. Our recent surveys and photogrammetric analysis show that the glacier has not advanced since 1988, and has actually retreated slightly along its northeastern edge.

In contrast, neighboring Norris Glacier was in a maximal position as recently as 1911 (Fig. 1) when it began retreating at an average rate of 10 to 15 m/yr. Since 1979, the rate of retreat has been 50 m/yr. All other glaciers draining from the Juneau Icefield have also been retreating (Field, 1975). The Mendenhall Glacier near Juneau has been retreating since about 1770 AD and recession averaged about 40 m/yr between 1909 and 1948 (Lawrence, 1950).

Most previous investigators attributed the "Taku anomaly" to climate-related influences such as changing levels of maximum snow accumulation (for example, Lawrence, 1950; Miller, 1963; 1985; Pelto and Miller, 1990). In contrast, we consider that the present advance of the Taku Glacier is

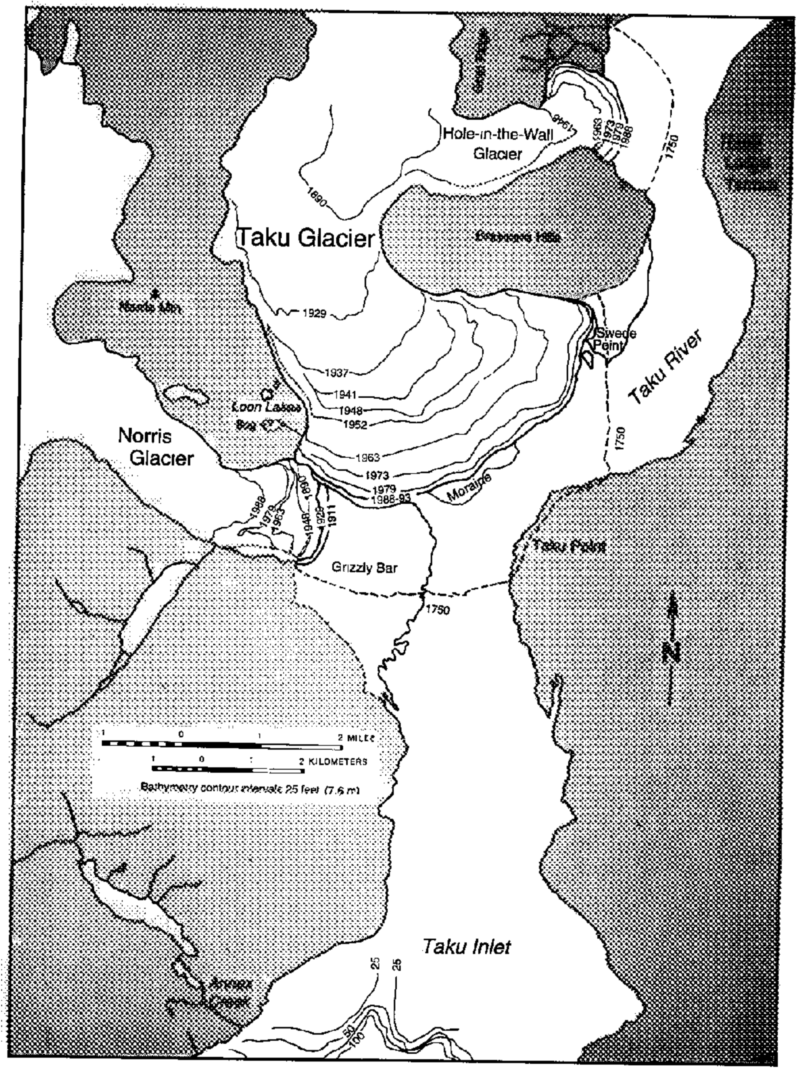

Fig. 1. Map showing the advance of Taku Glacier and retreat of the Norris Glacier for selected dates between 1890 and 1993. Positions shown are from USC&GS surveys (1890, 1937 and 1952), from aerial photos (1929: U.S. Navy; 1941: unknown; 1948: USGS, 1963: U. of Washington; 1973: U.S. Air Force; 1979: NASA; 1988: NOAA), and from our geodetic surveys (1993). The dotted line shows the position of the 1750 AD Neoglacial maximum as inferred by trimlines and moraines (Lawrence, 1950).

directly related to the calving-glacier cycle and that climate effects are secondary (Post and Motyka, 1995). Post (1975), Brown and others (1982), and Meier and Post (1987) developed the calving glacier hypothesis based on observations of Columbia Glacier and other calving glaciers with additional important refinements contributed by a host of others (see Post and Motyka, 1995, for a review).

Briefly, a calving glacier will cycle between four terminal positions. (1) The stable, retracted position of the terminus is usually located in shallow water near the head of the fjord. (2) The glacier will begin advancing by deposition and pushing of a terminal moraine shoal which separates the terminus from deeper tidal water where calving can be rapid. If the glacier attempts to advance beyond its shoal moraine, the terminus will quickly fracture because of the deeper water, become unstable and calve back to its shoaling moraine. This advance is generally slow in deep fjords (rarely more than a few meters per year) because of the amount of material needed to maintain the moraine. (3) As the glacier continues to advance, the ablation area increases and ablation plus calving eventually balances accumulation. Only then, usually when the AAR reaches 0.70 or so, does the glacier become increasingly sensitive to climate change. (4) Recession from the terminal moraine shoal results in the ice face terminating in deeper water. Calving increases and the terminus becomes unstable when calving speed surpasses flow rate. Calving speed is directly related to flow rate and channel geometry (width and depth) and retreat usually accelerates as the terminus moves into increasingly deeper water. Calving speed during drastic retreat far surpasses accumulation and, depending on channel geometry, recession

Table 1. Rate of advance of the Taku Glacier as determined from surveys, vertical aerial photography and USC&GS charts.

Period	Time yr	L_t km	A/yr km^2/yr	σ km^2/yr	Adv m/yr	σ m/yr	AAR
1890							0.88
1890-1929	39	2.00	0.153[a]	0.015	76	2.0	0.86
1929-1937	7.8	2.78	0.462	0.018	158	3.2	0.85
1937-1948	11.2	3.95	0.375	0.009	90	1.3	0.85
1948-1963	15.0	5.85	0.428	0.014	64	2.0	0.84
1963-1973	10.0	7.27	0.392	0.011	53	1.5	0.84
1973-1979	6.0	7.76	0.261	0.019	34	2.5	0.83
1979-1988	8.8	8.01	0.110	0.014	14	1.7	0.83
1988-1993	5.0	8.17	0.00	0.01	0	1.0	0.83

[a] Minimum value.

L_t = length of terminus averaged between dates; A = areal expansion; σ = estimated uncertainty; Adv = rate of advance, averaged over length of terminus; AAR = accumulation to total area ratio at ending date.

may be up to several km annually. Recession continues regardless of climate changes until the glacier stabilizes, usually in shallow water as in (1) above, where the cycling process will resume.

Dendrochronology of forest trimlines and lateral moraines indicate the Taku Glacier was at its Neoglacial maximum position as recently as 1750 AD, and began retreating shortly thereafter (Lawrence, 1950; Motyka et al., 1994). Trimlines and scour marks at Taku Point show the glacier crossed the Taku River and covered Taku Point to elevations of up to 60 m above sea level (Fig. 1), creating a huge glacier-dammed lake. At least two earlier Holocene advances also caused lakes to form as evidenced by three wave-cut terraces along the south wall of the Taku River valley and by radiocarbon studies of glacier-dammed lake sediments deposited during periods of glacier expansion (Motyka and Beget, in press).

Based on a passage in Vancouver's 1794 journals and on the ages of trees that were being overrun by advancing ice in 1949 (Lawrence, 1950) we estimate the rate of retreat was at least 0.2 km/yr. This rate of retreat lies at the low end of rates reported for historically retreating calving glaciers in Alaska (Meier and Post, 1987). The farthest retracted position of the Taku Glacier is unknown but is unlikely to have been much farther back than its 1890 surveyed position. Tidewater glaciers fronting in deep water (>100 m b.s.l.) that are in their advancing phase advance at relatively slow rates,~ 10 m/yr (Meier and Post, 1987). Using this value for the pre-1890 rate of advance constrains the furthest retracted position to no more than 1 km from the glacier's 1890 position.

Sedimentation, Channel Geometry, and AAR

Between 1890 and 1963, the rate of advance of the Taku Glacier was two to three times greater than observed for other Alaskan fjord-type glaciers that are currently in the advancing mode of their respective cycles (cf. Meier and Post, 1987). We attribute this rapid advance to a combination of high positive net balance (Pelto and Miller, 1990), channel geometry, and rapid filling of "Taku Fjord" with sediments derived from the Taku Glacier, Norris Glacier, and the Taku River. Figure 2 shows the configuration of "Taku Fjord" in 1890. The basin shallowed to the south beyond Taku Point where sediments had accumulated while the Taku Glacier was in its Neoglacial maximum position against Taku Point. Deltaic deposits from the Taku River were prograding into the fjord from the east with much of the suspended sediment load being deposited into the basin. The fjord was also filling with sediments from the Norris Glacier on the west and the Taku Glacier on the north.

Although the Taku Glacier had a very high AAR at the turn of the century (~ 0.88) calving controlled the rate of advance as long as the glacier terminated in deep water (100 in 1890). The rate of advance began to increase as sediments from the Taku Glacier, Norris Glacier, and Taku

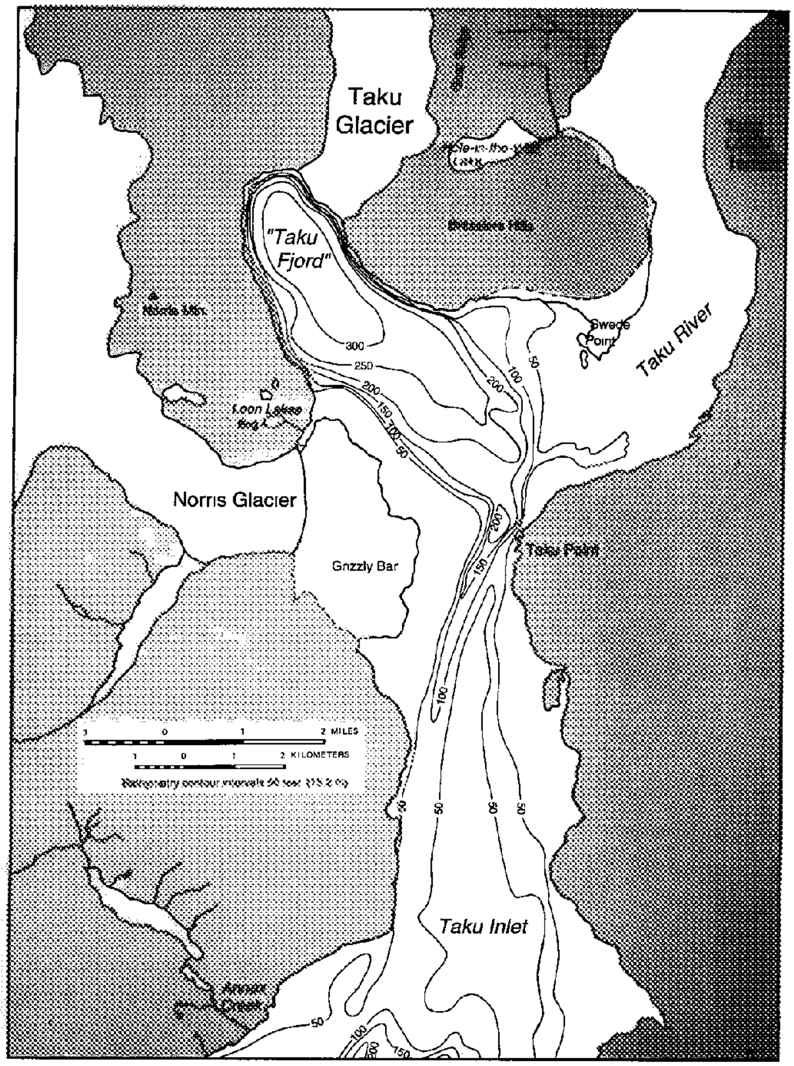

Fig. 2. The U.S. Coast & Geodetic Survey (USC&GS) charted Taku Inlet in 1890 (Survey #2055) and shows Taku Glacier in its furthest retracted observed historic position. The glacier fronted in a large tidal basin ("Taku Fjord") with depths of more than 100 m (330 ft) below sea level. Following the retreat of the glacier, sediments from Taku River and the Taku and Norris Glaciers rapidly filled the deep fjord.

River gradually filled "Taku Fjord". By 1931 a shoaling moraine had formed along broad sections of the terminus which substantially reduced calving and increased the rate of advance. The glacier also entered a narrower part of its channel (Fig. 1) which further increased the rate of advance. By 1937 when the USC&GS resurveyed Taku Inlet, "Taku Fjord" had largely been filled by glacier ice and sediment; water depth at the terminus was only 7 m (Fig. 3). Maximum water depth in what remained of the fjord was 45 m. Moraines had emerged above high tide line along most of the terminus by 1948.

We attribute much of the decline in the rate of linear advance after 1937 to the broadening of the terminus as the glacier continued to advance down valley and began spreading out over tidal flats (Fig. 1; cf. also L_t, Table 1). This hypothesis is supported by examining the areal rate of expansion (A/yr, Table 1) which remained approximately the same until 1973, indicating the amount of ice being added to the lower ablation zone remained relatively constant. Both the rate of terminus advance and of areal expansion began declining after 1973 with the terminus becoming nearly stationary after 1988. Although decline in AAR probably contributed to the slow down, its current value of 0.83 is still significantly well above the equilibrium threshold value of 0.70 found for other Alaskan fjord-type glaciers. A warming trend that began in the mid-1970s does not appear to have been the cause of the slow-down as mass balance studies by Pelto and Miller (1990) indicate the glacier had

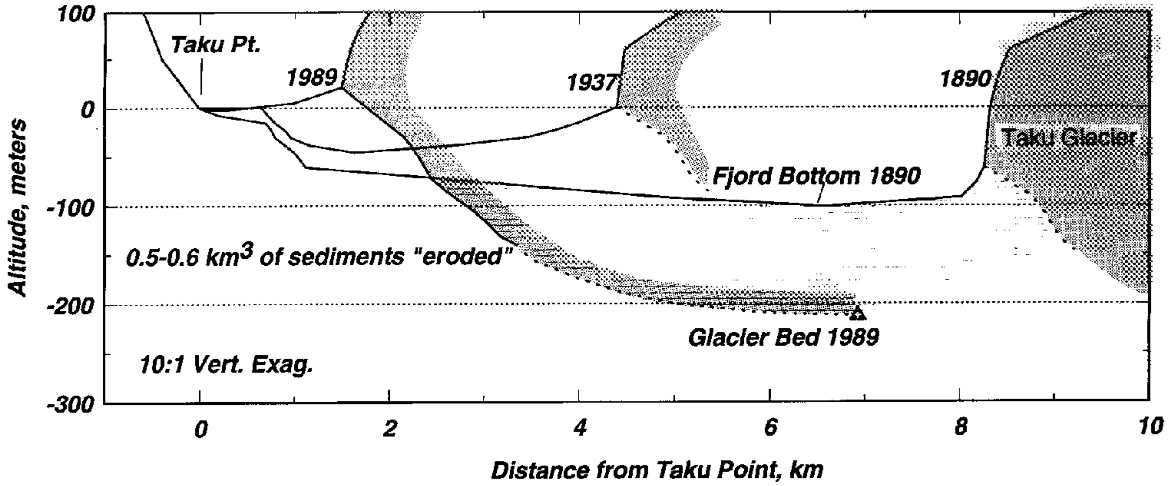

Fig. 3. Longitudinal cross-section of the Taku Glacier showing the terminus position in 1890, 1937, and 1989. "Fjord" depths for 1890 and 1937 were obtained from USC&GS charts. The 1989 glacier bed was determined by radio echo sounding (Motyka and Trabant, unpublished data). The triangle is the deepest sounding made along this transect and is 212 m below sea level, over 100 m below the 1890 fjord bottom. The glacier bed is dashed where inferred.

a strong positive net balance through 1986.

We believe that changes in basal conditions are the cause of the slow down in glacier advance and its current hiatus. Glacier expansion has compacted sediments against Taku Point and deepened the glacier's channel (Fig. 3). The result is that the positive net balance is presently going into thickening the glacier. Between 1948-1989, the elevation of the ice surface increased 90 m in the lower ablation zone, 40m in the upper ablation zone, and 25 m in the lower accumulation zone (R.J. Motyka, unpublished data). We believe the glacier will resume advancing once it thickens sufficiently and the surface gradient at the terminus increases to a critical point.

The glacier is also thickening downward as it compacts, pushes, and erodes sediment that was deposited in the fjord prior to its advance. The cross-section shown in Fig. 3 shows fjord depths and positions of the terminus along the axial plane of the channel as determined from USC&GS data files and charts (1890 and 1937) and from our surveys and photogrammetric analysis (1989). The depth of the 1989 glacier bed was determined from radio echo soundings (R.J. Motyka and D.C. Trabant, 1989 and 1990, unpublished data). These echo soundings show the glacier has displaced sediments to 210 m below sea level, 110 m lower than the maximum 1890 fjord depth. If we assume that the depth to the glacier bed at the terminus in 1890 was similar to that in 1989, then about 0.5 to 0.6 km^3 of sediments present in 1890 have been displaced by the advance of the Taku Glacier.

Sediment had likely been accumulating into the tidal basin for over a century before 1890. Maximum depths in recently deglaciated fjords typically exceed 300 m below sea level (examples: Upper LeConte Bay, Endicott Arm, Tracy Arm, John Hopkins and Tarr Inlets; see Post and Motyka, 1994 for review) and sub-bottom profiling of sediments in some fjords frequently disclose bedrock at far greater depths. Thus an additional 100 m or more of sediments likely still underlie the glacier bed.

As the glacier advanced, deposition of sediments in Taku Inlet beyond Taku Point accelerated. Jordan (1962), comparing USC&GS charts, computed that the amount of sedimentation between 1952 and 1960 over a 5.5 km section of upper Taku Inlet totaled 0.124 km^3. This sedimentation was over double the amount deposited there between 1890 and 1952. The longitudinal cross-section through upper Taku Inlet (Fig. 4) clearly illustrates the accelerated sedimentation in Taku Inlet after 1937 as the glacier advanced, filling in the fjord with ice and sediments. We estimate the total volume of sediments deposited in Taku Inlet to Annex Creek at 0.6-0.7 km^3. The delta at the head of Taku Inlet prograded outward at the rate of about 75 m/yr between 1960 and 1980. Water depth in front of the delta is about 100 m b.s.l.

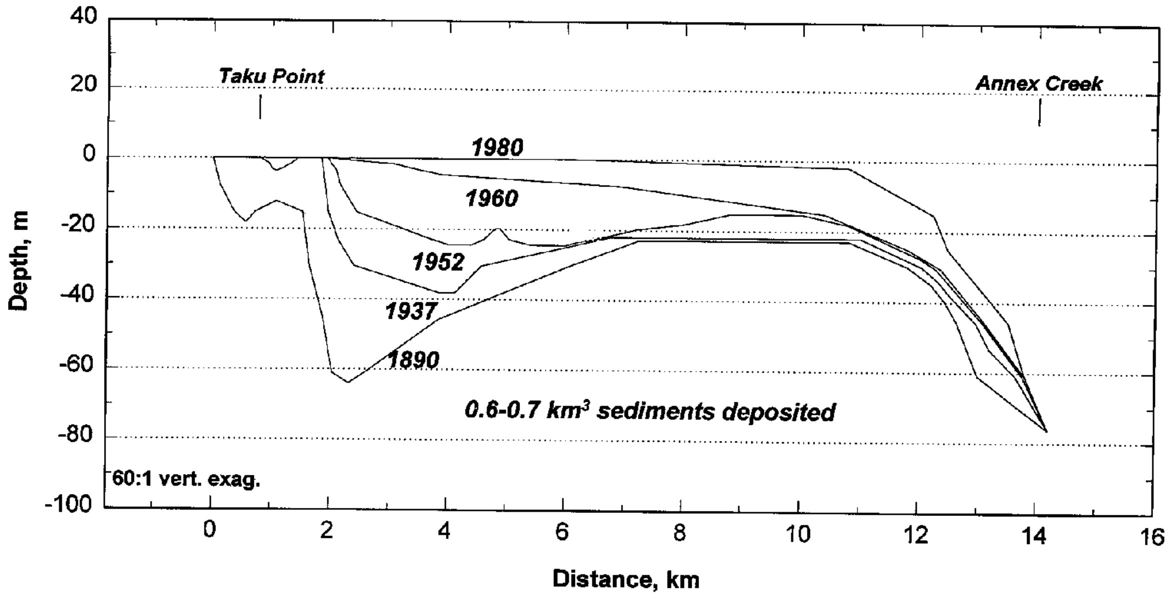

Fig. 4. This longitudinal bathymetric profile through upper Taku Inlet illustrates the accelerated deposition of sediments as the Taku Glacier progressively advanced down its channel. Depths were obtained from USC&GS charts (1890, 1937, 1952, and 1960) and from soundings made by the U.S. Geological Survey ship R/S Growler in 1980.

Conclusions

The Taku Glacier is a fjord-type glacier whose current advance is linked to the calving-glacier cycle of rapid retreat followed by slow advance. Rapid sedimentation that lead to cessation of calving, high AAR, and channel geometry were the primary causes for the rapid advance that the Taku Glacier experienced between 1890 and 1973. Sedimentation in "Taku Fjord" was facilitated by the nearly enclosed tidal basin which entrapped glacier sediments and the large amounts of sediment derived from a major river that discharged directly into this basin. The advance of the Taku Glacier has displaced at least 0.5-0.6 km^3 of sediments that were present in the fjord in 1890. As the advance continued, sedimentation increasingly shifted into Taku Inlet. Shoaling of upper Taku Inlet progressed from 1 km up river of Taku Point in 1890 to 10 km out into the inlet by 1980.

We attribute the slowing of the Taku Glacier advance and its current standstill to changes in conditions as the glacier progressively deepened its channel, and deposited and compacted sediments in front of its terminus. Much of the positive net balance in recent years appears to be thickening the glacier rather than expanding its area. If the glacier continues to thicken, it should eventually begin re-advancing. The current AAR of ~0.83 is well-above the equilibrium threshold value of ~0.70 found for other Alaskan glaciers, which indicates that the glacier mass balance should be robust enough to support continued advance of the glacier for years to come.

Simple calculations show that with the current mean annual ELA, the ablation zone would have to expand by another 126 km^2, doubling its current size, to achieve an AAR of 0.70. Such an expansion would probably impact the main channel of the Taku River, which lies only 900 m from the present terminus. If the glacier does advance to the Taku River, the river itself will help inhibit advance by increasing melting and glacier calving. Major climate change, such as might be caused by global "greenhouse" warming, could also affect the advance of the Taku Glacier.

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Climatic Controls on Glacier Mass Balance in Glacier Bay National Park and Preserve, Alaska

by

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Abstract

The importance of sediment dynamics on controlling the behavior of tidewater termini is becoming clear. However, climatic forcing on glaciers in Glacier Bay National Park and Preserve needs to be addressed to evaluate its relative importance. Little climatologic data exist for the region, so a preliminary assessment of climate forcing has been performed using data collected by the Icefield Ranges Research Project (IRRP), meteorologic observations from near sea level weather stations, and a reconnaissance mass balance study using snowlines determined from aerial photographs of Glacier Bay. The emphasis is on the climatic regimes that influence glaciers flowing into Tarr and Muir Inlets.

Grand Pacific Glacier is fed by high elevation névés in the Fairweather Range and has been advancing into Tarr Inlet since the 1920s. Its upper névés are located, in part, west of the Fairweather divide where they should receive heavy coastal maritime precipitation; however, accumulation area ratio (AAR) and balance ratio (BR) calculations indicate that Grand Pacific Glacier is too poorly nourished to maintain a tidewater terminus. Muir Glacier is fed by low elevation névés in the Takhinsha Mountains and has the lowest equilibrium line altitude (ELA) of all glaciers studied. Despite a low ELA, it has only recently established quasi-stability following more than 100 years of retreat.

Precipitation in Glacier Bay is introduced directly from the Gulf of Alaska. Heavy precipitation on the coastal flanks of the Fairweather Range and a precipitation shadow extending across Glacier Bay and the Takhinsha Mountains are expected; but IRRP observations, local glacier mass balance investigations, and regional wind patterns indicate that this concept is oversimplified. High peaks along the crest of the Fairweather Range are an effective barrier to storms moving NE from the Gulf of Alaska that cause storms to be deflected and enter Glacier Bay from the south.

Asynchronous response of glacier behavior to climatic forcing observed by meteorologic trends and reconnaissance glacier mass balance investigations indicate that tidewater termini in Glacier Bay are insensitive to climatic forcing. Morainal bank sediment dynamics at Grand Pacific and Muir Glaciers appear to modulate calving speeds and termini behavior by controlling grounding-line water depth, which at least over short periods of time is more important than climatic forcing.

KEY WORDS. Glacier Bay, glacier, climate, tidewater termini, mass balance.

Recent studies by Mayo (1988), Sturm et al. (1991), Powell (1991), and Hunter and Powell (this volume) have documented periods of non-climate controlled terminus fluctuations in south and southeast Alaska. It is the hypothesis of Powell (1991) and Hunter (1994) that recent advance and retreat of tidewater termini in Glacier Bay

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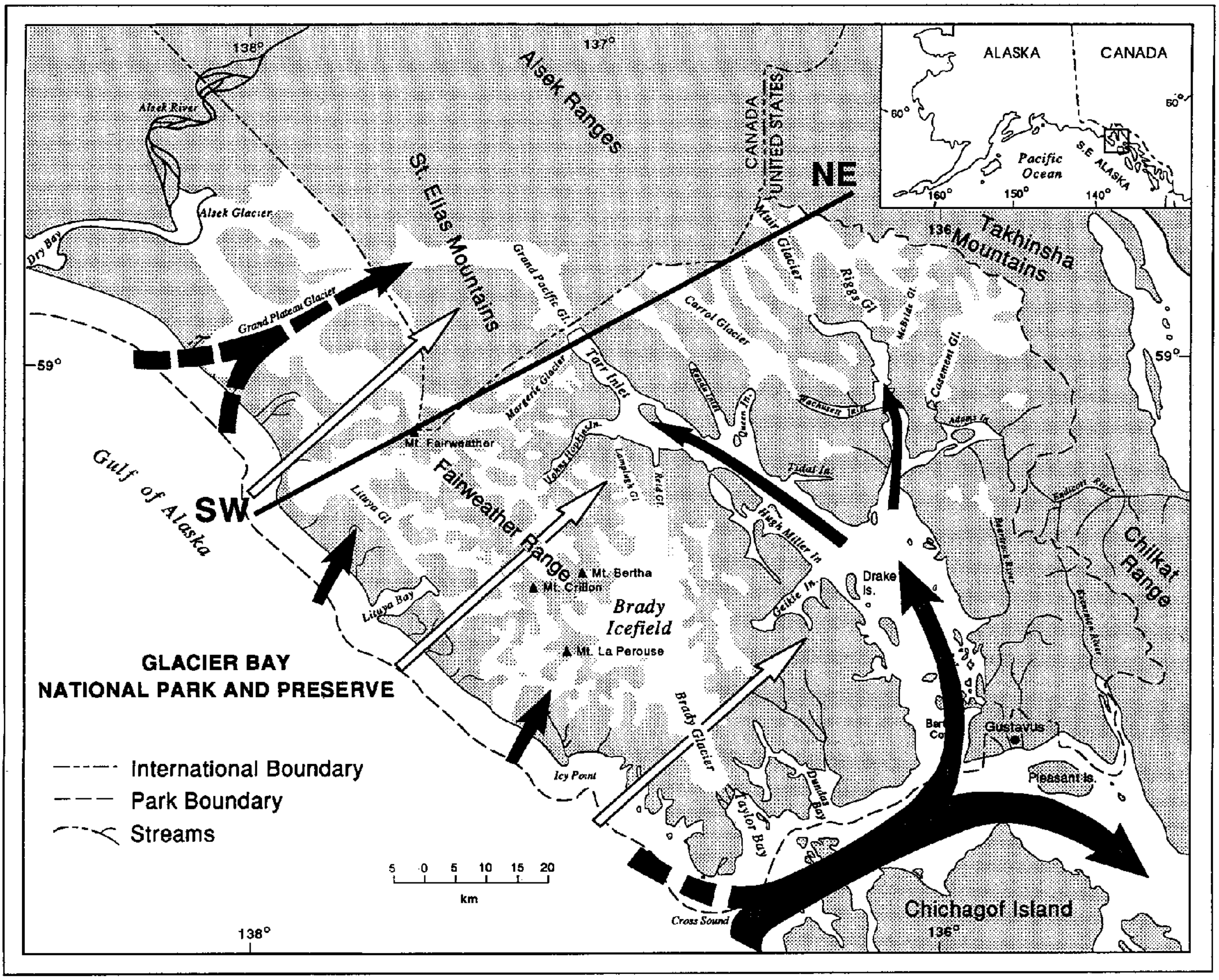

Fig. 1. Location map for GBNPP showing generalized directions of storm tracks based on early studies (white arrows) and this study (gray arrows). Solid line shows location of topographic profile in Fig. 2.

National Park and Preserve (GBNPP; Fig. 1) are controlled by grounding-line water depths and not by short-term changes in climatic forcing (i.e., temperature and precipitation). Mass balance of these glaciers is strongly affected by calving that represents the dominant means of ablation (cf. Mercer, 1961a). Brown et al. (1982) and Pelto and Warren (1992) have demonstrated numerically that calving rate is related to grounding-line water depth. Detailed investigations of ice-proximal sediment dynamics (e.g., Hunter and Powell, this volume; Hunter, 1994) indicates that sedimentary processes at the grounding lines of Muir and Grand Pacific Glaciers can modulate water depth on the order of 100 m over short-time intervals (a few weeks to a year). These water-depth fluctuations have a considerable effect on calving speed and terminus stability, allowing a glacier to self-regulate advance or retreat through sediment dynamics.

It is necessary to understand climatic forcing in the region in order to propose an accurate model describing the feedbacks controlling glacier mass balance and a terminal response of advance or retreat. The most comprehensive discussion of climate in Glacier Bay is included within Goldthwait et al. (1966) as part of an ecological study of lower Muir Inlet. This study contains measurements of wind, solar radiation, humidity, evaporation, and cloud cover within the bay, some of which were made at stations on Casement Glacier. While numerous studies have reported short periods (weeks to a few months) of temperature and precipitation observations (all made near sea level), there have been no detailed studies of weather patterns within GBNPP despite its enormous value to understanding glacial regimes and plant succession. Climatic implications have been drawn from reconstructed glacial histories (e.g., Goldthwait, 1967; Goldthwait et al., 1963) and sporadic observations of snowline (Field, 1947) or equilibrium line altitudes (ELA). Recent studies of glacial processes in GBNPP (e.g., Cowan, 1988; Powell, 1991) have relied on these early studies to interpret climatic forcing and weather patterns that influence glacier dynamics by suggesting that Muir Inlet and the Takhinsha Mountains are in a precipitation shadow of the Fairweather Range. They expect heavy orographic precipitation to fall on the continental flanks of the Fairweather Range while interior Glacier Bay is drier because of moisture depletion east of the range as storms move directly from the Gulf of Alaska and track straight inland (Fig. 1). Analyses of regional meteorological data and observations from the Icefield Ranges Research Project (IRRP) indicate that the previous interpretations are oversimplified. An important modification suggested by Hunter (1994) is that weather systems channel moisture into parts of the interior of Glacier Bay via low mountain passes and major fjord valleys (Fig. 1) representing a critical shift in the interpretation of glacier nourishment and mass balance.

Revised Interpretation of Weather Patterns

The revised interpretation of weather patterns by Hunter (1994) for GBNPP suggests that the alpine climate affecting glacier mass balance is best described as a two component system similar to that found by the IRRP (e.g., Taylor-Barge, 1969; Bushnell and Marcus, 1974). Detailed analyses of high elevation weather patterns and tropospheric disturbances on 500 mb weather charts indicate that storm events monitored at high elevations (about 5,000 m a.s.l.) are controlled by middle tropospheric pressure patterns. However, coastal weather up to elevations of about 2,000 m are influenced by the Aleutian Low, which causes heavy orographic precipitation where moisture laided maritime air is uplifted along coastal flanks of the St. Elias Mountains. The result is a two-component system characterized by heavy storm activity near sea level with precipitation increasing up to about 2,000 m elevation. Above this elevation, precipitation declines and snow drifting becomes increasingly important in snow accumulation patterns (cf. Bushnell and Marcus, 1974).

Wind patterns and storm access to Glacier Bay are both critical to glacier nourishment because of the introduction of moisture into the bay. Weather station records for the southeast Alaska region around GBNPP (e.g., Brower et al., 1977) indicate that prevailing winds are from the southeast. These winds are associated with north and eastern portions of cyclones (i.e., storms) as they become impinged along the Alexander Archipelago and coastal mountains (see discussion in Hunter, 1994) and are associated with peak moisture (Brower et al., 1977). This is also indicated by snowline elevations along the outer coast of GBNPP which rise from below 600 m on the Brady Glacier to between 760 m and 1,000 m on tributaries of Grand Plateau and Alsek Glaciers (observed on 1979 high altitude aerial photography). This apparent rise in snowline represents a "continentality" trend along a south to north transect on the outer coast that is contrary to the idea of moisture coming directly off of the Gulf of Alaska.

Hunter (1994) argues that storms encountering the Fairweather Range deviate either north or south where they penetrate inland via the Alsek River valley or Cross Sound. This is due to the effectiveness of storm blocking by the Fairweather Range where activity of the Aleutian Low is confined to elevations below 2,000 m (cf. Taylor-Barge, 1969). Figure 2 shows that the mountain complex around Mt. Fairweather presents a significant obstacle to storms by forming a mountain barrier that extends about 150 km from the vicinity of Alsek River to east of Icy Point. This barrier is interrupted by the Grand Plateau-Grand Pacific pass that forms a divide (<1,600 m) that may reduce the effective length of the barrier. However, the elevation of this divide probably prohibits most storms from crossing and only the most energetic systems have enough kinetic energy to cross the divide and introduce precipitation to the upper névés of Grand Pacific Glacier.

Most storms entering Glacier Bay do so by entering Cross Sound and traversing the low mountains southeast of the Brady Icefield (Fig. 1). Once inside the bay, prevailing winds drive moisture up the west branch of Glacier Bay and Muir Inlet. Moist maritime conditions, not a well-developed precipitation shadow, are indicated by environmental lapse rates around 0.5 °C/100 m reconstructed from snowline elevations by Hunter (1994). This is significant in Muir Inlet where upper névés (glacier accumulation basins) are below the 2,000 m elevation limit of the Aleutian Low (Fig. 2) indicating that maritime moisture is added directly to upper catchment areas of Muir Glacier.

Regional temperature and precipitation trends have been analyzed by compiling weather data from 42 meteorologic stations within a 240 km radius of Gustavus at the mouth of Glacier Bay (Fig. 3). The circumscribed area was chosen in order to include the nearest station north of Glacier Bay on

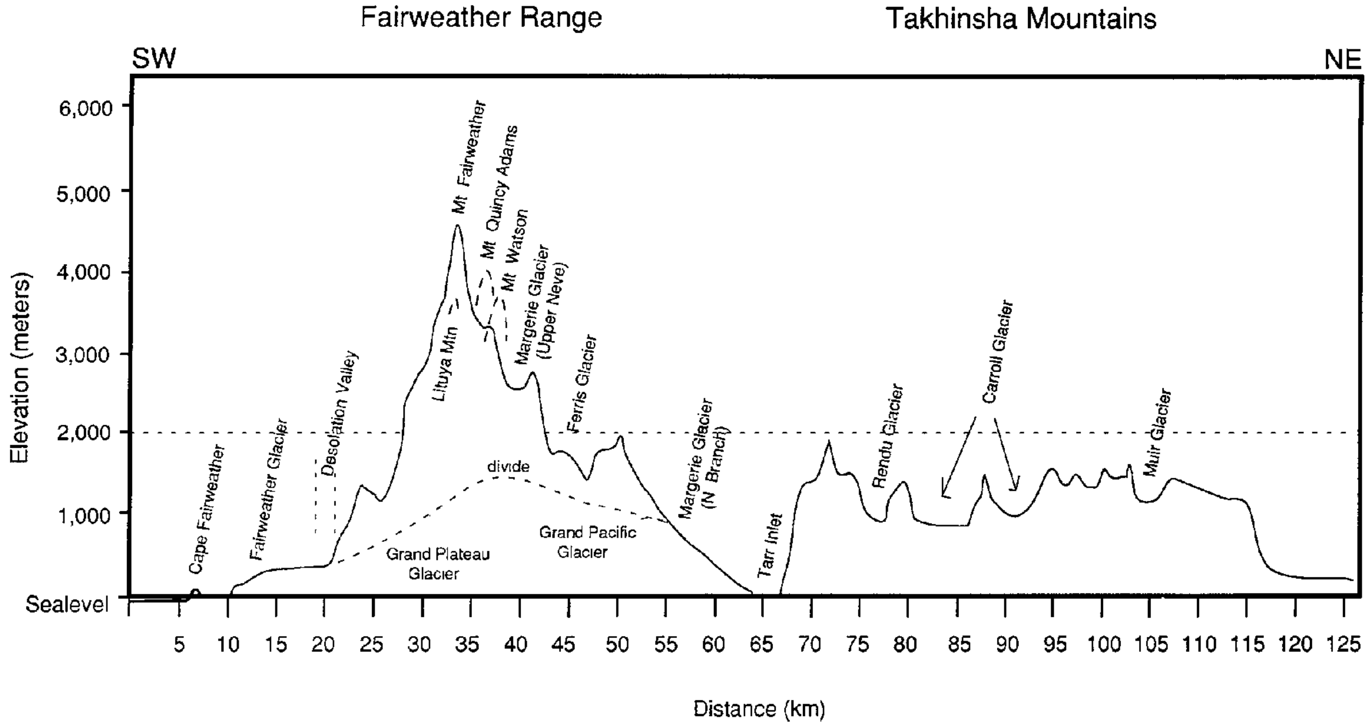

Fig. 2. (Above) Topographic profile across Fairweather Range and Takhinsha Mountains extending from Cape Fairweather to the Tsirku River. The mountain complex of the Fairweather Range rises high above the 2,000 m a.s.l. limit of Aleutian Low storm activity Low elevations of the Takhinsha Mountains lie within the range of influence of the Aleutian Low. Dashed line shows the profile of the Grand Plateau-Grand Pacific pass.

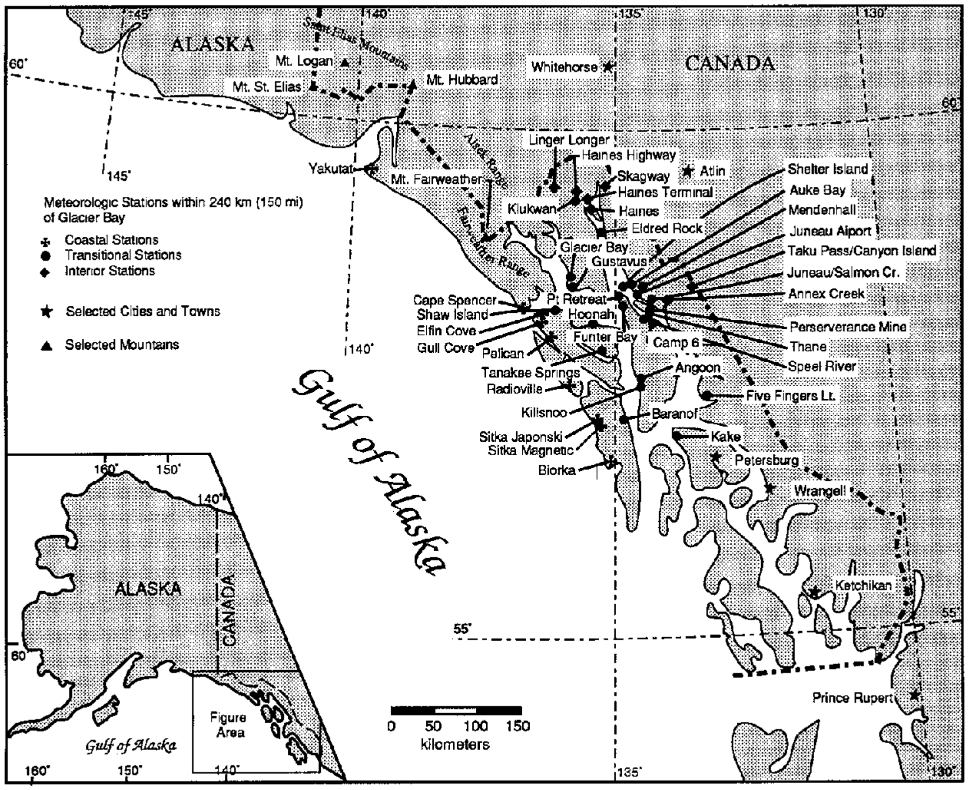

Fig. 3. (Left) Location of meteorological stations used to analyze regional temperature and precipitation trends.

the Pacific coast (Yakutat). This data base should provide more significant framework than one based on only a few stations because it provides a regional picture and minimizes microclimatic affects at individual stations. Data used are grouped into three classes based on their relationship to the Gulf of Alaska (U.S. Department of Commerce, 1915-1990; Hunter, 1994). These are (1) *coastal stations* located adjacent to the Gulf of Alaska, (2) *transitional stations* located east of the first orographic barriers and along the fringes of numerous bays, fjords, and inlets, and (3) *interior stations* that are isolated from marine waters by their distance inland and/or elevation.

Five-year running means of temperature and precipitation indicate a 15 to 20 year cyclicity where precipitation highs are roughly in phase with warm intervals (Fig. 4). Interior stations also demonstrate a general cooling (or divergence) relative to warming at coastal and transitional stations during the 1970s and 1980s (Fig. 4B). Previous warm periods occurred during the 1930-1940s, and a short interval near 1960. Two cool periods occurred, one near 1950 and a second in the early 1970s. These temperature fluctuations roughly correspond to global temperature trends reported by Folland et al. (1992) although these Alaska data are accentuated by a factor of about two. Both coastal and transitional stations (Fig. 4A) appear to be closely linked to sea surface temperature (SST) while interior stations have deviated from coastal and interior trends since the 1970s (Fig. 4B).

Reconnaissance Glacier Mass Balance Investigation

Accumulation area ratio (AAR) and balance ratio (BR) were used to evaluate the mass balance of Grand Pacific and Muir Glaciers. Each of these ratios produces a dimensionless value representing spatial (AAR) or elevational (BR) distribution of the accumulation area as a proxy indicator of snow accumulation (nourishment) versus

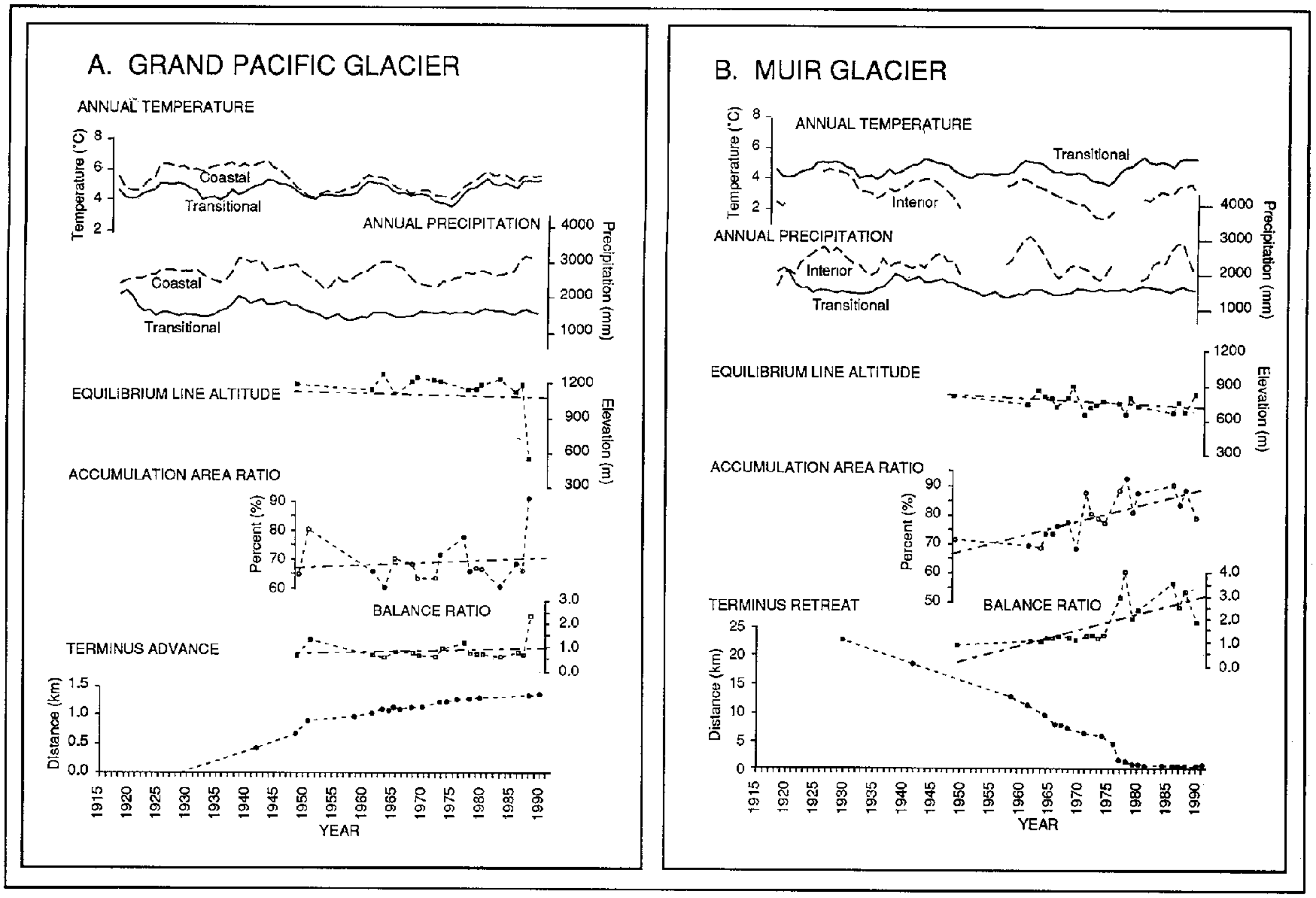

Fig. 4. Summary diagram of glacier mass balance investigation of (A) Grand Pacific Glacier and (B) Muir Glacier. Mass balance indices (ELA, AAR, and BR) are plotted along with precipitation and temperature data for adjacent climatic zones and corresponding terminus advance or retreat.

ablation (melting, evaporation, sublimation, and calving). Both techniques use snowlines recorded by U.S. Geological Survey aerial photographs, satellite imagery, and field observations from late August to early September between 1948 and 1990. Snowline elevations at this time of the year represent annual snowlines at the end of the ablation season in southeast Alaska (Mercer, 1961a) that can be used to approximate ELAs. The data set is incomplete for this interval, with about 50% coverage; however, it is the most complete record for the GBNPP region.

AAR is a basic and widely used glacier mass balance index defined by Meier (1962) as:

$$AAR = S_c/S$$

where S_c is the surface area of the accumulation zone and S if the total surface area of the glacier. This is a simple ratio describing the spatial relationship of accumulation versus ablation and produces an average value of 0.67 for a terrestrial glacier in equilibrium. Calving mechanics influences AAR by reducing the ablation area as the efficiency of ablation at the terminus is increased. As a result, glaciers with high calving rates tend to exhibit high AAR values (0.84), moderately calving glaciers (0.76), and slowly calving are roughly equivalent to terrestrial glaciers (Pelto, 1987).

Furbish and Andrews (1984) developed the BR to assess glacier mass balance while considering the area-elevation distribution (hypsometry) of a glacier. This is potentially more informative than AAR because basin geometry and precipitation distribution affect where accumulation will be greatest and how snow and ice are funnelled through the glacier to the terminus. Different glacier geometries will respond at different rates and magnitudes to the same climatic forcing events. BR is defined by the ratio:

$$BR = b_{nb}/b_{nc}$$

where b_{nb} is net annual budget in the ablation zone and b_{nc} is the net annual budget in the accumulation zone. Both b_{nb} and b_{nc} are acquired through field measurements on the glacier surface; however, this equation can also expressed as:

$$BR = Z_cA_c/Z_bA_b$$

that can be solved graphically by knowing the glacier hypsometry and ELA. Mean elevations of the accumulation zone (Z_c) and ablation zone (Z_b), and the areas of the accumulation zone (A_c) and ablation zone (A_b) can be read directly off of the hypsometric curve. BR values of about 2.0 are predicted for a terrestrial glacier in equilibrium where the size of the accumulation zone is approximately twice that of the ablation zone. For a glacier where ablation is dominated by iceberg calving the size of the ablation zone is reduced and BR values should be greater than 2.0.

Mass balance indices for the period of 1948 to 1990 are summarized in Table 1 and Figure 4. Average ELA levels are highest on Grand Pacific Glacier (1,089 m) on the continental side of the Fairweather Range and lowest at Muir Glacier (754 m) on the maritime slopes of the Takhinsha Mountains (Fig. 1). Recent trends in glacier mass balance are shown in Figure 4 for both Grand Pacific and Muir Glaciers. With the exception of 1988 when the snowline was anomolously low, the ELA at Grand Pacific Glacier (Fig. 4A) has not changed significantly. AAR and BR have fluctuated about a central mean; however, neither show any significant change. ELA at Muir Glacier has decreased consistently since 1948, while fluctuating between 900 m and 600 m along a regression line with a negative slope (Fig. 4B). Such a trend is not shown in the plots of AAR and BR which both record a rapid change in mass balance during a phase of rapid terminus retreat in the 1970s. AAR increased from about 0.70 (1948-1965) to more than 0.90 (1978) while BR also went from below 1.0 to more than 4.0. The close relationship between both AAR and BR trends, and rate of terminus retreat indicates that calving speed was more influential in the development of the recent mass balance state of Muir Glacier than was climatic forcing.

Discussion and Conclusion

Climate in the GBNPP region is complex and needs to be understood in order to develop comprehensive models of glacier dynamics and variation. Tidewater terminating glaciers in the park respond in a dynamic manner to both climatic forcing and to calving-related feedback mechanics at the terminus. This is evident in the recent terminus behavior that is tied more closely to the development of morainal banks (Hunter and Powell, this volume) than changes in climate. Recent responses of Grand Pacific and Muir Glaciers are depicted in Figure 4 where terminus behavior, climate variables (temperature and precipitation), and mass balance indices (ELA, AAR, and BR) are plotted simultaneously.

A downward trend in ELA at Muir Glacier roughly correlates with the initiation of interior cooling in the early 1960s (Fig. 3). Cooling up to 1970 was accompanied by minor fluctuations in both AAR and BR; however, these indices remained low for a glacier characterized by a high calving rate. In the early 1970s, Muir Glacier retreated rapidly with a peak of 2.7 km/yr between 1976 and 1977 (Hunter, 1994). Retreat during this period caused rapid abandonment of lateral ice on the sides of Muir Inlet that resulted in a rapid reduction of ablation area. This is recorded by the sporadic increase in AAR which reached its maximum after 1977. BR also rose sharply at that time from about 1.0 to greater than 4.0, recording a drastic shift in hypsometry such that the spatial extent of the mean accumulation area became four times greater than that of the ablation zone (Table 1). Both of these indices record a drastic change in mass balance as the accumulation zone became disproportionally large (cf. Mercer, 1961b). Muir Glacier retreated into a narrow segment of Muir Inlet in 1979 and terminus retreat slowed until quasi-stability was established between 1984 and 1986 (Hunter and Powell, this volume). The terminus has not fluctuated significantly in the subsequent years although rapid fjord infilling has accompanied the new stability. This has resulted in the eventual transition to a terrestrial glacier in 1993 producing a condition where Muir Glacier should now be able to advance as long as the ice-contact delta protects the grounding line from deep water conditions.

The regime of Grand Pacific Glacier represents an advanced stage of the newly developed regime at Muir Glacier. Snowline elevations and mass balance indices exhibit at best a weak correlation with precipitation and temperature trends (Fig. 4). In general, neither ELA, AAR, nor BR indicate that there were any consistent shifts in mass balance over the duration of the record. The ELA of Grand Pacific Glacier has consistently been the highest (1,090 m) of all glaciers studied (Table 1). Average values of 0.69 for AAR and 0.89 for BR are both low and indicate that the glacier is poorly nourished, indicating a weak precipitation shadow in the lee of the Fairweather Range and the influence of the continental air mass to the northeast. This AAR value is equivalent to that expected for a terrestrial glacier while BR is a half of that expected. Despite these indicators of glacier regime, Grand Pacific Glacier has been advancing into Tarr Inlet for more than half a century. This is explained by the combined effects of reduced calving rates moderated by shallow water depths at the grounding line and a pulse of ice from the Ferris tributary during the 1960s and 1970s; however, the Ferris portion of Grand Pacific Glacier has been thinning since the mid 1980s. Ice from the Ferris tributary has dominated flow into Tarr Inlet during this interval while indices were higher (ELA = 930 m; AAR = 0.77; BR = 0.91) than those of the main trunk glacier. With continued thinning of Ferris ice it is improbable that advance of the Grand Pacific Glacier can be maintained.

Table 1. Indices of glacier mass balance studies in GBNPP between 1948 and 1990 (from Hunter, 1994).

Glacier	ELA (m a.s.l.)	AAR	BR
Grand Pacific	1,089 ± 185	0.69 ± 0.08	0.89 ± 0.44
(Ferris Tributary)	927 ± 65	0.77 ± 0.04	0.91 ± 0.10
Margerie	845 ± 140	0.87 ± 0.02	1.74 ± 0.27
Muir	754 ± 72	0.79 ± 0.07	1.83 ± 0.96

(Error estimate for 1 standard deviation)

The only glacier investigated that exhibits a strong glacier health is Margerie Glacier. Its ELA is the second lowest (following Muir) and has exhibited consistently high AAR (0.87) and BR (1.74) values (Table 1), both of which have increased steadily since the middle 1960s. In response, the terminus has been slowly (~10 m/yr) advancing into Tarr Inlet.

From the observations of Grand Pacific and Muir Glaciers, it is apparent that climatic forcing cannot be called upon to explain recent terminus behavior. Behavior of these glaciers is moderated by fjord cross sectional area including both fjord geometry (bedrock) and sediment fill. These variables control grounding-line water depth and the area of the ice cliff exposed to tidewater that affect the flux of ice to through calving. Reducing or removing calving (i.e., Muir Glacier) as an ablation process causes an almost immediate (few years) shift in glacier mass balance (e.g., Mercer, 1961a and b) while the effects of climatic changes take decades to centuries to reach the terminus and are out-of-phase with the impulse they reflect.

Future Work

Research is needed in order to develop a comprehensive understanding of climatic forcing in GBNPP. Such an understanding is vital to the interpretation of both the glacier history and ecology that are the focal points of scientific research in the park. Despite the obvious value of climate investigations in the region they have not as yet been performed.

Research programs currently in development are being designed to address this gap in GBNPP. The research is three fold, including (1) quantitative glacier mass balance studies, (2) meteorologic observations, and (3) continued glacier monitoring. The former requires that detailed topographic maps of selected glaciers be produced while running snowpit study and ice coring studies. Meteorologic stations need to established at sea level and higher elevations in order to resolve climatic variability and gradients across GBNPP and in the mountains where the glaciers originate. These studies need to be tied into regional and global observation networks to evaluate trends and significance of climate variability in this International World Heritage Site. Finally, glacier monitoring in Glacier Bay has resulted in the most complete and best documented glacial retreat record in the world. The value of this record has been marked by numerous pioneering studies in glacier dynamics, glacial geomorphology, and ecological succession. This record needs to be continued into the next century and this must include both terminal mapping and process monitoring so that revolutionary monitoring of sediment-glacier feedbacks can be continued.

Acknowledgments

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Thirty Years of Glacier Process Studies at Burroughs Glacier, Wachusett Inlet, Glacier Bay, Alaska

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Abstract

Burroughs Glacier is a stagnating remnant of a much larger Neoglacial ice mass that covered most of Glacier Bay. Detailed studies of glaciology and glacial geology at the southeastern part of the glacier have been conducted since about 1960. Many photostations in the area were originally established by W.O. Field in 1941, and these have been repeatedly occupied by subsequent workers. The photographs from these stations show the history of rapid deglaciation in the area and the development of vegetation.

KEY WORDS: Burroughs Glacier, Glacier Bay, Alaska, glacier fluctuations, deglaciation, glacial process.

Burroughs Glacier lies in a triangular mass of land between Wachusett Inlet to the south and Muir Inlet to the east and north, in Glacier Bay National Park and Preserve (Fig. 1). Now entirely confined to a valley, the glacier has been without an accumulation zone since before 1892 when H.F. Reid made the first topographic map of the area. That original ice mass, known as the Cushing Plateau, reached an elevation of about 700 m and eventually separated into the Plateau and Burroughs Glaciers as the Bruce Hills were exposed during downwasting. The Plateau Glacier retreated rapidly (about 150 m/yr) between 1915 and 1930 via a terminus calving in Wachusett Inlet (Field, 1959) and finally disappeared about 1976. Burroughs Glacier, which did not have a calving margin, has retreated more slowly (Table 1).

The southeastern part of the Burroughs Glacier covered a hilly landscape with relief of only a few hundred meters; thus it has behaved like a lowland glacier with nunatak tops exposed first and valley bottoms deglaciated later. Because of this setting, Burroughs Glacier has been used as an analogue for studying deglaciation in hilly areas of New

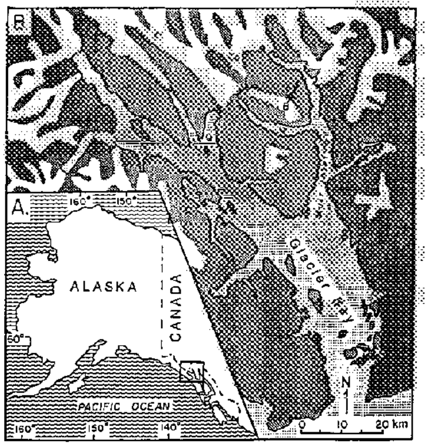

Fig. 1. Maps showing the location of Glacier Bay (A) and Burroughs Glacier (B). W, Wachusett Inlet; B, Burroughs Glacier; C, Carroll Glacier; Cu, Cushing Glacier; Q, Queen Inlet (figure modified from Smith, 1990, Geological Society of America Bulletin).

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D.R. Engstrom (Ed.), National Park Service, Anchorage, 1995

Table 1. Ice-margin retreat and ice-surface lowering rates for Burroughs and Plateau Glaciers

DESCRIPTION	YEAR	ICE-MARGIN RETREAT (m/yr)	ICE-SURFACE LOWERING (m/yr)	Source
Plateau Glacier				
Tidal	1915-29	150		Field (1959)
Tidal	1929-40	145		Field (1959)
Tidal	1941-48	221		Field (1959)
Tidal	1948-60	530		Mickelson (1971)
Tidal	1960-70	350		Mickelson (1971)
Remnant (E margin)	1960-70	140		Mickelson (1971)
Wachusett Inlet	1890-1956		12	Syverson (1992)
Burroughs Glacier				
N of Sta. 7	1926-41	21		Field (1959)
	1941-48	130		Field (1959)
NW margin	1960-70	50		Mickelson (1971)
SE margin	1960-70	9-60		Mickelson (1971)
Burroughs L.	1969-79	90		Syverson (1992)
Burroughs L.	1979-90	30-110		Syverson (1992)
Calving L.	1979-87	100		Syverson (1992)
Calving L.	1987-90	30-70		Syverson (1992)
Crest	1935-48		2-5	Field (1992)
Crest	1948-60		0.8	Taylor (1962)
At 440 m in 1960	1960-70		4.6	Mickelson (1971)
At 205 m in 1960	1960-70		9.5	Mickelson (1971)
N Bruce H. at 370 m	1972-73		2.7	Larson (1978)
S margin	1972-73		7.1	Larson (1978)
Burroughs L.	1970-79		12	Svyerson (1992)
Calving L.	1970-87		8	Svyerson (1992)

England that were glaciated during the Pleistocene (Mickelson, 1971a; Goldthwait and Mickelson, 1982). In addition, it has proved to be an ideal laboratory for the study of ice-marginal processes, especially because of the extensive photographic documentation of the southeastern terminus of the glacier and surrounding areas.

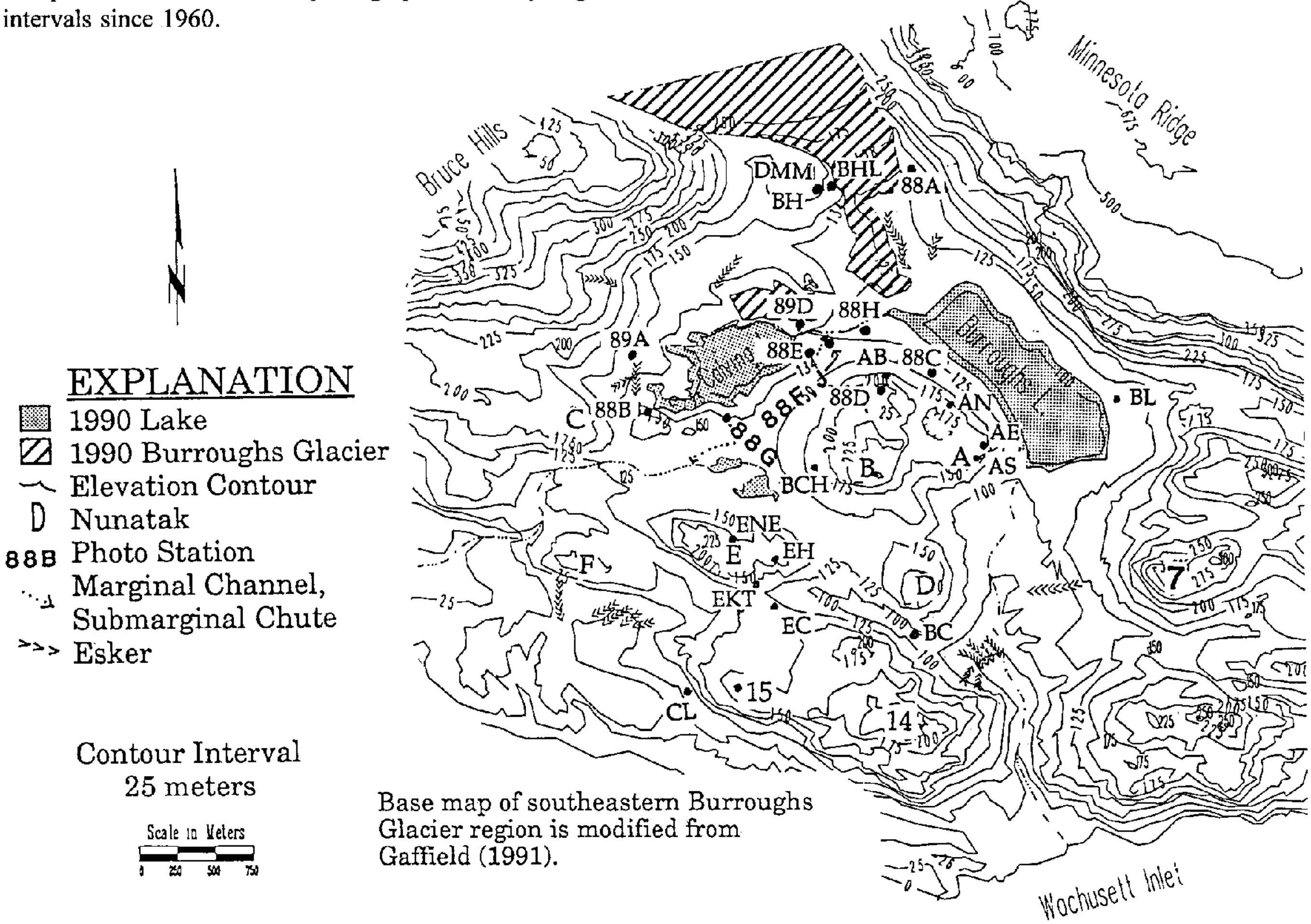
The purpose of this paper is to review highlights of recent glacier process studies undertaken at Burroughs Glacier and to give a brief review of the photographic record available from aerial photographs and from ground photostations. The National Geographic Society (project 4087-89) has funded recent studies summarized below.

Early Work

Early maps of Glacier Bay were published by H.P. Cushing (1891) and H.F. Reid in 1892. Reid (1896) then published a topographic map covering most of the Cushing Plateau and adjacent areas. Field parties, primarily led by W.O. Field, began visiting the photostations shown in Figure 2 in 1935, and a succession of photos has been taken since that time. In addition, the U.S. Geological Survey has taken oblique and vertical aerial photographs at fairly regular intervals since 1960.

The first detailed study of Burroughs Glacier was that of L.D. Taylor (1962), who concentrated on its glaciology. Taylor documented ice structures and ice fabric and concluded that several different ice types (fine, coarse, and very-coarse grained) exist in the glacier. He also recognized that ice structures produced by ice movement in 1960 were superimposed on older structures that developed when the glacier was thicker and flowing in a different direction during the Neoglacial maximum. His work provided an excellent baseline for later studies of glacial geology at the southeastern terminus of Burroughs Glacier.

Mickelson (1971a) conducted the first glacial geology study of the southeastern part of Burroughs Glacier. He took a large number of photographs and documented the nature and rate of till deposition, and the formation of landforms such as eskers and ice-marginal channels (Mickelson, 1971a). Using changes in ice-flow direction based on fabric measurements, maps, and aerial photos, he concluded that till deposition occurred at a rate of 0.5 to 2.5 cm/yr. (Mickelson, 1973). Several of the photostations documented in this paper were originally established by D.M. Mickelson in 1969 and have been revisited in several later years (Table 2).



Base map of southeastern Burroughs Glacier region is modified from Gaffield (1991).

Fig. 2. Map of the southeastern terminus of Burroughs Glacier and surrounding area showing the locations of photostations discussed in the text and listed in Table 2.

TABLE 2. Summary of photo record of Burroughs Glacier, 1935 to 1993.

Station and Fig. 2 abbreviation ( )	Year 35	41	46	50	58	59	60	62	63	64	65	69	70	72	73	74	77	78	86	88	89	90	93
Vertical air			x				x		x	x	x	x	x	x	x		x					x	
Oblique air	F						x		x	x	x	M	M					M	M	M	M	M	M
Station 7 (7)		F		F			T											M	M			M	
Station 9 *		F		F														M				M	
Station 9a *				F			T											M				M	
Station 14 (14)		F		F	G	G	T						M					M	M			M	
Station 15 (15)													M					M	M			M	
Nun A north (AN)																		M	M	M		M	M
Num A south (AS)												M						M	M	M			M
Nun A east (AE)												M						M	M	M			M
Nun AB (AB)																				M	M	M	M
Nun B (B)													M					M	M		M		
Nun B Channels (BCH)													M					M	M	M	M	M	M
Nun D (D)								P				M						M	M				
Nun E-NE (ENE)												M	M					M	M		M	M	M
Nun E High (EH)												M	M					M	M		M	M	M
Nun E low kt (EKT)												M	M					M	M		M	M	M
Nun E Cache (EC)												M	M					M	M			M	
Camp Lake (CL)								P				M							M				
Burroughs Lake (BL)													M						M				M
Bob Creek (BC)																		M	M		M	M	
Bruce Hills (BH)																		M	M		M		S
Bruce Hills low (BHL)																							M
NW end knob																		M			M	S	
GL 1 *												M	M					M	M			S	
GL 2 *												M	M					M	M			S	S

Table 2. Summary of photo record of Burroughs Glacier, 1935 to 1993 (Continued)

Station and Fig. 2 abbreviation ( )	Year																						
	35	41	46	50	58	59	60	62	63	64	65	69	70	72	73	74	77	78	86	88	89	90	93
(88A)																					S	S	S
(88B)																					S	S	S
(88D)																					S	S	S
(88E)																					S	S	S
(88F)																					S	S	S
(88G)																					S	S	S
(88H)																					S	S	S
(89A)																						S	S

SOURCE AND LOCATION OF PHOTOS:

F = W.O. Field, American Geographical Society, now at Univ. Alaska
G = R.P Goldthwait, Byrd Polar Institute, Ohio State Univ., Columbus, OH
M = S.M. Mickelson, Univ. Wisconsin, Madison, WI
P = R.J. Price
S = K.M. Syverson, Univ. Wisconsin, Eau Claire, Eau Claire, WI
T = L.D. Taylor, Albion College, Albion, Mi

Recent Studies

1986 - 1990

A group of fifteen students and professionals visited Burroughs Glacier for about two weeks in June 1986. In addition to reoccupying photo stations, several small research projects were undertaken. Two of these studies have been published (James, 1988; Simpkins and Mickelson, 1990) and all seven are documented in "Deglaciation at the SE end of the Burroughs Glacier, Glacier Bay, Alaska" (unpublished, 1987). This volume contains papers on supraglacial sediment, pollen and vegetation relationships, deposition of eskers, rates of organic carbon accumulation in soils, bird species distribution, and hydrogeochemistry. This collection of papers is in the library of Glacier Bay National Park and Preserve and in the Geology Library at the University of Wisconsin (Madison).

Simpkins and Mickelson (1990) conducted a study of groundwater geochemistry near the southeastern margin of Burroughs Glacier, and found that the dominant ions were Ca^{++} and HCO_3^-. In addition, they found that groundwater changes chemically from a calcium sulfate water near the ice margin to a calcium bicarbonate water farther away from the margin near Wachusett Inlet.

Several studies were conducted in 1988, 1989, and 1990 as part of a research expedition to the Burroughs Glacier by the Department of Geology and Geophysics at the University of Wisconsin (Madison). One of the main purposes of the trip was to reoccupy photostations and to document changes near the southeastern margin of the glacier since earlier studies by Taylor (1962) and Mickelson (1971a).

As part of this expedition, K. M. Syverson did a survey of deglaciation processes and events at the southeast end of Burroughs Glacier between 1970 and 1990 (Syverson, 1992). He also studied the effect of supraglacial sediment on ablation rate (Syverson, this volume), the formation and sedimentology of eskers (Syverson, Gaffield, and Mickelson, 1994), the pattern of deglaciation as recorded by directional features such as striations, crag-and-tail features, and till fabric (Syverson, 1990), the evolution of ice-marginal channels, and the sedimentology of ice-marginal lakes (Syverson, 1991).

More specifically, Syverson (1990, 1992) found that the orientation of crag-and-tail features and the long axes of bullet boulders reflect the final ice-flow direction immediately preceding deglaciation, as compared to striations or till fabric, which may record earlier directions of ice flow. In his study of esker development and sedimentology, Syverson concluded that many esker paths followed the hydraulic gradient reconstructed from maps of the glacier showing ice thickness. In addition, his study of ice-marginal-lake sedimentology at Calving Lake showed that about 80% to 90% of lacustrine sediment by volume was deposited in nearshore deltas and fan-deltas. Syverson also documented the sedimentology and morphology of craters formed by icebergs that impacted the lake bottom.

Three M.S. studies by E. Silvola, N.R. Ham, and S.J. Gaffield were also done during the period from 1989 to 1990. Silvola documented the deglaciation of the northwest end of the Burroughs Glacier (Silvola and Mickelson, 1990). Ham (1991b) examined processes of till deposition, the importance of pebble fabric in distinguishing basal till from debris-flow sediment, and the micromorphology of basal till (Ham and Mickelson, 1994).

Basal till deposition at Burroughs Glacier begins when debris-rich basal ice stagnates beneath thinning ice during deglaciation. Once the debris-rich ice is exposed at the ice margin, interstitial ice melts and the sediment dewaters, forming basal till (Ham, 1991b; Ham and Mickelson, 1994). Ham (1991b) also showed that pebble fabric can be used to distinguish debris-flow sediment from basal till at Burroughs Glacier. Basal till typically has a moderate to strongly-developed pebble fabric parallel to ice flow, whereas, the debris flows examined in this study typically have random clast orientations, and many clasts have high plunge angles (Ham, 1991a, 1992).

Gaffield (1991a) constructed a Geographic Information System for the southeast end of the Burroughs Glacier using topographic maps from 1948, 1960, 1970, and 1990. From this GIS he calculated the distribution of driving stress at the base of the glacier and, with Syverson, the distribution of hydraulic head (Syverson, Gaffield, and Mickelson, 1991; Gaffield and Mickelson, this volume). Gaffield also evaluated processes that may have been responsible for the preferential deposition of till on the up-ice sides of nunataks at Burroughs Glacier and suggested that till deposition took place in areas of low driving stress (Gaffield, 1991a; Mickelson and Gaffield, 1992).

History of Photo Stations

The photostation record at Burroughs Glacier extends back to 1941 when photostations were established on nunataks 7, 14, and 15, and station 9 high on the north side of the Burroughs Glacier at Glacier Pass. These stations were established by W.O. Field on an expedition from the American Geographical Society. Black and white photographs from the stations are in the W.O. Field collection, now housed at the University of Alaska, Fairbanks. These photostations were next occupied in 1950 by Field, by Taylor in 1960, and by Hazelton in 1962. R.J. Price presumably also took photos from these stations in 1962, but the whereabouts of the photos are unknown.

Station 7 was exceptionally well chosen. It has been occupied through 1990, and it is still possible to see the ice margin in the distance. Stations 14 and 15 were useful mainly for documenting the rapid retreat of the calving Plateau Glacier in Wachusett Inlet. Both of these stations are now completely covered by alder. They were last occupied in 1990 and are useful for documenting the development of vegetation since 1970. Figures 3 and 4 show how dramatically the Plateau Glacier and the southeastern part of the Burroughs Glacier have wasted away since 1950.

Mickelson occupied the stations of W.O. Field in 1969 or 1970 and established stations on the summits of many nunataks in the area. Nunataks A, B, D, and three stations on nunatak E have cairns that were set up in 1969. These overlooked isolated ice masses under which eskers developed and around which ice-marginal channels formed. By 1993 the ice margin was not visible from nunataks D, E, B, or A south. They were, however, revisited in 1978, 1986, and 1988 through 1990 and can be used to document the establishment of vegetation on a broad scale. A number of local photostations were set up in 1969 and 1970. These are listed in Table 2 and their locations are shown in Figure 2. Photography was repeated from some of these locations as late as 1993. Numerous local photo stations were also set up in 1988 and 1989 by Syverson (Fig. 2), and these were occupied in 1993.

Thousands of photographs have been taken in support of research in the Burroughs Glacier area since photo stations were established by W.O. Field in 1941. The slides held by Mickelson including some duplicates from Field, Goldthwait, and Taylor are cataloged. A copy of this catalog is available in the library at Glacier Bay National Park and Preserve and from Mickelson.

Summary

The Burroughs Glacier has been extensively studied over the past 30 years. Most studies have focused on glaciology and processes of glacial deposition and landform development. Photostations established in 1941 by W.O. Field have been repeatedly occupied over the past 50 years, resulting in a detailed photographic record of deglaciation and vegetation development in the Burroughs Glacier area. A high priority of future research in the area must be continued occupation of the photostations.

The reference list includes research done at Burroughs Glacier over the past 40 years. Copies of most of the reports, papers, and theses are on file in the library of Glacier Bay National Park and Preserve.

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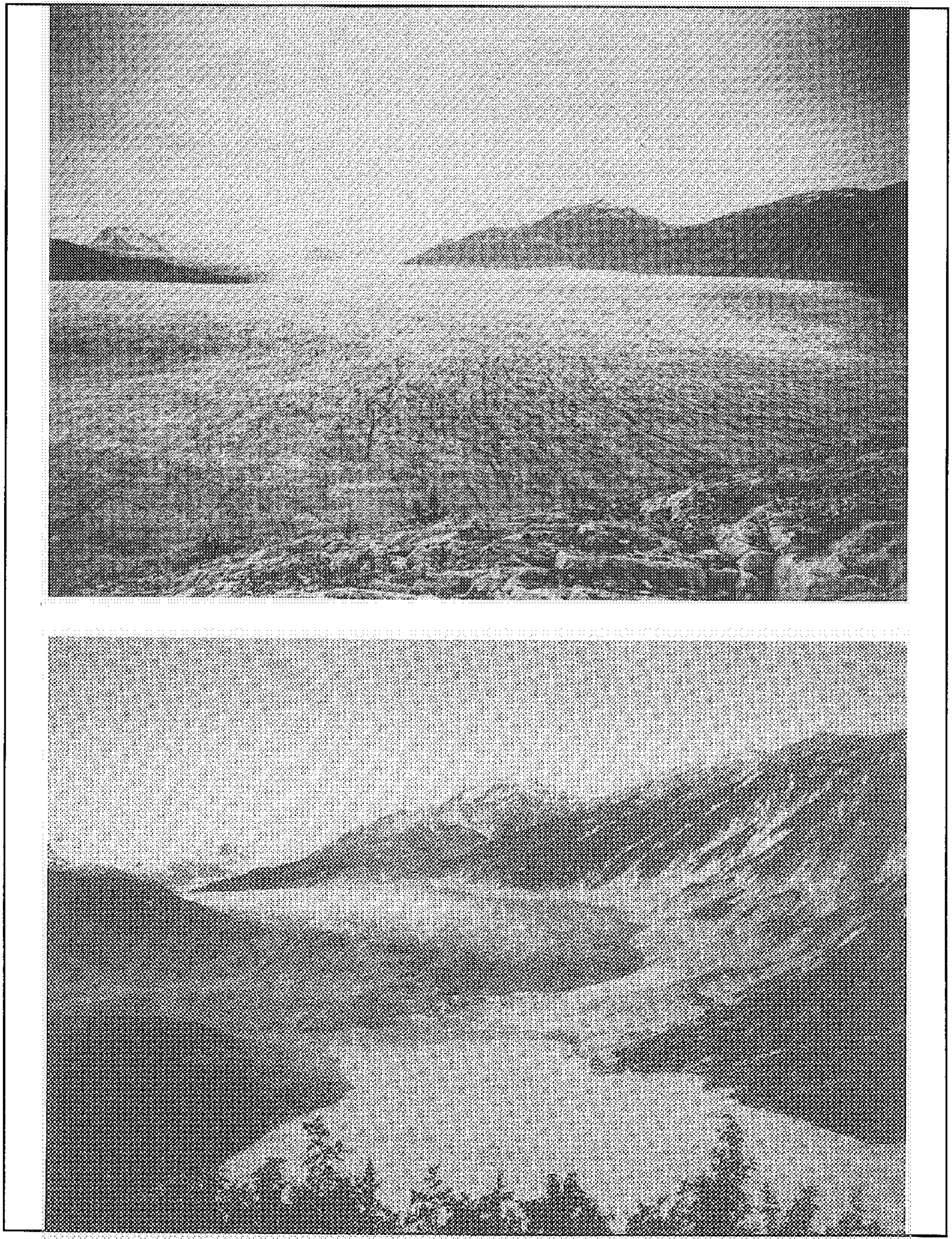

Fig. 3. Photographs of the southeastern margin of Burroughs Glacier taken from photostation 7 (location shown in Fig 2). Upper photo is from 1950, and the lower photo is from 1990. View is to the northwest with Minnesota Ridge on the right.

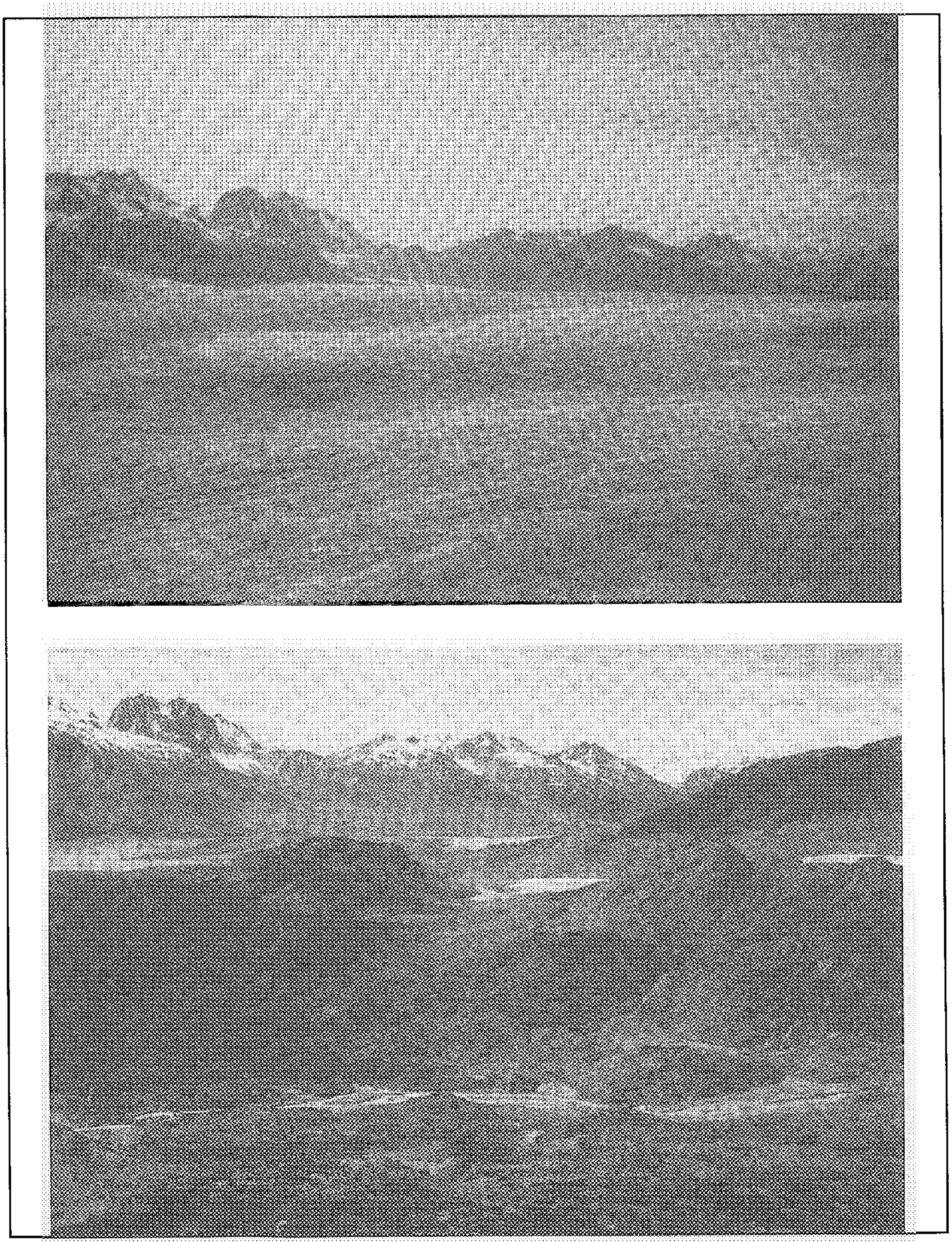

Fig. 4. Photographs of the Plateau Glacier and the southeastern part of Burroughs Glacier taken from photostation 7 (location hown in Fig.2) View is to the west Upper photo is from 1950, and the lower photo is from 1978.

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Ablation of Debris-Covered Ice and the Formation of Pitted Outwash Plains at Burroughs Glacier, Southeastern Alaska

by

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Abstract

Ablation rates for debris-covered and clean ice in a maritime climate were measured at the Burroughs Glacier from June 25 to August 20, 1990. Average daily maximum and minimum temperatures measured 60 cm above the ice surface were 18.4° C and 7.8° C during this period.

The mean ablation rate for clean ice (given in centimeters of ice removed) was 6.7 ± 0.2 cm/d. Debris layers <0.5 cm thick slightly decreased ablation rates relative to clean ice. An ablation rate of 6.9 cm/d (102% the clean ice rate) was associated with patchy medial moraine debris 0.7 cm thick. Thicker debris insulated the underlying ice and decreased ablation rates. Ablation rates associated with debris cones at the Burroughs Glacier were 5.5 cm/d (81% the clean ice rate) beneath sand 3 cm thick and 4.1 cm/d (60% the clean ice rate) beneath sand 5 cm thick. Ablation was ≤0.2 cm/d (≤3% the clean ice rate) during a 44-day period beneath gravelly sand 1.1 to 2.1 m thick.

Pitted outwash plains form in dynamic environments where fluvial sand and gravel bury ice blocks. The sediment collapses as the underlying ice melts, and the resulting kettles may fill with fluvial sediment during short time intervals.

KEY WORDS: Ablation, supraglacial sediment, debris cone, medial moraine, outwash plain, southeastern Alaska, Burroughs Glacier, Glacier Bay.

Glacier termini frequently have large volumes of supraglacial and englacial debris. The thickness and extent of supraglacial sediment exerts a strong control on the rate of ice ablation and on equilibrium-line altitudes (Driscoll 1980; Clark et al. 1994). In addition, melting glacier ice influences the movement of supraglacial sediment and affects the types of glacially deposited landforms observed (Watson 1980). In general, most studies on the ablation of glacier ice conclude that a thin layer of debris enhances ablation, whereas an increasing thickness retards ablation. Lister (1953) found that debris layers <0.4 cm thick enhanced ablation rates in Iceland. Østrem (1959) noted that ablation rates increased beneath a debris cover up to 0.5 cm thick, but then rapidly decreased with increasing debris thickness at Isfallsglaciären, Sweden. Loomis (1970) measured maximum ablation rates beneath a 1 cm debris layer on the Kaskawulsh Glacier, Yukon Territory, Canada.

Taylor (1962), Peterson (1970), Mickelson (1971), and Larson (1978) measured ablation rates for clean ice in Glacier Bay. However, few data other than the work of

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Lister (1953) exist for ablation rates beneath debris layers in maritime climates such as Glacier Bay. The purpose of this study was to measure ablation rates beneath medial moraine, debris cone, and coarse-grained deltaic sediment, and also to study pitted outwash plain formation in the southeastern Burroughs Glacier region. Field work for this project was conducted in 1988-90 and 1993.

Burroughs Glacier is located in Glacier Bay National Park and Preserve, between lat. 58° 57' and 59° 1' N and long. 136° 13' and 136° 22' W in southeastern Alaska (Fig. 1). This maritime climatic zone is characterized by small daily and annual temperature ranges, high relative humidity and cloudiness, and long periods of precipitation (Loewe 1966). Workers in Glacier Bay have collected meteorological data showing mean monthly temperatures during summer field seasons ranging from 9-13° C (Mickelson 1971).

Meteorological data were collected during this ablation study, June 25 to August 20, 1990, and are tabulated in Syverson (1992, Appendix A). Average daily maximum and minimum temperatures measured 60 cm above the ice surface were 18.4° C and 7.8° C during this period. The highest temperature recorded during this study was 30° C on August 12, 1990. Measurable precipitation fell during 25 of 56 days, resulting in 399 mm of total precipitation (Fig. 2). Long periods of warmth and sunshine alternated with extended periods of overcast conditions and rainfall. The largest precipitation events occurred on August 9 and August 18, when 54 and 56 mm of rain fell, respectively.

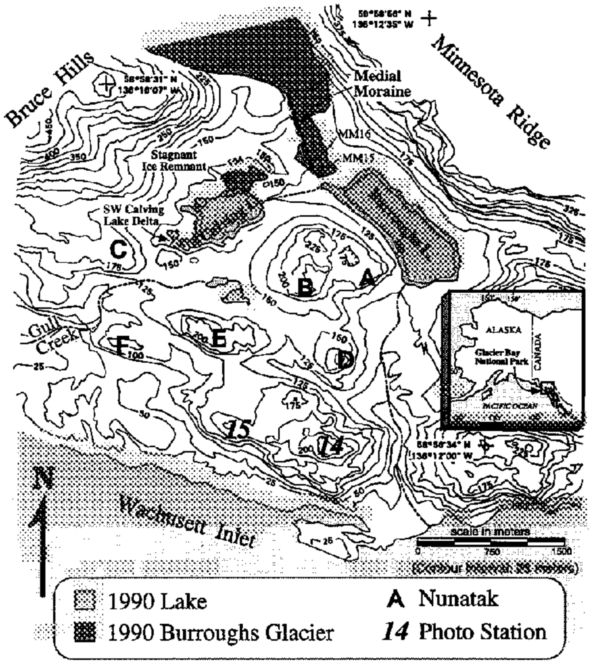

Fig. 1. Maps showing the location of Glacier Bay National Park (inset) and the southeastern Burroughs Glacier region. Study sites mentioned in the text are labeled. Modified from Gaffield (1991) and Syverson et al. (1994).

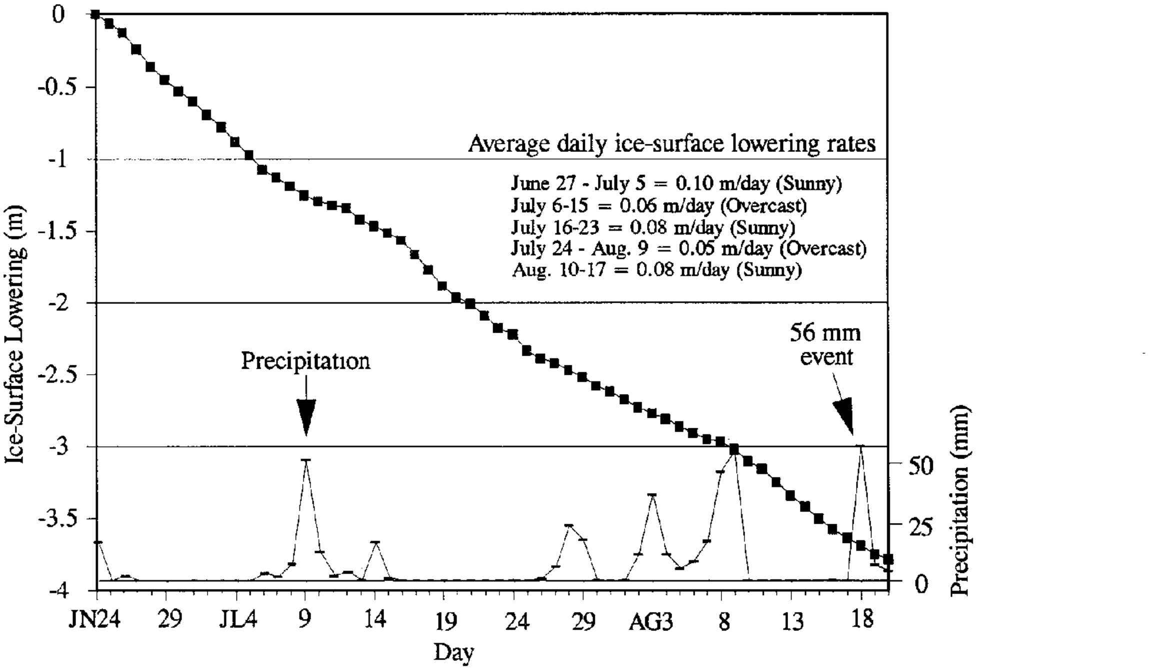

Fig. 2. Graph of daily ice-surface lowering and precipitation at station 14 [S14], southeastern Burroughs Glacier, June 24 to August 20, 1990. Mean ice-surface lowering rates during sunny and overcast periods are listed.

Ablation at Stagnant Ice Remnant

To investigate ablation rates beneath debris of differing thickness, a test plot was set up during the 1990 field season on a small ice remnant north of Calving Lake (Fig. 1). The ice surface had an elevation of ~140 m above sea level [a.s.l.] and sloped southward at 3-4° (Syverson 1992). Ice crystals ranged from 15-40 cm in the longest dimension and averaged 25 cm in diameter. The ice surface was uniform and free of sand and pebbles. Some silty clay accumulations were present in cavities 1-2 cm deep on the ice surface. These accumulations were greenish gray (5GY 5/1), spherical, 1-2 cm in diameter, and contained ~70% clay and ~15% silt. Clean ice contained disseminated sandy silty clay at concentrations of ~0.1% by mass.

Four clean ice plots were used to determine ablation rates for the ice surface. Wooden ablation stakes were used at two of these plots (station 8 [S8] and station 14 [S14]). Holes were drilled at clean ice sites using a 14-cm diameter ice auger. Ablation stakes marked in 10 cm increments were placed in the holes to measure ablation rates. A maximum-minimum thermometer was attached to the S14 ablation stake 0.60 m above the ice surface. It was read daily and adjusted to maintain the same height above the ice surface. Ice-surface lowering was measured daily at S14 by comparison to increments on the ablation stake.

A benchmark serving as a reference point for ice-surface elevations was set up on a hill crest east of the ice remnant. Ice-surface elevations were leveled once per week using a Wild NAK 1 automatic level. Surface elevations were measured by placing the leveling rod on an aluminum plate on debris at the center of the plot. All leveling traverses were closed by making back sights to the benchmark. Ice-surface elevation changes provide valid ablation data if ice is stagnant and if subglacial melting is minor relative to surficial melting. In order to prove this, it is necessary to show that ice-surface lowering measured by leveling equals the amount of ablation indicated by ablation stake measurements. Leveling and ablation stake data at S8 and S14 coincided (Syverson 1992), and therefore the ice mass was stagnant in 1990. Field work at the site in September 1993 after the ice had disappeared confirmed that the former ice remnant was <14 m thick (and incapable of flow) in 1990. We use the terms ablation and ice-surface lowering interchangeably when discussing processes at Burroughs Glacier. All ablation values are expressed as a thickness of ice removed.

Ice-surface lowering results are summarized in Table 1. Clean ice plots experienced 3.60-3.84 m of surface lowering during a 56-day interval (a mean rate of 6.7 ± 0.2 cm/d, $n = 4$). Larson (1978) measured ice-surface lowering at the southeastern Burroughs Glacier (elevation 150 m a.s.l.) between September 1972 and September 1973. His ablation stake data showed lowering of 7.13 m/yr (5.9 cm/d, using a 120-day melting period suggested by Taylor (1962) for this elevation at Burroughs Glacier).

Sand (sand:silt:clay ratio of 80:18:2) and till (63:26:11) were placed on clean ice in 2 x 2 m control plots with depths of 0.5 cm, 1.0 cm, 2.0 cm, and 4.0 cm to investigate ablation rates at the stagnant ice remnant. Attempts to maintain a constant sediment thickness failed. Heavy rainfall during the second week of July removed most of the debris. Control plots with debris covers of 0.5 cm sand, 0.5 cm till, and 1 cm till displayed enhanced ablation on June 25 after debris had been on the ice for 2-4 days. The centers of these plots formed shallow depressions on the ice. By the final observation date on August 21, plots that formerly had till debris 0.5 cm and 1 cm thick were 10-15 cm higher than the surrounding clean ice surface (indicating a retarded ablation rate), and the plot that initially had sand 0.5 cm thick was at the same height as the surrounding ice. Control plots with debris >1 cm thick became higher than the surrounding clean ice surface as ablation progressed.

The slope of the line in Figure 2 shows that maximum ice-surface lowering (8-10 cm/d) occurred during warm, sunny periods when little precipitation fell. Minimum ice-surface lowering (5-6 cm/d) occurred during the cooler, overcast days associated with precipitation. A scatter plot of daily ablation versus mean daily temperature suggests a linear relationship. Regression analysis on daily ablation at the clean ice control plot (S14) as a function of mean daily temperature results in a least-squares equation of:

$$\text{Ablation (cm/d)} = 0.564T - 0.859$$

where T is the mean daily temperature in the range between 9° C and 21° C. The correlation coefficient r is 0.66, indicating a moderate correlation. An F test shows that this relationship is significant at the 99.9% level. Mean daily temperature explains 44% of the ablation variations.

Ablation was retarded slightly even though most debris was removed from the plots. This study and work by Lister (1953) in Iceland suggest that thin debris does not affect ablation rates markedly in a maritime climate. Lister (1953) reported that ice with debris 0.2 cm thick melted slightly more rapidly than clean ice in a maritime climate, and that debris 0.4-0.7 cm thick retarded ablation. Retarded ablation at the Burroughs Glacier control plot with 0.5 cm till (and even less after erosion occurred) was not expected based on the work summarized in Table 1 by Østrem (1959), Loomis (1970), and Small and Clark (1974). Enhanced ablation did occur for a short time after debris application, but the ice soon lowered at approximately the same rate as the surrounding ice. Small and Clark (1974, Table I) state that a 1-cm-thick layer of fine debris increased ablation 22-72% over the rate for bare ice. They argue that even a small

Table 1. Summary of ablation rates beneath debris layers relative to clean ice

Location	Measuring Period	Debris Thickness (cm)	Ablation Rate (cm/day[*])	% of Clean Ice Abla. Rate	Reference
Isfallsglaciären, Sweden	3.7 wks 3.7 wks 3.7 wks	0 6 20	4.5 3 <1	100% 67% <22%	Østrem, 1959
Glacier de Tsidjiore Nouve, Switzerland	4 wks 4 wks 4 wks 4 wks 4 wks	0 1 (F)[†] 2-3 (P)[†] 3 (C) 6 (C)	2.14 3.69 2.51 1.80 1.35	100% 172% 117% 84% 63%	Small and Clark, 1974
Kaskawulsh Glacier, Yukon	3.4 wks 3.4 wks	0 22	5.4 0.6	100% 11%	Loomis, 1970
Klutlan Glacier, Yukon	950 yrs[‡]	≤300	19 cm/yr	--	Driscoll, 1980
Adams Inlet, Alaska, kame terrace	8 wks 8 wks	400 (C)[†] 50-80 (C)	24 cm/yr 0.8	-- --	McKenzie, 1969
Adams Inlet, Alaska	1.1 wk	30 (C)	1.1 cm/yr	--	McKenzie & Goodwin, 1987
Burroughs Glac., AK Medial Moraine 16 Medial Moraine 15 Debris cone-E Debris cone-W Delta	8 wks 7.3 wks 7.3 wks 3.9 wks 3.9 wks 6.3 wks	0 0.7 (C) 2 (C) 3 (C) 5 (C) 110-210 (C)	6.7 6.9 6.3 5.5 4.1 ≤0.2	100% 102% 94% 81% 60% ≤3%	Syverson, this study

[*] Except where units specified in cm/yr

[†] Letters indicate sediment grain size. C = coarse, F = fine, P = patchy debris

[‡] Length of ablation approximation

amount of fine-grained debris can have a profound effect on ablation.

The maritime climate, by way of clouds and rain, may play a role in the lack of ablation rate enhancement observed beneath debris layers <0.5 cm thick at Burroughs Glacier. Overcast days (and associated precipitation) accounted for 25 of 56 days during the ablation-measurement period. During these days, solar radiation did not fall directly on the ice and debris, so the darkening effect of debris was not a factor. Rainfall temperatures were not measured during the study period, but heat carried by rainfall melts ice on the glacier surface, and this is a major contributor to ablation in a maritime climate. Ablation rates during cool, overcast periods were generally 5-6 cm/d (Fig. 2), so melting caused by rainfall and above-freezing air temperatures was important during these times.

Ablation Beneath Debris Cone Sediment

Ablation was measured beneath two debris cones at the stagnant ice remnant north of Calving Lake (Fig. 1). The debris cones were similar to those described elsewhere by Sharp (1949), Boulton (1967), Watson (1980), and others. The debris cones were 2 m high, ~10 m long, and 1.5 to 6 m wide. Each cone contained a thin surficial mantle of poorly sorted gravelly sand (average sand:silt:clay ratio of 89:7:4, n = 2). The highest elevation of ice within each debris cone was measured weekly from July 24 until August 20.

Debris on Debris Cone West was up to 20 cm thick at the crest, but on average it was 4-10 cm thick. Debris slumped rapidly as the underlying ice melted. Debris was 3-7 cm thick (average 5 cm) on the sides of the debris cone. The ice surface in Debris Cone West lowered 1.11 m (4.1 cm/d) in 27 days (60% of the rate observed for clean ice, Table 1). The ice surface in Debris Cone East (mean sediment thickness 3 cm) lowered 1.48 m (5.5 cm/d) in 27 days (81% of the clean ice rate, Table 1). These values are similar to those reported in Table 1 by Østrem (1959) and Small and Clark (1974).

Ablation Beneath Medial Moraine Sediment

A medial moraine forms a northwest-southeast- trending ridge of debris-covered ice 1.7 km long at Burroughs Glacier (Fig. 1). Its surface is covered by abundant sand and angular diorite pebbles, cobbles, and boulders. Silty, clayey sand (mean sand:silt:clay ratio of 61:29:10) is 0.3-2.5 cm thick on the moraine crest. Average silty clayey sand thickness over the entire moraine is 0.7 cm. Bare ice is common between patches of debris. The moraine crest rises 7 to 10 m above the surrounding clean ice surface near the margin and the sides slope at 15-20°. The medial moraine contains numerous moulins up to 10 m in diameter and 10 to 20 m deep.

Two stations were set up on June 27, 1990, to measure ablation on the medial moraine (Fig. 1). Station MM15 was located at the most southeasterly extent of the medial moraine. Pebbles and cobbles with a-axes ≥5 cm long covered ~50% of the moraine surface at the site. Silty clayey sand was 1-2.5 cm thick and averaged 2 cm thick. Station MM16 was ~100 m northwest of MM15. Pebbles and cobbles with a-axes ≥5 cm long covered 45% of the moraine surface. Silty, clayey sand was patchy at the site and ranged from 0.3-1.0 cm thick (0.7 cm average).

Ice-surface lowering was measured by making stadia surveys from a stable benchmark with a Keuffel and Esser Co. KE-6e theodolite. Ablation rates at stations MM15 and MM16 were 3.2 and 3.5 m respectively during a 51-day period, a mean rate of 6.3-6.9 cm/d, and 94-102% of the 6.7 ± 0.2 cm/d rate observed for clean ice at the stagnant ice remnant (Table 1). Ice at MM16 lowered more rapidly than clean ice, although this rate falls within one standard deviation of the clean ice rate. The mean ablation rate beneath medial moraine sediment (6.6 ± 0.4 cm/d, n = 2) is not different from the clean ice rate at a 95% level of significance.

The medial moraine was 10 to 18 m high at the same area in June 1986 (Heiny and Rodenbeck, Univ. of Wisconsin, unpublished data), but it was 7 to 10 m high in 1990. Photographs indicate that the moraine has been melting out in the vicinity of stations MM15 and MM16 since approximately 1976. Assuming no differential ice flow during 1976-1986, this suggests a 1.0-1.8 m/yr differential ablation rate between the debris-covered medial moraine ice and the surrounding clean ice, and a daily differential ablation rate of ~0.8-1.5 cm/d using the 120-day annual melting period cited by Taylor (1962).

The calculated mean differential ablation rate between the medial moraine and the adjacent clean ice in 1990 is 0.4 to -0.2 cm/d. The negative differential ablation rate for MM16 indicates that the ice surface beneath the debris was lowering slightly faster than clean ice. The 0.4 cm/d rate is 27-50% of the differential ablation rate calculated for 1976 to 1986, suggesting that the ablation rate beneath medial moraine sediment has increased relative to the surrounding clean ice.

Loomis (1970) and Small and Clark (1974) state that ablation increases as a medial moraine gets higher and steeper because debris slumps and flows down the sides, exposing clean ice to the air and accelerating ablation. For this reason medial moraines generally are limited in height (Loomis 1970; Small and Clark 1974). The height of the Burroughs Glacier medial moraine has decreased between 1986 and 1990. The removal of debris and the increased abundance of moulins and collapse features within the medial moraine have exposed ice at depths to warm air and have enhanced ablation.

Ablation Beneath Thick Sand

Meltwater deposited deltaic sand and gravelly sand on stagnant ice in the most southwesterly part of Calving Lake (Fig. 1) starting in 1978 (Syverson 1992). A 1979 aerial photograph shows several small eskers in the area, so some of the sediment in this delta may have discharged from englacial tunnels. Excavations indicate that the sediment is predominantly ripple-laminated, fine- to coarse-grained sand. Interbedded sandy silt and sand 1-12 cm thick are found at the surface. Ice was not visible at the site in September 1988 when the first observations were made (Fig. 3). By July 18, 1989, a 4-m-high ice cliff was present beneath

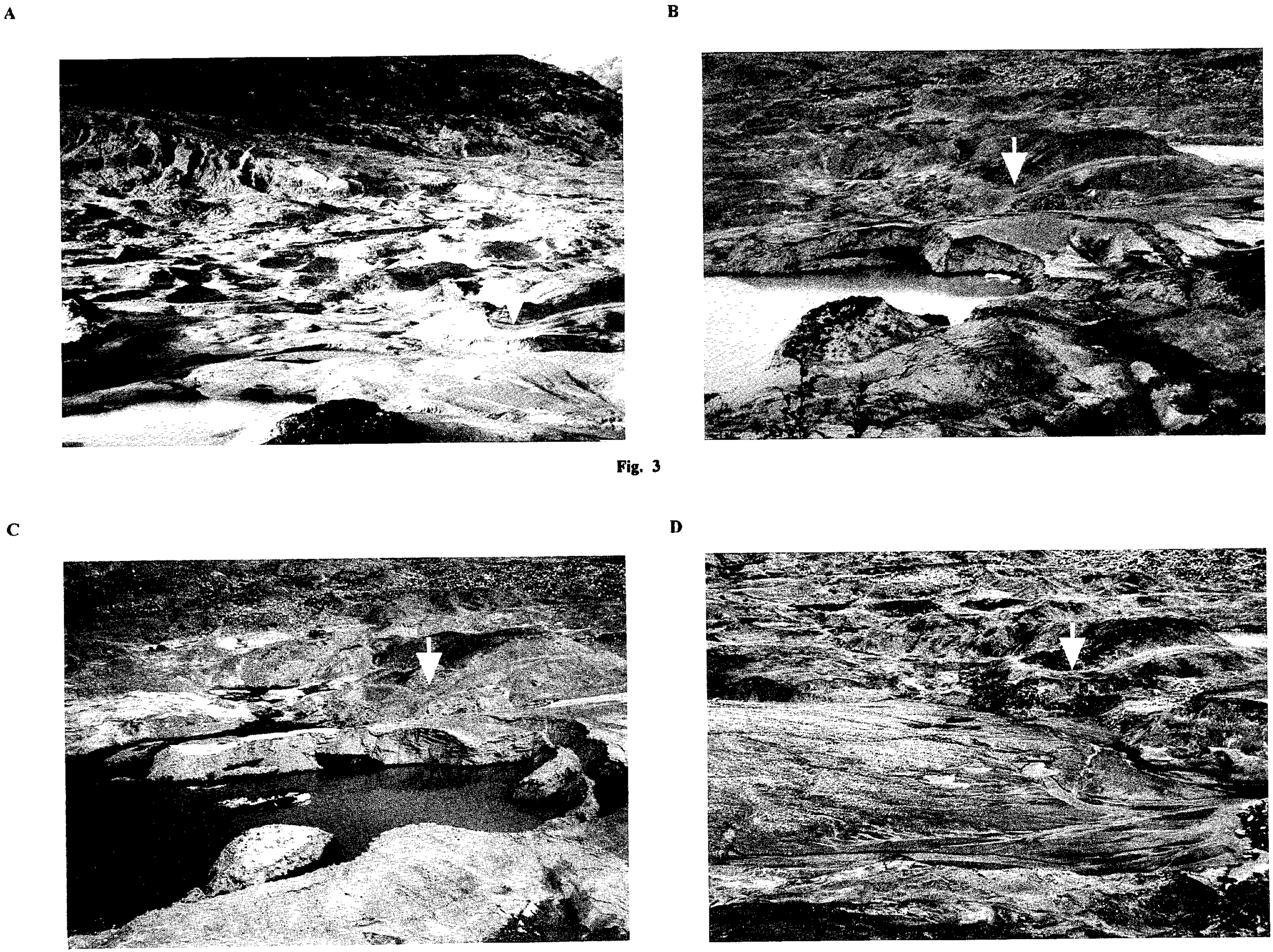

Fig. 3

Fig. 3. (preceding page) Collapse-and-fill cycles on a pitted outwash plain, southwestern Calving Lake delta. Arrow indicates a beach strandline as a reference point in each photograph. See text for more details. **A.** September 15, 1988. Small lake is present. **B.** August 5, 1989. Collapse has formed a larger kettle lake. Dark-colored zone above water level is sand-covered ice. A 9-m-wide block is ready to collapse along fissure. **C.** August 17, 1989. Block outlined by fissure in Figure 3B has collapsed to enlarge the lake. **D.** June 26, 1990. Lake has completely filled with sediment. Small ponds on stream surface caused by the melting of buried ice.

debris 2 m thick. Probing the depth to ice in several places in 1990 indicated that a block of ice with relatively low surficial relief was buried beneath ~1.1-2.1 m of sand and gravelly sand in the ablation study area (John Whedon, Univ. of Wisconsin, unpublished field notes).

Thirty points were located by stadia survey (completed July 4, 1990) to monitor slope retreat and ice-surface lowering; fifteen points were marked for remeasurement. Another stadia survey map of the delta was made 44 days later on August 17, 1990. Of the fifteen identical points measured on July 4 and August 17, three points showed surface lowering of 0.1, 0.1, and 0.4 m. The 0.4 m elevation decrease was measured on a slump block at the collapsing delta margin. The two 0.1-m-lowering values (0.2 cm/d) were measured 1 m and 4 m from the collapsing delta margin. The remaining twelve points did not show measurable surface lowering. By September 1993 the former delta surface was hummocky with a relief of 0.5 to 0.8 m and attempts to locate ice beneath the sediment were unsuccessful.

Ablation results at the Burroughs Glacier beneath sandy gravel 1.1 to 2.1 m thick are less than rates reported by McKenzie (1969) and greater than rates reported by McKenzie and Goodwin (1987). McKenzie (1969), based on heat flux calculations, determined that the rate of ice-surface lowering caused by conduction would be ~24 cm/yr (0.2 cm/d, based on a 120-day melting period) beneath gravel ~4 m thick in Adams Inlet, Glacier Bay. He also measured ablation beneath kame terrace sediment 0.5-0.8 m thick that averaged 0.8 cm/d during July and August 1967 (and up to 1 cm/d during rainy periods). Data from Burroughs Glacier indicates lower rates. Lowering of 0.1 m in 44 days represents a rate of 0.2 cm/d during the peak ablation season. Rates <0.2 cm/d are indicated by the numerous points that did not show measurable change. McKenzie and Goodwin (1987) reported ice-surface lowering rates of 1.1 cm/yr beneath a sandy gravel layer 0.3 m thick during an 8-day period in July 1978 in Adams Inlet.

Low melting rates have been observed beneath thick debris in other areas (Sharp 1949; Driscoll 1980; Watson 1980; and others). Driscoll (1980) found ice 45 m thick beneath an 800-year old moraine at the Klutlan Glacier (Yukon Territory, Canada), located in a cold, dry climate. Wright (1980) used low ablation rates to explain problematic basal peat ages in kettle lakes in Minnesota. He suggested that buried ice remained in the Minnesota landscape for 7000-9000 years during the time from 20,000-11,000 B.P..

Pitted Outwash Plain Development

Pitted outwash plains form as meltwater streams deposit stratified sand and gravel on blocks of stagnant ice. Buried ice blocks eventually melt out and the overlying sediments collapse to form depressions commonly called kettles. The process of pitted outwash plain genesis has been reviewed in detail by Price (1973). A specific example from Burroughs Glacier applies to other areas.

Pitted outwash plains form in extremely dynamic environments where several collapse-and-fill cycles can occur. This is illustrated at the southwestern Calving Lake delta (Figs. 1 and 3). Cracks observed in September 1988 suggested that much of this sediment was underlain by stagnant ice, so Syverson set up photographic station 88B to monitor collapse at the site. Figure 3 shows the dramatic changes at the site during a two-year period. A lake present in 1988 (Fig. 3A) expanded as buried ice melted and the overlying sediment collapsed. In 1989 (Figs. 3B,C) the lake enlarged as collapse proceeded. Water flowing eastward from the Bruce Hills (Fig. 1) constantly deposited sediment in this lake. The lake basin had completely filled by June 1990 (Fig. 3D) and the stream flowed into Calving Lake across a sandy gravel fluvial plain. Pools appeared on the fluvial plain as the summer of 1990 progressed (Fig. 3D). These incipient kettles formed as shallow buried ice melted locally and caused subsidence of the fluvial plain. The kettles became focal points for sedimentation, and by September 1993 the pools had been filled by fluvial sediment and no kettles were observed on the fluvial plain.

The formation and filling of kettles has occurred repeatedly in the area. Figure 4 shows a small subsidence/collapse-and-fill structure excavated by stream erosion at the site. The collapse feature is located in clast-supported pebble gravel. A bed of medium-grained, planar-laminated sand delineates a depression 0.8 m deep. The depression outlined by the sand lens is filled with a concentration of cobbles 0.3 m thick and overlain by horizontally bedded sandy gravel.

This structure formed after fluvial sand and gravel was deposited on a stagnant ice block. As the underlying ice melted, the sediment subsided and a small kettle formed.

This occurred while fluvial deposition was taking place, as indicated by the thicker accumulation of sand in the kettle. Sand deposition was followed by a high water-velocity event that filled the kettle with cobble gravel. This obliterated the surficial expression of the kettle, and later the overlying horizontally bedded gravel was deposited. Sedimentary structures such as this in ancient glacial sediment indicate syndepositional collapse.

Slope retreat at the site shown in Figure 3 occurred as melting ice and fluvial erosion led to collapse and removal of sediment. The total slope retreat during the first eleven months of observations was 30.4 m (33.2 m/yr, September 15, 1988, to August 17, 1989). No significant slope retreat occurred during the 1990 summer field season. The slope retreated 11 m during August 17, 1989, to August 17, 1990, a rate of 11 m/yr. The average rate of slope retreat during the 23-month observation period was 21.6 m/yr. McKenzie and Goodwin (1987) reported a 6.8 m/yr rate of kame terrace retreat for 1966-67 in Adams Inlet (also in Glacier Bay). Observations in September 1993 indicate that little slope retreat has occurred since August 1990.

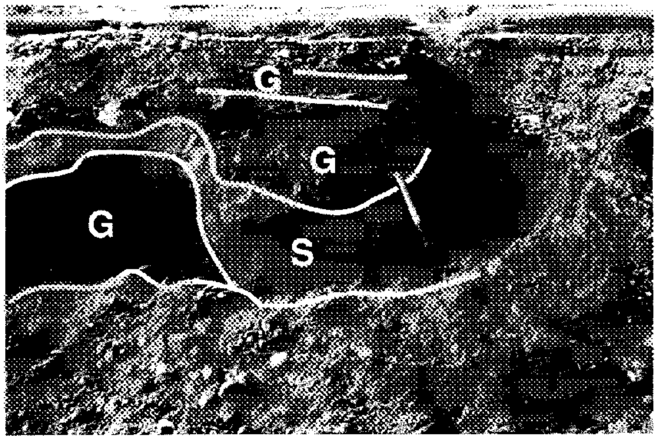

Fig. 4. Filled kettle in southwestern Calving Lake delta indicating syndepositional collapse. Bed of medium-grained, planar-laminated sand 15 cm thick (S) outlines collapse structure. This sand bed thickens to 50 cm at the base of the depression and contains a lens of massive, coarse sand 20 cm thick. It is overlain by cobble gravel (G, top of shovel handle) and horizontally bedded sandy gravel (G, near surface). Shovel handle is 0.55 m long.

Summary

Ablation rates relative to clean ice are summarized in Table 1. Clean ice surfaces lowered at an average rate of 6.7 ± 0.2 cm/d. Ablation rates beneath medial moraine debris 2 cm thick to a patchy 0.7 cm thick were 6.3 to 6.9 cm/d, respectively (94-102% the clean ice rate). Ablation rates relative to clean ice decreased slightly at Burroughs Glacier control plots with debris covers <0.5 cm thick. This observation and the work of Lister (1953) in Iceland suggest that thin debris layers do not influence ablation rates as much in maritime climatic zones as in other climatic zones. Observed ablation rates at Burroughs Glacier decreased with an increasing thickness of debris. Ablation rates beneath debris layers 2 to 5 cm thick were 94% to 60% of the clean ice rates. Ablation measured beneath gravelly sand 1.1-2.1 m thick during a 44-day period indicated ice-surface lowering at a rate ≤0.2 cm/d (≤3% the clean ice rate).

Pitted outwash plains form in very dynamic environments. Ice is buried by fluvial sand and gravel, kettles form as the melting of buried ice causes sediment collapse, and then kettles fill with fluvial sediment during short time intervals. This sequence of events was documented at the southwestern Calving Lake delta during a 23-month period. Collapse-and-fill cycles on a pitted outwash plain may be repeated several times before all buried ice blocks melt. Sediment-filled kettles indicated by deformed bedding and overlain unconformably by horizontally bedded sediment result from syndepositional collapse in the glaciofluvial or fluvial environment.

Acknowledgments

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Driving Stress, Hydraulic Head and Landform Genesis at the Southeastern Burroughs Glacier

by

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Abstract

Topographic maps of Burroughs Glacier surfaces in 1948, 1960 and 1970, and the deglaiated land surface in 1990, were incorporated into a geographic information system (GIS), and hydraulic head and driving stress maps were generated for the area deglaciated between 1948 and 1990. Two eskers are parallel to the calculated hydraulic gradients, rather than the bed slope, indicating that their paths were controlled by the overlying ice. Several other eskers trend parallel to the bed slope making it unclear whether slope or hydraulic gradient is responsible for their formation.

The average driving stress of Burroughs Glacier decreased from 1.3 bars in 1892 to 0.51 bars in 1970 and varied in a complex manner related to the bed topography. Driving stress generally was low on lee sides, tops, and stoss sides of bedrock hills, and higher beneath thicker ice between the hills. On the stoss side of nunataks, debris-rich ice evidently stopped moving and accumulated due to low driving stress, later melting out to form thick till deposits.

KEY WORDS: Alaska, Burroughs Glacier, driving stress, drumlins, glacier hydrology.

For most modern glaciers, little information is available about the conditions below the ice. Conversely, detailed information about landforms and sediments left behind by ancient glaciers has been gathered, but the characteristics of the glacier ice that formed these features are generally unknown. This study of former driving stress and hydraulic head distribution is possible near the southeastern terminus of Burroughs Glacier because topographic maps of past ice surfaces are available for 1948, 1960 (Taylor, 1962) and 1970 (Mickelson, 1971). Because of the rapid deglaciation that has taken place (up to 250 m vertically and 4500 m horizontally since 1948) landforms are now exposed in areas where these parameters can be calculated for three different times in the past. In this paper we briefly summarize a geographic information system (GIS) we constructed and then discuss our reconstruction of driving stress and hydraulic head in the area deglaciated between 1948 and 1990. We then compare esker paths and gradients to evaluate whether they can be used to reconstruct hydraulic heads.

Background

Study Area

Burroughs Glacier is located in Glacier Bay National Park and Preserve in southeastern Alaska and is a stagnating remnant of a much larger Neoglacial ice mass. The ice reached its Neoglacial maximum about 1700 A.D., when it extended 60 km south of the modern Burroughs Glacier to the area near Bartlett Cove, (Goldthwait, 1966). A map of Glacier Bay in 1892 (Reid, 1896) shows that all but the highest ridges near Burroughs Glacier were covered by an ice mass known as the Cushing Plateau (Fig. 1). Rapid calving in lower Glacier Bay had begun between about 1817 and 1842, leading to substantial thinning of the ice mass (McKenzie, 1970) and rapid retreat of the calving margin up Muir, then Wachusett Inlets. Down-

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wasting caused the emergence of nunataks, that diverted ice flow and eventually separated the Cushing Plateau into Burroughs, Plateau, Cushing and Carroll Glaciers. By 1892, the highest elevations of Burroughs and Plateau Glaciers were below the equilibrium line elevation. Cut off from any accumulation, the Burroughs and Plateau Glaciers have rapidly downwasted (Mickelson, 1986).

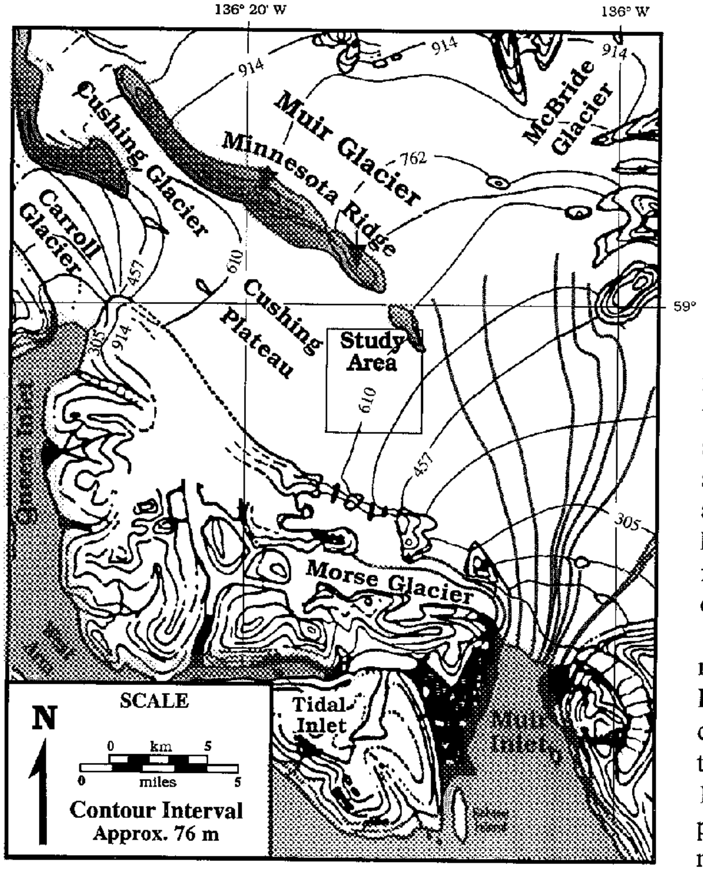

Fig. 1. Map of Muir Inlet region in 1892. The modern Burroughs Glacier occupies the area covered by the Cushing Plateau in 1892, and box indicates SE Burroughs Gl. study area shown in figures 2, 3, 4 and 5. Adapted from Reid (1896)(Syverson, in press).

Hydraulic Head and Driving Stress

The flow of subglacial water is controlled by the gradient in the hydraulic head at the base of the glacier. Shreve (1985) described the hydraulic head of water in subglacial tunnels as:

$$h = 0.9 H + z \qquad (1)$$

where h is the hydraulic head, H is the ice thickness, and z is the elevation of the glacier bed. This equation assumes that the water pressure in the tunnel equals the pressure in the ice surrounding the tunnel, which requires that the tunnel remain full of water at all times. Shreve (1985) suggests that for ice thicker than about 100 m, ice flow adjusts the diameter of the tunnel in response to changes in discharge quickly enough that this assumption holds reasonably well. This relationship also assumes that the pressure in ice surrounding the tunnel equals the overburden pressure and that all other stress components are relatively small. The driving stress is the net hydrostatic force per unit map-area which acts in the direction of maximum ice-surface slope (Whillans, 1987). Driving stress was calculated as:

$$t = - r gH \, dH/dx \qquad (2)$$

where r is the density of glacier ice (assumed to be 900 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), H is the ice thickness, and dH/dx is the ice-surface slope (Whillans, 1987). The movement of a glacier is in response to this driving stress.

The locations of some former subglacial tunnels at Burroughs Glacier are marked by eskers (Fig. 2). These landforms consist of sediment that was deposited by meltwater streams in subglacial tunnels and remain as topographic ridges after deglaciation. Most of the eskers are small (less than 6 m high), sharp crested, commonly cross small hills, and contain poorly-sorted, poorly-bedded gravel and sand. The general lack of sedimentary structures implies high sediment influx rates to the ice tunnel during esker formation and/or rapid deposition late in the history of the esker tunnel (Syverson, 1991; Syverson et al., 1994).

Thick accumulations of till are common on the northwestern (stoss) sides of the nunataks at the southeastern Burroughs Glacier. Till has been observed melting out of debris-rich basal ice layers on the up-ice sides of some of the nunataks (Mickelson, 1971; Ronnert and Mickelson, 1992; Ham and Mickelson, 1994). Mickelson (1971) proposed that where driving stress was low, the basal debris-rich ice stopped moving and was overridden by more debris-rich ice, resulting in the accumulation of thick till.

Methods

Hydraulic head and driving stress maps were constructed for southeastern Burroughs Glacier for 1948, 1960 and 1970 by comparison of past ice surfaces with the bed topography. Topographic maps of the 1948, 1960, and 1970 ice surfaces and the 1990 land surface were digitized and incorporated into a GIS using the mainframe version of ARC/INFO created by the Environmental Systems Research Institute, Inc.

The GIS was used to directly compare the topographic maps for each year and quantify the change in ice surface elevations. Six topographic highs located on each of the four maps served as control points that were used to transform the maps to the same scale and coordinate system.

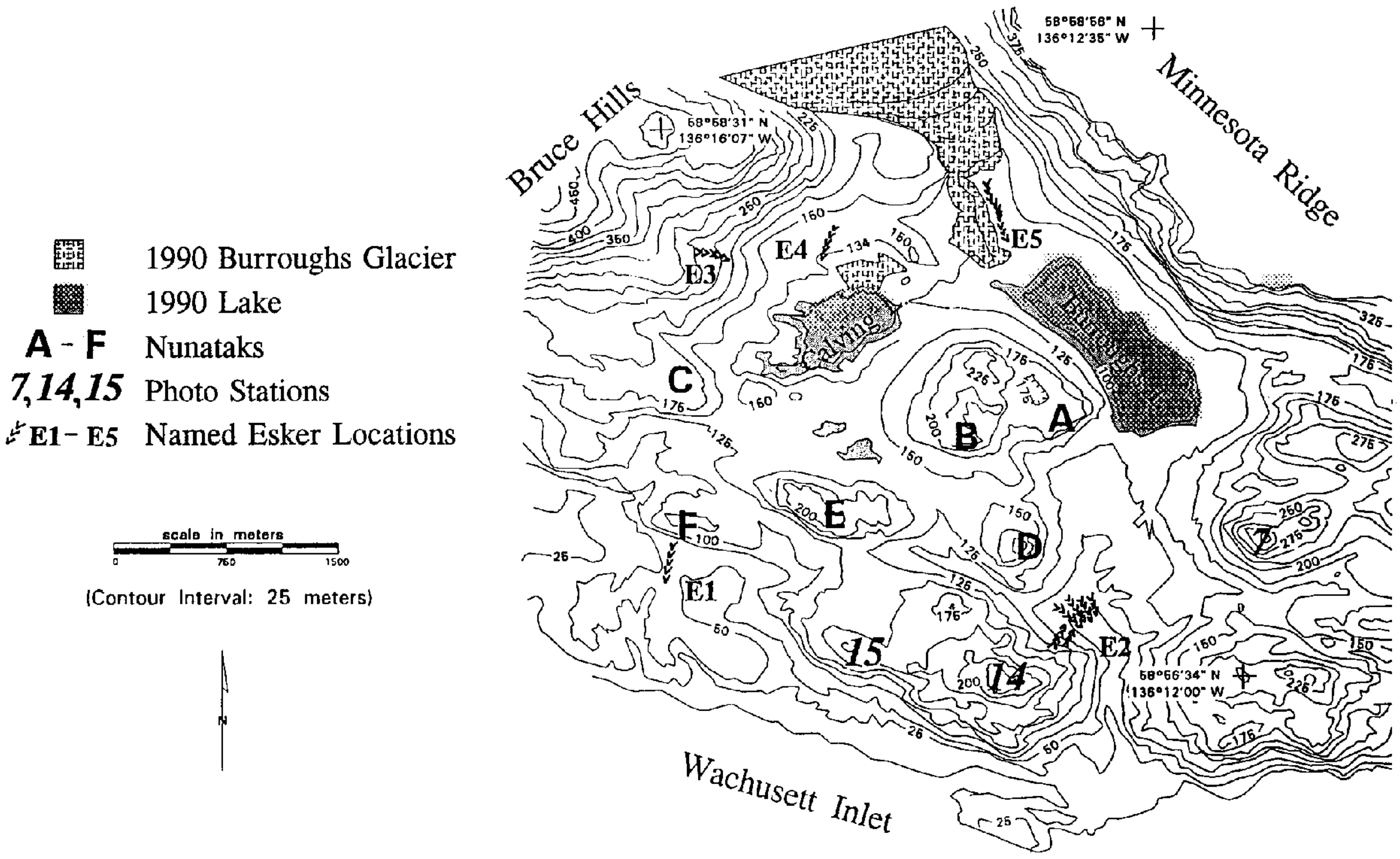

Fig. 2. Topographic map of SE Burroughs Glacier area in 1990 showing shape of bed in 1948, 1960 and 1970 and 1990 distribution of ice. Upper case letters refer to nunataks named by Taylor (1960) and numbers are W.O. Field photo stations (7, 14, 15).

The positions of the six reference points on the 1948 USGS quadrangle were recorded in Universal Transverse Mercator (UTM) coordinates, and each of the maps was transformed to the UTM system. This allowed the maps to be overlaid with a standard deviation of the horizontal position of approximately 21 meters.

Triangulated irregular networks (TINs) were generated from the digitized elevation data for 1948, 1960, 1970 and 1990. A TIN is a three-dimensional model of a surface that is comprised of triangular facets that connect three data points. Elevations were sampled by overlaying a rectangular grid on the TINs. The horizontal spacing of the grid was 100 m in both the north-south and east-west directions, and there were 9152 grid points. The elevations of the TINs were sampled at each grid point, except where the grid extended beyond the boundaries of a map.

Ice thickness was calculated by subtracting the 1990 land-surface elevation from the elevations of the ice surfaces in 1948, 1960 and 1970. The data were compiled in tabular format, and calculations were performed in a spreadsheet program. Ice thickness could not be calculated at grid points inside the 1990 ice margin, where the topography is unknown, or outside of the ice margin for earlier years. The number of grid points at which ice thickness was calculated for 1948, 1960 and 1970 are 1792, 1147 and 614, respectively.

Ice thickness was then used to calculate hydraulic head using eqn. (1) and the driving stress using eqn. (2) for each grid point with an ice thickness value. The calculated values were contoured in ARC/INFO, and driving stress and hydraulic head maps were generated.

Results

Hydraulic Head Analysis

The hydraulic head maps were compared with the bed topography and esker paths to evaluate whether esker paths and gradients can be used to reconstruct hydraulic heads in now extinct stagnating glacier remnants in rugged topography. Neither the esker (E1) in the lee of nunatak F nor the esker (E5) near the 1990 ice margin trends down the

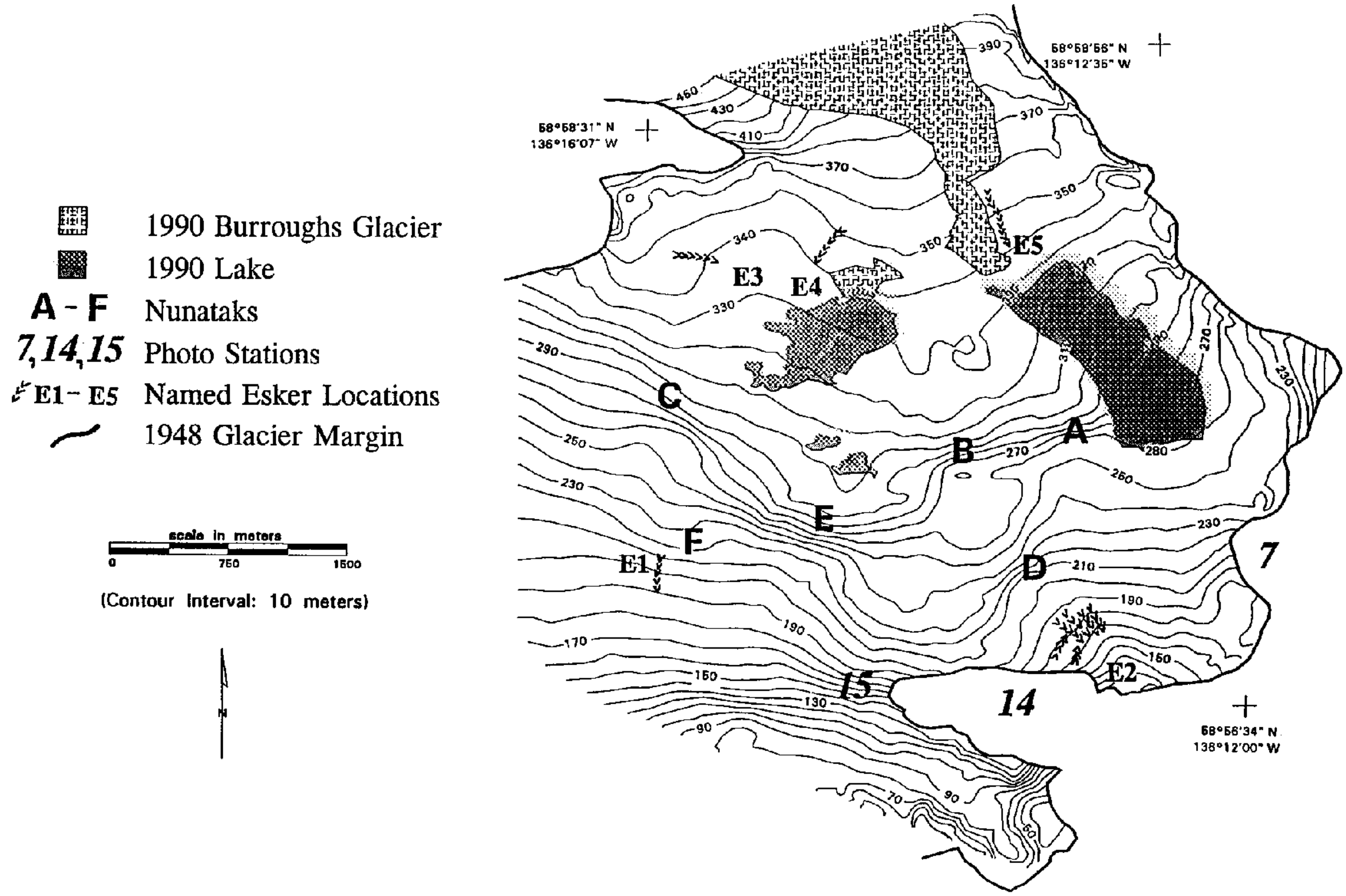

Fig. 3. Hydraulic head map of SE Burroughs Glacier in 1948 with present day eskers shown (E1 to E5).

bed slope (Fig. 3). Apparently they were controlled by the hydraulic head of the glacier, so they must have formed below ice thicker than 100 m. The 4 parallel eskers in the lee of nunatak D (E2) follow both the slope of the bed and the gradient in the calculated hydraulic head. Thus, it is uncertain whether these eskers formed below thick or thin ice. The 2 other eskers at E2 carried water back under the ice, opposite the hydraulic gradient. All other eskers in the area probably formed below ice thinner than about 100 m, because their paths show greater topographic influence than is predicted by the hydraulic head contour maps.

The assumption that the subglacial tunnels were constantly full of water apparently is not met for parts of Burroughs Glacier during deglaciation. The eskers discussed above that are not parallel to the calculated hydraulic gradient apparently formed below ice thinner than 100 m, and their paths were controlled primarily by the slope of the bed. The second assumption, that non-hydrostatic stresses were small relative to the overburden pressure, probably holds quite well for Burroughs Glacier during deglaciation. Such stresses should be highest where the slope of ice surface or bed is steep. However, it has been shown that non-hydrostatic stresses near the nunataks, where the ice-surface and bed slopes were steep, were small in 1960 and 1948 (Gaffield, 1991).

Driving Stress Analysis

Comparison of topographic maps of the surface of southeastern Burroughs Glacier for 1948, 1960, and 1970 with the map of the bed topography shows that the surface of the glacier steepened over hills on its bed. As a result, the driving stress values calculated for these three years vary in a complex manner, ranging from less than 0.5 bars to more than 1.5 bars over distances less than 500 m (Fig. 4). Low values of the driving stress occurred over the tops of the nunataks, where the ice was thin. High values of the driving stress occurred between the nunataks, where the ice was thick and the ice-surface slope was steep. The average

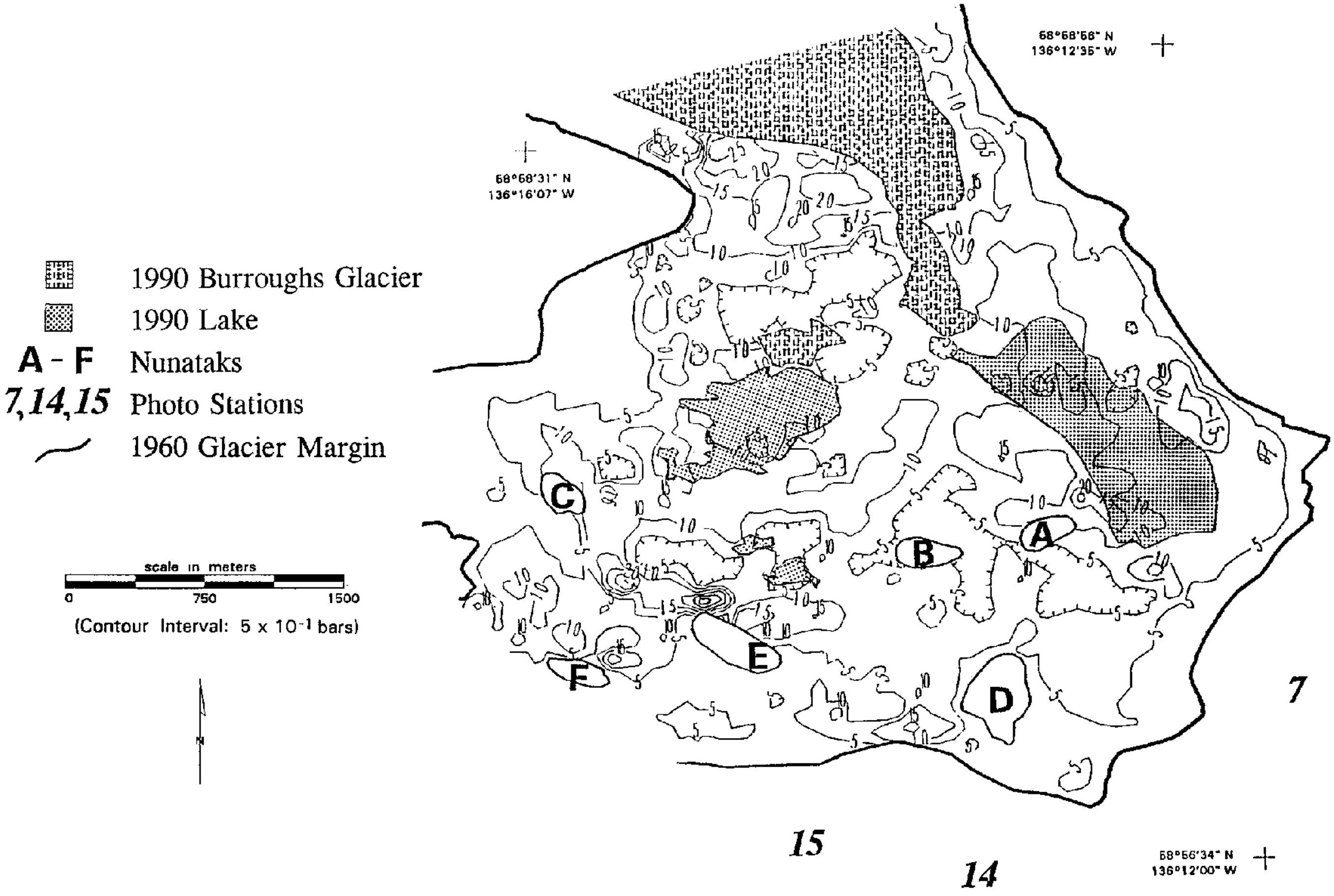

Fig. 4. Distribution of driving stress (x10^{-1} bars) in 1960.

Table 1. Average Driving Stress for Southeastern Burroughs Glacier

Year	Average Driving Stress (bars)
1892	1.31[1]
1948	0.86[2]
1960	0.72[3]
1970	0.51[4]

[1] Average of values calculated at several points along a flowline crossing the study area.

[2] Average for the area deglaciated between 1948 and 1990.

[3] Average for the area deglaciated between 1960 and 1990.

[4] Average for the area deglaciated between 1970 and 1990.

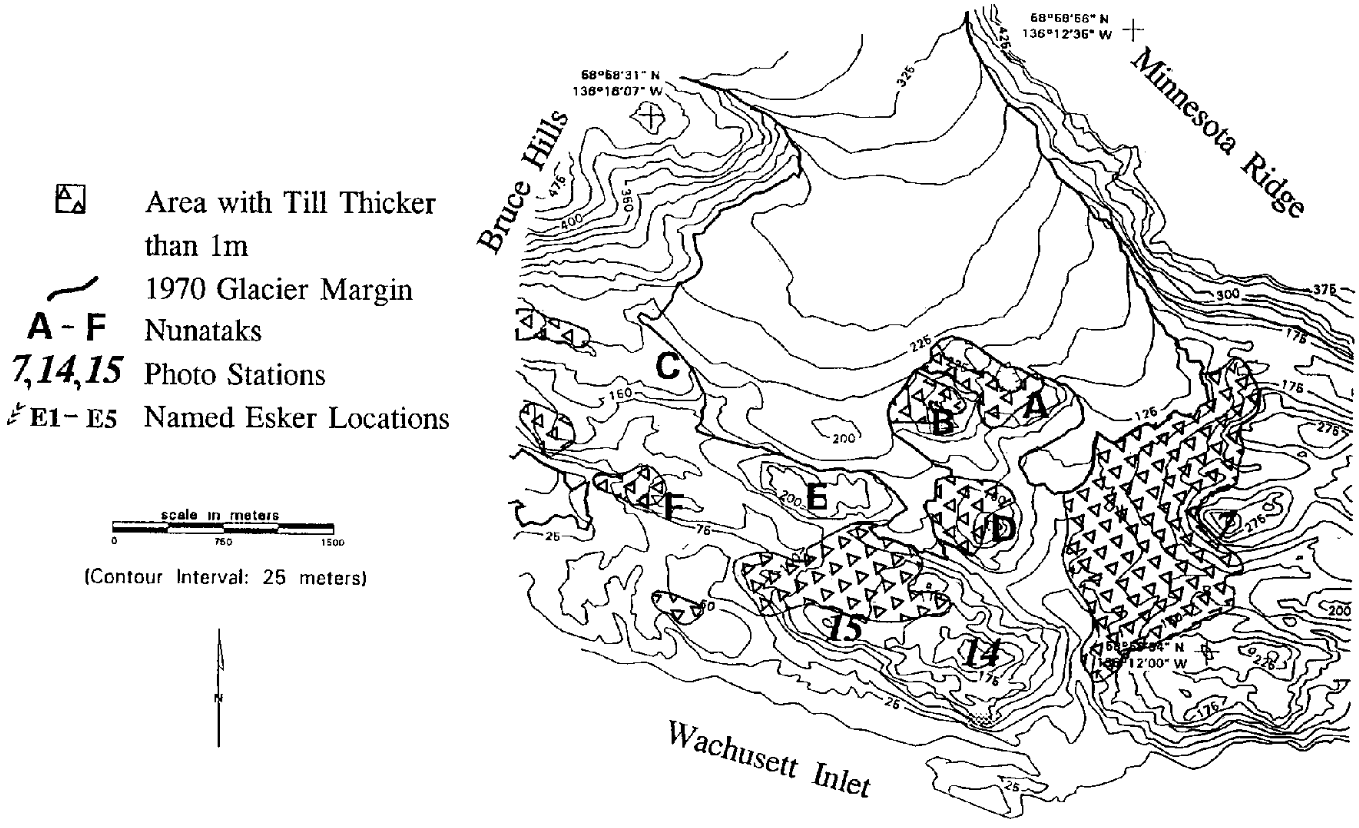

Fig. 5. Areas of thick (>1 m) till in area covered by 1948 ice.

driving stress (eqn. 2) over the ice-covered area decreased between 1892 and 1970 (Table 1).

Low driving stress may be related to the deposition of thick till on the stoss sides of nunataks (Fig. 5). Debris evidently was transported to these locations from farther up glacier under higher driving stress. As stress decreased, debris-rich ice that would later melt to form till accumulated. Driving stress was also low over the lee sides of the nunataks, where till is thin. This thin till is probably a result of the diversion of debris-rich ice around the nunataks in a manner similar to that suggested by Boulton (1974). Where observed at Burroughs Glacier, ice is clean at the bed on lee sides of nunataks.

A quantitative relationship between the driving stress and the bed topography would be useful for modelling ice masses that disappeared during the Pleistocene. However, determination of such a relationship was not accomplished in this study. The elevation of the bed and the maximum slope of the bed at each point of the grid show very little correlation to the calculated values of the driving stress. Because the ice surface tends to steepen where the bed slopes up glacier, the direction of bed slope, which could not be measured in the GIS, also controls the driving stress. Improvements in GIS software to allow the sampling of slope in a specified direction might allow a quantitative relationship between driving stress and bed topography to be developed.

Conclusions

Spatial analysis using a GIS is a technique that can be used for the manipulation and interpretation of the large volume of topographic data that documents the deglaciation of the southeastern Burroughs Glacier. It allows both visual and quantitative interpretation of ice loss and the mapping of hydraulic head and driving stress at the base of the glacier.

The paths of two eskers in the study area are parallel to the hydraulic gradient rather than the bed slope, therefore these eskers apparently formed in water filled tubes under greater than 100 m of ice. Other eskers trend parallel to the bed slope and are not parallel to the calculated hydraulic gradients, probably because the ice was thin when the eskers formed.

The average driving stress of Burroughs Glacier decreased from 1.3 bars in 1892 to 0.51 bars in 1970, and it varied in a complex manner related to the bed topography. Driving stress ranged from less than 0.5 bars to more than 1.5 bars over distances less than 500 m. Driving stress generally was low on lee sides, tops, and stoss sides of bedrock hills. It was higher beneath thicker ice between the hills. This observation supports the hypothesis that till was deposited where driving stress was low and debris-rich ice stopped moving. On the lee sides of nunataks, driving stress was low but debris-rich ice was absent.

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Micromorphology of Basal Till, Burroughs Glacier, Alaska

by

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Abstract

Thin sections from gravelly, silty-sandy basal till recently deposited by the Burroughs Glacier, Glacier Bay, Alaska, show micromorphologic features indicative of processes of glacial sediment transport and deposition. A casing of fine-grained sediment (silt and clay) around sand grains to small pebbles, and very weakly-developed skelsepic plasmic fabric likely resulted from the rotation of larger grains in basal debris-rich ice that underwent shear, either during active glacial transport or stagnation under thinning ice. The plasmic fabric is weakly developed primarily due to the small amount of clay (typically <10%) in the till. Elongate, channel-like voids observed in some of the thin sections may have resulted from dewatering as basal till was deposited by melt-out from stagnant, debris-rich ice at the ice margin.

KEY WORDS. Burroughs Glacier, basal till, micromorphology.

Only a few studies have concentrated on the description and interpretation of the micromorphology of glacial diamictons (Van der Meer, 1993, and references therein). Studies of sediment micromorphology can include the description of sediment textures and structures, diagenetic features, mineral and particle characteristics, sand and silt particle orientations, and plasmic fabric (oriented domains of clay) (Van der Meer, 1987, 1993). The study of plasmic fabric in sediments was originally developed by Brewer (1976) for the study of soils. Recently some geologists have begun to use micromorphology, especially the description of plasmic fabric, as a means of identifying the genesis of Pleistocene glacial diamictons (Van der Meer, 1987, 1993; Van der Meer and others, 1983; Van der Meer and Laban, 1990; Menzies and Woodward, 1993; Menzies and Maltman, 1992). However, almost no studies have focused on the micromorphology of sedimentary deposits at modern glaciers where the genesis of the sediment is known independently based on other observations. Such studies are important for evaluating the usefulness of micromorphology in distinguishing different genetic types of Pleistocene and pre-Pleistocene glacial deposits.

In this paper, we present a brief summary of our study of the micromorphology of basal till deposited by the Burroughs Glacier, in southeast Alaska. We first summarize processes of till deposition at the glacier based on our earlier work and then discuss our observations of till micromorphology in this context.

Setting

Burroughs Glacier, located between Muir and Wachusett Inlets in Glacier Bay National Park and Preserve (Fig. 1), is a rapidly wasting, stagnating remnant of a much larger Neoglacial ice mass that covered most of Glacier Bay. The region near the southeastern terminus of the glacier consists of bedrock hills up to about 100 m high that were progressively exposed as nunataks when the Burroughs Glacier downwasted following the Neoglacial maximum.

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Basal till, in places more than 10 m thick, mantles much of the lowland areas between these former nunataks. Processes of till deposition at Burroughs Glacier have been studied for a number of years and are well documented (Mickelson, 1971, 1973, 1986; Mickelson and others, 1991; Gaffield, 1991; Ham, 1991; Ham and Mickelson, 1994; Ronnert and Mickelson, 1992; Syverson, 1992).

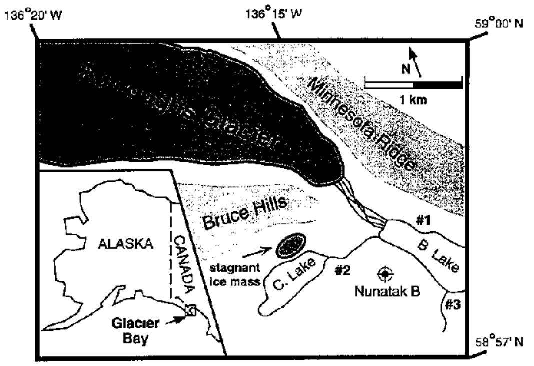

Fig. 1. Location map of Glacier Bay National Park and Preserve and the southeastern terminus region of Burroughs Glacier. Numbered sites indicate places where basal till samples were collected for thin-section study (C.Lake = Calving Lake, B.Lake = Burroughs Lake).

Basal till deposition

The following discussion of till deposition is summarized from Ham and Mickelson (1994). Much of the surface of Burroughs Glacier is devoid of supraglacial sediment. Most sediment is transported in the basal zone of the glacier and, where seen at the margin, consists of a 1-to-3 m thick layer of debris-rich ice that is commonly overlain by a layer of relatively clean ice, approximately 0.5 m thick, containing widely-spaced pebbles to small boulders but very little fine sediment. These layers of ice and debris are overlain by clean ice of the englacial zone. The basal debris-rich ice contains approximately 60% to 70% sediment by volume (Ronnert and Mickelson, 1992), and the upper surface of this layer is covered by striated pebbles to boulders, and crag and tails.

Basal till deposition that is observed at the ice margin begins when the basal debris-rich ice stops flowing beneath thinning ice. Fabric measurements made by Mickelson (1971, 1973) indicate that the debris-rich ice does not stop moving simultaneously but instead stagnates progressively from the bottom upward. Shear surfaces develop in this debris-rich ice as the boundary between flowing and stagnant ice moves upward. Accumulations of till, in places more than 10 m thick, on the up-ice sides of bedrock hills suggest that slabs of basal debris-rich ice are stacked beneath the glacier in these locations, perhaps due to low driving stress in these areas (Gaffield, 1991).

Basal till is finally deposited by melt-out from stagnant, basal debris-rich ice that is exposed at the ice margin. The till is typically gray, matrix-supported, gravelly, silty-sandy diamicton, and the average grain-size distribution for 40 samples of the till is 57% sand, 36% silt, and 7% clay (<2 mm fraction; Mickelson, 1971). Basal till at Burroughs Glacier shows features typically associated with lodgement till even though the final mode of till deposition is melt-out from stagnant, debris-rich ice. Ham and Mickelson (1994) have suggested that the till does not show any sedimentologic features typical of melt-out till because of the very high debris content of the basal layer of the glacier.

Methodology

Fifteen oriented samples of till for thin section analysis were collected in stream cuts at three locations near the southeastern terminus of Burroughs Glacier (Fig. 1). The sample sites had been ice free for less than 20 years at the time of collection and one site had been ice free for only five years. The samples were collected by pressing a 9 cm x 5 cm x 4 cm tin frame into a vertical or horizontal face. The orientation of the frame was noted, and the frame was excavated from the exposure, wrapped in plastic wrap, tin foil, and duct tape, and placed in a waterproof sample bag to prevent drying. Samples were oven dried at 35°C for 48 hours and vacuum impregnated with Scotchcast Resin #3 (3M Company). The samples were cured for one week at 18°C and a second week at steadily-increasing temperatures to a maximum of 100°C. This technique is not known to cause changes in the structure of the sediment (Brian Hess, 1994, verbal communication). Samples were cut using a rock saw, and 25 thin sections were made. The thin sections were ground to a thickness of about 20 microns and examined under a petrographic microscope. The final dimensions of the thin sections were approximately 2 cm x 3 cm.

Thin section descriptions and discussion

The following descriptions use the terminology of Brewer (1976) for plasmic fabric (oriented domains of clay). Plasmic fabric has become an important tool in studies of till micromorphology because it is believed to be produced by stress imposed on till during transport or deposition (Van der

Meer, 1987). Plasmic fabric is visible under crossed polarizers because of the higher birefringence and extinction pattern of clay, and to some extent silt particles (Van der Meer, 1987; Brewer, 1976). Features described here were observed in most of the thin sections examined in this study. Sand and silt grains are typically angular to subrounded and consist of a mixture of monomineralic grains and lithic fragments (Fig. 2). Many of the monomineralic grains are quartz and feldspar derived from granite and granodiorite. Lithic components are typically metasiltstone and other metamorphic rocks. A minor component of the lithic fragments is granite and granodiorite. Flow structures, textural banding, and diagenetic features in the till were not observed in any of the thin sections.

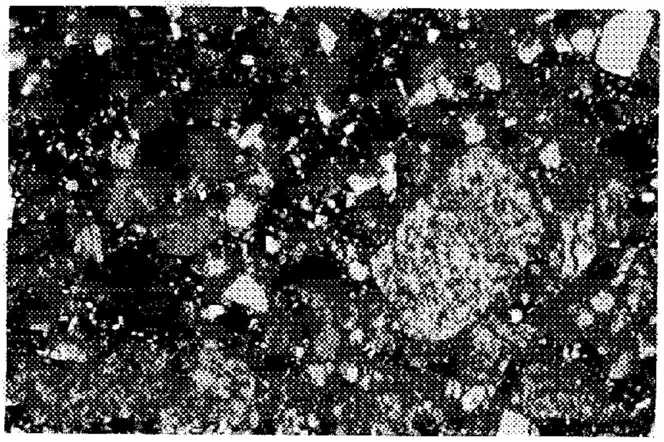

Fig. 2. Typical polarized-light photomicrograph of basal till deposited by Burroughs Glacier. Note the lack of plasmic fabric due to the low clay content of the till (typically <10% in the <2 mm fraction). The width of view is 9 mm.

The bulk of the area in the thin sections away from larger grains typically does not show any plasmic fabric (Fig. 2). A casing of fine-grained material (silt and clay) and very weakly-developed skelsepic plasmic fabric was observed around several sand grains and small pebbles in a few thin sections (Fig. 3). In soils, skelsepic fabric is usually attributed to swelling pressures against the surface of skeletal grains due to wetting and drying cycles (Brewer, 1976). However, this process is not applicable to basal till from Burroughs Glacier because the till was only recently deposited and we believe unaffected by significant wetting and drying cycles in the present humid, maritime climate. Lafeber (1964) attributed skelsepic fabric to the rotation or translocation of skeletal grains under pressure, and Van der Meer (1987) suggested that in tills the pressure is exerted on particles during or after lodgement. More recently, Van der Meer (1993) suggested that skelsepic fabric may be associated with deformation of subglacial sediment. In the case of till deposited by Burroughs Glacier, we suggest the possibility that the skelsepic fabric and the casings of fine-grained material observed around skeletal grains developed by grain rotation under pressure due to shear in deforming, basal debris-rich ice. The formation of these features may be related to the very high debris content of the basal ice layer. Alternatively, these features could be inherited from processes of sediment transport and non-final deposition that took place under thicker, faster-flowing ice, such as deformation of unfrozen, subglacial sediment, and were subsequently inherited in the debris-rich ice and preserved in the basal till during deposition. However, the nature of these other processes is not known because they are nearly impossible to observe directly.

Van der Meer and Laban (1990) report that basal tills are typically characterized by a "well to strongly-developed skelsepic fabric", and that thin sections from flowtills from the Alps and modern glaciers in Spitsbergen possess only a weakly-developed skelsepic fabric. A well-developed skelsepic fabric cannot form in basal till with relatively little clay, such as that deposited by the Burroughs Glacier, and high proportions of fine carbonate or silt can mask oriented clay as well (Brewer, 1976; Van der Meer, 1987, 1993).

The carbonate content of till deposited by Burroughs Glacier is negligible (typically <5%; Mickelson, 1971). Thus, the predominant factor inhibiting the development of a strong plasmic fabric is probably the lack of abundant clay in the till (typically <10% in the <2 mm fraction), although the presence of silt may be masking plasmic fabric to some degree. Our observations indicate that the degree of development of skelsepic fabric cannot be used independently as an indicator of sediment genesis. Instead, the development of plasmic fabric must be examined with respect to the grain-size distribution and composition of the sediment being studied as suggested by Van der Meer (1987, 1993).

In addition to the features described above, elongate and circular voids with smoothed and semicircular walls were seen in several of the thin sections (Fig. 4). These structures are preserved even in samples collected to depths of 2.5 m. The origin of the voids is not clear. The voids formed after the debris-rich ice became stagnant because they show no sign of deformation due to moving ice. They may have formed by the expulsion of water in discrete openings during the melt-out process when basal debris-rich ice was exposed at the ice margin.

In summary, Our observations show that basal till at Burroughs Glacier is deposited at the ice margin by melt-out from debris-rich ice that previously stagnated beneath thinning ice during deglaciation. We suggest that fine-grained casings around larger grains and skelsepic plasmic fabric observed in some thin sections from the till are the direct result of active glacier processes, specifically the rotation of larger grains in sediment undergoing shear as proposed by Van der Meer (1987, 1993). Observations at the ice margin indicate these features may have formed in frozen sediment (debris-rich ice). The casings and plasmic fabric are likely preserved during the melt-out process because of the very high debris content of the debris-rich ice. The origin of voids in the till may be associated with dewatering during melt-out of the till from stagnant, debris-rich ice.

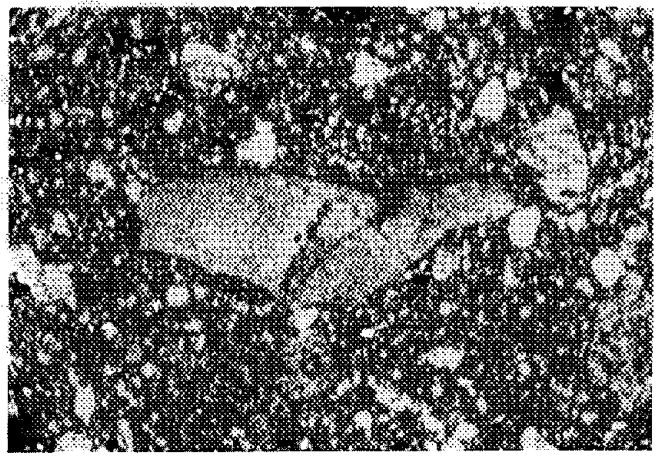

Fig. 3. Plain-light photomicrograph of a thin, poorly-developed casing of fine-grained sediment (dark areas) around a larger, skeletal grain in till. The width of view is 9 mm.

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We thank Kent Syverson, Steven Gaffield, John Whedon, and Lars Ronnert for their assistance in the field, and Brian Hess for making the thin sections. We also thank the staff of Glacier Bay National Park and Preserve for providing critical logistical support for this project. Our research was funded in part by the Department of Geology and Geophysics, University of Wisconsin-Madison, and the National Geographic Society (Grant 4087-89).

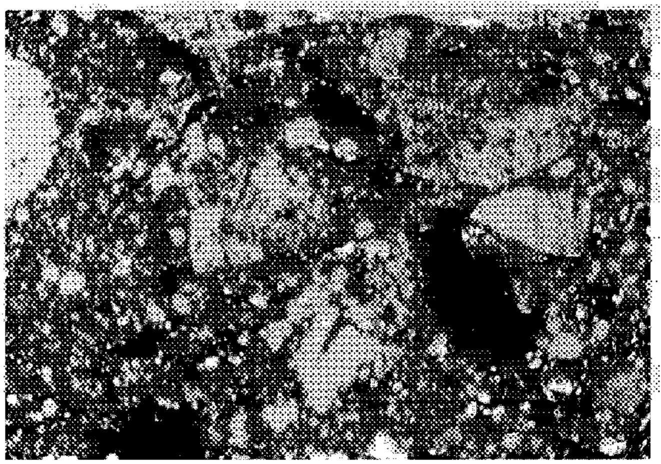

Fig. 4. Polarized-light photomicrograph of a channel-like void (black are filled with resin) in till. The width of view is 9 mm.

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Repeat Photography and Landscape Change at Glacier Bay, 1879 - 1993

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Abstract

In Glacier Bay National Park, where the rate of ice retreat from Neoglacial maximum positions has been great, repeat photography is an important tool for the documentation and study of landscape change. Fundamental contributions to knowledge of the pattern and process of succession can be made, and study site decision-making enhanced for new research, if Glacier Bay area photographic collections are preserved and if scenes are periodically rephotographed. There are many sources for Glacier Bay area photography and some of the more useful or substantial collections are introduced. Guidelines are given for conducting a repeat photography program and for the handling and storage of processed slide film. The usefulness of repeat photography at Glacier Bay is shown with several photographic sequences taken at important photo stations.

KEY WORDS. Succession, landscape dynamics, glacier fluctuation, repeat photography methodology, slide collection, archival methods.

Those who are interested in the cultural, physical, and biological components of the Glacier Bay landscape can be aided by historical photographic collections. The kinds of changes that can be documented well by repeat photography include human impacts and recovery, glacier recession and advance, erosion and deposition, rising shorelines, water level changes, plant colonization and growth, tree mortality, and patterns of use by organisms.

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[1] Deceased 16 June 1994.

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D.R. Engstrom (Ed.), National Park Service, Anchorage, Alaska, 1995

The discussion that follows provides a variety of starting points for investigators who wish to search for Glacier Bay photographs. The earliest photographs taken at Glacier Bay are from the 1880s. Slides made from many old photographs are on file in the National Park Service collection at Bartlett Cove, though the date, photographer, and location are not always recorded on the mount. In some instances it is possible to substitute accurate sketches for photographs. John Muir made at least six sketches in 1879 and others in 1890 (Muir 1915). One of those made in 1879, converted to an etching by J.A. Fraser, was published in *Century Magazine* in 1895 and has also appeared in Bohn (1967), Lawrence (1979), and here (Fig. 1, top). The most extensive collection of Muir's papers, sketches, and photographs is in the Holt Atherton Special Collections of the University of the Pacific, Stockton, California. Much of the collection has been microfilmed (see Limbaugh and Lewis 1986). Photographs taken by J.F. Morse in 1890 and H.F. Reid in 1892 are in Reid's materials included in Photographic Collection Album 115 of the Alaska State Library. Examples of etchings and photographs from the Harriman Expedition of 1899 may be seen in Burroughs (1901) and Gilbert (1904).

Glaciers have been photographed from identifiable stations at Glacier Bay by many investigators (Table 1). Photography from William O. Field's stations began in 1926 and provides an excellent base for repeat photography and the study of changes in land, topography, glaciers, waters, and vegetation. Field's photography is extensive and well-documented. Many of his photo stations have been reoccupied in more recent years by his son John and by Park Service staff. Catalogs of aerial and surface views have been prepared by Field as well as sketch maps showing his photo stations. His materials are archived at the University of Alaska-Fairbanks (see below). Early aerial photography was conducted by the U.S. Navy; an example of a photograph taken in 1929 appears in Bohn (1967). Other fine resources are Austin Post's annual Alaska Glacier Survey and Bradford Washburn's photography. Donald B. Lawrence has his own extensive collection and photographs taken by William S. Cooper and Robert E. Howe; Dave Bohn and Mark G. Noble have their respective collections, as do many others who have photographed the Glacier Bay landscape. We encourage anyone with images valuable to future research at Glacier Bay, and which are documented as to place and date, to seek a permanent repository. Institutions that have photographs taken at Glacier Bay include the Alaska State Library in Juneau, the University of the Pacific, and the Archives of the Alaska and Polar Regions Department, Elmer E. Rasmuson Library, University of Alaska-Fairbanks.

Repeat Photography Methodology

When a scene is to be rephotographed a copy (not a valuable original) of the earlier photograph at that site must be taken into the field. Prints or duplicate transparencies can be made for this purpose and protected from moisture and dirt with suitable plastic protectors. Photocopies of notes that would aid in the effort to accurately repeat the photograph should also be available. The intent is to precisely relocate the point from which the photograph was taken, assure correct composition, and select the best time of day. A lens of the same focal lens as that used previously should be used. If this is not known, lenses of various focal lengths should be available. For aerial photography the pilot should have copies of the earlier photographs so that the correct altitude and direction of view can be attained.

The initiation of a new repeat photography program needs advance planning and the selection of a suitable photo station requires some intuition. If you are young make plans now to repeat your own photographs. Select a location where 1) marked changes are expected in a single lifetime (but instruct successors to follow you), 2) there is likely to be unobstructed visibility with the passage of time, such as from a cliff edge, top of a huge erratic boulder, or island close to the mainland, and 3) access and relocation will be possible even decades later. For relocating your photo station, or an undocumented camera site established by someone else, determining the correct line of site is important. To relocate plots an easily recognizable feature on the horizon that can be lined up with a durable feature in the foreground will provide the line of site, along which the plots must lie. Keep in mind that bears will chew on painted objects and may damage or remove some types of markers. Select a photo station that will be unattractive to campers, or to hikers or wildlife that might make trails, unless impacts are the subject of your research. Where possible, include a scale in the photograph and make a note of it's dimensions. We recommend that all photo stations and study sites be located using Global Positioning System technology and that those positions be submitted to Park managers.

Select a lens of suitable focal length. Lawrence, Howe, and Alexander Milner have used 35 mm; Field and Noble have used 50 mm, and they and Lawrence have also used telephoto lenses. Keep a field notebook exclusively for photography, preferably one with waterproof paper. A photocopy, on archive-quality paper, of any valuable notebook should be stored at a different location than the original; consider giving another copy to a trusted colleague or whoever may one day repeat your photographs. Select suitable film and have it processed by a laboratory that prints exposure number, month, and year on each mount. To

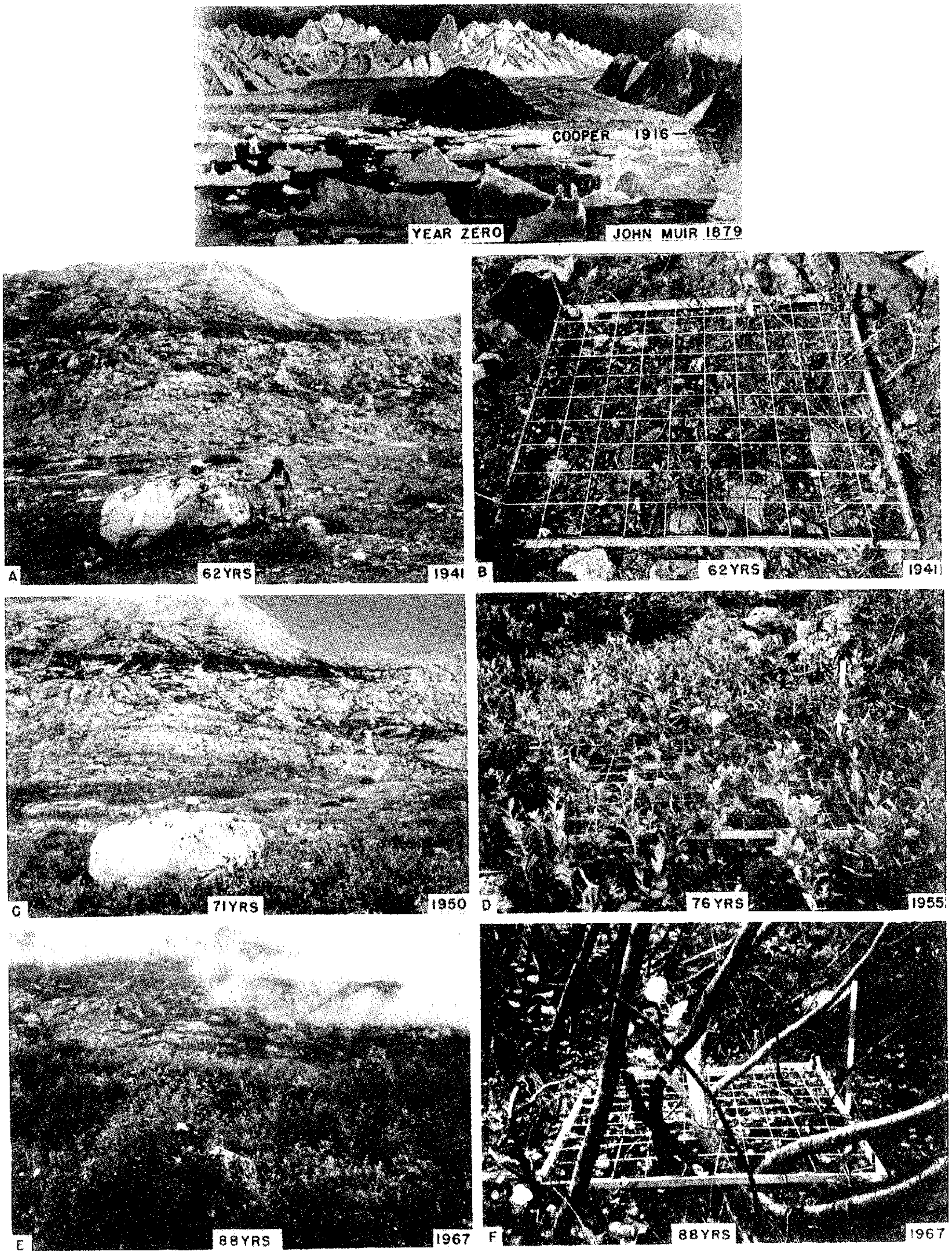

Fig. 1. Primary succession on glacial till over an 88-year period at Cooper Station 26 (top, A, C, E) and on his nearby Quadrat 1 (B, D, F) following recession of Grand Pacific Glacier Additional photographs of this quadrat have been published elsewhere (Matthews 1992) This is the place where the receding ice edge was located at the time of John Muir's visit in 1879 and where W S Cooper established a study area in 1916 Major plant cover is provided by Sitka alder. From Lawrence (1979)

Table 1. Persons who have been recorded as having taken photographs of glaciers at Glacier Bay National Park. This list includes persons who took one or more identifiable photographs; most of their photographs were taken from established photo or survey stations. The position and affiliation (or sponsor) is given, if known, and these are not repeated unless changes occurred or if necessary for clarity. The names of U.S. National Park Service (NPS) personnel are given if they were recorded as responsible for photographs taken at established stations. Many of those listed here visited Glacier Bay for reasons other than glaciological observation. It should be noted that valuable photographs have been taken by many other individuals but most of these have not yet been repeated. Additions to this compilation are welcome. AGS = American Geographical Society; USGS = United States Geological Survey.

Date	Photographer
1890	H.F. Reid (geologist), Case Institute (includes photographs by J.F. Morse)
1892	H.F. Reid
1894	Parties of the International Boundary Commission
1899	G.K. Gilbert (geologist), USGS; E.S. Lewis (photographer) & C.H. Merriam (botanist), U.S. Biological Survey, Harriman Alaska Expedition
1906	F.E. & C.W. Wright (geologists), USGS
1907	F. Morse, D.H. Nelles, & L. Netland (surveyors), Int. Bound. Comm.
1910	O.M. Leland (surveyor), Int. Bound. Comm.
1911	L. Martin (geographer), Univ. of Wisconsin, National Geographic Society
1912	W.M. Dennis & N.J. Ogilvie (surveyors), Int. Bound. Comm.
1913	L. Martin & F. Thwaites (geographers), Univ. of Wisconsin; C.L. Andrews (photographer), probably of Juneau, later of Eugene, Oregon
1916	W.S. Cooper (ecologist), Univ. of Minnesota
1919	J.B. Mertie (geologist), USGS
1921	W.S. Cooper
1924	A.H. Brooks & A.F. Buddington (geologists), USGS
1926	B.S. Wood (surveyor) & W.O. Field (geographer), Harvard Univ.
1929	W.S. Cooper
1931	C.W. Wright; H.F. Reid, Johns Hopkins Univ.
1935	W.S. Cooper; W.O. Field, unaffiliated
1936	J.C. Reed (geologist) & R.H. Sargent (topographer), USGS
1940	V. Cahalane (zoologist?), NPS; J.C. Reed
1941	D.B. Lawrence (ecologist), Univ. of Minnesota; W.O. Field, AGS
1942	J.C. Reed
1943	W.A. Wood
1946	D.N. Brown (businessman), Meridan, Connecticut
1947	J.A. Dyer, Sierra Club
1949	D.B. Lawrence & L. Hulbert (ecologist), Univ. of Minnesota
1950	D.B. Lawrence; D.N. Brown
1952	D.B. Lawrence, R. Crocker (soil scientist), Univ. of California, R.E. Schoenike (forester), Univ. of Minnesota, & R. Sprague (plant pathologist), Washington State Univ.; R.U. Light (physician & geographer), AGS
1955	D.B. Lawrence, R.E. Schoenike
1956	W.S. Cooper
1958	W.O. Field; M.T. Millett (geographer), Brigham Young Univ.; R.P. Goldthwait (geologist), Ohio State Univ.; K. Youmans, NPS
1959	L.D. Taylor (geologist), Ohio State Univ.
1960	G.M. Haselton & L.D. Taylor (geologists), Ohio State Univ.
1961	W.O. Field & M.T. Millett
1962	R.J. Price (geographer), Ohio State Univ.
1963	R.P. Goldthwait; Larsen; G.M. Haselton
1964	J. Calvin; W.O. Field & M.T. Millett

1965 D. Bohn (photographer), Berkeley, California
1966 W.O. Field & D. Bohn, AGS
1967 W.O. Field; G.M. Haselton, Clemson Univ.; A. Adelberger; D.B. Lawrence; G. Nicholls, New Zealand Park Service
1968 W.O. Field, J. Lakovitch (geographer), M.T. Millett, AGS party; D.B. Lawrence; J. Taylor, New Zealand Park Service; W.A. Reiners (ecologist), Univ. of Minnesota; I.A. Worley (botanist), Univ. of British Columbia; P. Wardle (ecologist), New Zealand Dept. of Scientific and Industrial Research
1969 D.V. Harris (geologist), Colorado St. Univ. & D.M. Mickelson (geologist), Univ. of Wisconsin
1970 D.M. Mickelson
1971 W.O. Field, M.T. Millett, & A.S. Post (glacial hydrologist), USGS, AGS party
1972 L. Mayo (geologist), USGS; A.S. Post; R.E. Howe, NPS; D.B. Lawrence
1974 W.O. Field & G.M. Haselton, AGS party; M.G. Noble (ecologist), Univ. of Minnesota
1975 G.M. Haselton
1976 W.O. Field
1978 D.M. Mickelson; G. Streveler (biologist), NPS
1979 R. Kirk (writer), NPS
1982 Bright & E. Jones-Toscano (rangers), NPS; W.O. Field, AGS-National Geographic Society party
1983 K. Heacox & E. Jones-Toscano (rangers), W.O. Field, NPS party
1984 K. Heacox & L. Selig (rangers), NPS
1985 K. Heacox & E. Jones-Toscano, NPS
1986 NPS party
1987 J. Mow (ranger), NPS
1988 P. Gottler & L. Hunter (geologists), Northern Illinois Univ.; K. Hartnet (ranger) & Yurick, NPS party; R.E. Howe, NPS
1989 S. Brown, USGS & J.O. Field, Tufts Univ., USGS-AGS party; C.C. Morrison (geographer), New York State Dept. of Environmental Conservation & M.T. Morrison (staff), New York Legislature; L. Hunter
1990 L. Hunter
1991 L. Hunter
1992 J. Richards (ranger), Captain J. Luthy, R.E. Howe, & B. Paige (naturalist), NPS parties

ensure that your photographs are valuable to others in the future, even if notes are unavailable, each should bear a unique identification number, date taken, name of photographer, location, direction of view, altitude if an aerial, and focal length of the lens used. If ink is used make sure that it is permanent. A numbering system that has worked well for Lawrence for 50 years (and others who now use it too) uses three numbers to identify each photograph. The form is: year - roll number that year - exposure number; for example, photograph 93-6-15 is the fifteenth exposure on the sixth roll taken in 1993.

Handling and Storage of Processed Slide Film

To ensure that your efforts in repeat photography remain useful to yourself, as well as to future Glacier Bay investigators, the quality of your images must be protected. Attention needs to be given to the handling of the images, the environment in which they are stored, and the materials with which they come into contact.

Handling

Handling and use cause most of the damage to images so make an effort to minimize these activities and perform them with care. Consider storing your most valuable masters (i.e., original images) and using only duplicates for most study and projection. The appendix to American National Standards Institute (1991) provides a discussion of the advantages of maintaining work and storage copies. Thin cotton gloves should be worn when handling masters as surface contamination can stain the image and promote fungus growth.

Clean slide film only when necessary and use the least damaging treatment. For instance, never use fluids if tapping, blowing (with a syringe, not your breath), or vacuuming are sufficient. Sundt (1989) recommends cleaning a brush in denatured or ethyl alcohol and, when completely dry, using it to lift the particle rather than sweeping it across the film. The application of fluids should be a last resort and used in accordance with the recommendations of the film manufacturer. The fluid should be applied to a clean cotton swab and the film contacted only briefly in one direction, without rubbing. Remember that water can only be used on the base of the film; application to the other side may soften and damage the emulsion. Solvents can usually be applied to either side (check cleaner directions and the recommendation of the film manufacturer) and are used to remove greasy stains, such as fingerprints, sticky residues, or fungi. PEC-12 is a cleaner that has been tested by the Image Permanence Institute at the Rochester Institute of Technology and is sold by suppliers of archival products. We recommend that any fluid cleaner be tested on a less valuable image of equivalent film type and age before being used on a valuable master. If the lacquer on older (approximately pre-1974) Kodachrome emulsions is removed, new lacquer must be applied to the cleaned film to maintain the stability of the dyes. Be certain not to permit sticky tape to come into contact with film. If you find fungi on any of your images, take immediate action to prevent further growth by making changes in the storage environment and refer to Eastman Kodak Company (1989) for removal methods. Sundt (1989) offers many helpful guidelines for slides mounted between glass.

The ultraviolet (UV) radiation from fluorescent lights, which are frequently used in light tables, can cause color dyes to fade. Lamps of lower UV emission can be chosen and UV-shielding material can be placed between the lamp and the slide. Projection light intensity and duration should be minimized, especially for valuable masters. The fan should be operating properly with nothing restricting air circulation. Lenses and heat filters that are standard equipment for a projector should be unbroken and properly positioned to reduce heat damage to slides.

Storage

Slides remain under storage conditions for long periods of time, usually far more time than they are handled or used. The site must provide protection and the environment must ensure the long-term stability of the dyes. The storage location should be chosen or designed to minimize the potential for theft or for damage from fire, water, vermin (e.g., carpet beetles and silver fish), or atmospheric pollutants (e.g., solvents in fresh paint). If you store your most valuable masters in a fire resistent cabinet it is important to determine if the insulation is a type that releases moisture when subjected to heat. Color slides are attacked by carpet beetles so should not be stored with clothing, fabrics, or where lint accumulates; see the recommendations of Eastman Kodak Company (1985) if there is insect damage and fumigation is necessary. Atmospheric pollutants can damage slide film, making many laboratories unsuitable for even short-term storage.

Storage containers (sleeves, pages, boxes, or cabinets) should keep dust and other types of contaminants away from the slides and should be demonstrated to be made of archival-quality materials. Avoid completely those containers made of wood, non-archival paper, and vinyl. The chemical instability of polyvinylchloride (PVC), for instance, produces hydrochloric acid and fumes, which easily damage emulsions. Plastics that are stable, lacking low molecular weight plasticizers, are generally considered acceptable for long-term storage, though metal cabinets with a baked enamel finish are preferable. If you suspect that a problem has been caused by your containers, replace them immediately. See American National Standards Institute (1991) for more information about storage containers and to learn about other pertinent standards.

Slides should be stored in the dark, with little exposure to sunlight or fluorescent lamps. Kodachrome film is subject to less dark-storage fading than is Ektachrome (Eastman Kodak Company 1985). Temperature variation in your storage location should be minimized and it is necessary to guard against condensation when temperature is reduced or when slides are removed from cold storage. Kodachrome film should be conditioned at 70°F (21°C) and 25-30% relative humidity and then sealed in a moistureproof container if cold storage is used. Allow the temperature of cold slides to reach room temperature before opening a sealed storage container. Most photographers will find dye stability acceptable if the temperature is cool (but non-condensating) and relatively uniform, the location is dark, and relative humidity is maintained at 25-40%. Below 25% the emulsion may become dry and brittle (Eastman Kodak Company 1988). Many Glacier Bay images are stored in the humid environment of southeastern Alaska. Dyes are less stable at high relative humidities and, above 60%, the emulsion swells and may be more prone to colonization by fungi. The high temperatures of projection may help to control fungi (Eastman Kodak Company 1989, Sundt 1989). However, we recommend that slides be kept dry and fungus-free by controlling humidity, using a dehumidifier or air conditioner if necessary. If a desiccant must be used its condition and effectiveness should be monitored frequently; care is needed to guard against overdrying.

We recommend that you check your slides periodically for damage and change any aspects of the storage environment necessary to promote their safety and quality. If the implementation of a conservation program is not practical, at least take action to protect your most valuable Glacier Bay images. They may become of immense value to the appreciation and understanding of the Glacier Bay environment, but that value will be realized only if you act now to provide the protection they deserve.

Examples of Repeat Photography at Glacier Bay

The plates (Figs. 1 - 3) use repeat photography to illustrate landscape dynamics at several locations in Glacier Bay National Park. The two sequences in Fig. 1 are from a study area established in 1916 by Cooper (1923) and restudied by him in 1921, 1929, and 1935. Since 1941 this area has been restudied by Lawrence and his colleagues on many occasions. This is one of several important sites at Glacier Bay that provide the longest documented record in the world of vegetational change on terrain of known age following glacial recession (Lawrence 1979, White 1985). These sequences demonstrate how instructive repeat photography can be when carefully executed. Our hope is that this tradition of repeat photography will be continued by all who cherish and seek to understand the natural history of Glacier Bay.

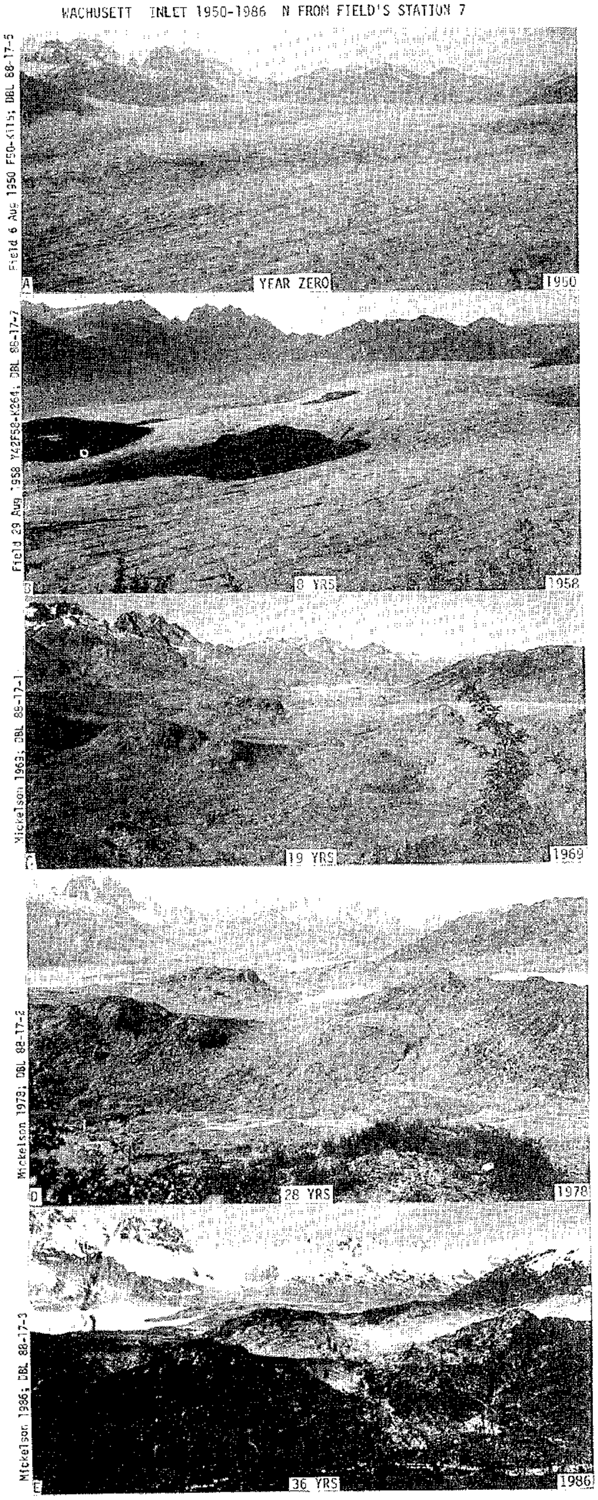

Fig. 2. Thirty-six years of landscape change in the Wachusett Inlet area During this period nunataks appeared in Burroughs Glacier, a new landscape was revealed as ice melted, and plants colonized the area ·The view is north from W O Field's Station 7

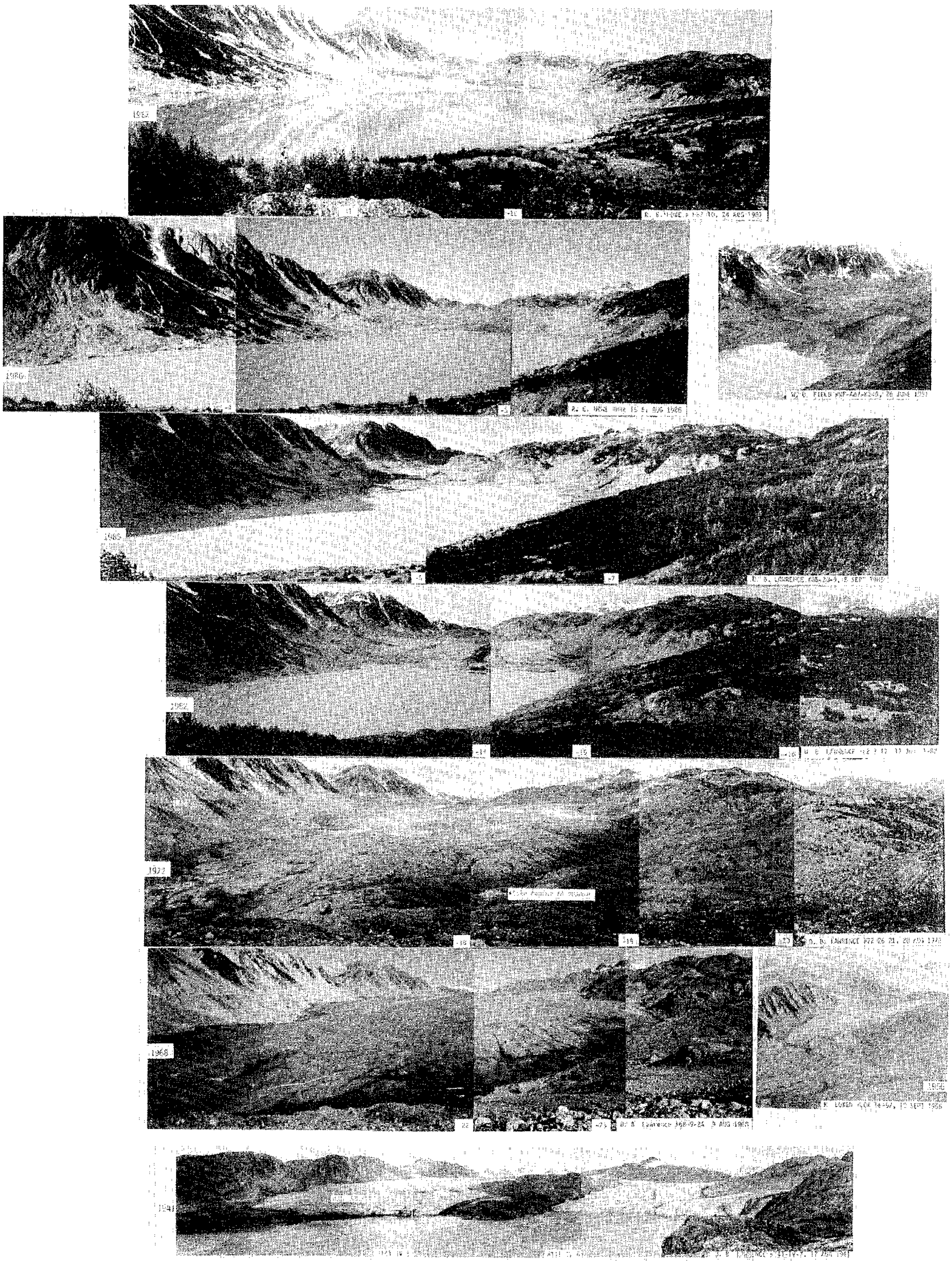

Fig. 3. Forty-six years of landscape change as the melting remnant of the Muir Glacier, north of Minnesota Ridge, was replaced by Lake Lawrence (provisional name). The bottom panorama, taken in 1941 from Nunatak Knob, shows the remnant area on the left, Muir Glacier in the middle, and McBride Glacier entering from the right. The area is shown in aerial photographs taken in 1956 and 1987 (single photographs to the right of the 1968 and 1986 panoramas, respectively). The panoramas from 1985 onwards were taken from a slightly different location because the original photo station was overgrown by the developing vegetation The new lake is first evident in the 1972 panorama

Acknowledgments

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Mechanisms of Primary Succession at Glacier Bay: Implications for Present and Future Vegetation Patterns

by

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Abstract

In primary succession following deglaciation at Glacier Bay, Alaska, we tested the hypothesis that the major effect of initial nitrogen-fixing colonizers is to facilitate establishment of late-successional dominants and that other possible causes of successional change (e.g., life-history factors governing seed rain and competitive interactions among species) need not be invoked. Early successional species (fireweed and *Dryas*) had smaller seeds, younger age at first reproduction, shorter lifespan, and shorter height at maturity than did mid-successional (alder) and late-successional species (spruce). Alder and spruce seed rain was negligible in the pioneer stage and increased through succession except for a decline in alder seed rain in the late-successional spruce forest. Vegetation in each successional stage inhibited germination and initial establishment of sown spruce seeds. Growth and nitrogen accumulation of naturally occurring and transplanted spruce seedlings was most rapid in the *Dryas* and alder stages and slowest in the spruce stage. In general, both at Glacier Bay and elsewhere, life-history traits determine the pattern of succession. Changes in competitive balance accompanying successional changes in environment provide the mechanism for changes in species dominance. Initial site conditions and species interactions (including facilitation, where present) influence the rate of change and final state of community composition and productivity. Because of the changing importance of these multiple processes, pathways of succession have changed and will continue to change as the glacier retreats further from seed sources of spruce.

KEY WORDS. Competition, facilitation, germination, growth, Glacier Bay, succession.

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Based on the classical works of Cooper (1923), Crocker and Major (1955), and Lawrence et al. (1967), Glacier Bay is generally recognized as the best documented example of terrestrial primary succession following deglaciation. This research has become the basis of the general conceptual model for mechanisms of primary succession in terrestrial ecosystems (Connell and Slatyer 1977). This work demonstrated that recently deglaciated soils at Glacier Bay are extremely low in available nitrogen (Crocker and Major 1955), and that, following invasion by the nitrogen-fixing alder, poplar and spruce grow more rapidly, and nitrogen becomes less limiting to plant growth (Lawrence 1951). Based on these observations at Glacier Bay and similar observations elsewhere (Matthews 1992), it has been widely recognized that many early successional plants facilitate the invasion of the forest trees that eventually dominate later stages of post-glacial primary succession. In this article we summarize a series of observations and field experiments (Chapin et al. 1994) which show that facilitation is only one factor involved in primary succession at Glacier Bay and discuss the implications of these observations for past, present, and future patterns of succession at Glacier Bay.

Study Site

Glacier Bay in southeastern Alaska (59°N, 136°W) is a Y-shaped fjord over 100 km long, whose lowlands were covered by glacial ice until about 230 yr ago (Cooper 1923). The subsequent rapid glacial retreat, averaging 0.4 km/yr (Goldthwait 1966) exposed extensive areas of glacial till to plant colonization. Four major successional stages are commonly recognized in this 230-yr sequence: a pioneer community with a "black crust" of blue-green algae, a *Dryas* stage with a more or less continuous mat of *Dryas drummondii*, scattered willows (*Salix* spp.), alder (*Alnus sinuata*), and poplar (*Populus trichocarpa*), an alder stage with dense thickets of alder, and a spruce stage dominated by *Picea sitchensis* (e.g., Cooper 1923, Reiners et al. 1971).

With the help of the National Park Service, we located four areas, each about 2 km^2, of each successional stage. In these sites we collected seeds of alder and spruce to measure seed mass, documented age of first reproduction, measured seed rain, sowed seeds to determine patterns of seed germination and initial seedling survival, and transplanted seedlings of alder and spruce to determine the impact of each successional stage on seedling growth and nitrogen accumulation, as described by Chapin et al. (1994).

Results

The seeds of early successional species (*Epilobium*, *Dryas*) were lighter than those of mid-successional alder, while the late-successional spruce had the heaviest seeds (Table 1), suggesting that ease of dispersal contributes to the successional pattern at Glacier Bay. Moreover, seeds of many early and mid-successional species (e.g., *Epilobium*, *Dryas*, *Salix*, *Populus*) have hairy appendages that aid dispersal. Early successional colonists (e.g., *Dryas*, *Epilobium*) differed from mid- and late-successional species in having a younger age at first reproduction, shorter lifespan, and shorter maximum height. Given this pattern of life-history traits, succession could only proceed from pioneer to *Dryas* to alder to spruce. Thus, life-history traits determine the pattern of succession at Glacier Bay.

As expected, seed rain by each species was most abundant in the stage in which it dominated and less common in the preceding stage (shown for spruce in Fig. 1). Only a few seeds were encountered two stages prior to the stage at which a species dominated. Thus, only alder seeds reached seed traps in the pioneer stage (Chapin et al. 1994).

Sown spruce seeds had highest germination in the pioneer and spruce stages, but only in the pioneer stage was there significant survivorship of these germinants (Fig. 1). Removal of surface litter and organic layers enhanced (or tended to enhance) survivorship in all except the pioneer stage, where removal of the black crust reduced survivorship by 41%. Those spruce germinants that survived achieved greater mass in the pioneer or *Dryas* stages than in stages with a closed canopy. These results indicate that each stage inhibited initial seedling establishment of spruce relative to the pioneer stage, in part due to the presence of overlying litter and organic horizons. By contrast, the thin algal crust of the pioneer stage tended to inhibit germination but facilitate survivorship of spruce.

Spruce seedlings transplanted into each successional stage and left for three years before harvesting were facilitated by the *Dryas* and alder stages and inhibited by the spruce stage relative to seedlings grown in the preceding stage. This pattern was generally shown for total seedling mass, above-ground production, and total height growth (Fig. 2) and is similar to the pattern observed with naturally occurring seedlings (Chapin et al. 1994). Spruce seedlings grew most rapidly and achieved largest biomass in the alder stage. There was negligible mortality of spruce seedlings over the 3-yr study in any successional stage. Spruce seedlings in the alder stage approximately doubled their total N pool during the 3-yr experiment, whereas seedlings in the pioneer and spruce stages lost N, due to some combination of leaching, tissue turnover, and incomplete recovery of fine roots.

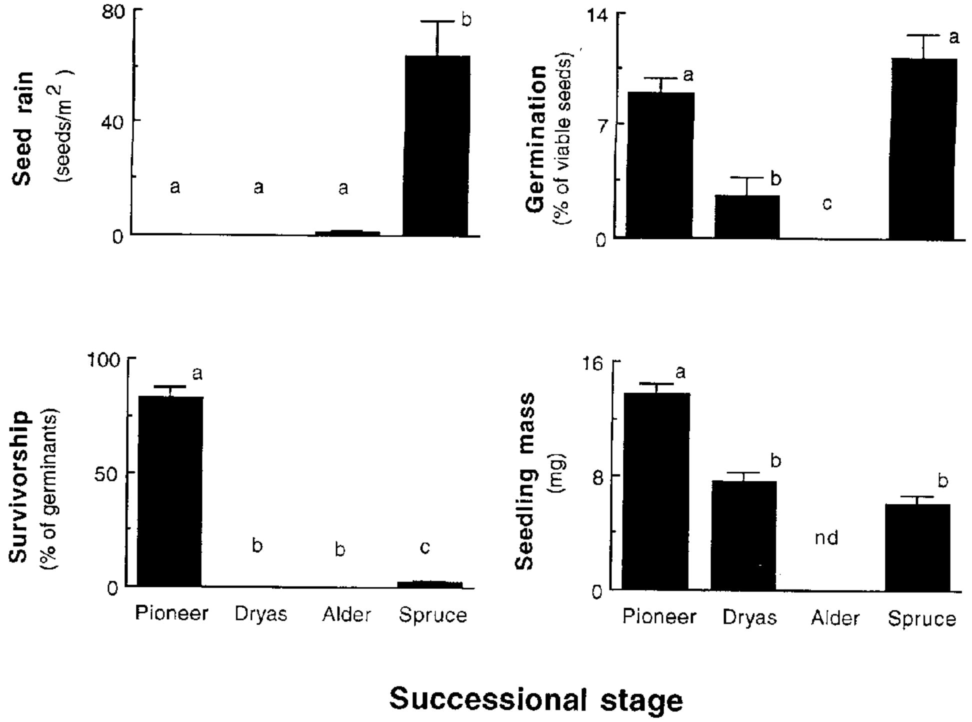

Fig. 1. Naturally occurring seed rain and the germination, survivorship, and seedling mass two years after sowing spruce seeds into each successional stage. Means with the same letter are not significantly different ($p<0.05$). From Chapin et al. (1994).

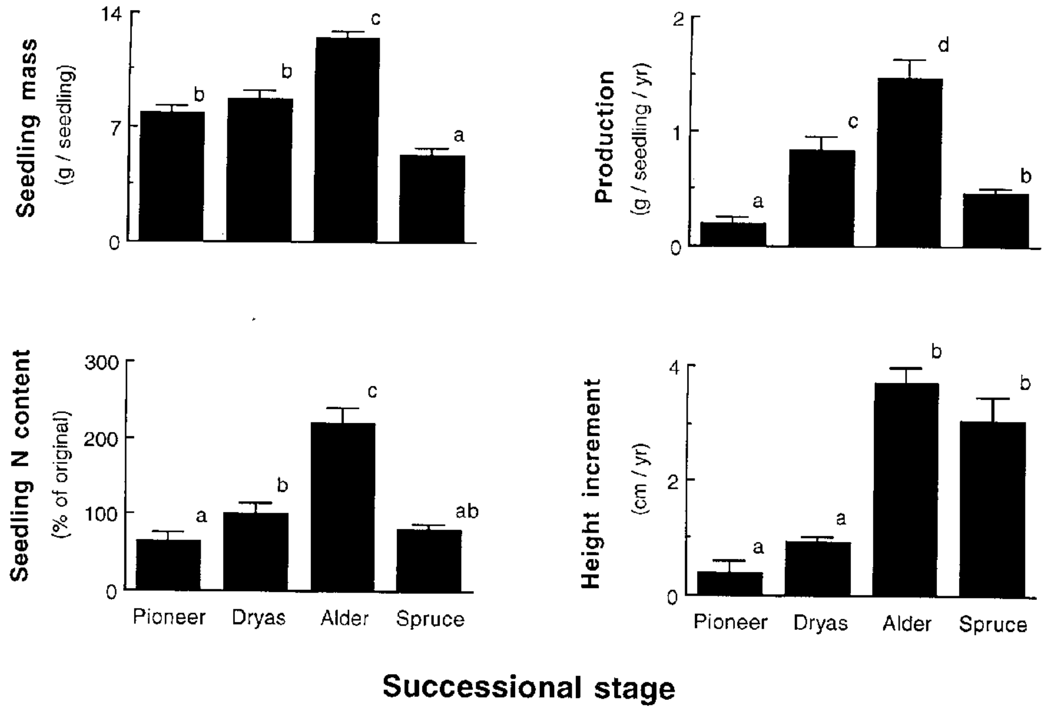

Fig. 2. Biomass, aboveground production, annual height increment, and nitrogen content of spruce seedlings transplanted into each successional stage and harvested after 3 yr. Means with the same letter are not significantly different ($p<0.05$). From Chapin et al. (1994).

Table 1. Life-history traits of plants that dominate different successional stages. Modified from Chapin et al. (1994).

Species	Successional stage	Seed mass (μg/seed)	Maximum height (m)	Age at first reproduction (yr)	Maximum longevity (yr)
Epilobium	*Pioneer*	72	0.3	1-2	20
Dryas	*Dryas*	97	0.1	6-8	50
Alnus	*Alder*	494	4	8.1	100
Picea	*Spruce*	2694	40	30-50	700

Discussion

Our study demonstrates that facilitation is only one of several important mechanisms causing successional change at this site. Plant life-history traits associated with dispersal ability are critical to early successional dynamics at Glacier Bay, where 100 km of linear glacial retreat during the past two centuries resulted in newly exposed terrain becoming progressively remote from seed sources in mature communities. Both long-distance seed dispersal and short generation time are prerequisites for plants reaching early successional communities, including our pioneer and *Dryas* stages.

Succession from *Dryas* to the alder stage involves competitive displacement as tall shrubs shade out shorter plants (*Dryas, Epilobium,* etc.). Similarly, because the height at maturity of spruce is greater than that of alder, spruce eventually out-competes alder. In both cases, final size and longevity are major factors causing successional change.

The basic pattern of succession to taller plants occurs despite the strong net inhibitory effect (nearly 100%) of *Dryas* and alder on initial establishment of their successors (alder and spruce, respectively). Thus, if mid- and late-successional species do not disperse to new sites before initial colonizers modify the microenvironment for seedling establishment, invasion will be slowed or prevented by initial vegetation (Egler 1954). For those spruce seedlings that established prior to arrival of the dense alder thicket, the net effect of the alder stage is facilitative, despite competitive impact on spruce through preemption of light and soil resources. Thus, life-history traits, competitive inhibition, and facilitation are all essential in explaining successional change at Glacier Bay, as concluded in other post-glacial successional seres (Burrows 1990, Matthews 1992). We conclude that, in general, life-history traits and availability of propagules determine the pattern of succession, changes in competitive balance that accompany successional changes in environment provide the mechanism for changes in species dominance, and initial site conditions and species interactions influence the rate of change and final state of community composition and productivity.

These observations and experiments have implications for past, present, and future patterns of succession at Glacier Bay. The results suggest that alder inhibits initial establishment but promotes growth of established spruce seedlings. Glacial retreat has been so rapid at Glacier Bay that recently deglaciated terrain has become progressively more remote from late-successional spruce forests. Following initial retreat, the terminal moraine was within a few kilometers of mature spruce forest, which provided sufficient seed rain that a spruce forest established directly without a pronounced alder stage (Fastie 1995). Forests above the glacial trim line continued to provide a ready seed source as far north as York Creek. From Sandy Cove to Muir Point, spruce seed sources were more distant, and the earlier age of first reproduction and more rapid dispersal of alder than spruce enabled alders to colonize before spruce and form thickets. There were enough spruce seeds, however, that spruce seedlings were apparently able to establish at the same time as alder at these sites. The rapid growth of alder on these pioneer soils enabled alder to form dense thickets which facilitated the growth of established spruce seedlings. These spruce eventually emerged above the alder canopy to form a rapidly growing spruce forest of low to moderate density. North of Muir Point, poplars appear to be a more important component of the post-alder forests, and spruce are less dense, probably reflecting the more rapid dispersal of poplar than of spruce. In these stands the initial seed rain of spruce was probably low, and the organic accumulation in the alder stage inhibited subsequent spruce establishment.

In sites that are currently in the pioneer stage there are abundant poplar seedlings, very few spruce, and gradually invading alders. Because of the strong inhibitory effect of alder on initial germination and establishment of spruce seedlings, we predict that spruce trees will initially be very sparse in stands developing near the present terminus of

Muir Glacier. We expect that this site will become an alder thicket, as has occurred on sites further south, but that this will be replaced by a dense poplar forest which initially contains few spruce. Because spruce establishment is strongly inhibited by the presence of an organic mat, spruce invasion at these sites may be quite slow. Small streams, landslides, animal activity and other disturbances to the alder thicket may be essential for spruce establishment. Thus, we expect that new sites at Glacier Bay will continue to pursue distinct successional pathways, as has occurred in the past, and that an understanding of life-history traits and competitive and facilitative interactions will all be important in interpreting and predicting future patterns of succession.

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Calibration of a Forest Gap Model for Glacier Bay: Exploring Multiple Successional Pathways

by

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Abstract

The forest chronosequence at Glacier Bay, originally assumed to represent a single successional pathway, is presently thought to be a patchwork of several successional pathways. We used an individual-based forest simulator (i.e., gap model) to investigate possible historic scenarios based on the initial floristic composition (IFC) and the relay floristic (RF) hypotheses to reproduce successional patterns along the chronosequence. The model was calibrated primarily by altering the time of species establishment and soil productivity to match species size-class distributions for three sites: an ≈80 yr alder/willow/cottonwood thicket, a ≈220 yr spruce/hemlock stand, and a >500 yr hemlock/spruce stand. The modeled growth increments of Sitka spruce from the RF and IFC scenarios were different and corresponded to tree core data from upper and lower bay sites respectively. When run with two slightly modified RF and one IFC scenario, the model was able to reproduce the measured species' biomass along a 210 yr portion of the chronosequence, further corroborating the presence of distinct pathways. Lastly, the model was used to forecast forest dynamics as a consequence of the spruce bark beetle infestation that had occurred over the last decade. The simulations predicted that the forests of the lower bay are resilient to ≤20% spruce mortality However, areas of ≥40 % spruce mortality exhibited the release of western hemlock from the understory and a premature transition from a spruce- to a hemlock-dominated stand, thereby further confounding future analyses which substitute space-for-time.

KEY WORDS: Bark beetle, chronosequence, initial floristic composition, gap model, relay floristic, successional pathways.

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Demonstrated by the continual debate throughout this century (McIntosh 1985), plant succession cannot be explained by a single process or a suite of the same processes for every vegetated system. Even from what is probably the best documented example of primary succession, Glacier Bay, Alaska, the importance of processes which contribute to vegetation dynamics is subject to debate. The traditional perception of primary succession at Glacier Bay as following a single pathway at all sites has provided the impetus for numerous chronosequence studies. However, because vegetation on surfaces of different age may result from different historical pathways, these space-for-time substitution studies may yield misleading inferences (Fastie 1990). For example, though nitrogen-fixing alder is generally believed to precede (and possibly facilitate as well as compete with) spruce during forest succession at Glacier Bay, spruce has replaced willow thickets without the presence of an alder stage in patches along the west arm of the bay (Cooper 1931). Moreover, along the east arm of the bay, early growth rates of Sitka spruce from more recently deglaciated surfaces do not match those on older surfaces (Fastie 1990) suggesting different environmental controls for similar aged stages. To further complicate future chronosequence analyses, recent patchily distributed bark beetle disturbance has produced up to 80% spruce mortality (Eglitis 1988) in portions of the lower bay. Thus, multiple pathways, not adhering to the classic single pathway view of primary succession, continue to develop within the park boundaries.

From experimental studies at Glacier Bay (Chapin et al. 1994), it appears that life history strategies (e.g., species invasion, establishment, growth, and longevity) largely determine the successional sequence and endpoint of these systems (Walker and Chapin 1987). However, facilitative or competitive interactions among species may regulate the rate of change or degree to which certain life history traits contribute to successional dynamics. Simulation models can be used to predict outcomes of succession based on life history traits (Huston and Smith 1987, Walker and Chapin 1987) and to explore successional pathways resulting from stochastic events (e.g., seed arrival, disturbance) and/or biological interactions (e.g., competition for light).

One type of vegetation simulation model termed "gap model" (Huston and Smith 1987) is widely used to study forest succession and to predict an ecosystem's response to altered environmental conditions. These models combine species-specific features which relate to the birth, growth, and death of individual trees and site-specific parameters such as the availability of light, water, and nutrients or the presence of natural or anthropogenic disturbance to follow changes in biomass, species diversity, habitat attributes, etc. over time. The objectives of this paper were to parameterize and calibrate a gap model to simulate possible past successional pathways which may have produced the present patterns observed along the chronosequence and to predict possible future pathways at Glacier Bay resulting from recent bark beetle disturbance.

Methods

We chose the generic gap model ZELIG (Urban 1990) running in the individual plot mode (10 x 10 m) to simulate successional pathways at Glacier Bay. This model was developed to serve as an easily implemented framework for cross-site comparisons of forested ecosystems. Its modular structure allows for simple ad hoc modifications for model experiments such as those performed here.

Species and Site Parameters

Three tree species: Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), black cottonwood (*Populus trichocarpa*), and three shrub species: Sitka alder (*Alnus sinuata*), Sitka willow (*Salix sitchensis*)and feltleaf willow (*S. alaxensis*) are common along the Glacier Bay chronosequence. For the model, the willow parameters reflect intermediate values available for the two species. The necessary parameters (e.g., maximum age, dbh, and height) for spruce, hemlock, and cottonwood and some of the parameters for alder and willow were obtained from previous modeling efforts (Dale et al. 1986, Burton and Cumming 1991, Urban et al. 1993) and other publications. There are, however, discrepancies among these sources due to the different methodologies and location biases used to estimate parameters (Weishampel 1994).

To derive parameters unavailable for the non-commercial species, we followed prior systematic procedures where possible. For example, minimum and maximum degree-days (5.56° C base) to gauge species growth using a parabolic response to thermal effects, were educed from the northern and southern boundaries of the largest contiguous species range found in silvics manuals. As the allometric relationships between biomass and diameter at breast height (dbh) of Sitka alder and willow were assumed to be similar in Bormann and Sidle (1990), so were several of their parameters. Shade and drought tolerance of Sitka alder and willow, like red alder (Burton and Cumming 1990, Urban et al. 1993) were low, but not to the extent of cottonwood. But, as a nitrogen fixer, Sitka alder, unlike red alder (also a nitrogen fixer) in Burton and Cumming (1991), was assigned a higher tolerance for nutrient stress. Given measured data from a 2.64 ha ≈80 yr stand, the site and species parameters for alder and willow, the growth parameters were estimated using two iterative estimation programs (GEST and CONTEXT from Urban 1990).

To execute the model, climate (i.e., insolation, precipitation, and temperature) and soil parameters (i.e., field capacity, wilting point, and fertility) are required. Monthly weather data were obtained from Bartlett Cove records from 1960 to 1991. Thus, microclimatic differences present for younger sites in the upper bay were not accounted for by the model. Because Glacier Bay's latitude exceeded the potential evapo-transpiration correction terms used by ZELIG's Thornthwaite-Mather methodology, a Priestley-Taylor approximation of the Penman-Monteith equation was substituted. Radiation parameters were calculated using the SOLAR program from Urban (1990) using monthly cloudiness values for Juneau, Alaska.

The sandy loam to loamy sand soils of Glacier Bay exist in various stages of development (Bormann and Sidle 1990). As the forest floor depth increases with time, the bulk density decreases producing changes in field capacity and wilting point depths. However, given the precipitation and thermal regimes from Bartlett Cove, the water balance model used in ZELIG was insensitive to a range of soil properties as moisture deficits were nonexistent. Values of 15.0 cm of water held at field capacity and 5.0 cm of water held at wilting point representing a loamy sand soil in British Columbia (Burton and Cumming 1991) were used. The soil fertility parameter reflects the maximum annual productivity in above-ground woody biomass ($Mg \cdot ha^{-1} \cdot yr^{-1}$). Bormann and Sidle (1990) found the maximum annual net productivity of young (≈110 yr) spruce stands at Glacier Bay to be 8.0 $Mg \cdot ha^{-1} \cdot yr^{-1}$. Discounting leaf production, 7.0 $Mg \cdot ha^{-1} \cdot yr^{-1}$ was used as a guideline. The fertility parameter was assumed to be constant for the duration of each simulation. Thus, a prolonged presence or absence of nitrogen-fixing alder neither enhanced nor restricted above-ground productivity. Without this feedback, model extrapolations beyond a certain time period do not accurately depict the soil resources.

Simulating Successional Pathways

Because it is believed that sites north and south of Sandy Cove followed different pathways (Fastie 1990), two scenarios were modeled. They were broadly based on the initial floristic composition (IFC) hypothesis, where all species establish simultaneously (Egler 1954), and the relay floristic (RF) hypothesis, where certain species are delayed possibly representing differences in seed dispersal and arrival time or the necessity of previously established species to prepare (i.e., facilitation) or leave (i.e., inhibition) the environment. The IFC scenario was calibrated by altering the soil fertility index to match size-class distribution data for two chronosequence locations: ≈220 yr Bartlett Cove and >500 yr Pleasant Island sites. The RF model scenario was calibrated by altering the soil fertility index and species arrival times to match data collected from ≈80 yr sites north of Muir Point along Adams Inlet (Weishampel 1994). Soil fertility parameters were selected to reflect the presence and duration of an alder dominated community. Once calibrated, simulation results were compared with tree core data (Fastie 1990) to assess the ability to mimic spruce growth rates found at a ≈100 yr Muir Point stand and a ≈210 yr Bartlett Lake stand thought to represent the RF and IFC hypotheses, respectively.

In an attempt to reproduce biomass contributions of the major species found by Bormann and Sidle (1990) at four chronosequence sites, two different species invasion scenarios and an IFC scenario for two time periods were simulated. To a certain extent, we followed the logic that heavier spruce and hemlock seeds would not disperse as readily as lighter plumed alder, willow, and cottonwood seeds. Thus, the further up bay the colonizable surface, the more time required for the heavier seeds to arrive. Also, we assumed soil fertility along the chronosequence to exhibit a sigmoidal increase with the establishment and maintenance of an alder-dominated community, followed by a gradual decrease reflecting resource utilization after the demise of the alder-dominated community due to interspecific competition. For the 64 yr site, primarily an alder thicket, the arrival of willow and cottonwood was delayed 10 yrs, spruce 40 yrs, hemlock 150 yrs, and the soil fertility factor was reduced to 4.0 $Mg \cdot ha^{-1} yr^{-1}$ to represent an earlier successional stage with reduced nitrogen. For the ≈110 yr site, dominated by spruce with remnants of an alder thicket, the arrival of spruce was delayed 15 yrs and hemlock 150 yrs, and the soil fertility factor was raised to 10.0 $Mg \cdot ha^{-1} \cdot yr^{-1}$ to represent a more fertile mid-successional stage. The IFC scenario was used to reproduce the ≈160 and the ≈210 yr sites with a soil fertility factor of 7.0 $Mg \cdot ha^{-1} \cdot yr^{-1}$ not having the full benefit of a alder-dominated community. Above-ground dry biomass estimates were from Bormann and Sidle (1990) and Yarie and Mead (1992). Conversions from wet to dry weight for cottonwood and spruce used the percent moisture contents from aspen and true firs, respectively (Yarie and Mead 1982).

Simulating Effects of Bark Beetle Disturbance

An ongoing use of gap models is to predict the frequency and intensity effects of disturbance on the successional trajectories of species. Using parameters from the IFC scenario that were used to reproduce the forest composition of the lower bay (i.e., a ≈220 yr spruce/hemlock stand), we explored the ramifications of recent bark beetle

(*Dendroctonus rufipennis*) infestation on the predicted successional sequence. In addition to the normal ambient and stress-related mortality, at simulation year 220, the forest was subject to 20, 40, 60, or 80% spruce mortality representing the range of infestation observed by Eglitis (1988) that had occurred within a 10 yr period. Of the nearly 6000 ha infested at Glacier Bay, 24% had <20% spruce mortality, 31% had 20-40% mortality, 24% had 40-60% mortality, and 21% had ≥60% mortality. The modeled mortality, like the measured mortality, was evenly distributed among dbh size-classes. The effects of these regimes on spruce recovery and the timing of hemlock dominance were predicted. More realistic simulations might sustain lower mortality rates over a several year period and have the probability of tree infestation correspond to physiological stress levels.

Results and Discussion

Model Calibration and Verification

To match the RF scenario to the dbh size-class data collected along Adams Inlet representing an ≈80 yr stand (Fig. 1a), it was necessary to delay the establishment of spruce, considered an early- to mid-seral species, 40 yrs, and hemlock, considered a mid- to late-seral species, >80 yrs. Fertility was increased to 10.0 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ to represent a soil that supported an alder-dominated community. This configuration produced a dense understory comprised primarily of 5-10 cm dbh alder and willow overtopped by scattered 5-20 cm dbh cottonwoods. Spruce was scarce at ≈80 yrs. And as shown by the model, it is doubtful that it will play as prominent role 20 yrs later as found in ≈100 yr sites just south of Adams Inlet. However, the model overestimated the alder 5-10 cm dbh size-class and underestimated the alder and cottonwood <5 cm classes. Although alder and willow generally are multi-stemmed (mean stems per alder was 2.9; willow averaged 1.3 stems), the model grew single-stemmed trees. For comparative purposes, multi-stemmed clusters were compressed into a single stem while maintaining the basal area (i.e., overall $\text{dbh} = [\sum_{i=1}^{n} \text{dbh}_i] / \sqrt{n}$, where n is the stem number and dbh_i is an individual stem's dbh following Burton [pers. comm.]). To calibrate the IFC scenario to the dbh size-class data collected at Bartlett Cove representing a stand of ≈220 yrs (Fig. 1b), the soil fertility factor was decreased to 4.0 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ to reflect the inhibition of an alder-dominated community by the simultaneous recruitment of spruce. At 220 yrs, the canopy was dominated by spruce with an understory of hemlock. The modeled spruce dbh size-class peaked at 50-60 cm, whereas the measured dbh size-class peaked at 30-40 cm. Thus, the basal area for the modeled spruce was higher and the stem density was lower than the measured data. To a certain extent, this discrepancy also existed with hemlock as the modeled dbh size-class peaked at 20-30 cm, whereas the measured dbh size-class peaked at 10-20 cm. Alder also existed in greater numbers in the understory than found in the simulation. But the general trends of stem density and basal area among species were consistent.

Extending this IFC scenario to the >500 yr stands at Pleasant Island produced consistent results for hemlock (Fig. 1c) as simulated (1000 yr) and measured data peaked at 10-20 cm. However, the stem density was higher and the basal area was lower for the measured data. The model incorrectly permitted spruce to have a prominent position in the understory. As a result, the stem density was substantially higher than the measured data, though the basal areas were comparable. This suggests that the model was not accounting for or was incorrectly simulating certain factors which would prevent spruce establishment after 500 yrs. The most obvious alterations would be to raise the shade intolerance factor for spruce following Dale et al. (1986) and Burton and Cumming (1991) or that the light reaching the floor from the primarily hemlock canopy should be diminished. But also, it must be considered that the Pleasant Island sites are estimated to be >500 yrs old (Reiners et al. 1971) and the simulated data represents a single year.

The species' basal area trajectories from the RF and IFC simulations presented results which differ from the traditional view of succession at Glacier Bay. When the establishment of spruce and hemlock was delayed (Fig. 2a), the basal area of the three pioneer species increased nearly ten-fold. Alder dominated during the first 200 yrs, after which the longer-lived cottonwood dominated the canopy, suppressing alder and willow. Requiring about 250 yrs to become established, spruce began near exponential growth with hemlock following it closely in the understory. At ≈800 yrs, the basal area of hemlock surpassed that of spruce. In the IFC scenario (Fig. 2b), spruce quickly gained prominence while hemlock maintained a stable presence in the understory. After 600 yrs, spruce was relegated to a secondary role as hemlock dominated the over- and understory. The three shorter-lived species, alder, willow and cottonwood, were outpaced and overtopped contributing a minor role in early succession. In both scenarios, alder persisted as a gap colonizer. The traditional view of succession at Glacier Bay would be more closely aligned with the RF scenario where alder played a dominant role after glacial retreat, but, spruce dominance would occur sooner at ≈100 yrs.

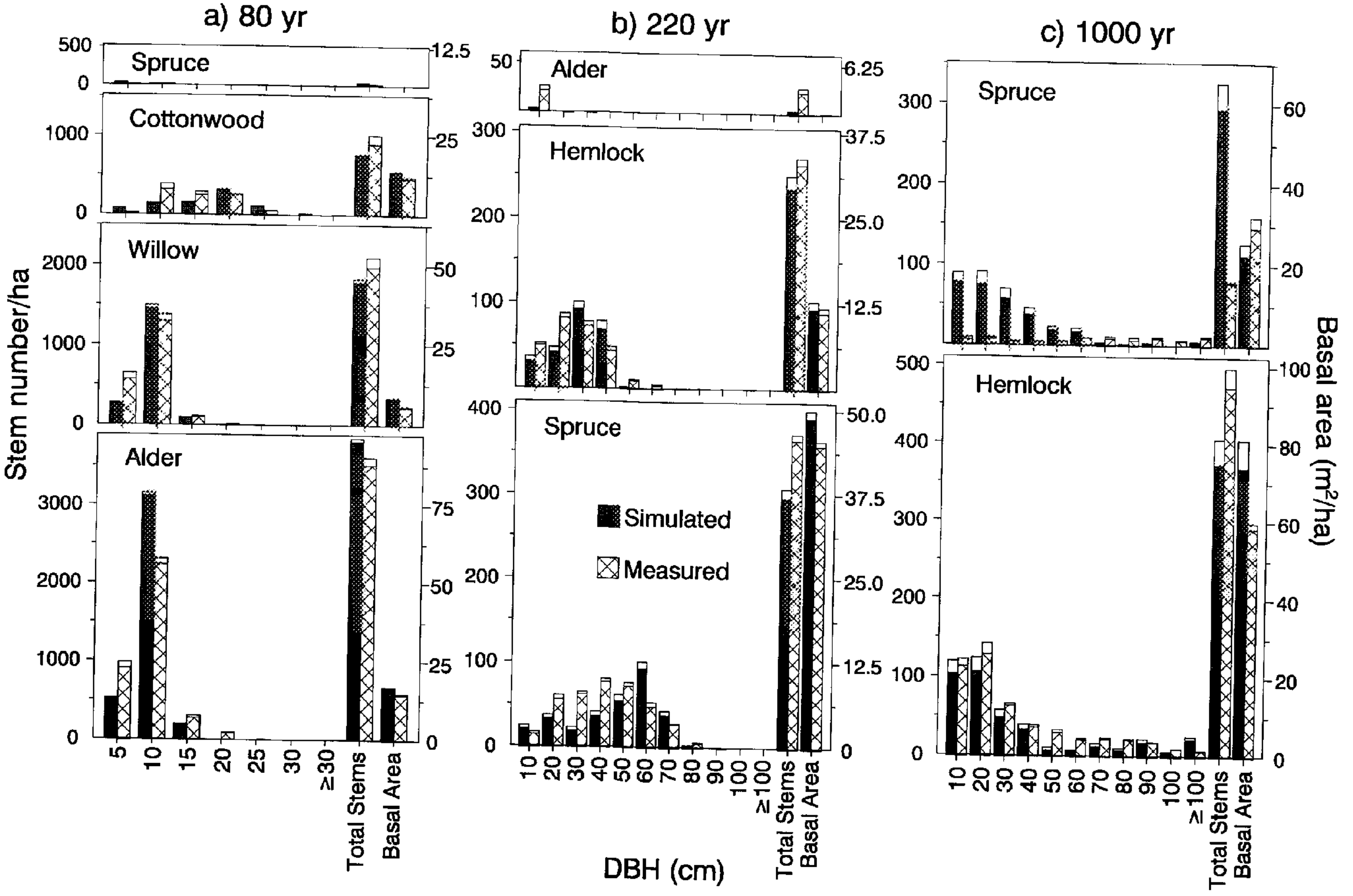

Fig. 1. Species' size-class distribution, density, and basal area from: a) a modeled 80 yr stand using a RF scenario and four measured ≈80 yr, 0.64 ha plots along Adams Inlet; b) a modeled 220 yr stand using an IFC scenario and four measured ≈220 yr, 1 ha plots at Bartlett Cove; and c) a modeled 1000 yr stand using the IFC scenario and four measured >500 yr, 1 ha plots at Pleasant Island. Extensions above the measured and simulated data represent ± standard error for four and 100 plots, respectively.

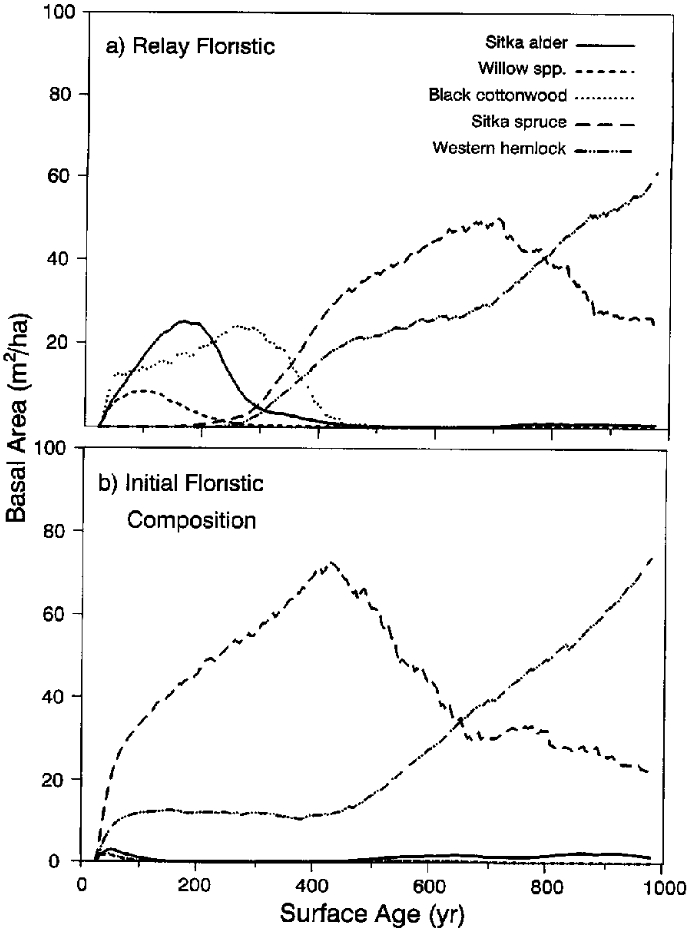

Fig. 2. Basal area trajectories of the five simulated species for the a) RF and b) IFC scenarios averaged over 100 plots.

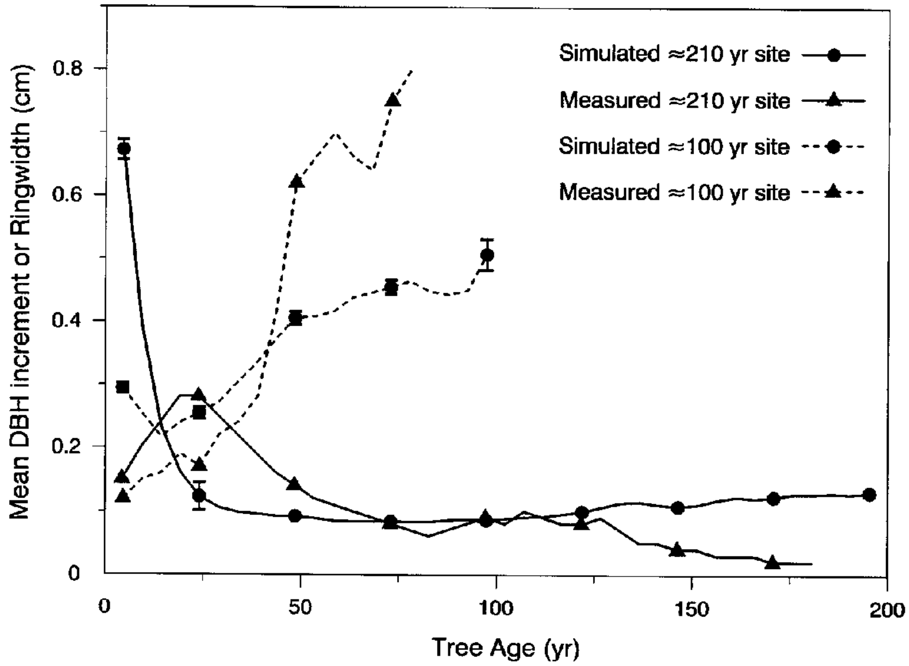

Fig. 3. A comparison of five-year mean diameter increments from the simulated RF (i.e.,≈100 yr site) and IFC (i.e., ≈210 site) scenarios to the measured ring widths (Fastie 1990). Error bars on the simulated data represent ± standard error for ≈100 simulated spruce trees.

Spruce Growth Patterns

The comparison of five-year means of the simulated diameter increment to the measured spruce ring widths from Fastie (1990) revealed some similarities (Fig. 3). Both the modeled and the measured growths depicted early suppression in the RF scenario (i.e., ≈100 yr sites) from a dense, primarily alder overstory. A subsequent release was exhibited at the ≈100 yr site after 25 yrs of growth, but not at the ≈210 yr site (i.e., IFC scenario) for both the modeled and measured data suggesting the existence of different successional pathways. If representing identical growth patterns, the simulated diameter increment should be twice the measured ring width which was not the case. Additionally, the first ten years of modeled growth from the ≈210 yr site was substantially greater than the measured growth, and the release from suppression was more pronounced with the measured growth than the modeled growth for the ≈100 yr sites. However, exact duplication of the measured ring widths was not expected as ZELIG plants trees with 2.5 cm dbh, thus early growth patterns should differ from measured data. Furthermore, the weather generator was based solely on ≈30 yr monthly precipitation and temperature means and standard deviations, and therefore, does not coincide with year-to-year climate variations. As found with the ringwidths at the upper bay site, the general pattern of suppression and release was consistent with the RF, but not the IFC scenario.

Biomass along the Chronosequence

The results of the three simulations used to reproduce the species contributions to the sigmoidal biomass increase along the east arm of Glacier Bay (Fig. 4) were dramatically different. This demonstrates that slight delays in species arrival and establishment and possibly slight fluctuations in soil fertility could lead to striking differences in successional development. In the first scenario (Fig. 4a), alder was given a foothold which allowed it to dominate the nutrient-poor environment. In the second scenario (Fig. 4b), representing a more fertile environment, the establishment of spruce was delayed 15 yrs. However, by 110 yrs, spruce dominated this pathway. The increase in soil fertility from 4.0 to 10.0 $Mg \cdot ha^{-1} yr^{-1}$ permitted the nearly exponential increase in biomass reaching >300 $tonnes \cdot ha^{-1}$ by 110 yr as noted by Bormann and Sidle (1990). But because the initial soil fertility values remained unrealistically constant throughout a simulation, it is unlikely that a nutrient-poor alder-dominated community (Fig. 4a) or a nutrient-rich spruce-dominated community (Fig. 4b) would persist. The IFC scenario, as found previously (Fig. 4c), yielded a spruce dominated forest with a secondary role for hemlock for a 220 yr period.

When snapshots of these scenarios were combined, a picture (Fig. 4d) emerged that was not much different from the Bormann and Sidle (1990) biomass curves (Fig. 4e). The simulated composite revealed a decrease in spruce biomass from 110 to 160 yrs (which was absent from the measured biomass), and the contributing role of willow and cottonwood after 60 yrs to the overall biomass was lower in the simulated version. But overall, the general appearance of the simulated composite biomass which showed younger stands dominated by alder and older stands dominated by spruce and the magnitude of the species biomass contributions were similar to the measured stands.

Bark Beetle Effects

Using the IFC scenario to reproduce the spruce/hemlock forest of the lower bay, the basal area of hemlock surpassed spruce at ≈700 yrs (Fig. 2b). Spruce basal area peaked at ≈400 yrs at nearly 80 $m^2 \cdot ha^{-1}$. The reduced vigor of spruce found in the modeled and measured trees (Fig. 3) makes them susceptible to bark beetle attacks (Eglitis 1988). When subject to 20% mortality at 220 yrs, the peak in spruce basal area at ≈400 yrs was not as pronounced as found with the control (Fig. 5a). There was a slight increase in the basal area of hemlock immediately after the simulated infestation, but spruce remained the dominant species until ≈700 yrs. Because mortality was evenly distributed among spruce size-classes, succession proceeded as expected, however, there was a slight release of hemlock as competition for light was reduced (Eglitis 1988). With 40-60% mortality (Fig. 5b and c), there was a significant increase in hemlock, the basal area peak of spruce was reduced to <60 $m^2 \cdot ha^{-1}$, and the basal area of hemlock overtook that of spruce ≈200 yrs earlier than the control. With 80% mortality (Fig. 5d), the basal area of the two species remained roughly equal for the next 300 yrs following the attack. The range of ecosystem responses: from resiliency at 20% mortality, to the acceleration of successional change at 40 and 60% mortality, to an immediate transition at 80% mortality, increases the patchiness of the successional landscape. Hence, future analyses of forest succession at Glacier Bay will need to consider the effects of this disturbance.

Conclusions

These heuristic exercises represent a first cut at applying the gap model approach to address "what if" questions regarding succession at Glacier Bay. By varying the timing of species establishment and soil fertility, the model was

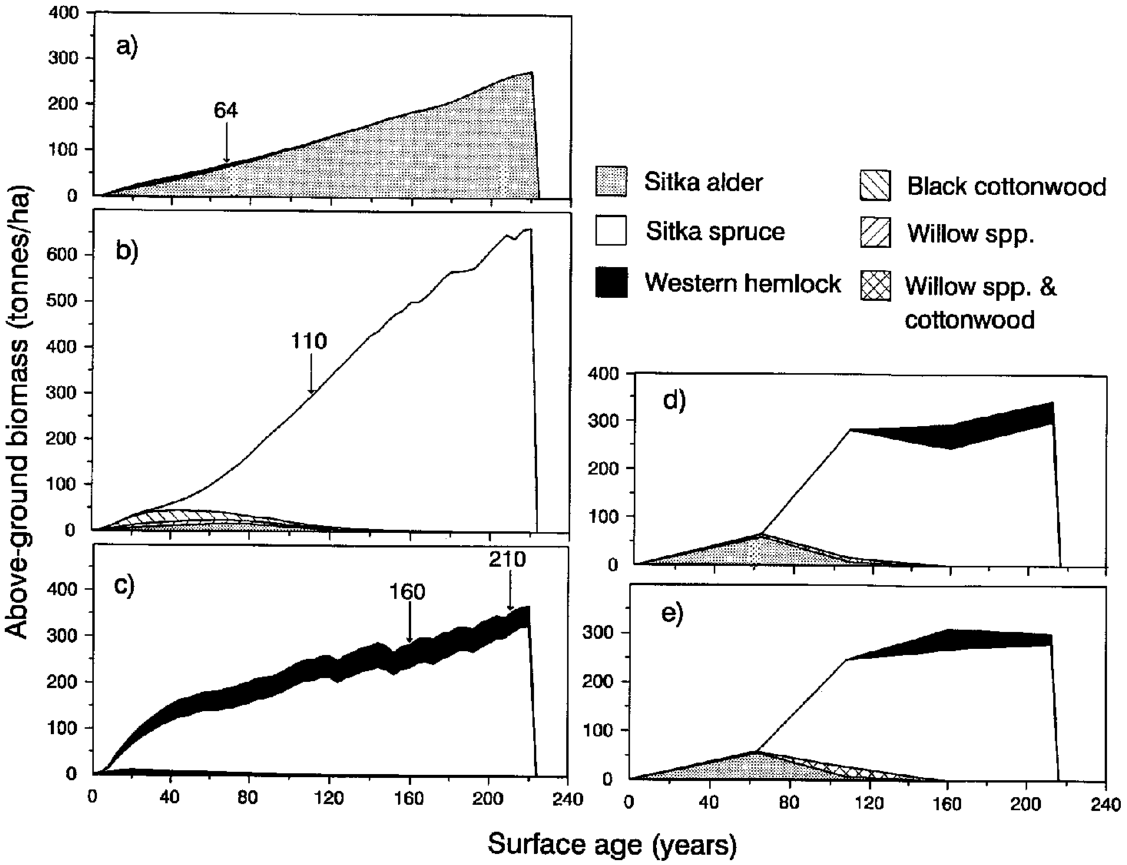

Fig. 4. The average species biomass contributions from 100 plots to three possible successional pathways derived by: a) delaying the establishment of willow and cottonwood 10 yrs, spruce 40 yrs, and hemlock 150 yrs with a soil fertility of 4.0 Mg ha^{-1} yr^{-1}; b) delaying the establishment of spruce 15 yrs and hemlock 150 yrs with a soil fertility of 10.0 Mg ha^{-1} yr^{-1}; and c) using an IFC scenario with a soil fertility of 7.0 Mg ha^{-1} yr^{-1}. d) Combined biomass contributions for the time periods designated by the arrows from the three scenarios and e) as observed by Bormann and Sidle (1990).

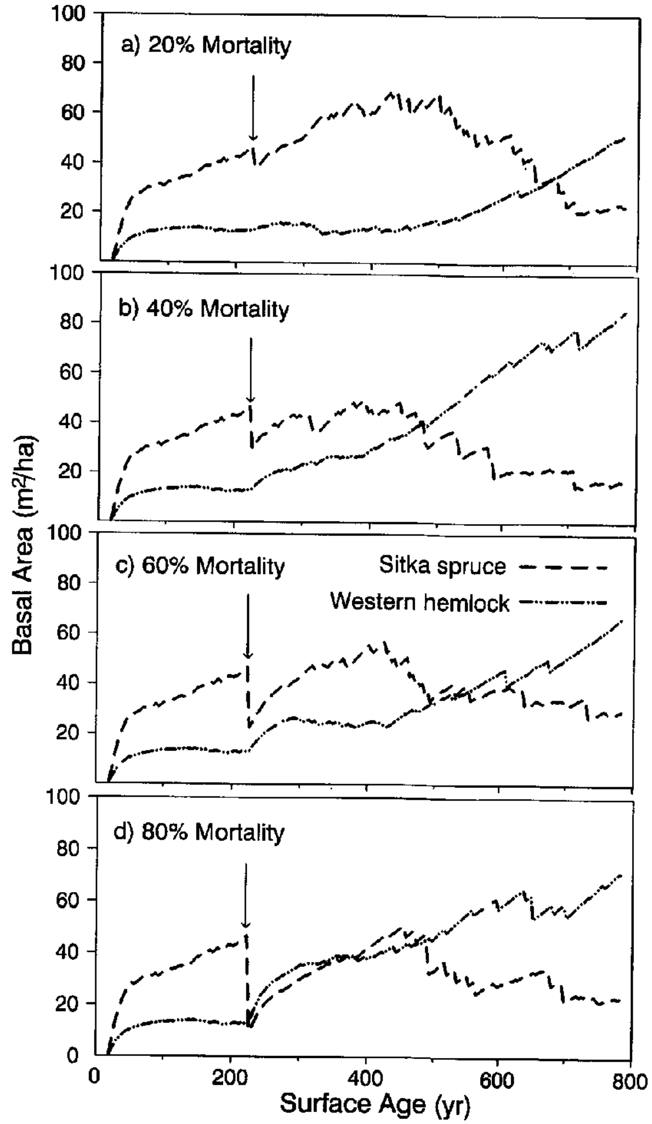

Fig. 5. Average basal area trajectories over 100 plots for the mid- and late-successional species, spruce and hemlock, when subject to different levels of spruce mortality. The arrow indicates year 220 when the simulated bark beetle disturbance occurred.

used to simulate RF and IFC successional pathways. Through minimal calibration, the RF and IFC scenarios generated species size-class distributions that were consistent with measured patterns from ≈80 and ≥220 yr sites. These scenarios also produced differences in spruce growth that were consistent with ring width increment data (Fastie 1990). With slight modification to these scenarios, the model duplicated Bormann and Sidle (1990) biomass curves. This illustrates how differences among life history attributes can yield diverse pathways (Walker and Chapin 1987, Huston and Smith 1987) and be misinterpreted as a single one. Additionally, the model demonstrated how differing intensity levels of beetle-induced mortality may produce new pathways. Thus, this portrayal agrees with Fastie (1990) and suggests that events of a stochastic nature (e.g., timing and location of colonization and disturbance) which prevent a simple chronosequence interpretation (i.e., space-for-time substitution along the transect of glacial retreat) arose in the past and continue to arise in the present at Glacier Bay.

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Evaluating the Consequences of Species Interactions During Primary Succession at Glacier Bay, Alaska

by

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Abstract

Conclusions about the importance of facilitation of Sitka spruce (*Picea sitchensis*) by Sitka alder (*Alnus sinuata*) during primary succession at Glacier Bay depend on how species interactions are defined and how their outcome is measured. The response of spruce at the level of the population is of primary interest, although individual plant response is often easier to measure and is assumed to be correlated with population response. Simultaneous facilitative and competitive effects of alder on spruce may be commonplace, but it is the net response of spruce that influences successional change. The response of spruce to alder changes with successional age and with spruce life-history stage, and therefore depends on the time interval over which the interaction is integrated. In Muir Inlet, the time-integrated response of spruce to alder may be negative for at least the first 50 years of the interaction until spruce emerges above an alder canopy and can fully exploit the improved soil fertility under alder. Measures of stand function (net productivity, nutrient accumulation) may be more appropriate indices of the long-term facilitative or competitive response of spruce than commonly used measures such as stand density, cover, or biomass. It is important to be explicit about the level of ecological organization, time frame, and operational definition of response when reporting conclusions about facilitative or competitive interactions during succession.

KEY WORDS: competition, facilitation, Glacier Bay, primary succession, Sitka alder, Sitka spruce.

Facilitation and Competition

Facilitation is a successional model in which early plants modify the environment and thereby allow the establishment or improve the success of later successional plants (Connell and Slatyer 1977). In the original version of this model, the modified environment, or competition from later plants, causes a decrease in success of the early plants. Some interpretations of the facilitation model emphasize the effect of early plants on the establishment of later plants (Connell and Slatyer 1977), although in most interpretations, improved growth of established plants indicates facilitation. The term facilitation has been used recently in a broader context to refer to any plant interaction (not necessarily in a successional context) in which one species improves the success of another (Fowler 1986, Walker and Chapin 1987, Goldberg and Barton 1992). Because these definitions are not interchangeable, it is important for any discussion of facilitation to carefully define the term. In this discussion, I use only the broader definition of facilitation as any beneficial effect of one plant (or plant population) on another.

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In ecological effect, facilitation and competition are opposites; plants can either provide a benefit to other plants (facilitation) or inhibit them (competition). Competitive interactions are thought to be important in most environments, but examples of facilitation are less common. This asymmetry is probably a result of natural selection against individuals that benefit others to their own disadvantage. Harsh environments, especially the environment in early primary succession where soil resources are limiting to plant growth, are the environments in which facilitation is expected to be most common (Connell and Slatyer 1977). Because of its presumed importance in these environments, and because of the context of the original facilitation model, facilitation has been associated primarily with succession, whereas competition has been a fundamental component of general ecological research and theory.

Population Versus Individual Response

Experimental methods for detecting the existence and identifying the mechanisms and consequences of competition are well developed (reviews in Connell 1983, Fowler 1986, Aarssen and Epp 1990, Goldberg and Barton 1992). The theoretical importance of plant competition is its potential to alter the abundance or dominance of plants, and thereby alter the structure and function of communities. The consequences of competition are generally studied at the level of the population, although the mechanisms of competition are often studied at the level of individuals. As with competition, the importance of facilitation is its potential to cause population-level changes. However, the response of populations cannot always be measured directly because field experiments continue for only a few years, and populations of long-lived plants often require years or decades to respond to species interactions. For example, more than a decade may be required to decrease the stand density or basal area of shrubs that are the target of competition (e.g., by shading) from taller trees. Consequently, the response of individual plants (e.g., growth rate, physiological condition, reproductive output) to species interactions is often measured instead of stand-level response. It is assumed that the measured short-term response of individuals will be manifested eventually in a population response of the same direction (Goldberg and Barton 1992). A population response of plants can be a change in stand density or population growth rate, but can also involve changes in the species' contribution to cover, basal area, biomass, or productivity.

The Net, Time-integrated Response of Spruce at Glacier Bay

Although a plant can have simultaneous positive and negative effects on its neighbors, it is the net effect of plant interactions that causes population change (Connell et al. 1987, Walker and Chapin 1987). Field experiments at Glacier Bay have identified some of the positive and negative components of the interaction between the most important successional species. The improved soil fertility under thickets of Sitka alder (*Alnus sinuata* [Reg.] Rydb.) can facilitate the growth of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) seedlings, but the alder shrubs compete with spruce seedlings for light and soil resources. The net response of young spruce seedlings appears to be positive compared to seedlings growing without any of the impacts of alder thickets (Chapin et al. 1994). During the many decades that a spruce tree may grow in an alder thicket, the net effect of alder may alternate between negative and positive (Fig. 1). For example, the duff and leaf litter under alder thickets, and possibly seed and seedling predators inhabiting the thicket, strongly inhibit the germination of spruce seeds and establishment of seedlings (Chapin et al. 1994). After seedlings are established, they are facilitated by the increased soil fertility under alder. During the

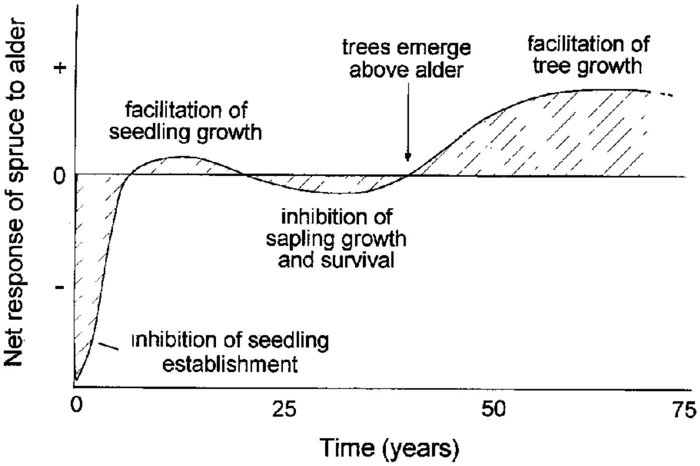

Fig. 1. Generalized net response of spruce growing in alder thickets in Muir Inlet. Hatched areas indicate facilitative (above zero) or inhibitory (below zero) net response of spruce to alder. The sign and magnitude of the net interaction are inferred from field experiments and measurements (Chapin et al. 1994, Fastie 1995), and observations at different chronosequence stages. The interaction begins (year 0) when spruce seeds arrive in an alder thicket. Alder thickets may persist for 100 to 150 years at Glacier Bay

subsequent two to four decades, spruce saplings are commonly damaged and sometimes killed by swaying alder branches (personal observation). When a spruce tree grows tall enough to emerge above the alder branches, its growth rate increases dramatically, suggesting that the shade and physical damage under the alder canopy has had a substantial competitive effect (Fastie 1995). The rapid growth of spruce trees fully emerged above alder suggests that the fertile soil of an alder thicket has a facilitative effect on individual trees that may last for several decades. Because the effect of alder on the population of spruce is of interest, it may be misleading to consider only a subset of these interactions. The net response of the population of spruce is the sum of the outcomes of all of these interactions. However, different sequences of similar positive and negative effects could produce dramatically different outcomes. For example, inhibition of tree seedling establishment by a shrub thicket and subsequent facilitation of the few surviving trees could result in a forest very different from one subjected to early facilitation of establishment and subsequent inhibition of tree growth.

Evaluating the long-term outcome of species interactions

On the eastern shore of Glacier Bay and in Muir Inlet, dense, long-lived alder thickets have had an important role in succession at all sites deglaciated since 1840, but at older sites in the lower bay, such alder thickets were never present (Fastie 1995). Spruce forests have developed at both types of sites, so it is possible to compare spruce populations affected by dense alder with spruce populations not affected by dense alder. The differences include the dramatically reduced early stand density of spruce and the rapid trunk growth and well-developed crowns of individual spruce trees where alder has been important (Table 1). Where alder has not been important, the stand density of spruce after 50 years of recruitment was about three times greater than at sites with alder, and individual spruce trees grew slowly (Table 1). Where alder is an important species, its opposing effects on spruce population size (negative) and individual spruce tree growth (positive) suggest that categorizing this long-term interaction as either facilitative or competitive is problematical. Spruce stands developing from alder thickets are dramatically different from spruce stands without alder,

Table 1. Stand density of spruce 50 yr after spruce recruitment began, percent of overstory spruce in which ring width (10-yr means) doubled within 10 yr, and 10-yr means of ring width immediately following release in these trees. Means for all three of these measures differ significantly between the five young sites and the three old sites (* = $P < .05$, *** = $P < .001$).

Site location	Site age (yr)	Spruce density at age 50 yr (trees/ha)	% of trees with ring-width release	10-yr mean ring-width after release (mm)
Goose Cove	55	94	100.0	7.9±1.2
Klots Hills	78	118	84.6	5.5±0.6
Morse Creek	93	213	78.3	6.0±0.4
Muir Point	105	186	91.1	5.8±0.4
Sandy Cove	148	87	72.2	5.1±0.5
mean of 5 young sites:		140±28	85.2±5.4	6.1±0.5
York Creek	164	607	22.8	3.4±0.1
Beartrack Cove	153	1147	17.2	3.4±0.4
Bartlett Lake	221	857	22.7	3.1±0.2
mean of 3 old sites:		870±191*	20.9±2.3***	3.3±0.1***

but may not be more successful, by any meaningful measure, than stands without alder.

This raises the question of how to evaluate whether or not facilitation or competition has occurred. Determining the direction and magnitude of the short-term response of individual plants is straightforward. But studies that propose to evaluate the response of plant populations to species interactions require specific criteria of positive or negative population response. Because changes in population density are often associated with compensatory changes in plant size (widely scattered trees generally grow faster and larger thancrowded trees), stand-level measures that combine density and size, such as cover, basal area, or biomass, are more appropriate measures than density or size alone. However, a measure of stand function, such as productivity (annual biomass increment per unit area) or nutrient accumulation rate (annual increment in nutrient pool per unit area), may provide the most meaningful index of stand success. For example, at Glacier Bay, there may be no difference in biomass per unit area between stands of scattered, large, fast-growing spruce emergent above alder and stands of dense, slow-growing spruce where alder has not been important. But if it can be demonstrated that sparse stands of spruce where alder is important have a higher productivity or nitrogen accumulation rate than similar-aged stands without alder, then facilitation of spruce by alder is indicated.

If the magnitude or direction of the population response to a species interaction changes during succession, the observed outcome of the interaction can depend on the time interval over which it is observed (Abrams 1987). Ideally, the net, long-term outcome of the interaction can be measured after the magnitude and direction of the response has become constant and the net outcome no longer changes substantially. With long-lived plants, this is often impractical, and shorter intervals are commonly evaluated. Also, it may be of interest to determine the net outcome of a species interaction during shorter intervals in order to track the changing effect of competition or facilitation on community structure. At Glacier Bay, the direction of the net response of spruce to alder thickets may change three times during the first several decades of the interaction (Fig. 1). Because of the strong inhibitory effect of alder on spruce seedling establishment, the net, time-integrated response of spruce populations may not be positive until after the first half century of the interaction (Fig. 1).

Although the net, long-term, functional response of spruce populations may be a more definitive measure of the consequences of the alder-spruce interaction at Glacier Bay, measures of the shorter-term responses of population density or individual plant performance are also informative. These measures will be most useful if they are reported in the context of a long-term, population-level, functional response of spruce to alder.

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A Stable Isotopic Investigation of Nitrogen Dynamics at Glacier Bay, Alaska

by

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Abstract

As part of a study on nitrogen (N) dynamics during primary succession, N stable isotope ratios ($\delta^{15}N$) were measured in foliage and O horizon soil of six successional sites ranging in age from 20 to 225 years along the east side of Glacier Bay.

Within-site differences in $\delta^{15}N$ among woody plant species were attributed to preferences for either ammonium, nitrate, or symbiotically fixed atmospheric nitrogen. Among-site differences in individual species were attributed to site differences in $\delta^{15}N$ of available soil N. Among-species differences in C/N values imply strong variations in the ability to convert mineralized N into new growth. N mineralization data are consistent with less available N in older, spruce-dominated sites.

A $\delta^{15}N$ near 0‰ for alder leaves confirms that this species derives most of its N from atmospheric fixation. No significant among-site differences were seen in alder $\delta^{15}N$.

A significant decline in spruce $\delta^{15}N$ with increasing successional age presumably reflects declines in $\delta^{15}N$ of mineralized N available for uptake. The lack of a similar decline in O horizon soil $\delta^{15}N$ indicates that at older sites only part of the total soil N pool is contributing significantly to plant N pools. At older sites, there may be isotopically distinct pools of slowly recycled and quickly recycled N.

Differences in $\delta^{15}N$ among plants at a 55-year-old site illustrate how one could determine the proportion of plant N derived from soil ammonium or soil nitrate through $\delta^{15}N$ signatures.

KEYWORDS: primary succession, nitrogen isotopes, nitrogen dynamics.

Nitrogen (N) is generally considered to be the limiting nutrient for plant growth in terrestrial systems, particularly in temperate and boreal forests. Because almost no N is present in the primary minerals of rock and soil, the pools of soil N available for plant growth during primary succession are derived from the atmosphere. Most N first passes through vegetation before accreting in the soil.

Previous research at Glacier Bay includes studies of the N-fixing role of the actinorrhizal shrubs alder and *Dryas* in fixing N into the soil (Lawrence, 1958), the growth of soil N pools during succession (Ugolini, 1966), and changes in organic and mineral N pools in soils, vegetation, and litter during succession (Bormann and Sidle, 1990). Although a consensus exists that most N in these ecosystems is derived from N fixation, how that fixed N becomes available to non-fixing species has not been studied. In addition, how N use may differ among species and with changes in site age has not been fully investigated. The natural abundance of ^{15}N in plants and soils can provide information about the

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patterns of N cycling and plant use of N, information otherwise unavailable without extensive experimentation.

Isotopic ratios for N are commonly expressed in delta (δ) notation by comparing the ratio of $^{15}N/^{14}N$ in the standard, atmospheric N_2, to the sample by the following formula: $\delta^{15}N = (R_{sample}/R_{standard} - 1) \times 1000$, where $R = ^{15}N/^{14}N$. During reactions such as ammonification, nitrification, and denitrification, fractionation favoring one isotope can occur. This will generally result in a product of a lower δ (depleted in the heavy isotope) and a residual substrate pool of a higher δ (enriched in the heavy isotope). During physical processes (such as diffusion) fractionation can also occur, again favoring the movement of the lighter isotope. As a result soil ammonium and nitrate, precipitation ammonium and nitrate, and recently fixed atmospheric N_2 all have different $\delta^{15}N$ signatures.

In a study of second-growth conifer and alder stands, Binkley et al. (1985) concluded that the interpretation of ^{15}N natural abundances in evaluating forest N dynamics is difficult as a result of within-pool variability and numerous interacting processes that can affect $\delta^{15}N$ signatures. However, the use of $\delta^{15}N$ values to investigate N cycling during primary rather than secondary succession has strong advantages that make interpretation easier. For example, the absence of initial soil N pools means that all ecosystem N at young sites is of recent origin. At Glacier Bay, low N inputs from precipitation result in almost all N deriving from a single source, microbial fixation of atmospheric N_2.

This study examined $\delta^{15}N$ changes in soil and foliage along a successional chronosequence on the east side of Glacier Bay. The objective was to use stable isotopes to investigate the N cycle between soils and vegetation. The comparison among sites and among species of $\delta^{15}N$ signatures and other data (e.g., foliage C/N) should provide insight into the mechanisms of N dynamics in soils and vegetation during succession.

Methods

Six sites between 20 and 225 years old on the east side of Glacier Bay and Muir Inlet were studied in 1991 and 1992 (Table 1). Sites were selected to represent major stages in forest development in Glacier Bay. Fastie (1994) has studied sites 1, 2, and 5. Weishampel (this volume) has studied sites 3 and 6.

At each site, foliage samples were collected from five specimens of *Dryas* (*Dryas drummondii* Richards.), alder (*Alnus sinuata* (Reg.) Rydb.), willow (*Salix alaxensis* (Anderss.) Cov. and *S. sitchensis* Sanson), cottonwood (*Populus trichocarpa* Torr. & Gray), and spruce (*Picea sitchensis* (Bong.) Carr.) (if present). Organic soil horizons at each site were also sampled (n=5). Samples were oven-dried at 40°C. Percent carbon, percent nitrogen, and C/N ratios were determined on a Carlo Erba Nitrogen Analyzer 1500. Samples for stable isotope analysis were prepared using the Dumas sealed-tube method (Macko, 1981). After cryogenic separation of CO_2 and N_2, $\delta^{15}N$ was determined on a VG Prism Series II isotope ratio mass spectrometer (n=5, typically).

Nitrogen mineralization rates were estimated through incubation of buried bags (Nadelhoffer et al., 1984). Incubations were for 28 days in 1991 (n=9 per site) and 24 days in 1992 (n=5 per site), and were begun on June 11 in 1992 and June 15 in 1991. Preliminary results include the pre-incubation ammonium and nitrate concentrations for 1992 and post-incubation concentrations for 1991. We assumed that pre-incubation concentrations were roughly equivalent in 1991 and 1992, which allowed us to subtract 1992 pre-incubation ammonium and nitrate levels from ammonium and nitrate levels after 4 weeks of incubation in 1991 to arrive at estimates for mineralization.

Results were analyzed with a one-way, two-tailed ANOVA at a significance level of 0.05. Means are reported plus or minus the standard error.

Results and Discussion

$\delta^{15}N$ Results

Significant differences in $\delta^{15}N$ were observed among species at the same site and among sites in the same species. Species preferences for ammonium, nitrate, or symbiotically fixed N may have determined differences among species at individual sites, whereas site differences in $\delta^{15}N$ of available soil N may have determined among-site differences in signatures of individual species.

Both alder and *Dryas* can derive most of their N from atmospheric fixation by symbiotic actinorrhizal microbes. In a survey study, foliage of N-fixing plants had $\delta^{15}N$ signatures from 0‰ to -2‰ (Virginia et al., 1989), which is similar to the range for *Dryas* and alder reported here (Figure 1). When grown in a N-free medium so that all plant N is derived from the atmosphere, *Alnus glutinosa* had a $\delta^{15}N$ of -1.9‰±0.4‰ (Beaupied et al., 1990) and *Alnus rubra* had a $\delta^{15}N$ of -0.6‰±0.4‰ (Binkley et al., 1985). Mead and Preston (1992) concluded from an 8-year experiment with ^{15}N additions that Sitka alder derived 94-99% of its N from atmospheric fixation. The average of $\delta^{15}N$ across all sites at Glacier Bay was -1.7‰±0.1‰, which suggests that alder derived almost all of its N from fixation.

Table 1. Age, date of deglaciation, and dominant vegetation at 6 study sites.

Site	Name and Location	Approximate Age; Year Deglaciated	Dominant Vegetation
1	Bartlett Cove	225 1765 AD	spruce
2	Beartrack Cove	165 1825 AD	spruce
3	Muir Point	110 1880 AD	alder
4	Adams Inlet	90 1900 AD	alder
5	Goose Cove	55 1935 AD	alder
6	Upper Muir Inlet	20 1970 AD	*Dryas*, willow, cottonwood

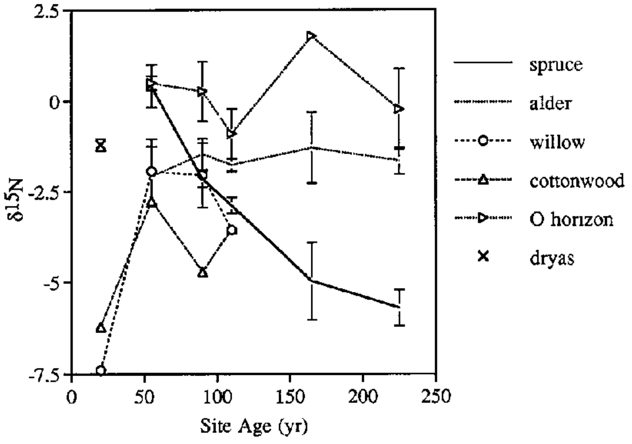

Fig. 1. Relationship of site age to $\delta^{15}N$ in foliage and soil. Error bars represent standard error of the mean.

No isotopic compositions have been reported previously for *Dryas*, but the average of -1.2‰±0.2‰ for this species at the Muir Inlet site indicates that the plant derives its N from fixation, particularly when contrasted with the average for non-N-fixing plants at the same site ($\delta^{15}N$ = -6.6‰±1.9).

Foliage $\delta^{15}N$ for all non-nitrogen fixing plants is consistent with expectations for plants which derive N from mineralized soil N. An exception is at the youngest site where low $\delta^{15}N$, high C/N in foliage of cottonwood and willow, the absence of an O horizon, and low soil N concentration were found. Because $\delta^{15}N$ of ammonium and nitrate in precipitation are generally negative (Peterson and Fry, 1987) some of the plant N at this 20-year-old site may be derived from small atmospheric inputs of ammonium and nitrate.

Precipitation inputs of N in southeast Alaska are low, approximately 1 kg/ha/yr (computed from Bormann et al., 1989). Therefore, most ecosystem N in Glacier Bay is ultimately derived from fixation by plants. If no fractionation occurs after fixation, the soils, being the largest pool of ecosystem N, should have the signature of atmospherically fixed N. However, organic horizon soils averaged significantly higher ($\delta^{15}N = +0.5‰$) than the value for recently fixed N in alder and *Dryas*. The higher values in O horizon soils could reflect losses of isotopically light ammonium, nitrate, and organic N to groundwater and streamwater and N losses to the atmosphere through denitrification.

The isotopic signature of spruce foliage should reflect the wide variety of conditions at the sites where it was present. The significant decline in spruce $\delta^{15}N$ with increasing successional age presumably reflects declines in $\delta^{15}N$ of mineralized N available for uptake (which was not measured). The lack of a similar decline in O horizon soil $\delta^{15}N$ suggests that only some O horizon N is contributing significantly to plant N pools. Two possibilities for this pattern are suggested. If a high fraction of total soil N is recycled at younger sites we would expect a close agreement in isotopic values between soil N and plant N, even if non-recycling soil N is isotopically heavier. If only a small proportion of total soil N is recycled at older sites, and this fraction is isotopically lighter than soil N that does not recycle, then plant $\delta^{15}N$ will be lighter than the bulk soil pool. An alternative hypothesis presupposes that the fraction of soil N that is mineralized may remain the same among younger and older sites. However, in younger sites insufficient time has elapsed for fractionating processes to result in the separation of recycled soil N and non-recycled soil N into isotopically distinct fractions. In older sites, isotopically distinct pools of slowly recycled and quickly recycled N have formed.

The observed differences in $\delta^{15}N$ among plants at Goose Cove can be used to illustrate how one could determine the proportion of plant N derived by different species from soil ammonium or soil nitrate (Table 2) through $\delta^{15}N$ signatures. Although this exercise is not conclusive, as the actual $\delta^{15}N$ for the endmembers soil ammonium and soil nitrate are only estimated, we believe that with measurement of the endmembers this technique is feasible.

In experiments cited by Ingestad (1979), Sitka spruce utilized approximately 20% nitrate across a wide range of ammonium/nitrate ratios. This held true whether nitrate was 20%, 40%, or 60% of total supplied N. Bormann and Sidle (1990) found that soil nitrate was 26% of total mineral N at a 62-year-old site with similar vegetation to Goose Cove. At Goose Cove, initial soil nitrate was 10% of total mineral N and net nitrification was 65% of total mineralization. Thus, a value of 20% for nitrate uptake by spruce seems reasonable (Table 2b).

Binkley et al. (1985) found that soil nitrate was 6.2‰ lighter than soil ammonium in productive stands of mixed alders and conifers in Washington. We assumed a similar difference between soil ammonium and nitrate at Goose Cove as seen in the Binkley et al. (1985) study. Assuming that a spruce $\delta^{15}N$ of +0.5‰ represented 80% ammonium and 20% nitrate use and that $\delta^{15}N$ of ammonium was approximately 6‰ greater than soil nitrate, the calculated endpoints for ammonium and nitrate are +1.5‰ and -4.5‰ respectively (Table 2a). Given these endpoints, cottonwood was calculated to use 71% nitrate and 29% ammonium, with willow taking up slightly less nitrate, 57% of total plant N (Table 2b).

C/N Results

The ratio of carbon to nitrogen in plant tissues and soils provides important information on N availability and differences in the use of N. Cottonwood and willow exhibit a wide range in C/N values along the chronosequence. At the youngest site, cottonwood and willow have a high C/N of 26-27 (Figure 2). This indicates a severe N deficiency, as noted by other researchers in Glacier Bay on vegetation in early succession (Lawrence, 1979). At older sites cottonwood has a relatively constant foliage of 16-17 despite differing N availabilities, probably because cottonwood translates a higher N uptake into more photosynthetic tissue and a higher growth rate. We hypothesize that at sites older than the youngest site cottonwood grows sufficiently fast to maintain a relatively constant tissue N concentration, even when N is abundant. In contrast, willow foliage C/N is apparently more sensitive to the N supply; varying from 11-17 at older sites. We also hypothesize that under conditions of high N availability, willow does not respond by producing proportionally more new biomass. Therefore, as N availability increases N concentrations also increase. This growth response of luxury consumption is a common feature of species adapted to nutrient-poor environments (Chapin, 1980).

A comparison of spruce and O horizon C/N revealed an interesting contrast. Soil C/N showed a significant difference between the youngest three sites with O horizons (dominated by alder C/N = 16-18), with a C/N of 16-18, and the oldest two (dominated by spruce, C/N = 29-31). For spruce foliage however, only the oldest site (site age 225 years) had significantly higher C/N. Other factors being equal, this suggests that the degree of N limitation and the proportion of soil N that is bound up in slowly recycling fractions increases between these two sites. We suggest that the longer time during which spruce has dominated the Bartlett Cove site compared to the Beartrack Cove site has allowed the buildup of a more recalcitrant soil N. This has in turn led to a more N-limited system. The absence of a response of alder C/N to changing soil C/N confirmed its independence from the soil as a N source, as was also seen in $\delta^{15}N$ signatures.

Mineralization Data

We expected the pattern of N mineralization to vary greatly during succession as the forest community changed from alder-dominated to spruce-dominated, with accompanying changes in soil age, litter quality, and N use. Mineralization results suggest that mineral N is less available in older, spruce-dominated sites, with progressively slower turnover of N in older sites (Table 3). The increased residence time of soil N with greater site age is attributed to decreased litter quality in later succession and to increased immobilization of N in recalcitrant soil fractions.

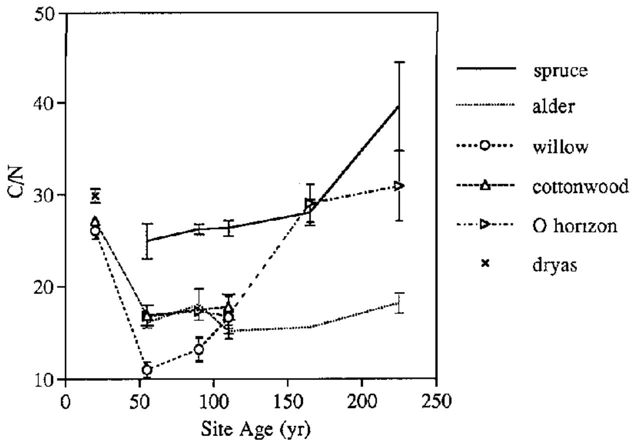

Fig. 2. Relationship of site age to C/N in foliage and soil. Error bars represent standard error of the mean.

Table 2. Species N supply at Goose Cove. a. Calculated theoretical isotopic endpoints for N form used by plants. b. Percentage of N supply of different forms for three species. Endpoints in a. used to calculate values in b. Spruce values in b. taken from Ingestad (1979).

a.

N Form	$\delta^{15}N$
NH_4^+	+1.5‰
NO_3^-	-4.5‰

b.

Species	Spruce	Willow	Cottonwood
NH_4^+	80%	43%	29%
NO_3^-	20%	57%	71%

Table 3. O horizon N mineralization. %N in soil combined with column 4 data to produce column 6.

Site Age (y)	Net Ammonification µmoles N (100 g soil*month)$^{-1}$	Net Nitrification µmoles N (100 g soil*month)$^{-1}$	Net Mineralization µmoles N (100 g soil*month)$^{-1}$	Percentage Nitrogen in Soil	Millimoles N mineralized (1000 g N*month)$^{-1}$
225	132	305	437	0.95%	460
165	184	369	553	0.80%	690
90	431	1390	1821	1.43%	1270
55	394	665	1059	0.70%	1510

Conclusions

Significant differences in the $\delta^{15}N$ signatures in plant tissues of woody species at the same site appear to be attributable to differential preferences for ammonium, nitrate or symbiotically fixed nitrogen. Significant differences within a species among sites of different ages appear to be a consequence of the $\delta^{15}N$ of the available soil N. The C/N ratios in woody plant foliage also demonstrate a significant pattern of among-species and among-site variation that is largely attributable to the pattern of response to N availability in the species, and to the pattern of N availability at sites of differing age and history of development. Nitrogen mineralization rates in the soils also suggest a pattern of reduced mineral N on older, spruce-dominated sites.

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Nitrogen Fixers in Early Primary Succession on Surfaces of Two Ages at Wachusett Inlet, Glacier Bay National Park and Preserve, Alaska

by

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Abstract

This study examined the order of establishment and distribution of N_2-fixing and non-fixing vascular plants on glacial till surfaces at Wachusett Inlet that had been exposed for 10-15 years. Age of the surface at two sections of a 2000 m transect was 8-9 years younger due to local surface erosion. The abundance of N_2-fixing and non-N_2-fixing vascular plant species varied widely along the transect. Soil physical and chemical properties, especially inorganic N concentrations, are correlated with the density of N_2-fixing plants. The mean soil mineral N concentration (15 cm column) was 2.9 ± 0.2 $\mu g\ g^{-1}$ at the recently eroded zones and 4.3 ± 0.2 $\mu g\ g^{-1}$ at the more stable areas. Total mean soil N (15 cm column) was 44.35 ± 13.3 $\mu g\ g^{-1}$ at the eroded areas and 178.7 ± 14.3 $\mu g\ g^{-1}$ at the more stable areas. The older surfaces also had significantly lower pH and soil bulk densities, greater plant density, and greater species richness. Significant N transfer apparently occurs between N_2-fixing *Dryas* and *Alnus* and adjacent, already-established non-N_2-fixing *Salix* taxa. These patterns confirm and refine previous observations that slightly older surfaces have higher soil N concentrations, plant density and species richness, and lower pH and soil bulk density than younger surfaces and that N transfer occurs between N_2-fixing and adjacent non-N_2-fixing taxa.

KEY WORDS. *Alnus*, *Dryas*, erosion, nitrogen transfer, plant abundance, primary succession.

Glacier forelands offer special opportunities to assess the role of nitrogen fixing plants during early primary succession. Substrates within early seral stages have very low levels of soil nitrogen which is the most important macronutrient required for plant establishment, growth, and reproduction (Borman and Gordon 1989). At Glacier Bay National Park and Preserve (GBNPP), N_2-fixing actinorhizal shrubs (*Dryas drummondii*, * *Alnus crispa* ssp. *sinuata*, and *Shepherdia canadensis*) nodulated by the actinomycete

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*Nomenclature follows Hultén (1968)

Frankia, leguminous taxa nodulated by *Rhizobium*, and cyanobacteria (*Nostoc* and *Anabena*) associated with the "Black Crust" matrix (Worley 1973), commonly colonize these early seral stages. Actinorhizal taxa are capable of stimulating, through indirect nitrogen transfer, and adjacent, already-established, non-N_2-fixing woody vascular plants such as *Populus*, *Picea*, and *Salix* (Schoenike 1958, Lawrence et al. 1967, Lawrence 1979, unpublished observations, Kohls et al. 1994). This work extends previous observations showing that rapid soil N accumulation during the early stages of primary succession at GBNPP appears to be related to the distribution and abundance of N_2-fixing actinorhizal plants (Crocker and Major 1955, Lawrence et al. 1967, Bormann and Sidle 1990). Our rationale for conducting this work was to: (i) measure the distribution and relative abundance of dominant actinorhizal and non-N_2-fixing vascular plant species found along surfaces that had been subject to very recent erosion and areas that had remained relatively undisturbed for ca. 15 yr along a 2000 m transect in an early seral stage; (ii) assess the effect that the actinorhizal plants have on physical and chemical soil properties; and (iii) explore to what extent these taxa function as a source of N for non-N_2-fixing species.

Methods

Site description

The study was conducted from June 26 to July 18 1991. A transect running W-E over a distance of 2000 m at a nearly uniform elevation of 10-15 (MSL) was established on the N side of upper Wachusett Inlet (Figure 1). An early seral stage next to the north shore of Wachusett Inlet was chosen because it constitutes an accessible example of early primary succession at GBNPP. Inspection of vertical aerial photos: IR (1979), natural color (1990), and field observations (1991) made it possible to identify two portions of the transect that had been subjected to severe erosion (gullying), presumably due to heavy rains or snow-melt following deglaciation. There the parent soil material had been exposed, altering the process of vegetation change. These eroded areas contrasted sharply with areas subject only to normal erosion. Two distinct zones, at 600 to 700 m and 1300 to 1800 m from the starting point of the transect were identified as having been subject to this intense erosion roughly a decade after deglaciation, and ca 8-9 yr before the current study (Figure 1). The regosolic soils that are in the process of development on this glacial till are coarse to moderately textured and moderately to highly calcareous, almost devoid of available N, with no visible soil profile observed along the entire transect.

Soil sampling and analysis

Permanent ($400m^2$) circular plots were established at 50 m or, more frequently, at 100 m intervals along the transect by driving a 5' length of electrical conduit into the substrate at plot center. Within each plot, soil samples (n=4) were collected at 7.98 m along each magnetic N, S, E, and W azimuth from plot center with an approximate surface area of 45 cm^2 to a depth of 15 cm and an approximate total volume of 2500 cm^3. The soil samples were cooled on ice for 21 days, subsequently frozen, air dried for 30 days and sieved to 2.0 mm in the laboratory. Four soil samples per plot were collected for bulk density determination. The samples for bulk density determination were subsequently composited to form one sample for each plot. Bulk density was ascertained by determining the soil pore space > 2 mm, mixing and weighing each composited dry sample, sieving to 2 mm and dividing the soil mass by total volume of each soil pit. For other soil analyses, subsamples (n=4) were removed from the same soil pits prior to combining soil for bulk density determinations. Soil organic matter content was measured by loss on ignition as described by Lim and Jackson (1982). Soil pH was measured in a saturated paste and equilibrated for 1 hr in 2:1 distilled water for four replicate samples per plot.

Total N concentration values were determined for four samples per plot, based on micro-Kjeldahl methods as described by Bremmer and Mulvaney (1982). Substrate mineral (inorganic) nitrogen values were based on extraction with KCl (Keeney and Nelson 1982) and the $NO_2^- + NO_3^-$ (further identified as NO_3^-) and NH_4^+ concentrations determined by steam distillation and acid titration with 0.02N H_2S0_4.

Plant floristics, sampling, and analysis

To form each plot, four 11.28 m nylon ropes were secured at plot center along each magnetic N, S, E, and W azimuths. These form four radii of a circular plot, with a total area of 400 m^2. The areas of all *Dryas* mats within each plot were calculated based on the means of four measured radii. All shrub species were identified to species, and stem diameter was measured at 10 cm from the base of the root crown (DAB) for all shrub species > 1.0 cm. At 11.28 m from plot center along each magnetic N, S, E, and W azimuths, four 0.5 m^2 square plots were established and percent cover of all species was estimated at increments in seven size classes: <1 %; 1-2 %; 2-5 %; 5-10 %; 10-25 %; 25-50 %; and 50-100 %, using a modified version of the Braun-Blanquet system (1951).

Basal stem sections at root crown of at least three representative specimens of *Dryas drummondii*, *Alnus crispa*

Fig. 1. Location of study site at the northern end of Wachusett Inlet, Glacier Bay National Park and Preserve.

spp. *sinuata*, and *Salix* (*sitchensis* or *commutata*) were collected from each large plot for age analysis. Leaf samples were collected at each plot with at least three replicate plants per species of the N_2-fixing *Dryas* and *Alnus* and the non-N_2-fixing *Salix* species. Each *Salix* sample was annotated as to whether it was collected from a site adjacent to the periphery of a *Dryas* mat or the canopy edge of an *Alnus* thicket (< 100 cm). The plant material was air dried in paper bags in the field and for 24 hrs at 70°C in the laboratory. Plant tissue samples were ground and analyzed for total N concentration as described by Bremner and Mulvaney (1982).

Statistical analysis

Means and standard errors for were calculated for raw data for replicate samples from each plot, therefore the unit of replication is the plot (n=20). Data were analyzed for variance using Anova and a Sheffe's F test to determine statistically significant ($P \leq .05$) differences between plots. Substrate mineral N and total N were regressed against *Alnus* and *Dryas* density and tested by analysis of variance.

Results and Discussion

Dramatic differences in both soil properties and plant species density and richness were observed between the sites that had been subject to heavy erosion when contrasted with the areas that had been less drastically eroded within post-neoglacial time.

Bulk density

Soil bulk density for the heavily eroded areas, essentially the parent material, was 1.54 ± 0.04 g cm^{-3}, and was significantly greater ($P < .05$) than for the non-eroded areas (1.38 ± 0.03 g cm^{-3}) (Table 1).

Soil organic matter

Soil organic matter in the eroded areas was 0.23 ± 0.01 % and was significantly less ($P < .05$) than those samples obtained from the non-eroded areas (0.52 ± 0.07 %) (Table 1).

Soil pH

The pH of the substrate over the entire transect ranged from 7.90 ± 0.05 to 6.49 ± 0.02. Mean substrate pH was significantly lower in the uneroded areas (6.89 ± 0.06) than in the eroded zones (7.34 ± 0.11, $P < .05$) (Table 1). A decline in soil pH with surface age is a feature that is common to glacial forelands (Matthews 1992).

It has been well documented that the decomposition of *Alnus* litter results in a rapid decline in soil pH at GBNPP (Crocker and Major 1955). This trend was observed here within a number of the plots where *Alnus* was abundant (Tables 1 & 4).

Soil nitrogen

Total N concentration in soil was low (124 ± 18 $\mu g\ g^{-1}$) and was significantly lower ($P < .05$) in eroded areas (44.4 ± 13.3 $\mu g\ g^{-1}$) than in uneroded areas (179.0 ± 14.3 $\mu g\ g^{-1}$) (Table 1). NH_4^+ content varied from 3.91 ± 0.01 to 1.83± 0.05 $\mu g\ g^{-1}$ over the length of the transect. Soil NO_3^- concentrations ranged from 1.53 ± 0.03 to 0.26 ± 0.06 $\mu g\ g^{-1}$ over the length of the transect. Concentrations for mineral (inorganic) N were significantly different ($P < .05$) for NO_3^- in eroded areas (2.30 ± 0.14 $\mu g\ g^{-1}$) than in uneroded areas (3.20 ± 0.15 $\mu g\ g^{-1}$) and for NH_4^+ (0.60 ± 0.01 $\mu g\ g^{-1}$) in the eroded areas than in the uneroded areas (1.01 ± 0.01 $\mu g\ g^{-1}$) (Table 1).

An increase in substrate N is generally associated with a concomitant increase in substrate age (Crocker and Major 1955, Bormann and Sidle 1990). We found a consistent increase in total soil N or mineral N within the uneroded plots along the 2000 m transect and where the density and species richness of the actinorhizal taxa were greater (Tables

Table 1. Values for soil bulk density, loss on ignition (L 0.I), pH, total N, total mineral N, $NH_4^{'}$, and NO_3^- from 20 (400m^2) plots (n=4/plot) along a 2000 m transect adjacent to Wachusett Inlet Data are ordered to reflect the areas determined to have been subject to post-neoglacial erosion and those that had remained relatively undisturbed See text for methods

Plot number	Bulk density ($g\ cm^{-3}$)	L.O.I. (%)	pH	Total N ($\mu g\ g^{-1}$)	Mineral N ($\mu g\ g^{-1}$)	NH_4 ($\mu g\ g^{-1}$)	NO_{3-} ($\mu g\ g^{-1}$)
Plots Subject to Severe Local Erosion; n=8	1.54±0.04	0.23±0.01	7.34±0.11	44.35±13.3	2.9±0.21	2.3±0.14	0.60±0.01
Plots Subject to Normal Erosion; n=12	1.38±0.03	0.52±0.07	6.89±0.06	178.7±14.3	4.3±0.20	3.2±0.15	1.01±0.01

Values are means ± standard error; all means are significantly different (P<0.05).

Table 2. Ages of two N_2-fixing actinorhizal taxa and the non-N_2-fixing *Salix* spp. and mean foliar N concentrations of *Salix* spp growing either distant or adjacent to *Dryas* or *Alnus* sampled from within 20 (400 m^2) plots (n=3/plot) along a 2000 m transect adjacent to Wachusett Inlet

Plot Number	*Dryas* (age years)	*Alnus* (age years)	*Salix* spp. (age years)	*Salix* foliage %N	*Salix* foliage %N
n=8	Plots Subject to Severe Local Erosion			Adjacent to *Dryas*(<1.0m) 2.76±0.1	Adjacent to *Alnus* (<1.0m) 3.80±0.1
	5.30±0.38	4.1±0.10	4.90±0.06		
n=12	Plots Subject to Normal Erosion			Distant from *Dryas*(>1.0m) 2.21±0.05	Distant from *Alnus*(>1.0m) 2.49±0.1
	10.8±0.96	7.5±0.69	10.03±1.0		

Values are means ± standard error; means within each column are significantly different (P < .05).

Table 3. Regression analysis of *Dryas* (% cover) and *Alnus* (stem density) on total soil inorganic N ($N0_3^- + NH_4^+$) and total soil N from 20 (400 m^2) plots along a 2000 m transect adjacent to Wachusett Inlet.

Taxon †	**Nutrient ($\mu g\ g^{-1}$)‡**	**Equation**	**F**	**r^2**	**P**
Dryas	Inorganic N	y = 27.12 x - 52.99	45.1	0.715	.0001
Dryas	Total N	y = 0.066 x - 2.690	38.5	0.682	.0001
Alnus	Inorganic N	y = 5.407 x - 12.88	43.4	0.707	.0001
Alnus	Total N	y = 0.362 x - 5.837	76.3	0.809	.0001

† n ≤ 114 *Alnus* stems per plot and n ≤ 210 *Dryas* mats per plot

‡ n=4 soil samples per plot

1 & 4). Due to the time between sampling and extraction, the values for soil mineral N should be treated cautiously. Nonetheless, these data confirm previous observations that the actinorhizal taxa are instrumental in improving the soil N status of these early seral stages (Crocker and Major 1955, Lawrence et al. 1967).

Relationships between substrate N and actinorhizal taxa

There are significant positive correlations between total soil N and *Dryas* cover ($R^2 = 0.68$, $P < .05$), and total soil N and of *Alnus* stem density ($R^2 = 0.82$, $P < .05$) (Table 3). When total mineral N concentration (NH_4^+ and NO_3^-) was regressed against *Dryas* cover, a significant positive relationship resulted ($R^2 = 0.72$, $P < .05$). A very similar significant positive relationship ($R^2 = 0.71$, $P < .05$) was found between density of *Alnus* stems and total mineral soil N (Table 3).

Age of woody taxa

Ages of *Dryas*, *Alnus*, and *Salix* were all found to be significantly different ($P < .05$) when the strongly eroded and less eroded zones were compared, with the older specimens found in the less disturbed areas (Table 2). Based on age determination of the three woody taxa, it is suggested that significant local surface erosion of the two disturbed zones occurred 8-9 yr prior to 1991. These data also suggest that the *Salix* spp. became established at roughly the same time as *Dryas*. *Alnus* was already well established in this early seral stage and showed only a mean 2-yr difference (younger) as compared with the two other taxa.

Species abundance and frequency

The patterns of plant community development were highly varied and there appeared to be no consistent pattern of plant community structure. The vascular vegetation was very sparse, particularly within the eroded zones, as is characteristic of the early seral stages in GBNPP (Reiners et al. 1971). There was a dramatic contrast between species abundance by percent cover and distribution between the older and younger substrate zones. Species diversity and percent cover on the older surfaces were 2 to 6 times greater than on the younger surfaces (Table 4).

Nitrogen transfer

The mean values for foliar N concentrations were in: *Dryas*, 2.03 ± 0.03 %, *Alnus*, 3.31 ± 0.06 %, and the two *Salix* spp. combined, 2.91 ± 0.08 % ($n \approx 60$ plants per species). There were significantly greater mean values ($P < .05$) for foliar N accumulation in *Salix* spp growing adjacent (< 1.0 m) to *Dryas* 2.76 ± 0.10 %, as compared with those more distant (> 1.0 m) from the edge of the mat 2.21 ± 0.05 %. When *Salix* spp. grew adjacent to the outer edge of the *Alnus* canopy (< 1.0 m), foliar N was 3.8 ± 0.07 % and away (> 1.0 m) was 2.5 ± 0.04 %, suggesting that substantial nitrogen transfer occurs between the adjacent N_2-fixing *Dryas* and *Alnus* and the non-fixing *Salix* spp. (Table 3). Schoenike (1958), Lawrence et al. (1967), Lawrence (1979), Chapin et al. (1994) have observed significantly increased growth rates in *P. balsamifera* ssp. *trichocarpa*, *Picea*, and *Salix* spp. associated with either *Dryas* or *Alnus* at GBNPP. Kohls et al. (1994) observed that percent foliar N concentrations were significantly higher in three species of *Salix* and *P. balsamifera* that were growing adjacent to *Dryas* as opposed to distant from the *Dryas* mats in a glacial foreland in the Canadian Rockies.

The enhanced growth rates and significant increases in foliar N concentrations of the adjacent non-fixing taxa suggest that these species are stimulated via the process of N transfer, albeit indirectly, by fixed N possibly exuded from the roots of the N_2-fixing species or mainly through decomposition of the leaves of N_2-fixing *Alnus* or *Dryas* plant components.

These observed patterns suggest that already established non-N_2-fixing *Salix* spp. are indirectly assimilating N from adjacent N_2-fixing taxa and that *Alnus* is contributing more fixed N than *Dryas* and that previously observed enhanced growth rates of non-fixing taxa are stimulated through the process of N transfer by adjacent N_2-fixing taxa (Lawrence et al. 1967, Lawrence 1979). These results also imply that the greater species diversity observed at the older surfaces may be due to the significantly greater substrate N concentrations as a consequence of greater N_2-fixing taxa densities.

Summary

This study has allowed us to describe the role of actinorhizal plants in the nitrogen economy of two early seral stages of different age on glacial till at GBNPP. The pattern of stimulation via N transfer has been observed repeatedly between legumes and non-N_2-fixing grasses in agricultural settings (see Brophy et al. 1987). However, less attention has been paid to quantifying this process within plant communities in successional studies in natural areas. These observations suggest that adjacent, already-established non-fixing species growth and development are enhanced by adjacent N_2-fixing taxa. These results also confirm the extremely varied nature of the post-glacial landscape at GBNPP due to erosional processes and the role of actinorhizal plants and soil N accumulation. The diverse

Table 4. Synoptic table of common woody and herbaceous plant species within 20 (400 m^2) plots at Wachusett Inlet Glacier Bay National Park and Preserve, Alaska 0 = not present; 1= < 1 % , 2=1-2 % , 3= 2-5 % ,4= 5-10 % 5 = 10-25 % , 6=25-50 % , 7=50-100 %; species with very low occurrence are not shown. Plots are ordered to reflect the areas determined to have been subject to post-glacial erosion and those that had remained relatively undisturbed Botanical nomenclature follows Hultén (1968). Data compiled using a modified version of Braun–Blanquet (1951).

Plot number	1.6	1.7	1.13	1.14	1.15	1.16	1.17	1.18	1.1	1.2	1.3	1.4	1.5	1.8	1.9	1.10	1.11	1.12	1.19	1.20
	Plots Subject to Severe Local Erosion								Plots Subject to Normal Erosion											
Barren (No observed vegetation)	7	6	7	7	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6
Woody taxa																				
Alnus crispa ssp. *sinuata*	3	3	2	0	0	0	0	1	4	4	3	4	4	2	3	6	6	5	1	4
Dryas drummondii	1	1	1	1	1	1	0	1	4	4	3	3	3	1	3	2	3	1	2	4
Populus balsamifera ssp. *trichocarpa*	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	1	1
Salix alaxensis	1	1	1	1	0	0	0	0	1	1	1	0	1	1	1	2	1	1	1	1
Salix arctica	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
Salix barclayi	1	0	0	0	1	0	0	0	0	1	1	1	1	0	1	0	0	0	1	1
Salix commutata	1	2	1	1	0	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
Salix reticulata	0	0	0	0	1	0	0	0	1	1	0	0	1	0	1	1	1	0	0	1
Salix sitchensis	1	1	1	1	1	1	1	1	2	1	1	2	1	1	1	1	1	2	0	1
Salix stolonifera	1	0	1	0	1	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
Shepherdia canadensis	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	2	1	1	1	1
Herbaceous taxa																				
Antennaria pallida	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Arabis lyrata ssp. *kamchatica*	1	0	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1
Carex circinnatta	1	1	1	0	0	0	0	1	0	0	1	1	1	2	1	1	1	1	1	1
Carex stenophylla ssp. *eclocharis*	1	0	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1
Crepis nana	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1
Dryopteris fragilis	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	1	1	1	1	0
Epilobium latifoilum	2	1	2	2	2	1	1	1	2	2	3	2	4	2	2	3	2	5	1	1
Equisetum arvense	0	1	0	0	0	0	0	0	1	1	0	0	0	0	1	1	1	3	1	2
Equisetum variegatum	1	2	2	2	4	0	0	1	2	2	2	1	5	1	1	0	2	2	2	1
Festuca brachyphylla	1	0	0	0	0	0	0	0	1	0	0	1	0	1	1	1	1	1	1	1
Galium triflorum	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	1	0	0
Parnassia palustris	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	1	1	1	1
Platanthera hyperborea	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Puccinellia nutkaensis	1	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	1	1	1	1
Stellaria crispa	0	0	1	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1
Trisetum spicatum	1	1	1	0	0	0	0	1	1	1	1	1	1	2	1	1	1	1	0	1
Number of Species Present / Plot	17	12	12	9	9	6	4	10	19	21	21	19	22	19	25	23	22	24	22	24
"Black Crust"	3	5	5	5	5	3	4	4	4	6	4	3	5	4	4	6	3	3	3	

topography and secondary disturbance following deglaciation at GBNPP has resulted in a mosaic of plant communities and associated N accumulation and fluxes. The results presented here demonstrate that dramatic differences in soil N concentrations and vegetation structure are particularly prevalent during the early stages of primary succession, due to post-glacial allogenic factors.

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Structure and Composition of a Forested Beach Ridge Chronosequence on the Yakutat Foreland, Alaska

by

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Abstract

Forest structure and composition were compared across a chronosequence of geomorphically similar beach ridges. The beach ridges were divided into three age groups (young [<300 years], middle-aged, and older ridges of unknown age) based on their distance landward from the current beach. The dominant vegetation on all beach ridges is Sitka spruce/devil's club (*Picea sitchensis/Echinopanax horridum*). Along the chronosequence, there is a trend towards larger tree size. The soils change from immature Entisols on the youngest ridges to deep Spodosols with ortstein development on the oldest ridges. Evidence from one stand suggests that western hemlock (*Tsuga heterophylla*) may be increasing in importance as these ridges age.

KEY WORDS: spruce, succession, Yakutat, beach ridge, chronosequence.

Studies of vegetation succession have been ongoing at Glacier Bay and environs for the last 80 years (Clements 1916; Crocker and Major 1955; Ugolini and Mann 1979; Fastie 1994). The study of chronosequences provides an opportunity to examine inferred vegetation and soils successional pathways. In this paper, the vegetation structure (density/ha and basal area/ha for tree species) and composition (percent canopy cover for vascular species and dominant mosses) of uplifted beach ridges were described along an putative chronosequence. The beach ridges occur on well drained sandy soils all within ten kilometers of the coast.

Study Area

The study site is on the Yakutat Ranger District (USDA Forest Service) between the Gulf of Alaska and the Saint Elias Mountains (59° 31'N, 139° 40'W). The district is bounded by the Wrangell-Saint Elias and Glacier Bay National Parks and is one of the most tectonically active regions of the Pacific Rim (Molnia 1986). The climate of the region is cloudy, cool, and wet, the airport in Yakutat receiving 3850 mm of precipitation each year, over twice the annual precipitation for Gustavus. The precipitation for Yakutat is distributed throughout the year, with June being the driest month (185 mm) and October the wettest (580 mm) month. The mean annual temperature is 3.8°C (National Climatic Data Center 1993).

The foreland is a complex of Holocene moraines, outwash plains, uplifted estuaries, outburst floodplains and uplifted beach ridges. The present beach runs nearly the entire 70 kilometer length of the Yakutat foreland while the uplifted beach ridges primarily occur along a 25 kilometer section of coast of the Yakutat foreland between Dry Bay and the Dangerous River (Figure 1). The beach ridges range from about 5 meters in elevation near the coast to 35 meters in elevation about 7 kilometers inland. Beach ridges were predominantly formed by uplift associated with tectonism and isostatic rebound coupled with longshore ocean currents moving sediment north along the coast. Variations in the sediment supply from the Alsek and other rivers have probably determined the rate of progradation along the shoreline as is suggested for the Icy Cape foreland (Plafker et al. 1980). It is likely that the outburst floods coming

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down the Alsek were one of the main sources of sediment for shoreline building during the last millennium (cf., Clague and Rampton 1982).

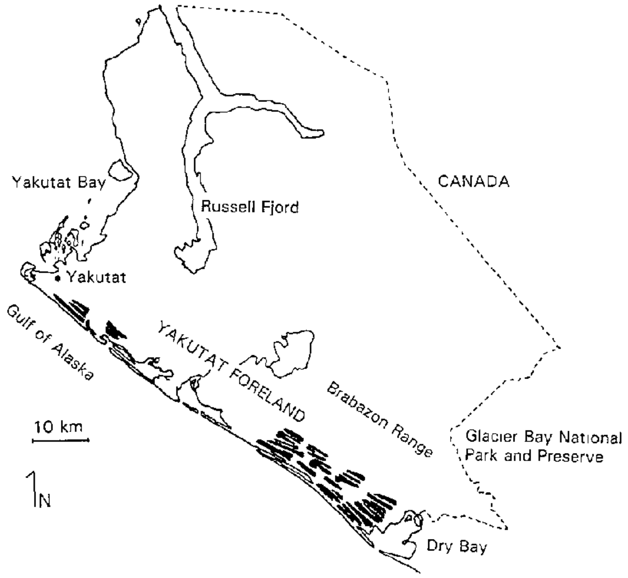

Fig. 1. Map of the Yakutat Ranger District showing the approximate size and spatial arrangement of the uplifted beach ridges on the Yakutat foreland.

Methods

Ridges were selected for sampling because of their relative accessibility from the town of Yakutat. Fifteen plots on beach ridges were assigned to three age classes based on distance of the ridges from the coast. Six stands were sampled on young ridges, four on middle-aged ridges, and five on old beach ridges. Additionally, one very dense ecotonal spruce stand was also sampled between the present beach and the young ridges.

Field methods generally followed those developed by the USDA Forest Service in the Pacific Northwest and Alaska (Martin and Borchers 1991). A 500 m^2 circular plot was randomly placed within each sampled stand. Within each plot, percent canopy cover was recorded for each plant species to the nearest one percent between one and ten percent cover, and in five percent cover classes thereafter. Each tree was assigned to either the canopy ($\geq$10 cm dbh) or regeneration class (<10 cm). The canopy trees were divided into overstory and subcanopy. Overstory individuals received full sunlight from above and some from the sides, while subcanopy individuals received direct sunlight through small holes in the canopy and were subject to lateral competition from crowns of overstory individuals. Diameter at breast height (dbh; 1.4 meters) was collected for all living stems in the canopy class. One of the largest trees in each plot was cored, when the pith could be reached, and the annual growth rings counted. A standard soil profile description was completed for each plot (Soil Survey Manual 1984).

A constancy/cover table (constancy = percent of plots with that species present; cover = mean percent canopy coverage) was developed to summarize the species cover data to compare trends across the chronosequence. Within each beach ridge age class, the tree diameter data was converted to mean number of stems per tree size class, and a histogram was used to visually compare the different aged groups. Additionally, the stand density (plants/ha) and basal area (m^2/ha) for the overstory and subcanopy were calculated for Sitka spruce in the three age classes of the beach ridge chronosequence. Means are presented in the text ± 1 standard deviation (SD) unless otherwise noted.

Results

The present non-forested beach is dominated by two communities. In the supratidal zone and on dunes, a beach rye grass/beach pea (Elymus arenarius/Lathyrus maritimus) community dominates, while landward is a strawberry/yarrow (Fragaria chiloensis/Achillea borealis) community (Shephard 1995). A young, excessively stocked spruce forest (dog hair thicket) with only a moss understory is a transitional community on surfaces <130 yr old. An older portion of this ecotonal community was sampled once (the stand was approximately 90 years old based on tree cores), and is worth noting as a comparison with the three beach ridge age classes. The density was 920 spruce/ha and the basal area was 78.3 m^2/ha. Based on observations and aerial photography interpretation, these very dense spruce stands are the dominant ecotonal community between the beach meadow community and the Sitka spruce/devil's club community.

During the first 2 to 7 centuries of succession, the forest that develops on beach ridges is a remarkably homogeneous Picea sitchensis/Echinopanax horridum community (Figure 2, Table 1). Over the entire chronosequence the cover values for Picea range from 25-75% and Echinopanax cover ranges from 40-90%.

There are several trends across the ridges. Highbush cranberry (Viburnum edule) constancy is typically 83% on the younger beach ridges, but is completely absent on the older ridges. From youngest to oldest ridges, the percent cover increased for salmonberry (Rubus spectabilis) (from

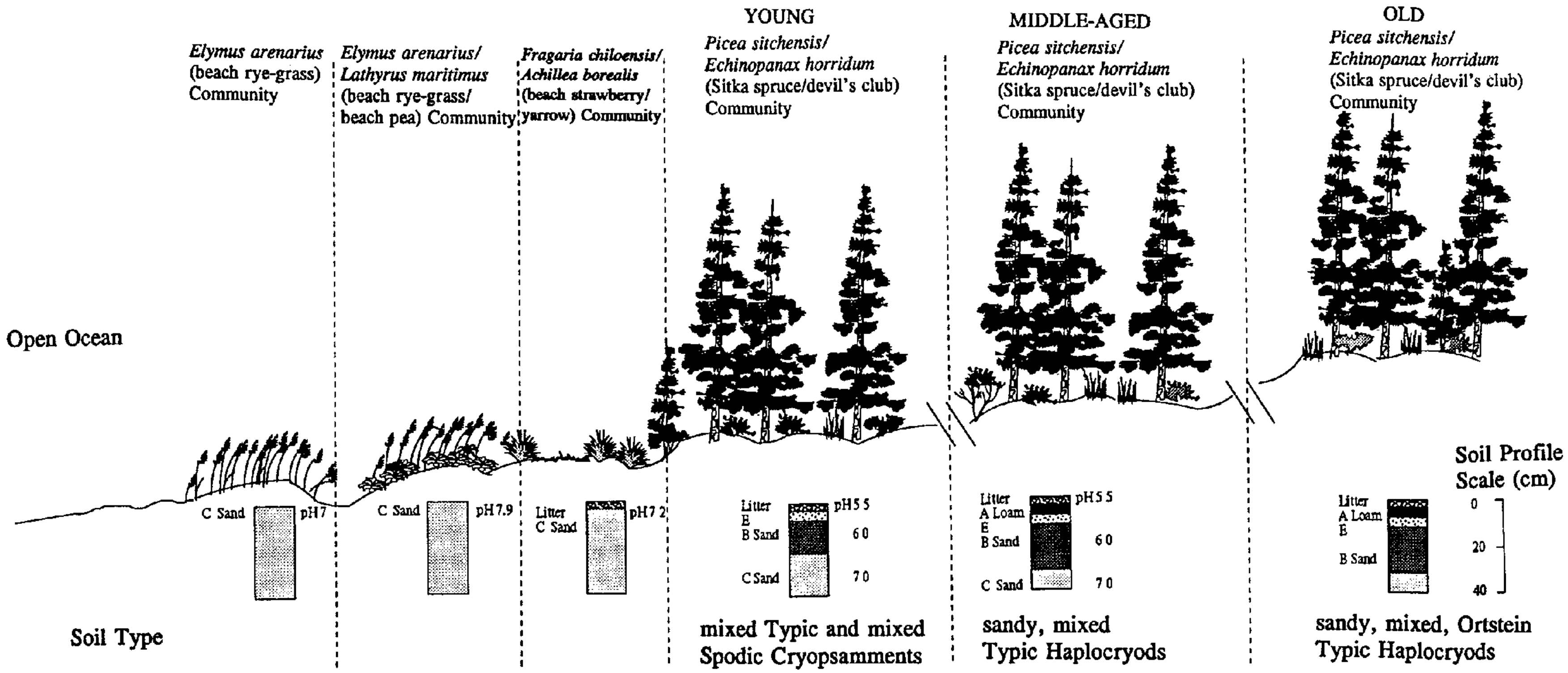

Fig. 2. Schematic diagram showing the successional pattern and gradients of soil horizon development on uplifted beach ridges of the Yakutat foreland.

Table 1. Constancy (CON) and percent cover (COV) for species exceeding 20% constancy for all stands on young, middle and old uplifted beach ridges. REGEN are saplings <10 cm dbh.

	YOUNG		MIDDLE		OLD	
	N=6		N=4		N=5	
SPECIES	CON	COV	CON	COV	CON	COV
TREES						
Picea sitchensis (Bong.) Carr	100	56	100	36	100	46
Tsuga heterophylla (Raf.) Sarg.	0	0	0	0	20	40
Picea sitchensis REGEN	100	2	50	1	40	1
Tsuga heterophylla REGEN	33	2	0	0	60	2
SHRUBS						
Alnus crispa sinuata (Regel) Hult.	0	0	25	10	40	4
Echinopanax horridum (Sm.) Decne. & Planch.	100	56	70	70	100	67
Rubus spectabilis Pursh	67	1	100	12	100	15
Vaccinium spp.	100	17	100	2	100	10
Viburnum edule (Michx.) Raf.	83	2	0	0	0	0
HERBACEOUS						
Circaea alpinum L.	67	3	100	28	80	6
Cornus canadensis L.	100	2	0	0	20	1
Listera cordata (L.) R. Br.	50	1	0	0	60	1
Rubus pedatus Sm.	100	23	75	2	80	18
Streptopus amplexifolius (L.) DC.	100	2	100	1	100	2
Tiarella trifoliata L.	100	9	100	8	100	8
FERNS						
Athyrium filix-femina (L.) Roth	83	2	100	11	80	9
Dryopteris dilatata (Hoffm.) Gray	100	9	100	3	100	11
Gymnocarpium dryopteris (L.) Newm.	100	5	100	6	100	6
Lycopodium annotinum L.	50	4	25	1	20	1
Polystichum braunii (Spenn.) Fee	0	0	75	3	20	1
Polypodium vulgare L.	100	1	100	100	60	1
Thelypteris phegopteris (L.) Slosson	0	0	100	1	80	1

1% to 15%) and Sitka alder (Alnus crispa sinuata) (from 0% to 4%) which grew in canopy gaps at the older sites. Although percent cover of mosses was not recorded for all plots, the main moss species of the younger beach ridges are Hylocomium splendens, Rhytidiadelphus loreus and Dicranum sp., while on the older beach ridges, Climacium dendroides codominates with the other three mosses. One of the five stands from the old ridges had an overstory dominated by western hemlock (Tsuga heterophylla), with large Sitka spruce intermixed.

Mean spruce dbh increased from 52 ± 22 cm on the young ridges to 69 ± 29 cm on the old ridges (Figure 3). Overall, less than 1% of the spruce tallied was greater than the 90 cm diameter size class on the young ridges, while 24% of the spruce were greater than the 90 cm size class on the old ridges. Neither the density (spruce/ha) nor the basal area (m^2/ha) showed a consistent trend across the chronosequence, as the middle-aged ridges had the lowest stocking. Nonetheless the spruce density of the old ridges decreased 35% compared to the young ridges, while the basal area of the old ridges increased 20% compared to the young ridges (Table 2). Recruitment of spruce into the subcanopy decreases over the chronosequence, as both the density and basal area decrease with age across the chronosequence. Few western hemlock occur across the chronosequence. There were 13 trees in one stand on one of the old beach ridges that ranged in size from 12 to 105 cm dbh (Table 2); none on the middle-aged ridges; and one tree in the subcanopy on the young beach ridges.

On the youngest beach ridges, seven spruce cored at breast height had 150-280 annual rings. The specific age range is unknown for the intermediate and old beach ridges since the trees were too large to be cored with available equipment. However, based on the cores taken and the forest and soil structure the forests are interpreted to be first generation. The inferred age for the entire chronosequence is approximately 200-700 years, although the dating and explanation of the beach ridges is beyond the scope of this paper. Molnia (1986) has radiocarbon bulk dates from 180 ± 70 to 2560 ± 80 yrs BP for wetlands between several ridges that we sampled. However, the radiocarbon-dated basal organics may be contaminated from outburst flood events depositing older organics on a younger surface, and hence may not reflect the date of beach ridge formation and initial forest establishment (D. Peteet, personal communication 1993).

Tree ages have been investigated for four successive uplifted terraces north of Yakutat near Icy Cape (Beavan et al. 1979; Jacoby and Ulan 1983). In that chronosequence the substrate varied from clay to gravel. Jacoby and Ulan (1983) interpret the beach ridge forests to be first generation. Beavan et al. (1979) estimate the forest ages to be 80, 420, 590, and 680 years old based on the thousands of tree stumps left by recent logging.

Soils

The soils on the beach ridges are primarily Spodosols, and follow a successional sequence across the ridges from immature soils on the youngest ridges (Spodic Cryopsamments) to well-developed Spodosols with an organic-sesquioxide cemented horizon on the oldest ridges (ortstein Typic Haplocryods). B horizon thickness averaged 25 cm ± 6 on the youngest beach ridges and increased to 75 cm ± 6 on the oldest beach ridges. Similarly, the albic, or E horizon, averaged 3 cm ± 1 when it occurred on the youngest beach ridges and 8 cm ± 5, on the oldest beach ridges where it was always present.

Discussion

The present beach likely represents the initial phase of plant succession for this chronosequence. Spruce seedlings become established in the Fragaria chiloensis/Achillea borealis backbeach meadow, but generally do not survive, probably due to excessive salt spray. Further removed from the ocean, however, spruce seedlings can establish and will succeed in the Fragaria/Achillea community. The ecotonal spruce community has three times the density of spruce as the young beach ridges. The high density may be a result of factors such as numerous safe germination sites, high light availability, and little root competition in the old backbeach meadow.

It appears that a Picea sitchensis/Echinopanax horridum community becomes established about 130 years after beach ridge formation, after which time a spruce forest persists for several hundred years. Recruitment of seedling and saplings into the subcanopy declines over this chronosequence (Table 2). This is the same pattern seen at the oldest sites near the mouth of Glacier Bay (Fastie 1994), and may be because spruce soil inhibits germination and initial establishment of seedlings (Chapin et al. in press). The middle-aged ridges have the lowest density and basal area of the three age groups. This may be because of our small sample size, or because these ridges followed a somewhat different successional pathway caused by other factors.

Western hemlock occurred in only one stand in the old beach ridges. For this stand, the density of western hemlock in the subcanopy was over three times the subcanopy density of spruce (Table 2). This suggests that the nearly pure Sitka spruce stands may be replaced with a mixed Tsuga heterophylla/Picea sitchensis community. This change may be due to the development of soils along the chronosequence or to other factors such as increased western hemlock seed

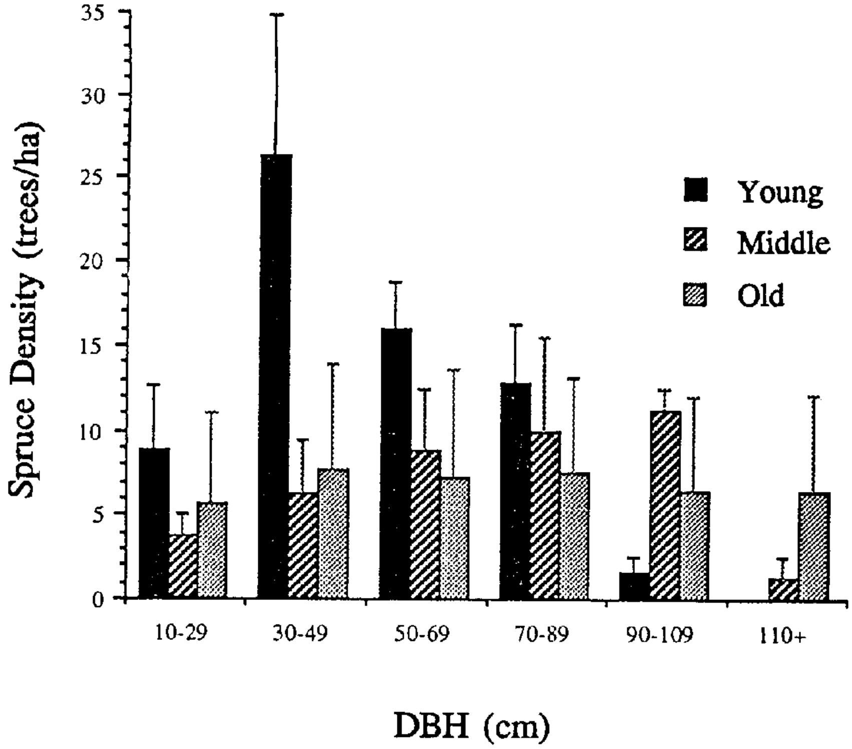

Fig. 3. The mean number (± SD) of Sitka spruce (*Picea sitchensis*) per hectare within each size class for the three age groups of uplifted beach ridges.

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Table 2. Stand density (plants/ha) and basal area (m^2/ha) of Sitka spruce in the three age classes of the beach ridge chronosequence. Data are means ± 1 SE. Sample size (*n*) is the number of 500 m^2 sampling plots per age class.

	SPRUCE*						
		Stand density			Basal area		
	n	Sub-canopy	Over-story	Total trees	Sub-canopy	Over-story	Total trees
YOUNG	5	84±26	252±34	336±13	6.8±4	75.9±11.0	82.7±8.4
MIDDLE	4	25±10	140±29	165±25	2.1±1	68.8±11.0	70.9±10
OLD	4	20±8	200±36	220±43	1.5±1	102.9±4.3	104±3.9

* For the one stand in which western hemlock occurred (on the old beach ridges), hemlock subcanopy stand density = 80; overstory stand density = 180. Subcanopy basal area = 1.4; overstory basal area = 57.3. SE is not given as they were all in one plot.

rain or changes in the understory light environment which can affect seed germination and survival.

The excessively stocked ecotonal forest suggests that these beach ridges follow a successional model for sites close to a spruce seed source, and hence go through a densely stocked phase much like sites near the terminal moraine in Glacier Bay (Fastie 1994). One of the differences may be that for the oldest sites in Glacier Bay both Sitka spruce and western hemlock seed rain existed, while for Yakutat, western hemlock seed rain may have been rare, with the exception of the one stand (Table 2). However, for the oldest Glacier Bay sites (Fastie 1994), the stem density is higher, while the basal area is lower than for the young beach ridges (Table 2). This suggests that other factors such as nutrient availability or initial seedling density and the ensuing rate of stem exclusion may also be important differences between Glacier Bay and Yakutat successional pathways.

If iron cementation continues within the B horizon it may eventually form an iron pan and impede water movement. A successional change from forest to peatland caused by iron pan development has been described for old beach terraces in the Lituya Bay region (Ugolini and Mann 1979). Hence, after several thousand years a peatland may also develop on the Yakutat beach ridges. Indeed, a peatland is typically the last stage in plant succession on level surfaces (without soil disturbance) in Southeast Alaska (Ugolini and Mann 1979).

Differences in seed rain, substrate, disturbance or climate must be considered when studying chronosequences (Fastie 1990). Distance to reproducing spruce stands has played a significant role in the rate of early spruce invasion at different sites in Glacier Bay, and explains a portion of the different successional pathways between young and old sites (Fastie 1994). Spruce seed rain is probably not an important factor in Yakutat, as spruce has been present in the Pike Lakes area (20-35 kilometers from the oldest beach ridges) for the last 10,000 yr (Peteet 1991), and it is likely that spruce has been present for the last few millennia in other areas closer to the oldest beach ridges. Substrate differences among ridges are minimal in this sequence since beach sand is the parent material for all ridges. There is no apparent evidence of differences in disturbance regime among ridges, or a regional shift in disturbance regime occurring during the development of the chronosequence. However, major climatic fluctuations such as the Little Ice Age could have altered successional patterns, and might be a factor in the structural differences within the middle-aged ridges (Table 2).

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How Unique is Primary Plant Succession at Glacier Bay?

by

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Abstract

I compared primary succession at Glacier Bay, Alaska to succession on the floodplain of the Tanana River in central Alaska, and to other primary seres from around the world in order to test the validity of generalizing about successional processes from site-specific studies. Experimental studies at Glacier Bay and at the Tanana River were similar enough to provide an opportunity for a detailed cross-site comparison. Despite substantial differences in the physical characteristics of the soils at the two sites, overall patterns of nitrogen accumulation were similar, presumably due to the major influence of alder at both sites. However, the initial levels of nitrogen were higher at the Tanana River than at Glacier Bay. Similar experiments at the two sites indicated that the growth of natural and transplanted spruce seedlings increased in the alder stage at Glacier Bay but not at the Tanana River. Soils of the alder stage from Glacier Bay but not from the Tanana increased growth of spruce seedlings in a greenhouse. Surveys of other primary seres suggest Glacier Bay had one of the slowest rates of nitrogen accumulation not only among other post-glacial seres but among most other primary seres. Outside of Glacier Bay, experimental evidence of facilitation by nitrogen fixers is lacking. Low initial levels of nitrogen and relatively low rates of nitrogen accumulation at Glacier Bay, coupled with a moist climate favorable for growth may provide unusually favorable conditions for growth of and facilitation by vascular plants associated with symbiotic nitrogen fixers.

KEY WORDS: Alder, facilitation, Glacier Bay, nitrogen, plant succession, seedlings, spruce, Tanana River.

Glacier Bay is widely cited as a classical example of facilitation in primary succession because correlations have been documented between soil nitrogen increases and the presence of the nitrogen-fixing alder (*Alnus sinuata*) (Crocker and Major 1955). Lawrence et al. (1967) demonstrated experimentally that alder stimulated growth of cottonwood (*Populus trichocarpa*) at Glacier Bay. Only recently has experimental evidence been provided to support the long-held assumption that alder also facilitates the growth of the late successional spruce (Picea sitchensis) (Chapin et al. 1994). However, succession is the result of many interacting processes (Pickett et al. 1987, Walker and Chapin 1987) and studies of plant succession at Glacier Bay confirm that alder not only facilitates but also inhibits spruce growth (Chapin et al. 1994, Fastie 1994).

Evidence of the importance of facilitation at Glacier Bay does not imply that facilitation is important in succession elsewhere. In this manuscript I examined the validity of the generalizations made about primary succession based on studies at Glacier Bay. I compared nitrogen accumulation at

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Glacier Bay to accumulation in other primary seres throughout the world. I also tested whether the relative importance of facilitation depended on initial nitrogen levels by comparing succession at Glacier Bay with succession on the Tanana River floodplain in central Alaska where the successional pathways were similar but where initial nitrogen levels were higher.

Study Sites

Plant succession on the Tanana River floodplain (TN) in central Alaska (Viereck et al. 1993) is similar to succession at Glacier Bay (GB) (Cooper 1923, Reiners et al. 1971). In addition, similar experimental methods were used in a study of TN conducted between 1981-1984 (Walker et al. 1986, Walker and Chapin 1986, Walker and Chapin 1987, Walker 1989) and in a study of GB conducted between 1985-1989 (Fastie 1993; Chapin et al. 1994; Chapin et al., this volume; Fastie, this volume). The similarity of methods provided a rare opportunity for a detailed comparison of successional mechanisms at the two sites. Both studies had replicate sites (TN:5; GB:10) in several successional stages (TN:6; GB:4) dominated by similar plant genera (Table 1). Seed mass, plant height, age of first reproduction, and longevity of plants all increased during succession. The comparisons exclude successional stages dominated by *Populus* because *Populus* stands were not studied at GB. One important difference in sampling was the depth of samples of mineral soil (TN: 20 cm; GB: 10 cm).

Results

Despite substantial differences in the physical characteristics of the soils between TN and GB (Fig. 1a-1c), nitrogen dynamics were similar (Fig. 1d-1f), presumably due to the dominant influence of alder at each site. Mineral soil pH (Fig. 1a) declined at both sites due to the influence of acidic litter, but bulk density of mineral soil particles <2 mm diameter (Fig. 1b) was much higher at GB than at TN due to higher sand content of the glacial till (GB: sand 65%, silt 25%, clay 10%; TN: sand 34%, silt 64%, clay 2%). Gravimetric water in mineral soils (Fig. 1c) decreased during succession at TN as both vertical and horizontal distances from the river increased; soil water increased during succession at GB. Mineral soil nitrogen concentrations (Fig. 1d) and nitrogen pools (Fig. 1e) increased at both sites and the initial levels were higher at TN than at GB. The higher pool sizes at TN may in part reflect the deeper soil samples. Yet, when mineral soils were sampled to 48 cm depth at an alternative series of GB sites, N pool sizes were still less than at comparable TN sites (pioneer stage: 17 ± 1 g/m^2; alder stage: 51 ± 7 g/m^2; spruce stage: 101 ± 14 g/m^2; Fastie 1993). Nitrogen accumulation rates in mineral soil were also higher at TN than at GB (Fig. 1f), even when deeper mineral soil samples were taken at GB (alder: 0.92; spruce: 0.46; Fastie 1994). The extremely high rates of accumulation in the willow stage at TN have several possible explanations: a) continued nutrient additions in flood waters from upstream alder stands, b) mixing of organic layers with mineral soils, c) rapid growth of free-living nitrogen-fixers in the anaerobic environment, and d) the stochastic nature of alder establishment, leading to high local spatial variation in soil N levels (Walker 1989).

Seed rain at both sites was highest in the stage dominated by the plant species producing those seeds (Fig. 2), and numbers of seeds were remarkably similar considering the differences in species and environment. Chapin (1993) noted the importance of seed mass in determining seed arrival times in primary succession. Lighter-seeded species such as *Dryas* (GB) or *Salix* and *Populus* (TN) were usually the first colonizers. Heavier alder and spruce seeds were slower to reach the early successional stages. The presence of spruce seeds in early succession at TN reflects the shorter distance between early and late successional stages at TN than at GB where recently exposed moraines are far from a spruce seed source. Older moraines at GB may have been more readily colonized by spruce seeds from nearby old growth forests (Fastie 1994).

Factors limiting seed germination were also similar at both sites. Germination of sown alder seeds was limited to early successional stages on undisturbed surfaces at both sites (Fig. 3a) but alder seeds germinated in later successional stages at both sites when the inhibiting leaf litter, moss and organic horizons were removed (Fig. 3b). Spruce was able to germinate on undisturbed alder litter at TN and on the undisturbed spruce forest floor at GB (Fig. 3c). Exposure of mineral soil, therefore, did not alter germination patterns of spruce as it did with alder (Fig. 3d). At both sites alder could not continue to colonize after establishment of the alder thicket, but spruce was not limited in the same way.

The ability of seeds to grow once they arrived at a stage was tested with measurements of naturally occurring spruce seedlings and seedlings transplanted into each successional stage. The relative growth rate (RGR) of naturally occurring spruce seedlings (based on current year twigs and leaves) declined in the alder stage at TN compared to the pre-alder silt (Fig. 4). Similar measurements of spruce seedlings at GB suggested highest growth occurred in the *Dryas* stage. However, calculations of RGR that incorporated secondary stem growth at GB indicated higher growth of spruce in the alder than pre-alder stages (Chapin et al. 1994). Thus, the more complete measure of growth that included secondary growth showed a net facilitation of spruce relative growth by the alder stage. Secondary growth was not measured at TN.

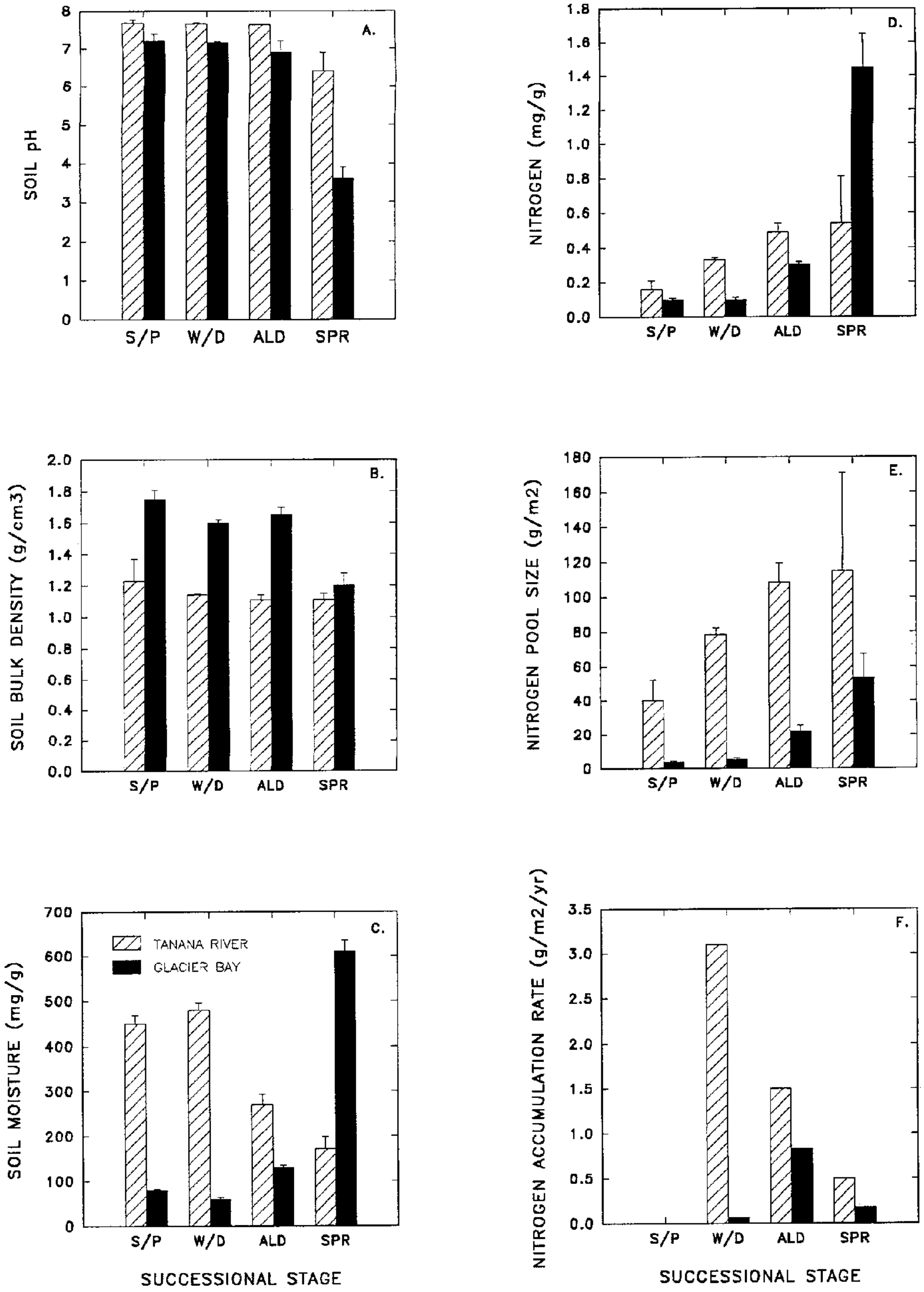

Fig. 1. Soil pH, bulk density, and soil moisture (left column) and mineral soil nitrogen concentrations, pool sizes, and accumulation rates (right column) at the Tanana River (hatched bars) and Glacier Bay (solid bars) at four successional stages: S/P = silt (Tanana) or pioneer vegetation (Glacier Bay); W/D = willow (Tanana) or *Dryas* (Glacier Bay); ALD = alder at both sites; SPR = spruce at both sites. See text and Walker (1989), Chapin et al. 1994 for details.

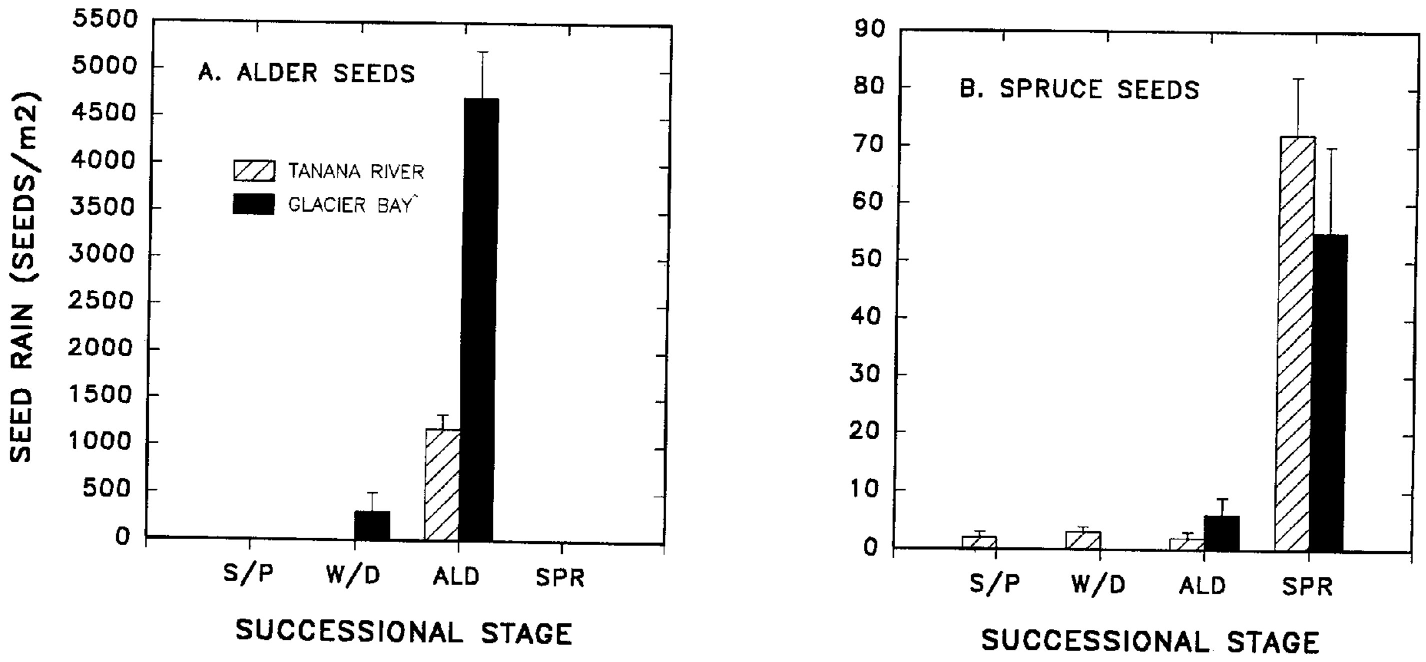

Fig. 2. Seed rain trapped during one fall and winter for alder and spruce seeds at TN (1982) and GB (1987) in four successional stages. Stages are identified in Fig. 1. Adapted from Walker et al. 1986 and Chapin et al. 1994.

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Table 1. A comparison of successional stages and dominant vascular species at the Tanana River and Glacier Bay Approximate ages of each stage are shown in parentheses.

Stage	Tanana River	Glacier Bay
Silt / Pioneer	None (0)	None (5)
Willow / *Dryas*	*Salix alaxensis* (10)	*Dryas drummondii* (30)
Alder	*Alnus tenuifolia* (30)	*Alnus sinuata* (60)
Spruce	*Picea glauca* (125)	*Picea sitchensis* (200)

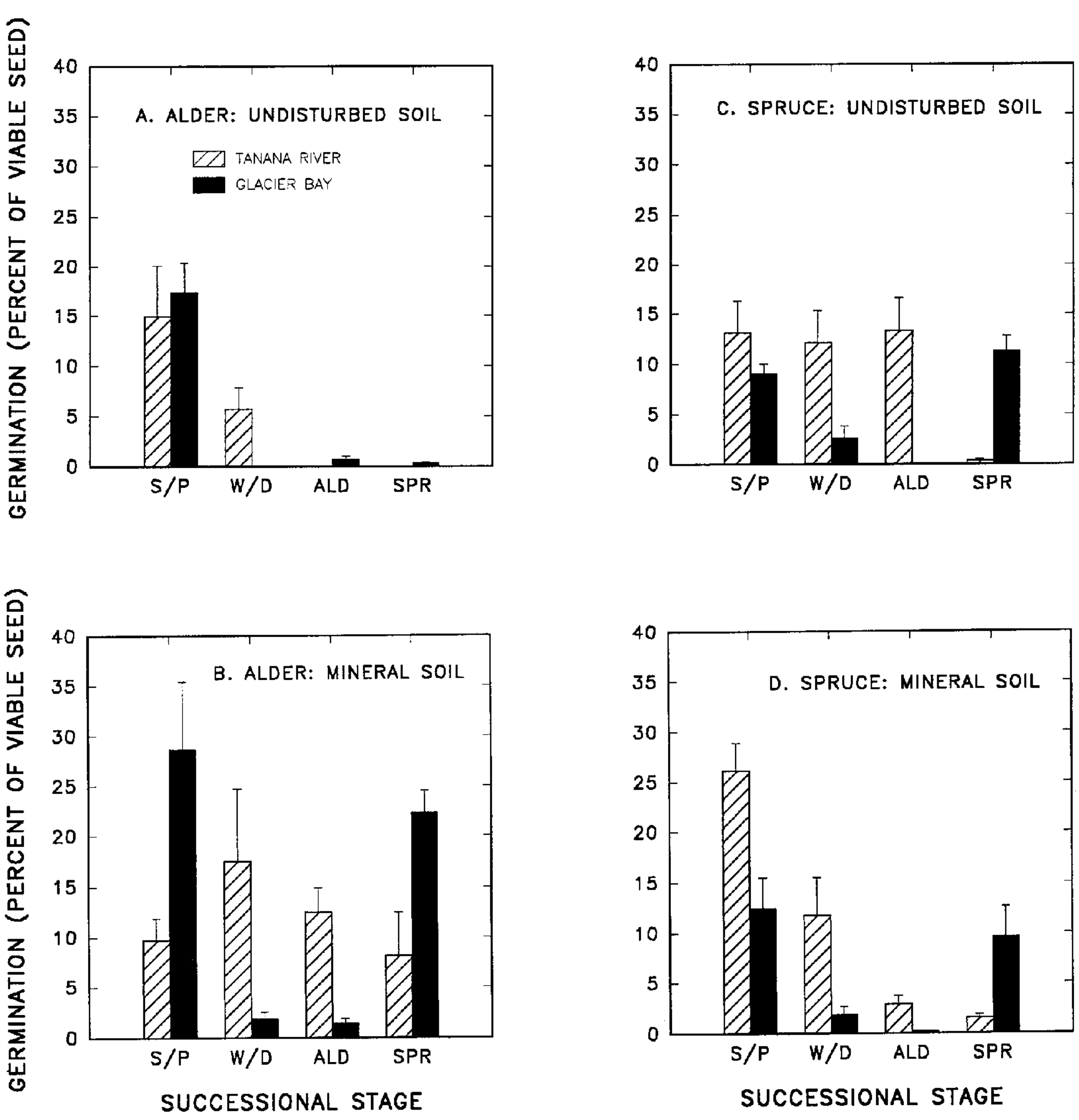

Fig. 3. Germination of alder and spruce seeds on undisturbed and disturbed (surface litter removed to expose mineral soil) substrates at two sites and four successional stages. Stages are identified in Fig. 1. Adapted from Walker et al. 1986 and Chapin et al. 1994.

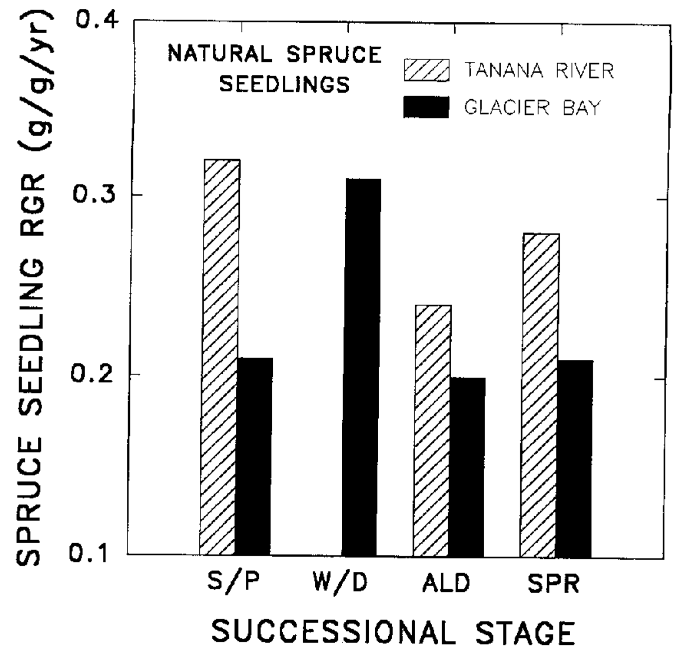

Fig. 4. Relative growth rate (RGR) of naturally occurring spruce seedlings at two sites and four successional stages. Stages are identified in Fig. 1. Adapted from Walker and Chapin 1986 and Chapin et al. 1994.

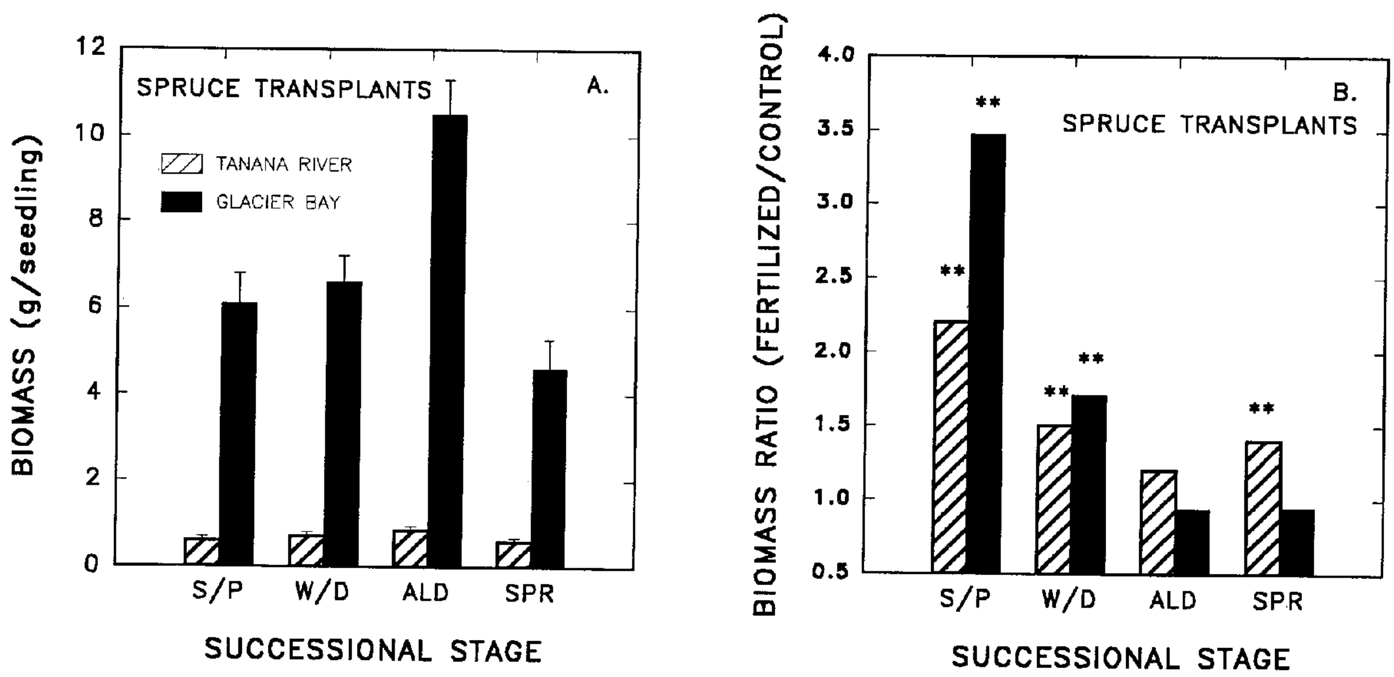

Fig. 5a. Biomass of spruce seedlings transplanted into four successional stages at two sites. Seedlings were harvested after 2 (TN) and 3 (GB) growing seasons in the field. **Fig. 5b.** Ratios of biomass of fertilized to control spruce seedlings at four successional stages at two sites. Asterisks indicate a significant fertilizer effect. Fertilizers (NPK at TN, ground alder leaves at GB) were applied at rates similar to normal nutrient additions from alder. Adapted from Walker and Chapin 1986 and Chapin et al. 1994.

Table 2. Seedling growth in a greenhouse in soils from four successional stages (roots plus shoots; mg/plant).

Species	Site	Silt/Pioneer	Willow/*Dryas*	Alder	Spruce
Alder	TN	175 ± 70	nd	60 ± 20	nd
	GB	13 ± 2	1567 ± 317	298 ± 181	3225 ± 583
Spruce	TN	6 ± 1	nd	4 ± 1	nd
	GB	27 ± 2	41 ± 3	43 ± 5	147 ± 29

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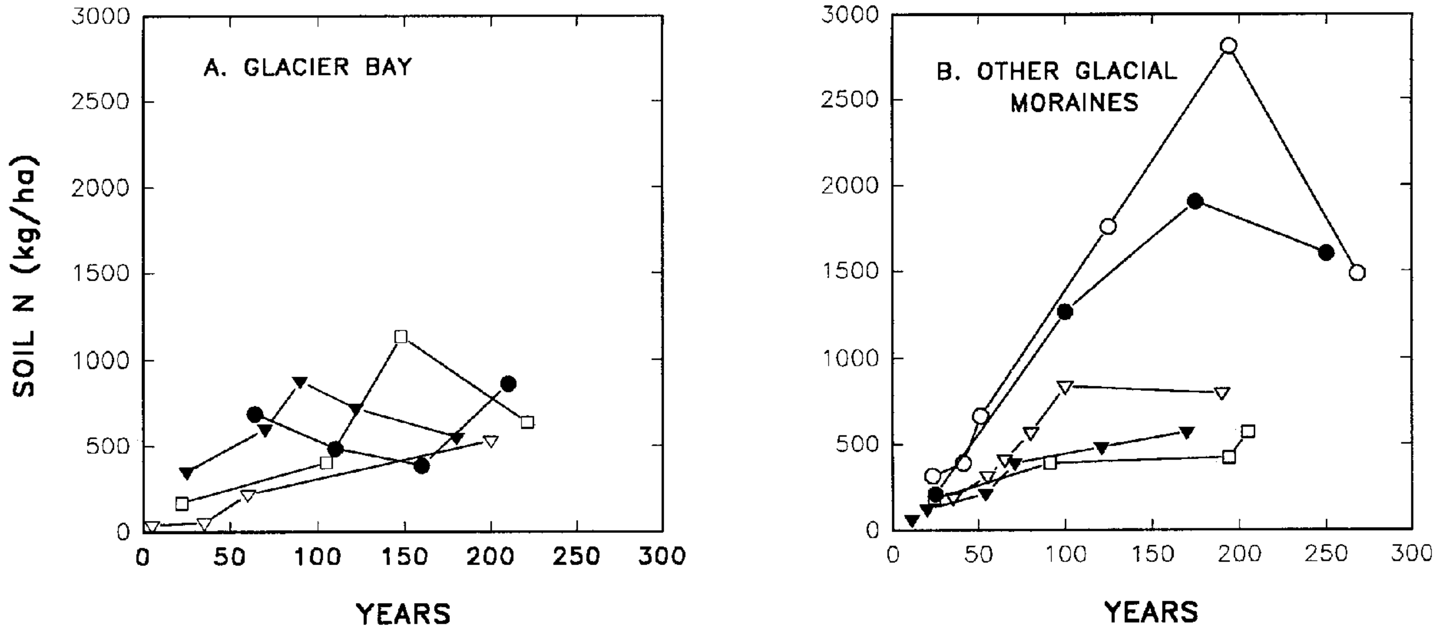

Fig. 6. Total soil nitrogen in surface mineral soils to depths of 10-25 cm from four different data sets from Glacier Bay (6a) and from five different glacial moraines with dominant N fixers (6b). kg N/ha = bulk density X depth (cm) X ppm N/10. Modified from Walker 1993. Key for **6a**: open squares: Fastie 1994; closed circles: Bormann & Sidle 1990; closed triangles: Crocker & Major 1955; open triangles: Chapin et al. 1994. Key for **6b**: open circles: Jacobsen & Birk 1980; closed circles: Viereck 1966; open triangles: Sondheim & Standish 1983; closed triangles: Crocker & Dickson 1957 (Mendenhall Glacier); open squares: Crocker & Dickson 1957 (Herbert Glacier).

Transplanted spruce seedlings showed a significant increase in growth in the alder stage compared to pre-alder stages at GB but not at TN (Fig. 5a). However, growth of willow and poplar seedlings did increase in the alder stages at TN (Walker and Chapin 1986). The difference in spruce seedling responses to the alder stage may be due to the higher nitrogen levels in pre-alder soils found at TN than at GB. In addition, growth of alder and spruce seedlings in pre-alder and alder soils under controlled greenhouse conditions did not differ in the relatively high- nutrient soils of TN (Table 2) (Walker and Chapin 1986) but growth of alder and spruce did increase with soils of successive stages (Chapin et al. 1994) in the relatively low nutrient GB soils. Alternatively, the alder thicket may be more important in providing mycorrhizal fungi or increasing soil water-holding capacity for spruce seedlings at GB than at TN.

The alder stage clearly increased the nutrient content of spruce seedlings. Nitrogen and phosphorus concentrations in transplanted spruce seedlings were higher in the alder stage than in pre-alder stages at both sites (Walker and Chapin 1986, Chapin et al. 1994). Significant increases in dry mass of fertilized spruce seedling transplants compared to unfertilized controls occurred in both pre-alder stages at both sites but not in the alder stage itself (Fig. 5b), suggesting that nutrients did not limit spruce growth in the alder stage.

Alder thickets may have detrimental effects on spruce seedlings as well. Possible root competition between overstory alder and understory spruce seedlings was investigated by trenching at both sites. Soil nitrogen (at TN) increased in trenched plots, and growth, nitrogen, and phosphorus concentrations of spruce seedlings were higher in trenched plots than controls at both sites, suggesting an inhibitory effect of the alder stage on spruce seedlings.

Discussion

Primary succession at TN is similar in many ways to succession at Glacier Bay. Despite differences in soil physical characteristics, patterns of soil nitrogen increase are similar, although at different magnitudes and rates. At both sites, colonizing spruce seedlings are both facilitated and inhibited by existing alder stands. Yet facilitation of spruce seedlings by the alder stage appears to be relatively more important for spruce seedlings at GB than at TN. Higher soil N levels at TN provide a plausible explanation for these site differences.

The comparison of GB and TN suggests that despite strong similarities, generalizations about the role of facilitation and inhibition developed at GB cannot be applied to TN without some modification. Glacier Bay has even less similarity to other primary seres. For example, the rate of nitrogen accumulation in mineral soil at GB (Fig. 6a) was among the slowest for post-glacial seres with dominant nitrogen fixers (Fig. 6b) (depending on which study one uses to represent GB). Variability among soil nitrogen studies at GB resulted in part from different sample sites and methodologies (Fig. 6a) and suggests the difficulty in making intra- and inter-site comparisons. Nitrogen accumulation can be much slower on post-glacial seres in severe alpine or arctic environments (Matthews 1992), and post-glacial seres were slower to accumulate nitrogen than any other type of primary sere except sand dunes (Walker 1993).

Experimental evidence of facilitation by vascular nitrogen-fixing plants in primary succession is limited to GB (Lawrence et al. 1967, Schoenike 1984, Chapin et al. 1994). Although a facilitative role for vascular nitrogen-fixers is widely assumed, the majority of observations in one survey suggested that the direct effect of nitrogen fixers on other species was more often inhibitory than facilitative (Walker 1993). Nevertheless, nitrogen fixers are often centers for colonization by other species in early succession (Matthews 1992) for reasons unrelated to their ability to fix nitrogen (e.g., they alter light and water availability, or provide suitable microsites for germination). The importance of microbial colonizers as obligatory precursors in primary succession is better established (Wynn-Williams 1993).

Too little is known about N accumulation and the relative importance of facilitation in primary succession to make detailed comparisons among GB and other primary seres. Stochastic and environmental factors that affect colonization and growth of dominant nitrogen fixers such as alder or *Dryas* may be as central in determining the importance of facilitation as the initial nitrogen levels in the soil. Walker (1993) found no correlation between the abundance of vascular nitrogen fixers and nitrogen accumulation rates. Yet as succession proceeds, and autogenic processes dominate (Matthews 1992), the importance of facilitation is expected to decline (Walker and Chapin 1987). The low initial levels of N at GB, coupled with a moist climate favorable to growth may provide an optimal environment for establishment of alder and therefore increase the importance of facilitation compared to other primary seres.

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Patterns of Early Lake Ontogeny in Glacier Bay as Inferred from Diatom Assemblages

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Abstract

We studied a series of recently formed lakes along a deglaciation chronosequence in Glacier Bay National Park to examine changes in water chemistry, primary production, and biotic composition that accompany the early ontogeny of north-temperate lakes. Successional trends in these freshwater ecosystems have been explored with a two-tiered approach that includes (1) the comparison of limnological conditions among lakes of known age and in different stages of primary catchment succession, and (2) the inference of water-chemistry trends in individual sites based on fossil diatom stratigraphy This paper emphasizes the reconstruction of limnological trends from fossil diatom assemblages. The modern distribution of diatoms in relation to water-chemistry gradients within 32 lakes of varied age is used to derive a transfer function for the reconstruction of chemical trends from fossil assemblages in sediment cores. The modern data suggest that pH and TN (total nitrogen) exert significant and independent controls on diatom distributions, and thus trends in these variables are reconstructed for Bartlett Lake, as an example of our approach. Core reconstruction corroborates patterns in pH suggested by the modern chronosequence and shows a gradual decline in lakewater pH after about 100 years. The Bartlett Lake core also follows the chronosequence pattern in TN concentration, with an initial increase followed by a decline after ca. 100 years. Reconstructions from other sites, however, suggest that trends in total nitrogen concentration are variable, and thus that localized patterns of plant colonization and soil development may result in regional variability in lakewater nitrogen concentration over time.

KEY WORDS: Chronosequence, diatoms, paleolimnology, succession, lake chemistry

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The description and evaluation of patterns and controls of long-term limnological change over time has been a major theme in limnology since the work of Pearsall in the English Lake District in the 1920s (Pearsall 1932). Because direct observation of lake development over long temporal scales (decades, centuries, millennia) is usually impossible, limnologists rely on fossil records from lake sediments to infer patterns of limnological development and derive hypotheses about the factors controlling direction and rate. A variety of chemical and biological fossils have been utilized in these paleolimnological investigations of lake ontogeny, but one of the most widely used and sensitive groups of fossil indicators are diatoms, an abundant and ecologically diverse algal group sensitive to changes in lake chemistry and morphometry.

The Glacier Bay region offers an unusual opportunity to study patterns of early limnological development in boreal regions by comparing lakes within landscapes of differing ages and inferring patterns of limnological change from this chronosequence of sites. In essence successional patterns for lakes can be described with a space for time substitution in the same way that terrestrial succession has been described through the classic work of plant ecologists including Cooper (Cooper 1923), Lawrence (Lawrence 1958), and their colleagues.

We use a suite of regional lakes and lake catchments to evaluate several hypotheses advanced in the literature about patterns of limnological change in boreal regions. Our work includes an evaluation of chemical and biological trends in a chronosequence of 32 lakes (Engstrom and Fritz 1990), as well as the inference of temporal trends in individual sites based on diatom analysis of sediment cores. This paper includes both an examination of successional patterns in diatoms in the chronosequence and the reconstruction of water-chemistry change in one of these sites from the stratigraphy of fossil diatoms. These water-chemistry reconstructions are based on transfer functions derived from the relationships between diatoms and water-chemistry gradients in the modern lakes.

Site selection

Diatom and water-chemistry gradients were analyzed in 32 glacially formed lakes within Glacier Bay National Park. The lakes range in age from ca. 10 to 12,000 years and are in primary catchments in low-elevation forelands along the Bay and Outer Coast. Approximately two-thirds of the lakes are along the lower and east arms of Glacier Bay proper (10-220 yrs), 5 are in the Lituya Bay area (350-400 yrs), 4 south of Lituya Bay along the Outer Coast (400-2700 yrs), and 3 are outside the Neoglacial ice limit on Pleasant Island (>10,000 yrs) (Figure 1). The lakes vary in water chemistry and size, although most are relatively small (<8 ha.). Chemical and morphometric characteristics of the sites are summarized by Engstrom and Fritz (1990).

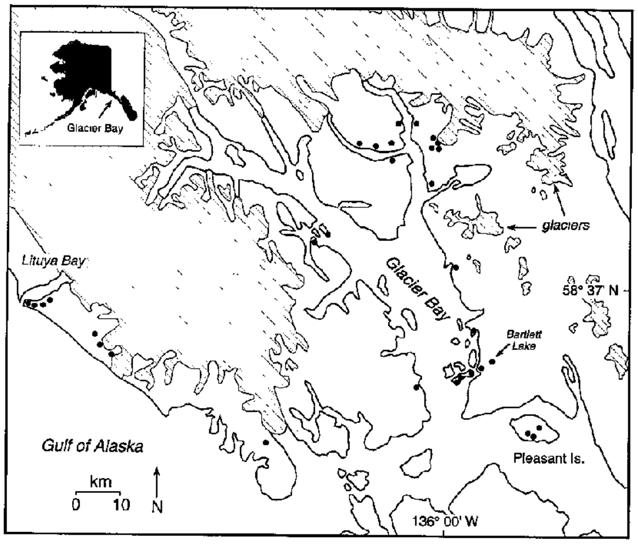

Fig. 1. Map of Glacier Bay, showing the location of the lake sites.

Methods

Field sampling and analytical methods

Each lake in the chronosequence was sampled for chemical analysis in July 1988, May 1989, and September 1990. pH and conductivity were measured in the field, and water samples were filtered for chlorophyll analysis. Color and alkalinity were measured within 12 hours of sample collection. Water was filtered and frozen for subsequent analysis of dissolved organic carbon (DOC), dissolved Si, and anions, and additional unfiltered water samples were transported to the laboratory for nutrient analysis and measurement of major cations.

The diatom analyses presented here are based on surface-sediment samples (the uppermost 1 cm from sediment cores) that represent a temporal integration of several years of sediment accumulation and a spatial integration of both littoral and open-water habitats. Sediment cores were collected from the deepwater zone of each lake with a piston corer mounted on rigid drive rods. Cores were sectioned in the field at 0.5-1.0 cm intervals, and samples were stored in polypropylene jars at 4° C until subsampled. Cores from sites older than 150 years were dated by ^{210}Pb analysis, using the constant rate of supply model (c.r.s.) to calculate age (Eakins and Morrison 1978).

Subsamples of sediment were prepared for diatom analysis by oxidizing organic matter in hot nitric acid and potassium dichromate for 15 minutes, followed by repeated rinsing of the subsample with distilled water to remove oxidation by-products. Prepared sediment was dried onto coverslips, and coverslips were mounted on slides with Naphrax. Diatoms were counted on an Olympus BH-2 microscope at a magnification of 1000x using an oil immersion objective (N.A.=1.4). A minimum of 500 individuals was counted in the surface samples and 400 in core samples.

Statistical analyses

The relationship between diatom distribution and environmental variables was determined using detrended canonical correspondence analysis (DCCA), an ordination technique that compares lakes based on their diatom assemblages and constrains each of the axes to be linear combinations of measured environmental variables. This technique is described in greater detail by ter Braak (1987). A number of variables are highly correlated (e.g. Ca, alkalinity), and thus only select variables were included in the analyses presented here.

Results and Discussion

The distribution of many diatom taxa is related to lake age (Figure 2). *Achnanthes ploensis* is present only in lakes less than 50 years in age, and *Amphora perpusilla* is abundant in many lakes less than 120 years but is rare in older sites. The benthic *Fragilaria* spp. are not present in the youngest lakes but appear in abundance after ca. 50 years. A number of taxa occur in many of the sites in the lower and east arms of Glacier Bay, including *Cymbella microcephala, Navicula cryptocephala, Navicula radiosa* v. *tenella*, but not in older sites, whereas taxa such as *Fragilaria virescens* v. *exigua, Cymbella gaeumannii,* and acidophilous *Aulacoseira* spp. are present only in the older lakes of the Outer Coast area and on Pleasant Island. *Achnanthes minutissima* is one of the few taxa that shows no age-related trends, and the *Cyclotella stelligera/glomerata/pseudostelligera* group appears in lakes of varied age.

An ordination of the diatom and water-chemistry data with DCCA suggests the major environmental gradients correlated with diatom distribution (Figure 3). The first axis is related to major-ion chemistry, including pH, calcium concentration, total silica concentration, and other correlated factors, such as alkalinity, conductivity, and water color. The second axis is related primarily to nutrient (total nitrogen TN, total phosphorus TP) and chlorophyll-a concentrations. Axis 1 and 2 account for 12.5% of the total variance in the diatom data. A low percentage of explained variance is common in complex multi-species assemblages, such as are characteristic of diatom communities in many freshwater lakes. The two principal gradients in the diatom/water-chemistry data are clearly correlated with lake age. The youngest lakes cluster in the upper left of the ordination plot (high pH, low TN), those ca. 100-300 years in the lower left of the ordination (high pH, high TN), and the older sites >300 years are arrayed along the right side of the first axis (lower pH, intermediate TN).

These data can be used to derive transfer functions for the reconstruction of water chemistry from diatom assemblages and subsequently to infer past trends in water chemistry from diatom assemblages in sediment cores. Further details on transfer function development and core reconstruction are in ter Braak (1990). Statistical analysis of the Glacier Bay diatom data using forward selection suggests that pH and TN concentrations exert significant and independent influences on diatom distributions, and thus we have reconstructed pH and TN concentrations from stratigraphic diatom data in cores.

The diatom stratigraphy of a sediment core from Bartlett Lake (Figure 4) is used as an example of the reconstruction of temporal trends in pH and TN. The core shows clear changes in the diatom assemblage over time, with *Gyrosigma spencerii, Achnanthes minutissima, Fragilaria pinnata*, and *Nitzschia fonticola* dominant in the basal sediments, deposited in the early years after lake formation. Subsequently these taxa are replaced by increasing percentages of *Fragilaria construens* v. *venter, Navicula seminuloides, N. leptostriata, Stauroneis anceps* v. *gracilis*, and *Eunotia naeglii*. Application of the transfer function to these data suggests a gradual decline in lakewater pH from ca 7.6 at the time of lake formation to 6.5 in the modern day. TN reconstruction suggests an increase in TN concentration in the early years following lake formation followed by a decline after about 100 years.

The modern water-chemistry data from the chronosequence of lakes (Engstrom and Fritz 1990) suggest that lakes begin to decline in pH 100-300 years after formation. Core reconstructions from 10 lakes ranging in age from 100 to 2000 years, including Bartlett Lake, show pH declines in lakes >100 years in age (Fritz, unpublished data). Thus, the cores verify that pH trends as inferred from the spatially arrayed modern chronosequence reflect temporal pH trends in individual sites. However, the initial starting conditions and the magnitude and rate of pH change varies among lakes, which suggests that local factors, particularly lake hydrology (Almendinger 1990), play an important role as well. TN reconstructions from these 10 lakes show more variation in pattern than is present for pH (Fritz, unpublished

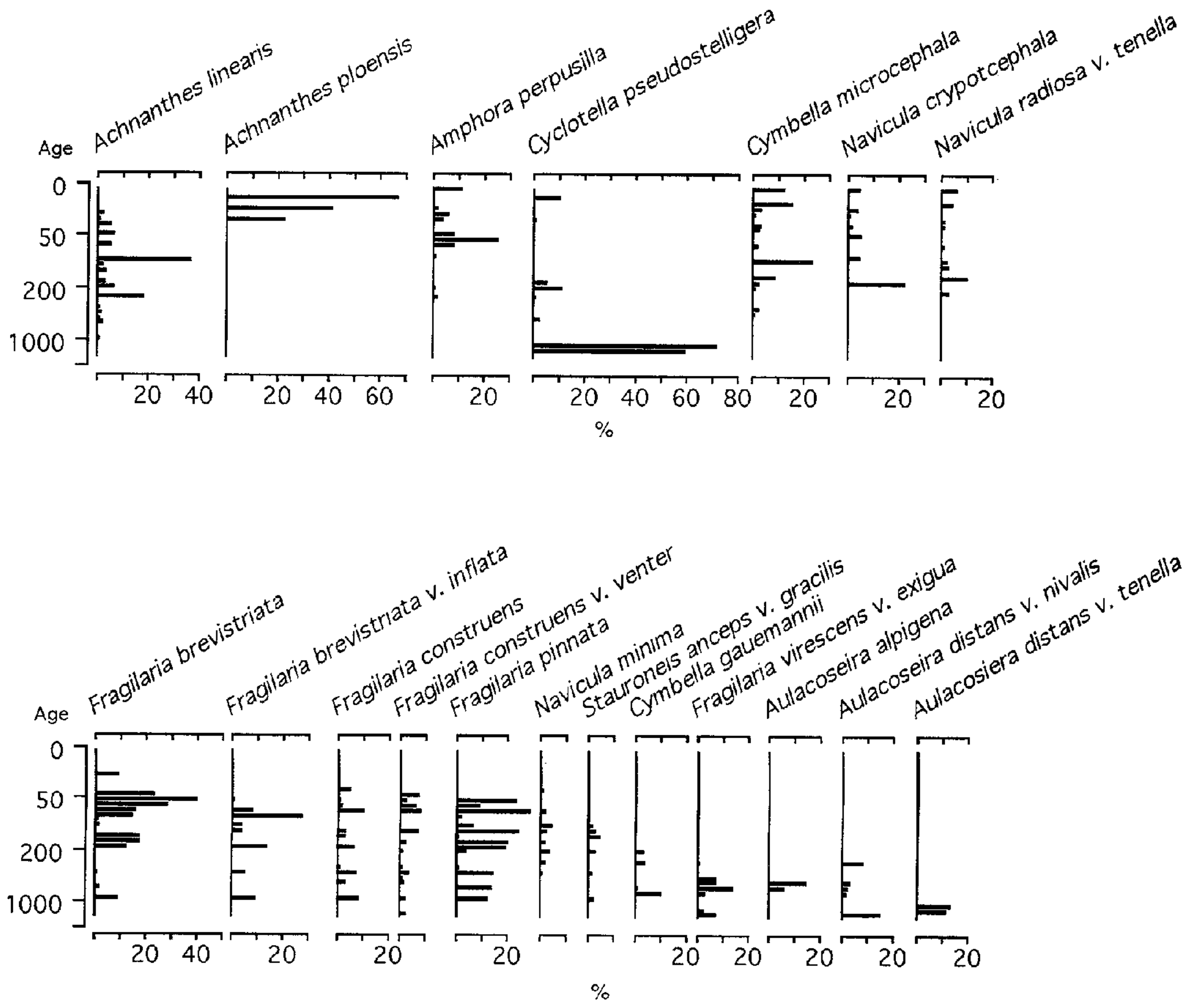

Fig. 2. Plot of the relative abundance (%) of selected diatom species along an age gradient. Lakes are arrayed on the vertical axis in order of increasing age (in years).

data). Most of the lakes in the east arm of Glacier Bay show generalized patterns similar to that of Bartlett Lake, with an early increase in TN concentration followed by a subsequent decline. Lake cores from the Outer Coast, however, show different patterns thus suggesting different environmental controls. The variability in pattern probably reflects the variability in plant succession and subsequent soil development described in recent studies on plant succession (Chapin *et al.* 1994).

The modern analyses of water-chemistry trends in the lakes of the Glacier Bay chronosequence and the diatom-inferred water-chemistry patterns suggest that both broad-scale regional processes and local variability play significant roles in determining lakewater chemistry. The dominant regional pattern is one of a gradual decline in lakewater pH through time, beginning one to several hundred years after lake formation. This decline in pH is probably primarily a result of the development of indurated soil horizons (Ugolini and Mann 1979) and the subsequent shift from a lake system dominated by calcareous groundwater flow to one receiving primarily surface runoff and flow through peaty soils. A depletion of base cations from catchment soils by leaching may also contribute to gradual loss of alkalinity. In terms of nutrient concentrations, the

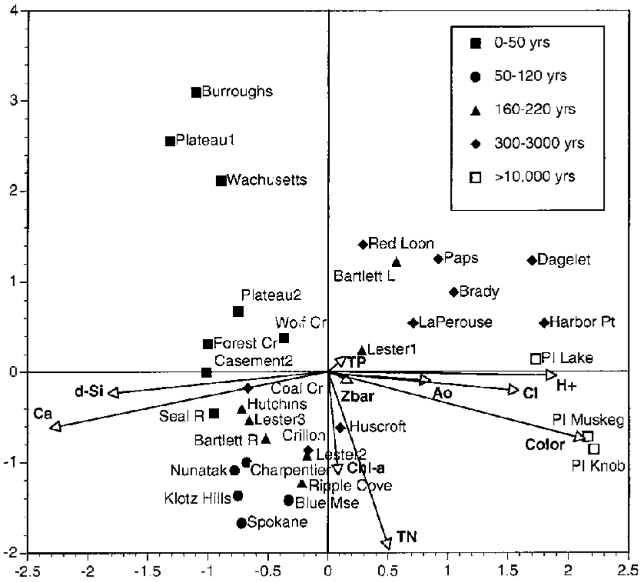

Fig. 3. DCCA ordination of the diatom assemblages in Glacier Bay lakes in relationship to selected environmental gradients. The arrows show the direction of maximum variation of the measured environmental variables (dissolved silica, d-Si; mean depth, Zbar; lake surface area, Ao; hydrogen ion concentration H+; other symbols as mentioned in text). Sites plotting close together have similar diatom composition, while those at distance from one another are more dissimilar.

chronosequence data suggest that lakewater nutrient trends, specifically those in total nitrogen, follow patterns in soil nitrogen as suggested by Crocker and Major (1955) with a gradual increase in concentration, followed by a subsequent decline. Core reconstructions, however, suggest variability in temporal changes in lake nitrogen, possibly reflecting variability within the region in plant succession and soil development. Clearly subsequent research should involve coupled studies of the chemical and hydrologic linkages between aquatic and terrestrial systems, thus providing a mechanistic understanding of the processes that drive the observed patterns of limnological change.

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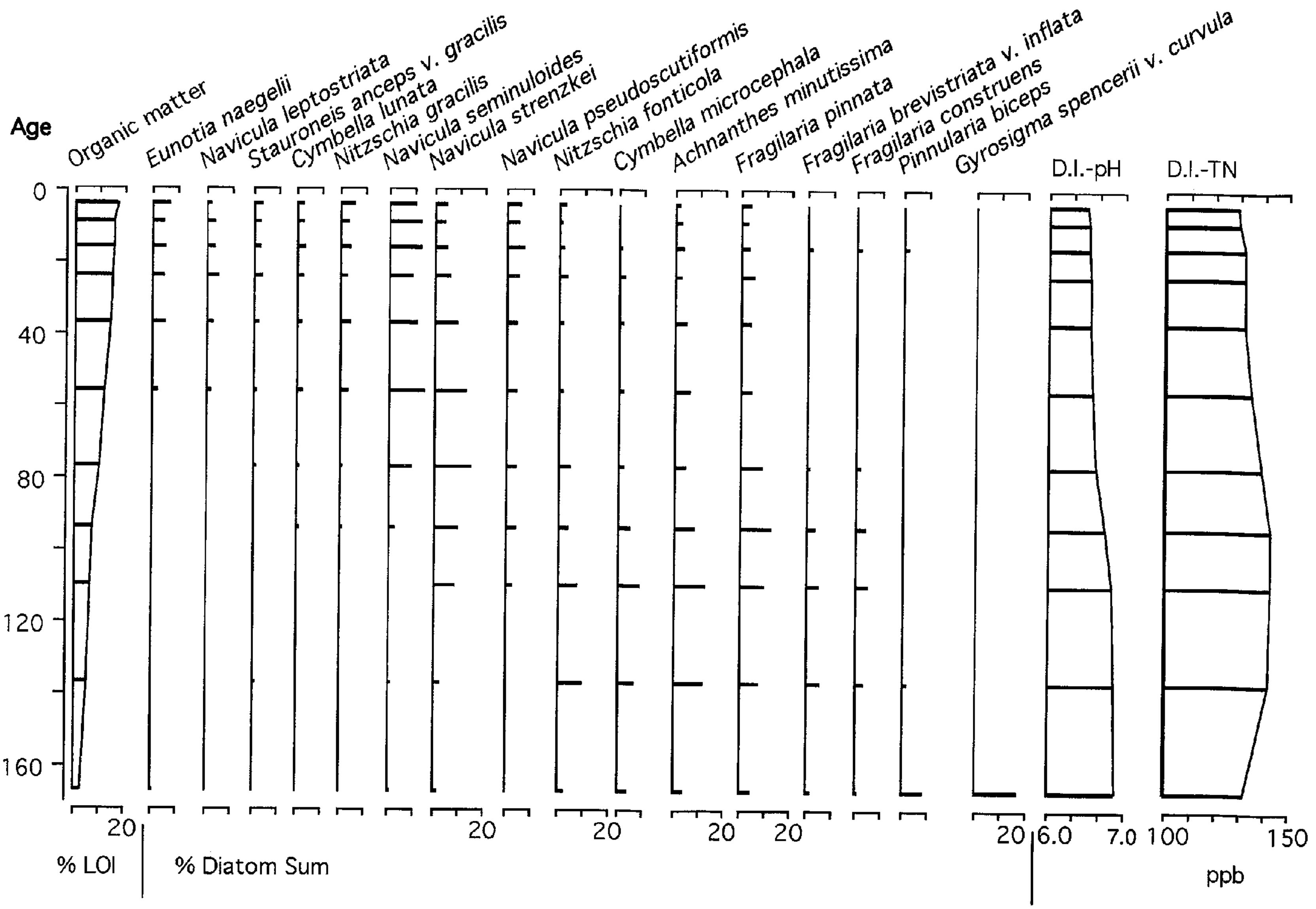

Fig. 4. Stratigraphy of the dominant diatoms in the Bartlett Lake core (% relative abundance) and diatom inferred (D.I.) values for pH and TN, as reconstructed from diatom assemblages. Sediment age is determined by ^{210}Pb dating.

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Long-term Changes in Zooplankton Community Structure Inferred from a Chronosequence of Lakes in Glacier Bay National Park, Alaska

by

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Abstract

The influences of physical/chemical variables and the presence of fish on zooplankton community structure are evaluated for a chronosequence of 32 lakes in Glacier Bay National Park, Alaska. Most of the lakes were recently formed by neoglacial ice recession and range in age from decades to hundreds of years and older. Apparent color, pH, chlorophyll *a*, presence/absence of planktivorous fish and maximum lake depth were identified by canonical correspondence analysis (CCA) as the most important variables in determining zooplankton community structure. Planktivorous fish occur in only one of the youngest lakes (<35 years) with high pH and low apparent color and in just two of the oldest lakes (>350 years) with low pH and high apparent color. Large bodied zooplankton, some of which are predacious on other zooplankton species, are rare or absent from lakes with planktivorous fish. Physical/chemical conditions, predation, and competition all appear to influence zooplankton community structure. However, long-term changes in the abiotic conditions resulting from changes in catchment soils and hydrology can alter the intensity of predation and competitive interactions.

KEY WORDS: Zooplankton, chronosequence, community structure, predation, environmental gradients.

Invertebrate and fish predation (Riessen et al., 1984; Brooks and Dodson, 1965), competition (Gilbert, 1988), anthropogenic acidification (MacIsaac, et al., 1987), and nutrient inputs (O'Brien, et al., 1992) are considered dominant factors structuring zooplankton communities. Interactions among these factors may also occur including changing competitive abilities (DeMott and Kerfoot, 1982) or predation pressure as environmental conditions change (Gliwicz and Pijanawska, 1989), or modification of the outcome of a competitive or predatory interaction between two species by a third species (Arnott and Vanni, 1993). Most of these observations are based on studies that range in length from a few days to several months, although some workers have examined changes in zooplankton community structure over several years (e.g. Sierszen and Frost, 1993).

Changes in zooplankton assemblages over longer time periods (hundreds to thousands of years) are examined by paleolimnological methods using the sediment record. However, the perspective of paleolimnological studies is limited because: (1) seasonal associations of the organisms may not be apparent, even in cores with yearly resolution (varves), (2) many organisms do not preserve well in lake sediments, and (3) the physical/chemical conditions of the

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lake water at the time of deposition cannot be directly measured.

An alternative approach for studying long-term changes in zooplankton communities is to compare a chronosequence of lakes of known ages, substituting space for time as the major environmental gradient. This approach, a mainstay of terrestrial community ecology, has seldom been applied to freshwater ecosystems. For the chronosequence approach to be valid several conditions must be met: (1) The lakes must be geographically close to avoid confusing species replacements over time with zoogeographic distributions along other environmental gradients (e.g. climate). (2) The ages of the lakes must span the time-period of interest and must be accurately known. (3) The lakes must undergo similar changes in physical/chemical conditions over time. The advantages of studying zooplankton community structure in a chronosequence of lakes are that contemporaneous species associations can be studied and that the physical/chemical conditions of the water can be measured at the same time that the zooplankton samples are collected.

In this paper we use the chronosequence approach to investigate changes in zooplankton communities that may occur over time-spans of decades to millennia. The venue for the study is Glacier Bay National Park in southeastern Alaska, where catastrophic recession of Neoglacial ice has left a landscape studded with lakes of known ages and in various stages of primary catchment succession. The major issue that we address here is how long-term physical/chemical changes in lakes, mediated by landscape-level forces, alters the outcome of biotic interactions to shift the composition of zooplankton communities. Of particular interest in this study are changes in trophic state, pH and related variables, and light attenuation from DOC (dissolved organic carbon). Long-term changes in these abiotic variables have been identified from paleolimnological studies and are of potential importance to zooplankton community structure.

This study builds on our parallel investigations of lake ontogeny in Glacier Bay in which both the chronosequence approach (Engstrom and Fritz, 1990) and paleolimnological methods (Fritz and Engstrom, this volume) were used to study temporal changes in physical/chemical conditions among a suite of 32 lakes. These lakes, which form the basis for our current study, were created by a series of glacial advances and retreats dating back to late-Wisconsin time. Most of the lakes were formed by recession of Neoglacial ice from low elevation forelands along Glacier Bay and range in age from 10 to about 275 years; others created by earlier glacial episodes are 400 to 13,000 years old. Within this chronosequence young lakes tend to have waters with high alkalinity and pH, low apparent color, DOC and nutrients (total nitrogen, TN, and phosphorus, TP). The older lakes tend toward low alkalinity and pH, high apparent color and DOC, and are also low in nutrients. The chronosequence approach also suggests that these lakes undergo an initial increase in TN corresponding to the establishment of N-fixing alder species in the catchment and a subsequent decrease as alders decline in importance. Engstrom and Fritz (1990) conclude that changes in catchment soils and hydrology, driven by terrestrial plant succession, are the primary forces affecting the physical/chemical conditions of lakes in Glacier Bay.

Study Sites and Methods

Lake selection, sampling techniques and physical/chemical conditions are described in greater detail by Engstrom and Fritz (1990) and Fritz and Engstrom (this volume). Lakes selected for study had stabilized catchments and did not directly receive silt-laden glacial runoff. Lake ages were estimated from the deglaciation chronology for Glacier Bay and by radiocarbon dating of basal sediments from older lakes of early Neoglacial or Wisconsin age.

Zooplankton samples were collected with an 80 μm Wisconsin net (100 cm^2 opening) towed vertically through the entire water column at about 0.5 m $second^{-1}$ from the deepest point in each lake. One to several tows were taken at each sampling. The lakes were sampled once each year over a three-year period: July 1987, September 1988 and May 1989. The presence/absence of fish was determined by visual observation during lake sampling rather than from trap or net collections. Because the study lakes are small, shallow and protected from wind and wave action, the water surface was usually flat, and fish, three-spine stickleback (*Gasterosteos aculeatus*) and dolly varden trout (*Salvelinus malma*), could be readily seen swimming or surfacing for food. As each lake was visited several times during the course of the study and fish presence/absence was verified on each occasion, we feel confident that all lakes that have fish present were correctly identified.

Cladocerans and copepods were identified to species except *Alona* spp. and *Ceriodaphnia* spp., which were identified to genus. Rotifers and *Chaoborus* spp. were also identified to the genus level. Three replicate 10-ml subsamples of crustacean zooplankton were enumerated in a counting wheel, except where numbers were low and the entire sample was counted. Immature *Daphnia* spp. and large copepodites were counted as adults. All *Chaoborus* spp. instars were counted as one category. Twenty transects each of two 1-ml subsamples were counted in a Sedgewick-Rafter cell for rotifers. In samples with low numbers of rotifers, up to 80 transects were counted in four 1-ml subsamples.

The average concentrations (individuals L^{-1}) of each taxon was calculated for each lake, and taxonomic groups were weighted for body length (Table 1) to give larger species more importance. The logic behind this weighting is that one individual of a large species has more of an impact on its environment (e.g. food resources) than an individual of a smaller species. In addition a taxon's weighted abundance for each lake was scaled by quartiles as follows: 0=0, >0 - 1 =1, >1 - 10 =2, >10 - 100 =3, >100 =4. This transformation, which down-weights abundance, was used because our low sampling frequency does not adequately portray seasonal or year-to-year variation in zooplankton densities or relative abundances.

Canonical correspondence analysis (CCA), an ordination technique for direct gradient analysis, was used to examine the relationship among zooplankton assemblages and environmental variables. Pearson correlation matrices and forward selection of environmental variables were used to determine which variables exerted significant and independent influence and thus should be included in the ordination (ter Braak and Prentice, 1986). Taxonomic groups that had only a single occurrence within the data set were excluded from the analysis.

Results

Zooplankton densities ranged from <1 L^{-1} to >750 L^{-1} for a single sampling. The average density for all samples was 126 individuals L^{-1}. Lakes contained from 2 to 16 taxonomic groups, with an average of 10.6 taxa per lake. *Cyclops scutifer* (a cyclopoid copepod) occurred in all 32 lakes and is discussed separately from other invertebrate predators.

Water chemistry data are summarized in Table 2. All of the lakes are oligotrophic, with chlorophyll *a* concentrations between 0.04 and 1.20 $\mu g\ L^{-1}$. Apparent color ranges from 0 to >150 Pt color units and pH from about 5 to 8.

Many environmental variables are positively correlated with pH (Table 3), including alkalinity and conductivity, whereas apparent color, DOC, and age are negatively correlated with pH. Using forward selection, five environmental variables were found to explain the variance in the zooplankton data almost as well as the original twenty variables. Apparent color, pH, the presence of planktivorous fish, chlorophyll *a*, and maximum lake depth are most important in determining zooplankton distributions in Glacier Bay.

The eigenvalues, which give the amount of variance explained by the ordination, were 0.229, 0.136, 0.105 and 0.074 for the first four canonical axes, respectively. Correlations between environmental variables and canonical axes suggest that apparent color, pH and maximum lake depth are most correlated with CCA axis 1, with correlations of -0.54, 0.61 and 0.21 respectively. The presence of planktivorous fish was most correlated with CCA axis 2 (0.59) and chlorophyll *a* with axis 3 (0.70). Monte Carlo permutation test (99 permutations) of the first canonical axis and an overall test were both highly significant (p=0.01).

A CCA biplot of zooplankton taxa and environmental variables (Fig. 1) shows the relationship among the taxa and the environmental variables. Although highly collinear with other variables, lake age and DOC were plotted passively (with no influence on the ordination; ter Braak and Prentice, 1986) to illustrate their relationship to the major environmental gradients. Taxa on the left side of the biplot occur in lakes with lower pH and highly colored water. Taxa in the lower and left sides of the biplot tend to occur in lakes without planktivorous fish. For example, *Heterocope septentrionalis* (Hs) tends to occur in low pH, highly colored lakes without fish, whereas *Bosmina longirostris* (Bl) is found primarily in higher pH, less colored lakes, and occurs in all lakes that have planktivorous fish.

A CCA biplot of sites (lakes) and environmental variables (Fig. 2) shows the relationship between zooplankton assemblages averaged over three years and major environmental axes. A separate CCA analysis was performed using individual zooplankton and environmental data from each Spring, Summer and Fall sample for each lake (not illustrated). A pattern similar to that based on averaging the three samples for each lake was obtained. Lakes without fish or large invertebrate predators tend to be younger and have low color and high pH (lower center and lower right side of Fig. 2). In contrast lakes with planktivorous fish tend to be somewhat older, circumneutral, and have low color (upper right side), except Harbor Point (Har), Brady (Brad), Bartlett Lake (BL) and Pleasant Knob (PK) which are slightly acidic and tend to be more colored (upper center). Lakes with large invertebrate predators tend to be older, acidic and highly colored (left side).

To explore further the interaction between apparent color and fish presence in structuring zooplankton assemblages, the percent abundance of individuals in each of four ecological groups (see Table 1) is plotted against color in lakes with and without fish (Fig. 3). Rotifers are the most abundant zooplankters in lakes with fish present, although, *Bosmina longirostris* and *Cyclops scutifer* occur in all of these lakes as well. Large-bodied cladocerans occur in five of the lakes that have planktivorous fish (41%), but only at relatively low densities (~1 L^{-1}). Five of the lakes with planktivorous fish have invertebrate predators present; *Chaoborus* spp. occurs in three lakes and *Polyphemus pediculus* and *Diaptomus fransiscanus* each occur in one lake, but only in very low numbers (<0.05 L^{-1}). When large cladocerans and

Table 1. Taxa of zooplankton used in CCA analysis, CCA codes, and size/ecological classes.

Cladocera	**CCA Code**	**Size/Ecol. Class**	**Weight ***
Daphnia pulex	Dp	Large Crustacean	10
D. galeata	Dg	Large Crustacean	10
D. rosea	Dr	Large Crustacean	10
Holopedium gibberum	Hg	Large Crustacean	10
Bosmina longirostris	Bl	Small Crustacean	1
B. coregoni	Bc	Small Crustacean	1
Ceriodaphnia spp.	Cer	Small Crustacean	1
Alona spp.	Alo	Small Crustacean	1
Polyphemus pediculus	Pp	Invert. Pred.	10
Copepoda			
Cyclops scutifer	Cs	Invert. Pred.	10
Diaptomus kenai	Dk	Invert. Pred.	100
D. fransiscanus	Df	Invert. Pred.	100
Heterocope septentrionalis	Hs	Invert. Pred.	100
Other Crustacea			
Gammarus lacustris	Gl	Invert. Pred.	1000
Chaoborus spp.	Cha	Invert. Pred.	100
Rotifera			
Keratella spp.	Ker	Rotifer	0.1
Polyarthra spp.	Pol	Rotifer	0.1
Kellicotia spp.	Kel	Rotifer	0.1
Gastropus spp.	Gas	Rotifer	0.1
Ascomorpha spp.	Asc	Rotifer	0.1
Monostyla spp.	Mon	Rotifer	0.1
Fillinia spp.	Fil	Rotifer	0.1
Euchlanus spp.	Euc	Rotifer	0.1
Ploesoma spp.	Plo	Rotifer	0.1
Lepadela spp.	Lep	Rotifer	0.1
Asplanchna spp.	Asp	Rotifer	0.1
Tricocerca spp.	Tri	Rotifer	0.1
Brachionus spp.	Bra	Rotifer	0.1
Lecane spp.	Lec	Rotifer	0.1

* Approximate body-length weights assigned to each taxon

Table 2. Study lakes, CCA codes, and three-year means of selected environmental variables.

Study Lakes	CCA Code	Age (years)	pH	Color (Pt units)	DOC (mg/L)	Cond (μS/cm)	Ca (mg/L)	Alk (μeq/L)	total-N (μg/L)	total-P (μg/L)	Chl-a (μg/L)
Casement 2	C2	10	8.18	0	1.02	157	28.16	1173	55	5.5	0.04
Plateau 2	Pl2	10	7.93	0	1.29	57	9.70	505	114	9.3	1.18
Casement 1	C1	20	8.35	1	1.83	199	34.69	1773	161	3.1	0.23
Plateau 1	Pl1	20	8.14	0	1.01	199	36.49	1463	199	8.6	0.24
Burroughs Glacier	Bur	25	8.11	0	1.33	204	37.07	1192	111	4.9	0.23
Wachusett	Wac	30	8.23	0	0.91	161	22.77	1082	168	5.2	0.18
Seal River	Seal	30	8.11	0	2.02	262	49.01	2436	264	3.2	0.32
Forest Creek	For	35	8.24	2	1.73	255	52.56	2732	146	4.1	0.25
Wolf Creek	Wol	45	7.89	8	2.21	61	10.68	526	209	9.2	0.38
Nunatak	Nun	50	8.17	2	1.57	199	36.16	1554	336	5.2	0.28
Klotz Hills	Klo	80	8.05	6	3.62	243	44.09	2406	271	6.0	0.39
Charpentier	Cha	100	8.04	8	2.47	136	24.17	1337	213	5.7	0.47
Blue Mouse Cove	BM	110	7.47	36	5.42	75	12.40	635	338	8.1	0.42
Spokane Cove	Spo	120	8.06	4	2.10	251	40.84	2259	284	3.7	0.21
Hutchins Bay	Hut	160	8.29	5	2.78	134	20.70	1187	216	4.9	0.53
Bartlett River	BR	180	8.15	4	3.24	87	15.10	820	260	9.5	0.34
Lester 1	L1	180	6.27	38	5.12	21	1.31	34	295	9.9	0.30
Lester 2	L2	180	7.70	25	4.88	75	11.74	610	266	10.5	1.05
Lester 3	L3	180	7.91	8	3.24	238	41.81	2247	222	7.5	0.63
Ripple Cove	Rip	190	7.97	2	1.69	145	25.12	1033	235	3.8	0.67
Bartlett Lake	BL	220	6.19	2	2.11	8	0.56	12	122	7.9	0.28
Paps	Pap	350	6.55	80	7.97	52	1.96	75	147	5.1	0.12
Harbor Point	Har	350	5.62	93	8.69	63	0.92	-22	270	9.0	0.45
Coal Creek	Coal	350	7.83	13	2.08	213	29.86	1691	138	5.9	0.49
Huscroft	Hus	400	7.27	28	3.72	66	7.14	346	215	5.5	0.36
Crillon	Cril	400	7.19	25	5.08	70	9.71	533	167	3.8	0.07
Dagelet	Dag	1100	6.18	33	2.87	21	0.47	20	167	3.9	0.08
Brady	Brad	1200	6.34	33	2.32	15	0.85	31	154	5.3	0.11
La Perouse	LaP	2700	6.96	55	4.52	55	5.53	397	138	10.2	0.31
Pleasant Knob	PK	12000	6.18	81	10.66	27	1.85	57	263	4.1	0.70
Pleasant Island	PI	13000	5.40	170	12.14	18	1.62	10	273	6.3	1.21
Pleasant Muskeg	PM	13000	4.74	143	13.71	19	0.76	-30	396	7.7	1.24

Table 3. Correlation matrix of selected environmental variables.

Age	1									
pH	-0.66	1								
Color	0.83	-0.87	1							
DOC	0.80	-0.83	0.95	1						
Cond	-0.42	0.76	-0.60	-0.58	1					
Alk	-0.39	0.77	-0.61	-0.57	0.97	1				
TN	0.33	-0.23	0.33	0.45	-0.06	-0.03	1			
TP	0.02	-0.25	0.20	0.22	-0.44	-0.41	0.21	1		
Chl a	0.63	-0.31	0.51	0.51	-0.25	-0.21	0.35	0.32	1	
Zmax	0.27	0.11	0.10	0.09	0.07	0.06	0.21	-0.21	0.19	1
Fish	-0.07	0.06	-0.11	0.00	0.03	0.12	-0.03	0.14	0.01	-0.06
	Age	pH	Color	DOC	Cond	Alk	TN	TP	Chl a	Zmax

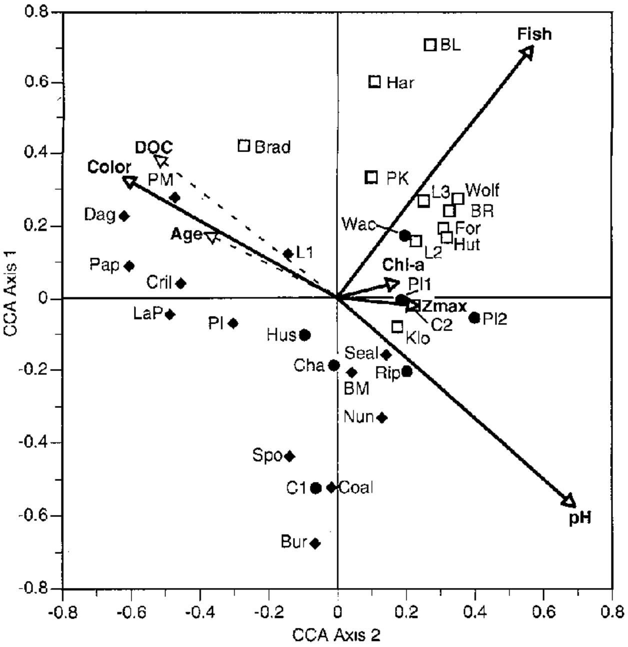

Fig. 1. CCA Biplot of zooplankton taxa (see Table 1 for codes) and their position relative to the major environmental gradients; ■ Large Cladocerans, ○ Small Cladocerans, ▲ Invertebrate Predators, ◇ Rotifers. Environmental variables with dashed lines were plotted passively (see text for explanation).

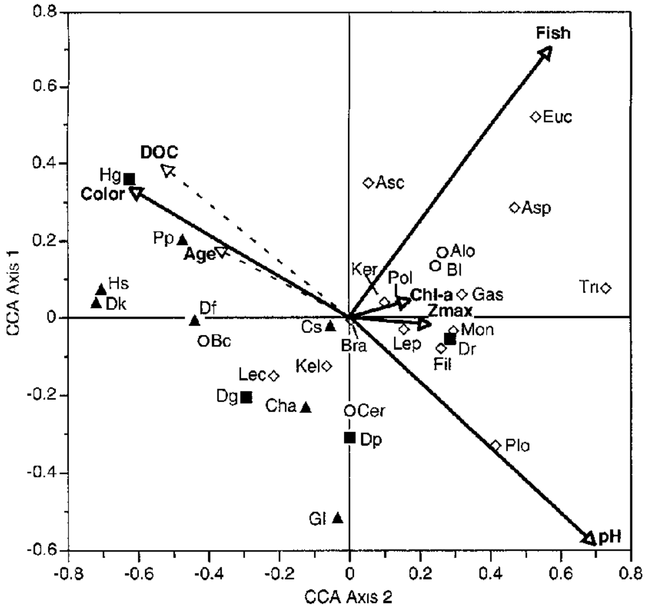

Fig. 2. CCA Biplot of study lakes (see Table 2 for codes) and their position relative to the major environmental gradients; □ Lakes with fish present, ◆ Lakes with invertebrate predators present, ● Lakes without fish or invertebrate predators (except *Cyclops scutifer*). Environmental variables with dashed lines were plotted passively (see text for explanation).

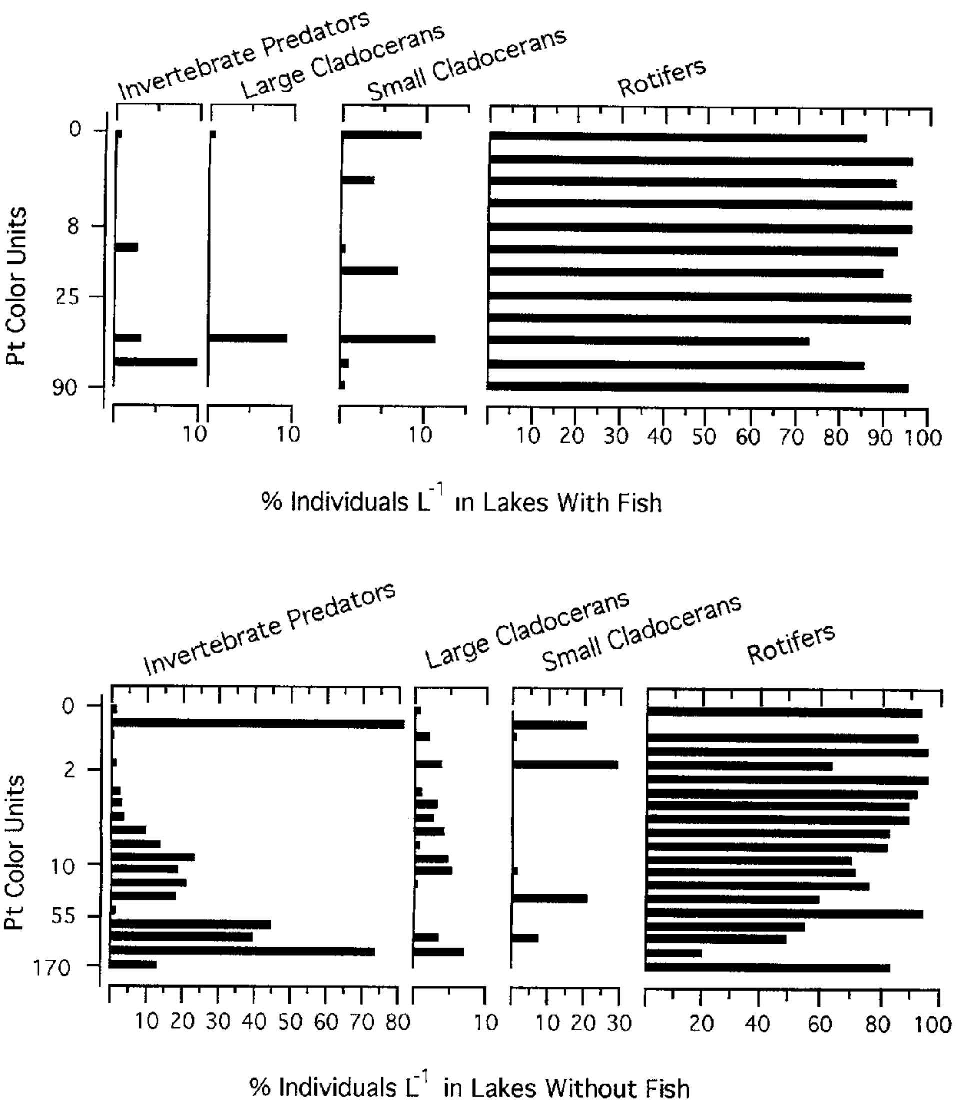

Fig. 3. Relative abundance (individuals L^{-1}) of ecological groups (Table 2) vs. lake color (Pt color units) for lakes with fish (top) and lakes without fish (bottom).

invertebrate predators are present in lakes with planktivorous fish it is usually in lakes above 5 Pt color units.

Large cladocerans occur in 18 of 20 lakes (90%) without planktivorous fish and invertebrate predators occur in 13 (65%) of these lakes. Large cladocerans co-occur with invertebrate predators in 11 of the 20 lakes. *Gammarus lacustris* occurs only in low color, alkaline lakes. Calanoid copepods occur in lakes with color above 25 Pt units, with one exception. *Chaoborus* spp. shows no pattern with color or pH. *C. scutifer* is more abundant in lakes without fish than in lakes with fish present. *Bosmina longirostris* is present in only half of the fishless lakes. Rotifers are clearly the most abundant zooplankton in most lakes without planktivorous fish, however, the relative abundance of rotifers declines as the number of invertebrate predators increases with greater apparent color.

Discussion

Zooplankton were present in all 32 of the study lakes. Fryer (1985) found that zooplankton were able to colonize newly formed bodies of water within the first year after formation. The two youngest lakes, Casement-2 (C2) and Plateau-2 (P2) (ca. 10 years in age), had 2 and 10 taxa, respectively. C2, has the lowest concentration of TN, while

P2 has a TN concentration approximately two times higher. This contrast suggests that nutrient limitation of primary production, not time, may restrict the colonization of young lakes by zooplankton.

All of the study lakes are oligotrophic. The younger lakes with low color and higher pH are dominated by rotifers, *Bosmina longirostris* and *Cyclops scutifer*. In oligotrophic lakes, selective feeding may allow some zooplankton species to outcompete others. For example small cladocerans, such as *Bosmina* spp., have been found to outcompete *Daphnia* spp. in neutral to alkaline waters with low food concentration (DeMott and Kerfoot 1982). Cyclopoid copepods may also outcompete *Daphnia* spp. in low food situations, apparently by selective feeding (McNaught 1975). Small cladocerans, however, do not appear to be able to reduce rotifer numbers (Gilbert 1988). Thus, our observations from oligotrophic, low color lakes are consistent with the above authors' results concerning zooplankton competition under low food conditions.

In lakes where fish were not observed there is a trend toward more invertebrate predators and large cladocerans and fewer rotifers with an increase in apparent color (Fig. 3). Arnott and Vanni (1993) observed a similar pattern in naturally acidified Northern Wisconsin bog lakes and concluded that the interaction of predation and abiotic factors may be responsible for the structure of zooplankton communities in their study lakes. DOC attenuates light effectively, including UV-B wavelengths (280 to 320 nm), and undergoes photochemical breakdown to hydroxyl radicals that are biologically harmful (Mopper and Zhou, 1990). The observed shift in the size structure of zooplankton assemblages as DOC increases may be due to a taxon's tolerance to certain wavelengths of light and/or to hydroxyl radicals produced from the photochemical breakdown of DOC. Alternatively, the shift in zooplankton size structure may be a release of large zooplankton taxa from fish predation as lake conditions deteriorate for visual predators with increasing color and light attenuation (Aksnes and Giske, 1993). *Chaoborus* spp. (Riessen et al. 1984 and 1988), *Gammarus lacustris* (Anderson and Raasveldt, 1978) and calanoid copepods (Arnott and Vanni, 1993) may affect zooplankton composition by selectively preying upon smaller species. Large herbivores, which are difficult for most invertebrate predators to consume (Riessen et al, 1984), were found in 11 of the 13 lakes with invertebrate predators. The long-term shift in size selective predation, favoring small taxa when visual predation by fish is important, to large taxa favored by tactile invertebrate predators, is most likely mediated by changes in physical/chemical conditions within the lake.

Sticklebacks and dolly varden trout, euryhaline species that are able to invade from saltwater, were not observed in the youngest lakes with high pH and low apparent color or in most of the older, more acidic and highly stained lakes. Many of the study lakes have probably never been colonized by fish because of geographic barriers to migration from source populations. The effects of fish on zooplankton populations are well documented (Hrbácek, 1962; Brooks and Dodson, 1965 and others). In this study, larger zooplankton species are rare or absent from lakes where planktivorous fish were observed. Low food concentration has been found to force *D. longispina* to remain in surface waters where they are subject to high predation rates by planktivorous fish (Johnsen and Jakobsen, 1987). With the low primary productivity of lakes in Glacier Bay, it may not be possible for large zooplankton taxa to find refuge from fish predation by migrating vertically.

Conclusions

Although the size of a waterbody and the number of nearby sources of colonizers are theoretically important in determining the number of species found in a lake (Dodson, 1992), these factors alone cannot explain patterns of zooplankton distributions (Fryer, 1985). The physical/chemical and biotic conditions at the time of an introduction are important in determining the success of a potential colonizer (Neill, 1978; Robinson and Dickerson, 1987), and may be more important than the age of a lake in determining zooplankton associations (Whiteside et al., 1980). Predation and competition appear to be structuring zooplankton communities in Glacier Bay lakes within a given set of physical/chemical conditions. As the physical/chemical conditions of a lake change, due to changes in hydrology and soil development (Fritz and Engstrom, this volume), the intensity of size-selective predation and the competitive ability of a species may be altered, resulting in species replacements. The specific associations in a given lake will depend on the sequence and frequency of zooplankton introductions, the ability of planktivorous fish to colonize, and the rate of change of the physical/chemical conditions.

Our results suggest that changes in the terrestrial environment are driving long-term changes in zooplankton community structure in the lakes of Glacier Bay by changing physical/chemical conditions and in turn competition and predation pressures. The most important of these physical/chemical parameters appear to be pH, apparent color and chlorophyll *a*, and other environmental factors correlated with these variables. Possible mechanisms for the long-term changes in zooplankton species associations include light attenuation by DOC, which may reduce the effects of UV radiation and/or predation from visual predators, and toxicity of hydroxyl radicals from the photochemical breakdown of DOC.

A clear understanding of the mechanisms by which physical/chemical changes mediate the outcome of biotic interactions will require field experimentation as well as more intensive sampling than was possible in this initial survey. The temporal trends inferred from the chronosequence approach also need to be verified by paleolimnological methods that utilize zooplankton remains in lake sediments to reconstruct the ontogeny of individual lakes. Nonetheless, the patterns displayed by our chronosequence approach are consistent with experiment and theory in size-selective competition/predation, but incorporate the additional time dimension over which forces of primary succession alter the boundary conditions for biotic interaction.

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Community Development in Wolf Point Creek, Glacier Bay National Park, Alaska

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Abstract

Colonization of Wolf Point Creek in Muir Inlet has been documented over a 12-year period from 1978 until 1990. Invertebrates displayed a distinct successional pattern over the study period, particularly the Chironomidae, and a number of the pioneer colonizers are no longer found. Times of colonization to maximum densities and maximum species diversity were at least 10 years apart, and water temperature is considered the most significant factor in determining the year of colonization of invertebrate taxa. Salmonids colonized the stream in 1988 and analyses of diet of juvenile Dolly Varden showed preferential selection for blackfly and small chironomid larvae. This study suggests that within a stable stream channel, the early pioneer chironomid colonizers have become eliminated through competition and that deterministic trends to the invertebrate colonization and succession pattern are apparent

KEYWORDS: Streams. temperature, invertebrates, salmonids, succession.

Although one of the oldest concepts in ecology, succession is still one of the most controversial. Traditionally succession has been viewed as site-specific temporal changes in plant communities but more recently the concept has been applied to streams (Fisher 1983; 1990).

Succession is most simply defined as community changes that occur at a site following a disturbance (Fisher 1990) and involves colonization and subsequent change (Fisher 1983). Invertebrate colonization and recovery to previous densities and species diversity through secondary successional processes, particularly where drift is present, typically occurs within one year for most types of disturbance (Milner 1994a). Primary succession occurs at a site where no trace of the previous community exists (Fisher 1990). Few documented cases of colonization and recovery of biotic communities in barren natural streams through primary successional processes exist, particularly where upstream colonizers are absent as a source of drift (Cushing & Gaines 1989).

Spatial scale is very important in examining primary successional processes in streams. Although the colonization of implanted artificial substrates could be considered primary successional changes, the scale is usually so small that the substrates are overwhelmed by rapid colonization from adjacent communities and there is no opportunity for distinct communities to exist (Fisher 1990). The difference between

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primary and secondary succession is typically only apparent at scales which limit colonizers, which in streams probably involves reaches 10^3 to 10^4 meters in length (Fisher 1990). Hence stream colonization and succession studies must be performed on the spatial scale of whole river segments or entirely new systems to override the influences of local within-stream colonization patterns (Malmqvist *et al.* 1991). Few lotic successional studies have worked at this scale. Few studies have also exceeded two generations of most species and therefore it maybe difficult to separate colonization and recovery from natural variation (Yount & Niemi 1990).

Recently formed streams following glacial recession in Glacier Bay National Park afford the opportunity to examine colonization and succession in natural systems at the scale of the entire stream channel without upstream source areas for initial colonization. These streams afford insights into post-glacial colonization patterns, processes that must have similarly occurred following the retreat of glaciers after the Wisconsin Ice Age when half of North America and northern Europe was covered in ice. They also provide indications of the patterns and temporal scales of biotic community recovery following major disturbances. From 1977 to 1980 biological communities were examined along a chronosequence of five streams to examine temporal changes in community structure (over 150 years) on the basis of spatial differences. Results indicated that the overall pattern of biotic community development in post-glacial streams is controlled principally by abiotic factors, particularly flow and sedimentation effects (Milner 1987; Milner & Bailey 1989). In the absence of large woody debris following glacial recession, the retention of a lake within the watershed to buffer flow variations and to settle coarser sediment is of critical importance to the development and productivity of the biotic communities (Sidle & Milner 1989). However, within this pattern of physically dominated long-term changes in stream dynamics, biotic communities in the shorter term may be influenced by the colonization patterns of the immigrating species and the interactions between these species. This paper documents changes in the biotic community since 1980 at one of these streams in Glacier Bay, Wolf Point Creek. Only five taxa of chironomid larvae had colonized this stream up to 1980 (Milner 1987).

Study Site

With rapidly retreating tidewater glaciers, remnant ice-sheets become isolated and meltwater may feed new streams as occurred with Wolf Point Creek (59° 05N, 136° 10W) in Muir Inlet (Figure 1). The mouth of the stream channel was released from the ice in the late 1940s and the lake (unofficial name - Lawrence Lake) which feeds the stream began to form in 1967 as the remnant ice continued its retreat behind a bedrock control. The ice has continued to retreat to present day forming a lake 2 km long with an area of 1.35 km^2 (as of 1991). The first bathymetric survey of Lawrence Lake conducted in 1991 indicated two basins and the maximum depth between 30 and 35 m. It is evident that this lake will be a permanent feature of the landscape for many hundreds of years. Wolf Point Creek is a first order stream and aerial photography conducted in 1990 indicated a length of 1.8 to 2 km. The stream channel at the lake outlet cuts through a bedrock control creating a series of falls of over 30 m in height before flowing over unconsolidated materials of glacial moraine, till and outwash deposits. It is anticipated that these falls constitute a barrier to fish migration (Milner 1994b).

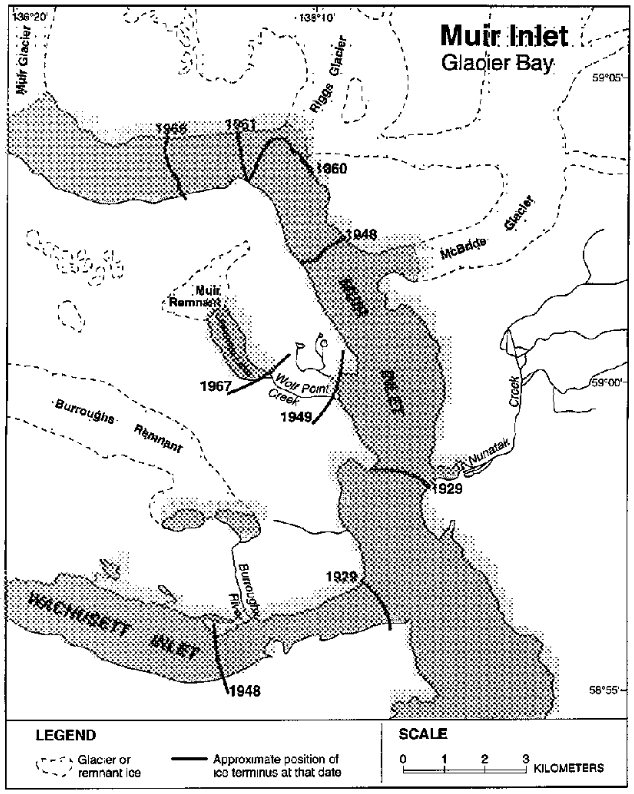

Fig. 1. Map of Muir Inlet to show location of new streams including Wolf Point Creek.

In 1977 the upland areas of the Wolf Point Creek drainage were dominated by alder, but on the floodplain of the stream channel, only isolated clumps were present, along with

Dryas due to the braided course of the original stream (Figure 2). However in the last four and five years a distinct riparian zone of willow has developed along the stream channel which by 1992 had attained a height of 2 to 2.5 m (Figure 3).

Methods

A 15 m representative sampling station has been established in Wolf Point Creek since 1977 and is located approximately 0.9 km from the mouth and halfway along the stream length (Fig. 1). It is estimated that this station was uncovered from the retreating ice around 1960 but it is probable that the channel was ill-defined and braided as the initial retreat occurred and prior to the formation of the lake. One intensive sampling station has been considered sufficient as representative of the stream biotic communities due to the homogenous nature of the substrate and flow patterns and that sampling has indicated no significant longitudinal differences in the benthic community structure (Milner 1983; unpublished). At the sampling station substrate size is typically between 6 cm and 25 cm, depths are between 20 cm and 70 cm and velocities between 50 — 90 cm s^{-1}.

Methods of invertebrate sampling in 1978 and 1979 used the lifting of individual stones as described in Milner (1987). In conjunction with channel development studies (Sidle & Milner 1989) benthic invertebrates were collected using stone lifting and kick nets in August 1980, and in May and August of 1982, 1983, and 1984. Unfortunately, these samples were not quantitative and were collected principally to obtain chironomid larvae for rearing to adults for identification and to ascertain if any further taxa had colonized the stream. Invertebrate samples were collected at the sampling station in 1986, 1988, 1989 and 1990 using a modified Surber sampler with a 353 micron mesh net. Samples were immediately preserved in 70 percent ethanol. Samples were sorted in the laboratory and chironomids were identified by the micro-dissection and mounting of representative head capsules. Biovolumes were calculated using two tubes of similar size containing equal volumes of water. For each sample, preserved invertebrates were added to one tube and then drops of water were added to the other via a microliter dropping pipette until liquid levels were equal. The amount added to the second tube was taken as an estimate of biovolume. Although these values may be underestimates of true biovolumes, as preserved samples were used (Smit, Van Heel & Wiersma 1993), the principal goal was to evaluate relative year to year variations in approximate biomasses. Adult insects were collected using sweep nets and Malaise traps. Voucher specimens are deposited at The Institute for Arctic Biology, University of Alaska and for the chironomids belonging to the genera *Diamesa* (Meigen) at the Zoological Museum, University of Bergen, Norway and the Natural History Museum in London.

Minnow trapping was undertaken to examine colonization by salmonids. At each sampling period, between 5 and 10 minnow traps (3 mm mesh) were baited with salmon eggs and set in the stream section for a period of 1.5 to 2 hours. Minnow trapping was also carried out along the length of the stream. Length measurements were made of any juvenile salmonids captured and in some instances weights were taken. In 1990 juvenile fish were preserved in 70 percent ethanol for analysis of stomach contents to ascertain what major taxa were being predated upon to examine the potential effect on invertebrate community structure. Salmon eggs were placed in cuvettes with holes to prevent egg ingestion during sampling. To ascertain the extent of prey selection, the relative abundances of food items in the diet were compared with their relative abundance in the stream from Surber samples using a selectivity index (L) recommended by Gabriel (1978);

$$L = l_n[(p_1q_2)/(p_2q_1)]$$

where L = log of the Odds ratio. Values range from zero to + infinity indicating positive or negative selection, p_1 = percentage of diet of a given prey taxa, q_1 = percentage of diet of all other prey taxa, p_2 = percentage of food complex in environment of the given taxa, q_2 = percentage of food complex in environment of all other taxa.

Results

Macroinvertebrates displayed distinct successional community changes with stream development from 1978 to 1990. To avoid possible seasonality differences in community structure, only data from samples collected in late summer (mid-August to mid-September) will be compared (Table 1). Samples collected at other times of the year will be discussed where additional taxa were collected. In 1978 the only invertebrates found were five larval taxa of the Chironomidae (Diptera) which typically displayed positive associations with filamentous algal growth using a modified Chi-squared test (Milner 1987). Water temperatures were low averaging 2° C. Four of the five chironomid taxa were in the genus *Diamesa* with the most dominant species belonging to the *Diamesa davisi* group. This group has been reviewed by Willassen (1985) and includes two species found in Wolf Point Creek; (1) *Diamesa lupus* (Willassen) which is a new species presently known only from Glacier Bay and the Jasper-Banff area of

Fig. 2. Study reach in Wolf Creek in 1983

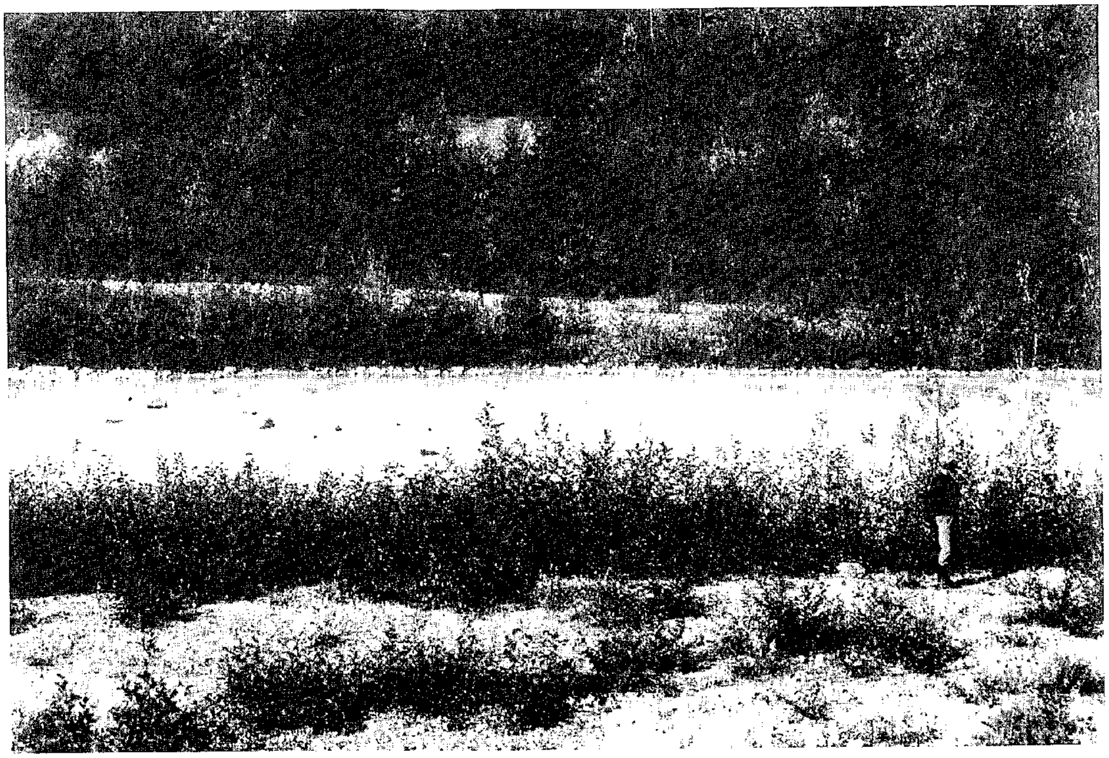

Fig. 3. Study reach in Wolf Creek in 1992

Table 1. Mean (±SE) August-September densities of invertebrates (numbers $0.1m^{-2}$) in Wolf Point Creek in five years between 1978 and 1990 (n = numbers of samples)(from Milner 1994b).

Year		1978	1986	1988	1989	1990
n		58	10	9	10	9
DIPTERA						
Chironomidae						
Diamesinae	*Diamesa davisi* group	275 (±2.2)	29.9 (±6.3)	35.4 (±4.9)	0.4 (±0.3)	2.0 (±0.7)
	Diamesa sp. B	95.4 (±1.5)				
	Diamesa sp. C	31.4 (±8.8)	0.8 (±0.3)			
	Diamesa sp. D	2.4 (±1.2)				
	Diamesa sp. E		1.7 (±0.6)			
	Pagastia sp. A		1.0 (±0.4)	2.3 (±0.9)	3.6 (±1.0)	74.7 (±7.5)
Orthocladiinae	*Eukiefferiella* sp. A (*gracei* group)		1.9 (±0.5)	0.3 (±0.2)	0.6 (±0.5)	
	Eukiefferiella claripennis		0.8 (±0.2)	14.2 (±3.2)	2.9 (±1.1)	2.9 (±0.6)
	Orthocladius sp. A	34.4 (±0.6)	34 1 (±6.8)	13.0 (±2.4)	6.4 (±1.3)	1.8 (±0.4)
	Orthocladius mallochi			9.3 (±2.8)	10.7 (±6.0)	10.2 (±1.9)
Chironominae	*Tanytarsus* sp. B			0.1 (±0.1)		
Simuliidae	*Prosimilium* sp.			1.8 (±1.3)	35.1 (±12.2)	5.3 (±2.1)
Tipulidae	*Limnophila* sp.				0.7 (±0.5)	0.1 (±0.1)
EPHEMEROPTERA						
Baetidae	*Baetis* sp.		1.7 (±0.4)	1.0 (±0.4)	2.6 (±0.7)	2.9 (±0.8)
Heptageniidae	*Cinygmula* sp.				0.3 (±0.1)	
PLECOPTERA						
Chloroperlidae	*Neaviperla forcipata*			2.1 (±0.8)	5.7 (±1.3)	8.9 (±2.2)
	Capnia sp.		0.3 (±0.2)	0.4 (±0.4)		
TRICHOPTERA						
Limnephilidae	*Ecclisomyia* sp.			0.1 (±0.1)		
TOTAL FAUNA		438.6 (±4.9)	72.2 (±15.9)	80.0 (±17.5)	68.4 (±24.4)	108.7 (±16.2)

Alberta, Canada, and (2) *Diamesa alpina* (Willassen) which is a first record of this species for North America. These identifications were based on the rearing of a number of larvae to adult imagos but presently the larvae are undescribed and hence cannot be distinguished. *Diamesa sp.* B (probably *sommermanni*) was the second most common species with *Orthocladius sp.* A the other principal species. Low densities of *Diamesa sp.* C and *Diamesa sp.* D were also collected. These are my code letters given to differentiate distinct species based on larval morphology and do not match code letters given by other workers. The relatively intensive qualitative macroinvertebrate collections made concurrent with stream channel investigations during the period 1981 to 1983 ascertained that no other taxa than chironomids were present at that time (Milner 1994b).

Quantitative samples collected in 1986 revealed an increase in species diversity and the incursion of the mayfly *Baetis sp.* (Baetidae - Ephemeroptera) into the community. In May the stonefly genus *Capnia* (Capniidae - Plecoptera) was also found. These taxa presumably colonized between 1984 and 1986. Water temperatures had increased to 6° C. Densities and biovolume were still dominated by chironomids but densities had dropped significantly from 1978 levels. The number of chironomid species had increased to seven and *Orthocladius sp.* A had become co-dominant with the *Diamesa davisi* group. *Diamesa sp.* B and D were absent. In 1986 small numbers of the chironomid *Pagastia sp.* A were first collected. In addition, in early July samples, small densities of *Orthocladius rousellae* (Soponis) were found which were also present in early summer samples in 1988 and 1989.

Significant changes in the chironomid community were evident from 1988 to 1990. The *Diamesa davisi* group and *Orthocladius sp.* A were significantly lower in abundance. Another *Orthocladius* species, *Orthocladius mallochi* (Kieffer) was first apparent in the 1989 samples when it was the dominant chironomid and maintained similar densities in 1990. *Pagastia* sp. A densities increased and by 1990 it was the dominant chironomid exceeding 80 individuals 0.093 m^{-2} . In 1988 another species of stonefly, *Neaviperla forcipata* (Chloroperlidae), was first apparent in the late summer community and this predatory species showed significant density increases in 1989 and 1990. By 1990 Chloroperlidae (all *Neaviperla forcipata*) made up 17 percent by biovolume of the principal families. *Capnia* was still found in small numbers in early summer samples although *Clinocera* was no longer present. *Prosimulium sp.* (Simuliidae) was first collected in 1988 and *Limnophora sp.* (Tipulidae) in 1990. Relatively large numbers of early instar *Prosimulium* were found in 1989 making up over 50 percent by density of the principal families present although biovolume contribution was only 17 percent. Total Empdidae and Tipulidae densities were less than 1 percent. By 1990 August water temperatures averaged 9° C (Figure 4).

Total densities were relatively similar from 1986 to 1990 although significantly lower than densities found in 1978. Invertebrate biovolumes did increase in 1990 due to the increased abundance of *Pagastia sp.* A, a large chironomid species, but did not reach the levels shown in 1978 (Milner 1994b).

Minnow trapping for juvenile salmonids over the study period 1978 to 1990 first revealed the presence of young of the year Dolly Varden charr (*Salvelinus malma* Walbaum) in 1988, indicating that this species had probably colonized the stream the previous year. Approximately 20 pink salmon (*Onchoryhnchus gorbuscha* Walbaum) carcasses were found in Wolf Point Creek in September 1989. In 1991 over 1000 pink salmon were estimated to have spawned in this stream. From minnow trapping in 1990, when small numbers of juvenile coho salmon were collected, it is also evident that coho salmon first spawned in this stream in the fall of 1989. Table 2 shows that over 76 percent of the diet of juvenile Dolly Varden were chironomids followed at 14 percent by simulids. There was a positive selection for simulid larvae (L = +1.22) compared to their densities in the benthos, together with a positive selection for smaller chironomid larvae (L = +0.36). However there was a negative selection for the large chironomid *Pagastia*, and overall a negative selection for chironomids (L = -0.34) (Milner 1994b).

Discussion

Four main sources of colonization were identified by Williams and Hynes (1976) namely: downstream migration or drift, upstream migration within the water, vertical upward migration from the hyporheic zone and aerial oviposition. In the absence of the first three of these sources (refugia like the hyporheic zone were not present in this barren new stream) aerial oviposition is clearly the initial mechanism of colonization. Hence most insects have a distinct advantage over non-insect forms in possessing a winged terrestrial stage. Colonization will then depend upon distance to source areas of the potential colonizing pool (Gore 1982). Drift may become more important as the community becomes established. Assuming the creation of the stream at the sampling station at Wolf Point Creek occurred at a conservative date of 1960, it is evident that no non-insect forms have become established in this stream after 30 years of colonization, presumably as a result of the difficulty of crossing mountain and ocean barriers.

Figure 4 summarizes the colonization sequence of invertebrate taxa from 1978 to 1990 and includes average August/September stream temperatures for each year. Since

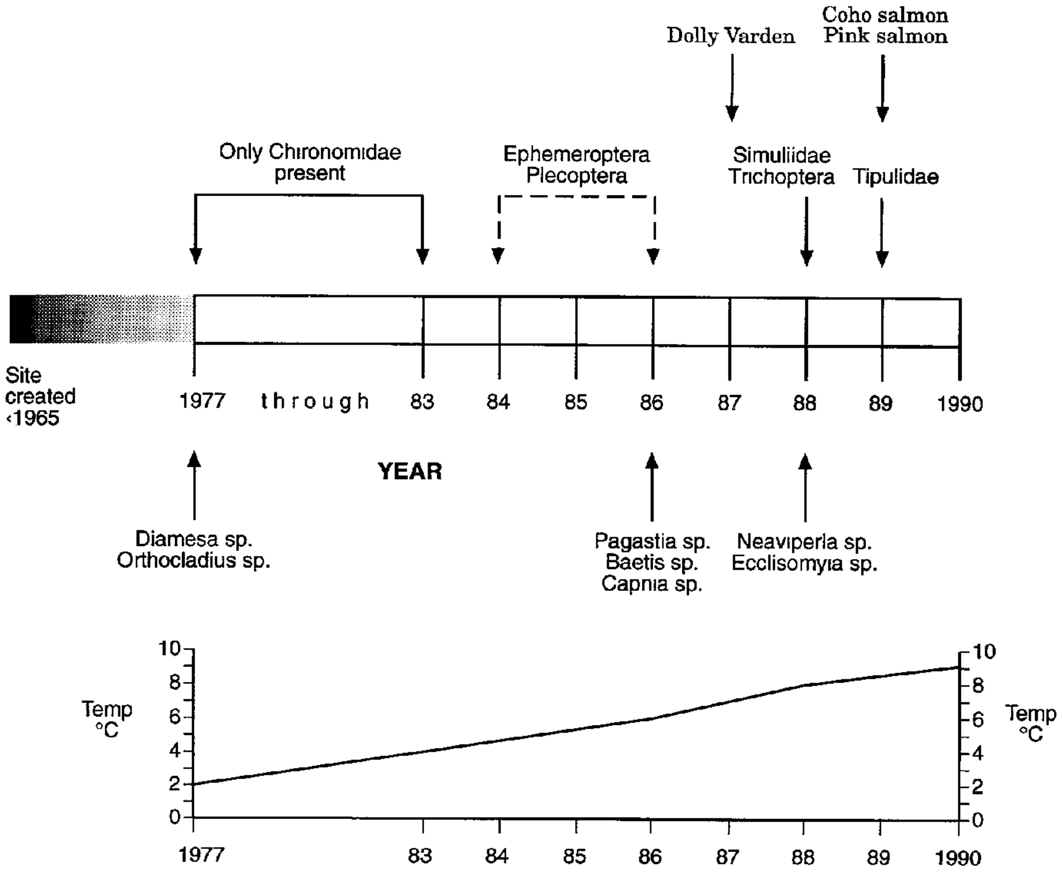

Fig. 4. Sequence of invertebrate colonization with associated stream temperatures in Wolf Point Creek from 1978 to 1990 (from Milner 1994b).

Table 2. Frequency of occurrence, and numbers of prey items found in stomachs of 13 juvenile *Salvelinus malma* in August 1990. All prey items are insect larvae unless stated otherwise (from Milner 1994b).

Prey types	Frequency of occurrence (%)	$\bar{x}$ number per fish	Percentage total prey items
Baetis sp.	31	0.3	0.7
Neaviperla sp.	77	2.1	4.3
Limnephilidae	8	0.1	0.2
Pagastia sp. A	100	28	56.6
Other Chrionomidae	100	9.9	20.1
Chironomid pupae	62	1.3	2.7
Chironomid adults	8	0.1	0.2
Simuliidae	92	7.1	14.1
Simuliid pupae	23	0.5	0.4
Tipulidae	15	0.2	0.4

colonization and change in dominance of the invertebrate community has been documented, site specific temporal succession has occurred in Wolf Point Creek over the study period. The principal change in invertebrate dominance has been within the Chironomidae family and a number of the early colonizers (most notably *Diamesa spp.* B, C and D) have likely become extinct in the stream.

Cross-sectional studies at the sampling station between 1982 and 1985 indicated a stable channel with little erosion and deposition due to the presence of the large feeder lake (Sidle & Milner 1989). This stability is further indicated by the development of a close border of riparian vegetation along the channel. Substrate size, current velocities, water depth, and turbidity have remained similar from 1978 to 1990. Qualitative observations of periphyton growth indicate that despite turbidities of 120—140 NTU, many stones have supported extensive mats of *Ulothrix sp.* at similar levels throughout the study period. Hence the two variables that have shown the most significant changes and have potentially influenced invertebrate colonization in Wolf Point Creek are time and temperature.

It is possible that the distinct colonization and successional sequence observed between 1978 and 1990 in Wolf Point Creek was due to the longer dispersal times for certain taxa to cross water and land barriers to reach the drainage. However such taxa as *Pagasta sp.* A, *Baetis sp.*, and *Neaviperla forcipata* were collected in Nunatak Creek during 1977 and 1978 (Milner 1987). This clearwater creek is only 1.5 km away across the fjord (see Fig. 2) and it would seem unlikely that this distance would constitute a sufficient barrier to dispersal and establishment of these taxa if stream conditions were suitable. Brundin (1967) considered small-winged and relatively light chironomids to have a high dispersal capacity, even over wide oceanic expanses.

Temperature would therefore appear to be the most important parameter influencing the invertebrate colonization and succession patterns documented in Wolf Point Creek over the study period. Temperature increases from 1977 to 1990 as the ice has further ablated have permitted additional taxa to colonize and increase community diversity.

A major question is whether the early successional *Diamesa* chironomids are cold stenothermal species unsuited by the increase in water temperatures as stream development proceeds; local extinction then occurs as a result of unsuitable warming water temperatures. Preliminary data from a newly deglaciated stream in Kenai Fjords National Park, southcentral Alaska, is of interest in this context (Milner, 1994b). August water temperatures here attain 8—9° C. However the stream possesses an extremely unstable channel subject to frequent spates. The invertebrate community is dominated by chironomids of the *Diamesa davisi* group. Small numbers of the stonefly *Neaviperla forcipata* and *Baetis sp.* are also present. These data would infer that *Diamesa* chironomids are able to maintain populations at higher temperatures in the presence of low numbers of other taxa. Hence if colonization by other taxa had been prevented in Wolf Point Creek, it is suggested that *Diamesa* chironomids would still dominate the community today even at temperatures up to 9° C. Since *Diamesa* sp. B became extinct and numbers of the *Diamesa davisi* group significantly decreased before the arrival of the stonefly predator *Neaviperla forcipata*, these data suggest that competition (and not predation) may be an important structuring factor in this successional sequence.

Can *Diamesa davisi* group and *Diamesa sp.* B chironomids then be considered fugitive species? Fugitive species colonize disturbed patches because of the reduced densities of other fauna that will competitively exclude them later. On the other hand opportunistic species depend upon disturbance to create required microhabitats [e.g. scoured surfaces with low epilithon] (Downes & Lake 1991). Evidence for lotic fugitive species, as opposed to good opportunists, is not extensive (Lake 1990) but it would appear that these early *Diamesa* colonizers can also be considered fugitives and not opportunists. Previous studies indicated that increased densities of these organisms are significantly associated with filamentous algal growth (Milner 1987) and thus are unlikely to require disturbances to create suitable microhabitats. In this case the refugia for these colonizers is the kryal zone ($T_{max} \leq 2°$ C) of glacial rivers which is potentially a permanent habitat for these organisms. The extremely low water temperatures restrict or prevent colonization by other taxa.

This study supports the earlier view that Dolly Varden are typically the first of the salmonids to colonize new stream habitats as the juveniles are primarily bottom feeders (Milner & Bailey 1989). Hence Dolly Varden are at an advantage over juvenile coho salmon (*Onchoryhnchus kisutch* Walbaum) in habitats that are characteristically dominated by riffles and glides with an absence of pools. In a nearby clearwater stream, chironomids were shown to contribute nearly 90% of the diet of juvenile Dolly Varden, which exhibited a strong positive selection for them (Milner & Bailey 1989). In this study chironomids constituted 76 percent of the diet and overall there was a negative selection for them. The positive selection for Simulidae larvae in this stream may be because they are easier prey items for fish to see on the rocks than the chironomids which are typically associated with the filamentous algae. No terrestrial insects were found to constitute the diet of the fish examined.

Conell and Slatyer (1977) identified three general mechanisms by which succession occurs; facilitation where species colonization is advanced by the presence of the previous community; inhibition, where colonization is delayed by the presence of the present community; and tolerance where biotic interactions have no effect on the rate of succession. Lake (1990) considers that in stream communities tolerance is likely to be the most applicable of these three mechanisms. The evidence from this study of Wolf Point Creek infers that succession in this new stream following deglaciation is a function of a competitive elimination of early pioneer colonizers followed by tolerance provided abiotic factors are favorable - these abiotic conditions are temperature and channel stability. However facilitation or inhibition were not tested and thus these mechanisms cannot be eliminated.

The succession of lotic communities in post-glacial streams within Glacier Bay would seem to fit Pickett, Collins & Armesto's (1987) ideas of a hierarchical approach to succession in that different processes affect succession according to the level of examination. At the between stream level, community development in post-glacial streams is abiotically controlled according to the model presented in Milner (1987). However at the reach level within a particular stream this study infers that when conditions (in this case a large feeder lake) reduce disturbances due to flow variations and sediment deposition, biotic factors can influence the early stages of succession.

An important hypothesis proposed by Cushing & Gaines (1989) for testing in streams is that "colonization/recolonization and recovery of benthic insects is dominated by stochastic processes". Fisher (1990), following an analysis of 18 postflood successional sequences, suggests that succession in streams is not deterministic; a similar conclusion reached by Minshall *et al.* (1983) after the Teton River flood. However the rapid colonization of disturbed or clean stones in streams is indicative of high resilience, an attribute typical of deterministic communities (Lake & Doeg 1985). A degree of determinism would be suggested if the similar sequence of taxa colonization and succession observed in Wolf Point Creek was repeated in other new streams following deglaciation. Burroughs River (see Fig. 1), a turbid meltwater system, supported similar chironomids in 1978 as Wolf Point Creek (*Diamesa davisi* group, *Diamesa* sp. B and *Orthocladius* sp. A) when temperatures were 2° C (Milner 1983). In 1991 (temperatures = 5° C), *Baetis* and *Neaviperla forcipata* were found to have colonized and *Diamesa* sp. B was absent (Alexander Milner unpublished data). Longitudinal zonation of taxa in glacial rivers in Alaska, Scandinavia and the European Alps appears to follow similar trends (Milner and Petts 1994). Invertebrate communities in glacial rivers are dependent upon distance downstream from the glacier margins or time since deglaciation which results in potential deterministic patterns to community structure. Determinism appears to be influential at the genera and family level in this type of lotic biotope. Milner and Petts (1994) propose a model where the community structure is initially dominated by *Diamesa* chironomids, followed by Orthocladinae, other Diamesinae, Baetidae, Chloroperlidae and Simulidae as temperatures and channel stability increase.

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Predicting Salmonid Occurrence from Physical Characteristics of Streams in Glacier Bay National Park and Preserve

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Abstract

In Glacier Bay National Park and Preserve (GBNPP), many of the more than 310 streams along ca. 1,500 km of shoreline have been formed within the last 250 years following rapid glacial recession after Neoglacial maxima. Marked changes in the physical, chemical, and biological characteristics of these stream systems during post-glacial development have influenced salmonid distribution and abundance. Although limited information exists, more detailed inventory and characterization of stream habitat is essential for assessing and managing salmonid resources within the Park and Preserve.

An inventory database of physical and spatial characteristics of streams in GBNPP was developed. A simple model based on stream gradient and water clarity/ flow stability criteria is proposed to identify streams that may potentially support salmonid populations. Stream catchments were categorized by area into logarithmic size classes (i.e., < 1, 1-10, 10-100, and 100-1,000 km^2) and 73% were $\leq$ 10 km^2. Streams in catchments $\leq$ 10 km^2 were generally short (mean length < 2.5 km), steep (mean gradient > 17%), first-order streams. Between 40 and 68% of streams in each of the four catchment size classes were dominated by surface runoff from snowmelt or precipitation. Lakes fed by surface runoff influenced 19 to 55% of streams in smaller catchments ($\leq$ 10 km^2) while glacial sources dominated stream flow in 38 to 55% of streams in catchments > 10 km^2. Although streams within GBNPP were generally short and steep, or dominated by turbid glacial meltwater sources, 60% were predicted to possess salmonid populations. Seven of the eight large, low-gradient river systems in the 100-1,000 km^2 catchment size class are known to provide important salmonid habitat.

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Recently deglaciated streams in Glacier Bay are predicted to be colonized by salmonids as glacial influence diminishes, channel stability increases, and spawning and rearing habitat quality improve. However, as habitat quality increases through time (on the scale of thousands of years), habitat quantity may eventually decline due to sediment transport and channel incision.

KEY WORDS. Salmonids, habitat, gradient, stream order, glacial meltwater, proglacial lake, turbidity

Development of salmonid habitat is related to landscape formation following glacial recession (Benda et al. 1992). In Glacier Bay, new stream systems have been formed within the last 250 years following rapid glacial recession after Neoglacial maxima. Physical (Sidle and Milner 1989), chemical, and biological characteristics (Milner 1987, Milner, this volume) of stream systems in GBNPP change significantly during post-glacial development. As glaciers recede and vegetational communities develop, sediment loads decline and variation in discharge attenuates. Stream channels associated with lakes appear to stabilize much more rapidly due to hydrological controls on discharge variation and settling of sediment loads (Milner 1987).

Changes in the quality and quantity of stream flow influence the abundance and distribution of salmonids within the Park (Milner and Bailey 1989). Sidle and Milner (1989) suggest that fish habitat improves as pools develop, riparian cover becomes established, and sediment transport declines after deglaciation. Salmonids are an important component of recreational, subsistence, and commercial fisheries within GBNPP. Moreover, these species are important in nutrient and energy exchange between freshwater and marine ecosystems.

Limited information on the distribution and abundance of salmonid species within the Park exists and the scope, quality, and utility of these data are variable. In fact, much of this information is insufficient for accurate assessment of the presence or absence of salmonid species in many stream systems for which information exists. Establishing a stream catchment inventory and hydrologic database for GBNPP is crucial for long-range planning and management decisions regarding fisheries, native allotment issues (water rights), and oil spill response. We used topographic maps and aerial photographs to inventory and characterize stream systems and associated catchments in GBNPP. Physical characteristics of stream systems were used to develop a database in which each database record represented an individual stream system and physical parameters defined database fields. Because salmonid distribution is primarily related to stream water velocity and influenced secondarily by turbidity (Murphy et al. 1989), we developed a simple model to predict streams potentially containing salmonid populations based on stream gradient and water clarity/ flow stability criteria using the database.

Stream gradient influences water velocity, and few salmonids occur at velocities above 30 cm/s (Murphy et al. 1989). Although few salmonids occurred in steep first- and second-order streams of the Salmon River in central Idaho, Platts (1979) reported abundant chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*O. mykiss*) spawning and rearing habitat in stream orders 3 to 5 with 4-7% gradient. Similar work in southeast Alaska suggests that the majority of anadromous salmonid spawning and rearing habitat occurs in lower stream sections with gradients < 6% although steelhead and resident salmonids (i.e., Dolly Varden [*Salvelinus malma*], and coastal cutthroat trout [*O. clarki*]) have been reported in high gradient (≤ 15%), deeply incised, mountain slope (elevation > 300 m above adjacent lowlands) streams and high to moderate glacial meltwater streams (Paustian et al. 1992). Thus, a limit for stream gradient of ≤ 15% in the first half km or more above the stream mouth was set as a criterion for salmonid presence.

Water clarity also affects salmonid distribution in glacial streams (Murphy et al. 1989). A continuum of suspended sediment concentration and turbidity ranging from relatively clear lake-fed streams lacking glacial influence (< 30 NTU) to highly turbid glacial meltwater systems (≥ 400 NTU) exists for southeast Alaska stream systems (Lloyd 1987, Murphy et al. 1989). Although chinook, coho (*O. kisutch)*, and sockeye (*O. nerka*) salmon have been documented to rear in turbid glacial meltwaters in Alaska, reduced densities of coho and sockeye salmon occur in highly turbid waters ≤ 400 NTU (Murphy et al. 1989). In contrast, juvenile coho salmon acclimated to clear water have been documented to avoid turbid waters > 70 NTU (Bisson and Bilby 1982).

Although salmonids are known to occur in turbid meltwater streams, a temporal component of stream development resulting in increased habitat stability of turbid meltwater streams may be important for salmonid colonization of these systems. In Glacier Bay, Milner (1987) documented a turbidity range of 0-20 NTU for clearwater streams and 140-160 NTU for two glacial meltwater streams fed by proglacial lakes associated with glacial remnants. No juvenile or adult salmonids were found in these two glacial streams prior to 1985 (Milner and Bailey 1989). However, Dolly Varden first colonized one of these streams, Wolf Point Creek, in 1987 followed by pink and coho salmon in 1989 (Milner 1994). Because the majority of turbid meltwater streams occurring within Glacier Bay are relatively young (< 250 years before present, [B.P.]) and are undergoing development, they probably have not yet been extensively colonized by salmonids. Thus the criterion of water clarity/ flow stability for predicting salmonid presence is defined to include not only those streams influenced by surface runoff but also glacial meltwater systems influenced by proglacial lakes which function to trap larger sediments (> 0.1 mm) and stabilize flows.

Methods

Physical parameters of existing streams and associated catchments were recorded from 1:63,360 scale series United States Geological Survey (USGS) topographic maps. Most (25 of 39) USGS topographic maps of GBNPP were based on aerial photographs taken between 1948 and 1960. Similar-scale 1979 color infrared aerial photographs (United States Department of Agriculture, Aerial Photography Field Office) were also used to provide the most updated information on stream morphology. Changes in glacier termini and stream morphology were evident in 1979 aerial photographs relative to earlier topographic maps.

All data for each stream system were entered as individual records into a FoxPro database (vers. LAN 2.5 for Windows). Each database record represented an individual stream system and physical parameters defined database fields. Stream records were referenced in the database by a unique National Park Service (NPS) and Alaska Department of Fish and Game (ADF&G) number. ADF&G catalog numbers were recorded for stream systems within the Park from an atlas and corresponding anadromous waters catalog published by ADF&G's Habitat and Restoration Division (ADF&G 1992). The ADF&G atlas and catalog provide a documented record of stream systems used by anadromous fish. In addition, the ADF&G Commercial Fisheries Division designates streams possessing important anadromous fisheries with a separate numbering system which was also included in the database. Stream mouth locations were determined either from 1:63,360 scale maps or in the field with a Global Positioning System during aerial or boat surveys. Locational coordinates of stream mouths were recorded as Universal Transverse Mercator coordinates.

Catchment boundaries based on the topographic divide (Gordon et al. 1992) were delineated on topographic maps. A transparent gridded overlay was used to categorize stream catchment area into one of four logarithmic size classes (i.e., ≤ 1, > 1-10, > 10-100, and > 100-1,000 km^2). Only streams recorded as perennial streams on USGS topographic maps were recorded. Individual streams were identified as discharging into salt water at high tide.

The Alsek River's 28,000 km^2 catchment was omitted from analysis because most of the Alsek catchment occurs outside GBNPP and this system was an order of magnitude larger than any other catchment within the park. However, the complexity and importance of this large river system in terms of salmonid spawning and rearing habitat should not be overlooked.

We used a hand-held cartometer to determine stream length from topographic maps along the longest axis of each stream. Measurements integrated all fresh waters from the mouth to headwaters including lakes (i.e., from the high tide line to the upper extent of blue lines on topographic maps). Similarly, mean stream gradient was calculated using elevation indicated by contour lines at the upper extent of blue lines relative to mean sea level (Gordon et al. 1992). Stream order, which provides a means of ranking the relative size of streams, was determined for each stream system according to the method of Strahler (Gordon et al. 1992).

We used color infrared aerial photographs from 1979 to evaluate water clarity and flow stability of streams. The predominant water source of each stream system was identified as either glacial meltwater or surface water (snowmelt or rain) based on water color and the presence or absence of glacial ice within the catchment. The presence and number of lakes in each catchment were recorded. We evaluated water source as well as number, location, and size of lakes and recorded the predominant water source for each catchment as either glacial meltwater, proglacial lake, surface water (snowmelt or rain), or lake basin.

A simple model designed to predict the presence of salmonid populations in GBNPP streams was developed based on two main criteria: 1) a gradient of ≤ 15% in the first 0.5 km or more above the stream mouth, and 2) water clarity/ flow stability inherent in surface runoff-, lake-, or proglacial lake-influenced stream systems. At least twenty percent of streams in each catchment size class were randomly selected and stream profiles were plotted in order to evaluate whether streams met the gradient criterion. We used color infrared aerial photographs to verify water clarity and flow stability of streams meeting the gradient criterion. Clearwater/ stable streams contained at least one or more lakes clearly influencing discharge by virtue of size and location or were predominantly fed by surface water. Stream systems influenced directly by meltwater from glacial ice did not meet the water clarity/ flow stability criterion. Results were then extrapolated to the total complement of streams.

Results

Over 310 stream systems were evident along ca. 1,500 km of shoreline within GBNPP. The highest density of streams

Table 1. Characteristics of stream systems in Glacier Bay National Park and Preserve by catchment size. Length includes the main stream channel from the mouth at high tide to the upper extreme of headwaters or lake basins as indicated by 1:63,360-scale USGS topographic maps. Similarly, stream gradient is based on the elevation at the upper extant of headwaters. Stream order is based on the method of Strahler (Gordon et al. 1992). Means (X) and standard deviations (s) are presented.

Catchment Size		Length (km)			Gradient (%)			Order		
Class (km^2)	Number	X	s	Range	X	s	Range	X	s	Range
≤ 1	31	0.9	0.5	0.3 - 3.1	17.7	20.3	0.9-68.6	1.0	0.2	1-2
> 1-10	195	2.4	1.4	0.1-11.9	18.1	16.3	0.2-94.5	1.2	0.4	1-3
> 10-100	75	7.6	3.5	0.8-19.3	7.0	4.7	0.1-25.9	2.1	0.7	1-3
> 100-1000	8	24.4	5.9	13.7-28.7	1.7	1.2	0.2 - 3.4	3.0	0.8	2-4

Table 2. Predicted occurrence of salmonid populations in Glacier Bay National Park and Preserve. Numbers were extrapolated from subsamples of streams in each size class using gradient and water clarity/ flow stability criteria. The gradient criterion was met by streams with gradients ≤ 15% in the first 0.5 or more kilometers above the stream mouth. Clearwater/ stable streams included all streams meeting the gradient criterion with dominant surface runoff, lake, or proglacial lake sources influencing water clarity and flow stability.

Catchment Size (km^2)	Sample Size		Subsamples Meeting Criteria		Predicted Salmon Streams
	Population	Subsample	Gradient # (%)	Clarity/Stability # (%)	
≤ 1	31	10	6 (60)	6 (60)	19
1-10	195	40	26 (65)	25 (62)	121
10-100	75	15	14 (93)	8 (53)	40
100-1000	8	8	8 (100)	6 (75)	6

occurred in Muir Inlet (Fig. 1). Fifteen of the most tightly clustered streams in this area were located in Wachusett Inlet. Similarly, 14 streams occurred in Tarr Inlet along the northern-most reach of the West Arm. A dense cluster of streams occurred in Dundas Bay and, with the exception of the high concentration of streams between Icy Point and Lituya Bay, streams along the Outer Coast were sparsely distributed.

Stream systems within the park occurred in 4 catchment size classes with the exception of the Alsek River. Catchment size was positively related to stream length and order and was negatively related to gradient (Table 1). Most (73%) streams occurred in catchments $\leq$ 10 km^2 while 27% of streams occurred in larger catchments. Streams in catchments $\leq$ 10 km^2 were generally short ($<$ 2.5 km) and steep with a mean gradient greater than 17%. Catchments $>$ 10 km^2 were generally second- or third-order streams greater than 7.5 km in length with mean gradients of 2-7%. Eight stream systems existed in the 100-1,000 km^2 catchment size class; six of which (the Doame, Dundas, Beartrack, Bartlett, Salmon, and Excursion Rivers) were important in terms of salmonid habitat.

Stream profiles suggested quantitative differences in low-gradient salmonid habitat in large river systems relative to smaller streams (Fig. 2). More than 88% of stream length for streams in 100-1,000 km^2 catchments exhibited gradients $\leq$ 15%; in fact, more than 80% of stream length for streams in this catchment size class exhibited gradients $\leq$ 5% (Fig. 2a). The 5% gradient was exceeded at a distance of 23-26 km from stream mouths at 200-250 m elevation for 5 of the 6 streams illustrated in this size class. The 15% gradient was exceeded only in the upper reaches of the Beartrack, Adams Inlet, and Excursion Rivers. Five of the 6 randomly selected streams in the 1-10 km^2 catchment size class possessed gradients $\leq$ 15% throughout 27-80% of their length (Fig. 2b). The profile for NPS stream #371 converged with the 15% gradient at 0.6 km, while the 15% gradient was exceeded at 1.0-1.6 km above stream mouths in the other streams meeting the gradient criterion. Stream gradients in this catchment size class exceeded the 15% criterion for salmonid accessibility at a much lower elevation (40-140 m) than did larger stream systems and appreciably less low-gradient salmonid habitat was available.

Precipitation and snowmelt in the form of surface runoff or lake basin accumulation appeared to be the predominant water source for most streams in the two smallest ($<$ 1 and 1-10 km^2) and largest (100-1,000 km^2) catchment size classes (Fig. 3). Forty to 68% of streams among the four catchment size classes were influenced largely by surface runoff due to snowmelt and precipitation. Surface runoff fed lakes influenced 55% and 19% of streams in the $<$ 1 and 1-10 km^2 catchment size classes, respectively. Lakes fed by surface runoff influenced stream flow in only 4 of 75 (5%) stream systems in 10-100 km^2 catchments. Glacial sources including meltwater directly from glacial ice as well as proglacial lake discharge provided stream flow in 55% of streams in 10-100 and 38% in the 100-1,000 km^2 catchments. Glacial meltwater directly from glaciers influenced few streams in smaller catchments but was an important source for 43% and 25% of streams in the 2 larger catchment size classes (10-100 and 100-1,000 km^2). Proglacial lakes directly influenced stream flow in 12-13% of streams in the 10-100 and 100-1,000 km^2 catchments.

Based on gradient criteria alone, 60% or more of randomly selected streams in each catchment size class exhibited gradients $\leq$ 15% in the first half km or more above stream mouths (Table 2). Proportionately fewer streams in the 3 catchment size classes $\leq$ 100 km^2 were predicted to be accessible to salmonids relative to streams in the largest catchment size class. With the exception of streams in the 10-100 km^2 catchment size class, 60-75% of randomly selected streams met the water clarity/ flow stability criterion for salmonids. Forty-seven percent of randomly selected streams in the 10-100 km^2 catchment size class were influenced by glacial meltwater and lacked dominant proglacial lake influence. Although streams within GBNPP were generally short and steep or dominated by turbid glacial meltwater sources, 60% were predicted to possess salmonid populations.

Discussion

Streams within Glacier Bay were deglaciated as recently as 250 or fewer years B.P. following the late Neoglacial advance, and many of these systems are currently being colonized by salmonids (Milner 1987, Milner and Bailey 1989). Streams along the Outer Coast and in Excursion Inlet have generally been subjected to less recent glacial disturbance ($>$ 2,000 years B.P.) and salmonid stocks are well established.

The youngest and most rapidly developing stream systems occur within Glacier Bay. These dynamic systems, characterized by high rates of sediment transport, variable flows, and high turbidity, typically provide poor quality salmonid spawning and rearing habitat. Based on a chronosequence study of 5 streams in GBNPP ranging in age from 30 to 150 years, fish habitat improves with development as pools form, riparian cover increases, and sediment transport decreases (Sidle and Milner 1989). Flow buffering lakes enhance this improvement in fish habitat.

Continual incision and sediment transport associated with stream development processes affect channel width and gradient, particularly in headwater areas. For example, Benda et al. (1992) determined that incision of the South

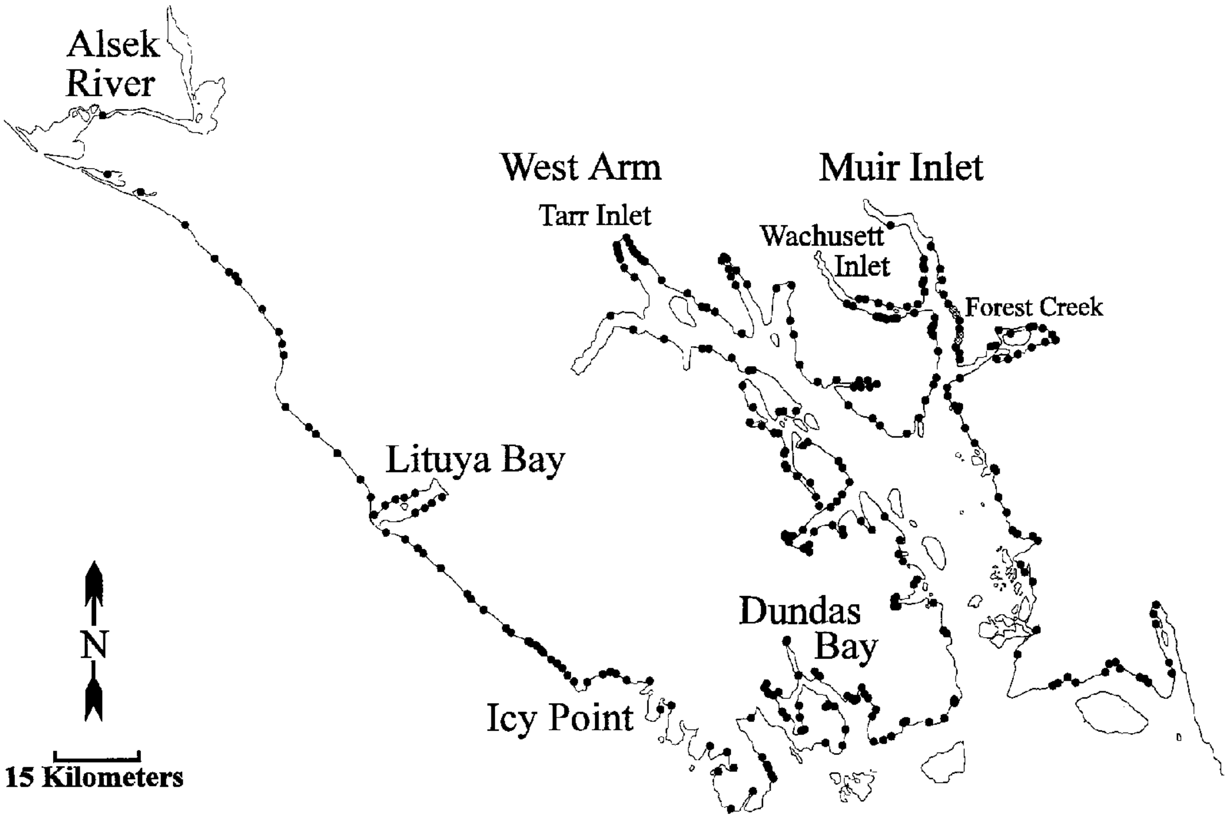

Fig. 1. Distribution of databased streams in Glacier Bay National Park and Preserve. Stream mouth locations are indicated. Lightly shaded stream mouth locations in the Forest Creek area designate two sets of braided channels once fed by Casement Glacier but now dry

Fork of the Stillaguamish River into glacial sediments in the Cascade Mountains of northwest Washington 14,000 years after glacial disturbance reduced valley floor widths and increased gradients in older terrace reaches of headwater tributary streams. These habitat changes are more suitable for resident salmonid species and steelhead trout than other anadromous species. Both spawning and rearing habitat quality on the South Fork increased with catchment stability and successional development of forests following deglaciation but decreased quantitatively through channel width narrowing as a consequence of channel incisement over 14,000 years (Benda et al. 1992). Recently deglaciated streams within Glacier Bay are expected to be colonized by salmonids as glacial influence diminishes, catchment stability increases, and habitat improves (on the scale of tens to hundreds of years). However, if stream development in GBNPP parallels development of the Stillaguamish River, the quantity of habitat may decline on the scale of thousands of years due to sediment transport and channel incision.

Streams in GBNPP are similar to streams elsewhere in southeast Alaska, and many are characterized by small catchments, short stream length, and steep gradients (Schmiege et al. 1974). Limited water holding capacity of small catchments, steep gradients, and heavy precipitation in southeast Alaska result in unstable flow characteristics (James 1956 cited in Schmiege et al. 1974). Unstable flows prevent establishment of riparian vegetation which provides cover and woody debris serving as in-stream structure important to salmonids (Milner 1987). Streams in catchments ≤ 10 km^2 are often inaccessible to salmonids due to high stream gradients, high flow velocity, seasonally low water, anchor-ice formation in winter, and migration barriers. These streams generally contain negligible spawning or rearing habitat and few salmonids (Platts 1979). However, both pink (*O. gorbuscha*) and chum (*O. keta*) salmon are known to spawn successfully in intertidal marine habitats and therefore require minimal stream habitat. These species even spawn in the intertidal zone below inaccessible streams (Lucy Wold, USFS, pers. comm.).

Previously established correlations show that large catchments tend to contain longer streams with gentler gradients and fewer first-order tributaries than smaller

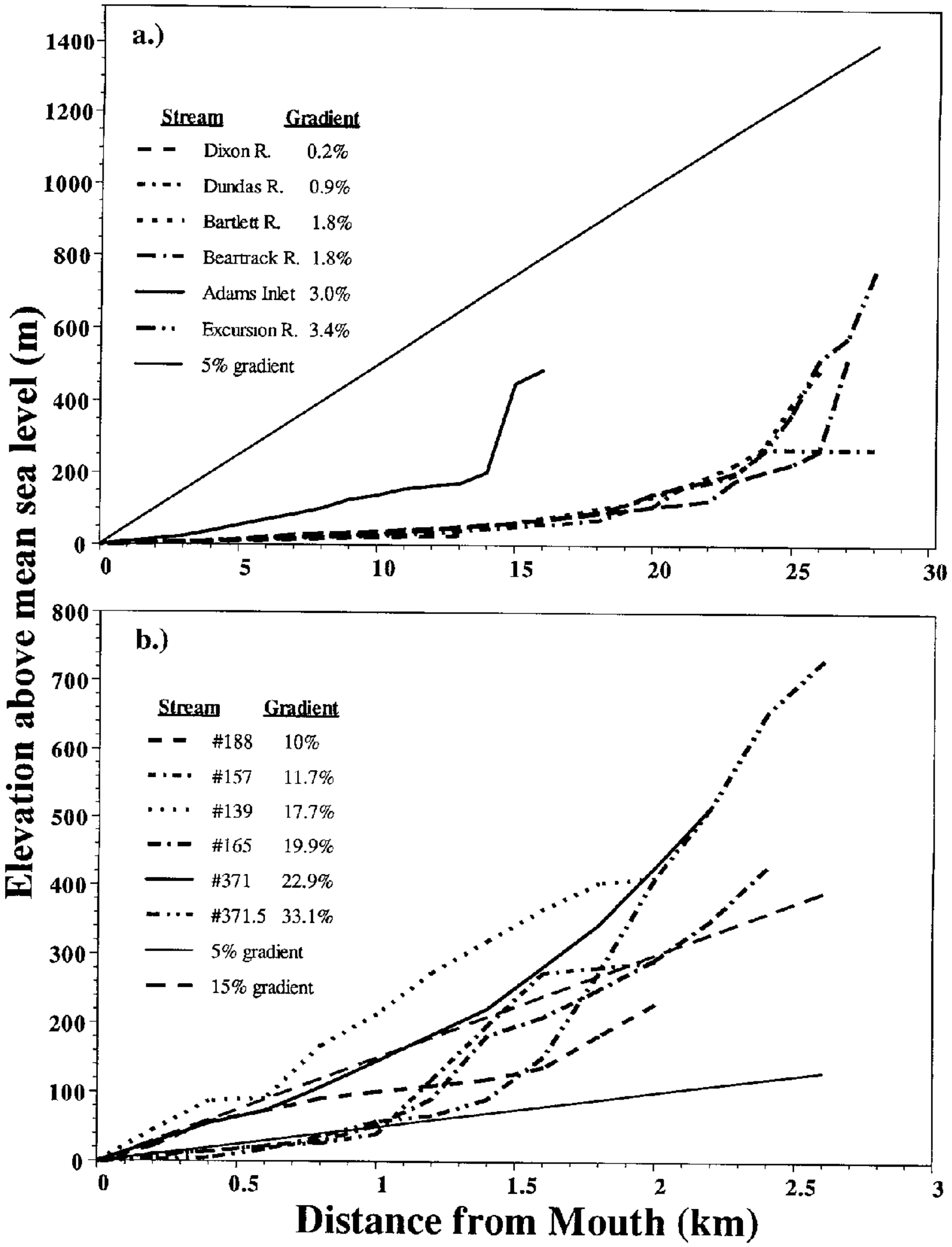

Fig. 2. Stream profiles for select streams in GBNPP: a.) profiles of streams in 100-1,000 km^2 catchments. b.) profiles of streams in 1-10 km^2 catchments. Distance from stream mouth was measured from the upper extent of tidal influence at mean high tide.

catchments with steep slopes and high-gradient streams (Morisawa 1968). Platts (1979) determined that the number of fish species and total numbers of fish increased with stream order and corresponding decreased gradient. Spawning runs consisting of hundreds to tens of thousands of fish among at least two to seven anadromous salmonid species have been reported to occur in seven of the eight largest stream systems in GBNPP (ADF&G 1992, NPS unpublished data). Similar runs are known to occur in streams in the 10-100 km^2 catchment size class. Thus, although small streams are more abundant they compose a smaller portion of the total available stream habitat within the park and the diversity and abundance of anadromous salmonids is probably much greater in larger streams.

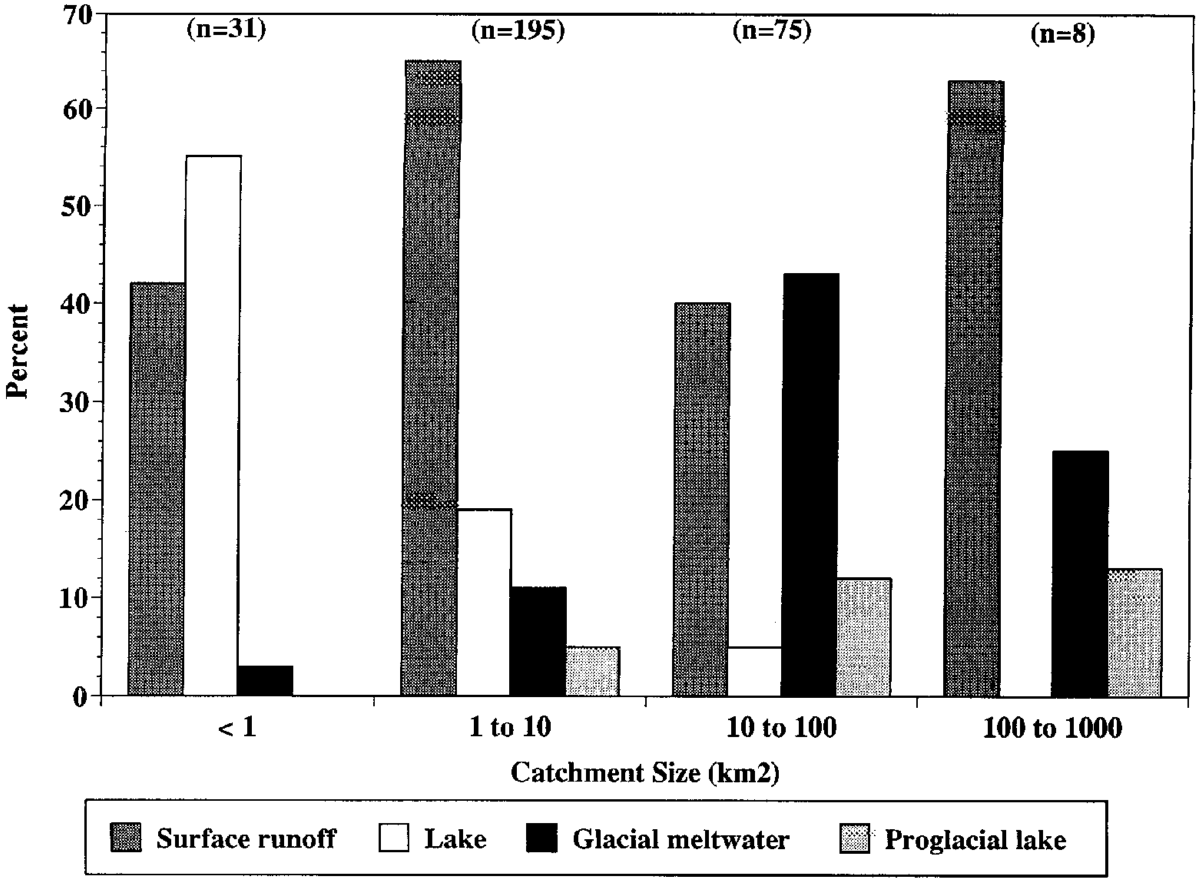

Fig. 3. Dominant source of influence on stream discharge for streams in catchments of different size. Surface runoff includes precipitation and snowmelt sources. Lake is defined as surface runoff basins dominating stream discharge. Glacial meltwater is stream discharge issuing directly from the glacier. Proglacial lakes include lakes dammed by glacial ice and lakes formed behind moraines where glacial ice forms part of the lake margin though not the actual barrier.

Suspended sediment loads and turbidity vary among stream systems and are dependent upon dominant water sources. Suspended sediment concentration or turbidity data are unavailable for most streams within GBNPP but dominant water source provides an index for suspended sediments and turbidity among stream systems.

Murphy et al. (1989) suggest that turbidity caused by glacial silt may not negatively affect salmonids and that turbidity effects may be confounded with other parameters such as habitat stability. In fact, work by one of us (A.M.M.) in a stream system in GBNPP, that was released from the ice in the late 1940s with flows stabilized by a proglacial lake formed in 1967, suggests that habitat stability is more important for salmonids colonizing glacial meltwater streams than water clarity (Milner 1994).

The ratio of lake:watershed area determines the hydraulic influence of lakes on stream systems which subsequently affects habitat stability in terms of variation in flow and suspended sediment concentration. Lakes typically function as sediment traps, and depending on lake size, buffer flow variation (Milner 1987). Glacial meltwaters are typically quite turbid (> 30 NTU), and proglacial lakes similarly function to trap larger sediments (> 0.1 mm) but have little effect on reducing turbidity (Milner and Petts 1994). Milner (1987), summarizing developmental pathways of streams in GBNPP, reported that the hydraulic effect of lakes in buffering flow variation provides more favorable conditions for algae and moss, which in turn promote benthic invertebrate production. Stable stream flows allow establishment of riparian vegetation along stream margins, and vegetation and woody debris are crucial in providing shade, cover, and habitat for salmonids (Milner and Bailey 1989). Stable stream flow reduces effects of extremes in discharge, mitigating the effects of floods and drought on salmonids. The role of the ratio of lake:watershed area in stabilizing flow and promoting habitat stability and salmonid colonization in developing streams requires further investigation.

Information on salmonid distribution and abundance in GBNPP is extremely limited, particularly for some of the smaller stream systems, and is essential for evaluating the accuracy of the model. The model predicts that six of eight streams in the 100-1,000 km^2 catchment size class should contain salmonids. In actuality, seven of the eight streams in this catchment size class have been well documented to contain salmonids. The model failed to predict the occurrence of salmonids in the Dixon River, a turbid glacial meltwater system. Five of the eight streams in the 10-100 km^2 catchment size class predicted to contain salmonids based on model criteria (Table 2) have previously been documented to contain salmonids (NPS unpublished data). Information on the three additional streams predicted to contain salmonids and the seven streams failing to meet gradient and water clarity criteria is currently lacking. Very limited information exists regarding salmonid presence or absence in catchments ≤ 10 km^2. Although information on salmonid distribution and abundance is currently inadequate for evaluation of the model, gradient appears to be a good predictor of salmonid habitat accessibility. However, turbidity in the absence of strong proglacial lake influence is not always a good predictor of salmonid absence as indicated by the Dixon River. A survey of the distribution and abundance of salmonids in a representative subsample of streams among catchment size classes within GBNPP is necessary for further evaluation and revision of the model.

Contour intervals of 33 m for 1:63,360 scale USGS topographic maps precluded identification of barriers or obstructions (i.e., waterfalls, cascades, log jams, etc.) occurring at lower reaches. Edgington et al. (1987), in evaluating channel type classification for documenting anadromous salmon streams, emphasized that neither aerial photographs nor visual observation from a helicopter could adequately assess barriers and that this was best accomplished through ground truthing. Mean gradient integrated over the total length of a stream system provides an inadequate measure of salmonid accessibility because steep gradients or barriers may preclude access at lower reaches. Ground surveys profiling stream channel elevation from the point of salmonid access (i.e., stream mouth) would provide a much more accurate picture of salmonid accessibility.

Small stream systems and subglacial streams were under-represented or omitted from the database. Many small perennial and intermittent stream systems occur in catchments ≤ 10 km^2 within the Park. However, topographic maps were based on aerial photographs, and stream channels in small catchments can be obscured by the overlying vegetation canopy. Moreover, many of these small stream systems may not have been evident during periods of reduced precipitation and run-off or during earlier development when the aerial photographs were obtained on which topographic maps are based. Similarly, stream systems entrained within tidewater glaciers were omitted from the database. Although these stream systems in aggregate probably contribute substantial volumetric inputs to marine waters, they probably provide little salmonid habitat..

Two final caveats concern the application of this database and associated model development: 1) information presented in this work represents the status of streams as they were 14 or more years ago, and 2) work in this area emphasizes the need for periodic updating of mapped information. The physical characteristics of stream systems are dynamic, particularly in recently deglaciated areas where the chronology of glacial recession in individual catchments should be investigated and recorded in the database. Some streams may now be dry as exemplified by a number of streams in the Forest Creek catchment on the east side of Muir Inlet (Fig. 1). Ground truthing and field work are essential for verifying information obtained from topographic maps and aerial photographs contained in this work.

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International Gaging Station Established on the Alsek River

by

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Abstract

The Tatshenshini and Alsek rivers constitute a large and diverse river system that originates in Canada and runs southwest through the Alaska coastal mountain range. In 1992, the National Park Service, in cooperation with the U.S. Geological Survey, the Water Survey of Canada, and the International Joint Commission (U.S. State Department) established a continuous hydrological recording gage station on the Alsek River in a wilderness area within Glacier Bay National Park and Preserve. The 1992 calendar-year data shows that the peak summer flow in July (3,653 cms/129,000 cfs) was 40 times greater than the low winter flow (91 cms/3200 cfs), reflecting the predominant glacial influence in the warmer summer months. The gaging station will provide valuable baseline data for management decisions that are critical to the future protection of the Alsek and Tatshenshini rivers in Canada and the United States.

KEY WORDS: Rivers, flow, water quality, wilderness, mining impacts.

The Tatshenshini and Alsek rivers converge approximately 11 km east of the Alaska-Canada border where the river, at this point named the Alsek River, flows into Alaska forming the northern boundary of Glacier Bay National Park and Preserve, and eventually flows into the Gulf of Alaska at Dry Bay.

The Tatshenshini River, (drainage area = 6508 km^2) rises in the drier interior region of Canada and flows through an area of higher precipitation in Alaska where it receives a number of glacier-fed tributaries (16% of catchment). The Alsek River is larger (drainage area = 20,400 km^2, measured

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upstream of the Tatshenshini confluence) of which 20% of the catchment is covered by glaciers.

The Alsek River below the confluence is characterized by braided channels, steep gradients, and high volumes of glacial meltwater and high sediment transport. Glacial meltwater, in addition to snowmelt runoff and rainfall, feeds the Alsek-Tatshenshini river system which reaches maximum stage in July and early August. Seismic activity also plays a significant role in the behavior of this river system; for example, in 1975 an earthquake caused the mouth of the Alsek River to shift 1 km to the west (Alaska Geographic Society, 1975).

The lower river, which includes Alsek Lake, is a major migratory route for various animals and provides aquatic and riparian habitat for sea birds, waterfowl, seals, moose, bears, wolves, and salmon. Because of its unique setting and its outstanding wilderness qualities, the Tatshenshini-Alsek river system has become a popular destination for river-runners.

The NPS Role in Managing the Alsek River

Glacier Bay National Park was expanded in 1980 by the Alaska National Interest Lands Conservation Act (ANILCA) to include the lower Alsek River from the U.S.-Canada border to the Gulf of Alaska. ANILCA mandated that the land "be managed for the following purposes among others: To protect a segment of the Alsek River, fish and wildlife habitats and migration routes..." (ANILCA Sec.202 (1)).

In light of this mandate and potential water resource threats from proposed upstream mining activities, the National Park Service, in cooperation with the U.S. Geological Survey (USGS), the Water Survey of Canada, and the International Joint Commission (U.S. State Department), established a continuous recording gage station in July 1991 on the Alsek River to collect data on daily and seasonal river flow characteristics and baseline water quality. In August 1992, the Alsek River gage (Fig. 1) was officially designated by the governments of the United States and Canada as an International Gaging Station, which directs that the U.S. and Canada cooperate in field data collection, analysis, and report publication.

Selection of the Gaging Site

The establishment of the gaging station within Glacier Bay National Park and Preserve was a challenge for the National Park Service, USGS, and the Water Survey of Canada in terms of environmental constraints and field logistics.

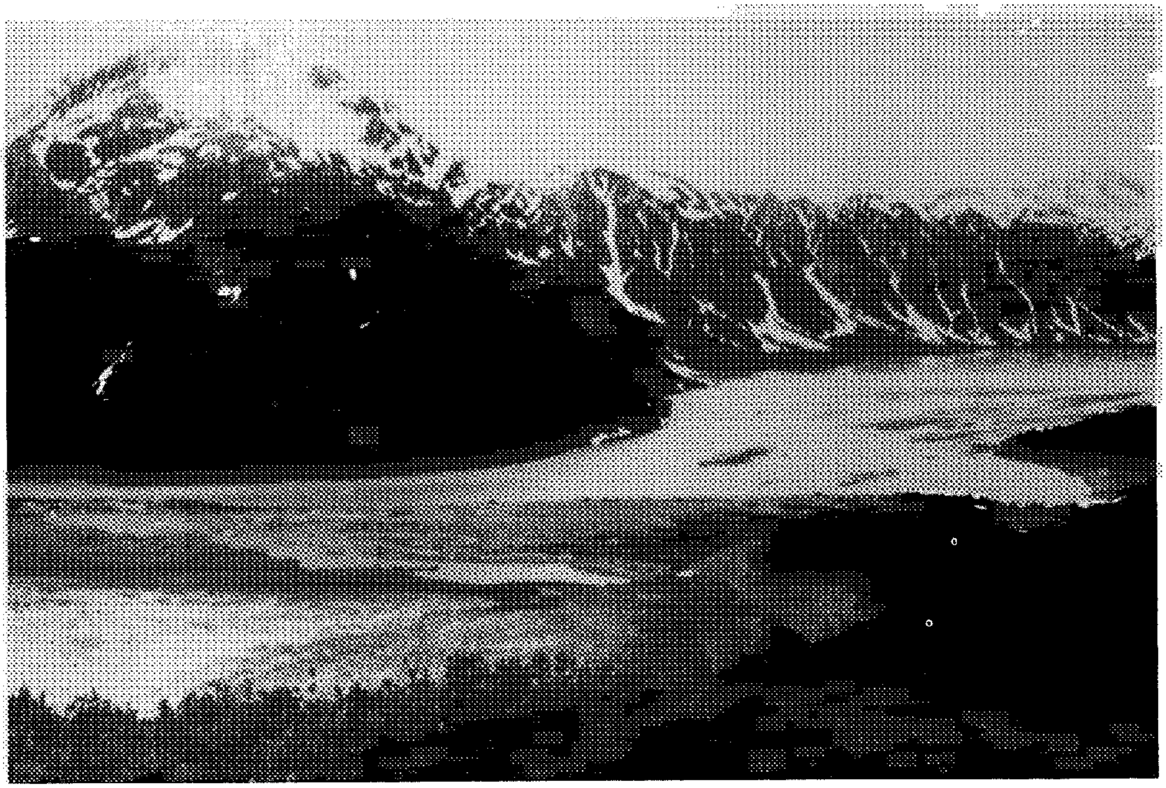

Fig. 1. Alsek River gaging site is located and well hidden on the right bank bluff across from Walker Glacier (pictured in the foreground). (summer conditions)

Many factors were considered in site selection including the remote location within a designated park wilderness, difficulties of access, and potential disturbance to river-runners from gage station activities. Aircraft access tothe gage station is carefully timed and routed to minimize disruption; however, frequent poor weather, wind, and severe winter conditions often hamper aircraft operations and limit the ability of field staff to safely conduct river operations.

There were, and continue to be, other operational challenges in conducting field work including: identifying a stable channel section to take flow measurements; measuring massive glacial meltwater input and dramatic fluxes in flow; swift river velocity; employee safety; and on-site equipment and boat storage in a wilderness area.

Sampling Regime

USGS or Water Survey of Canada staff visit the station every two months throughout the year to service the recording gage and take flow measurements to correlate flow with gage height which will be used to establish an accurate rating curve when enough points are obtained over years. As of September 1993, real-time gage-height data are being transmitted from the gaging station to the GOES-2 stationary-orbit weather satellite. This data is directly received by the USGS office in Tacoma and then is transmitted to the USGS office in Anchorage every four hours.

The 1992 calendar-year data demonstrated that the peak summer flow in July (3,653 cms/129,000 cfs) was 40 times greater than the low winter flow (91 cms/3200 cfs). This peak flow predominantly reflects the influence of glacier meltwater and late snowmelt runoff in the relatively warmer summer months (Figure 2). Storm events in early spring, prior to major summer glacier melt, resulted in flows that were substantially lower (340-538 cms/12,000-19,000 cfs) than the peak summer flow. Similarly, early snowmelt runoff in May and early June averaged less than half the peak summer flow in July. The 1993 and 1994 calendar-year data showed the same trends with peak summer flows of 3,596 cms/126,992 cfs in July 1993 and 3483 cms/123,000 cfs in August 1994 (Figure 3).

Rainfall data is not available from the gage site to accurately separate the effects of precipitation and glacial melt. There is cumulative rainfall data, however, for the 1994 summer season collected at the Dry Bay Ranger Station near the mouth of the Alsek River. Although it has not yet been determined if rainfall at the mouth is correlated with rainfall at the gage, the 1994 rain data shows peak rainfall at the mouth in May (29.94 cm/11.79 in) and July (34.74 cm/13.68 in), while the corresponding hydrograph shows relatively low flow in May and high flows in July and early August. This indicates the significant effect of glacial meltwater, relative to rainfall, during the consecutive high-insolation mid-summer days. The June 1994 rainfall (5.87 in/14.91 cm) and the August 1994 rainfall (5.13 in/13.03 cm) was less than half of the rainfall measured in May and July, while the total July river flow was three times greater than the total May flow, further indicating the relatively small effect of rainfall on the total flow of the

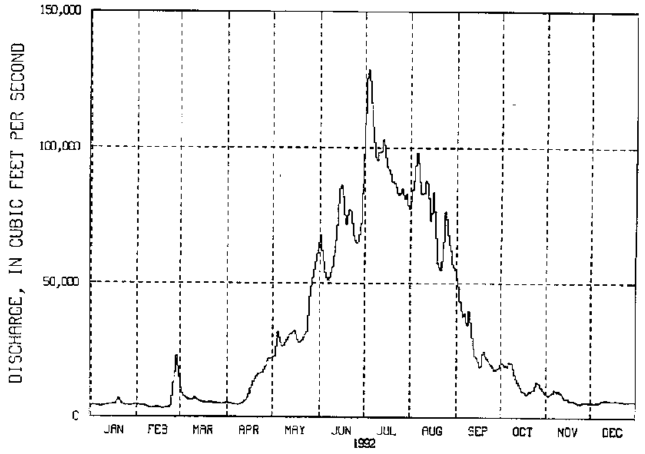

Fig. 2. Mean daily discharge (cfs) for Calendar-Year 1992 at the Alsek River gaging station, Alaska. (conversion: 1 cfs = .02832 cms)

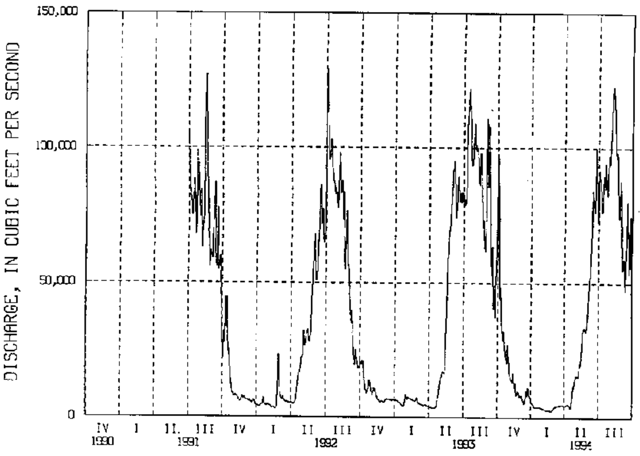

Fig. 3. Mean daily discharge (cfs) for Calendar Years 1991-1994 at the Alsek River gaging Station, Alaska. (Quarter I = January-March; Quarter II = April-June; Quarter III = July-September; Quarter IV = October-December)(conversion: 1 cfs = .02832 cms)

Alsek. Even during extended dry periods, it has been observed that the river continues to flow at a high stage (personal communication, Mike Sharp, Dry Bay Ranger Station, 1995).

Water quality parameters are measured and bed material samples are collected twice a year, based on the National Water Quality Assessment Program. Sediment chemistry is being analyzed as part of the USGS National Sediment Research Project. The parameters measured include water and air temperature, pH, specific conductance, alkalinity, hardness, cations/anions, dissolved oxygen, nitrogen, phosphorus, suspended sediment, turbidity, and dissolved metals.

The water in the Alsek River runs clear during the winter months (October-May) when the glaciers are not contributing meltwater. During the summer months, turbidity was measured up to 440 NTU (Table 1). Alkalinity is relatively low year-round, measuring 48-97 mg/l; similarly, hardness ranged from 59-110 mg/l. Based on the limited record of data to date, total phosphorus appears to be at its highest concentration in July. Nitrogen, however, does not demonstrate this summer increase.

Table 2 shows results of six of 21 metals measured in suspended sediments, bed sediments and in the dissolved form in the water column. Iron, aluminum and manganese showed notably higher concentrations in the suspended and bed sediments than any of the other metals measured. Aluminum and iron also show a relatively high dissolved concentration. The full data set of metal results is available from the USGS, Alaska. Chemical sampling is slated to continue at the Alsek River gaging station through 1995, at which time it may be discontinued due to a reduction in the Collection of Basic Records (CBR) program.

Summary

The gaging station on the Alsek River provides valuable baseline data on a southeast Alaska glacial river, one of just a few rivers that runs through the coastal range.

Results to date have shown that glacial meltwater drives the Alsek river flow, with peak flows occurring in July and early August. Low flow, which generally occurs in February, is on the average less than 5% of peak summer flow. During the winter, the river runs clear but becomes very turbid in the summer when the glacial meltwater contributes suspended particulate. Aluminum and iron occur naturally in relatively high concentrations in suspended sediments, bed sediments and in a dissolved state in the water.

The Alsek River data collected at the gaging site will be useful for other physical process research on topics such as debris flows, island formation, and even seismicity. These data will also prove critical in supporting park management decisions related to recreation and fisheries management and in planning with Canada for international management of the watershed.

Of added importance is the fact that Glacier Bay National Park and Preserve was designated as a World Heritage Site in 1992, and management of the lower section of the river is now subject to this designation which requires protection of the significant characteristics upon which the designation was based. A continued cooperative water monitoring program by the United States and Canada is essential to meet these mandates.

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Personal Communication, 1995. Mike Sharp, National Park Service Pilot-Ranger, (Glacier Bay National Park and Preserve), stationed at Dry Bay, Alaska.

Table 1. Water quality parameters measured in the Alsek River, 1991-1994

Date	Temp °C	pH	Alkalinity mg/l as CaCO3	Hardness mg/l as CaCO3	Dissolved Oxygen mg/l	Specific Conduct. µS/cm	Dissolved Solids mg/l	Turbidity NTU	Suspended Sediment mg/l	Total-N mg/L	Total-P mg/L
Dec 18, 91	0.0	7.8	80	110	--	250	--	8.5	--	0.200	0.500
Mar 21, 92	3.0	7.7	89	110	--	250	138	2.2	--	0.230	0.030
Jul 1, 92	9.0	8.5	48	70	--	159	78	400.0	--	0.077	0.750
Sep 2, 92	5.0	8.4	48	62	--	140	75	180.0	514	0.070	0.010
Oct 26, 92	3.0	--	65	92	--	196	109	32.0	--	0.170	0.060
Jan 5, 93	0.0	8.0	95	--	--	250	--	3.6	--	0.025	<0.010
Feb 17, 93	0.0	8.1	81	110	--	252	136	5.6	--	0.024	0.010
Apr 28, 93	4.0	8.2	83	110	10.6	246	138	20.0	315	0.320	<0.010
Jul 12, 93	5.5	8.1	42	--	--	114	--	--	--	0.061	0.880
Sep 14, 93	5.0	7.8	56	59	--	135	77	440.0	--	0.110	0.090
Jun 21, 94	--	8.4	54	72	--	148	83	160.0	--	0.093	0.430
Aug 31, 94	4.0	8.6	97	62	12.90	150	108	250.0	--	--	0.290
Nov 9, 94	0.0	8.0	71	--	--	210	--	--	--	0.160	0.010

Table 2. Metal concentrations in water and bed sediments in the Alsek River, 1991-94.

Dissolved Metals[1] (μg/l) [Cu, Mn, Cr, Zn = ppm; Al, Fe = wt%]

Date	Cu	Mn	Cr	Zn	Al	Fe
Dec 18, 91	--	<1	--	--	10	20
Mar 21, 92	--	--	--	--	--	--
Jul 1, 92	--	--	--	--	--	--
Sep 2, 92	1	3	2	<3	90	56
Oct 26, 92	--	--	--	--	--	--
Jan 5, 93	--	--	--	--	--	--
Feb 17, 93	--	--	--	--	--	--
Apr 28, 93	<1	1	<1	5	30	11
Jul 12, 93	--	--	--	--	--	--
Sep 14, 93	--	--	--	--	--	--
Jun 21, 94	<1	5	1	4	20	130
Aug 31, 94	<1	8	2	23	90	49
Nov 9, 94	--	--	--	--	--	--

Suspended Sediment Metals[1] [Cu, Mn, Cr, Zn = ppm; Al, Fe = wt%]

Date	Cu	Mn	Cr	Zn	Al	Fe
Dec 18, 91	--	--	--	--	--	--
Mar 21, 92	--	--	--	--	--	--
Jul 1, 92	--	--	--	--	--	--
Sep 2, 92	--	--	--	--	--	--
Oct 26, 92	--	--	--	--	--	--
Jan 5, 93	--	--	--	--	--	--
Feb 17, 93	--	--	--	--	--	--
Apr 28, 93	48	870	--	100	6.2	4.9
Jul 12, 93	--	--	--	--	--	--
Sep 14, 93	--	--	--	--	--	--
Jun 21, 94	44	740	83	160	5.9	4.3
Aug 31, 94	--	--	--	--	--	--
Nov 9, 94	--	--	--	--	--	--

Bed Sediment Metals[1] [Cu, Mn, Cr, Zn = ppm; Al, Fe = wt%]

Date	Cu	Mn	Cr	Zn	Al	Fe
Dec 18, 91	--	--	--	--	--	--
Mar 21, 92	--	--	--	--	--	--
Jul 1, 92	--	--	--	--	--	--
Sep 2, 92	30	700	63	62	6.6	3.6
Oct 26, 92	--	--	--	--	--	--
Jan 5, 93	--	--	--	--	--	--
Feb 17, 93	--	--	--	--	--	--
Apr 28, 93	26	660	60	51	7.3	3.7
Jul 12, 93	--	--	--	--	--	--
Sep 14, 93	--	--	--	--	--	--
Jun 21, 94	31	630	66	55	7.3	3.5
Aug 31, 94	--	--	--	--	--	--
Nov 9, 94	--	--	--	--	--	--

[1] Sus. Sed. =concentration of metal on suspended sediment<2mm;total acid digestion; ICP/AA analysis
Bed Sed. =concentration of metal in bed sediments<2mm; total acid digestion; ICP/AA analysis
Wt.% =ppm/10,000

Qualitative Successional Models in Glacier Bay: a Comparison of Terrestrial, Marine, Stream, and Lake Ecosystems

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Abstract

Studies of Glacier Bay terrestrial, lake, stream, and marine ecosystems provide a unique opportunity to compare and contrast processes of primary succession among four quite different biological systems that are simultaneously developing along the same chronosequence.

Primary succession in terrestrial plant communities is influenced by life history traits, competitive interactions, and facilitation. The vegetation modifies the physical environment which in turn changes the biotic community, a process that continues for hundreds of years from initial colonization to the establishment of an equilibrium mature community Biological mediation is the hallmark of terrestrial succession. Lake and pond systems develop in parallel fashion due to critically important abiotic effects of hydrology and water chemistry controlled by catchment soils and vegetation. Gradual loss of alkalinity and dystrophication with accompanying nutrient enrichment results in a mature lake community after 500-1000 years. Although initial site conditions play an important role, most subsequent community development is strongly influenced by successional changes in the adjacent terrestrial system. Stream community development is abiotically controlled, principally by channel stability and water temperature. The presence of lakes

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within the stream system, as buffers of variations in discharge, can be crucially important to determining rate of development as well as establishment of riparian vegetation. Stream communities can mature in decades to hundreds of years depending on degree of channel stability. Marine intertidal primary succession appears to be minimally responsive to processes in the other systems and is almost wholly abiotically controlled by physical factors mediated by tidewater glaciers. Rocky intertidal communities in Glacier Bay may become maximally developed (for a given glacial proximity) within a decade.

We offer an integrative conceptual model for primary succession in Glacier Bay, which considers the principal characteristics of community development within each system and the effects that these processes have on other systems.

KEY WORDS. Succession, community development, colonization, chronosequence, ecosystem, glacial recession, Glacier Bay.

Glacier Bay has a well documented history of rapid glacial retreat during the past two and one-half centuries with subsequent emergence of an extensive fjord system and adjacent terrestrial uplands. As new terrain has been colonized, the unique scientific opportunity to study the process of biological community development on a large scale has been widely recognized (United States Department of the Interior 1933). Consequently, Glacier Bay has long been an important site for studies of primary succession following glacial recession.

Successional theory was originally formulated within the arena of terrestrial plant community development. William S. Cooper's studies of plant succession in Glacier Bay between 1916 and 1935 contributed significantly to that newly emerging body of knowledge (Cooper 1923, 1931). Cooper's work has been continued and extended by important studies of the role of nitrogen-fixing plants (Lawrence 1951; Lawrence et al. 1967), changes in soil chemistry through succession (Crocker and Major 1955; Ugolini 1968), processes of paludification (Noble et al. 1984), and a general appreciation of the multiplicity of successional pathways and mechanisms (Fastie 1988; Chapin et al. 1994). In addition, Glacier Bay has hosted studies of succession in glacial streams (Milner 1987; Sidle and Milner 1989; Milner 1994), limno-terrestrial connections in the control of lake development (Engstrom and Fritz 1988; Fritz and Engstrom *this volume*), and the role of tidewater glaciers in determining the pattern of development in marine intertidal communities (Sharman 1987).

During the three Glacier Bay Science Symposia, 1983-present, 25% of all contributed technical presentations focus on succession (Wood et al. 1984; Milner and Wood 1988; *this volume*). Indeed, 39% of this volume's 33 technical contributions focus primarily on aspects of biological community development. Clearly, research in Glacier Bay has contributed significantly to successional theory in all the major ecosystems; its potential for additional contributions in the future is unlimited.

Successional research in Glacier Bay can be divided into four broad ecosystem categories: terrestrial, lake and pond, stream, and marine. Nowhere else has succession been so broadly studied in a single area. The present literature provides a unique opportunity to compare characteristics of successions among these four systems that occur together spatially and whose development is responding simultaneously to similar conditions of glacial retreat.

The goal of this paper is to present some preliminary ideas gleaned from our consideration of the similarities and differences among processes of primary succession processes in the four ecosystems. This is not intended to be a detailed review of what is understood about community development in Glacier Bay, but we will summarize the major findings of recent work, endeavoring to elucidate characteristics that contribute to a broad comparative view.

The Terrestrial Model

The best understood succession to date in Glacier Bay is that of terrestrial plants. As outlined elsewhere in this volume (Chapin et al.), plant growth is limited early in succession by nutrient availability, principally by nitrogen and phosphorus. In addition, it appears that life-history traits and the availability of propagules determine the pattern of succession; the mechanism that actually drives the process through time is dominated by the competitive balance among plants. These floral changes accompany changes in the abiotic environment. Initial site conditions, and to some degree facilitation (the process by which a group of plants modifies environmental conditions in such a way as to make the environment less favorable to itself and more favorable to later colonizers) influence the rate of change (Chapin et al. 1994).

Life-history traits, competitive interactions, and facilitation are all critical determinants of primary succession in Glacier Bay. Hence, multiple mechanisms influence succession which then can follow several different pathways. From an overview of all Glacier Bay terrestrial succession research, it is clear that the general floristic pattern one observes on the landscape over time is the result of the interaction among soil development, plant succession, and paludification (the process by which forest is replaced by muskeg, wherein the forest floor becomes waterlogged and causes the death of dominant overstory trees). The entire process, from pioneer colonizers to "climax" muskeg, requires several hundreds of years.

A critical characteristic of this model is that terrestrial succession appears to be principally mediated by the biota; i.e., the plants drive the changes that the community undergoes.

The Lake/Pond Model

The development of lakes and ponds following deglaciation is best understood in terms of water chemistry and hydrology. As the adjacent terrestrial community succeeds to a spruce/hemlock forest, changes in catchment soils and vegetation create the conditions which drive lake/pond succession. As the vegetation develops, soils become more acidic, peat growth is encouraged and paludification occurs, leading to lake/pond dystrophication. Lakes and ponds become progressively less alkaline (i.e., the water becomes peat-stained and acidic) and increase in dissolved organic carbon in the form of humic acids (Engstrom and Fritz 1988). Nitrogen export to lakes also increases during the early stages of terrestrial succession (Fritz and Engstrom *this volume*), and changes in aquatic communities related to local colonizations and extinctions occur as well (Olson et al. *this volume*). In addition to terrestrial successional influences, hydrologic and geologic differences among sites are critical to determining the rate and direction of lake succession. As in the terrestrial system, lake/pond communities reach a relatively stable endpoint only after several hundreds of years.

.Here there exists a strong and very important link between lakes and the adjacent terrestrial system: stream and groundwater controls are critical, and these are in turn affected by adjacent terrestrial soils and vegetation.

The Stream Model

The pattern of primary succession in streams is abiotically controlled, primarily by the factors of channel stability and water temperature. Both factors tend to increase with time since deglaciation, leading to increased degree of community development within the stream system. The presence of lakes within the watershed contributes significantly to channel stability, principally because of their ability to buffer fluctuations in stream discharge and settle coarser sediments (Sidle and Milner 1989). Stable streambanks allow the development of a close border of woody riparian vegetation which further enhances channel stability and adds important nutrients (primarily nitrogen). Woody riparian vegetation also moderates stream water temperature and contributes instream woody debris which creates habitat. Stream discharge is further buffered (and channel stability enhanced) by development of vegetation throughout the terrestrial catchment basin, which increases water-holding capacity of soils, retards surface flow, and decreases erosion. It appears that stable channels in streams may provide conditions permitting competitive elimination of early invertebrate colonizers by later groups (Milner 1994). In general, Glacier Bay stream communities within stable channels develop to a mature state in less than 100 years, while those within unstable channels require more than 200 years.

Stream community development is quite dependent upon the presence/absence of lakes within the stream system. In turn, streams can affect lake development by contributing nutrients when anadromous fish spawn, die, and decompose in streams above lakes. There is some secondary influence on stream community development by the adjacent terrestrial system. Streams can in turn affect successional patterns in terrestrial communities by providing mesic floodplain habitat for early colonizers; however, frequent disturbance via flooding across unstable channels can maintain these communities at early successional stages.

The Marine Model

Primary succession in rocky intertidal communities (limited information exists for other marine community types) is driven primarily by the influence of abiotic factors including water temperature, salinity, high levels of suspended particulates, and scouring by icebergs. Extremely cold temperatures and low salinities are physiologically stressful for these marine organisms, and high levels of suspended particulates create problems for effective settlement, feeding, respiration, and photosynthesis. Ice scour perturbs boulder habitats and physically abrades the rock surfaces upon which organisms live. Young environments close to tidewater glaciers provide, at best, marginal living conditions for most marine species, and community development is clearly limited by this suite of physical and physiological stresses (Sharman 1987). This is an example of a truly abiotically-controlled situation where environmental conditions are not biologically mediated, as in the terrestrial model. The principal variable is distance from tidewater glaciers; the apparent importance of the time/age component is merely coincidental (Sharman 1987). (Turbid outwash streams entering the marine environment from young, poorly developed terrestrial landscapes near tidewater glaciers can, with the exception of icebergs, contribute the same suite of abiotic influences. Their character is usually directly attributable to channel and catchment instability due to the early stage of development of the terrestrial environment - a biologically mediated effect. However, the collective influence of these streams is generally believed to be considerably less than that of the tidewater glacier at the head of the inlet.) Life-history traits allow rocky intertidal communities to colonize relatively rapidly, but the development process is dominated by abiotic factors. Assuming constant distance from a tidewater glacier and its associated physical influences (i.e., the glacier doesn't move and its physical influences do not change greatly over time) it appears that rocky intertidal communities can develop from early pioneer stages to the mature "climax" (for that particular glacial proximity) in a decade or less.

Comparisons and Contrasts

Biological (as well as physical and chemical) primary succession occurs in all four systems, even though timescales and particular governing factors vary. Glacier Bay research supports a growing body of work elsewhere collectively suggesting that while the basic components of successional mechanisms are similar in all four ecosystems, their relative importance varies dramatically. These components are: life history traits, initial site conditions, tolerance of the physical environment, competitive interactions, grazing and predation, and modification of the environment by organisms (which then shifts competitive balance and community composition).

Life history traits, especially as they relate to dispersal of propagules, determine which species are the colonizers in each system (probably equally important in all systems). Initial site conditions - the geologic or topographic setting - are crucial to setting the course succession will take in the lake, stream, and marine models. Tolerance of severe physical environment appears to be very important in marine intertidal and stream systems, because these systems are so highly disturbed. Alternatively, physical disturbance is less important in terrestrial and lake systems, so if organisms can get there they usually can survive in early succession. It seems likely that competitive interactions are a very important mechanism causing changes in species composition in all systems. As the physical environment changes, different species gain the competitive advantage and displace colonizing species (alternatively, in the developing stream system environmental stability can allow dominance and exclusion of one species over a preceding one). Grazing and predation probably also contribute strongly to this in aquatic systems but much less so in most terrestrial systems.

The critically important variable responsible for fundamental differences in succession among these systems is the extent to which successional changes in organisms causes changes in environment (which in turn alters competitive balance). This variable exerts a very strongly controlling influence in the classic biologically-mediated succession that occurs in the Glacier Bay terrestrial system. Terrestrial ecosystems have biotically controlled cycles of energy, water, and nutrients. Nutrients are tightly recycled; changes in soil chemistry and pH caused by plants have direct feedbacks to the vegetation. Plants buffer the physical microenvironment in terms of soil stability and temperature. Terrestrial plants are large, so all of these biotic effects on the physical environment are large; the biological community itself governs vegetative change by modifying the physical environment.

In aquatic systems, by contrast, plants are usually small and shorter-lived, and cycles are relatively open and lack the strong buffering capacity (against disturbance) contained in soil and vegetation. Biotic effects on the environment that may strongly influence successional processes are thus comparatively small. Observed successional patterns in lakes (and to a lesser extent streams) are substantially determined by factors controlled not within their own systems, but outside them; successional processes occurring within the adjacent terrestrial realm can have a powerful effect. The observed marine intertidal pattern in Glacier Bay is much more abiotically-controlled, with virtually no influence by the terrestrial biological system. Extremely strong physical gradients mediated by tidewater glacier dynamics almost entirely control degree of community development. Near-glacial marine intertidal assemblages have little chance of altering their environment to buffer, for example, the effects of a 10,000-kg iceberg grounded onto a beach, or 2 cm of suffocating glacial silt being deposited at low tide.

Summary: Large-scale "Pattern Succession" in Glacier Bay

We believe that Glacier Bay presents a unique opportunity in that a body of research has documented, to varying degrees, what causes primary successional pattern in four major biological systems that happen to be co-developing. This aspect of co-development is critical to allowing us to understand the large-scale patterns produced to date in each ecosystem, with the knowledge that one developing system may indeed be influencing successional patterns observed in others. We propose a general framework in which to view successional pattern on the Glacier Bay landscape (Table 1). Our hope is that this perspective will encourage continuation of the longstanding tradition of successional research here. Specifically, we hope that this comparative framework will foster a new level of successional study that integrates across the four major ecosystems to examine the linkages that exist among them.

Table 1. Comparative aspects of primary succession among four major ecosystem types in Glacier Bay

ECOSYSTEM	PRINCIPAL FACTORS INFLUENCING SUCCESSION	TIME TO DEVELOPMENT OF MATURE COMMUNITY (YRS)	EFFECT ON DEVELOPMENT OF OTHER ECOSYSTEMS
Terrestrial	BIOTIC - life history traits, facilitation, competitive interactions; environmental (especially soil) conditions influenced by vegetation.	500-1000	Influences water chemistry of lakes. Contributes secondarily to stream channel stability and adds nutrients; riparian vegetation adds woody debris and ameliorates water temperature.
Lake/Pond	ABIOTIC - initial site conditions; pH and alkalinity, nutrients (as mediated by catchment soils).	500-1000	Provides channel stability and reduces sediment effects in streams; may increase stream water temperature.
Stream	ABIOTIC - channel stability and water temperature.	>200 in unstable channel; <100 in stable channel	Where stable channel, development of terrestrial vegetation in floodplain; where unstable, maintains early terrestrial floodplain succession via disturbance. Where fish spawn upstream of lake, may increase lake nutrients. Turbid outwash streams produce tidewater glacier-like effects on adjacent marine intertidal communities.
Marine Intertidal	ABIOTIC - water temperature, salinity, high suspended sediment, ice scouring.	10(?)	None direct. Quality of rearing habitat may affect streams by influencing survivorship of emergent juvenile pink/chum salmon fry.

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Nearshore Distribution and Abundance of Dungeness Crabs in Glacier Bay National Park, Alaska

by

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Abstract

As part of an ongoing, multi-agency study to determine the effects of closure of the commercial fishery for Dungeness crabs, *Cancer magister*, on crab population structure we examined patterns of distribution and abundance of crabs in nearshore habitats at five locations in and near Glacier Bay National Park. Sampling was conducted in April and September 1992 and April 1993 prior to the anticipated closure of the fishery in the park. Divers censused crabs by sex and reproductive state (ovigerous/nonovigerous females) along belt transects (2m x 100m) laid perpendicular to shore in the depth range 0 m (mean lower low water) to 18 m.

Preliminary results from the first three sampling periods revealed that the average densities of Dungeness crabs at the five locations ranged from 78 to 2012 crabs/ha. Crab densities differed between populations depending on sex, reproductive state of females and sampling period. Male crabs showed reduced densities at Gustavus Flats in April 1992 ($P<0.01$) and 1993 ($P<0.001$). Ovigerous females had greater density at Bartlett Cove in April 1993 ($P<0.001$). Sex ratios were frequently skewed toward females. At Bartlett Cove and Gustavus Flats females outnumbered males

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in April 1992 and 1993 ($P<0.001$). Most of the females at Bartlett Cove and Gustavus Flats in April 1992 and 1993 were ovigerous ($P<0.001$). Males tended to occupy greater depths than females in April 1992 ($P<0.05$) but not April 1993 ($P>0.05$). The mean depth of males shifted from deeper to shallower water between April and September 1992 ($P<0.001$). The depth distribution of ovigerous crabs did not differ from that of nonovigerous female crabs. Future research prior to the anticipated closure of the commercial Dungeness crab fishery in Glacier Bay will include a tagging study to determine the extent of crab movement and further study of the temporal as well as the spatial variability observed in the structure of these populations.

KEY WORDS: *Cancer magister*, density, distribution, sex ratio, Dungeness crab fishery.

In 1984 the National Park Service adopted regulations prohibiting commercial fishing in national parks. To date the regulations have not been enforced in Glacier Bay National Park (Taylor and Perry 1990). However, the National Park Service has recently considered closing Glacier Bay to commercial fishing. Closure of the commercial fishery for Dungeness crabs in all or a portion of park waters in conjunction with a continuation of the fishery in adjacent areas would present a rare opportunity for a field experiment testing the impact of fishing on Dungeness crab population structure.

The commercial fishery for Dungeness crabs may influence crab population structure in several ways. For example, high rates of exploitation often tend to truncate the size distribution of males near the legal size limit. When such a distribution prevails in a crab population, cessation of fishing should, over time, result in a shift in that population to larger males. Because males mate with females smaller than themselves (Snow & Nielson 1966; Shirley and McNutt 1987), an increase in the abundance of large males may result in a greater probability of successful fertilization of the eggs of large females. If prior to the closure of the fishery male size limits the successful fertilization of the eggs of a significant proportion of large females then the proportion of large females that become ovigerous may increase following closure of the fishery. The level of exploitation in Glacier Bay in recent years has not been reported, but Dungeness crab harvests increased over 300% to 365 thousand pounds in the period 1983 to 1987 (Taylor and Perry 1990).

In April 1992 a multi-agency study involving the National Park Service, the Auke Bay Laboratory, the University of Alaska and the Alaska Department of Fish and Game was begun to examine the structure of Dungeness crab populations in anticipation of a closure of the crab fishery in Glacier Bay. The study includes visual transect and crab pot sampling. Here we present preliminary results of the visual transect sampling of the nearshore (depth≤18m) component of Dungeness crab populations in Glacier Bay National Park prior to the anticipated closure of the commercial fishery there. Results of the crab pot sampling which include data on those Dungeness crabs found at depths greater than 18m are reported elsewhere [(pots were fished as deep as 25m) (Leder et al., this volume and Leder 1994)]. The purpose of this part of the study was to characterize the size and structure of the nearshore component of Dungeness crab populations at selected sites in and near Glacier Bay while the crabs were under commercial exploitation. Our objectives were to estimate the density of Dungeness crabs at study locations, compare densities between locations by sampling period, determine the bathymetric distribution of crabs by sampling period and compare the densities and distributions of crabs between sexes and female reproductive classes.

Methods

Five locations in or adjacent to Glacier Bay National Park were chosen for study (Fig. 1). Two study sites (North and South Beardslee Islands) were located within the wilderness area of the park. Two sites (Berg Bay and Bartlett Cove) were located within the park, but outside the wilderness area. One site (Gustavus Flats) was outside and adjacent to the park.

Each location was considered to harbor a separate population of Dungeness crabs. We define a population as "all individuals of one species occupying a defined area and usually isolated to some degree from other similar groups" (Lincoln and Boxshall 1987). Although this is a more restrictive definition than that used by many ecologists (eg. Krebs 1978, Ricklefs 1979), it is appropriate for this study because the extensive exchange of individuals between crab populations at Glacier Bay would obscure changes in population structure caused by closure of the commercial fishery. From short-term ultrasonic biotelemetry studies conducted on Dungeness crabs in Glacier Bay and elsewhere in southeastern Alaska (O'Clair et al. 1990) and a year-long biotelemetry study on Dungeness crabs near Juneau, Alaska (O'Clair, unpublished) the movement of crabs between bays in southeastern Alaska appears to be quite limited. The oceanography of Glacier Bay is poorly known as are the dynamics of larval transport in the region of Glacier Bay, therefore we cannot be certain that these populations are completely isolated genetically. We are currently implementing a tagging study to determine whether the populations are reasonably segregated from one another, especially with regard to adult crabs.

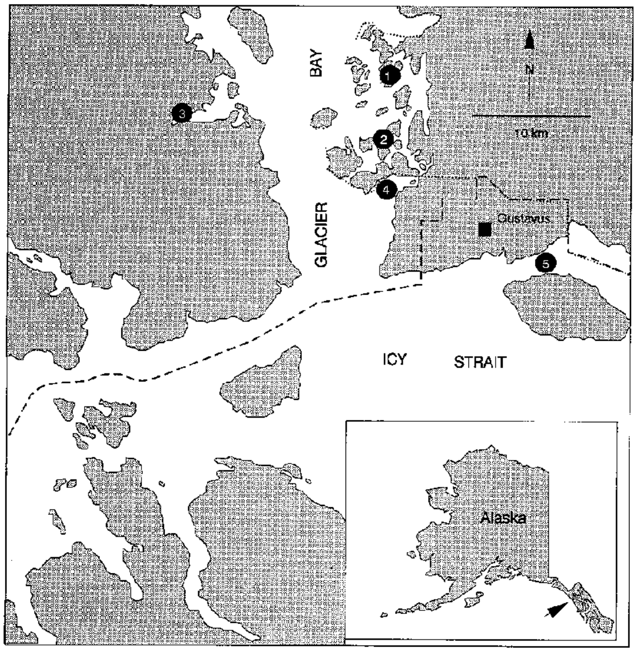

Fig.1. Study locations in and adjacent to Glacier Bay National Park. Numbered locations are (1) North Beardslee Islands, (2) South Beardslee Islands, (3) Berg Bay, (4) Bartlett Cove, (5) Gustavus Flats. The dashed line marks the border of the park; dotted line marks the border of the wilderness area.

Divers censused Dungeness crabs on 2 m x 100 m belt transects in the depth range 0 (mean lower low water) to 18 m. The transects, positioned randomly, were laid perpendicular to shore and divided into 2x10 m quadrats within which crabs were counted. Usually 15 transects were established at each site during each sampling period. The number of quadrats per site per sampling period ranged from 109 to 150. We recorded the depth range of each quadrat. Adult crabs [carapace width (CW) > 116 mm for males; CW > 100 mm for females] were counted separately by sex and female reproductive class (ovigerous and nonovigerous). Crabs bearing an egg clutch on their pleopods were considered to be ovigerous. Because of limited dive time nonovigerous females were not examined further for matted pleopodal setae (a sign of recent larval hatching), sperm plugs or any other indication of reproductive status (but see Leder et al., this volume and Leder 1994).

We sampled all sites on 7-12 April 1992, 17-21 September 1992 and 19-25 April 1993. We chose these periods to preclude mutual interference between our sampling activities and the commercial fishery and to avoid compromising diver safety. [The commercial fishery is open in that part of southeastern Alaska that includes Glacier Bay during the periods 15 June through 15 August and 1 October through 30 November (Alaska Department of Fish and Game 1994)]. Sampling during these periods provided us with data on crab populations prior to the beginning of and after the end of the main part of the commercial fishing season for Dungeness crabs. Sampling was also limited to that period when ovigerous crabs would be available for study. Our observations of other populations of Dungeness crabs in southeastern Alaska indicated that most females extrude their eggs from August to October and that larval hatching usually occurs from April to June (Shirley and O'Clair unpublished data).

Analysis of variance (ANOVA) was used to test for differences in densities and depths of crabs. The Kruskal-Wallace test was substituted if the data did not meet the assumptions of the ANOVA. All tests of crab density were made between locations within sampling periods. Sex ratios and ovigerous:nonovigerous female crab (ON) ratios were compared within location for each sampling period using single degree of freedom G-tests. Williams' (1976) correction was applied to G to obtain a better approximation of χ^2 Exact probabilities were calculated for the relative frequencies when sample sizes were 25 or less (Sokal and Rohlf 1981). All ratios were tested against the null hypothesis of unity. Comparisons of means were judged significant if the probability (P) of a Type I error was less than 0.05. To maintain an experimentwise error rate of $\alpha = 0.05$ for the sex and ON ratio tests each individual test was adjusted to a significance level of $\alpha^1 = 0.003$ using the Dunn-Šidák method (Ury 1976). Because this nonstandard critical value of α is not found in χ^2-tables the next lower tabled value of $\alpha = 0.001$ was used for the individual tests.

Results

Crab density ranged from 78 to 2012 crabs/ha at the study sites over the three sampling periods. Within each sampling period crab density did not differ between locations ($P>0.05$; Fig. 2). However, when the densities of males and ovigerous and nonovigerous females were considered separately significant differences were observed between study locations depending on the sampling period. Male crabs had reduced densities at Gustavus Flats in April 1992 (Kruskal-Wallace test; $P<0.01$) and April 1993 ($P<0.001$; Fig. 3A). (No males were observed on the transects at Gustavus Flats in April 1992.) The density of ovigerous crabs was greater at Bartlett Cove than at other locations in April 1993 ($P<0.001$) but not April 1992 (Fig. 3B). When study locations were lumped no differences were observed in ovigerous crab densities between April 1992 and April 1993. Nonovigerous female crabs showed reduced density in Berg Bay in September 1992 ($P<0.01$; Fig 3C.).

When sex ratios deviated from unity they were usually skewed toward females in nearshore waters during the period of study (Fig. 4A). Berg Bay was the only site where the sex ratio was skewed toward males when not 1:1. Males represented 86% and 82% of the crabs counted on transects at Berg Bay in September 1992 and April 1993 respectively. Females outnumbered males at Bartlett Cove and Gustavus Flats in April in 1992 and 1993. The percentage of crabs that were female ranged from 90% at Bartlett Cove in April 1992 to 100% at Gustavus Flats in April 1992. When the sex ratio departed significantly from unity in the Beardslee Islands females outnumbered males (percentages of crabs that were female ranged from 66% at South Beardslee Islands in April 1993 to 72% at South Beardslee Islands in April 1992; Fig. 4A). The tendency for the sex ratio to become skewed toward females in April but not September at Bartlett Cove and the North Beardslee Islands (April 1993 only) probably reflected the movement of males into shallow water in September (see results on depth distribution below).

When the ovigerous:nonovigerous female (ON) ratios deviated from 1:1 at Bartlett Cove and Gustavus Flats in April they were skewed toward ovigerous crabs (Fig 4B). The percentage of female crabs that were ovigerous ranged from 76% (68% of all crabs) at Bartlett Cove in April 1992 to 94% (93% of all crabs) at Bartlett Cove in April 1993. In each instance when a significant departure from unity was observed in the ON ratio in September nonovigerous females outnumbered ovigerous crabs (Fig. 4B). In those instances the percentage of females that were nonovigerous in September ranged from 77% at North Beardslee Is. to 85% at Bartlett Cove.

The ON ratio observed at three of the five study locations (North Beardslee Is., Bartlett Cove and Gustavus Flats) shifted from one close to unity or one skewed toward nonovigerous females in September 1992 to one skewed toward ovigerous crabs in April 1993 (Fig.4B). Because the brooding period extends roughly from September to the following April-June one would expect a similar ON ratio in these two periods. The most likely explanation for the significant shift in the ON ratio that we observed between September 1992 and April 1993 is that, at least at these locations in 1992, a significant proportion of the period of egg extrusion in Dungeness crabs extended after September.

The distribution of crabs with depth differed between sexes depending on sampling period. (Study locations were lumped for the analysis of depth distribution.) The average depth of males was greater than that of females in April 1992 ($P<0.05$) but not April 1993 (Fig. 5A&C). The average depth of males shifted to shallower water between April 1992 and September 1992 ($P<0.001$; Fig. 5A&B).

Discussion

The preliminary results of our study of the nearshore component of Dungeness crab populations in and adjacent to Glacier Bay National Park indicate that the structure of the crab populations at depths ≤ 18m varied between localities depending on the sampling period. Although crab population density did not vary between study sites within sampling periods, we observed differences in some measures of population structure at the subpopulational level, specifically between sexes and female reproductive classes.

The locations most similar in crab population structure were Bartlett Cove and Gustavus Flats. There, female crabs tended to be more numerous than males and ovigerous crabs usually outnumbered nonovigerous females in April of 1992 and 1993. Leder (1994) reports the results of the crab pot sampling conducted at the same time as our transect sampling in Glacier Bay. Her results were similar to ours in that female crabs tended to outnumber males at Bartlett Cove and Gustavus Flats in April except at Bartlett Cove in April 1992 where male and female abundances did not differ significantly. Because crab pots probably undersample ovigerous crabs (Howard 1982, O'Clair et al. 1990) ratios of ovigerous to nonovigerous female crabs in the pots are probably not comparable to ours. The densities of ovigerous crabs at Bartlett Cove and Gustavus Flats showed some tendency to exceed those at other sites in April of 1992 and 1993, but the difference was significant only at Bartlett Cove in April 1993. Because ovigerous crabs are frequently contagiously distributed (large aggregations of ovigerous crabs were observed by divers at both Bartlett Cove and Gustavus Flats during the present study) within-location variability in ovigerous crab densities can be great. High within-location variability reduces the sensitivity of statistical tests used to detect changes in the density of ovigerous crabs between locations and, therefore, can obscure between-location differences in density.

The population of crabs that differed the most in population structure from the others was that at Berg Bay. Berg Bay was the only location where the sex ratio was skewed toward males in two of three sampling periods. [Leder (1994) found that males outnumbered females in the pots during all three sampling periods at Berg Bay.] Berg Bay was also the only site where nonovigerous females (exceeding 80% of females) outnumbered ovigerous crabs on the transects in April when the opposite was often true at other locations. This result was not consistent with the positive relation that one might expect between the male:

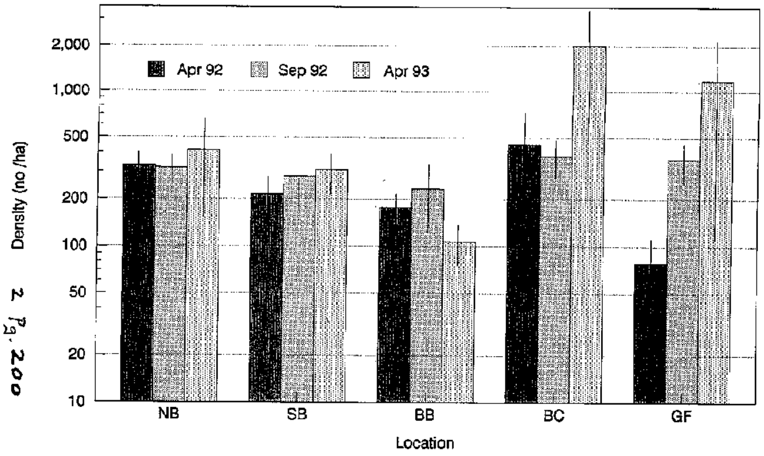

Fig.2. Density of Dungeness crabs at five locations in and near Glacier Bay National Park during three sampling periods. Bars are one standard error of the mean. Abbreviations are: NB, North Beardslee Islands; SB, South Beardslee Islands; BB, Berg Bay; BC, Bartlett Cove; GF, Gustavus Flats.

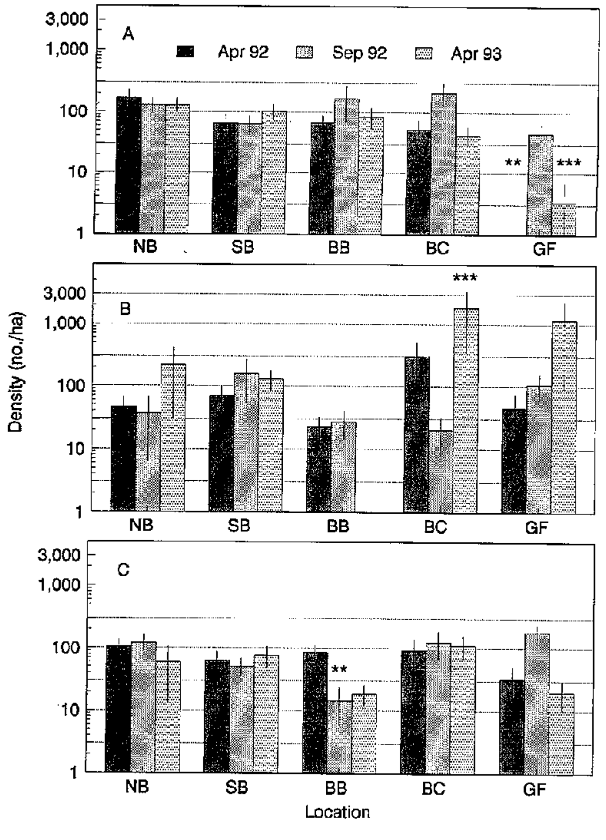

Fig.3. Density of male(A), ovigerous(B) and nonovigerous female(C) Dungeness crabs at five locations in and near Glacier Bay National Park during three sampling periods. Bars are one standard error of the mean. See Fig. 2 for abbreviations. Significance levels (**, P<0.01, ***, P<0.001) correspond to differences between particular sites and all other sites sampled within a sampling period.

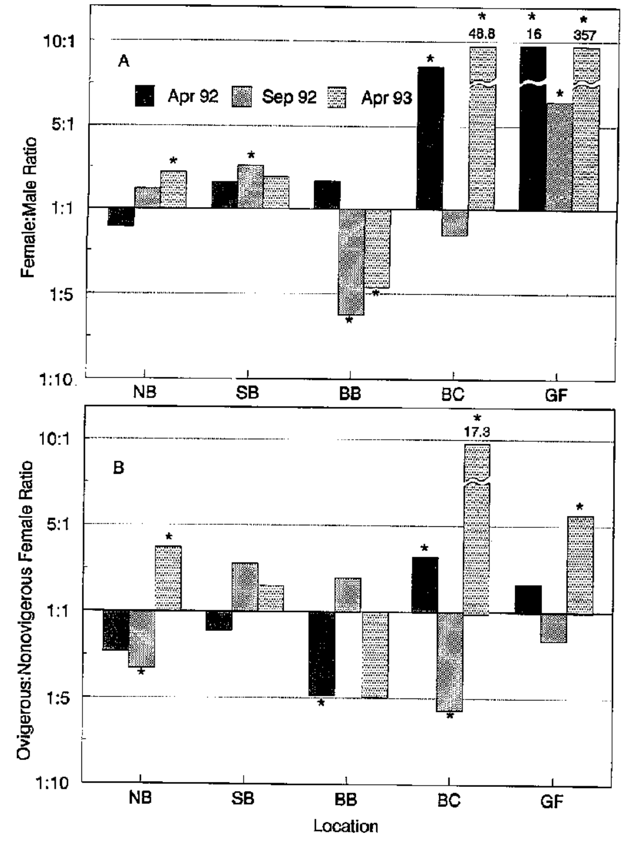

Fig.4. Sex ratios(A) and ratios of ovigerous to nonovigerous females(B) for Dungeness crabs at five locations in and near Glacier Bay National Park during three sampling periods. See Fig. 2 for abbreviations. The significance level (*, P<0.001) is that for each individual test of the degree of deviation of the observed ratio from the expected ratio of 1.1. The significance level of the individual tests was adjusted to maintain the experimentwise error rate at α = 0.05.

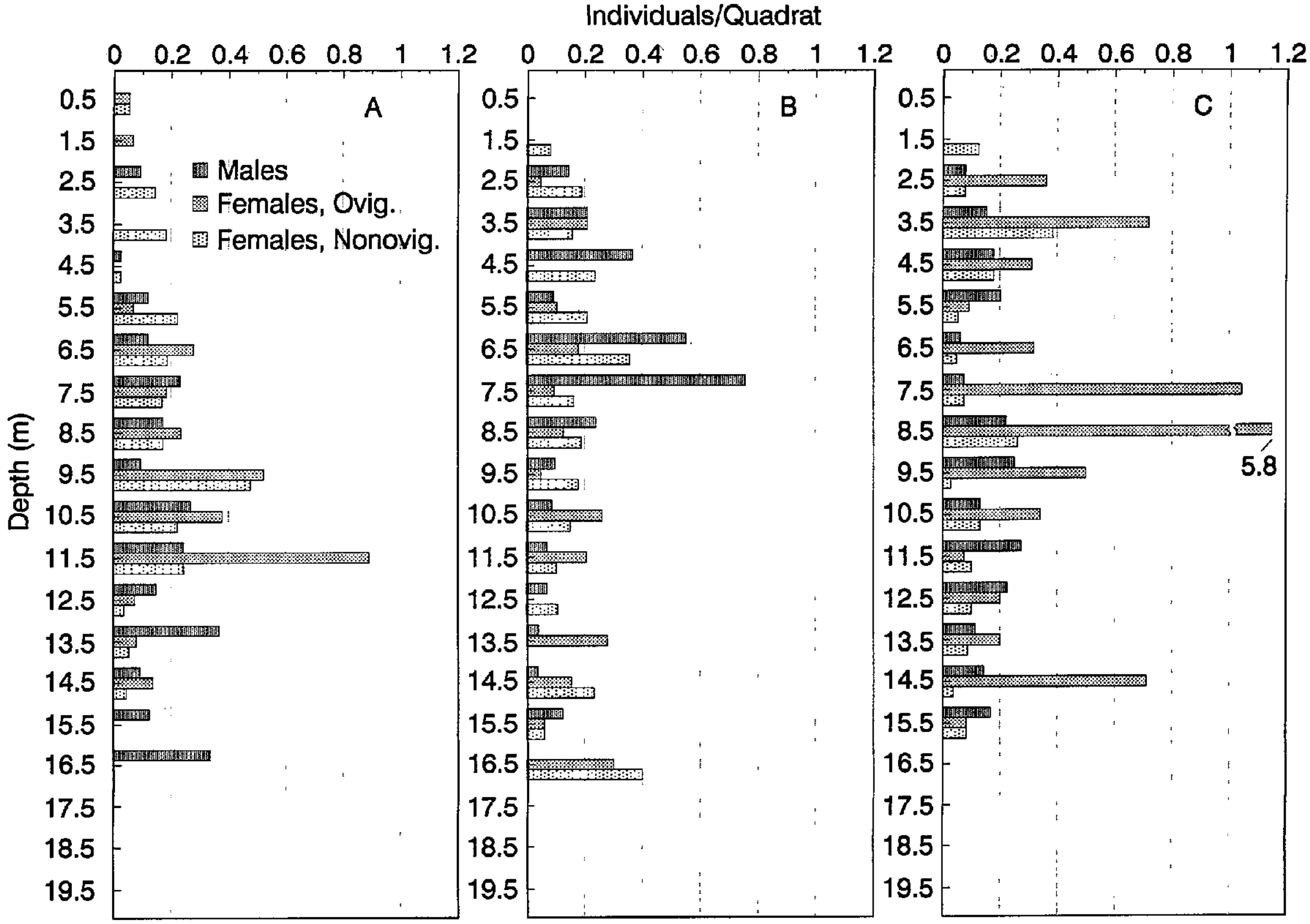

Fig.5. Distribution with depth of male, ovigerous and nonovigerous female Dungeness crabs at five locations (combined) in and near Glacier Bay National Park during (A) April 1992, (B) September 1992 and (C) April 1993.

female and ovigerous:nonovigerous female ratios if one assumes that the number of ovigerous crabs is limited by the number of adult males in the population. Leder's (1994) finding that the proportion of reproductive females (females with eggs or matted setae) collected in the spring at Glacier Bay was not related to the sex ratio in the previous fall there brings this assumption into question.

In addition to the differences listed above for Berg Bay, crab abundance in pots was lower at Berg Bay than at the other study sites except in April 1993 when abundance was the second lowest in value (Leder et al., this volume), although this trend was not significant on the transects. It is not clear why the crab population at Berg Bay differed in these ways from those at other study sites, but this information will be essential to the interpretation of the effects of a crab-fishery closure whether Berg Bay is included in the area closed or not.

The significant reduction in male densities at Gustavus Flats compared to other sites in April 1992 and 1993 was probably not caused by the intensive Dungeness crab fishery that takes place there. The density of males at Gustavus Flats did not differ from male densities at other sites in September 1992, about a month after the end of the summer commercial season when the crab fishery was most active. It is more likely that reduced densities of males were observed at Gustavus Flats in April because at that time most males occupied depths greater than 18 m, the lower limit of the transects. By September the density of males increased on the transects presumably owing to immigration from greater depths. The average depth of males on the transects (all study sites combined) tended to shift from deeper to shallower water between April and September 1992 indicating a temporal shift in male depth between spring and fall 1992.

Our results indicate that there existed substantial variability in the structure of the nearshore component of crab populations between some locations during our study. Here we have emphasized the spatial differences observed between populations in the first year of the study. Future research prior to the anticipated closure of the fishery in the park will focus on tracking temporal change in the populations under study to determine if the pattern of differences observed between locations changes over time. In addition, a tagging study has been initiated to determine the extent of movement of the crabs at each location, and especially to examine the degree of exchange of individuals, if any, that takes place between the separate Dungeness crab "populations" at Glacier Bay.

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Male Size and Female Reproduction in Dungeness Crab in Glacier Bay, Alaska

by

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Abstract

To determine effects of abundance and size of male Dungenss crabs on aspects of female crab reproductive biology we sampled crabs with commercial crab pots in five bays in or near Glacier Bay National Park in April and September 1992 and April 1993. Size of all crabs and reproductive condition of females were recorded for crabs collected at each study site.

Preliminary results of this sampling revealed substantial variability in crab reproductive measures among study sites. At one bay reproductive females constituted a higher percentage of the catch of females in April (1992, 36%, 1993, 65%) than at other bays (1992, ≤22%; 1993 ≤27%). Other differences among bays included differences in sex ratio and sizes of crabs. The differences observed at some bays were related to relative intensity of crab fishing and/or male size. At one bay, where fishing intensity was presumed to be relatively high, the sex ratio was skewed towards females, and reproductive females were smaller ($P<0.001$) than non-reproductive females. Reproductive females from that bay appeared to exhibit greater variability among individuals in the color of their egg clutches than did females in other bays. In another bay where fishing intensity was presumed to be low, the sex ratio was skewed toward males and mean size of males was greater than at other sites ($P<0.05$). Reproductive females at that bay averaged larger ($P<0.05$) than non-reproductive females.

The spatial variability in abundance and reproductive state of crabs in our study, at some locations, supported the hypothesis that male size can influence the size of reproductive females and perhaps the variability in egg developmental stage in ovigerous crabs. The proposed fishery closure in part of Glacier Bay may cause shifts in male sizes allowing an assessment of the effects of male size on female reproductive measures.

KEY WORDS: *Cancer magister*, reproduction, size, abundance, sex ratio, Dungeness crab fishery.

Dungeness crabs (*Cancer magister*) are an important commercial resource from central California to the Aleutian Islands of Alaska. Dungeness crab fisheries along the Pacific coast are managed by size, season, and sex specific

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harvest strategies. Only males are harvested in this fishery, and in Alaska, the minimum legal size is 165 mm carapace width (CW), measured immediately anterior to the tenth anterolateral spine.

In southern portions of the Dungeness crab range, the female reproductive cycle begins with mating in May-September (Butler 1960, Wild 1980). Eggs are extruded several months after mating and are fertilized as they pass by the spermathecae within the oviduct (Wild 1980). Hatching occurs during the winter (Wild 1980). Since Dungeness females can store sperm, molting and mating are not necessary for a viable egg mass (Diamond and Hankin 1985).

Mating occurs when the female is in the soft-shell condition (Butler 1960). A male will pair with a female when she is in the premolt condition. He will clasp the female in a premating embrace standing over her until she is ready to molt. The female molts, and the crabs mate. The male will remain with the female in a postmating embrace while her shell hardens.

The harvest of large males may affect the mating probability of large females since females always mate with larger males (Butler 1960). In a study of mating Dungeness crabs in southeastern Alaska, males were at least 10 mm larger in CW than females and averaged over 50 mm larger (Shirley 1988). Similar results were presented by Smith and Jamieson (1991) with mating pairs collected from Dixon Entrance and near Tofino, British Columbia. A heavily exploited population might contain few males larger than legal size, and this may limit the availability of mates for larger females.

Our objective in this study was to determine whether the abundance or size of males was related to the size of reproductive females or the timing of reproductive events in five locations in or near Glacier Bay.

Materials and Methods

Study Area

The study area consisted of five bays in the Glacier Bay region of southeastern Alaska: north Beardslee Islands (58°33'N 135°54'W), south Beardslee Islands (58°30'N 135°54'W), Berg Bay (58°31'N 136°13'W), Bartlett Cove (58°27'N 135°53'W), and Gustavus Flats (58°23'N 135°43'W; Fig. 1). Four of the bays are within Glacier Bay National Park, and Gustavus Flats is adjacent to the park's boundary in Icy Passage.

Sampling Procedure

Sampling was conducted in April and September, 1992, and April, 1993. Spring sampling occurred before the commercial fishery opened (June 15), and fall sampling occurred during a 6- week closure period (August 15 - September 30). Sampling periods were selected to avoid bias imposed by commercial fishing activities on sampling results, to permit comparisons before and after the main commercial season, and to coincide with significant female reproductive events such as egg extrusion in the fall and hatching in the spring. Differences in catch caused by shifts in seasonal and depth distribution may have occurred, but these biases are assumed to have been the same among bays.

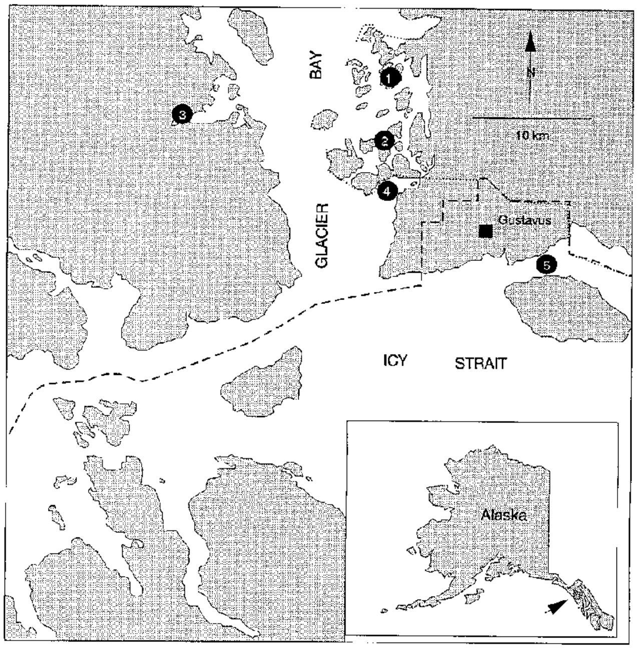

Fig. 1. Map of study area. Sampling areas are: 1 = North Beardslee Islands, 2 = South Beardslee Islands, 3 = Berg Bay, 4 = Bartlett Cove, and 5 = Gustavus Flats.

Commercial crab pots were baited with salmon, squid, and herring and allowed to fish for 24 hours. Escape ports were covered in order to retain all crabs. Fifty pots were set in each bay on five consecutive days during each sampling period. Pots were set in strings parallel to the shore along predetermined isobaths. The proportion of each study location that was covered by the crab pot arrays was estimated by drawing the pot arrays on a topographic map of the location, determining the areas of the pot arrays and the study location with AutoCAD, and calculating the quotient of the two areas. The proportion of the study area by the pot arrays varied from 8% at Gustavus Flats to 29% at South Beardslee Islands. These estimates were conservative because they estimated the area containing the pots rather than the area fished by the pots. Depth and time of pot set were recorded, and depth was later converted to true depth measured from datum (mean lower low water).

When possible, divers collected 30 ovigerous crabs for egg sampling from each bay during each sampling period. Ovigerous crabs were collected as they were encountered on randomly placed transects (see O'Clair et al, this volume for details of the dive sampling), therefore the stage of egg development in the broods of the collected females should be representative of the area sampled. The ovigerous crabs collected by divers were used for egg color comparisons, but these crabs were not used for the other analyses because data on the condition of pleopodal setae (matted or not) was not collected from the diver-observed crabs.

When each pot was retrieved, counts of individuals of all species captured by the pot were recorded. Dungeness crabs were measured, examined and most were returned to the water unharmed. Sex and carapace width were recorded for all crabs. Carapace width immediately anterior to the tenth anterolateral spine was measured to the nearest millimeter with calipers. Females were examined for sperm plugs, eggs and matted setae. Egg color of ovigerous females was recorded.

When a female Dungeness crab first extrudes eggs, the eggs are bright orange in color. They darken as eye pigmentation increases during development and are brown when they hatch (Wild 1980). We categorized the clutches into three color categories: orange, orange-brown, and brown and used these categories as an index of developmental stage. Matted setae remain on the pleoplods of females whose eggs have just hatched.

The Bonferroni/Dunn method for multiple comparisons was used in conjunction with analysis of variance to compare means among the bays. *T*-tests were used for comparisons between pairs of observations. Results were considered significant if $p<0.05$.

Results

We collected 6925 crabs from pots and dives. From the pots we collected 1189 males 1046 females from spring 1992, 2304 males 957 females from fall 1992, and 667 males 434 females from spring 1993. Of the females from the pots, 59 were ovigerous in spring 1992, 8 in fall 1992, and 83 in spring 1993. The divers collected 318 ovigerous females: 92 from spring 1992, 115 from fall 1992, and 111 from spring 1993.

The patterns of Dungeness crab abundance and reproductive condition were generally more consistent among sampling periods than among sites within a sampling period. The rank order of abundances for males and females was approximately the same for all sampling periods. Ovigerous crabs and females with matted setae (hereinafter referred to as reproductive females) were rare in all fall samples and generally more abundant in the spring samples. More crabs were collected in each bay in fall 1992 than in other sampling periods; the least number of crabs was collected in spring 1993. A highly skewed sex ratio, with more females than males, was found in Gustavus Flats for all sampling periods, while the reverse was true for North Beardslee Islands and Berg Bay.

More reproductive females were collected in the pots in spring than fall. In the spring sampling periods, the North Beardslee area produced few ovigerous crabs (1% and 10% for 1992 and 1993, respectively), whereas Bartlett Cove produced many reproductive females (36% and 63% for 1992 and 1993, respectively; Fig. 2). (Percentages were used to standardize the results among bays.) In the fall sampling period, the egg extrusion season was probably just beginning which may account for the few ovigerous females collected in the pots at most sampling areas. However in Berg Bay, 9% of the female crabs entering the pots in the fall were ovigerous.

The color of eggs from ovigerous crabs collected by divers was compared among bays (Fig. 3). In spring, more females collected from the North Beardslee area were brooding eggs that were orange or orange-brown, whereas more ovigerous crabs from Bartlett Cove were brooding eggs that were brown. In the fall, most ovigerous crabs had orange eggs, but some females in Bartlett Cove and Gustavus Flats had eggs which were orange-brown.

Sex ratios varied greatly among bays during the three sampling periods (Fig. 4). At Gustavus Flats the sex ratio was highly skewed towards females during all sampling periods. At Bartlett Cove the ratio was skewed toward females in spring 1993. At all other locations the sex ratio was skewed towards males for all sampling periods.

The mean carapace width of reproductive females was calculated for each bay (Fig. 5). The average size of reproductive females collected in pots was significantly smaller in Gustavus Flats than in all other bays except North Beardslee waters. However, only five reproductive females were collected at the North Beardslee site, while from 29 to 160 reproductive females were collected at the other bays. Gustavus Flats was the only area where the average size of reproductive females was significantly smaller than non-reproductive females (*t*-test, $P<0.05$), and Berg Bay was the

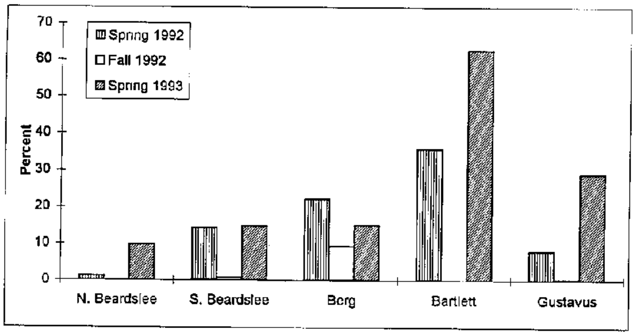

Fig. 2

Fig. 2. Percentage of reproductive (with eggs or matted setae) female Dungeness crabs. Crabs were caught in pots at five sampling areas during three sampling periods: spring 1992, fall 1992, and spring 1993.

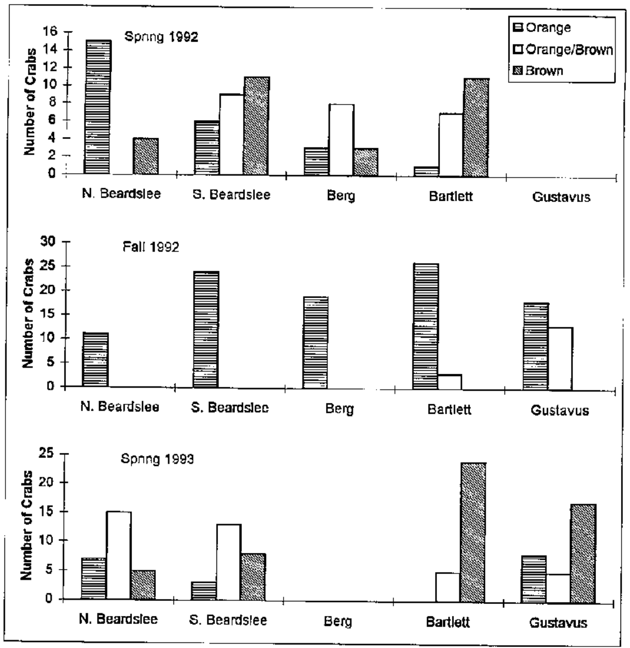

Fig. 3

Fig. 3. Number of female crabs brooding eggs in three color categories. Crabs were collected by divers at five sampling areas during three sampling periods: spring 1992, fall 1992, and spring 1993.

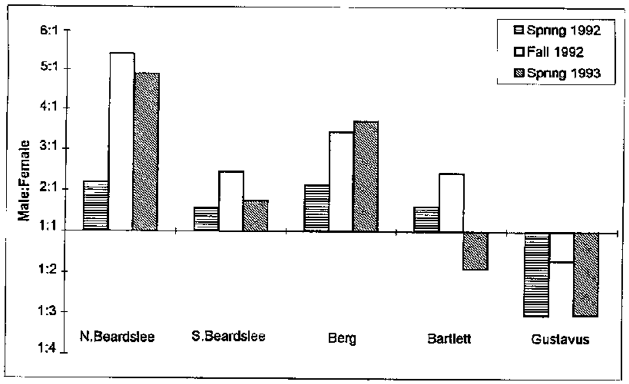

Fig. 4

Fig. 4. Male:female sex ratio of crabs collected by pots at five sampling areas during three sampling periods: spring 1992, fall 1992, and spring 1993.

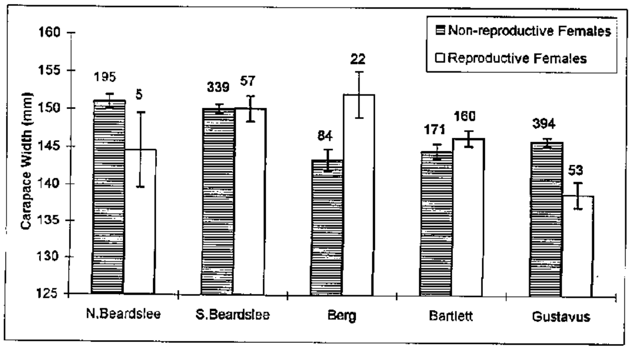

Fig. 5

Fig. 5. Mean size of reproductive and non-reproductive female crabs collected by pots at five sampling areas in spring. Spring 1992 and spring 1993 samples were combined. Error bars are ± one standard error.

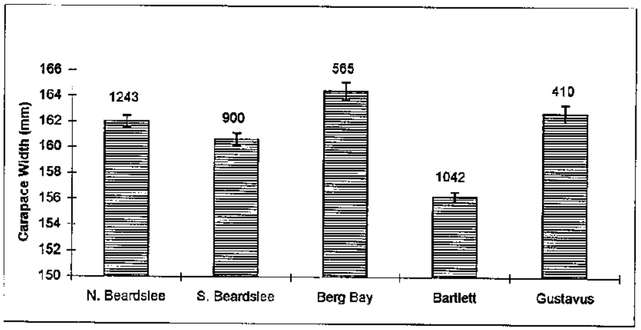

Fig. 6

Fig. 6. Mean size of males collected by pots at the five sampling areas. Spring 1992, fall 1992, and spring 1993 samples were combined. Error bars are ± one standard error.

only site where reproductive females were larger than non-reproductive females (*t*-test, $P<0.05$).

The mean male size was calculated for all bays (Fig. 6). Mean male carapace width in Bartlett Cove was significantly less than at all other bays (Bonferroni/Dunn, $P<0.05$), and mean carapace width for males in Berg Bay was significantly greater than at other sites (Bonferroni/Dunn, $P<0.05$).

Discussion

The timing of reproductive events in the female Dungeness crab may be controlled by a variety of factors including temperature, photoperiod and genetics. Another factor which may influence the timing of reproductive events in female crabs and the size of reproductive females is the abundance and size of the males in the population. For instance, if a population contains many large males then the probability of a female encountering a suitable, larger male would be greater than if there were few large males. Because the mating season extends over a period of several weeks, most females may find mates, but small females, which have a greater size range of males available to them, may encounter a mate sooner than large females. A female which mates earlier during the mating season may extrude eggs earlier than a female which mates later in the season, and when sampled at any time during the brooding season, the female which mated earlier may have eggs in a later developmental stage. Therefore, if commercial fishing activities reduce the abundance of large males in a population, the shortage of large males may be reflected in the size of reproductive females (Smith and Jamieson 1991) or in the variation of egg development of the female crabs. Aspects of Dungeness crab biology that can alter these outcomes include the ability of a female to store sperm and polygyny (Cleaver 1949, Butler 1960).

Although separate commercial catch statistics were not available for each of our study areas, the exploitation rate in each area may be ranked relative to the other areas. Gustavus Flats probably has the highest crabbing pressure because it is outside the park boundary and no special permit is required for commercial crabbing there. Gustavus Flats is also nearer populated areas than are the other study areas. Bartlett Cove may experience the second highest exploitation rate. It is near populated areas and also receives heavy sport-fishing pressure from park service personnel. North and South Beardslee Islands probably experience intermediate exploitation rates, and Berg Bay is probably exploited the least. Berg Bay is farther from populated areas than all the other study areas, therefore it may not be as economically advantageous to fish there.

At Gustavus Flats, where the sex ratio was skewed towards female crabs during all sampling periods, reproductive female crabs were significantly smaller than non-reproductive females. At Berg Bay sex ratios were skewed towards males and the mean size of males was great (about 164 mm CW). Larger females in Berg Bay may have found mates more easily than at the other locations. This may have been the reason the average size of reproductive females was larger than non-reproductive females at Berg Bay.

At Gustavus Flats more females with eggs in the later stage of development were captured in spring 1993 than at North and South Beardslee Islands and Berg Bay. Nevertheless, there were still large numbers of crabs with eggs in the early stages of development at Gustavus Flats in spring 1993. Some eggs brooded by crabs in Gustavus Flats were in intermediate stages of development in the fall when, at most other bays, crabs were brooding eggs only in the early developmental stages. Because a variety of developmental stages occurred in both spring and fall samples, either mating and egg extrusion occurred over an extended period of time or developmental rates are variable. Because males were less abundant in Gustavus Flats, some females may have had difficulty finding mates, therefore mating and egg extrusion may have occurred over a longer period of time than in the other bays. However, if the rate of development of the eggs is variable among females and is responsible for the variety of developmental stages observed in the population, it could be caused by environmental or genetic factors. Wild (1980) observed that temperature affected the rate of development of Dungeness crab eggs, but the greatest temperature difference recorded among our study sites within a sample period was 0.5°C.

At Bartlett Cove male and female crabs were abundant and smaller on average than crabs from other bays. Because of their small size more males at Bartlett Cove may escape harvest by the fishery, therefore more males may be available as mates for the females. This high abundance of males may be the reason for the high abundances of reproductive female crabs and the synchronous development of the females' eggs in Bartlett Cove.

The chronology of the reproductive biology of female Dungeness crabs varied between bays located within 50 km of each other in southeastern Alaska. Females in Bartlett Cove appeared to have advanced egg development and eggs hatched earlier in the spring than in the three sampling sites located further within Glacier Bay. Female crabs from Gustavus Flats seemed to exhibit much variation in their developmental rate with some eggs still bright orange while the eggs of other females had recently hatched. The variations in timing and other aspects of reproduction may be influenced by physical characteristics of the bays, but some population attributes, such as the abundance of large males relative to the size distribution and abundance of females, should also be considered.

One test of the hypothesis that male size and abundance can influence the size of reproductive females and possibly the timing of female reproductive events would be to close the Dungeness crab fishery in some bays and allow large males to increase in abundance in the population. One could then observe the effect of the additional large males on the size of reproductive females and the variability in the timing of reproductive events. Since males can be polygynous and females can store sperm, high levels of exploitation may not affect reproduction in Dungeness crabs. However, the existence of areas like Gustavus Flats, which harbored small reproductive females and where variation in egg developmental stages among crabs was great, may indicate an effect of exploitation on the male size distribution. This exploitation effect could result in lower larval production because only smaller crabs are able to reproduce.

Adequate assessment of environmental conditions and other factors that may influence the size of reproductive females and the timing of reproductive events was limited in this study and should be included in any future investigations. The data presented here indicate that there was variation among the sites with regard to crab abundances and aspects of female reproduction and the variation was consistent throughout all sampling periods. However, additional information on environmental conditions, population genetics of the crabs, and more detailed quantification of fishing pressure on the crabs in each study area is required before definitive conclusions can be drawn on the effect of male size and abundance on female reproductive biology.

Acknowledgments

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Prey Preference of Pacific Halibut (*Hippoglossus stenolepis*) in Glacier Bay National Park

by

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Abstract

Stomach contents were collected from sport-caught halibut in Glacier Bay National Park. Stomach samples containing a combination of fish and invertebrate species were observed less frequently than expected. Small, subtidal, noncommercial crab and cod-like fish (Gadidae) appear to be the most important prey items in the diet of Pacific halibut. Preliminary findings suggested that diet changes dramatically with age. The frequency of occurrence of crustaceans and small forage fishes declines with an increase in age while the frequency of occurrence of cod-like fish (Gadidae) and sculpins (Cottidae) increases with an increase in age. In addition, there were few halibut that contained prey items from different taxa whereas multiple items from a single taxa or prey group were common.

KEY WORDS. Diet study, diet indices, foraging, predation and home range.

Knowledge about the diet of Pacific halibut (*Hippoglossus stenolepis*) would provide important information about the role of this species in the marine ecosystem. Diet studies provide information about food web relationships, habitat preference, and distributional patterns. It is difficult to make direct observations of the diet of marine fish, thus stomach contents are collected to identify what the predator has eaten and the relative importance of various prey items in it's diet (Wooton 1990).

Food habits analysis is also an essential method for examining diet overlap between age classes of a species. Intraspecific competition for resources is an important component in the life history of a species. Diet analysis can be a powerful tool in determining the distribution of the population, especially if there is diet overlap between age classes (Werner 1979; Werner and Gilliam 1984).

Few studies have examined the food habits of Pacific halibut. Diet of Pacific halibut changes with depth, area and season (Bell and St. Pierre 1970; Best and St. Pierre 1986; IPHC 1987; Brodeur and Livingston 1988). No studies provide detailed information regarding the diet of Pacific halibut in southeast Alaskan waters.

This paper examines results obtained from the sport-caught samples for trends in the diet with respect to age. Possible foraging patterns are also presented.

Methods

Stomach contents were collected from halibut caught on sport charter boats fishing within Glacier Bay National Park, Alaska. Each stomach sample was removed from an individual halibut at the sport cleaning dock. The samples were obtained from the charter boats by arriving at the dock prior to the boats returning from fishing and sampling their whole catch for that trip. These samples were frozen for future processing and prey identification. Sport-caught halibut samples were collected over two separate seasons, August 19 to September 3, 1991, and May 26 to August 8, 1993. Prey items were identified to the lowest taxonomic level possible and otoliths were collected for age analysis.

Proceedings of the Third Glacier Bay Science Symposium, 1993
D.R. Engstrom (Ed.), National Park Service, Anchorage, Alaska, 1995

Three main indices are used to quantitatively analyze diet: percent composition by number, percent composition by weight, and percent frequency of occurrence. The percent composition by number is determined by dividing the number of individuals in a prey group by the total number of prey items. Percent composition by weight is determined by dividing the weight of each prey group by the total weight of all prey groups. Percent frequency of occurrence is determined by diving the number of stomachs containing a particular prey group by the total number of stomachs with prey items. Percent frequency of occurrence emphasizes the variation in diet and will be the main index employed to examine the diet of Pacific halibut.

The degree of dietary overlap between two predator groups was calculated using Schoener's (1970) overlap index:

$$C_{xy} = 1.0\text{-}0.50 \sum_{i=1}^{n} \left| P_{xi} - P_{yi} \right|$$

Where C_{xy} is the degree of overlap between predator group x and group y, n is the number of prey categories, P_{xi} is the proportion by weight of the prey i in the diet of the predator group x, and P_{yi} is the proportion by weight of prey i in the diet of predator group y.

C_{xy} may range between 0 and 1, where zero represents no diet overlap and a value of one represents complete diet overlap (Schoener 1970). This index can be used as a test for overlap in diet between locations, seasons and age/size groups of a predator (Lang 1992). This index emphasizes the differences in predator's diet relative to the weight, thus the size, of the prey. Schoener's index is used in this paper to test overlap in diet between different age groups.

Results

A total of 205 sport-caught halibut were sampled of which 81 stomachs contained prey items. Twenty-two different species were identified as prey items from the stomachs of Pacific halibut and prey items were grouped into six categories (Table 1). When the prey items were grouped into the six major categories, the most frequently occurring prey group was Crustacean. This group also represented the largest percent composition by number and percent composition by weight (Fig. 1).

All stomach samples with prey items were grouped into four halibut age categories; 4-6 years, 7-9 years, 10-12 years, and 13 years and older. We tested for diet overlap among age groups using Schoener's index of dietary overlap (Table 2). There was a high degree of overlap between 4-6 yr. group and the 7-9 yr. group: 91%, and a low degree of overlap between the 4-6 yr. group and those halibut 13 years and older: 15%. This is due to the high number of Crustacean and small fish eaten by the younger halibut compared to the larger prey items, such as sculpins and gadids, eaten by the older halibut (Fig. 2): the frequency of occurrence of crustaceans and small fish decreased with increasing halibut age, whereas the frequency of occurrence of Cottidae and Gadidae increased with halibut age. The age group 13+ showed a decrease in the percent frequency of occurrence of crustaceans, though the frequency of occurrence of small fish did not decrease (Fig. 2).

To test for the existence of the hypothesized types of foraging modes, we divided the six prey categories into likely prey groups for the two foraging patterns, sit-and-wait and active search. Prey groups for the sit-and-wait foraging mode consisted of Gadidae, Cottidae and other invertebrates, while the second foraging mode, active searching, consisted of the Crustacean, cephalopods and small fish prey groups. Using only those stomach samples containing two or more items, we calculated the percentage of samples that were composed exclusively of prey items from one or the other foraging mode. Stomach samples having items from more than one foraging mode did not qualify as exclusive predators. Overall, only 11% of all samples containing two or more prey item had items from both foraging modes. Fifty-one percent of the samples contained only prey items from the active search category, while 38% of the samples contained prey items exclusively from the sit-and-wait category ($X^2 = 56.7$, N =75, $p = 0.0001$).

Discussion

The International Pacific Halibut Commission and National Marine Fisheries Service technical reports have stated the diet of Pacific halibut consists mainly of fish although diet changes with the size of the predator and the area in which the halibut were caught (IPHC 1987; Brodeur and Livingston 1988). Studies conducted in the Gulf of Alaska and British Columbia by the IPHC reported the diet of Pacific halibut consisted mainly of fish such as Pacific sandlance (*Ammodytes hexapterus*), walleye pollock (*Theragra chalcogramma*), and Pacific herring (*Clupea pallasi*). Octopus and Tanner crab (*Chionoecetes*) were also major contributors to the diet of halibut (Bell and St. Pierre 1970; Best and St. Pierre 1986). Novikov (1964) conducted one of the first diet studies of Pacific halibut in the Bering sea and concluded large halibut (>60cm) primarily ate fish while the diet of smaller halibut (30cm or less) was predominantly crustaceans.

Crustaceans and gadid fish appear to be the most important prey for Pacific halibut caught in Glacier Bay, Alaska. The majority of the crustaceans were small, subtidal and non-commercial species. Crustaceans were a large component of diet by all three indices: percent composition

Table 1. Prey items identified in stomach samples collected from sport-caught Pacific halibut August 19 to September 3, 1991, and May 26 to August 8, 1993, from Glacier Bay National Park, Alaska.

Group One	**Cephalopoda**	
	Majestic squid	*Berryteuthis magister*
	Octopus unidentified	
	Squid unidentified	
Group Two	**Crustacea**	
	Horse crab	*Telmessus cheiragonus*
	Dungeness crab	*Cancer magister*
	Pygmy cancer crab	*Cancer oregonensis*
	Cancer unidentified	
	Red king crab	*Paralithodes camtschaticus*
	Brown king crab	*Lithodes aequispis*
	Scaled crab	*Placetron wosnessenskii*
	Lyre crab	*Hyas lyratus*
	Kelp crab	*Pugettia gracilis*
	Decorator crab	*Oregonia gracilis*
	Tanner crab	*Chionoecetes bairdi*
	Magidae unidentified	
	Pandalus unidentified	
	Setosus hermit crab	*Pagarus setosus*
	Pagarus unidentified	
Group Three	**Other Invertebrates**	
	Basket star	*Gorgonocephalus caryi*
	Mussels unidentified	
	Gastropod unidentified	
Group Four	**Gadidae**	
	Walleye pollock	*Theragra chalcogramma*
	Pacific cod	*Gadus macrocephalus*
	Gadidae unidentified	
Group Five	**Cottidae**	
	Brown Irish Lord	*Hemilepidotus spinosus*
	Yellow Irish Lord	*Hemilepidotus jordani*
	Pacific staghorn sculpin	*Leptocottus armatus*
	Ribbed sculpin	*Triglops pingeli*
	Triglops unidentified	*Ammodytes hexapterus*
	Cottidae unidentified	
Group Six	**Small fishes**	
	Pacific Sandlance	*Ammodytes hexapterus*
	Pacific Herring	*Clupea harengus pallasi*
	Capelin	*Mallotus villosus*
	Myctophidae unidentified	

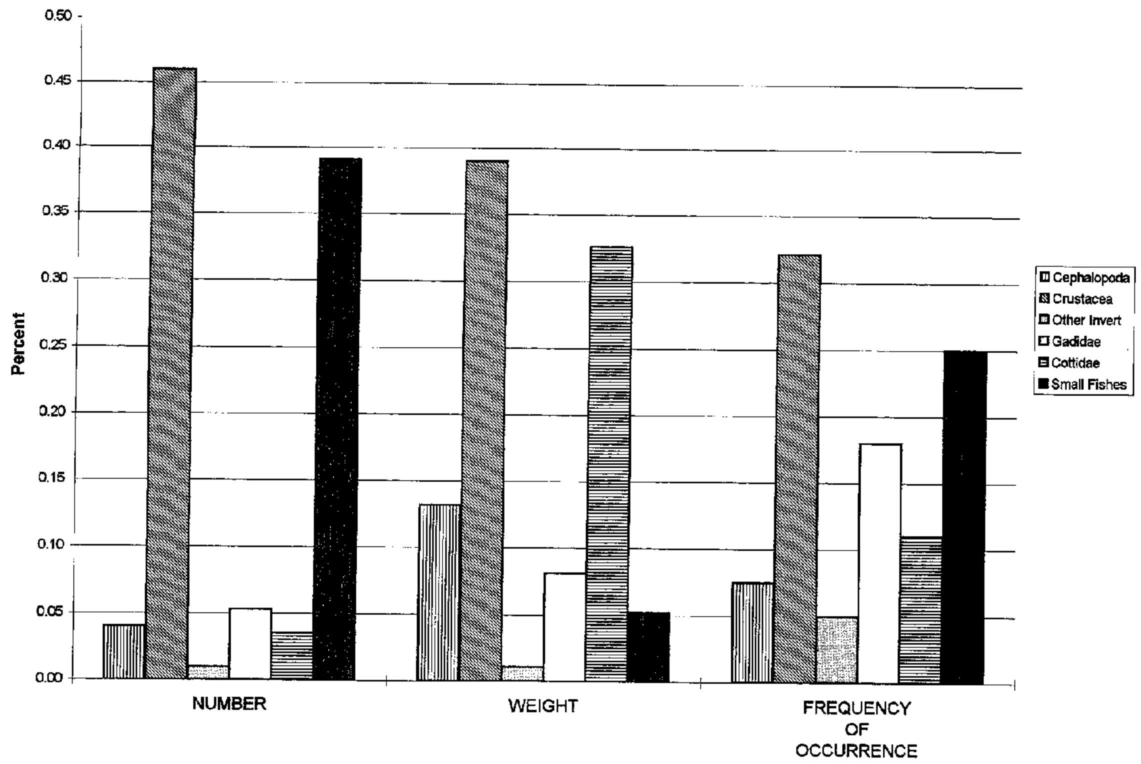

Fig. 1. Diet indicies used in analysis of Pacific halibut diet. Samples collected August to September 1991 and May to August 1993 from Glacier Bay National Park, AK. N=81

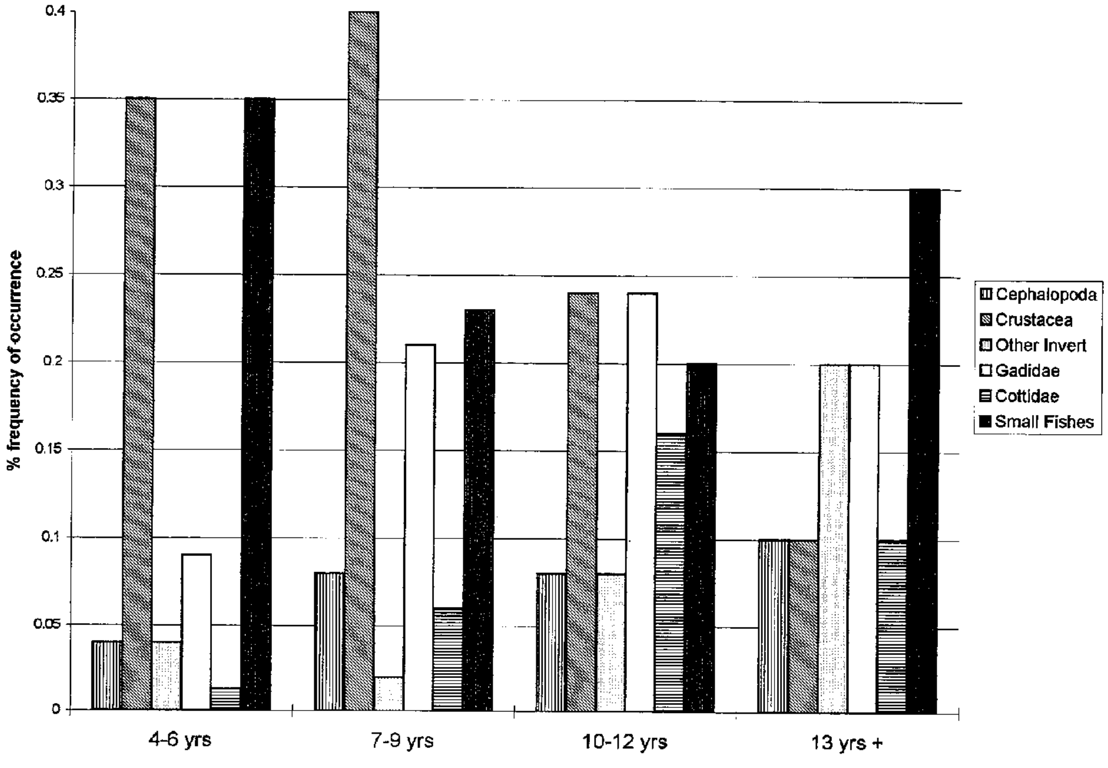

Fig. 2. Percent frequency of occurrence of prey groups for four age classes in the diet of Pacific halibut from samples collected in Glacier Bay National Park, AK. N=17, 4-6 years; n=36, 7-9 years; n=16, 10-12 years; and n=12, 13+ years.

Table 2. Diet overlap between different age groups of Pacific halibut collected August 19 to September 3, 1991, and May 26 to August 8, 1993, from Glacier Bay National Park, Alaska. N=81.

Age Groups	4 to 6 yrs	7 to 9 yrs	10 to 12 yrs	13+ yrs
4 to 6 yrs	1.00	0.91	0.29	0.15
7 to 9 yrs		1.00	0.37	0.21
10 to 12 yrs			1.00	0.67
13+ yrs				1.00

by both weight and number, as well as frequency of occurrence. Gadidae also had a high frequency of occurrence and a high percent composition by number; their percent composition by weight was low, probably due to the rapid digestion rate of these fish, especially the smaller individuals (Fig. 1).

Percent frequency of occurrence estimates the proportion of the sample population which feeds on a particular prey group (Windell and Bowen 1978; Hyslop 1980). This index indicates the presence or absence of a prey group in the diet, while percent composition by number reflects the relative abundance of prey groups in the diet. These two indices do not account for the relative biomass of the prey groups and may over-represent the smaller prey items in relation to larger prey in the diet. In particular, percent composition by number overestimates the importance of small items taken in large numbers (Windell and Bowen 1978; Hyslop 1980; Wooton 1990). On the other hand, percent composition by weight can overestimate the importance of heavy food items or be influenced by the digestion rate of the prey items (Hyslop 1980).

The diet of Pacific halibut in Glacier Bay changes dramatically with halibut age, the frequency of crustaceans and small fish in the diet declined with an increase in age, while the frequency of occurrence of gadids and Cottidae increased with an increase in age (Fig. 2). There was a high degree of overlap in diet between fish in consecutive age groups. This was probably due to the high number of crustaceans and small fishes eaten by the younger halibut compared to the larger prey items eaten by the older halibut (Fig. 2).

We hypothesized a least two likely foraging methods utilized by halibut: waiting for prey to pass by (sit-and-wait predation) or actively searching for prey. This hypothesis was derived from results described here detailing the co-occurrence of diet items and observed trends in movement patterns of sonic-tagged halibut (Hooge and Taggart 1995). The diet of many halibut, especially younger individuals, appeared to contain prey items associated with active foraging while the diet of many older individuals were characterized by items which could be associated with a sit-and-wait predation mode. Observations of sonic-tagged halibut indicate that larger halibut are more likely to exhibit small home ranges (and possibly territoriality), low spatial variability and site fidelity (Hooge and Taggart 1995). From this data we hypothesize that active searching for prey items is associated with less site fidelity, high spatial variability, no territoriality and younger individuals. Sit-and-wait predation would be associated with high site fidelity, home range exclusivity or territoriality, less spatial variance and characteristic of older individuals.

There appears to be diet specialization which may reflect the two foraging modes, sit-and-wait predation vs. active searching. Of all stomach samples that contained more than one prey item, 89% were exclusively composed of prey items from only one of the two separate foraging categories. If an individual was switching between the two foraging patterns, digestive delay of different prey items increases the probability of detecting prey items from the two foraging categories. This was highly significant, and indicates there is a change in the type of prey a halibut will eat over it's lifetime.

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Habitat Correlates of Pacific Halibut and Other Groundfish Species in Glacier Bay National Park

by

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Abstract

Originally conceived as a modified Schnabel (1938) design mark-recapture study, the unique random sampling regime of this longline tagging study has allowed us to describe habitat correlates of Pacific halibut (*Hippoglossus stenolepis*) and other demersal fishes. Pacific halibut and other fish were captured by longline sets of constant length and hook number distributed in a random stratified fashion. General Position System (GPS) location and depth were recorded at one-second time intervals during setting to obtain a depth profile and track of the set. Hooks were counted during pulling and the hook number was recorded for each fish and invertebrate to allow accurate determination of its capture location and depth. All fish were measured. Sediment type was determined from a grab sample taken at the mid-point of each set. Kruskall-Wallis ANOVAs were conducted to relate abundance of nine common groundfish species to substrate and to depth. Six species had significant relationships with substrate while all nine had significant relationships with depth. There were no significant relationships between fish size and substrate, and only Pacific halibut exhibited a significant relationship between size and depth (Kruskall-Wallis H=22.8, n=974, p<0.001).

KEY WORDS: *Hippoglossus stenolepis*, habitat, substrate, depth, distribution.

Many demersal fish species have relatively specific habitat requirements. These may be reflected in their depth and substrate distributions and may change ontogenetically or with season, location, or population size. Many authors have described increases in fish size with depth (Swain 1993; Richards 1986) and MacPherson and Duarte (1991) noted that temperature often decreases with depth and suggested that the positive size-depth relationship in demersal fishes may result from age-specific differences in temperature preferences. Age and species-specific differences in depth distribution have also been hypothesized to be a result of biotic factors such as prey abundance. Larson (1980) reported depth segregation of sympatric species of *Sebastes*.

While there is good information on the large-scale depth distribution of many northeast Pacific demersal fish species there is little small-scale information or information on size-

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specific depth distribution or on their distribution by substrate. The present study was conducted in a small area (90 km^2) with high fish sample sizes and both substrate samples and detailed depth measurements. This enabled us to describe fine scale distribution of nine demersal fish species in relation to substrate and depth. We also analyze relations between fish length and substrate and fish length and depth.

Methods

Research was conducted in an approx. 90 km^2 area with its center at approx. 58° 38' N and 136°10' W, 32 km inside the mouth of Glacier Bay, Alaska. The maximum National Oceanographic and Atmospheric Administration (NOAA) bathymetric sounding, which occurs in the mid-bay portion of the study area, is 325 m. The study area also includes two shallow reefs with depths less than 40 m, and Whidbey Passage with mid-channel depths of approximately 100 m.

In 1992, we sampled one day per week, beginning in June and continuing through November. During each sampling period we set and pulled four longline sets. Gear was standardized so that a longline set consisted of 400 fa of groundline with 200 snap-on hooks. We changed to a shorter, more intense sampling regime in 1993. There were two four-day sampling periods, one before and one after the June commercial halibut fishery opening. We set and pulled five longline sets daily. In an attempt to increase daily sampling effort, set length was increased in 1993 to 800 fa of groundline with 400 snap-on hooks. For both years, two halibut hooks (Mustad #15 circle hook) were alternated with one cod hook (Mustad #13 circle hook), along the length of the set. Starting positions for each set were chosen randomly from a computer-generated list of Universal Transverse Mercator (UTM) positions accurate to 1 m. However, there was no re-sampling within years of one km2 areas set in a grid over the study area. Setting direction was with the current, determined either by tide tables or visually. Although the 1993 sampling period was shorter, the effort was greater, 40 sets totalling 15,854 hooks were made while in 1992, 67 sets with 9,894 hooks were made.

While setting, depth (m) and UTM location were recorded every ten seconds of time with a computerized data-logger. Set times were staggered to account for the longer pulling time, the average soak time (±SE) was 5.9±0.128 hrs (n=97). Soak time is defined as the time from when the first anchor hits the water to the time when the first anchor pulled surfaces again. After setting gear, at the midpoint of each set, a profiling conductivity temperature depth meter (CTD) was dropped to the greater of 90% of chart depth or 1000 m, and 10-30 cm^3 of bottom sediment was collected using a Shipek grab sampler. At the time of sampling, substrates were categorized as rock, sand, silt, or clay, based on visual determination of the major constituent. Clay included samples described as: pure clay, and various clay matrices without rock. The silt substrate type was visually described as pure silt. The sand substrate type included pure sand, and a sand, silt matrix. Those categorized as rock were; bedrock, rock, and rock matrices in which sand, silt and clay were present in various combinations.

After the 6 hr soak period, the set was pulled. During pulling, hook number was recorded for each fish and invertebrate to allow determination of location (UTM) and depth (m) of capture from the set track information. All halibut were tagged with International Pacific Halibut Commission (IPHC) wire cheek tags, and measured for total length (±0.1 cm), head length (measured from the forward edge of the closed jaws to the hind edge of the cartilaginous operculum ±0.1 cm), and inter-ocular distance (±0.1 cm). Other fish species were measured for total length (±0.1 cm).

Halibut dispersion along a longline was analyzed using a modified nearest-neighbor analysis (Clark and Evans 1954). Average fish size, and total catch for each species, and total number of hooks set were calculated for each 50 m depth interval and substrate type. This allowed us to calculate catch per hook (CPH) for each species at each substrate and depth interval as an index of abundance. Because the distributions were not normal and exhibited heteroscedasticity, Kruskall-Wallis ANOVA (Zar 1974) and Spearman's Rank Correlation (Zar 1974) were used to determine statistical significance of relationships. Two-tailed significance levels were used for all tests.

Results

Dispersion

Although set start positions were randomly distributed, individual hooks were not; thus, a two-dimensional measure of dispersion of halibut along the longline was appropriate for describing their distribution pattern. There was a significant clumping of halibut along a set (Nearest Neighbour r=0.5, n=973, p<0.01).

Substrate

We limited our analyses to nine groundfish species that each comprised more than 1% of the total catch by numbers. These nine species accounted for 67% of the total catch of 3049 fish and invertebrates. In order of abundance, they were: Pacific halibut (32.2%), Pacific cod (*Gadus* *macrocephalus* 14.8%), black skate (*Raja kincaidi* 4.9%), walleye pollock (*Theragra chalcogrammus* 3.4%), yellow Irish lord (*Hemilepidotus jordani* 3.0 %), brown Irish lord (*Hemilepidotus spinosus*, 2.9%), rougheye rockfish (*Sebastes aleutianus* 2.4%), sablefish (*Anoplopoma fimbria* 2.0%), and great sculpin (*Myoxocephalus polyacanthocephalus*, 1.4%).

Results of analyses of fish abundance in relation to substrate type are shown in Fig. 1 for species with a significant relation of CPH to substrate type. Six species had significant relations of abundance with substrate: black skate (Kruskall-Wallis H=18.5, n=32, $p<0.001$); walleye pollock (H=10.3, n=32, $p<0.05$); rougheye rockfish (H=11.1, n=32, $p<0.05$); Pacific cod (H=13.6, n=32, $p<0.005$); yellow Irish lord (H=15.5, n=32, $p<0.005$); and Pacific halibut (H=16.8, n=32, $p<0.001$). Of these, Pacific halibut used rock and sand, yellow Irish lord sand and silt, Pacific cod and black skate used silt and clay while rougheye rockfish and walleye pollock used predominantly clay substrates.

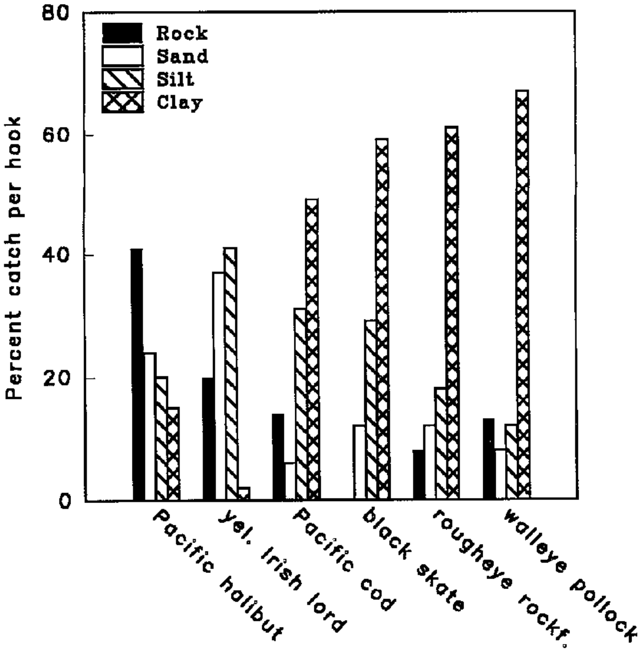

Fig. 1. Index of abundance by substrate type for Pacific halibut and five other demersal fishes.

Depth

Abundance at seven depth intervals is shown in Figures 2,3 and 4 for species with significant relations. All nine species had significant relations of abundance with depth, their respective statistics are: great sculpin (Kruskall-Wallis H=13.7, n=96, $p<0.05$); brown Irish lord (H=15.8, n=96, $p<0.05$); yellow Irish lord (H=12.8, n=96, $p<0.05$); Pacific halibut (H=33.4, n=96, $p<0.0001$); walleye pollock (H=31.8, n=96, $p<0.0001$); rougheye rockfish (H=18.7, n=96, $p<0.005$); Pacific cod (H=50.0, n=96, $p<0.001$); black skate (H=50.2, n=96, $p<0.0001$); and sablefish (H=62.0, n=96, $p<0.0001$). The most shallowly distributed species were: great sculpin which were found in waters of 0-100 m depth, yellow Irish lord (0-250 m with peak abundance from 0-150 m), and brown Irish lord (50-150 m). More broadly distributed were: Pacific halibut which occurred over the entire depth range of 0-325 m, Pacific cod and rougheye rockfish (50-325 m) and walleye pollock (distributed from 0-300 m with a peak abundance from 150-250 m). The most deeply distributed were: black skate which occurred from 50-325 m and were most abundant in 250-300 m, and sablefish (250-325 m).

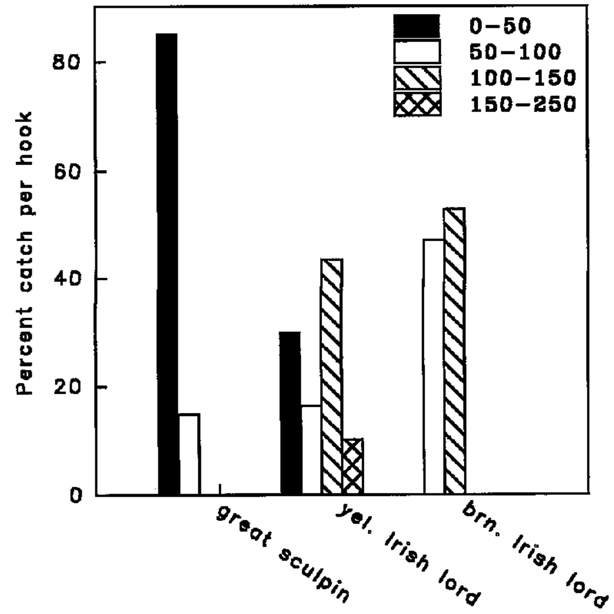

Fig. 2. Index of abundance by depth interval for three shallowly distributed demersal fishes.

Size

Although a Kruskall-Wallis ANOVA of average length by substrate was conducted, no significant relation was found for any species. Although Pacific cod and walleye pollock average length increased with depth, only Pacific halibut had a significant (Kruskall-Wallis H=22.8, n=974, $p<0.001$) relationship of size with depth (Fig. 5). Halibut length increased for depths from 0-250 m, and decreased thereafter.

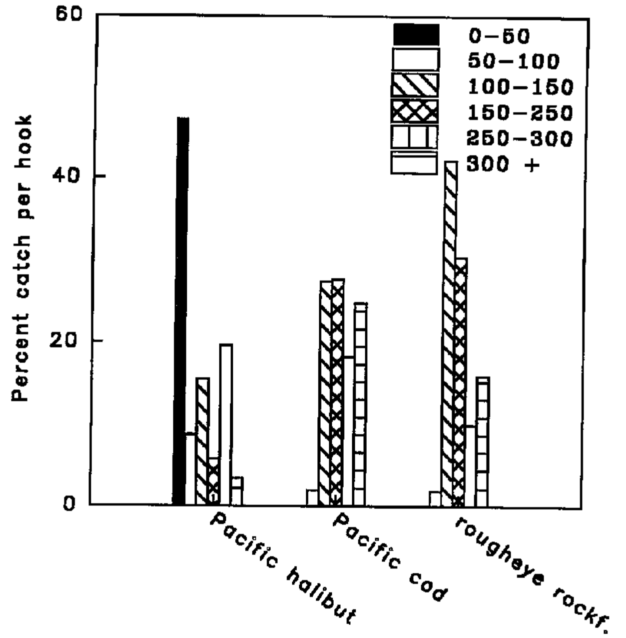

Fig. 3. Index of abundance by depth interval for Pacific halibut and two other widely distributed demersal fishes.

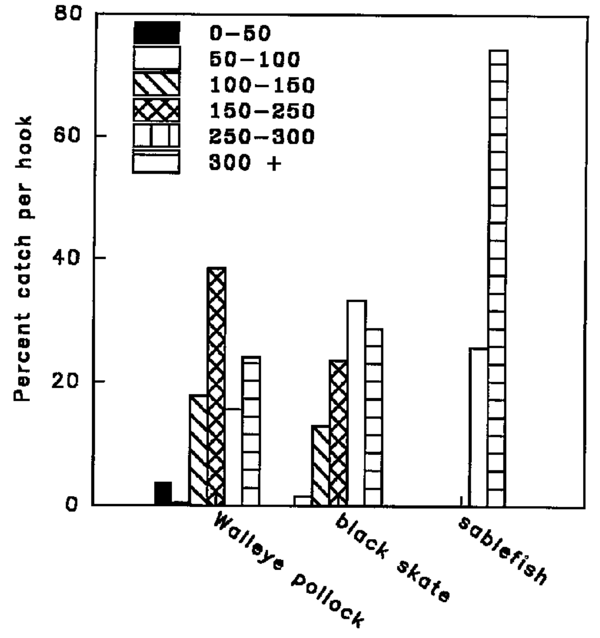

Fig. 4. Index of abundance by depth interval for three deeply distributed demersal fishes.

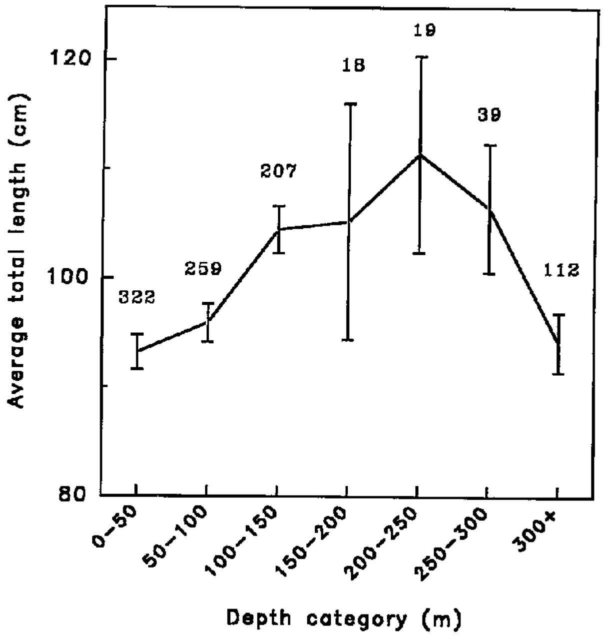

Fig. 5. Average total length by depth category for Pacific halibut.

Discussion

All nine fish species exhibited characteristic depth distributions, and in the case of Pacific halibut, average length increased with depth. This is consistent with the findings of Gabriel and Tyler (1980) who conducted cluster analysis on demersal fish assemblages, they reported that the assemblages were strongly associated with depth contours. Both the depth distribution of halibut which is described here and the finding of increases in halibut size with depth are consistent with Bell (1981) who reported that Pacific halibut juveniles (2-4 yrs) are most abundant in depths of less than 60 m (Bell 1981) and English (1966) who reported that older halibut occur in depths up to 1100 m but are most common in depths of 55-422 m. Skud (1978) noted that the average weight of halibut was greater in deeper water. An increase of fish size with depth has been demonstrated in many studies and has even been named: "Heincke's law" as it was first described be Heincke (1913). Richards (1986) described increases in average length with depth for *Sebastes* spp. MacPherson and Duarte (1991) hypothesized that this phenomenon is due to fish movement to deeper waters during ontogeny. The broad range of taxa for which the rule holds true led them to further suggest that it is an evolutionary response to the general decrease in water temperature with depth which allows fishes to optimize their metabolic rate. Lending support to this hypothesis, Thompson and Van Cleve (1936) reported that commercial fishing for Pacific halibut is usually conducted in waters of 3-8°C. Besides physical factors, biotic factors could also play a role. Depth distributions may be related to competition for food resources which generally decrease with depth. A confounding factor in this study is the wide range of time over which 1992 sampling occurred. However sample sizes were too small to allow analysis of temporal changes in depth or substrate uses.

The depth distributions reported here for the other eight groundfish species generally agree with the reported depth ranges. Pacific cod are reported to occur from depths of 1-550 m with the highest trawl catches occurring in depths of less than 180 m (Alverson et al. 1964). This agrees well with our data. Swain (1993) reported on age and density dependent bathymetric patterns of Atlantic Cod (*Gadus morhua*). He found that "for younger age groups, predicted density was greatest from 20-30 m at low abundance and from 70-90 m at high abundance while for older age groups density varied little with depth at low abundance but depended strongly on depth at high abundance with predicted density highest from 100-120 m for older cod when abundance was high". This agrees with the pattern of increasing length with depth which we observed here, although it was not significant. Gabriel and Tyler (1980) found the highest catch (lb) of both black skate and rougheye rockfish from depths of greater than 220 m. Similarly, Alverson et al. (1964) report rougheye rockfish from depths of 92-732 m with maximum trawl catch (lbs) from depths of 364-544 m. Our work agrees well for black skate but rougheye rockfish were more shallowly distributed (peak abundance at 100-250 m) in this area. Walleye pollock are found from depths of 1-550 m and Alverson et al. (1964) reported the highest trawl catch (lbs) occurring from depths of 90-270 m. Our values (peak abundance at 150-250 m) agree well with these. Sablefish are reported to depths of 1100 m, but trawl catch (lbs) is maximized at depths of 540-730 m (Alverson et al. 1964). Pearcy et al (1989) reported sablefish to be abundant in deep mud habitat with depths of 164-300 m. This agrees well with our findings as sablefish were most abundant in the deepest depth interval, although they did not exhibit a significant substrate relation. Yellow Irish lord are found in depths of 3-110 m (Peden 1964). We found them more deeply distributed (in depth intervals from 0-200 m).

Six of the nine species exhibited statistically significant substrate distributions. More detailed substrate sampling might elucidate trends between fish abundance and substrate type. Sediments are finer in deeper waters of the study area which makes it difficult to separate the effects of depth versus substrate on species distribution without multivariate analyses. However, it is notable that the relationship of abundance with depth exhibited a higher significance level than that with substrate for all species except yellow Irish lord. Many fish species do exhibit substrate preferences however, Atlantic cod juveniles preferentially settle on gravel substrate (Lough et al. 1989) and their survival is higher on that substrate (Gotceitas 1993). Richards (1986) described segregation by depth and substrate type for several species of *Sebastes*.

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Recovery Mechanisms of the Brown Alga, *Fucus gardneri*, Following Catastrophic Disturbance: Lessons from the *Exxon Valdez* Oil Spill

by

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Abstract

The recovery of the brown alga, *Fucus gardneri*, from the *Exxon Valdez* oil spill and associated cleanup activities was investigated in Prince William Sound, Alaska. Colonization can be divided into three components: 1) settlement of propagules, 2) recruitment, and 3) growth of recruits into adults. Settlement densities of *Fucus* in Prince William Sound were more than 120 eggs/cm^2, but these eggs rarely traveled more than 40 cm from their parent plants.

Recruitment of germlings was restricted to cracks and crevices in the substrate. *Fucus* did not recruit outside of grooves on artificial tiles, and recruit density was inversely related to groove width. The presence of an adult *Fucus* canopy enhanced recruitment. Lack of a canopy at denuded shores may have inhibited recolonization, but cracks and crevices in the substratum may have protected germlings enough to allow colonization to proceed.

The growth rate of a cohort of germlings was found to be between 2.5 to 3.33 cm/year. During the growth process the density of *Fucus* decreased markedly from 15,000 to 500/m^2. Growth appears not to be a limiting factor in the colonization of barren shorelines.

KEY WORDS: Algae, recruitment, settlement, *Fucus*, intertidal, recovery, colonization.

Rocky intertidal shores are often subjected to disturbances in which some or all of the biota are removed (Sousa 1984; Paine and Levin 1981; McCook and Chapman 1991). Mechanisms controlling recolonization after disturbance may depend on the spatial scale of the disturbance. For example, in mussel beds, small disturbance created patches are recolonized by migration of nearby mussels while large patches require settlement and recruitment from oceanic larval sources (Paine and Levin 1981). Although primary succession has been studied frequently on small scales, few studies have examined recolonization after disturbances of large spatial scales (> 100 meters). McCook and Chapman (1991) observed a large area of intertidal near Halifax, Nova Scotia which was scoured by rare sea ice, removing much of the fucoid algal canopy. The retreat of tidewater glaciers, such as that occurring in Glacier Bay, Alaska, can open very large areas of rocky intertidal to primary successional processes (Sharmann 1988). In Prince William Sound in 1989 much of the intertidal was denuded. In an attempt to rid shorelines of oil spilled from the *Exxon Valdez* tanker which ran aground on 24 March 1989, a variety of cleanup technologies were used, including washing the shorelines with hot water (up to 140°F) at high pressure using an OMNI barge (Nauman 1991). This treatment essentially removed all organisms from the shoreline as well as the oil (Houghton et al. 1991).

The brown alga, *Fucus gardneri* is a major component of protected rocky coastlines from Puget Sound in Washington state to Bristol Bay in Alaska (Kendziorek and Stekoll 1984; Ang 1991a,b; van Tamelen and Stekoll 1995). Since this

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seaweed constitutes most of the algal biomass on protected shores in Alaska (Kendziorek and Stekoll 1984; van Tamelen and Stekoll 1995), disturbances in this region result in large declines in the abundance of *Fucus*. Despite the prominence of this seaweed on eastern shores of the northern Pacific Ocean, surprisingly little is known about the mechanisms governing settlement, recruitment, and growth of this seaweed.

In the lifecycle of *Fucus*, adult plants produce eggs that are immediately fertilized and settle on the shoreline. Settled zygotes then begin growth and recruit into the population as germlings. After recruitment, the germlings must grow from 0.5 to three years before becoming reproductive (Ang 1991a; unpublished data). The colonization process of *Fucus* can be divided into three components: 1) settlement of eggs on the shoreline, 2) recruitment of zygotes into germlings, and 3) growth of the germlings into adult plants. Each of these components of colonization was addressed by examining *Fucus* recovering from the effects of the *Exxon Valdez* oil spill and subsequent cleanup efforts. Understanding of these components of colonization in Prince William Sound may shed light on similar processes in other areas of large disturbance such as Glacier Bay.

Methods

Study Sites

Studies were performed in Herring Bay on the northern end of Knight Island in Prince William Sound (Fig. 1). All sites consisted of basaltic bedrock and were protected from most wave action. These studies focus on mechanisms of colonization by *Fucus*, ignoring differences between oiled and unoiled sites. Details of the sites, including oiling history and cleanup treatments, are given in van Tamelen and Stekoll (1995) and van Tamelen et al. (in prep.).

Fucus Egg Dispersal Patterns

Dispersal patterns of *Fucus* eggs were investigated by monitoring egg settlement at various distances and directions from a single group of fertile plants. Two to four fertile plants that were releasing mucus were collected, rinsed in freshwater, and dried in the dark for 12 hours. These plants were attached to the center of two 4 m sections of 1.3 cm diameter PVC pipe joined in the middle so that the pipes were perpendicular to each other. These pipes were placed on a shoreline with one pipe parallel to the water line. The juncture of the pipes was at least 10 m from the nearest fertile *Fucus* plant.

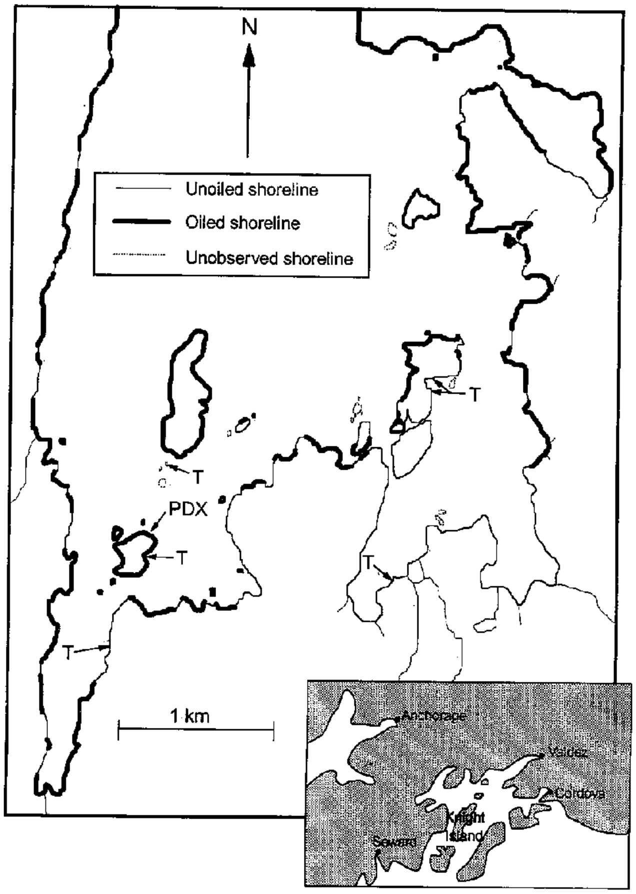

Fig. 1. Map of the study sites in Herring Bay. The inset shows the location of Knight Island in Prince William Sound. Oiled and unoiled shores were derived from Alaska Department of Environmental Conservation surveys. PDX indicates the population dynamics site, and T indicates the sites where tiles were placed.

The number of settling *Fucus* eggs was estimated with acrylic plates (6 mm thick) designed to catch *Fucus* eggs. The plates were 5x10 cm and had nine grooves etched in them. The width of the grooves (125 µm) was slightly larger than the width of an average *Fucus* egg (75 µm), and eggs falling on the plates were likely to be caught in the grooves. These plates were secured to the pipe with stainless steel screws and located 0, 10, 20, 40, 80, 120, and 200 cm from the source plants in all four directions. This apparatus was left in the field for 24 hours and then retrieved. The number of eggs on each plate was counted under a dissecting microscope (50x). This procedure was repeated four times from 6-10 July 1993 and eight times from 1-7 August 1993. Eggs were not always abundant on the settling plates, especially in August. Only those five trials in which more than 100 eggs were found on all of the plates combined were used for analyses. The percent of eggs falling in all four directions and at the various distances was calculated by dividing the number of eggs on each plate by the total number of eggs found for that trial.

Fucus Recruitment

The effects of substrate heterogeneity, tidal height, and *Fucus* canopy on recruitment were assessed with a multifactor experiment using ceramic tiles. Tiles (6x8 cm) were made with six grooves of three widths (0.80 mm, 0.50 mm, and 0.15 mm) and two depths (1.50 mm, 0.30 mm). The tiles were made with Pine Lake Red Stoneware clay and fired at cone 10 with no glazes or colorants. The six different sizes of grooves (3 widths x 2 depths) were randomly ordered horizontally on each tile. The tiles were attached to the substratum with a screw through a central hole in the tile.

Four plates were deployed at each of six sites. Two tiles were placed one meter apart at both 2.5 and 3.0 m above mean lower low water (MLLW). One randomly chosen tile at each level was designated as a *Fucus* canopy treatment, and the other tile had no *Fucus* canopy. If a *Fucus* canopy was present in the no *Fucus* canopy treatment, the plants able to cover the tile were removed. If there was no *Fucus* canopy in the *Fucus* canopy treatment, then *Fucus* plants, collected from the same tidal height, were transplanted just above the tiles by chipping off the rock with the plant attached and using Z-Spar marine epoxy putty to secure the rock and plant in place. The upper left tile of each quartet was randomly placed horizontally along the shore.

After almost 11 months in the field, from early July 1992 to late May 1993, the tiles were retrieved, and the number of germlings in each groove were counted under a dissecting microscope (50x). An area between the first and second grooves equal to the width of the widest groove was also observed to assess recruitment outside of grooves. To account for differences in surface areas of grooves of different widths, the total number of germlings in each groove was divided by the surface area of the groove, yielding the density of germlings in each groove.

The effect of groove size on germling density was statistically analyzed by treating each tile as a block with groove width and groove depth as factors in a two-way ANOVA. The effects of tidal height and *Fucus* canopy on germling recruitment were analyzed with a two-way ANOVA with site as a blocking factor, using the total number of germlings on each tile as the dependent variable.

Population Dynamics

The population structure of *Fucus* was monitored in the high intertidal at one oiled site that was subjected to intense cleanup efforts. In 1990 this site was virtually devoid of algae in the high and mid zones except for some very small, newly recruited individuals. Six permanently marked quadrats (20x50 cm) were established in 1990. The quadrats were randomly located both horizontally and vertically and were between 2.5 and 3.5 m above MLLW.

The size-frequency distribution of *Fucus* was determined in each quadrat by measuring the maximum length of all visible *Fucus* plants to the nearest 0.5 cm without removing plants from the substratum. The study plots were monitored every two weeks during a three-month period in 1990. In 1991, the quadrats were visited on three occasions, once each in April, June, and August. During 1992 and 1993 plots were sampled twice, once each in May and August.

Statistical Analyses

All statistical analyses were done using ANOVA techniques. Variances were checked for homogeneity with F-max tests. If raw data variances were found not to be homogeneous then they were log transformed, otherwise the raw data were analyzed. In one case, both the raw and transformed data did not have homogeneous variances and this is indicated where the data are presented. Post hoc comparisons were made with Tukeys' test.

Results

Fucus Dispersal Patterns

There was a greater proportion of eggs settling closer to source plants compared to further away, but there was no differences in the proportions of eggs settled up, down, or to the sides of source plants (Fig. 2). A two-way ANOVA with direction and distance as factors yielded a significant main effect of distance (n=5, F=9.70, p<0.001), no effect of direction (n=5, F=1.07, p=0.364), and no interaction (n=5, F=1.01, p=0.451). The variances, however, were not homogeneous, violating the ANOVA assumption of homogeneity. Significantly more eggs were found on the settling plates at 0 and 10 cm distances compared to plates 40 or more cm from the source plants. The maximum number of 1454 eggs on a single plate was seen 10 cm from the parent plants. This settlement density translates to about 121 eggs per square centimeter.

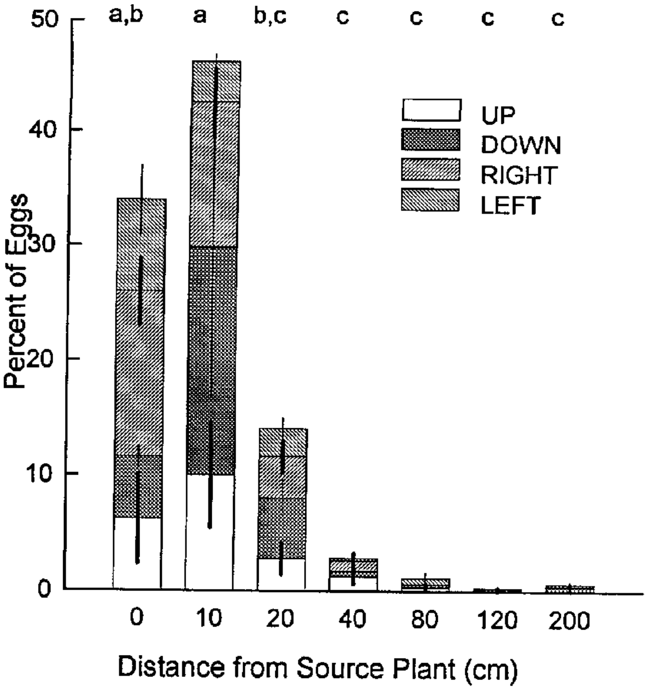

Fig. 2. The percent of eggs settling at various distances and in different directions from source plants. Error bars represent one standard error of the mean. Statistically indistinguishable bars (all directions combined) are indicated by the same letter above the bar. The variances were not equal in the analysis.

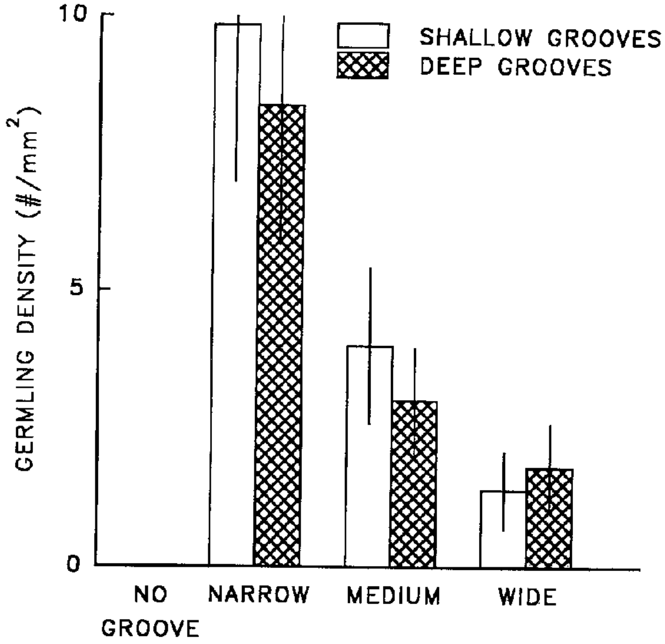

Fig. 3. The density of germlings in grooves of various sizes. Error bars represent one standard error of the mean. There was no significant difference between shallow and deep grooves, but there were differences between all the groove widths. The data, however, violated the assumption of homogeneity of variances.

Fucus Recruitment

Germlings did not recruit onto the tiles out of grooves (Fig. 3). There was no statistical difference between recruitment in deep and shallow grooves (2-way ANOVA, n=24, F=2.27, p=0.135), but there were differences in the density of recruits between wide, medium, and narrow grooves (n=24, F=19.92, p<0.001). Recruit density varied inversely with groove size. There was also a block (tile) effect (n=24, F=13.87, p<0.001), indicating differences in recruitment between tiles and suggesting spatially variable recruitment.

The two-way ANOVA on the number of germlings per plate yielded two significant effects (Table 1). First, there was a significant block (site) effect, indicating that there were differences in germling survival between sites. Second, germling survival was higher on tiles covered by *Fucus* canopy. There was no significant effect of tidal height on recruit density and no significant interaction.

Population Dynamics

Throughout the sampling period many of the permanent quadrats had few or no *Fucus* plants, resulting in the large standard errors (Fig. 4). *Fucus* plants successfully colonized only one or two of the six plots, demonstrating the patchy nature of *Fucus* colonization in the high intertidal zone. The pattern of colonization seen in these plots is similar to that seen in lower tidal levels and at other sites in Herring Bay (van Tamelen and Stekoll 1995). In 1990, one year after denudation, many germlings (<2 cm) were observed. These germlings grew into small (2-5 cm) plants that were abundant in 1991. In 1992, there were more medium sized (5-10 cm) plants and these grew into large (>10 cm) plants in 1992 and 1993. Plants, which settled and recruited in 1989, took three or four years to grow to 10 cm or more, which is an average population growth rate of 2.5 to 3.3 cm/year. As the plants grew to larger sizes their maximum density decreased from about 15,000/m^2 as germlings to about 500/m^2 as large plants (Fig. 4). During this time the percent cover of *Fucus* did not change at this site (van Tamelen and Stekoll 1995).

Discussion

The first stage of colonization for *Fucus* is the arrival of eggs produced by adult plants. The dispersal distance of eggs from source plants was very limited; most eggs fell within 20 cm of their source. One possible explanation for this short dispersal distance is that eggs are released in a mass of thick mucus. Since both eggs and mucus are

Table 1. Mean (±SE) number of germlings on tiles at two tidal levels and under or out of *Fucus* canopy. The tidal level is in meters above MLLW The results of the two-way ANOVA are also presented.

Tidal Level	+Canopy	-Canopy
3.0	701.33 (322.64)	142.33 (109.45)
2.5	804.83 (503.10)	465.33 (235.60)

Source	df	MS	F	p
Site	5	1923530	9.24	<0.001
Level(L)	1	272853	1.31	0.270
Canopy(C)	1	1210953	5.82	0.029
L*C	1	72270	0.34	0.565
Error	15	208218		

relatively dense and sink in seawater, most of the released eggs will remain in the mucus and near the parent plant as the mixture rapidly settles to the substratum. Another consequence of this strategy is that settlement rates of more than 120 eggs per square centimeter can be observed.

In Prince William Sound, some denuded areas were recolonized relatively rapidly by *Fucus* despite the limited dispersal distances. These shores lacked reproductive plants (van Tamelen and Stekoll 1995) and thus a local source of eggs. Very low settlement rates were also observed at these sites up to four years after the spill (van Tamelen et al., in prep.). The source of the colonizing eggs is not known. One possible source of eggs is from drifting fertile *Fucus* plants. These plants may have washed up or over the denuded shores and released their eggs.

In most areas, however, recolonization seems to have taken much longer. In these areas, other factors may be responsible for slow recolonization rates. Once eggs arrive on denuded shores, physical factors such as high heat and desiccation stress may impose constraints on the recolonization rates of *Fucus*. *Fucus* recruitment was greater under adult *Fucus* canopy, suggesting that the presence of a *Fucus* canopy enhanced the chances of germling survival. Brawley and Johnson (1993) observed lower temperatures and lower desiccation rates under algal canopies and consequently higher recruitment rates.

Fucus canopy, however, was not abundant at denuded sites, limiting recruitment in these areas. Cracks and crevices in the rock surface may provide another refuge from heat and desiccation stress (Lubchenco 1983). Recruitment of *Fucus* germlings occurred only in tile grooves in these experiments. Since the highest recruitment rates were observed in grooves with canopy present, there may be additive or synergistic effects of canopy and cracks or crevices. Without a canopy present, *Fucus* may still have low recruitment even in cracks and crevices.

Herbivory and the presence of barnacles have also been shown to affect recruitment of *Fucus*. Lubchenco (1983) showed that herbivores slowed recruitment of *Fucus*. Herbivores were not manipulated in this study, but in other experiments they seem to retard recolonization by *Fucus* in Prince William Sound (van Tamelen et al. in prep.). Barnacles, in a manner similar to cracks and crevices, enhanced *Fucus* recruitment rates in New England (Lubchenco 1983). We have observed that small *Fucus* plants in Prince William Sound are found frequently on barnacles, but larger plants are found more frequently in cracks and crevices (unpublished data).

As initial recruits grow and become reproductive they provide both protection from desiccation stress and a local source of eggs. This new canopy will further enhance the recolonization process. In the high intertidal, where desiccation can be severe, recruitment without canopy appears to be very sparse and patchy. A mechanism by which the high zone may be colonized is the upward extension of beds of *Fucus* plants lower on the shore. As these beds grow upward to form a canopy of reproductive plants, protection from heat and desiccation stress will be provided and a source of settling eggs will be present.

After recruiting, *Fucus* germlings must go through a period of growth before they become reproductive. In Prince William Sound this growth period took about three or four years with the population growing at a rate of 2.5-3.3 cm/year. This growth rate is typical for intertidal fucoids (Ang 1991b), although some plants have been observed to grow at faster rates (Keser and Larson 1984). As these plants grew their density decreased markedly, probably due to intraspecific competition (Kendziorek and Stekoll 1984,

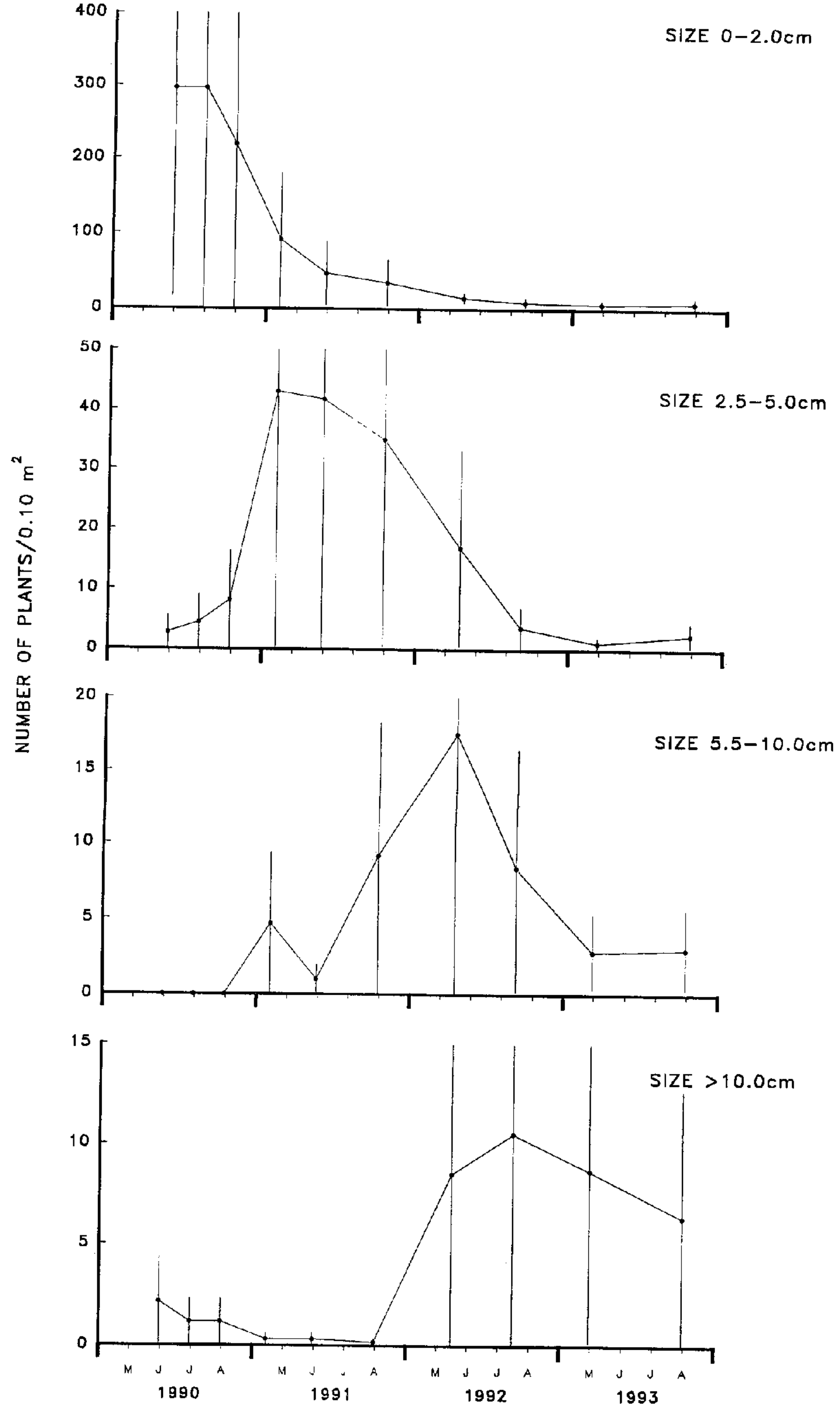

Fig. 4. The density of *Fucus* germlings (0-2.0 cm), small (2.5-5.0 cm), medium (5.5-10 cm), and large (>10 cm) plants in permanently marked quadrats. Sampling took place only during the summer months of May (M), June (J), July (J), and August (A) from 1990 through 1993. Error bars represent one standard error of the mean.

Ang and DeWreede 1992), but their percent cover did not change (van Tamelen and Stekoll 1995). If *Fucus* follows the -2/3 power law of other plants (White 1980), these large adults will have a greater biomass, but no greater percent cover, than the high density of small individuals, providing a protective canopy for new germlings.

Recolonization of large scale disturbances of wave protected shorelines in Prince William Sound may be slower compared to disturbances of smaller scales. At least two factors may contribute to this decreased recolonization rate. First, The dispersal distance of *Fucus* eggs was generally less than 40 cm. Therefore, disturbed patches with a diameter of greater than about one meter would have reduced settlement of *Fucus* eggs. Second, the absence of surrounding *Fucus* canopy may expose vulnerable germlings to desiccation stress, resulting in poor recruitment after settlement. Once germlings were established, however, growth would be normal and recolonization would be complete in about four years.

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Seasonal Characteristics of Humpback Whales (*Megaptera novaeangliae*) in Southeastern Alaska

by

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Abstract

Humpback whales were studied in southeastern Alaska to assess seasonal distribution and numbers, migration patterns, length of stay, female reproductive histories, and calf survival. A mean annual estimate and 95% confidence interval of whales present in the study areas was 404 ± 54 individuals. The longest length of stay was nearly 7 months, and the shortest transit to the Hawaiian mating and calving grounds was 39 days. Generally, birth intervals did not vary from one calf every two or three years; individual variation ranged from one to five years. There were few resightings of whales first seen as calves. The recovery of North Pacific humpback whales will only occur through an increase in the survival of calves to become sexually mature and reproducing adults.

KEY WORDS: Endangered species, humpback whale, population estimates, seasonal distribution, migration, reproduction, survival.

Previous studies on humpback whales (*Megaptera novaeangliae*) in southeastern Alaska focused primarily on two areas, the Glacier Bay-Icy Strait and Frederick Sound areas, during the summer months. These studies made important contributions to the knowledge of this species, but humpback whales are present in large numbers in other areas and in other seasons. This fact complicates the present understanding of the natural history and biology of the humpback whale in southeastern Alaska. The objectives of this study were to determine 1) seasonal distribution and numbers, 2) regional migration patterns and length of stay on the feeding grounds, and 3) reproductive histories of females, birth intervals, calf survival, and recruitment.

North Pacific humpback whales are seasonal migrants that feed on zooplankton and small schooling fishes in the cool, coastal waters of the western United States, western Canada,

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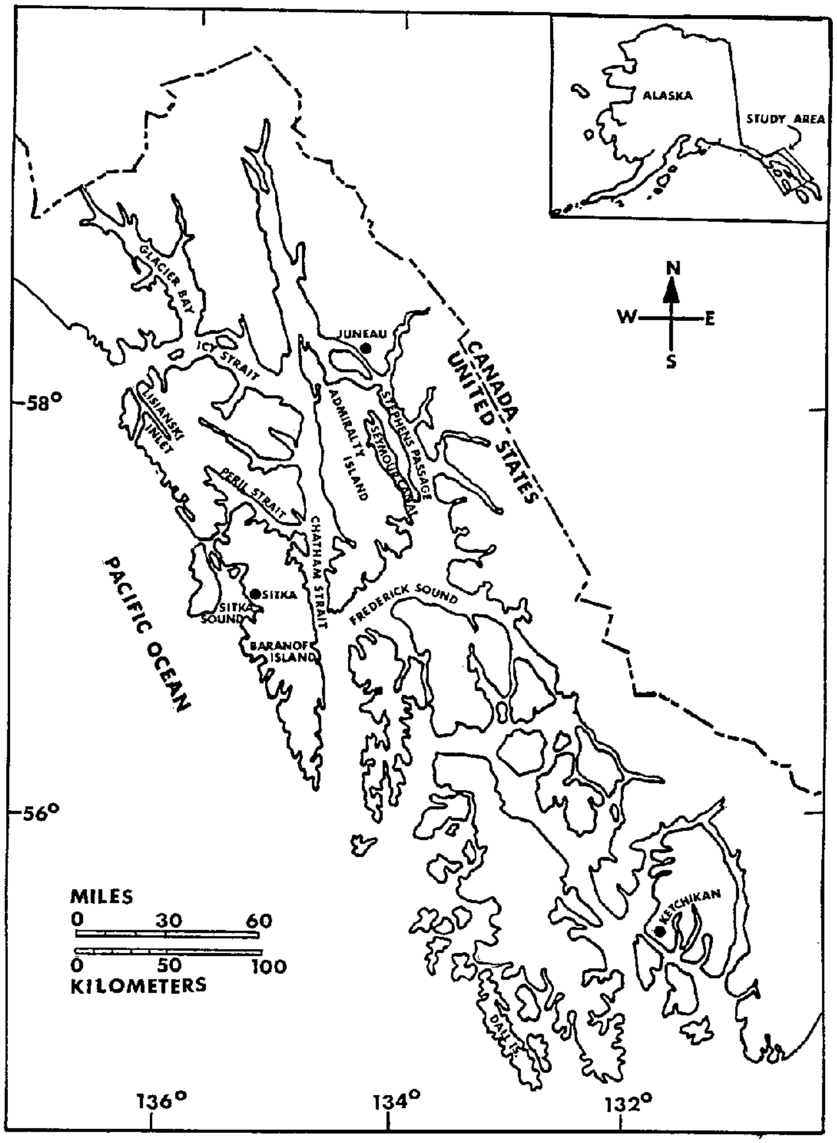

Fig. 1. Map of southeastern Alaska study areas.

and Russian Far East. The eastern North Pacific feeding area extends northward along the entire coast of California, Oregon, Washington, British Columbia, southeastern Alaska, Prince William Sound, the western Gulf of Alaska, and the Aleutian Islands, including the Bering Sea.

Humpback whales feed in discrete assemblages in areas that are geographically isolated. The largest number of humpback whales in Alaskan waters gather to feed in the southeastern part of the state. Humpback whales have been seen there in all months of the year (Straley, 1990); peak numbers occur during late summer (Baker et al., 1985). Individual humpback whales have been documented to remain in southeastern Alaskan waters for more than 6 months (Baker et al., 1992).

Female humpback whales generally have a 2- or 3-year breeding cycle, with a 12 month pregnancy and a 10.5 month lactation period (Chittleborough, 1958). An average birth interval of 2.8 years was calculated for females in southeastern Alaska, during the years 1981-86 (Baker et al., 1992). Humpback whales studied in the North Atlantic from 1979 to 1987 resulted in a mean birth interval of 2.4 years (Clapham and Mayo, 1990). Reproductive rates will give some indication as to the recovery of this population but data collected on calf survival and eventual recruitment of these offspring into the population will ultimately determine the recovery status of humpback whales in the North Pacific.

Methods

The study was conducted in southeastern Alaska, which is an extensive archipelago with glacial fjords, sounds, inlets, bays, and straits (Figure 1).

The three primary study areas were 1) Glacier Bay-Icy Strait, 2) Frederick Sound-Seymour Canal-lower Stephens Passage, and 3) Sitka Sound. Other areas, including Lisianski Inlet, Chatham Strait, and Peril Strait were surveyed occasionally.

This study was conducted from 1980-1992, with a primary focus on data collected from 1985-1992. Skiffs were used as survey vessels, ranging in size form 3.9m to 6.9m, and powered by 25hp to 75hp outboard engines.

Individual humpback whales were identified from photographs of natural markings on the ventral surfaces of their flukes (Katona et al., 1979). A 35 mm SLR camera, equipped with a motordrive or winder, and a 70-200 mm or 300 mm lens, was used to take the photographs. High speed black and white film was used in the camera.

Photographic comparisons were made with photographic collections of whales from southeastern Alaska and Hawaii (University of Hawaii, Honolulu, HI).

A resighting of a whale was confirmed when two or more photographs showed that the same black and white pattern on the flukes, the same trailing edge, and other distinctive markings were identical. Sightings of each whale during a given year were compiled and then added to the long-term sighting history of that whale or, if not sighted previously, a sighting history was initiated for that whale.

Photographs of the flukes were rated as "good," "fair," or "poor" quality, based on sharpness, contrast, and fluke angle. Poor quality photographs and photographs of the flukes of calves were excluded from analysis involving resighted individuals in estimates of population size.

A sighting matrix was developed from the sighting histories of individual whales for each of the primary study areas of Glacier Bay-Icy Strait, Frederick Sound, and Sitka Sound, as well as for the combined study areas in southeastern Alaska. These sighting matrixes summarized the numbers of adult humpback whales photo-identified each year, and this was the basis for the "capture-recapture" data analyses to estimate population size. The "recaptured" whales were those sighted and photographed in previous years, and the newly "captured" whales were those sighted and photographed for the first time in the given year. The sum of the resighted and newly sighted whales each year was equal to the total number of whales "captured" for that year. For each study area, the total number of newly sighted whales across all years was equal to the sum of individuals using the area.

The computer program JOLLY (available from James E. Hines, United States Fish and Wildlife Service, Patuxent Wildlife Research Center, Laurel, MD 20708) was used to compute open estimates of population size for each year and probability of capture across all years, using the sighting matrixes developed for each primary study area (Pollock et al., 1990).

The models available from program JOLLY are dependent on the assumptions of an open population (Seber, 1982). An open population model allows for changes in the population over the time of the study. The population is subject to birth, death, immigration, and emigration. Emigration is considered permanent, meaning once an animal leaves the population it is treated as a "death", and is considered a "new" animal if it enters the population again.

The reproductive status of females was determined from the presence or absence of a calf during one or more observations. Calves (animals less than one year old) were identified from their size (estimated length 4-8 m) and their close, consistent affiliation with the same adult whale, presumed to be the mother. Juveniles were whales one to five years old, whose age was determined from previous documentation of their birth year. Adults were whales known to be more than five years old, which is the age at which the majority of females have reached sexual maturity (Chittleborough, 1959; Clapham, 1992).

The reproductive rate was measured by determining the birth interval, which was defined as the number of years between observations with a calf for each female. Only females that had been observed every year between the years sighted with calves were used for this calculation.

Results

Distribution and Numbers of Whales

Numbers of whales observed through photo-identification

The sighting matrix developed for each primary study area provided information on the numbers of adult humpback whales photo-identified each year (Tables 1-4).

There were 119 adult humpback whales individually identified ("captured") in the Glacier Bay-Icy Strait study area, 372 in the Frederick Sound study area, and 275 in the Sitka Sound study area from 1985 to 1992. In the other study areas, 15 whales were individually identified in Chatham Strait, 12 in Lisianski Inlet, and 3 in Peril Strait. A total of 648 whales were individually identified in all of the study areas of southeastern Alaska during this period; this number does not equal the sum of individuals identified in all areas, because some whales were sighted in more than one area.

The sum of the sightings of individual whales identified in all study areas during 1985 to 1992 was 796. Of these, 500 (62.8%) were seen in one area only, and 296 (37.2%) were seen in more than one study area at least once, in the same year or different years, during 1985 to 1992. The percentage of whales sighted in one or more of the other areas ranged from 100% for Peril Strait to 28.5% for the Frederick Sound area (Table 5). This demonstrates that there is some fidelity to specific areas, although the extent of this fidelity is difficult to quantify due to unequal sampling effort across seasons and years in the study areas.

Numbers of whales estimated through capture-recapture methods

The yearly estimates of population size, standard errors, confidence intervals, and probability of capture, computed from program JOLLY, for the study areas of southeastern Alaska are presented in Table 6.

Seasonal Movements and Migration

Movement within southeastern Alaska

During 1985 to 1992, there were 92 whales that made 99 transits between study areas in southeastern Alaska, within

Table 1. Humpback whale sighting matrix for the Glacier Bay-Icy Strait study area in southeastern Alaska, 1985-1992.

TIME OF LAST CAPTURE	TIME OF RECAPTURE:								TOTAL # WHALES (Σ NEWLY CAPTURED)
	1985	1986	1987	1988	1989	1990	1991	1992	
1985	0	24	5	1	0	0	0	1	
1986	0	0	31	4	0	0	0	0	
1987	0	0	0	30	3	4	2	1	
1988	0	0	0	0	27	7	1	0	
1989	0	0	0	0	0	25	7	1	
1990	0	0	0	0	0	0	30	4	
1991	0	0	0	0	0	0	0	36	
RECAPTURED	0	24	36	35	30	36	40	43	
NEWLY CAPTURED	38	15	20	13	8	9	8	8	119
TOTAL CAPTURED	38	39	56	48	38	45	48	51	

Table 2. Humpback whale sighting matrix for the Frederick Sound study area in southeastern Alaska, 1985-1992.

TIME OF LAST CAPTURE	TIME OF RECAPTURE:								TOTAL # WHALES (Σ NEWLY CAPTURED)
	1985	1986	1987	1988	1989	1990	1991	1992	
1985	0	59	6	1	3	3	2	6	
1986	0	0	21	11	29	4	3	7	
1987	0	0	0	4	5	2	3	1	
1988	0	0	0	0	3	1	6	3	
1989	0	0	0	0	0	2	1	10	
1990	0	0	0	0	0	0	2	3	
1991	0	0	0	0	0	0	0	3	
1992	0	0	0	0	0	0	0	0	
RECAPTURED	0	59	27	16	40	12	17	33	
NEWLY CAPTURED	139	103	36	10	32	6	12	34	372
TOTAL CAPTURED	139	162	63	26	72	18	29	67	

Table 3. Humpback whale sighting matrix for the Sitka Sound study area in southeastern Alaska, 1985-1992.

TIME OF LAST CAPTURE	TIME OF RECAPTURE:								TOTAL # WHALES (Σ NEWLY CAPTURED)
	1985	1986	1987	1988	1989	1990	1991	1992	
1985	0	1	2	0	0	0	0	0	
1986	0	0	3	3	0	0	0	1	
1987	0	0	0	15	2	2	4	0	
1988	0	0	0	0	15	2	17	2	
1989	0	0	0	0	0	5	15	1	
1990	0	0	0	0	0	0	8	4	
1991	0	0	0	0	0	0	0	68	
RECAPTURED	0	1	5	18	17	9	44	76	
NEWLY CAPTURED	3	11	42	37	14	6	114	48	275
TOTAL CAPTURED	3	12	47	55	31	15	158	124	

Table 4. Humpback whale sighting matrix for all study areas in southeastern Alaska, 1985-1992.

TIME OF LAST CAPTURE	TIME OF RECAPTURE: 1985	1986	1987	1988	1989	1990	1991	1992	TOTAL # WHALES (Σ NEWLY CAPTURED)
1985	0	89	14	4	6	3	8	7	
1986	0	0	69	20	26	5	11	11	
1987	0	0	0	51	18	7	18	2	
1988	0	0	0	0	47	9	32	7	
1989	0	0	0	0	0	37	30	13	
1990	0	0	0	0	0	0	44	13	
1991	0	0	0	0	0	0	0	120	
RECAPTURED	0	89	83	75	97	61	143	173	
NEWLY CAPTURED	182	122	72	50	41	21	98	62	648
TOTAL CAPTURED	182	211	155	125	138	82	241	235	

Table 5. Number of humpback whales individually identified in each study area in southeastern Alaska, 1985-1992. Shown also are the number of whales seen in more than one area and the number seen only in one area during this period.

AREA	# PHOTO-IDENTIFIED	SEEN IN MORE THAN ONE AREA	SEEN IN ONLY ONE AREA
GLACIER BAY	119	71 (59.7%)	48 (40.3%)
FREDERICK SOUND	372	106 (28.5%)	266 (71.5%)
SITKA SOUND	275	95 (34.5%)	180 (65.5%)
CHATHAM STRAIT	15	10 (66.7%)	5 (33.3%)
LISIANSKI INLET	12	11 (91.7%)	1 (8.3%)
PERIL STRAIT	3	3 (100%)	0 (0%)
TOTAL	796	296 (37.2%)	500 (62.8%)

Table 6. Estimated annual population size for humpback whales in all southeatern Alaskan study areas, 1985-1992. Mean estimates of population size (N), standard error (SE), confidence interval (CI), and probability of capture (ρ), are shown from the appropriate Jolly-Seber capture-recapture model.

AREA	N	SE	CI	ρ (SE)
GLACIER BAY-ICY STRAIT	64	4.72	55-73	0.73 (0.03)
FREDERICK SOUND	379	55.99	270-489	0.18 (0.02)
SITKA SOUND	133	24.46	85-181	0.42 (0.13)
SOUTHEASTERN ALASKA	404	27.60	350-458	0.42 (0.03)

the same year. These 92 whales were included in the 296 whales observed in one or more study areas during 1985 to 1992 (Table 5), and compromise the subset that was observed in different study areas within the same year. This subset is used here to demonstrate seasonal movements within southeastern Alaska. Of these 92 whales, 86 made at least one transit, 4 whales made at least two, and one whale made at least three transits between study areas within the same year.

In general, there was a seasonal movement to the Frederick Sound area during late spring-early summer and mid-summer-fall. The seasonal movement in the fall and early winter was mainly to the Sitka Sound area and Lisianski Inlet.

Other observations showed the presence of the same whales across seasons in the same study areas. In 1985 and 1986 there were 21 whales that were sighted in the Frederick Sound study area during the summer and sighted later in the same study area in fall of the same year.

Length of stay on the feeding grounds

Between 1985 and 1992, one whale (#1073) remained on the feeding grounds 206 days. Whale #1073 was first sighted in 1991 in Icy Strait on June 3, next sighted in Sitka Sound on December 15, and last observed in Lisianksi Inlet on December 26.

Migration time to the Hawaiian mating and calving grounds

The shortest known migration time from the southeastern Alaskan feeding grounds to the Hawaiian breeding grounds was 39 days. Whale #339 was last seen in Sitka Sound on January 3, 1988 and was resighted by University of Hawaii researchers near the island of Hawaii on February 11, 1988. No other same year matches were found and whale #339 has not been sighted in southeastern Alaska since 1988. The migrational speed from Alaska to Hawaii, a distance of 4500 km, was about 4.8 km/hour and is 2 km/hour faster than any previously reported transit (Baker et al., 1985). The actual transit time probably was less because the whale probably was not photographed on the last day in Alaskan waters or on the first day in Hawaii.

Reproduction and Calf Survival

Birth intervals

From 1980 to 1992, a total of 136 of the photo-identified humpback whales in southeastern Alaska were identified as female. In that same period, these females were sighted with 222 calves. No female was seen with more than one calf per year.

To determine a birth interval, an individual female humpback whale must be seen in at least two different years with a calf. To remove ambiguity from the determination of birth intervals, the whale also must be seen every year between the years when sighted with calves. Of the 136 individual females, only 23 met that criterion.

For the 23 females with complete sighting records, 46 birth intervals were measured. These ranged in length from one to five years. The most frequent birth interval was 2 years (n=23), followed by 3 years (n=11), 1 year (n=8), 4 years (n=3), and 5 years (n=1).

Nine females with sufficiently long sighting records showed variation in birth intervals; three females were more consistent, and the rest were indeterminate. The most extreme case of variation was in whale #193, with two 4-year birth intervals, followed by two 1-year intervals.

For the 23 females with one or more completely documented birth intervals, the mean interval was 2.26 ± 0.71 SE years (n=46). That is, the adult females sighted in southeastern Alaska were accompanied by a new calf on an average of once every 2.26 years. Because these were calves that had survived their first oceanic migration from tropical or subtropical waters to southeastern Alaska, this is a conservative estimate.

Calf survival, recruitment, and return

Of the 222 calves observed from 1980 to 1992 in southeastern Alaska, 85 were successfully photographed for identification purposes from 1980 to 1991.

Of these 85 calves, 21 were resighted in southeastern Alaska as juveniles and adults. Because the maximum age at first resighting was 8 years, only the resightings of calves born in 1980 to 1984 qualified for calculation of the mean age at first resighting, and this was 4.0 years (SE=0.76, n=7).

Of the 21 calves that were resighted, 8 were observed when at least 5 years old, the presumed average age at sexual maturity but only two of them (#353 and #967), have been observed with calves. These were at ages of 8 and 12 years, respectively. Whale #353 was first resighted at age 3, and has been seen every year since then in Icy Strait. She bore her first calf at 8 years. Whale #967 was seen with a calf for the first time at the age of 12 years. Because the sighting record of this whale as an adult is not complete, her age at first birth is unknown.

The return of known-age whales to the feeding ground in southeastern Alaska, where they were first sighted as calves with their mothers, has been documented previously for three humpback whales (Baker et al., 1987). The return of 19 additional whales that were first sighted as calves is reported here for the first time. Two of these whales returned with their own calves.

Of the 21 calves that were observed to return to the southeastern Alaskan feeding ground, 11 were seen feeding as juveniles and adults near, but not with, their mothers. These observations were in areas where they were initially observed with their mothers as calves. This further corroborates the return of the same whales to the same subregion within a North Pacific feeding ground, as previously reported by Jurasz and Palmer (1981) and Baker et al. (1987).

Discussion

Distribution and Numbers of Whales

A considerable degree of fidelity to feeding areas has been demonstrated by this study. Nonetheless, for each of the three primary study areas, the total number of individual whales identified from 1985 to 1992 was nearly double the number observed in any given year. The difference between the 8-year total and the annual numbers could be due to 1) whales being missed, 2) whales failing to return every year, or 3) death. Death could not have been a major cause, as most of the whales did eventually reappear. We think fewer whales were missed in Glacier Bay-Icy Strait than elsewhere because of the comprehensive survey coverage, hence most of the "missed" whales simply did not return every year. This conclusion is supported by the fact that over half of the whales observed at least once in the Glacier Bay-Icy Strait area were seen also in the other study areas. This area may not be able to accommodate more than 60-70 whales per year, due to habitat limitations. These limitations could be due to prey availability, space, and competition with human or other marine mammal sources. In the Frederick Sound study area, where sampling effort was irregular, and the numbers of whales sighted per year fluctuated widely, we think a higher proportion of whales could have been missed during the sampling effort. The Sitka Sound study area had the most extreme annual variation in the number of whales and a marked increase in the number in 1991 and 1992. This was likely due to an influx of whales coming from other areas. Also some whales were missed because this area is difficult to study in the fall and early winter, when whale numbers are highest, because of inclement weather and limited daylight.

With any capture-recapture method used to estimate population size, it is important to consider the assumptions of the model and the effects of violations those assumptions. Equal probability of capture was the underlying assumption of these models that probably was violated. All whales did not behave in the same way when showing their flukes, hence were not equally identifiable. Furthermore, the distribution of whales was non-random, and the sampling effort was heterogeneous. Non-random distribution of whales was a problem in all study areas because some whales had a tendency to stay in one area and others moved around. There was not total mixing of the population between sampling periods. Heterogeneous sampling effort was a problem in the Sitka Sound and Frederick Sound study areas because Sitka Sound surveys were often prevented by inclement weather and rough seas, and the Frederick Sound area surveys were limited by irregular sampling effort among years. Not surprisingly, both these areas had somewhat low capture probabilities (<50%).

Violating the assumption of equal capture probability results in a negative bias and an underestimate of the population size. The magnitude of the bias is a function of sample size and the probability of capture. The higher the average probability of capture (over 50%), the less influence unequal capture probabilities have upon the estimate of population size (Carothers, 1973; Gilbert, 1973). The samples from the Glacier Bay-Icy Strait study area had the highest capture probabilities and most uniform sampling effort, hence population estimates for that area are probably less negatively biased than were those for the other study areas.

Seasonal Movements and Migration

The movements of whales in the Glacier Bay-Icy Strait area to the Frederick Sound area by late summer was strongly confirmed with 39 transits observed, only nine of which had been previously reported (Baker et al., 1992). A similar seasonal shift from other areas to Frederick Sound established that whales travel the inside waters of southeastern Alaska, rather than the more direct route, south of Baranof Island.

The seasonal movement from the summer to fall and early winter to the Sitka Sound area and Lisianski Inlet is a seasonal response to herring schools, which move in from open passages to overwinter in the deep, sheltered bays and sounds of southeastern Alaska. Sitka Sound and Lisianski Inlet are both areas where herring congregate in the fall and early winter (Larson et al. 1991). Half of the whales identified in Lisianski Inlet in the winter of 1991 had been observed earlier that year in at least one of the other study areas. One whale moved from the Glacier Bay-Icy Strait area, south to the Sitka Sound area, and back north to Lisianski Inlet. These fall and early winter movements into areas where herring overwinter have a major influence on the length of time spent on the feeding grounds by humpback whales. It is now apparent that many of the whales present during the spring and summer stay through late fall or early winter to capitalize on this energy-rich prey source, before their southward departure for the mating and calving grounds.

Earlier, Straley (1990) speculated that the whales present in southeastern Alaska during the fall and winter were late migrants--part of a staggered or irregular migration pattern, in which the whales that arrived early departed early, and these fall-winter animals reached southeastern Alaska later and returned later to the mating and calving grounds. With the shortest transit to Hawaii from southeastern Alaska being 39 days, and the longest length of stay in Alaska being nearly 7 months, a longer stay on the feeding grounds is possible than was thought previously. The duration on the feeding grounds may be especially long in years when food resources are abundant during the fall and winter. Humpback whales could stay on the feeding grounds for 8 to 9 months, leave in January, and still reach Hawaii in time for peak mating activities in February and March. This would still allow enough time to return to southeastern Alaska for the next summer's feeding season. The 7-month stay documented here is longer than any reported before, and the prospect of whales staying on the feeding grounds for up to two-thirds of the year is not unlikely.

Reproduction and Calf Survival

The average birth intervals for female humpback whales in this study did not differ from the previous estimate of one calf every 2 or 3 years. The data used to calculate birth intervals were all from females that had complete sighting records between births; that is, they had been observed every year during the intervals. Hence, there was no ambiguity in determining the number of calves between females for these females. Because many whales were not observed every year, however, a bias towards documenting the shorter, rather than the longer, birth intervals exists. This bias would lower the mean birth interval, or births would appear to be more frequent than they actually were. Another bias is introduced by the fact that what was recorded were the surviving calves that make it through the migration and to the feeding grounds, and not the actual birth interval observed on the mating and calving grounds. This bias would make the recorded birth intervals in this study more conservative than what they actually were.

There was considerable variation per individual female in the length of the birth intervals; some whales had regular and some had irregular intervals. Presumably, the minimal interval is one year, and all longer intervals are a function of the female's physical condition (Mizroch, 1983). That is, to maintain a pregnancy and nurse a calf, sufficient food must be found for at least one feeding season prior to conception and all through the pregnancy and lactation. In years when food is abundant, females can maximize their reproduction; in years when food is scarce, whales may move around more, searching for better food sources. Essentially, whale reproductive rates will vary as an adaption or in response, to changes in their environment (i.e., fluctuations in food availability). The females with the longest intervals between births may have had difficulty in fining adequate food and did not have sufficient energy reserves to ovulate, conceive, or nurse a calf until they rebuilt their energy reserves (Lockyer, 1986). The reasons for not building sufficient energy reserves could have been due to inexperience in finding food in lean years, or to a smaller body size; a larger body size gives a larger capacity to store more fat. The whales with less variable birth intervals may have been larger, older, and more experienced at finding food. Because humpback whales are long-lived animals, the need for producing offspring at frequent intervals is not as great as it is for other species with shorter life spans. Humpback whales have many years to produce calves, and they may not begin or complete a reproductive cycle until food availability is sufficient to allow them to store enough energy for reproduction. Ultimately, the success of different reproductive strategies for these females will be determined through documenting the survival of their offspring as juveniles and adults.

The return of whales whose ages were known, because they were first sighted as calves, continues to document maternally-directed fidelity to the feeding grounds in the North Pacific. In the North Atlantic, fidelity to the Massachusetts Bay feeding ground also has been documented (Clapham and Mayo, 1990). The return rate to Massachusetts Bay (37/46), however, was significantly greater than that to southeastern Alaska (21/85) (G-test, G=39.36, n=131, p=0.00; Zar, 1984). While this difference could be due to higher mortality, it could be attributed to more thorough sampling in Massachusetts Bay, compared with southeastern Alaska.

The average age at first birth has yet to be determined for North Pacific humpback whales. Given that the average age at sexual maturity elsewhere is 5 years the earliest average age at first birth would be 6 years, because a pregnancy lasts 12 months. Eleven of the whales in this study were 6 years old or older in 1992, and at least two of them were females. Only one of those females returned with a calf when the age at first birth could be determined, and she was 8 years old. Sexual maturity at 5 years may be the average age for North Pacific humpback whales, but whether any of them successfully conceive and maintain a pregnancy at this age is unknown.

The recovery of humpback whales in the North Pacific will only occur though an increase in the population.

Currently, we do not know the North Pacific population size of humpback whales in the North Pacific, the rate of calf survival, the age at first birth, or many other biological parameters for this endangered species. To assess whether the population of North Pacific humpback whales is increasing and recovering from exploitation, one of the foremost thrusts of future research should be to gather information on the life histories for whales of known age, especially females and their offspring, to document survival and reproductive rates. In southeastern Alaska, there have been few resightings of whales first seen as calves and later as juveniles and adults. How many of these calves area surviving and how many are recruited into the sexually mature population of reproducing adults is not yet known. This information will be of crucial importance for monitoring the recovery of humpback whales in the North Pacific.

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Variability in Counts of Individually Identified Humpback Whales in Glacier Bay and Icy Strait

by

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Abstract

The National Park Service has conducted a humpback whale monitoring program in Glacier Bay and Icy Strait since 1985. Annual monitoring counts of individually-identified whales are variable in Glacier Bay (range = 15-39), Icy Strait (range = 30-51) and both areas combined (range = 41-68). The bootstrap statistical method was used to evaluate the relationship between the number of surveys performed and the number of individual whales identified to: 1. determine the minimal and optimal number of surveys necessary for a valid, full-season (June 1 to August 31) whale count, and 2. determine whether the number of whales identified each year before 1985, when fewer surveys were conducted per year, are comparable with monitoring counts. Our results suggest that approximately 45 surveys are sufficient to generate a valid estimate of the number of different individuals whales using Glacier Bay and Icy Strait. Pre-1985 counts did not meet this criterion and are therefore not considered to be comparable to 1985-1992 monitoring counts of individually-identified whales. Further analysis of the bootstrap sampling distribution suggests that the optimal number of surveys performed is approximately 66. We infer from these results that the variability in 1985-1992 monitoring counts cannot be attributed to minor variations in survey effort, but instead reflects true variability in the number of whales present in Glacier Bay and Icy Strait.

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KEY WORDS. Whale, marine mammal, census, bootstrap, effort analysis, individual identification, Glacier Bay

Humpback whales migrate each year between summer coastal feeding grounds in high latitudes and winter breeding and calving grounds near islands or shallow banks in low-latitude waters. Known feeding areas in the eastern North Pacific occur along the rim of the Pacific basin from central California to the Aleutian Islands. Northern hemisphere humpbacks appear to form several geographically-isolated summer 'feeding herds' that congregate in low-latitude waters in winter (Baker et al. 1986; Katona and Beard 1990). The whales that use Glacier Bay and Icy Strait are considered to be part of the southeastern Alaska feeding herd, which was estimated to contain 404 humpback whales (mark-recapture 95% confidence limits 350-458) between 1985 and 1992 (Straley 1994). Straley (1994) estimated that 64 whales (95% confidence limits 55-73) visited the Glacier Bay - Icy Strait area each year between 1985 and 1992. Whales commonly move between Glacier Bay and Icy Strait within and between years (Perry et al. 1985; Gabriele 1993; Straley 1994), and related studies have shown movement between Frederick Sound, Sitka Sound, Chatham Strait and Glacier Bay - Icy Strait (Baker et al. 1986; Baker et al. 1992; Straley 1994). Temporal and spatial variability in the abundance and types of available prey appear to correlate with whale movement in southeastern Alaska (Krieger and Wing 1986; Straley 1994).

Humpback whales have been present in Glacier Bay since at least the 1930's (Vequist and Baker 1987). Vessel use of Glacier Bay began in the late 1800's (Bohn 1967), consistently increased throughout the twentieth century, then increased dramatically in the 1970's. Humpback whale studies began in Glacier Bay in the early 1970's, when Jurasz and his associates began identifying individual whales by their natural markings (Jurasz and Palmer 1981). In 1978, 16 of the 23 whales observed in Glacier Bay departed abruptly in mid-summer (Jurasz and Palmer 1981). Jurasz and others inferred that the whales had left because the level of vessel traffic had become intolerable, although other investigators hypothesized that the whales departed due to a decline in prey availability. Subsequent acoustic and behavioral studies corroborated aspects of each hypothesis (Baker and Herman 1989; Malme et al. 1982; Krieger and Wing 1986). The National Marine Fisheries Service recommended that the National Park Service (NPS) regulate vessel numbers and monitor whale numbers in Glacier Bay from June 1 to August 31 each year. Based on the number of whales and their temporal and spatial distribution, limits are placed on the number, speed and course of vessels in Glacier Bay.

The main goals of the NPS humpback whale monitoring are to determine the number of different whales in Glacier Bay and Icy Strait, to determine how many whales are 'resident' in the area, and to collect life history data including calving intervals and recruitment. Both the number of whales entering Glacier Bay and their duration of residency are important because they were components of the initial criterion for the whales 'premature departure' in 1978 (Jurasz and Palmer 1981). Beginning in 1985, we estimated the number of humpback whales using the area each summer as the total number of individuals identified in repeated surveys (range = 45-67 surveys) between June 1 and August 31. Previous surveys, however, were not conducted throughout the summer months and must be corrected for comparison with full season counts (Jurasz and Palmer 1981; Perry et al. 1985). Perry et al. (1985) defined a 'standardized period' of 9 July to 16 August to allow comparisons between counts in years in which there was not a full-season effort.

Given the considerable annual variability in the number of whales counted in Glacier Bay and Icy Strait between 1985 and 1993 (summarized in Gabriele 1993), and the use of these numbers in vessel management policy, it is desirable to investigate long term trends in whale numbers. In this paper we use existing whale identification data to determine the minimal and optimal number of surveys necessary for a full season count, to determine whether the 1982-1984 partial-season counts are comparable to full season counts and to investigate whether count variability might be attributable to inter-observer differences. Analyses such as this are important in evaluating the effectiveness of monitoring protocols and should be performed on all sampling methods, especially when long-term monitoring programs are to be implemented. Only after the reliability of the monitoring counts has been established can we begin to interpret trends in the data and attempt to account for the sources of variability.

Methods

Vessel Surveys: Surveys were conducted by NPS staff in Glacier Bay and Icy Strait between June 1 and August 31, in each year 1985-1992. Over the 8 years of this study, there were 3 different observers, each of whom had prior experience with humpback whale field research. Humpback whales were observed and photographed from a 17' Boston Whaler powered with a 50-60 hp outboard engine. The main

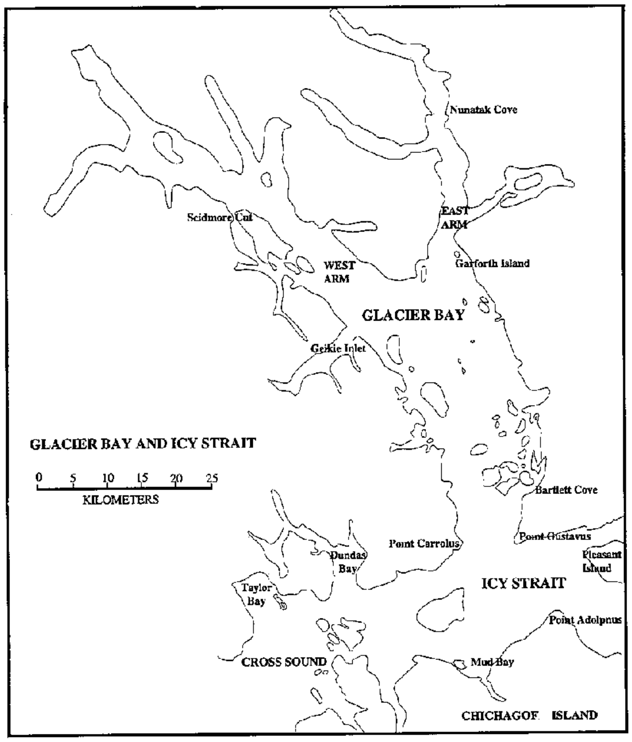

Fig. 1. Map of the study area, showing Glacier Bay and Icy Strait.

body of Glacier Bay (a rectangle defined by four corners: Point Gustavus, Point Carrolus, Geikie Inlet and Garforth Island) was usually surveyed three days per week. In accordance with Park policy developed by the Superintendent and Chief of Resource Management, surveys were not conducted in the same area on consecutive days in order to minimize the potential impact that monitoring efforts may have upon the whales. Surveys of the upperbay were conducted approximately bi-weekly or when whale sightings were reported by other vessels. Upper bay surveys extended as far north as Scidmore Cut in the West Arm and Nunatak Cove in the East Arm. Icy Strait surveys were performed approximately once per week, with the greatest survey effort in areas with the most whales, mainly along the shore of Chichagof Island from Mud Bay to Eagle Point, and the north and west shores of Pleasant Island. Although NPS whale management policies apply only to Glacier Bay, Glacier Bay and Icy Strait were both surveyed because the whales commonly travel between them and appear to use these contiguous areas as a single habitat.

Individual Identification: The ventral side of each whale's tail flukes have a distinct black and white pigment pattern that allows for individual identification (Katona et al. 1979; Jurasz and Palmer 1981). Whale flukes were photographed on ASA 400 black and white film using a 35 mm SLR camera equipped with a telephoto or zoom lens. Photographs of individuals were compared to previous Glacier Bay photographs and to available catalogs (Jurasz and Palmer 1981; Perry et al. 1985; Perry et al. 1988; von Ziegesar 1992) to determine the identity and past sighting history of each whale. Photographs from each year were examined to determine the number of different individuals sighted during the full season and the July 9 to August 16 standardized period (after Perry et al. 1985).

Data Analysis: A total of 2,074 sightings of individually-identified adult or juvenile humpback whales were entered into a computerized database. Calves are not included in these analyses because not all calves were individually-identified. Another database contained the dates of the 449 surveys performed during the monitoring program from 1985 to 1992, including surveys on which no whales were identified. The relationship between the number of surveys conducted and the number of individual whales identified per season was investigated in a bootstrap (Ephron and Gong 1983) statistical analysis. The survey database was sampled 1,000 times for each of ten levels of survey effort (x= 5, 10, 20, 30, 40, 50, 60, 70, 80 or 90 surveys) where the survey dates were randomly chosen (with replacement). The number of different individuals identified in each set of x surveys was recorded and descriptive statistics (mean, standard deviation, 95% confidence intervals) describing the number of individual whales were calculated and compared.

Results

A total of 119 humpback whales were identified from 1985 to 1992; 90 in Glacier Bay, and 99 in Icy Strait. Most were sighted in both areas. Total and standardized whale counts varied annually within the study period (Fig. 2). Total counts ranged between 41 in 1985 and 56 in 1992. Standardized counts ranged from 27 in 1985 to 51 in 1992. Standardized counts were a good index of full-season whale numbers (Spearman R = .9, $p < .05$), and accounted for an average of 77% (95% confidence intervals 73 to 82%) of the total count.

The relationship between the observer and the number of whales identified was investigated. The mean number of surveys conducted by each observer ranged from 48 to 62 (Fig. 3). The number of surveys performed depended on many factors, foremost of which was weather. The mean number of whales identified by each observer varied from 43 to 52. Because the sample sizes are small, statistical tests lack the power to detect potential differences among observers. However, it does not appear that the number of surveys per observer resulted in different numbers of whales identified (Fig. 3).

The bootstrap distribution of whale counts was curvilinear, and began to level out at counts greater than 45 surveys (Fig. 4). The mean number of whales counted in the bootstrap simulation increased about 10 whales for each additional 10 surveys from 5 to 40 surveys. At 50 and 60 surveys, the count increased an average of 3-4 whales for each additional 10 surveys, while at 70, 80, and 90 surveys, only 2 additional whales are counted for each additional 10 surveys. The maximal count for any set of surveys was 84 whales in 80 surveys. The points indicating actual survey effort and counts during the monitoring program fall well within the range of where the bootstrap curve begins to level off, suggesting that the monitoring counts of individually -identified whales were valid estimates of the number of whales in the study area (Fig. 4). In contrast, counts from 1982 to 1984 are located in the more steeply-sloping area of the bootstrap curve, suggesting that there was insufficient effort to consider these as full-season counts of whales in the Glacier Bay - Icy Strait area.

To determine the optimal amount of survey effort, we computed the difference between the mean number of whales counted in 90 surveys (64.2 whales, Fig. 4) and the mean number of whales for various numbers of surveys. The plot of that mean difference versus the number of surveys (Fig. 5) represents the theoretical effectiveness of a given number of surveys. The optimal number of surveys is defined here as that which provides a chosen level of effectiveness, while

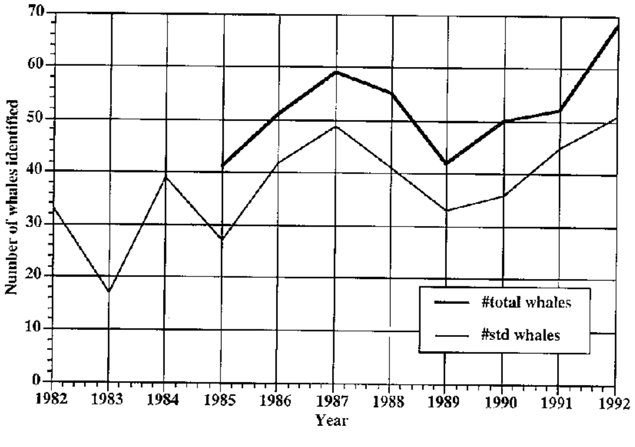

Fig. 2. Total count refers to the number of whales identified in Glacier Bay and Icy Strait between June 1 and August 31, 1985-1992. Standardized (std.) count includes only whales identified in the 'standardized period' July 9 to August 16, 1982-1992 (after Perry et al. 1985).

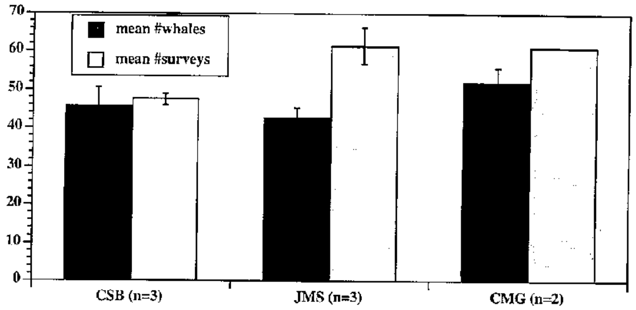

Fig. 3. Mean number of surveys and number of whales identified per observer, 1985-1992. Standard error bars are shown for each mean.

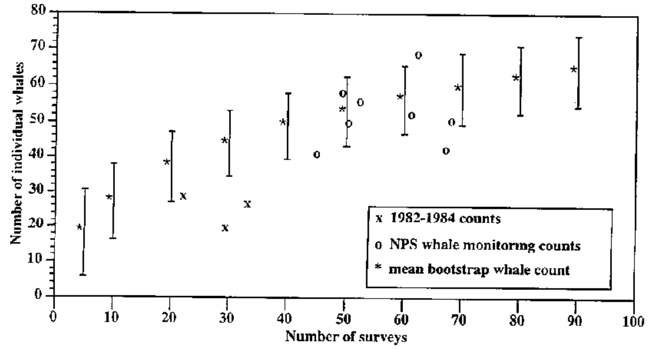

Fig. 4. Bootstrap simulation of whale counts with 95% confidence intervals.

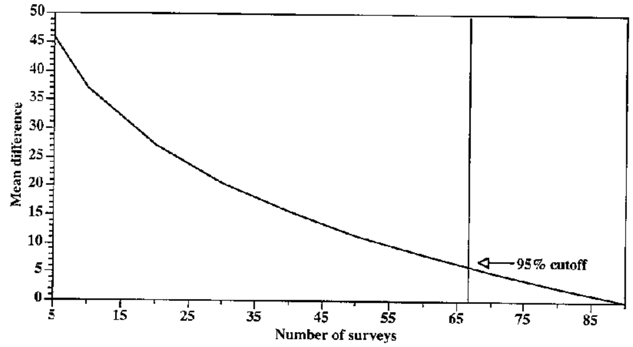

Fig. 5. Optimal number of whale surveys. "95% cutoff" at 66 surveys signifies that 95% of the area of the curve lies to the left of the line.

not sampling redundantly so that efficiency is reduced. We chose a criterion of survey effort yielding 95% effectiveness, and mathematically determined that 95% of the area under the curve (Fig. 5) lies to the left of a line drawn at approximately 66 surveys. According to this method of calculation, the optimal survey effort is 66 surveys. In order to obtain the remaining 5% of effectiveness, we would have to increase survey effort about 40%, from about 66 to 90 surveys.

Discussion

Our bootstrap analysis of individual humpback whale identification data suggests that a minimum of 45 surveys should be performed annually between June 1 and August 31 to generate a valid estimate of whales using the Glacier Bay - Icy Strait area. Each year within the humpback whale monitoring program has contained at least 45 surveys (Fig. 4), so the 1985-1992 monitoring effort has likely yielded a valid estimate of whale numbers. Combined with the lack of evidence of substantial inter-observer differences in effort or whale counts (Fig. 3), we conclude that the 1985-1992 monitoring effort produced reliable estimates of annual whale numbers. We infer that the variability in the counts in 1985 to 1992 (Fig. 2) was due to changing whale use of the Glacier Bay - Icy Strait area.

Our analyses also indicate that survey effort in 1982-1984 (Fig. 4) was insufficient for comparison to 1985-1992 full-season whale counts. In order for the 1982-1992 data to be considered as a single dataset, the standardized period would have to be used. Regression analysis indicated that the standardized count correlated well with the full-season count, which was not surprising because the standardized period generally encompasses the peak of the season. Variability in standardized counts appears to indicate variable whale numbers, however, standardized counts should probably only be used as an index of whale numbers because the proportion of the total count represented was variable.

According to the method we used to evaluate optimal monitoring effort, a substantial increase in survey effort would be necessary in order to make a theoretically 'complete' whale count (Fig. 5). Assuming that the bootstrap mean count for 90 surveys was the best indicator of the number of whales available to be counted, and setting our criterion at sampling 95% of this population, we determined that the most efficient survey effort would be approximately 66 surveys. Sampling at this level might yield optimally complete estimates of whale numbers but would be difficult to accomplish without violating Park policy regarding approaching individual whales on consecutive days and minimizing the possible impacts of monitoring on the whales. We therefore recommend that between 45 and 60 surveys per season would be the optimal balance of science and resource management.

The seasonal nature of whale presence in the study area does not appear to be particularly well modeled by the bootstrap. For example, because bootstrap sampling is done with replacement, the typical peak of the season (July and August) could be sampled more than would be possible in the real world. Thus, a certain number of surveys might be slightly less effective than is shown by the bootstrap counts, although the shape of the bootstrap distribution would remain the same (i.e. the minimal and optimal surveys would remain the same as those reported here). Other methods, mark-recapture in particular, could be used to evaluate the effectiveness of the surveys (e.g. Baker et al. 1992; Straley 1994). In one such study, mark-recapture estimates of the local population agreed closely with counts of identified individuals, and annual variability in Glacier Bay - Icy Strait population estimates were interpreted as an indication that in some whales did not visit the area every year (Straley 1994).

NPS concern over humpback whale management began under the assumption that intolerably high levels of vessel traffic would exert population-level effects on humpback whales, although other factors influencing whale numbers were poorly understood. The present study has shown that there is annual variability in the number of humpback whales in Glacier Bay and Icy Strait. We can now begin to evaluate factors that may influence these numbers, including vessel management, the distribution and abundance of whale prey, local movement of whales within southeastern Alaska and population parameters such as recruitment and female reproductive rates.

Accounting for variability in whale numbers suggests four avenues of study. First, quantitative monitoring of vessel noise in Glacier Bay and Icy Strait should be resumed and maintained in order to account for increased vessel traffic and to acquire sound signatures from newer vessels that were not using Glacier Bay during previous acoustic work (e.g. Malme et al. 1982). Although preliminary investigation suggests little relationship between vessel numbers and whale numbers 1985-1992 (NPS unpublished data), the potential effects of increases or decreases in vessel numbers merits continued study. Second, because whale distribution appears to be linked with whale prey availability (Krieger and Wing 1986; Straley 1994), sustained long-term studies of fluctuations in fish stocks and euphausiids should be conducted. Existing data and published work should be augmented with current information so that the duration and intensity of whale prey fluctuations can be quantified and predicted. Third, because the distribution of humpback whales in southeastern Alaska affects local whale abundance, it is important to understand whale movement within southeastern Alaska. A better understanding of whale movement could be accomplished with intermittent, synoptic photographic-identification projects in areas such as Stephens Passage, Frederick Sound, Sitka Sound and Chatham Strait, as well as expanding the work to previously unstudied areas. Fourth and finally, a continued effort to gather data on reproductive parameters of known individuals is essential. Calf return and eventual recruitment into the breeding population is particularly important because humpback whale feeding herds appear to be composed of individuals that return to their mother's feeding range (Perry et al. 1985; Baker et al. 1990; Straley 1994). Studies of reproduction are important because subtle vessel disturbance effects may influence long-term reproductive success (Baker and Herman 1989). Many studies on baleen whales have shown short term behavioral effects of human disturbance but have been unable to demonstrate effects on survival and reproduction, (see review in Richardson 1992). Long term monitoring of individual reproductive histories is possible using present methods, and important to monitoring the recovery of the humpback whale, which ultimately depends on individual reproductive success.

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Feeding Behaviors of Killer Whales in Northern Southeastern Alaska

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Abstract

Photo-identification studies of killer whales (*Orcinus orca*) were conducted from 1986 through 1993, primarily in the Glacier Bay - Icy Strait region of southeastern Alaska. Concurrent with these population studies, numerous observations of feeding killer whales were noted.

Killer whales were seen during every month of the year. In Glacier Bay and Icy Strait, 132 individuals were identified and classified into 15 different pods or groups. There was some indication that killer whales interacted with commercial and sport halibut (*Hippoglossus stenolepis*) fisheries. One instance of transient whales travelling in close proximity to a resident pod was documented.

Killer whales were observed interacting with fish (*Oncorhynchus* spp.), harbor seals (*Phoca vitulina*), Steller sea lions (*Eumetopias jubatus*), sea otters (*Enhydra lutris*), Dall's and harbor porpoise (*Phocoenoides dalli* and *Phocoena phocoena*), humpback whales (*Megaptera novaeangliae*), moose (*Alces alces*) and seabirds (*Mergus merganser, Mergus serrator, Melanitta nigra, Melanitta perspicillata, Rissa tridactyla, Brachyramphus mormoratus, Cepphus columbia, Phalacrocorax pelagicus, Gavia immer* and *Melanitta fusca*).

The killer whales' position at the top of the food chain may qualify these animals to be an indicator species of the health of the ecosystem in this region.

KEY WORDS. Killer whale (*Orcinus orca*), photo-identification, fisheries, feeding behaviors, indicator species.

Identification of individual killer whales (*Orcinus orca*) through photo-identification studies began in this area in 1984 (Leatherwood et al., 1984). Since the last Glacier Bay Science Symposium in 1988, research has intensified on the killer whales that are year-round inhabitants of southeastern Alaska. These studies have taken place primarily in northern southeastern Alaska, including Icy Strait and Glacier Bay.

A minimum population of 183 individuals utilizes all of southeastern Alaska as part of their range (Dahlheim and Waite, 1993). As industrial development in coastal areas increases, it becomes more imperative that we monitor the status of the whale populations that travel through and feed here.

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Research indicates that in the North Pacific there are at least two types of killer whales that form two distinct populations termed residents and transients (Bigg et al., 1987). Resident-types vocalize more and form larger, more stable pods of 10 to 50 individuals. From observational data it appears that resident pod members generally have more hooked dorsal fins and more black pigment inside the white saddle patch.

Transient-types form quieter, smaller, more fluid groups of 1 to 15 individuals. Observational data indicates their dorsal fins are broader-based and more triangular. They travel between southeastern Alaska and California (Goley and Straley, 1994), feed primarily on marine mammals, and are only photographed with other transients (Bigg, et al., 1987; Matkin, 1990).

The two resident pods (AF and AG pods) in the Glacier Bay - Icy Strait area travel between southeastern Alaska and Prince William Sound, eat fish, and are only photographed with other residents (Leatherwood, et al., 1984; Craig Matkin, pers. comm.; Matkin, 1990; Dahlheim, et al., 1993).

More recently, another type of killer whale (termed "offshores") has been described primarily off the west coast of British Columbia (Ford, et al., 1994). Although the characteristics of these whales are more similar to residents than to transients, they do not entirely fit into either category, and have not been photographed with either resident or transient groups.

This paper provides a summary of observations on the prey species and associated behaviors of killer whales feeding in northern southeastern Alaska. Killer whale interactions with the fisheries were assessed through opportunistic interviews to obtain baseline information on any problems for both whales and fishermen. Twenty instances of identified transient killer whales taking identified prey were quantified into the percent each prey item represented.

Methods

Photographs of the left side of the dorsal fin and saddle patch of individual whales were taken from 5- to 10-meter vessels at a distance of 10 to 20 meters. Black and white film (ASA 400 and 1600) was used with 35mm, single-lens reflex cameras equipped with motor drives and 300 mm, 200 mm, or 70-210 mm telephoto lenses. The film was exposed at ASA 1600.

Killer whales were classified according to an alpha-numeric system developed by the late Dr. Michael Bigg at the Pacific Biological Station in Nanaimo, British Columbia (Bigg et al., 1987; Ellis, 1987; Heise et al., 1992). Graeme Ellis (Pacific Biological Station) compared photographs for identification for this project from 1984 through 1990. The National Marine Mammal Laboratory staff analyzed the 1991 through 1993 photographs. An ongoing database of North Pacific killer whales is currently being catalogued at the National Marine Mammal Laboratory in Seattle and at the Pacific Biological Station in Nanaimo, B.C.

Reports from commercial and sport fishermen were followed up with more detailed interviews on an opportunistic basis. Observations of feeding behaviors were made from 1988 through 1993. Binoculars (or the naked eye when prey was close) were used to visually identify prey species. Prey remains were collected with a small-mesh net following some predation events. Transient predation on salmon (*Oncorhynchus* spp.) was determined from a photograph of the fish in the whale's mouth.

One harbor seal (*Phoca vitulina*) kill was confirmed by a video, one by collecting seal hair from the water at the site of a whale surfacing with a bloody carcass in its mouth, and one by observing a floating dead seal at an encounter site. All other harbor seal kills were determined from observations of whales repeatedly lobtailing on or carrying seals in their mouths.

One Steller sea lion (*Eumetopias jubatus*) kill was confirmed by a video and visual observation. The other two were from observations of the animal floating dead at the surface after attack by killer whales, and being taken below the surface by whales.

In two cases, animal fat was collected from the water after harbor porpoise (*Phocoena phocoena*) were observed in whales' mouths. Other predation on porpoise was based on their being closely followed within a few meters, thrown in the air or seen in whales' mouths.

One case of predation on seabirds was determined from photographs of birds in whales' mouths. The others were from visual observations of dead or maimed birds on the water or in whales' mouths.

Results

Sightings of killer whales were reported during every month of the year. Whales were photographed primarily in summer months (due to more research effort at that time), but data were collected from April through December. Whales were not photographed from January through March (due to less effort).

In this study, 132 individual killer whales were identified in the Glacier Bay - Icy Strait area, representing 15 different pods or groups. The two resident pods (AF and AG) combined totaled 54 individuals. The 64 transient individuals were categorized into 12 less stable groups. One pod (AP) is the offshore form. It was photographed once in the study area, and only 14 of the estimated 30 whales were ultimately photographed. They were not matched with any known resident or transient group.

There was some indication that AG pod interacted with the commercial and sport halibut (*Hippoglossus stenolepis*) fisheries. In September 1991 in Glacier Bay, AG pod was photographed a mile distant from a commercial longline set that sustained a small amount of damage to both fish and gear. One 40-pound halibut in the set had its spine severed at the tail. Another 40-pound halibut had two diagonal scrapes (about four inches apart) across the dark side of the length of its body. Both fish were unsaleable, but the fisherman never actually saw whales in his gear or next to his boat (Charles Clements, pers. comm.).

In October 1992, AG pod was photographed in Glacier Bay milling over a longline set that subsequently proved not only undamaged, but was one of the fisherman's best sets of the fishery opening (Patrick Sullivan, pers. comm.).

In September 1993 in Glacier Bay's Beardslee Entrance, a sport fishing charter captain observed an unidentified killer whale remove most of a meter-long halibut from his line. The killer whale approached within about 10 meters of the boat's stern to accomplish this (Clint Daly-Walker, pers. comm.).

Predation on other marine mammals by the resident AF and AG pods was not observed. Feeding observations on the resident AF and AG pods indicated they eat fish. In May 1993, two members of resident AG pod were seen feeding with about 10 Dall's porpoise (*Phocoenoides dalli*) in Icy Strait. Both species milled and porpoised rapidly together. The Dall's porpoise repeatedly swam back toward the killer whales as they herded small (unidentified) fish that occasionally erupted at the surface.

More commonly (N=3), resident pods fed on salmon. Associated behaviors with residents believed to be foraging for fish were travelling in a long line-abreast formation, breaking down into smaller sub-pods of 5 to 15 individuals, and rapid surface milling, particularly in tide rips. During these incidents, salmon were seen either in whales' mouths or jumping from the water next to whales.

Although they travelled and fed at different times in the same areas, resident and transient pods were never photographed commingling with each other. During an encounter in August 1992, two members of the transient AL group were documented following about 14 members of resident AF pod.

The transients, always keeping about 1/4 to one mile distance behind the residents, appeared to engage in the same behavior as the residents. They travelled, milled, rested and travelled in two separate groups for three hours. When travelling, the residents were in a line-abreast formation and were more surface active than the transients. Salmon were jumping throughout the encounter, but none were observed in whales' mouths.

Figure 1 presents the results of twenty incidents in which both the prey and the transient whales were identified. Predation on fish by a transient group occurred when AL group was documented (N=1) with salmon in their mouths. This represented five percent of all identified transient kills (Fig. 1).

Thirty-five percent (N=7) of all predation by transient groups was on harbor seals (Fig. 1). Six of those seven cases of harbor seal kills was by AL group, the remaining case by AH and AM individuals. The adult male T2 (AL 40), originally photographed as a British Columbia transient (Bigg et al., 1987), is a member of AL group. T2 was involved in two of AL group's six seal kills, and was not seen pursuing any other prey. He has been observed foraging alone or with one to five other members of AL group, and has been documented in the Glacier Bay area at least once every year since 1986.

The behavior of these transients in relation to harbor seals included percussive activity (Felleman et al., 1991). Whales repeated swimming by and hitting their tails on top of a harbor seal's head or throwing the seal into the air with their mouths. Occasionally the whales only rubbed their bodies against the seal instead of lobtailing on it as they passed by. The whales interacted with an individual seal between 5 and 25 minutes before taking it under the water surface for the final time.

On two occasions a single harbor seal escaped killer whale attack by climbing over the transom of a six meter long research boat for sixty and twenty minutes (respectively) while the whales cruised nearby. In the first incident, the whales did not approach the boat and may have been unaware of the seal's location (Scott Baker, pers. comm.). In the second incident, the whales were aware of the seal's location. They vocalized and approached the senior author's boat repeatedly, but stayed at least 10 meters away before leaving the area.

On two occasions, members of AL group captured a seal that was hovering near a boat and carried it underwater 8 to 40 meters away before releasing and continuing to interact with it (senior author and E.L. Sansum video). In another incident, a whale temporarily beached itself while swimming over a partially submerged reef, scaring nearby seals into the water (Anne Wakeford, pers. comm.).

Predation on Steller sea lions occurred in 15 percent (N=3) of observations of transient killer whale predation (Fig. 1). These included AH,AM and AO groups. Whales pursued sea lions by swimming very rapidly at the water surface. After singling out a sea lion, transients breached on it (Jan Straley, pers. comm.), threw it in the air with their mouths, took it underwater to drown it, or (when a sea lion was near dead) passed it to a female and calf to take down and eat.

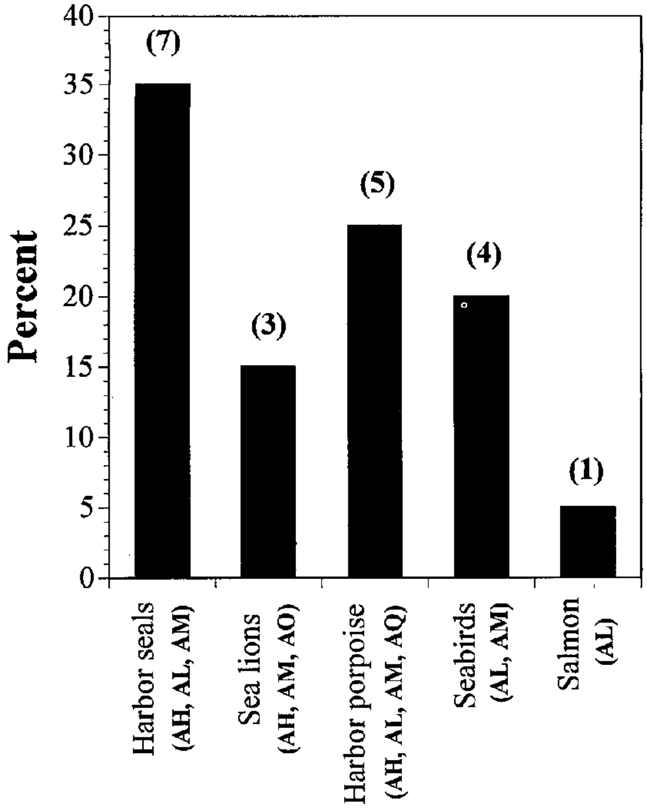

Fig. 1. Occurrence of predation on species taken in Glacier Bay and Icy Strait by identified transient killer whales. Sample sizes are in parentheses above bars. Killer whale pods are indicated in parentheses beneath bars.

Killer whales were never observed pursuing, killing or eating sea otters (*Enhydra lutris*), although they were frequently in the same general vicinity. Resident and transient whales did not alter their course to approach sea otters. If sea otters were floating in their path of travel (N=5), the whales went past or under them. A sea otter's presence was acknowledged only once as a member of resident AG pod spyhopped by inclining its head out of the water in the direction of a sea otter floating 30 meters away. The otter surfaced inside a nearshore kelp bed after the whales had passed.

Harbor porpoise represented 25 percent (N=5) of all transient kills (Fig. 1). These involved AH, AL, AM and AQ groups. Associated behaviors of the whales were surface milling, surrounding the porpoise, or hitting it into the air with their tail flukes or heads. Two AL individuals were observed slowly following a porpoise within a few meters for 45 minutes before consuming it. In a separate incident, a juvenile whale was observed carrying a skinned harbor porpoise in its mouth for 5 minutes before the porpoise disappeared.

We received no reports of humpback whales (*Megaptera novaeangliae*) being taken by killer whales in the Glacier Bay - Icy Strait region. Humpbacks usually (N=9) did not change their original behavior of feeding dives or direction of travel when killer whales were in the area. However, humpback whales occasionally (N=5) reacted to the passing of both resident and transient killer whales by breaching, pectoral fin slapping, lobtailing, tail swishing or swimming one-fourth to 3 miles away.

Killer whales can be a threat to humpbacks if they choose, however. In June 1990, a cruise ship pilot observed a group of three unidentified killer whales in lower Lynn Canal milling around and using their heads to push a humpback under water. The humpback was lying on its back, slapping the water with pectoral fins and tail flukes.

In September 1992, Jan Straley examined a humpback whale calf beached on the southwest side of Admiralty Island in Chatham Strait. A pod of unidentified killer whales had reportedly pursued a humpback whale calf in the area two weeks earlier. The carcass of the calf was bloated with 95 percent of its skin rotted off, but did not exhibit any visible signs of killer whale predation.

In June 1992, a pod of four unidentified killer whales consumed a moose (*Alces alces*) 1 mile off the south shore of Pleasant Island in Icy Strait, thus adding that species to the killer whale prey list (Michael Opp and John Barry, pers. comm.). The killer whales ate the larger of the two moose, and the smaller moose escaped into a nearby kelp bed where it later drowned.

Twenty percent (N=4) of all transient predation occurred on seabirds, only by AL and AM individuals (Fig. 1). Common and red-breasted mergansers (*Mergus merganser* and *Mergus serrator*), black and surf scoters (*Melanitta nigra* and *Melanitta perspicillata*) become flightless during their late summer molt. As these species rafted up for safety, killer whales chased them onto beaches or away from beaches, lobtailed and breached on them, caught them in their mouths, shook and ate them.

An AM female repeatedly carried a flightless black scoter in her mouth and released it in front of her calf (Mark Schroeder, pers. comm.). Juvenile black-legged kittiwakes (*Rissa tridactyla*) flying down to pick up small fish from the water's surface were consumed by unidentified killer whales that lunged out of the water to take the birds in their mouths (Jamie Coby, pers. comm.).

A marbled murrelet (*Brachyramphus mormoratus*) was thrown into the air with a whale's rostrum (Jack Swenson, pers. comm.). In another case, after a whale injured then abandoned a murrelet, another murrelet went up to 7 meters above the water surface when hit by a whale's tail flukes.

The unidentified whale then carried the bird to her calf, who tried unsuccessfully to catch it as it flapped along the water surface. This female repeated catching the murrelet and releasing it in front of her calf for about 30 minutes (Jim de la Bruere, pers. comm.).

Both resident and transient groups harassed seabirds including pigeon guillemots (*Cepphus columbia*), pelagic cormorants (*Phalacrocorax pelagicus*), common loons (*Gavia immer*) and white-winged scoters (*Melanitta fusca*). Whales milled around or released bubble trails under single birds, causing them to thrash at the surface and fly away.

Killer whales appeared to prolong kills before consuming (or sometimes abandoning) their prey. Whales sometimes breached, spyhopped, rolled, slapped their pectoral fins or tails on the water surface, rubbed against each other or engaged in sexual play. The functional significance of these behaviors prior to, during and after successful kills is unknown.

Discussion

This study represented a very small sample size (N=4 resident pod surface kills, and N=20 identified transient kills). It occurred in the northern part of southeastern Alaska (primarily Icy Strait and Glacier Bay) during summer and fall months. It mainly documented the prey and feeding behaviors of resident AG pod and transient AH, AL, AM, AO and AQ groups.

The total of 132 individuals identified in this area may be considered a low count. New individuals were photographed every year and researchers were not always able to photograph every individual during some encounters. Other population studies in southeastern Alaska indicated higher numbers. The National Marine Mammal Laboratory photo-identified 183 individual killer whales in all of southeastern Alaska (Dahlheim and Waite, 1993). This total included the 132 individuals in the Glacier Bay area.

Resident AF and AG pods have been photographed in Prince William Sound 10 times, five involving AF and five involving AG (Leatherwood, et al., 1984; Craig Matkin, pers. comm.; Dahlheim, et al., 1993). While there, these pods were sometimes photographed with a Prince William Sound resident pod (AB pod) that is habituated to stripping commercial longlines of their fish. Bullet wounds on some AB whales indicated that some individuals in AB pod may have been shot by fishermen (Matkin, et al., 1987). To date, killer whales in southeastern Alaska have exhibited no apparent bullet wounds in contrast to those seen in Prince William Sound and the Bering Sea (Dahlheim and Waite, 1992).

The commercial longline fishery in the Glacier Bay area was only open for a 24- to 48-hour period one to three times a year. Although AG pod was the most frequently photographed pod in this area (N=29 from 1983 through 1993), it appears that interactions with the commercial fishery are not significant at this time. Future monitoring may indicate if whales become habituated to the sport fishery that is open (and fished intensively) every day of the summer months and is only closed in January.

The diet of the smaller transient groups is more varied than that of the residents. During the single encounter with transients following residents, the transients were never seen with fish in their mouths. It is possible that the transients were taking advantage of the larger resident pods' ability to herd and catch salmon (Baird et al., 1992), however these interactions appear to be extremely rare. Studies in British Columbia indicated that transients generally ignore both residents and fish (Ford, et al., 1994). Some Prince William Sound transient whales feed occasionally on fish, but primarily on marine mammals (Matkin and Saulitis, 1994).

The extent to which transients eat fish is a question that presents considerable challenge and controversy. Fish consumption may take place without as much aerial activity as marine mammal and seabird kills. It may involve more subtle behaviors, and therefore be more difficult to document without examining whale stomach contents. This may have resulted in a bias in the data in that marine mammal and seabird predation was easier to detect.

Harbor seals are a relatively abundant and dependable food source. Particularly in summer months, they concentrate to give birth in key areas in Glacier Bay and travel throughout the Bay. The repeated 8-year presence of transient whale T2 (AL 40) in this region may suggest that this is one of several important feeding areas for AL group.

Although the data indicated that harbor seals were the most frequently taken prey for AL group (Fig. 1), in a period of a few hours they pursued and ate harbor porpoise and salmon, then attacked a marbled murrelet (senior author and Jack Swenson, pers. comm.). This demonstrated a measure of flexibility in transient eating habits (Felleman et al., 1991). Harbor seals occasionally made attempts at defending themselves. However, they did not exhibit the ability to fight back that was observed in sea lions (Baird and Stacey, 1988) or the rapid escape maneuvers of porpoises. Harbor seals appeared to be more easily captured by killer whales.

Killer whale pods did not take advantage of every kill opportunity presented to them. The dense fur, lack of much body fat and membership in the malodorous weasel family (*Mustelidae*) are suggested as reasons that killer whales do not readily prey on the abundant sea otter (Jefferson et al., 1991).

The first observations of killer whale predation on Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) in southeastern Alaska occurred in April 1992 (Dahlheim and

Towell, 1994). Sightings of these dolphins have increased in the past few years, particularly in nearshore waters of southern southeastern Alaska. This provides another food source for transient whales that tend to forage nearshore.

Humpback whales were available particularly in summer months. Their ability to fight attackers with their powerful tail flukes and long pectoral fins may deter killer whales from expending the energy that would be necessary for an attack. However, a swimming moose is a more helpless prey item, and the attack described here illustrates the killer whale's ability to be an opportunistic predator.

Further investigations will seek to illuminate the role seabirds play in the killer whale's life. Do seabirds represent significant biomass in the transient killer whale's diet? It has been suggested that predation on birds is energetically inefficient for the whales (Stacey et al., 1990; Williams et al., 1990). However, there may be the benefit of improving hunting skills through play behavior particularly since initial observations indicate it primarily involves females and juveniles. Behavior that appears as malicious or playful may actually be a learning experience that helps family members to survive (Martinez and Klinghammer, 1970).

With the exception of seabirds, the transient diet presented in Figure 1 is similar to results of other studies. Ford, et al. (1994) reported British Columbia transients primarily killing harbor seals, followed by porpoise and sea lions.

The data indicated that transients usually consume prey that is higher up on the food chain than residents' prey. Environmental contaminants are known to accumulate and concentrate in marine mammals. Researchers examining tissues of killer whales stranded in Washington, British Columbia and Alaska found high levels of toxic chemicals such as mercury, DDT and PCBs, some of which are thought to cause reproductive problems in other species (Calambokidis et al., 1990). Killer whales are already considered to have a normally low reproductive rate (Olesiuk et al., 1990).

Resident AF and AG pods' ranging to Prince William Sound may place them at risk of coming into contact with the effects of the 1989 *Exxon Valdez* oil spill or of future spills. This could occur by having offspring with a contaminated Prince William Sound pod such as AB pod that came in direct contact with the crude oil and subsequently lost 14 members (Matkin, et al., in press).

National Marine Fisheries Service has photo-identified only 717 killer whales in Alaskan waters from southeastern to the Bering Sea (Dahlheim and Waite, 1993). This is not a large population, considering it was thought there were thousands here before photo-identification techniques recently allowed accurate minimum counts to be made.

Long-term year-round monitoring of the population numbers of these uniquely identifiable whales may allow us to use them as an indicator species to monitor the health of the Alaska marine ecosystem in the future. Radical drops in numbers, changes in feeding patterns or use of their range may indicate problems in the environment. Reproductive and death rates of these whales could be compared over time and to whales in other regions.

The known and the unknown about killer whales adds an immeasurable dimension of wonder and quality to the areas they choose to inhabit. Maintaining an unpolluted ecosystem through education, industrial regulation and protective legislation will help these whales and their prey to survive.

Acknowledgments

From 1986 through 1988, photographs were taken by Glacier Bay National Park biologists Dr. Scott Baker and Dena Matkin as part of an ongoing humpback whale monitoring project. Since 1988,photographs were taken by Dena Matkin, Jan Straley, Chris Gabriele, Jack Swenson, Mark Schroeder and Anne Wakeford.

Bill Shadley provided most of the winter sightings and assisted in many photo-identification encounters. Two videos (one harbor seal kill and one sea lion kill) were contributed by E.L. Sansum, and Bruce and Karla Tedtsen respectively. Other identifications of prey species for Figure 1 were reported by Jan Straley (sea lion), Jack Swenson (salmon and seabird), Mark Schroeder (harbor porpoise and seabird), and Anne Wakeford (harbor seal). The remainder of prey species for Figure 1 were identified by Dena Matkin. All behavioral observations were made by Dena Matkin except where noted in the text.

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Long-term Trends in Abundance of Harbor Seals *(Phoca vitulina richardsi)* and Development of Monitoring Methods in Glacier Bay National Park, Southeast Alaska

by

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Abstract

Harbor seals in Glacier Bay National Park use more than 20 different land haulouts during summer months, and they are found in large numbers in a tidewater glacial fjord where they are widely dispersed on ice bergs. The use of two very different haulout substrates, and the large area over which seals may be found, have precluded parkwide counts of seals in the past. In 1992 counts of seals in a glacial fjord from land and counts of seals at land haulouts from aerial photographs were used to census harbor seals throughout Glacier Bay. The sum of mean daily high counts of seals in the Bay in August, 1992 was 5,982. At least 70% of the seals were found in Johns Hopkins Inlet, making this tidewater glacial system one of the largest documented breeding aggregations of harbor seals remaining in Alaska. Eighteen percent (1,090) were counted at the Spider Island reefs, the second largest haulout area in the Park and the largest land haulout. To assess the relative accuracy of aerial photographs compared to low-level counts, mean counts from land were compared to counts from aerial photographs of seals at Spider Island. Land-based counts from the low-level site were, on average, 51% (44%-61%) of counts from simultaneous photographs. To assess long-term trends in harbor seal abundance in Johns Hopkins Inlet, I compared the mean of daily high counts from the mid-1970s (Streveler 1979), from 1984 (Calambokidis, unpubl. data), and from my team's 1992/93 counts. The mean count from the early 1990s was significantly higher than that from the mid-1970s, however no change was detected between August 1984 and the early 1990s. These results indicate that the increase in seal numbers in Johns Hopkins Inlet occurred between the latter half of the 1970s and 1984. The proportions of mother/pup pairs in Johns Hopkins Inlet and Icy Bay (both glacial fjords) were higher than at the Spider Island land haulout and they appear to be higher than at land haulouts worldwide. Ice habitat generated in tidewater glacial fjords is important and ephemeral habitat for pupping and nursing harbor seals.

KEY WORDS: harbor seal, *Phoca vitulina,* censusing, pups, Glacier Bay, abundance, minimum population estimate (MPE), tidewater glacier.

Harbor seal *(Phoca vitulina richardsi)* numbers in parts of Alaska have declined by as much as 86% (Pitcher 1990), and this trend approximately parallels the unprecedented declines in northern sea lions *(Eumetopias jubatus)* in the central Gulf of Alaska and areas to the west (Braham, et al. 1980, Merrick, et al. 1987, Loughlin, et al. 1992). Similar declines are not evident for either pinniped species in Southeast Alaska (Hoover-Miller 1994) where there is some evidence of an increase in sea lion numbers (Loughlin, et al. 1992). However, census data for harbor seals in parts of Southeast Alaska have been considered inadequate for rigorous trend assessment (Hoover-Miller 1994). To address this limitation, I began working to standardize census methods in Glacier Bay National Park in 1992, and in 1991 the National Marine Mammal Lab (NMFS) initiated a three year study to determine minimal population estimates (MPE)

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for harbor seals throughout Alaska (Loughlin 1992, 1994).

Johns Hopkins Inlet in Glacier Bay has one of the largest documented breeding aggregations of harbor seals in Southeast Alaska (Calambokidis et al. 1987), and it may have one of the largest remaining groups of harbor seals in the State (Hoover-Miller 1994; Mathews 1992). However, between 1988 and 1991 harbor seal numbers in Johns Hopkins Inlet appeared to decline (Hoover-Miller 1994). I believe that this apparent trend was the result of non-standardized monitoring, rather than a real decline. Because harbor seal numbers have declined significantly in other parts of Alaska, the development and long-term use of standardized methodology to survey such a large group of harbor seals in a national park is of particular importance.

Harbor seals in Glacier Bay use more than 20 different land haulouts during summer months, and they are found in large numbers in Johns Hopkins Inlet, a tidewater glacial fjord where they haul out on ice bergs. The use of two very different haulout substrates, and the large area over which seals may be found, have precluded Parkwide counts of seals in the past.

In 1992 I received support from the National Marine Mammal Lab (NMFS, Seattle) and Glacier Bay National Park to conduct aerial surveys of land haulouts and land-based counts in Johns Hopkins Inlet for a Parkwide estimate of harbor seals. This paper summarizes the results of these surveys and the field work and describes other aspects of the development of harbor seal monitoring in Glacier Bay, including a comparison of the effectiveness of aerial photography of seals at land haulouts and counts from low-level sites on land.

Periodic studies of harbor seals in Glacier Bay spanning 20 years provide valuable information on numbers, reproductive timing, diurnal patterns, and other aspects of seal biology and behavior (Streveler 1979, Calambokidis et al. 1987, Mathews 1992, and unpublished NPS reports), including the effects of vessel traffic of seals resting on ice bergs (Calambokidis et al. 1983). To evaluate long-term trends in Johns Hopkins Inlet, where data from several years and from comparable studies were available, I compared census data collected during the mid-1970s (Streveler 1979), 1984 (Calambokidis, unpublished data), and my own work in 1992 and 1993 to determine if detectable changes in seal numbers had occurred.

As an index of the importance of an area as breeding habitat, proportions of pups in Johns Hopkins Inlet were determined using two different methods from land. In 1993 I also began developing a third method using aerial photographs to estimate pup proportions. An advantage of the aerial method is that the proportion of mother/pup pairs can be estimated even in areas where accurate counts cannot be made from land or air.

Methods

Study Areas

The two areas of focus for the work in Glacier Bay (58°N, 138°30'W) were Johns Hopkins Inlet and the Spider Island reefs (Fig. 1). Aerial surveys for seals at 40 previously-documented land haulouts in the Bay were conducted in 1992. In my summary of previous work on harbor seals I refer to counts conducted in Muir Inlet (Fig. 1). Located on the east side of Glacier Bay, Muir Inlet is a glacial fjord which was used by at least 1,300 harbor seals for pupping and molting during the 1970s (Streveler 1979). In the last decade Muir glacier has retreated, producing fewer and fewer icebergs. Pup proportions were estimated in both Johns Hopkins Inlet and in Icy Bay (50°N, 141°50'W), another tidewater glacial system located about 400 km northwest of Glacier Bay and adjacent to Wrangell-St. Elias National Park. Harbor seals are also found in Park waters along Icy Strait and the outer coast; however, these areas were not included in this study.

Censusing Methods: Counts from Land

In June and August 1992, a team of observers counted seals in Johns Hopkins Inlet and at the Spider Island reefs from land, but in 1993 only Hopkins Inlet was monitored. In the fjord we counted from an elevated site (~100 m), whereas the Spider Island teams counted from a site about 5 m above mean high tide on a small island located approximately one kilometer west of the haulouts (Fig. 1). In both areas, two observers simultaneously counted seals using 60 mm spotting scopes (Bausch and Lomb, 15X - 60X zoom; Swift, 20X) and three-digit counters.

The highest numbers of seals in Johns Hopkins Inlet are typically observed around midday (Calambokidis et al. 1987). Accordingly, two to four paired counts were made each day with at least one paired count within two hours of noon. For the June counts, seals were categorized as adults or pups. In August, no age class distinction was made, because older weaned pups are difficult to distinguish from adults at a distance. In 1992 we counted seals on June 16-18, July 18-20, and August 20-23, and in 1993 on June 13-17 and August 22-24. Only the June and August counts were used in this study, and only the August counts were used for the minimal population estimate, since this is when seals molt and spend more time out of the water (Calambokidis et al. 1983).

In Johns Hopkins Inlet, seals are typically dispersed over an area of more than four to six square kilometers, making systematic coverage with a spotting scope difficult. Beginning in 1992 I placed four vertical poles in a semi-circle in front of our observation site so that they divided our field of view into five subsections (Fig. 2). As a subsection pole came into view, the scope was carefully lowered one field height, tightened, and moved back in the opposite direction. This approach reduced the average coefficient of variation between observers from 24% (N=4) to 17% (N=7) (Mathews 1992).

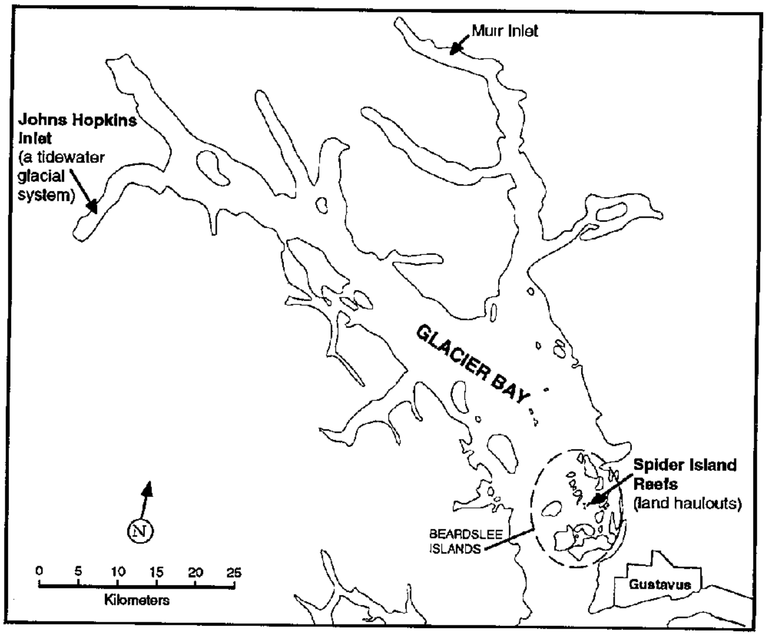

Fig. 1. Map of Glacier Bay, Southeast Alaska showing the two main study sites, Johns Hopkins Inlet and the Spider Island area in the Beardslee Islands.

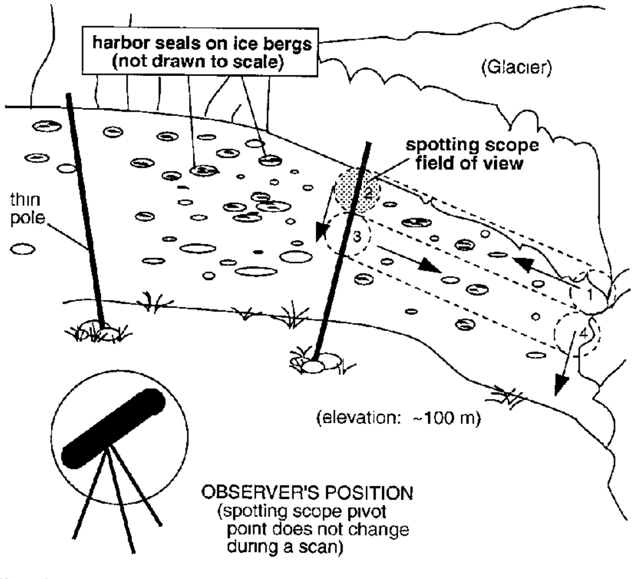

Fig. 2. Systematic scanning method using vertical poles for counting harbor seals on ice bergs in Johns Hopkins Inlet.

About 40 land haulouts have been documented in Glacier Bay since 1975 (Streveler unpublished data; Lentfer and Maier 1989; Mathews 1992). Currently about 20 haulouts are known to be regularly occupied in August (Mathews 1992 and *in* prep.), and over half of the seals observed at land haulouts during the August 1992 survey were found on the reefs and low islands to the south and west of Spider Island, in the Beardslee Island Wilderness area (Fig. 1). Aside from the counts in Johns Hopkins, all land-based counts were of seals in the Spider Island area. Because the observation site for Spider Island was not elevated, as it was in Johns Hopkins Inlet, the land-based method used in the Spider Island counts is considered different from, and inferior to, that used in Johns Hopkins Inlet. For the Spider Island censuses, two observers counted seals from an island approximately 1-2 km from haulouts. Beginning about two hours before low tide, paired counts were conducted until about two hours after low tide. Because counts took much less time (mean = 8 min) at the Spider Island site than in Johns Hopkins Inlet (mean = 73 min) more counts were conducted. In 1992 an average of 20 counts per day were made on 14 days.

Counts from Aerial Photographs

In 1992 two of six aerial surveys of Glacier Bay were flown in August during the molt, when highest numbers of seals at land haulouts are predicted (Calambokidis et al. 1983). No aerial surveys were conducted in 1993 due to a lack of funding. Counts from the August flights over land haulouts were used in conjunction with land-based counts in Johns Hopkins Inlet to determine a minimal population estimate (sum of high counts from all areas) for the Bay and to estimate a mean daily high count (Mathews 1992). During the flights, I attempted to photograph all known haulouts and to search for undocumented haulouts; however, heavy fog prevented surveys over several haulouts in the east arm of the Bay. The absence of seals at a known haulout was also noted.

When surveying the Beardslee Islands (Fig. 1), where the majority of the land haulouts including Spider Island are located, we flew a grid pattern at about 1000 feet. Once seals were spotted the pilot gradually dropped to 700 - 800 feet and began a wide loop around the haulout. Seals were photographed through an open window, using an Olympus OM 2S camera with an 80-200 mm zoom lens, motordrive and databack. Photographers used color slide film rated at 200 or 400 ASA and shot at shutter speeds between 1/250 and 1/1000 second. Location, time, altitude, and frame numbers were recorded for each occupied haulout, and we also noted whether haulouts were unoccupied or not checked. Groups of seals at all haulouts were small enough to fit in one frame, except the Spider Island reefs where a series of overlapping photographs were taken. The two best slides (or series) for each haulout were projected onto white paper so that seals could be marked and counted. The slide with the higher count was used in the Baywide estimate (most slides differed by fewer than four seals).

During the three flights over Spider Island on August 27 and 28, two observers made one or two paired counts from land within 15 minutes of when I photographed the haulout from the air. The mean value of the paired counts from the land observers was used to determined what proportion of the seals were detected by land observers (= count from land/count from aerial photograph).

Methods: Proportions of Pups

The proportion of pups (= pups /(pups + adults)) during June was estimated for seals at the Spider Island reefs, in Johns Hopkins Inlet, and in Icy Bay using one or two of three different techniques. The first method was simply to count all visible seals from land and to categorize each animal as either an adult or a pup. One problem with this approach, especially in Johns Hopkins Inlet where animals might be more than a mile away, is that pups in the distance are more likely to be missed than pups close by. To determine if this might be a problem, I experimented with a second technique in 1992 (Mathews 1992) and 1993 in which we categorized seals which drifted close enough to our observation site that we could reliably see and distinguish pups if they were present.

From June 15-17, 1993 we categorized subsets of 100 seals approximately every two hours from 07:00 to 21:00. One of the new observers consistently overestimated pups compared to the most experienced observer, so these estimates were not used. For this analysis, I assumed that mother/pup pairs were randomly distributed across the ice. However, age/sex segregation of harbor seals has been documented at land haulouts (Kovacs et al. 1990) and on glacial ice (Hoover 1993), so some counts may have been biased high if they happened to occur in these 'nursery' areas. We conducted subset counts throughout the day, during which large tidal and wind-driven movements of the ice occurred. Our pup proportions were similar to those from other glacial fjords (Figure 3). Consequently, the effects of segregation of mother/pup pairs on the average pup proportion was assumed to be minimal, although it may increase variance. Tests of this assumption will be made by comparing land-based pup proportions with those derived from aerial photographs (described below).

A third method was developed to estimate pup proportions of large aggregations of harbor seals where access to elevated overlooks or funding for land-based surveys is limited. This technique was first used in Icy Bay. During the June 15, 1993 flight over Icy Bay, the observer took a series of 170 non-overlapping photographs. Five rolls of color slide film (ASA 200 or 400) were used. To evaluate pup proportions from the aerial photographs, seals resting on ice bergs were scored as adults, pups, or unknown by viewing the slides with a dissecting microscope. Due to low light levels, the overall quality of these slides was low. However, 112 to 250 animals per roll could be evaluated. To derive a minimum estimate of pup proportions for Icy Bay, pup percentages were determined for each of the five rolls of film. A mean proportion for the one survey day was then calculated by averaging these five values (Fig. 3). Further development and improvement of this technique is underway.

To assess the relative importance of glacial fjords as pupping and nursing areas, I also compiled information on pup proportions at land haulouts (listed in Olesiuk et al. 1990) and at Aialik Bay, another glacial fjord (Hoover 1983). Table 1 and Figure 3 summarize the proportions of pups observed in these studies.

Streveler (1979) used three different observation posts to accomplish his counts of seals in Johns Hopkins Inlet. Thus, I considered his method more similar to that of our counts of 100 nearby animals. Three comparisons of mean pup proportions were made: 1) Johns Hopkins counts of all seals and counts of subsets of 100 nearby seals, 2) the mean values of counts in Johns Hopkins by Streveler for 1975-78 and nearby subsets in 1993, and 3) Johns Hopkins counts of all seals and low-level counts of the Spider Island haulouts. Mann-Whitney U tests were used to analyze each of the three pairwise comparisons.

Harbor Seal Trends, 1975-1993

One of the problems with analyzing data from the 12 different years in Glacier Bay when seal counts were made is that the effort (number of counts and days), observer experience, and haulouts examined vary considerably from study to study. To partially control for this, I only compared data collected by experienced or trained observers who worked in Johns Hopkins Inlet, since this is the main site within Glacier Bay which was examined in multiple years. I compiled count data from Streveler (1979), Calambokidis and coworkers (1987 and unpubl. data) and my teams (1992 and 1993). Mean values of the daily high counts for each study (June 1975-1978; August 1984; June and August 1992 and 1993) were averaged for each month and 'decade' (Table 2). Pairwise comparisons of means (Mann-Whitney U test) were made for the following datasets:

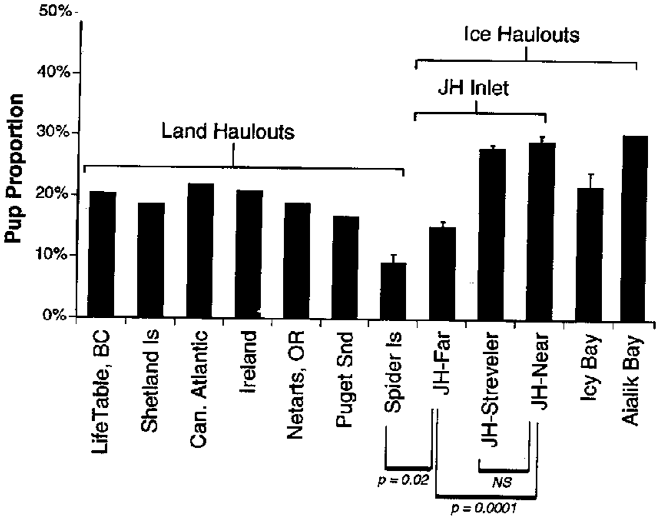

Fig. 3. Proportions of pups at haulouts in Glacier Bay and Icy Bay, Southeast Alaska (data from this report), at land haulouts worldwide (cited in Olesiuk et al. 1990), and at Aialik Bay, another glacial fjord in Alaska (Hoover 1983). Median values are plotted for published data presented as a range. (Mann-Whitney U tests; NS=not significantly different).

1) June 1970s to June 1992/93; and 2) August 1984 to August 1992/93 (Fig. 4). June counts occurred during the pupping season, whereas the August counts occurred during the molting period. Comparisons of counts from different months in different years were not made, although this would be feasible if appropriate correction factors were verified for this study site (Olesiuk et al. 1990)

Between 1973 and 1978, Streveler counted harbor seals in Muir Inlet in June. He also surveyed Johns Hopkins Inlet from 1975 to 1978 (Streveler 1979). To evaluate whether or not the increasing numbers of seals using Johns Hopkins Inlet might have come from Muir Inlet, I plotted data from Streveler's counts and analyzed for trends in years for which there were counts in both inlets (1975-78) (Spearmans Rank Correlation) (Fig. 5).

Table 1. Comparison of the proportion of pups at ice and land haulouts reported in this paper and from three other studies (Streveler 1979, Hoover 1983, and Olesiuk et al. 1990)

GLACIAL FJORDS				
Glacier Bay:	**Method Used (Researcher)**	**Mean %**	**SD**	**N**
Johns Hopkins Inlet	1) All Seals (Mathews)	15%	3.8	13
Johns Hopkins Inlet	2) 100 Nearby (Mathews)	29%	6.0	28
Johns Hopkins Inlet	1) All Seals (Streveler 1979)	28%	2.2	13
Icy Bay, Alaska	3) Aerial Photographs (Mathews)	23%	5.0	5
Aialik Bay, Alaska	1) All Seals (Hoover 1983)	22 - 39%		
LAND HAULOUTS				
Glacier Bay:		**Mean %**	**SD**	**N**
Spider Island Reefs	1) All Seals (Mathews)	9%	2.5	3
Cited in Olesiuk et al. 1990:				
Shetland Islands	(Venables and Venables 1955)	19%		
Atlantic Canada	(Boulva and Maclaren 1979)	20 - 24%		
Ireland	(Summers et al. 1980)	21%		
Tillamook Bay, OR	(Brown and Mate 1983)	14 -18%		
Puget Sound, WA	(Calambokidis et al. 1985)	17%		
	Data are rounded to the nearest percent.			

Table 2. Summary of daily high counts used to compare trends from the mid 1970s (Streveler 1979), 1984 (Calambokidis, unpubl. data) and 1992 and 1993 (Mathews)

	June 1975-78		August 1984		June 1992/93		August 1992/93	
	(Streveler 1979)		*(Calambokidis unpubl.)*		*(Mathews)*		*(Mathews)*	
	Jun 70s	Dates	Aug 84	Dates	Jun 92/93	Dates	Aug 92/93	Dates
	1089	6/19/75	3026	8/07/84	2185	6/15/92	3403	8/20/92
	1076	6/20/75	3549	8/08/84	3135	6/16/92	3714	8/21/92
	1475	6/19/76	3871	8/09/84	2713	6/17/92	5796	8/22/92
	1439	6/20/76	4314	8/10/84	2527	6/18/92	4147	8/23/92
	1319	6/21/76	5208	8/11/84	2539	6/13/93	4517	8/14/93
	1537	6/22/76	4736	8/12/84	2913	6/14/93	4049	8/15/93
	1616	6/15/77	3744	8/13/84	3477	6/15/93	2451	8/16/93
	1888	6/16/77	1722	8/14/84	4281	6/16/93		
	1456	6/17/77	2350	8/15/84	3212	6/17/93		
	1713	6/18/77	2123	8/16/84				
	2431	6/18/78						
	2313	6/19/78						
	2202	6/20/78						
Mean:	1658		3464		2998		4011	
N:	13		10		9		7	
SD:	420		1209		583		1088	
SE:	117		382		194		411	

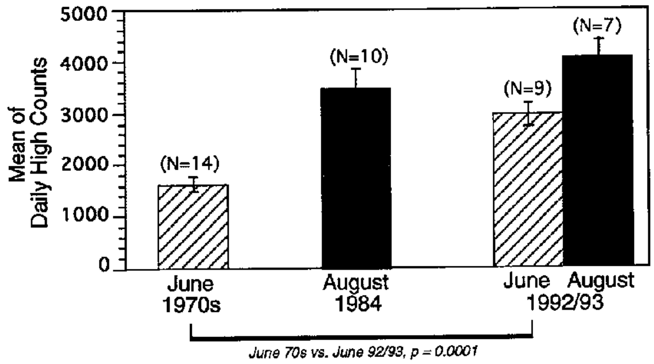

Fig. 4. Comparisons of mean values from daily high counts of harbor seals in Johns Hopkins Inlet for June 1975-1978 (Jun 1970s) from Streveler 1979, for August 1984 (Calambokidis, unpublished data), and for June 1992 and 1993, and August 1992 and 1993 (Mathews). The June 1992/93 mean was significantly higher than the June 1970s mean (Mann Whitney U test), whereas the 1984 and 1992/93 August counts were not significantly different.

Results

Harbor Seal Abundance Estimates

Based on the sum of counts from aerial photographs of land haulouts and the high count for Johns Hopkins Inlet, the high count (or MPE) for harbor seals in Glacier Bay in August 1992 was 7,620 (Mathews 1992). The sum of mean daily high counts in Johns Hopkins Inlet and the mean for the two aerial photographic surveys was 5,982 (95% CI = 4,715 to 7,248). In August 1992, an average of 71% (4,277) of the seals counted in the Bay were found in Johns Hopkins Inlet. The Spider Island reefs, a land haulout, supported the second largest aggregation of seals in the Park with 1,090 (18%) animals.

Comparison of Counting Methods at Land Haulouts

The mean count for the three, paired land-based counts of Seals on the Spider Island reefs was compared to the counts from corresponding aerial photographs. On average, observers at the low-level land site counted only 51% (range = 44%-61%) of the seals present.

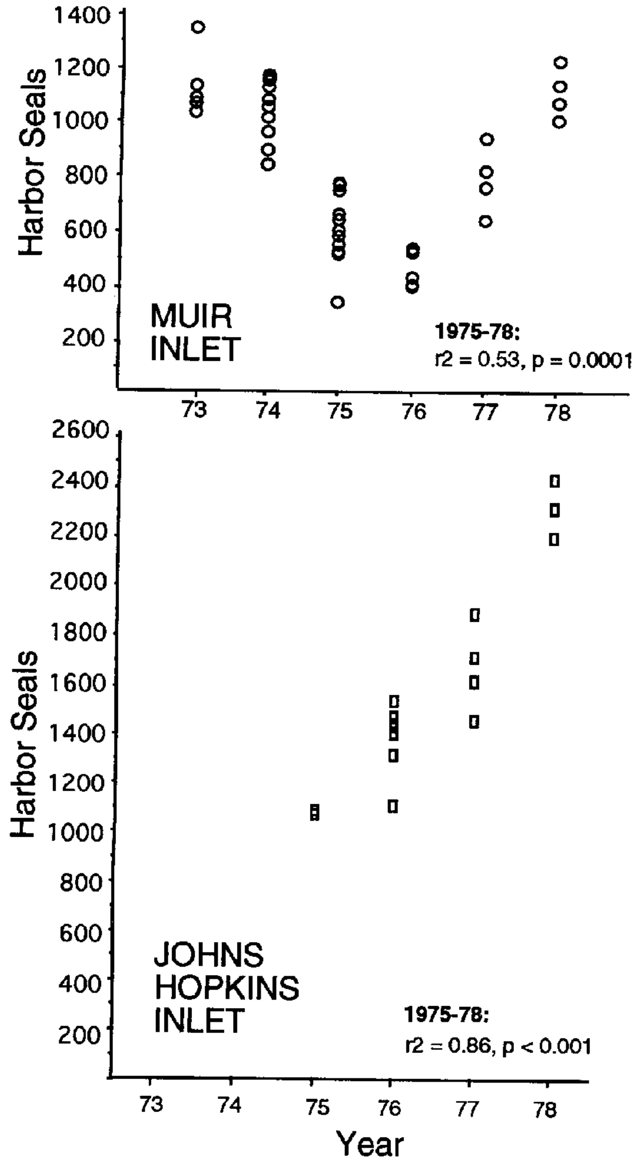

Fig. 5. Trends in harbor seal counts in Muir Inlet and Johns Hopkins Inlet from 1973 to 1978 (data are from Streveler 1979). Movement from Muir Inlet does not appear to account for the increase in Johns Hopkins Inlet.

Proportions of Pups

The proportions of pups estimated for all study areas using all methods are summarized in Table 2 and Fig. 3. Pup proportions from the counts of 100 nearby seals in Johns Hopkins Inlet in 1993 were significantly higher ($p = 0.0001$) than those from counts of all seals in the inlet. The estimate of pup proportion for Johns Hopkins from counts of all seals, both distant and far, was significantly higher than the pup proportions estimated using the same method at the Spider Island reefs ($p=0.02$). There was no statistical difference between the mean pup proportions recorded during Streveler's four summer counts (1979) and those from the nearby subset counts in 1993.

Trends in Johns Hopkins Inlet, 1975-1993

The mean of the daily high counts of adult harbor seals in June of 1992 and 1993 was significantly higher ($p = 0.001$) than the mean for 1975-1978. The mean number of seals counted in August 1984 was not different from the August 1992/93 counts (Fig. 4).

A review of Streveler's data from 1973 and 1978 indicates that there was a decline in seal numbers in Muir Inlet from 1973 to 1975, but that this was followed by an increase (Fig. 5). At the same time that seal numbers in Muir Inlet were increasing, numbers in Johns Hopkins Inlet increased significantly from 1975 to 1978 ($r2 = 0.86$, $p < 0.001$). Annual rates of increase ranged from 24-30% per year in Johns Hopkins Inlet.

Discussion

Harbor Seal Abundance Estimates

In August 1992 we observed more than 5,900 harbor seals in Glacier Bay, and an average of 4,277 seals were counted in Johns Hopkins Inlet, making this tidewater glacial system one of the largest documented breeding groups of harbor seals remaining in Alaska. In this study, no effort was made to correct for the proportion of seals in the water, so these counts clearly underestimate seal numbers. Correction factors derived from telemetry studies range from 1.5 to 1.8 (Huber et al. 1992), but I would predict that the correction factors for seals at land haulouts might differ from that of seals resting on ice bergs in glacial fjords.

Because harbor seals in Glacier Bay haul out on icebergs and at land sites, to estimate the number of seals found throughout the Park, different censusing methods are required depending upon haulout substrate. Results from this work demonstrate that, compared to counts from low-level land sites, counts from aerial photographs are superior for seals at land haulouts. This method also allows for surveys of the entire Park in only three hours and the photographic slides can be independently verified and archived.

Direct counts from photographs cannot currently be used to obtain total counts of seals on ice in Johns Hopkins Inlet or in Icy Bay during peak haulout periods. In summer months seals are dispersed on ice floes over such a large area that it is not possible to spatially orient photographs taken of the ice, and thousands of photographs would be required for full coverage of the fjord. However, the development of a photographic or videographic system using film with extremely high resolution and multispectral sensitivity could allow higher altitude images of large areas while still detecting harbor seals. Until such a system is developed and tested, counts of harbor seals from elevated sites on land are recommended for Johns Hopkins Inlet, since its steep walls offer good vantage points for much of the area used by seals.

In 1992, we observed 1,090 seals at the Spider Island reefs in August. Between 1982 and 1984 researchers (Calambokidis et al. 1987) counted a maximum of 536 seals in the Spider Island area. However, because the counts in 1984 were from land and the 1992 count was from aerial photographs, it is not possible to determine if there has been a change in harbor seal use of the Spider Island area. Indeed, if the error in the land-based counts conducted in 1984 is at all comparable to that demonstrated in 1992, then it would appear that there had been little change in seal numbers at this haulout between the mid-1980s and 1992.

Proportions of Pups

The proportion of pups observed at the Spider Island reefs was significantly lower ($p = 0.002$) than that observed in Johns Hopkins Inlet. Yet, the Spider Island counts were conducted from more than a kilometer away, at a low observation angle, and seals at these reefs are more highly clumped than those on ice bergs. Consequently, the chances of missing pups at the Spider Island haulout were probably greater than they were in Johns Hopkins. Pups appear to aggregate closer to the water (pers. observ.) at land haulouts, possibly reducing the chances of underestimating their numbers. However, aerial photography of both haulout areas during pupping is recommended for a more rigorous comparison of pup proportions in these two habitats. The photographs of the Spider Island haulout in 1992 were inadequate for reliably distinguishing pups, although this should be possible if flights were conducted on days with excellent lighting conditions.

Two different methods were used to determine pup proportions in Johns Hopkins Inlet in mid-June (land-based counts of all seals; counts of 100 close seals), and in Icy Bay pup proportions were estimated from aerial photographs on only one day (June 15, 1993). Mean pup proportions from these two study sites, from a third glacial fjord (Hoover 1983), from Spider Island, and from six land haulouts (Olesiuk et al. 1990) are summarized in Table 1 and Figure 3. Although I could not compare my results statistically to those from the six land haulouts, it appears that proportionately more females give birth and nurse in glacial fjords than at land haulouts, and/or that nursing females in these areas spend more time hauled out than other seals (Godsell 1988) (Fig. 3). Hoover (1983) also observed a relatively high proportion (22-39%) of mother/pup pairs in Aialik Bay, a glacial fjord on the Kenai Peninsula. Calambokidis (1987) reported that 40% of the seals in Muir Inlet and 37% in Johns Hopkins Inlet in mid-June, 1984 were pups. Ice habitat generated in tidewater glacial fjords appears to be important habitat for pupping and nursing.

Trends in Johns Hopkins Inlet, 1975-1993

The comparison of three harbor seal studies spanning two decades indicates that seal numbers in Johns Hopkins Inlet have increased significantly since the mid-1970s. June counts increased from the mid-1970s to the early 1990s, whereas no change was detected between August 1984 and the early 1990s. These results indicate that the increase in seal numbers in Johns Hopkins occurred between the latter half of the 1970s and 1984 (Fig. 4).

There are four non-exclusive explanations for the observed increase in numbers of seals at Johns Hopkins Inlet from 1975 to 1978: 1) harbor seals may have moved from Muir Inlet to Johns Hopkins Inlet, 2) the increase may have been due to an increase in reproduction and survival or 3) a decrease in mortality, or 4) seals may have immigrated to Johns Hopkins from areas other than or in addition to Muir Inlet.

The increase in numbers of seals in Johns Hopkins from 1975 to 1978 cannot be explained by seals moving from Muir Inlet, since numbers in both inlets increased significantly during this time (Fig. 5). Streveler's 1973-1978 (1979) counts of harbor seals in Muir Inlet suggest a decline from 1973 to 1975, followed by a steady increase until at least 1978 (Fig. 5). Although the method for quantifying ice cover was not clarified, Streveler suggested that there was less ice in Muir Inlet in 1975, and that this might explain the low numbers for that year.

Although we might predict that seals habituated to using glacial ice might relocate to another glacial fjord if ice habitat in one location declined, it seems unlikely that seals moved from Muir to Johns Hopkins Inlet in large numbers. In 1984 Calambokidis et al. (1987) observed a maximum of 1,167 seals in Muir Inlet and suggested that ice suitable for hauling out might limit seal abundance. By 1992 only around 200 seals were observed in Muir Inlet (Mathews 1992), and by 1994 the receding glacier grounded and no seals were observed on icebergs in this area. The data suggest that seals which had pupped and mated in Muir Inlet in the mid 1980s did not relocate to Johns Hopkins Inlet, since an increase from 1984 to the early 1990s was not detected. Alternatively, there may have been such a shift, but the power of the data may be inadequate to detect this.

Reduced mortality may have been a factor in the rapid, parallel increase in Johns Hopkins and Muir Inlets from 1975 to 1978. In 1968 bounties were no longer offered for harbor seals in southeast Alaska, and after 1972 hunting of harbor seals in Glacier Bay was no longer permitted. Olesiuk and co-authors (1990) suggest that the unprecedented growth (12.5%) of harbor seal populations in British Columbia waters was due, in part, to the cessation of commercial and bounty kills in 1970. However, by the early 1970s there were only two or three individuals involved in subsistence takes of harbor seals in Glacier Bay, so the numbers of seals taken per year was probably relatively low (Streveler, pers. comm.). Furthermore, the rate of increase in Hopkins from 1975 to 1978 was about two times that observed in British Columbia, and the maximum theoretical reproductive rate for pinnipeds is 12%. Thus, the observed increase in seal numbers in Johns Hopkins Inlet cannot be explained solely by increases in births and survival, or a decrease in mortality.

Immigration from areas other than Muir Inlet remains as the most likely factor in the observed increase in Johns Hopkins Inlet. Because there were no Parkwide surveys before 1992, we cannot confirm if there were shifts in seal distribution within Glacier Bay. Increases in substrate (ice) availability in Johns Hopkins Inlet may have been a factor in the increased use of this fjord.

Conclusions

In order to detect changes in seal numbers or distribution, standardized monitoring protocols of both habitat types in Glacier Bay need to be followed. If a decline or increase is observed in Johns Hopkins Inlet, or in other parts of Glacier Bay, the next challenge will be to determine if it reflects a change due to anthropogenic factors, or if it is due to natural changes in the marine ecosystem, such as the reduction in glacial ice bergs which appears to have occurred in Muir Inlet. The inherently dynamic nature of glacial systems makes addressing such questions extremely difficult. We need to be prepared to alter our approaches to monitoring mammals which are a part of naturally dynamic systems. A decline in seal numbers in Johns Hopkins Inlet could result from a loss of suitable ice habitat, a change in prey availability, or a decline in the health of the seal population, or a combination of these and other factors. While it is important to monitor harbor seals in Glacier Bay, without an ecological context for their use of the habitat our ability to determine the cause of a change in numbers will be limited. Measures of a population's health, such as pup production and survival, feeding ecology, or juvenile growth rates are needed in addition to monitoring trends.

Because of rapid declines in other parts of Alaska, harbor seals have been proposed for threatened status under the Marine Mammal Protection Act. Routine, standardized monitoring of healthy breeding groups in Alaska, particularly in a national park where there is some protection from disturbance and harvesting, is important for determining the cause(s) of the declines through comparative studies, and it is essential for early detection of declines in harbor seal populations which can occur precipitously.

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Census Methodologies of Black-legged Kittiwakes in Glacier Bay National Park

by

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Abstract

Black-legged Kittiwakes (*Rissa tridactyla*) have recently experienced widespread population declines and frequent colony failures throughout the North Pacific. At Glacier Bay National Park, the Margerie Glacier colony was censused visually in 1991 through 1993. In 1993 a new photographic census technique was also tested to assess its feasibility, accuracy, and ease of use. Three years of monitoring data indicate that kittiwake population size declined by about 10% over the three-year period, and that there were near-total colony reproductive failures in 1991 and 1992. Compared to visual colony counts made from a skiff, counting adult kittiwakes from projected 35-mm slides proved to be both more efficient and equally accurate.

KEY WORDS: Alaska, Black-legged Kittiwake, census technique, Glacier Bay, monitor, photography, population trend, *Rissa tridactyla*, seabird.

Black-legged Kittiwakes (*Rissa tridactyla*) are small long-lived gulls that nest colonially in dense aggregations on cliff faces and feed by shallow plunge-diving. In Glacier Bay they are thought to feed on capelin (*Mallotus villosus*), Pacific sandlance (*Ammodytes hexapterus*), herring (*Clupea harengus*), amphipods, and euphausiids. They are dependent on surface prey, in contrast to other seabirds such as murrelets that dive more deeply to feed on the same prey species. Black-legged Kittiwakes have been experiencing widespread population declines and frequent breeding failures throughout the North Pacific over the past 20 years (Hatch et al. 1993). Studies indicate that food limitations may be responsible for these dramatic reproductive fluctuations (Hatch and Hatch 1990; Hatch et al. 1993).

Population declines and reproductive failures such as those described elsewhere have also been observed at Glacier Bay National Park. There are eight colonies within the Park, four of which are on the outer Gulf of Alaska coast, and four of which are within the Bay proper. All of the outer coast colonies have experienced either declines in numbers or complete abandonment in the past five years. Within the Bay, population trends are more variable; some colonies are

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declining, while a new site, on Lone Island, was recently colonized. In this paper I will report on the recent censuses of the largest colony in Glacier Bay, as well as on new census methodologies being developed to more accurately and efficiently perform colony counts.

Methods

A concerted effort to accurately census and monitor Black-legged Kittiwakes at Glacier Bay began in the summer of 1991, and has focused principally on the Park's largest colony, at the Margerie Glacier (Climo and Duncan 1991; Lentfer 1992). The same census methods were used from 1991 through 1993; these consisted of two observers counting birds and nests visually with 8-10 power binoculars during mid-June, the middle of the egg-incubation period. Observers counted from a skiff 30-150 m in front of the colony. The Margerie Glacier colony has been divided into 20 plots along its length, for ease of counting. The boundaries between plots follow natural features of the cliff face, such as cracks and rock intrusions, and have been documented photographically to assure continuity between years. The entire colony (i.e. each plot), was counted a total of five times for both birds and nests; all plots were counted once before the next whole-colony count was begun. For each of the five counts, each observer independently counted the birds (and, separately, the nests) within one plot, and then the two compared their counts. If the two counts were not within 5% of one another, the plot was recounted until the two observers did agree to within 5% of each other's counts. Because they do not breed, first-year birds were not counted, and nests were only counted if they had a bird in attendance and had recently-added nest material incorporated into them. Each full colony count of both adults and nests required one-and-a-half to three days to complete.

To calculate each of the five complete visual colony censuses, each observer's accepted counts for all 20 plots were separately summed. The two observers' total colony counts were then averaged. This procedure was repeated for all five censuses of both adult birds and nests.

In late July and early August, at the height of fledging, we counted the total number of chicks in the colony on three occasions, each separated by approximately one week. Chicks were counted by both observers together, so that agreement was complete.

In 1993, photographs of the entire Margerie Glacier colony were also taken with a 35-mm camera and a 75-210 zoom lens, using 200 ASA Kodachrome color slide film. Five complete photographic sets of the colony were taken, ensuring enough overlap between adjacent frames to enable accurate counting of each plot. After the film was developed, birds only were counted for all five sets by projecting the slides onto a screen, with both observers together counting the projected kittiwakes. Thus, a single count was obtained from each of the five sets of photos. Photographing the entire colony once required approximately three hours; the subsequent counting of birds from one set of projected slides required approximately six hours.

Standard errors of the mean are provided rather than the standard deviations because the statistical tests compare averages. Chick counts were not analyzed statistically, as the maximum number of chicks recorded represented a minimum estimate of the number of chicks produced; this estimate, in turn, had an unknown relationship to the number of chicks fledged due to mortality, which was not measured. All statistical tests were nonparametric to avoid violating the assumptions of parametric tests while still maintaining nearly equivalent levels of power (Siegel 1956).

Results

The average number of adult kittiwakes at Margerie Glacier, determined by the traditional visual counting method, was 3680 ± 86 in 1993, 377 fewer birds than in 1991 (Fig. 1). This 5% annual decline was statistically significant (Spearman's Rank Correlation, $P = 0.027$). The total number of observed nests also declined significantly at about the same rate (Fig. 1), from 2939 ± 27 in 1991 to 2654 ± 33 in 1993 (Spearman's Rank Correlation, $P = 0.012$). Although not statistically testable, 1993's chick production was much higher than the previous two years; 48% of all nests produced at least one chick, compared to 5% and 10% in 1992 and 1991, respectively. In addition, 36% of all nests with chicks produced either two- or three-chick broods. In 1992 and 1991 the percentages of broods with two chicks were 28% and 23%, respectively; there were no three-chick broods in these years. The average number of chicks produced per nesting attempt was 0.66 in 1993, 0.07 in 1992, and 0.12 in 1991.

The mean number of adult kittiwakes counted from the five sets of slides in 1993 was 3691 ± 206, which did not differ from the visual censuses (Wilcoxon Matched-Pairs Signed-Ranks Test: $P = 0.8927$, two-tailed).

Discussion

As in many other parts of the North Pacific, Black-legged Kittiwakes appear to be having difficulty in Glacier Bay National Park also. The population size of the Bay's largest colony, at Margerie Glacier, declined by about 10% overall between 1991 and 1993, as measured both by the number of adult birds present and by the number of active nests. However, an analysis based on only three years' of data must be viewed with caution, as most colonies exhibit large

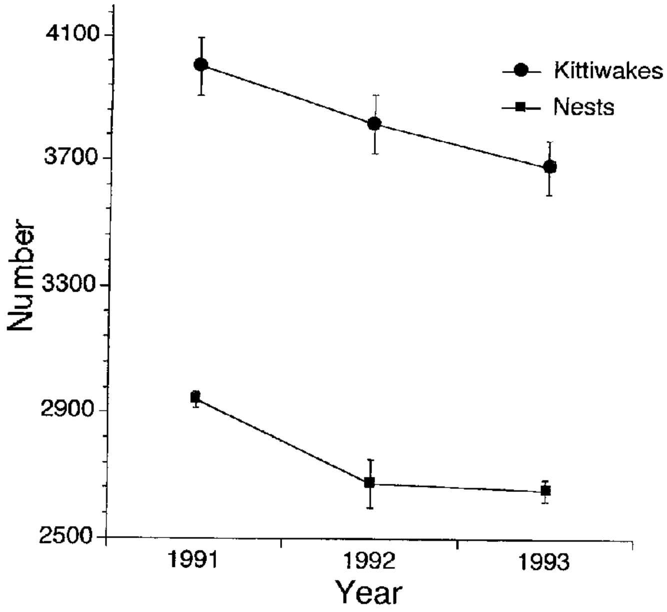

Fig. 1. The number of adult kittiwakes and nests at the Margerie Glacier colony from 1991 to 1993. Standard errors of the mean are shown.

annual variation in attendance and nest-building, making valid determinations of population trends very difficult (Hatch and Hatch 1988).

During this same period, the Margerie Glacier colony also exhibited poor reproduction; only in 1993 did more than 10% of active nests produce any chicks at all. This was also the only year in which chick production substantially exceeded 0.1 chicks per nest; below this level a colony is considered to have experienced a breeding failure for that year (Hatch et al. 1993). Currently, there is no evidence regarding the possible cause(s) of the Glacier Bay decline, although food resources may be implicated due to kittiwakes' reliance on the surface availability of prey; in other parts of the North Pacific indirect evidence points to food availability as a limiting factor (Hatch and Hatch 1990; Hatch et al. 1993). Thus, continued censusing of Black-legged Kittiwakes as well as an investigation into the birds' foraging ecology will be valuable both to assess the continuing status of the Bay's colonies as well as to document possible causal factors in population fluctuations and reproductive failures.

The new photographic census technique was very successful; the total number of adult birds as determined from the slides was nearly identical to that obtained from the traditional visual counts. In light of the fact that each set of photographic-slide counts required only one-third to two-thirds of the time needed for each visual census, this method appears to be much more cost-effective without any loss of accuracy or precision. Additional advantages to the photo technique include the ability to take multiple sets of colony photographs within brief periods of good weather, the ability to perform the slide-counting portion of the census during the off-season, the lack of inter-observer error, and the permanence of the photographic record. Although a few other workers have also discovered that photography can be used to study seabird colonies (Nettleship 1978; Harris 1987), the technique is still not widely used, and should be considered by those interested in long-term monitoring of seabird colonies.

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Breeding Ecology of the Black Oystercatcher in the Beardslee Island Region of Glacier Bay National Park

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Abstract

To study the breeding biology of the black oystercatcher (*Haematopus bachmani*), we located and repeatedly visited 59 nests in the Beardslee Island region of Glacier Bay National Park and Preserve (GBNPP), Alaska during the summer of 1989. The majority of nests were located on sparsely vegetated reefs. The density of nests on reefs was significantly higher (P= .002 Mann-Whitney U test) than the density of nests on forested islands. Nest density on Beardslee Island reefs was higher than densities in British Columbia and Prince William Sound. We tracked the fate of each of the 144 eggs found in the 59 nests. Forty-eight per cent of the eggs hatched, 26 % were eaten, 9 % were drowned, and 29 % disappeared for unknown reasons. Average clutch size was 2.66 eggs/clutch. This average is high compared to other areas throughout the oystercatcher's range. Hatching success was 1.34 chicks/nesting pair. Seventeen eggs were observed to have survived repeated submersion by high spring tides. Because breeding oystercatchers are relatively easy to monitor and the locations of their nests make them susceptible to shoreline disturbances, we propose the black oystercatcher as a species well suited for long-term monitoring of shoreline impacts.

KEY WORDS. Black Oystercatcher (*Haematopus bachmani*), Glacier Bay, breeding, nest density, egg mortality

The black oystercatcher (*Haematopus bachmani*) is a shorebird that nests on barren shores from Baja California to the Aleutian Islands. Numerous studies have focused on the breeding and feeding ecology of oystercatchers in British Columbia (Hartwick 1974, Groves 1984, L'Hyver and Miller 1991). The U.S. Fish and Wildlife Service (USFWS) has studied oystercatchers in Prince William Sound from 1989 to 1993 (B.A. Andres, USFWS, pers.comm.). Except for a distribution survey completed by USFWS (Nelson and Lenhausen 1983), little is known about the oystercatcher population in southeast Alaska. Nelson and Lenhausen (1983) identified GBNPP as having the highest concentration of breeding oystercatchers in southeast Alaska This study focuses on the breeding ecology of oystercatchers nesting in the Beardslee Islands in GBNPP, Alaska. Additionally, we provide rationale for long-term monitoring of black oystercatchers in GBNPP.

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Study Area and Methods

The Beardslee Islands are a group of low elevation islands near the mouth of Glacier Bay in southeast Alaska (Figure 1). The islands cover an area 8 km by 4 km. The majority of the islands are covered by a Sitka spruce *(Picea sistchensis)* dominated forest. In addition, there are several recently uplifted reefs dominated by rye grass (*Elmyus arenarius*).

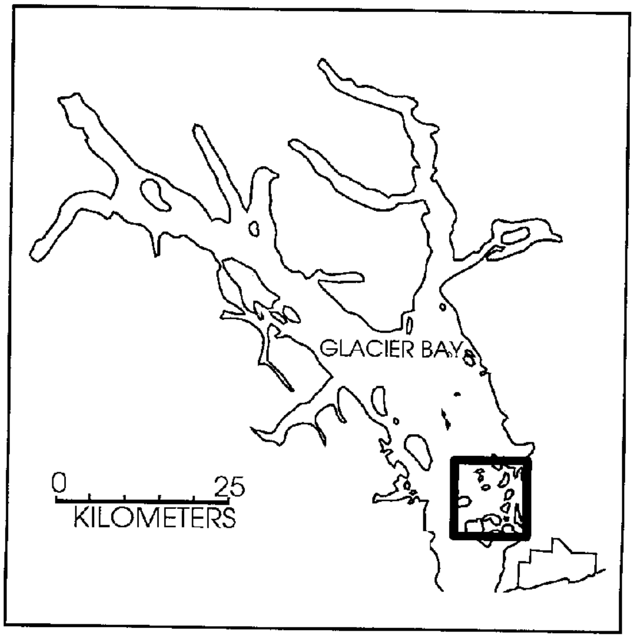

Fig. 1. Map of Glacier Bay, Alaska. Study area is outlined by box.

The entire shoreline of the study area was surveyed by 2 observers, using single fiberglass kayaks, between 30 May and 18 June,1989 to locate oystercatcher nests. Each nest was marked with a distinctive rock and was revisited 3 to 5 times during the study period (30 May through 10 July, 1989). During each visit the. number of eggs or chicks, condition of eggs, and evidence of predation was recorded. Clutch status was classified as hatched, eaten, drowned, or unknown. An egg was defined as hatched if a chick was seen actively breaking the egg shell or was seen in or near the nest. An egg was defined as eaten if a predator was seen eating the egg or if there was direct evidence of predation (predator tracks or smashed egg remains) around a nest where eggs had disappeared. An egg was defined as drowned if it failed to hatch or was lost or broken after being submerged by the tide. All eggs that disappeared or failed to hatch for unknown reasons were classified as unknown. Hatching success was calculated by dividing the total number of eggs which survived to hatching by the total number of nesting pairs.

The perimeter of each reef was measured by pacing the edge of the rye grass. Shoreline distance for the forested islands was measured from 1:64,000 topographic maps with a wheeled planimeter. Linear measurements were used to calculate nesting density of oystercatchers.

Results

Fifty-nine oystercatcher nests were found within the study area. Forty-five nests were on sparsely vegetated rye grass dominated reefs and 14 nests were found on forested islands. Nesting density on the reefs ranged from 10.8 nests/km to 53.5 nests/km with an average of 22.2 nests/km SD= 17.7 (n=5). Many nests on the reefs were within 15 m of each other and 2 were within 10 m. Nesting density on forested islands ranged from .17 nests/km to 3.34 nests/km with an average of 1.4 nests/km SD=1.29 (n=8). Nests on forested islands were restricted to those islands which had sparsely vegetated points extending out from the forest edge. Nesting density was significantly higher on reefs as compared to forested islands (Mann-Whitney U test p=.002). No nests were found on the mainland.

A total of 144 eggs were found in the 59 nests. Average clutch size was 2.66 eggs/clutch (n=59). Egg laying began in mid-June, peaked at the end of June and continued through mid-July (Figure 2). Sixty-nine (48%) of the eggs hatched. Hatching success was 1.34 chicks/nest. Thirty-seven eggs (26%) were eaten, 9 eggs (6%) drowned, and 29 (20%) were placed in the unknown category. It is likely that a portion of the eggs placed in the unknown category fell prey to predators; however, there was insufficient evidence to confidently deduce the cause of their disappearance.

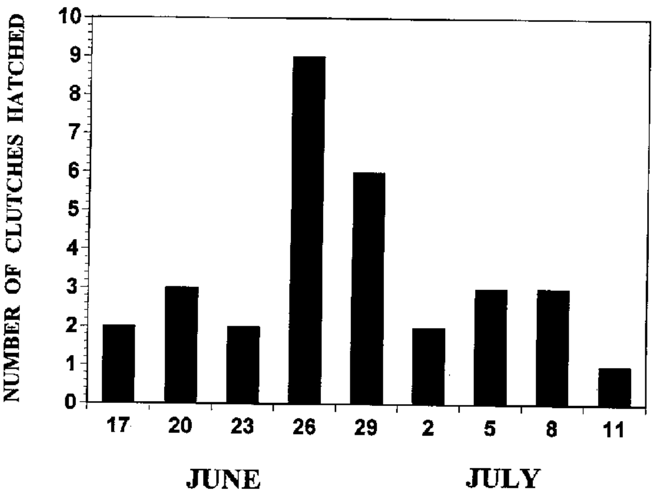

Fig. 2. Hatching phenology of oystercatcher eggs by three dayperiods in the Beardslee Islands, Glacier Bay, Alaska.

Discussion

Oystercatchers' selection of sparsely vegetated nesting habitat in the Beardslee Islands is consistent with habitat preferences documented in other studies (Vermeer et al. 1992, Hartwick 1974). Such habitat is provided by recently emergent reefs in the lower bay and by recent glacial retreat in the upper bay. The availability of this habitat in Glacier Bay explains, in part, the high concentration of breeding oystercatchers seen in Glacier Bay by the USFWS (Nelson and Lenhausen 1983). The nesting density on the Glacier Bay reefs is slightly higher than the highest densities reported from British Columbia (K Vermeer, Canadian Wildlife Service, pers. comm.) and Prince Williams Sound (B. A. Andres USFWS, pers. comm.). L'Hyver and Miller (1991) reported a slightly higher clutch size (2.70) for the Washington-Oregon region and slightly lower clutch sizes for other regions, suggesting productivity as well as density may be high in the Beardslee Islands.

Avian predation appeared to be the major source of egg loss in the Beardslee Islands, the common raven (*Corvus corax*) and, to a lesser degree, the northwestern crow (*Corvus caurinus*) are primary predators. Mammalian predators probably included black bear (*Ursus americanus*), river otter (*Lutra canadesis*), mink (*Mustela vison*), and coyote (*Canis latrans).*

Remarkably, oystercatcher eggs were able to survive submersion in salt water. Egg submersion, usually during storms, was reported as a major source of egg loss of oystercatchers nesting in British Columbia (Hartwick 1974). However, no information is available on eggs of any species surviving submersion in salt water. Twelve of the 59 nests located in this study were below the high spring tides and were submerged between 1 and 4 times during incubation. Seventeen of the 31 eggs in these nests survived to hatching. Dependent upon the stage of incubation, eggs either floated or stayed in the nest. Providing the eggs were not broken or completely lost in the tidal debris line, adults relocated their eggs and continued incubation upon retreat of the tide. In half the cases where eggs were floated from the nest the parents returned the eggs to the original nest site while the remaining parents continued incubation in the new location.

The black oystercatcher appears to be a species well suited for long-term monitoring in GBNPP because: 1) Glacier Bay is important oystercatcher habitat on a regional scale, 2) the shoreline is a sensitive habitat with numerous potential threats, 3) the study of oystercatcher breeding biology is a feasible undertaking.

The importance, on a regional scale, of Glacier Bay as breeding habitat for oystercatchers is evident in the results of the USFWS survey (Nelson and Lenhausen 1983) that showed only scattered pairs along the outer coast of southeast Alaska, whereas large concentrations were centered in Glacier Bay. The high breeding density and high average clutch size found in the Beardslee Islands further illustrate the importance of this area to oystercatchers. Monitoring the large breeding population in Glacier Bay might enable managers to detect changes in the health of the population throughout the region.

Little is known about the Glacier Bay shoreline and potential threats to breeding oystercatchers are currently ignored. Since visitation in Glacier Bay is almost exclusively by water, visitors, especially kayakers, are concentrated along the shore. The impact of this concentrated use in oystercatcher breeding habitat should be studied. The potential for oystercatcher/human conflicts is heightened because campers often choose the same gentle sloping gravel beaches for camp sites that oystercatchers choose for breeding sites. Water-born catastrophic events, such as oil spills, could conceivably have dire affects on oystercatcher populations. Baseline information on the location, density, and breeding success of oystercatchers is needed to assess the affects of the inevitable increase in backcountry use and impacts from catastrophic events. Changes in the health of the oystercatcher population, which can be easily studied, may be indicative of stress on other shoreline nesting birds such as the semi palmated plover (*Charadrius semipalmatus*), the Arctic tern (*Sterna paradisaea*), and the mew gull (*Larus canus*). To establish a baseline from which the health of the population can be adequately be monitored, a multi-year study encompassing all or a significant portion of the bay should be undertaken.

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Resident Peoples' Use of Protected Areas in the Circumpolar North

by

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Abstract

Throughout the northern latitudes protected areas have been established by national and regional governments for a variety of purposes. In nearly all cases, traditional resource uses by resident peoples have predated the creation of the protected area. This paper reviews policies that exist in eight circumpolar Arctic nations with respect to local uses of protected areas. The countries investigated are Canada, Greenland, Finland, Iceland, Norway, Russia, Sweden, and the U.S.A (Alaska). In all of these countries, resident peoples' use of parks and nature reserves is an important resource management issue.

All Arctic nations have included considerations for protected areas that provide for the traditional activities of resident peoples. Among the local uses that have been allowed to continue within the various circumpolar protected areas are off-road transport, hunting, fishing, trapping, gathering, grazing, and hand quarrying. Subsistence activities of aboriginal groups are allowed within most protected areas. In some cases special rights also are provided for local residents other than aboriginal people.

Among the northern countries' protected area programs, considerable accommodation has been made for resource uses by resident peoples; this has particularly been the case where uses have been by aboriginal groups. Also, in some cases resident peoples have been displaced in order to create a strict nature reserve. The resulting policy questions raise both social and ecological issues that must be addressed in protected area programs. Cooperative involvement of resident peoples in addressing these questions can establish the necessary socioeconomic and sociocultural context for protected area management. Policies that seek to bring local residents into the management frameworks for protected areas in the circumpolar north are increasingly being recognized as necessary for the attainment of habitat and species protection goals.

KEY WORDS: Protected areas, subsistence, Glacier Bay, circumpolar North.

One of the difficult management issues facing national parks and other protected areas in the world today is the relationship between the protected areas and local resident people. This is a problem area that is critically important to the future of Glacier Bay National Park and Preserve, and how it's resolved in Glacier Bay will significantly affect other uses of the park. Because the Glacier Bay area is recognized as both a biosphere reserve and as a world heritage site in addition to a national park it has, by definition, a global significance. This paper will address the issue of resident peoples' uses of Glacier Bay in that larger context. The objectives are to:

- review strategies for accommodating the needs of local resident people in protected area management programs throughout the circumpolar northern countries

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- articulate the problem of deciding whether to accommodate or dislocate resident peoples from protected areas
- propose a process by which important social policy questions such as these can be effectively addressed in protected area programs
- explore the prospects for implementing such a policy development process for protected natural areas in the U.S.

There is an increasing demand by the public for their effective involvement in resource management programs (cf. Nelson et al. 1993, Norrie 1993, Gasson and White 1993). Native American groups, including Alaska Natives, are playing a larger role in land and resource management and are increasingly assertive in seeking mechanisms for self-determination, cultural preservation, rural development, and regaining treaty rights. In several national parks, as in Glacier Bay, the rights of local Native groups is a pressing issue. Similar issues are being raised around the world (Birckhead et al. 1993, USDI NPS 1989).[1]

These trends and others place new demands on the resource manager's ability to respond to the needs of a changing constituency. Agencies are reconsidering some of the fundamental principles to apply to protected area programs in the context of increasing use of these areas, the inherent potential for conflict with local uses, and the evidence of an increasingly engaged local public.

Protected Areas and Local Residents

Historically, designation of national parks and certain other federally protected areas in the U.S. meant that most private land within the boundary would eventually be owned and managed by the federal government, and that local uses of the area would be expected to cease, or diminish over time. The U.S. national park model, which has been emulated worldwide, has in the past virtually assured that restrictions on local human populations living in and near designated park areas would occur without compensating actions on the part of government. As one result, some groups carry a festering resentment about insensitive treatment at the hands of the federal government, and some resource management regimes have proven to be politically unstable (West and Brechin 1991).

The more recent trend in designating protected areas in the United States (and in several other countries) has been for legislation to contain provisions protecting existing uses.[2] Also, budget constraints have frequently required managers to find ways to live with inholdings. But simple tolerance of inholdings, or the mandate to allow continuance of traditional uses, does not provide managers with the park policy and regulatory framework necessary to integrate these non-recreational activities with more conventional park uses. To arrive at a stable park management program, incorporating local uses of the park, a policy development process is necessary, with local involvement and support as a key element. Where Alaska is concerned, a useful context for this process is found in the policies related to indigenous peoples' use of the protected areas of the northern circumpolar countries.

Protected Areas in the Circumpolar Arctic

The eight northern circumpolar countries contain a substantial protected Arctic land area; these countries are Canada, Finland, Greenland, Iceland, Norway, Russia, Sweden, and the U.S. (Alaska). Within these countries, nearly 15 million square kilometers is considered Arctic. In the mid 1960s less that 50 million hectares of this Arctic area was included in some protected area category. In 1994 this total was over 200 million hectares (CAFF 1994).

Sweden was the first country to provide natural area protection in the Arctic, with several national parks being established in 1909. Other protected areas have been added in Sweden since then, including two reserves and three parks created in 1971 that cover over half of Svalbard. Both Iceland and Russia created their first national parks in 1930. In Alaska Mt. McKinley National Park was created in 1916, and Glacier Bay National Monument was created in 1925. The largest protected area in the world is the Northeast Greenland National Park, which now covers almost a million square kilometers. It was created in 1974 and expanded in 1988. Many other protected areas have been created in all the Arctic countries in the past 50 years, and the protected acreage now totals over two million square kilometers. Interestingly, out of all the circumpolar national protected areas established among these countries this century, only 22 were created before 1970, and 222 were created after 1970. Among the Arctic areas, Greenland has the greatest amount of land area in protected status (982,445 km^2), and Alaska is second (463,042 km^2), followed by Canada (326,880 km^2) and Russia (187,037 km^2) (CAFF 1994).

Approaches to Managing Traditional Uses in the Circumpolar North[3]

The IUCN protected areas category system provides a basis for evaluating management policies and programs across a variety of national jurisdictions (Table 1). For example:

In Canada, within IUCN category I and II areas (National Parks and Reserves) aboriginal peoples are allowed to continue traditional activities like hunting, trapping, fishing, collecting berries, and (in the Eastern Arctic) quarrying soapstone. Special rights for aboriginal peoples and other local residents also are provided in most other IUCN categories, generally under a system of regulations and permits. Canada has recognized broad rights of indigenous peoples; consequently these groups have generally been involved in the creation of protected areas. Co-management regimes have increasingly provided for shared responsibility in habitat protection and resource conservation.

In Alaska, subsistence and other traditional activities are allowed to continue in the ANILCA- created national parks (IUCN category II), by rural residents, but not in the pre-ANILCA parks.[4] National Park Service management of subsistence hunting is influenced by recommendations from local Subsistence Resource Commissions. Hunting, trapping, and fishing are permitted in most, but not all, of the other Arctic protected areas (categories III, V, VI, VIII).[5] Subsistence activities in Alaska are subject to management by the state, the National Park Service, the Forest Service, Bureau of Land Management, and the Fish and Wildlife Service, depending on the jurisdiction. Federal and state agencies provide various mechanisms for regulating eligibility and harvest.

In Finland, human interference is prohibited in strict nature reserves (IUCN category I) except that visitor use is allowed by special permission, and the Sami are permitted to herd reindeer in all but one of these protected areas. Within the national parks (category II), non-motorized access is allowed. In most protected areas subsistence activities, include hunting, fishing, and building shelters, are provided through permit to eligible local residents.

There are extensive rights for Native peoples' hunting, trapping, and gathering in Greenland's protected areas. In the Northeast Greenland National Park and other protected areas, hunting is locally regulated, and management is based on traditional land and wildlife management practices. In southwest Greenland caribou calving grounds are protected by designating 20% of the land around local communities as preserves, where no hunting is permitted. These areas resulted from negotiations between local authorities and the Greenland Home Rule Government. Other than for Native peoples' use, wildlife is strictly protected. Sea bird colonies are afforded various protections against human use and encroachment, depending on the species.

In Iceland's protected areas public access is assured, subject to certain limitations in each area, construction is strictly limited, and traditional uses such as grazing and hunting are considered valid. Management of hunting and grazing takes place through both a central government agency and local conservation committees.

In Norway's mainland national parks access is by non-motorized means only, except for the Sami. The Sami people also have specific rights concerning reindeer herding in the national parks. Hunting and fishing is allowed in most protected areas in mainland Norway. In the Svalbard protected area, where there is no Native population, only non-motorized access is allowed.

For Russia, in the category I protected areas ("Zapovedniks", or strict nature reserves), only scientific and research activity is allowed, with some exceptions made for traditional resource use by indigenous people. There are no specifically designated rights for indigenous or local people in any of the protected areas in the Russian Arctic, although in the category IV, VI, and VII areas, traditional forms and types of natural resource use are allowed to continue. Protected area policies are evolving. In the proposed Russian component to the Beringia International Park, accommodation for traditional use is widely viewed as essential to its successful creation.

In Sweden, as with the other Nordic countries, most uses in national parks are restricted, but the Sami people have specific rights (reindeer grazing and some hunting, fishing, and motorized access) in several of the protected areas.

All Arctic nations have provided some degree of natural area protection. In some areas (strict nature reserves in Finland, and the category I areas in Russia), all kinds of human use is heavily restricted. However, accommodation for traditional uses by local residents also is provided in at least some of each country's protected areas. In some cases the uses are restricted to aboriginal people only.

The pattern that emerges from this summary is that:

- the northern countries have experienced an explosion in the designation of protected areas in the past 20-25 years,
- these have included considerable amounts of area where uses by resident peoples were ongoing when the protected areas were designated
- in all countries some accommodation has been made for traditional uses to continue in some or all protected areas.
- in all countries except Greenland resident peoples also have been displaced in some protected areas.

Table 1. IUCN Protected Area Categories

				Recommended Status	**IUCN Category**
Protection of nature highest priority	Visitor use disturbing or of low priority	Visitor use and active management undesirable	Primarily for preservation	Strict nature reserve	I
			Primarily for research	Scientific reserve	I
		Zoned visitor use and/or some management desirable	Biologically valuable	Managed nature reserve	IV
			Geophysically or biologically spectacular	Natural monument	III
	Visitor use high priority	Not for consumptive use	Global priority	World Heritage Site	X
			National priority	National park	II
			Local priority	State park	II
		Consumptive use for local people	Global interest	Biosphere reserve	IX
			Regional interest	Anthropological reserve	VII
Protection of nature second priority	Water catchment vital	High visitor potential		Protective recreation forest	VIII
		Low visitor potential		Hydrological protective forest	VIII
	Water catchment not vital	Hunting or harvesting value high	Hunting a priority	Hunting reserve	VIII
			Traditional use a priority	Wildlife management zone	VIII
		Hunting or harvesting value low	Essentially natural	Agro-forestry reserve	VIII
			Essentially agricultural	Protected landscape	V

In CAFF (1994)

- displacement of resident peoples generally has occurred in strict reserves that are closed to all but scientific use.

Policy Questions

The pattern that emerges from review of these management programs provides a global context for protected area policy decisions in the U.S., but there are many underlying policy issues that are not as easily revealed. In Alaska, for example, the general policy guidance provided by ANILCA does not address many management concerns of park managers. These more specific policy questions will increasingly be important in future debates, when traditional uses and a protected area's management goals appear to conflict. The questions include:

- Should all local residents be allowed to continue to use park lands? Should some preexisting uses be recognized and not others? How should "traditional use" be defined?
- Do aboriginal peoples have special legal rights that need to be acknowledged?
- Do resource managers have a moral imperative to provide for cultural preservation or sustainable local economic development, in the context of protected area management.
- To what extent and in what ways should resident peoples' residing in or near protected areas be permitted to utilize natural resources of the area? Is there convincing evidence that resources are seriously affected by resident peoples' use? Should there be use limits, or restrictions on technology?
- Are there conditions under which resident peoples should be displaced from an area, and if so what are those conditions? If displacement should take place, how can this be done to minimize negative social impacts?

The answers to these questions will determine whether broad policy direction for protecting local use is meaningfully carried out. Depending on the outcome, the regulation of northern protected areas will either work to marginalize resident people's uses, and control their subsequent illegal use of the protected area, or to achieve a balance between socioeconomic and resource protection goals. So how will these questions be addressed?

The Policy Development Process

Involvement of the public in government policy development processes is not particularly new, but effective involvement is still rare. The operating principal behind effective citizen involvement in government decision making is that compliance with the rules will be far greater when publics have a hand in agreeing upon them in the first place. Political stability in resource management programs depends on this same degree of responsiveness to and effective involvement of local publics. Advancing these principles requires that agencies develop and evaluate new management alternatives that reflect both public and agency priorities. The agency must clarify the social and ecological consequences of each option, and must use participatory planning and conflict management processes to bring this information to an engaged public. This is conservation biology interacting with sociocultural dynamics, in a planning framework.

New Perspectives

It is fortunate for the future of protected area programs worldwide and in Alaska that governments are beginning to acknowledge the need for more effective public involvement in resource management programs. In a broad sense, the National Environmental Policy Act signaled such a commitment in the early 1970s, but more recent initiatives have been necessary to fulfill its promise. Among those that bear directly on the relationship of local peoples and protected areas are:

<u>The Alaska National Interest Lands Conservation Act</u>

The U.S. national parks model has been liberalized in recent years, particularly in Alaska, where in 1980 the Alaska National Interest Lands Conservation Act (ANILCA) specified that traditional subsistence hunting, fishing, and gathering shall be allowed to continue in the national parks and preserves that were created by the Act. ANILCA also provides a mechanism, including a public process, for federal land management agencies to determine which uses are traditional in a particular area. The numerous provisions of the Act related to subsistence use have provoked substantial stress in Alaska, but federal agencies have generally interpreted the Act literally, and established the requisite public advisory bodies. The ANILCA Regional Councils are granted significant authority.[6] The Subsistence Resource Commissions created for the new national parks have direct access to management decision making, but are strictly advisory.

The Biosphere Reserve

The Biosphere Reserve concept emerged in the early 1980s as a part of the UNESCO Man and the Biosphere (MAB) program. The Biosphere Reserves include a range of objectives including research and monitoring, as well as conservation. In most cases the human presence within a biosphere reserve is considered important to its functioning. In the Arctic countries, Biosphere Reserves have been established in Greenland, Norway, Russia, Sweden, Finland, Denmark, and Alaska. The Alaska Biosphere Reserves are at Glacier Bay, Denali, Noatak River, the Wrangell-St. Elias, and Admiralty Island. Biosphere reserves are intended to protect the Earth's environmental integrity while protecting the rights of people who live in and around parks and reserves. This attention to the rights of local residents, inherent in the biosphere reserve concept, is increasingly viewed as key to the sustainability and coexistence of socioeconomic development and biological conservation.

Federal Agency Policies for Native American Relations

In 1984 the NPS articulated a policy framework for relations between the NPS and Native groups, and provided specific recognition for the legitimacy of ceremonial practices and use of cultural sites. Consumptive uses are allowed where specifically provided by treaty or authorized by law (Turek, n.d.). The Director of the U.S. Fish and Wildlife Service recently signed a policy statement guiding agency relations with Native groups (USDI 1994). The Native American Fish and Wildlife Management Act, currently in Congress, seeks to define the role of Native American tribes in fish and wildlife management both on the reservations and on other lands traditionally used for hunting and fishing.[7] These actions reflect the emerging recognition that a closer working relationship with aboriginal groups is in the best interest of our resources, the resource agencies. and the American people.

"The Vail Agenda: Report and Recommendations to the Director of the NPS" provides another view of how resource managers are looking ahead, and responding to changes in society and demographics (Steering Committee 1992). The recommendations include the following.

> "In addition to research needs, contemporary commitments to pluralism offer the Park Service new opportunities to work with distinct communities and Native peoples to aid them in expressing their own heritage. The Park Service should establish partnerships that will facilitate the joint management of historical, cultural, and natural resources, as well as cooperative research programs with tribes, universities, and organizations." (p. 106).
>
> Individual parks should "coordinate their resource management goals with park neighbors."(p. 123)
>
> "A strong union between cultural and natural resource programs is essential for resource stewardship."(p. 128).
>
> "We recommend that the NPS develop an expanded social science capability and integrate it into the agency's natural resource program." (p. 97)
>
> "We recommend that the NPS establish a task force to improve the public involvement process within the agency."(p 97).
>
> ...the National Park Service and individual parks should... expand the concept of Park Citizen Advisory Groups to include additional parks," should "Greatly expand the role of the public in resource stewardship activities and eliminate the barriers to public participation," and should "Hold local forums to inform and allow the public to discuss resource issues of interest. These should be informal, and on a regular basis..." (p.133).

Conclusion

Policies that bring local residents into management of protected areas are necessary for the attainment of habitat and species protection goals and they are necessary to assure political stability in protected area management programs. This is the premise upon which the recent policy initiatives described here are based. Management agencies are coming to realize that the fate of protected areas is tied to the support, and hence the fate, of local peoples. Success of conservation programs depends on how well its strategies serve people--especially those most directly affected by them.

Few still believe that natural resource managers actually manage natural resources. Rather, they manage human behavior. This is the paradigm that increasingly will condition the management of protected areas. Fundamental to this view is the notion that effective resource management programs require public cooperation, especially by those publics most affected, and that successful cooperative relationships with user groups require an understanding of those groups. Particularly in Alaska, people want to be part of the land and wildlife management process, thus providing us with innumerable opportunities to gain allies in our work by building cooperative, mutually beneficial relationships.

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1. For a more thorough examination of the issue of aboriginal peoples' use of protected areas, see for example Carroll (1988), Richardson (1992), Wilkinsen (1993), West and Brechin (1991), Birckhead et al. (1993), USDI NPS (1989).

2. An example is the Alaskan National Interest Lands Conservation Act of 1980 (ANILCA) that provided for continuing subsistence use in the new national parks in Alaska. An example elsewhere in the U.S. is in the Badlands National Park, where Congress allowed continued hunting by the Oglala Sioux, on a portion of the park that includes tribal trust lands.

3. CAFF (1994) provides much of the source material for this section.

4. In 1980, ANILCA placed more than 393,000 km^2 of Alaska into new or expanded parks or refuges.

5. Subsistence hunting, trapping, and fishing are not allowed in State Game Sanctuaries and the pre-ANILCA national parks. Sport hunting and trapping are allowed in national preserves, but not in national parks. Sport fishing is allowed in all national parks.

6. Recommendations that are made by the regional advisory councils to the federal subsistence board are binding unless the recommendation is not supported by substantial evidence, violates recognized principles of fish and wildlife conservation, or would be detrimental to satisfaction of subsistence needs.

7. As of 1994 these were S. 1526 and HR 2874, for the Senate and House, respectively Because no action was taken in 1994, the bills are expected to be reintroduced during the 1995 session.

Historic and Contemporary Tlingit Use of Glacier Bay

by

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Abstract

This paper reviews historic and ethnographic data that document Tlingit use of Glacier Bay, the characteristics of subsistence harvests of Native communities in the Glacier Bay area, and the changing state and federal regulatory context that influences subsistence harvests. The paper focuses on results of recently completed and ongoing field research conducted by the Division of Subsistence, primarily in Hoonah. Research covered includes field interviewing done in 1985 to present and a 1993 project that gathered interview data from and surveyed Hoonah traditional hunters. The 1993 study focuses on traditional subsistence seal hunting in Southeast Alaska. Data presented document continued reliance on subsistence harvests by Tlingit Natives and others living in the communities bordering Glacier Bay National Park, significant subsistence use of natural resources found within the National Park despite regulatory restrictions, and the crucial cultural importance of Native sites presently under the National Park Service jurisdiction.

KEY WORDS. Tlingit Indians, hunting, fishing, cultural ecology, Native Americans, subsistence.

This paper reviews the ethnographic history of the Glacier Bay area and presents the findings of recent anthropological and historical research. Both sources point to long standing Tlingit habitation and subsistence use of Glacier Bay and the recent exclusion of the Huna Tlingit from their traditional territories. For many Hoonah residents, the story of Glacier Bay is about the cultural identity between the Huna Tlingit[1] and Glacier Bay and the recent loss of access to park areas that are part of Tlingit heritage.

This paper is intended to stimulate thought on very broad public policy questions concerning management of Glacier Bay National Park (GBNP) and the result of that management on Native peoples. Put most directly, do concepts of protection of wilderness and natural environments require the exclusion and prohibition of the traditional Tlingit subsistence hunting and fishing, and other cultural activities that have been part of the ecology of these environments for millennia? Do the concepts of *nature* and *wilderness* necessarily exclude the traditional activities of Native peoples? What ethics and values underlie this management strategy?

Documentation of Use of Glacier Bay Area

Passage and implementation of the State of Alaska subsistence law in 1978 and the Alaska National Interest Land Claims Act (ANILCA) in 1980 provided much of the impetus for contemporary field research conducted to document modern subsistence use of fish and wildlife in the Glacier Bay area and for review of the historical and ethnographic record for Southeast Alaska. These laws sought to delineate and protect customary and traditional resource use for subsistence purposes. Recent research examining and documenting cultural aspects of subsistence hunting and fishing has also been of interest to the Tlingit living in the area and to their representative organizations. Archival material provides information on activities in Glacier Bay after the creation of the park and on

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development of policies dealing with Native residents of the park and adjacent areas[2]. Because the subsistence resources found in GBNP continue to be important to residents of neighboring communities, field research in Hoonah has frequently included study questions that allow use of these resources to be assessed.

Prehistory

No one knows with certainty how the ancestors of the modern Tlingit reached SE Alaska. The most likely migrations routes were coastal, with bands moving into the area from either the north or the south or down river valleys from ice free interior areas. Tlingit may also have traveled over ice fields and glaciers between the interior and the coast. Both oral and written histories recount travel over the ice or even under the ice (Swanton 1909). The Taku Tlingit have an account of passage on a glacial river that passed under the Taku Glacier, and there are post contact accounts of Yakutat Tlingit traveling over ice to the Copper River and of Klukwan Tlingit crossing glaciers to get to the interior (Hope 1993). The different and differing accounts of migration indicate both that the original migration probably took place long ago and also that there have been important movements of Tlingit groups within SE Alaska (see De Laguna 1990 and Moss 1989).

In looking more closely at the area near Glacier Bay, we find that recent glaciation has erased some remains of ancient settlements, and that isostatic rebound and tectonic uplift make other old sites hard to located in much of the park area. To this date the park area has been only partially surveyed[3], and sites recorded in Tlingit oral history or mentioned by early non-Native explorers and in early the National Park Service (NPS) records have not been catalogued or thoroughly investigated[4].

What we do find, however, is that in addition to numerous sites of relatively recent Tlingit occupation found throughout this area, the Ground Hog Bay site located just outside the park boundary provides a record extending back to at least 9,000 years. The archaeological record does not tell us whether the earliest people in the Icy Straits area were the ancestors of contemporary Tlingit or another group. However, between 900 and 450 years ago, Ground Hog Bay was inhabited by people who built plank houses, used ground stone tools, and made decorative designs that are associated with Tlingit Indians (Ackerman 1968). Tlingit oral history describes the last glacial advance that forced people to relocate from Glacier Bay proper. According to the oral history one group settled in the Excursion Inlet/Home shore area. This settlement was at or near the Ground Hog Bay site. Another group settled at the present location of Hoonah after brief stays at Spasski Bay and perhaps other places near the entrance to Port Frederick.

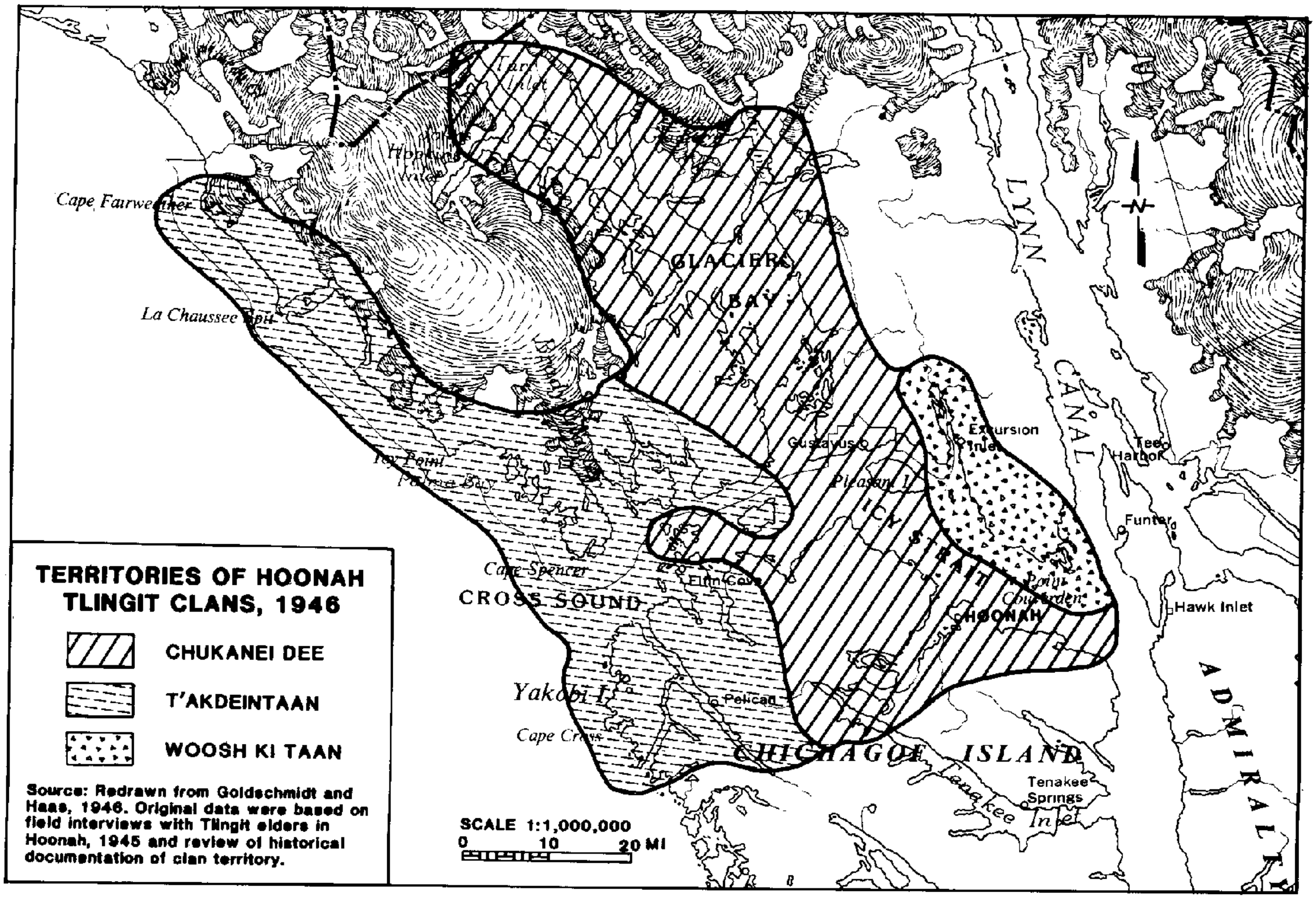
Clan ownership and legend refers to events before last glaciation. The Chookaneidi[5] trace their clan name and clan origin to Chookanheeni in the lower part of Glacier Bay. The name refers to a type of grass growing on flats at the head of Berg Bay; women seen gathering subsistence foods were given the name of the grass (James 1993, Marvin 1993). The village and burial ground said to have been at this site, as well as the entrance fort located on Lars Island, were under ice in the 1700s. Other oral history accounts describe a village site at Bartlett Cove and identify clan houses that were at that site. Many of the names of contemporary clan house groupings in Hoonah follow the names of the houses originally located in Glacier Bay. The Bartlett Cove area also was glaciated in the 1700s[6]. One widespread account refers to a time when there was a large lake within Glacier Bay that was probably a major red salmon system. Large ice-dammed lakes exited in the Muir and Adams inlet areas from 3000-2200 and 1800-1400 years ago; other short-lived lakes existed in the lower bay 850-300 years ago (Engstrom 1994, Anderson et al 1987). Tlingit oral history may be referring to these or other lakes. Huna elders believe that clans of the Huna *kwaan*[7] probably moved in and out of the bay numerous times depending on the ice condition.

In summary, Tlingit oral history appears to be supported by the archaeological record and shows very long-term habitation and use of the Glacier Bay area. Moreover, there is no contradiction of this strong evidence, namely there is nothing in the oral history or archaeological record that would indicate occupation of this area by another tribe or another ancestral home for the Huna Tlingit.

Post-Contact History

Tlingit is a matrilineal society with a strong emphasis on history. Places and events are encoded in songs, crests, and names. People continue to know their clan territory and the historical events that lead to ownership of particular areas. The clan territory map shown in Figure 1 is from work done in 1946 by Walter Goldschmidt and Theodore Haas. These researchers, Goldschmidt an anthropologist, and Haas, an attorney, interviewed elders in Southeast Alaska Native communities in work documenting possessory rights (1946).

The clan territories shown for the Huna T'ukdeintaan, Chookaneidi, and Wooshkeetaan include most of the areas within Glacier Bay where the Huna used natural resources and maintained camps (Fig. 1). Areas on the outer coast north of Cape Fairweather or Lituya Bay are part of the traditional territory of Yakutat Tlingit clans[8]. Glaciers have receded since the time Goldschmidt and Haas did their mapping.



Source: Redrawn from Goldschmidt and Haas, 1946. Original data were based on field interviews with Tlingit elders in Hoonah, 1945 and review of historical documentation of clan territory.

Fig. 1. Map of Glacier Bay area territories of Hoonah Tlingit clans, 1946.

The Huna Tlingit moved throughout their territory following a seasonal round of resource harvesting. Swanton (1908) listed six Hoonah villages at the time of contact. In addition to Hoonah, winter villages were located at Lituya before the destructive wave of about 1855, Excursion Inlet, Hoktaheen on Yakobi Inlet, Kaknau (Tlingit: Kax' Noowú), and near Ground Hog Bay. In this seasonal round the Huna lived at the winter village of Hoonah and other winter villages for part of the year and at fish camps, hunting camps, trapping camps, sealing camps, and berry picking areas when harvesting these resources. Some special camps were also made for sea otter hunting, perhaps fur seal hunting[9], and for trading with other communities. Yearly movement was from camp to camp.

This pattern of seasonal movement changed in the late 1800s. The Huna Tlingit became more centralized in Hoonah after a Presbyterian school was established there in 1881. The Hoonah site was originally a winter village, protected from the north wind. Huna elders have said that their ancestors established their winter village at this site after glacial advance forced them to leave their village site within Glacier Bay proper.

Russian and American Colonial Eras

The record of non-Native exploration of the Huna territory is replete with mention of Native peoples present and generally pursuing subsistence activities in what is now GBNP. La Perouse (1937) encountered Tlingits when he visited Lituya Bay in 1778 and described subsistence salmon fishing in which river weirs were used. Vancouver (1967) found Huna Tlingit in Icy Strait and Cross Sound in his voyages in the 1790s, and Menzies was partially provisioned through trade with Tlingits (Olson, 1993. pers. comm.). The ice from Glacier Bay proper had receded by the time John Muir visited Glacier Bay more than 100 years later. Muir was guided by Huna Tlingit hunters and stopped a number of times at seal hunting camps within Glacier Bay in his five visits between 1879 and 1899 (1915). Huna seal hunting and other subsistence activities were also duly noted during the 1899 Harriman expedition that entered Glacier Bay (Burroughs, Muir, et al 1899).

Commercial fishing became established in the Glacier Bay area between 1880 and 1910. Elders report that early canneries at Dundas Bay paid the T'ukdeintaan clan head for the right to catch fish from this area. A cannery also operated for a number of years at Bartlett Cove between 1882 and 1894 (Cobb 1930).

This early era was not without conflicts over natural resources. La Perouse had problems provisioning in Lituya Bay, probably because he did not compensate the Tlingit owners for the trees he cut and the fish and wildlife resources he wished to pack. The Huna are known to have defended their territory during the fur trade era. In 1862 they captured an encroaching Hudson's Bay vessel, and in 1867 they threatened the U.S. Revenue Cutter Lincoln when it entered Huna territory (Skidmore 1898 quoted in Klein 1975 and Beardslee 1882). Huna control over territory diminished after American purchase of Alaska in 1867 when other settlement and economic exploitation began in the area. Native people generally did not have full rights of citizenship and could not vote until 1924. This lack of legal standing and full citizenship excluded Natives from much of the resource development in mining, canneries, and homesteads during this time[10]. Huna were disenfranchised from later fox farming, mining, and homesteading enterprises. Huna ownership of fish streams was not consistently recognized by the emerging commercial fishing industry.

Despite the progressive losses of Huna control of resources and of recognized ownership of the Huna territory, there was no attempt on the part of government to put restrictions on the subsistence use of Glacier Bay or to limit access of the Huna to their traditional territory. In summary, although the colonial era brought many changes, and the Huna population became more centralized in Hoonah, Glacier Bay continued to be the site of important resource harvesting throughout this period.

The National Park Era[11]

The establishment of National Parks and Monuments in the early 1900s was premised on then current conceptions of nature and wilderness and on official policy of assimilation of Native peoples. John Muir's travels in Alaska and in Glacier Bay in particular did much to introduce Glacier Bay to the rest of the country and to begin the process of establishing Glacier Bay as a protected natural environment. Muir observed that industrial resource extraction and uncontrolled settlement would destroy special environments such as Glacier Bay. However, Muir was basically uninterested in Native Americans who he found within Glacier Bay; for Muir, their role was to act as guides and to facilitate his explorations. National policy was strongly assimilationistic throughout the years when decisions establishing Glacier Bay as a monument were underway. The prevailing view was that Natives would soon cease to follow traditional cultural patterns and eventually become indistinguishable from other Americans. This transition was frequently encouraged by forced schooling and restrictions on traditional cultural activities. Subsistence hunting and fishing tended to be viewed both by government and by some Native organizations as archaic cultural traits that would certainly disappear with modernization and education in Southeast Alaska[12].

In anticipation of the formation of a National Monument, some public lands were temporarily withdrawn from settlement, location, sale, or entry in 1918[13]. Calvin Coolidge created Glacier Bay National Monument by proclamation No. 1733 on Feb. 28, 1925. Most support for creation of the park appears to have come from persons who saw Glacier Bay as a natural wonder of national interest. William S. Cooper and the Ecological Society of America also supported creation of the monument as a site for research and envisioned the monument as an ideal location to study ecological succession[14]. The proclamation established an ice park and included much what was then important seal hunting territory for the Huna. Proclamation 1733 also withdrew other land adjacent to Glacier Bay National Monument, south to Cross Sound and Icy Strait, and east to Lynn Canal, including the Chilkat Range north to the international border.

Proclamation 1733 makes no mention of Huna use of the lands being made into a monument even though Huna use of Glacier Bay was well known and had been observed by many visitors to the area over the previous 50 years. Nonetheless, the monument was created to protect against mining, logging, and homesteading-- not to exclude Natives. The legislative background shows much discussion of boundary questions and issues concerning mining; however, at this point, it appears that Huna's interests were not considered in developing the 1925 proclamation.

We do know that there was no conception among the Huna that this special land status would limit their subsistence hunting and fishing. Elders recall meetings held in Hoonah before the proclamation was signed, in which they were told by federal government officials that national monument status would not change their hunting and fishing use. We have not been able to find records of these meetings. We can speculate that Huna elders were probably told that monument status would change use of the park for homesteading, mining claims, fox farming, establishment of canneries, etc. Although some Huna Tlingit were interested in mining and had prospected in Glacier Bay, most of the development use of Glacier Bay would have meant less control over land and resources by the Huna. For this reason the Huna may have accepted monument status, even seen it as a good thing, as a means of protecting their use of renewable natural resources. This would be similar to the rationale behind Native acceptance of the ANILCA parks created in Alaska in 1980-- that park status would preserve subsistence and limit other developments. More likely, however, this change in land status was poorly understood in Hoonah, and certainly was not seen to mean that traditional subsistence and cultural activities within the monument would be curtailed.

The 1925 proclamation had no demonstrable effect on the subsistence use of Glacier Bay by the Huna. People continued to use traditional camps and to harvest natural resources as they previously had without restriction or control by the federal government. These resources included most of land and marine resources present in the monument including mountain goat, black and brown bear, seals, and possibly moose, as well as the salmon, marine and freshwater fish, crab species, shrimp, and clam, cockle, chiton, octopus, and other intertidal resources that were traditionally used. The 1925 proclamation also did not affect the Huna fish camps or seal and other hunting camps in Glacier Bay. In short, the federal government appeared to be doing what Huna elders were told it would do, namely to close or limit homesteading and mineral development. As we have seen, prior to 1924, Indians were generally excluded from gaining title to land through homesteading and Indian involvement in mining had been limited.

In summary, the 1925 change in land status had little affect on Huna use of this area. Other changes taking place in SE Alaska were of much more consequence. These included depletion of natural salmon runs through poorly regulated commercial fishing, particularly by fish traps, forced schooling of Native children and government attempts at acculturation, and increased regulation of hunting and fishing with little attention to subsistence uses[15].

Huna elders believe that subsistence use of natural resources continued in Glacier Bay. They believe that subsistence harvests may have increased in the depression years when cash for purchased staples was in short supply because of low income from commercial fishing and canneries.

Documentation showing Hoonah residents concerns with possible curtailment of their use of monument areas begins in the late 1930s shortly before expansion of the monument[16]. One hundred and fifty-five Hoonah residents petitioned Anthony Dimond, Alaska delegate to the U. S. House of Representatives, in 1937 to open Glacier Bay for seal hunting, apparently to resolve a local hunting issue (Dimond, 1937). Other correspondence from William Paul in the late 1930s shows that National Park Service was attempting to restrict firearms within the monument boundary (Paul 1937).

On April 18, 1939 monument boundaries were expanded by Proclamation 2330 signed by Franklin D. Roosevelt to include not only the icy areas in upper Glacier Bay that were important for seal, mountain goat, and black bear hunting, but also the areas of lower Glacier Bay that included most of the camps and harvest locations used by the Huna for fish camps, trapping camps, and berry and plant gathering camps. The new boundary encompassed most of the lower Glacier Bay sites that are important in Huna oral history. Included were the village site at Bartlett Cove, the clan origin site at Chookanheeni (Berg Bay), and long-standing clan fish camps in Dundas Bay, at the entrance to Muir Inlet, at Point Carolus, and elsewhere. The new boundary also included the main clan territories for the three largest Huna clans--the outer coast areas, Taylor and Dundas bays owned under customary law by the T'ukdeintaan, the western part of Glacier Bay proper traditionally owned by the Chookaneidi, and the eastern part of Glacier Bay proper and part of Excursion Inlet traditionally owned by the Wooshkeetaan. In short, the expanded boundary included those areas of Glacier Bay that were most heavily used by the Huna for subsistence harvests. These areas are ones of particular cultural significance as well.

Soon thereafter National Park Service attempted to close the expanded monument to Native hunting and trapping. In correspondence to the Office of Indian Affairs, NPS maintained that hunting and trapping would not be permitted (Demaray to Collier, May 2, 1939). Negotiations later in 1939 allowed hunting and trapping to continue albeit with some uneasiness on the part of NPS (Cammerer 1939). In early records the Office of Indian Affairs frequently represented Hoonah's interests and argued for continuation of traditional hunting and fishing within the monument.

The 1939 proclamation itself is silent on continued Native subsistence use of the protected areas. I have found nothing in the documentation leading to the expansion of the monument that indicates that this proclamation intended to limit or eliminate Huna use of this area, and Huna elders did not expect the 1939 proclamation to change their use of the area[17]. In the years preceding the signing of the proclamation and in the subsequent implementation period, the Huna worked directly with NPS and through the Office of Indian Affairs on agreements that would recognize their right to continued seal hunting and egg gathering within monument boundaries. Park Service Director Cammerer clarified the position to be taken on Native hunting in fall of 1939 in a letter to the superintendent of Mt. McKinley National Park; his statement shows that he considered subsistence mainly in simple economic terms rather than examine its cultural basis. He stated, "It is our intention to permit the Indians to continue to take hair seals and to collect gull eggs and berries as they have done in the past, until a definite wildlife policy can be determined upon the basis of a field study and a substitute source of income can be provided for them." This policy was later confirmed in 1947 by letter to the Commissioner Office of Indian Affairs (Tolson 1947).

Further records concerning Huna hunting and fishing rights date from 1946, after three Hoonah residents were arrested by U. S. Fish and Wildlife Service for hunting and trapping in the monument. Federal agencies were concerned about Indians' use of rifles in the monument, perhaps because protection of brown bears had been a major argument in extending the monument boundary in 1939. Agreements covering seal hunting and occasionally egg gathering were in force between Office of Indian Affairs and NPS through April 4, 1974[18]. During the years following World War II period, progressive depletion of red salmon runs through excessive commercial fishing may have been a greater concern to the Huna than 1939 proclamation.

Hoonah's subsistence use of Glacier Bay changed temporarily during W.W.II when large numbers of active harvesters enlisted in the armed forces. Remaining hunters and fishers continued to supply Hoonah with its subsistence needs and continued to harvest resources from Glacier Bay; however, use of camps and traditional sites may have declined temporarily.

Post-War Restrictions

The National Park Service began more active management of Glacier Bay National Monument in the 1950s. NPS began issuing permits to Huna residents for seal hunting in 1953 through the city clerk in Hoonah, and permits began to be issued by rangers in Bartlett Cove on June 10, 1960[19] Prior to the issuance of permits there was little control or monitoring of the subsistence seal harvest by NPS, although park documents show concern with both the numbers of seals taken and with the appropriateness of Native seal hunting in a national monument. NPS rangers began to be stationed at Bartlett Cove in 1953, and boardings of sealing boats and checking of sealing camps became more common. Despite this growing NPS presence in Glacier Bay, subsistence hunting and fishing continued.

Seal hunting under permit continued through most of the 1960s with an agreement in force until 1974 in Glacier Bay. NPS harvest records showing 340 seal taken in 1961 and 1440 taken in 1964 under the permit system. By comparison 1,463 seals were taken under the federal bounty program in and near Glacier Bay in 15 months from March, 1939 to July, 1940[20]. Some of the seals taken in 1961 and 1964 may have been taken for the commercial market in seal skins that existed briefly in the early 1960s or for the state bounty[21]. There is no evidence that this level of harvest permanently depleted the seal population. In fact, the harbor seal population in Southeast Alaska has been robust throughout this era and does not appear to have been significantly diminished even when federal and state bounty programs were in effect or when market hunting was widespread[22]. However, before 1967 when bounty hunting in Southeast Alaska ended, NPS was justifiably concerned that the seal population of Glacier Bay might be wiped out. NPS thought that there were just 800-1000 seals in Glacier Bay in 1964; if this estimate had been correct, Native hunting pressure was high enough to hurt the population. In 1966 NPS raised its estimate of the number of seals in the Bay to 7-8000; at this population level, Native hunting was unlikely to adversely affect the seal population[23]. Ranger Janda concluded, "Although it is unlikely that the limited seal hunting in Glacier Bay National Monument has any effect on the overall population, we are greatly concerned as to the effect the hunting has on the park visitors' opportunity to see seals. The harassment and killing of these animals has made it impossible to get close to them on the ice floes." (Glacier Bay Administrative Files 1966) With this new population estimate, NPS shifted some of its focus from protecting the seal population to enhancing visitor interactions with seals. Although Native hunting did not appear to adversely affect the size of the seal population, hunting was thought to change seal behavior. NPS continued to vigorously push for a total ban on seal hunting and to actively discourage seal hunting and other subsistence use of the park.

The boarding of Mr. Willie Marks' boat the *New Annie* is widely perceived in the Native community as a watershed in Tlingit seal hunting in Glacier Bay waters. The *New Annie* was on a seal hunting trip to Glacier Bay and was towing one skiff[24]. In this incident the *New Annie* was boarded by NPS rangers. The seal hunters on board at the time had their rifles confiscated, after being told that seal hunting was illegal. Jimmy Marks (1993), who was present on the boat at the time, said he was told that the seal hunting from the *New Annie* was illegal because the boat owner, Willie Marks, was living in Juneau. Apparently NPS policy allowed for Hoonah residents' seal hunting but not for hunting by Juneau residents. As far as we know, hunters were not cited and no legal charges were filed from this incident. Although there may have been no clear regulatory or legal basis for excluding Native seal hunters at this time, this action sent a clear message to Native hunters. The boarding signaled the close of an era of open subsistence seal hunting in the bay. This incident took place in 1965 or 1966, or perhaps as late as 1967[25].

Two legal changes took place in the late 1960s and early 1970s that should have alleviated NPS concerns for potential overharvest of seals within Glacier Bay. State of Alaska legislation passed in July, 1967, ended the program of paying a bounty for seals in Southeast Alaska. Secondly, the federal Marine Mammal Protection Act (MMPA) was passed in 1972. Among its other provisions, this act provided for the continued subsistence hunting of marine mammals by Natives living in coastal areas and eliminated all seal hunting for non-Natives. The act emphasized the cultural importance of marine mammal hunting with cultural preservation a clear goal. The act also authorized limited non-wasteful use of marine mammals for handicrafts and specified that marine mammals or their parts could be sold to other Natives for consumption. By eliminating the bounty, limiting seal hunting to coastal Natives, and specifying legal uses of seals these pieces of state and federal legislation effectively ended the possibility of large uncontrolled harvests of seals in Glacier Bay. These pieces of state and federal legislation could have formed a framework allowing for continued Native seal hunting in Glacier Bay, since they resolved NPS's concerns with large scale seal hunting for pelts or bounty within Glacier Bay. Under the MMPA commercial hunting is not allowed, although traditional craft items made from seal skins may be sold. While the end of the bounty program and the MMPA hunting provisions should have allied NPS concerns over the biological effect of Native seal hunting, they did not appear to influence NPS more sweeping concerns over the appropriateness of any hunting within Glacier Bay.

The National Park Service moved quickly to ban seal hunting in the park shortly after passage of the act and was effective in banning seal hunting before the scope and applicability of the MMPA had been explored[26]. How and exactly when NPS effected a prohibition on seal hunting is unclear since no formal rule making took place. It appears that Frank See, the Mayor of Hoonah, was notified in 1974 by the chief ranger that NPS did not permit seal hunting[27]. Additional notice may have been sent in 1976 and 1978.

Since the boarding of the *New Annie* and the mid 1970s notification that seal hunting was illegal, subsistence seal hunting has continued, but it has been done quietly. Seals occur throughout the Glacier Bay area, and subsistence hunters have had the opportunity to hunt unobserved. Most seal hunting by Hoonah residents takes place from September through March when seals are prime for subsistence uses (Wolfe et al 1993). Few tourists visit the park during these months, no cruise ships ply Glacier Bay waters, and areas are infrequently patrolled by NPS[28].

Until recently, the NPS had not cited or prosecuted subsistence seal hunters, although hunting within park boundaries continued. In fall, 1992, however, a hunter was cited for taking a seal in Glacier Bay. He was told to do so by his maternal uncle. The seal was needed for a clan potlatch. This case was heard by Judge Singleton in a non-jury trial in federal court in September, 1993. The defense and the prosecution largely agreed on the facts of the case, namely that a seal had been taken by the defendant near Garforth Island. Three legal questions raised by the defense were raised for consideration by the federal judge. At issue was whether the Marine Mammal Protection Act provision for Native hunting allows such hunting to occur in Glacier Bay, whether the Native American Religious Freedom Act allows for seals to be taken for funeral potlatches, and whether the waters where the seal was taken are under State of Alaska or National Park Service jurisdiction. The State of Alaska intervened on the latter question.

Before Judge Singleton ruled on this case, the prosecution moved to dismiss charges, stating that the jurisdictional question should not be decided as part of a criminal proceeding and noting that a number of civil cases concerning State of Alaska and Federal Government jurisdiction under the Alaska National Interest Land Claims Act were already in federal court. Judge Singleton granted the motion to dismiss to the prosecution. The defense appealed the dismissal to the Ninth Circuit Court arguing that the outstanding issues need to be resolved. Meanwhile, NPS has begun rule-making to craft a regulation prohibiting Native seal hunting in GBNP that would not hinge on exclusive NPS jurisdiction over Glacier Bay waters.

Some subsistence harvesters interviewed in Hoonah report that they were similarly discouraged from using traditional fish camps and other camps by NPS administration in the post war period. They report that most camps and fish racks were burned down or removed in the early 1970s. Hoonah residents tend to believe that NPS destroyed camps and fish racks. This view is not corroborated by documentary sources, although there is evidence that NPS at times encouraged non-Natives living in the Glacier Bay area to run off Native hunters[29]. By the mid 1970s few Huna were able to use their traditional camps within Glacier Bay.

Although Glacier Bay has been a tourist destination since first reports of the area were written by John Muir in the late 1800s, with many ships visiting the bay before the 1899 earthquake choked the areas near tidewater glaciers with ice, mass tourism has become particularly important in the Bay since the 1970s[30]. This bloom of tourism has been attended by a greater NPS staff presence in the park and has coincided with NPS's progressive attempts to limit or eliminate traditional subsistence hunting and fishing by Huna Tlingit in the bay[31]. A major part of the rationale for this exclusion is that consumptive subsistence uses, namely subsistence hunting and fishing, are incompatible with this use of the park by tourists[32].

In 1986, researchers from the Alaska Department of Fish and Game, the Division of Subsistence, interviewed Hoonah residents and measured their use of Glacier Bay. We divided the Huna territory into 30 units and asked respondents what years they had used each unit; GBNP comprised 6 of the 30 units. Figure 2 shows the percent of active hunters in each year who used specific areas within the park over the 1921 through 1985 time period[33]. Several trends are evident for the Glacier Bay units[34]. First of all, the overall rate of use of all units other than the Cape Spencer/Lituya Bay and Excursion Inlet/Sawmill Bay units was quite high through at least 1950 with over 50% of active users reporting some use in that year[35]. Secondly, intensity of use in all units has declined precipitously since 1950; this decline coincided with progressive enforcement of NPS policy of excluding Huna and other subsistence users from harvest activity within GBNP boundaries. Finally, even though use has declined over the 1950 through 1985 time period, many active harvesters continue to use these units for harvest of subsistence foods[36].

The Division of Subsistence included survey questions concerning subsistence use of Glacier Bay in random sample household surveys conducted in 1986 and in a 1993 survey in which active seal hunters were interviewed. Both of these survey efforts documented substantial use of areas within GBNP boundaries for subsistence purposes.

In the 1986 survey we asked if households had used specific subsistence resources from within GBNP boundaries. We found that 90% of surveyed households had reportedly used king salmon, 65% coho salmon, 53% chum and sockeye salmon, 48% pink salmon, 66% halibut, 45% crab, 69% seals, 32% mountain goat, 77% bird eggs, and 90% berries. We also asked surveyed households to estimate the proportion of their total subsistence take that came from Glacier Bay when access to resources was unrestricted[37]. The mean household harvest from Glacier Bay comprised 55% of the estimated total annual subsistence take.

In the 1993 survey we found that 84% of seal hunters interviewed had at some time used Glacier Bay for subsistence hunting, fishing, or gathering. Interestingly, 45% of the seal hunters using Glacier Bay reported a first use after 1960. Table 1 shows the percent of Glacier Bay seal hunters interviewed in 1993 who have harvested other specific subsistence foods in GBNP; although the sampling frame is different than the one used in 1986, the percentages are roughly comparable[38].

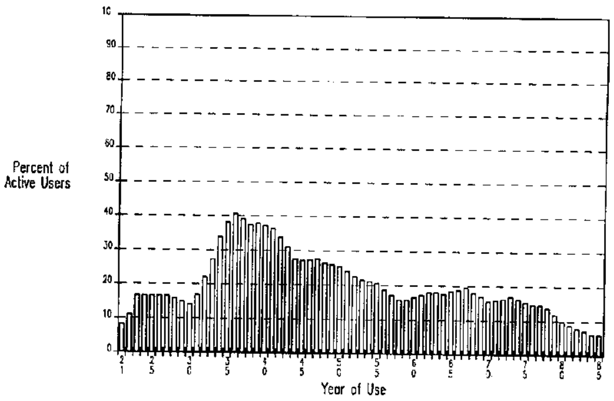
In the 1993 survey we also asked a number of questions concerning seal hunting and overall subsistence harvests within GBNP. Seal hunters reported that they took a mean of about nine seals per hunter, in years when they hunted seals in Glacier Bay[39]. According to seal hunters estimates, when access was unrestricted, 56% of all seals they harvested came from the waters of GBNP; similarly 47% of the total subsistence take came from the land and waters of GBNP[40]. We did not ask respondents about their current harvest levels within GBNP and are not able to report contemporary harvest levels.

Justifications for Exclusion, Law and Policy

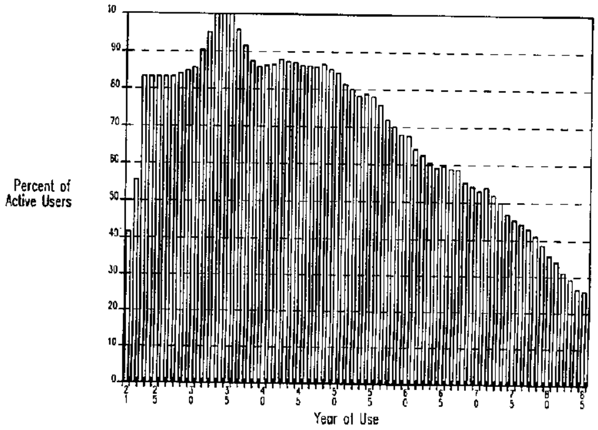
The relationship between the NPS public policy to exclude Huna Tlingit from subsistence and cultural uses of Glacier Bay and the legal framework that might support or disallow the exclusion is a peculiar one, and outstanding legal issues have not been resolved in court[41]. On the one hand, the 1925 and 1939 enabling acts did not appear to have any legal effect on Huna subsistence use of this area, yet NPS policy since the expansion of the Monument in 1939 and especially since the early 1950s has been to attempt to end use of Huna traditional camps within the park as well as restrict and eliminate use of the area for traditional hunting and fishing. In reviewing positions and actions taken by the federal government over the years, I have found that the policy of exclusion has been consistent, but that the legal justification for exclusion has changed significantly.

In 1985 when I first asked NPS what their legal basis for excluding Huna Tlingit was, I was referred to a 1965 in-house legal opinion stating that the 1959 decision in the Tlingit and Haida Indians of Alaska vs. United States case extinguished all Indian rights in this area (Meyer 1965). A few years later NPS maintained that the Alaska National Interest Land Conservation Act of 1980 prohibited subsistence since it did not specifically allow it[42]. Still later, after the State of Alaska issued permits for subsistence fishing in the waters of Glacier Bay, NPS did not enforce their closure policy and then went through formal rule making to prohibit subsistence fishing by regulation. And most recently, in court documents filed in the case against the young Huna seal hunter (see U. S. District Court for the District of Alaska Case No. A93-014 CR), NPS maintains that it has the right to eliminate this subsistence use based on the Organic Act of 1916 (amended) that predates creation of the monument and park.

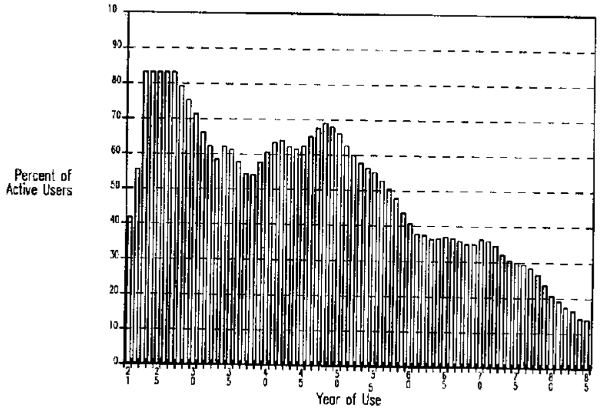
In related legal and legislative areas, the State of Alaska maintains that the state has ownership of marine waters claimed by NPS. The National Park Service has recently moved to phase out commercial fishing in all park waters, eliminating a major source of income to the Huna Tlingit



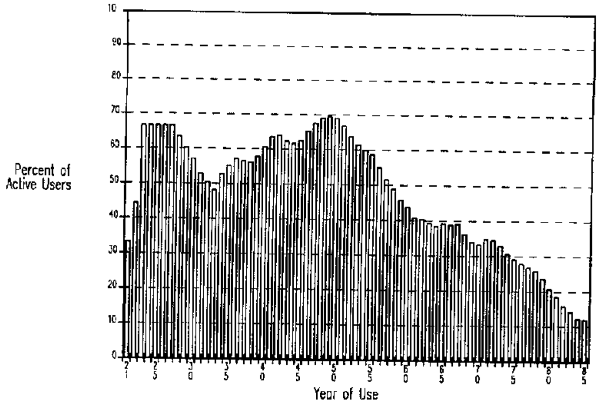
Unit 19, Cape Spencer/Lituya Bay.



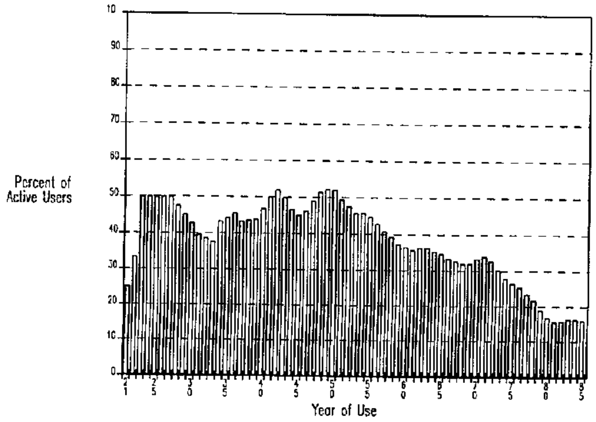
Unit 20, Dundas Bay/Fern Harbor.



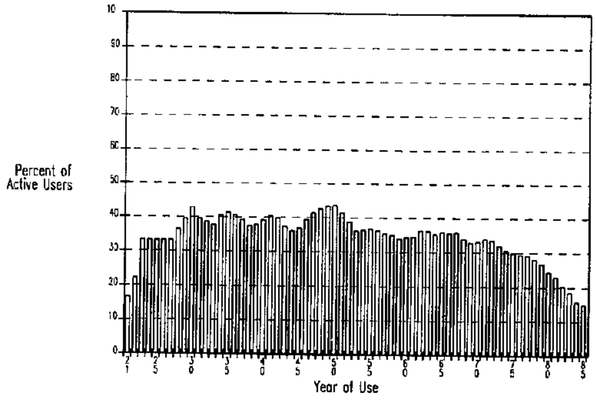
Unit 21, Berg Bay/Willoughby Island.



Unit 22, Upper Glacier Bay.



Unit 23, Beardslee Islands.



Unit 24, Excursion River/Sawmill Bay.

Fig. 2. Intensity of use in areas within Glacier Bay.

and residents of other communities that fish in these waters. And the Alaska congressional delegation has introduced legislation to permit both subsistence and commercial fishing to continue in waters within the park.

Table 1. Use of Other Subsistence Resources in Glacier Bay National Park by Glacier Bay Seal Hunters Interviewed in 1993.

Resource	Percent
King salmon	83%
Silver Salmon	58%
Chum Salmon	58%
Pink Salmon	22%
Red Salmon	17%
Halibut	83%
Herring	15%
Herring eggs	2%
Dungeness crab	63%
King crab	51%
Shrimp	46%
Black seaweed	29%
Red seaweed	27%
Seagull eggs	81%
Other bird eggs	17%
Mountain goat	27%
Moose	2%
Black bear	7%
Harbor seals	78%
Sea lions	0%
Berries	81%
Edible land plants	46%

Huna Tlingit Response

The Huna Tlingit show no signs that they will be willing to forgo access to and subsistence use of their traditional territory and have become more effective in working on this issue in recent years. Increasingly Tlingit use of Glacier Bay is becoming tied to the preservation of cultural traditions and cultural survival for many Hoonah residents[43]. The National Park Service policy, certainly since the 1939 monument expansion if not before, has aimed at eliminating traditional subsistence hunting and fishing by Huna Natives and others within the park. The fact that subsistence issues continue to be matters of contention 56 years later in 1995 marks both the critical cultural importance of Glacier Bay for the Huna kwaan and Tlingit political tenacity and endurance. Both the Hoonah Indian Association and the Huna Traditional Tribal Council are becoming more effectively organized and are pursuing resolution of Glacier Bay issues as the recognized Indian Government of the Huna Tlingit. They have called for management of Glacier Bay by the tribal government (Hoonah Indian Association 1994). Huna fishermen have reasserted their subsistence fishing rights at traditional harvest locations. In 1992, members of all Huna clans went by seine boat to Glacier Bay and held a memorial ceremony in the park, symbolically reestablishing the tie of the Huna to these lands and waters. There is widespread community support for the person charged in the current seal hunting case, and the Native American Rights Foundation is assisting in his defense.

Conclusion

This paper has outlined the historic and contemporary occupancy and subsistence use of the Glacier Bay by the Huna Tlingit. The historic and ethnographic data reviewed documents both the Huna Tlingit's long association with the Glacier Bay area and the NPS policy changes that have discouraged continued traditional Native use of the park. The documentation largely speaks for itself. Hopefully a better understanding of Tlingit use of park lands and waters may contribute to resolution of outstanding subsistence issues and to inclusion of Native history in our understanding of the wonder that is Glacier Bay.

Acknowledgments

Interviews Huna tribal elders and Hoonah community members provided original ethnographic data in this paper. I wish to thank them both for the time they spent with me and other researchers over that past decade and their willingness to share part of the oral history of Glacier Bay. I also thankfully acknowledge the careful review comments from symposium participants and other reviewers received on early drafts of this paper.

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1. Throughout this paper *Huna* or *Huna Tlingit* refers to the Tlingit cultural group presently centered in the community of Hoonah.

2. I rely heavy on Theodore Catton's administrative history of Glacier Bay National Park (1993a, draft) and Michael Turek's recently completed compilation of National Archive documents for archival material relevant to subsistence in Glacier Bay National Park (1993, unpublished manuscript).

3. Robert Ackerman's two summer field seasons in the 1960s are the most thorough work done to date in the park. Unfortunately, follow up studies have not been undertaken and cataloguing of artifact collections from this early work have not been completed (Ackerman 1968).

4. These include numerous contacts made in the 1800s as well as much more recent identifications. For example, John Muir visited Tlingit seal hunting camps on his early visits to Glacier Bay and on the Harriman expedition. Other accounts mention graves on Lester Island and clan houses in the Bartlett Cove area. To my knowledge examination of these sites has not been completed.

5. Huna clan names appear with different spellings. In this paper I use the spellings used by the Huna Traditional Tribal Council in its correspondence. These are: T'ukdeintaan, L'uknax.adi, Chookaneidi, Kaagwantaan, Wooshkeetaan, and Shangukeidi.

6. Captain George Vancouver faced a solid wall of ice at the entrance to what is now Glacier Bay in the late 1700s (Vancouver 1967 (orig.)1798, see also Cook and King 1784-85).

7. Kwaan refers to a grouping of Tlingit clans that live in a defined geographic area and shared a winter village or other residential site.

8. In Tlingit *at.oow* may refer to territory, titles, crests, or other property that are traditionally owned. Clans and house groups have recognized territories. Ownership was recognized in customary law. Clan and house heads had authority over their owned territory. Glacier Bay was *at.oow* for the Huna clans. For some characteristics of traditional or *at.oow* ownership see Dauenhaur and Dauenhaur (1987).

9. Elders believe that fur seal were once present within the Huna territory, including inside waters. Fur seal sightings occasionally take place at the present time, as well as sightings of elephant seals and other species exotic to Southeast Alaska.

10. Specifically Indians were not permitted to file for homesteads or to file mining claims during this time. Indians were generally unable to enter into the legal and financial agreements that established canneries.

11. Theodore Catton's (1993a, 1993b) and Michael Turek's (1993) review of National Park Service documents and history were extremely helpful for this section.

12. The Alaska Native Brotherhood, formed in the late 1920s, tended to agree with federal government efforts to acculturate Tlingits. The Brotherhood was strongly in favor of education and adoption of new cultural values, did not support use of Tlingit language or traditional cultural practices, and generally, in its early years, was not an active supporter of Native hunting and fishing rights (Drucker 1958).

13. Executive Order No. 2854, May 2, 1918 reserved land around Lituya Bay; Executive Order No. 2938, Aug. 16, 1918, enlarged this area. Both were signed by Woodrow Wilson.

14. Research interests were exclusively concerned with glacial geology and vegetational succession on land recently uncovered by glacial ice. The research interests that supported creation and expansion of the monument were not concerned with fisheries, marine mammals, or other marine biota.

15. Although early game regulations often included provisions for hunting for food by persons living in remote areas, there was no specific recognition of subsistence uses or hunting practices. Regulatory changes or enforcement had the potential to affect Native harvesting. For example, in Southeast Alaska hunting with dogs was discouraged; this, and other changes in brown bear hunting regulations, may have lead to a decline in Native hunting for this species (Thornton 1992).

16. Mr. William Paul's 1934 (1934a, 1934b) correspondence concerning possible monument boundary expansions shows that Natives were aware that changes in monument boundaries were likely.

17. According to Catton, (1993b) creating a refuge for brown bears was an important consideration in expanding the monument boundary.

18. Catton (1993b) refers to formal agreements between National Park Service and the Bureau of Indian Affairs in 1956, 1958, 1960, and 1962 that continue to recognize Hoonah's right to hunt seals in Glacier Bay. According to Catton this right was terminated on Apr. 4, 1974. Hoonah may have been notified of this change by letter in 1976 and 1978.

19. L. J. Mitchell, National Park Service, informed the Hoonah city clerk by letter on that date.

20. In a different estimate of the harvest for the 1939-40 year, Wendell H. Cordle reports to Superintendent Frank T. Been that 50 Native hunters took an estimated 50 seals each, mainly from Glacier Bay (Cordle 1940). By comparison, more recent data show about 400 seals taken by Hoonah residents for subsistence in 1992 in the Cross Sound and Icy Straits area, with some harvest continuing to take place in Glacier Bay (Wolfe et al 1993).

21. Both before and after statehood seal hunters turned in seal noses and received a bounty for seals killed. The bounty added incentive to harvest. In Southeast Alaska a bounty on seals was paid from 1927 to about 1966; from 1927 through 1959 bounty was paid under a federal program. After 1959 the State of Alaska paid a bounty on seals. Legislation was passed in July, 1967 restricting the bounty program to the Bering and Chukchi seas and the Arctic Ocean. The bounty rate was $2 per seal through fiscal year 1937-38 and $3 per seal through 1965-66 with a $6 bounty paid in fiscal year 1949-50 (Wolfe et al 1993).

22. Accurate population estimates for harbor seals in Southeast Alaska are not available for early years; however, seal bounty records do not show a declining population. Bounty records showing how many seals were taken in Southeast Alaska are available for 1927-42 and 1947-52. For these years a mean of 10,689 seals were bountied with a high of 16,945 seals taken for bounty in fiscal year 1939-40 and a low of 4,912 in fiscal year 1927-28, the first year of the program. By comparison, under 2,000 seals were found to be taken for subsistence purposes in Southeast Alaska in 1992 (Wolfe et al 1993). Aerial surveys conducted in 1993 estimated that there were a minimum of 22,447 seals in Southeast Alaska (Loughlin *et al*, 1994).

23. Catton 1993a provides a review of relevant NPS correspondence particularly 1964 letters of Ranger Butts to the Superintendent and 1965 and 1966 Ranger Janda correspondence and reports.

24. One National Park Service source refers to 12 skiffs.

25. Determining the exact year of the boarding is problematic; Schroeder and Kookesh (1990) earlier gave the date as 1966 or 1967. Catton (1993b) found no records of this incident. Jimmy Marks (1993) believes that it took place in 1965 or 1966. Florence Sheakley (1993), who is related to a number of the participants, was able to date the incident by remembered that her child was four years old when the New Annie was boarded.

26. The legal issue of the jurisdiction of the Marine Mammals Protection Act over Native hunting in Glacier Bay was presented by the defense in the 1993 criminal trial of a Huna hunter who took a seal near Garforth Island in Glacier Bay (see U. S. Govt. vs Greg Brown, Federal District Court, Anchorage #A93-014CR(JKF) and Federal Appeals Court for the Ninth Circuit #94-30019 CT AG CR-93014-JFK). As part of the defense, the Native American Rights Fund counsel maintained that the MMPA provides for certain types of seal hunting for coastal Indians and that NPS regulation or policy can not limit this provision. After the case was tried but before the judge made a decision, the prosecution moved to dismiss the case. The defendant was finally acquitted in January, 1995 by action of the Ninth Circuit. The court did not rule on the merits of the MMPA argument.

27. Theodore Catton refers to this letter (1993a).

28. In connection with research done under contract with the National Marine Fisheries Service, the Division of Subsistence interviewed Southeast Alaska seal hunters in 1993 and 1994 and asked them where they harvested seals. These unpublished data showed seal harvest locations within park boundaries at Excursion Inlet, Glacier Bay proper, Dundas Bay, and near Cape Spencer.

29. Catton refers to correspondence from the late 1930s and early 1940s showing that NPS officials in agreement with non-Native prejudice against-Natives and actions taken to run Natives out of the area (1993b). "Local whites, resentful of the special hunting privilege accorded the people of Hoonah, sought and received sanction from NPS officials to take matters into their own hands (Superintendent Frank Been, Mount McKinley National Park to Director, Jan. 9, 1940). Hoonah Natives soon found their seasonal cabins smashed up and posted with keep out signs, while on more than one occasion they were driven back to their boats by gunshots (William Wayne to Directors BIA, FWS, NPS, Division of Islands and Territories, June 11, 1948). According to one federal official, a Dundas Bay resident named Buck Harbeson 'instilled a healthy respect for the law in many would-be poachers in his vicinity and acquired a reputation among the Indians of the Icy Straits area, that is legend (McSpradden to Tomlinson, Feb. 19, 1945).' The NPS custodian in Sitka was even more blunt. Harbeson had sent several parties of Natives 'on their way at the point of a gun' he reported, adding, 'If that is true, he is undoubtedly an asset to that area (Pearson to Director, Sept. 16, 1948).'"

30. About 130 cruise ship entries will be made into Glacier Bay in the May through September, 1994, tourist season.

31. The restrictions on subsistence hunting and fishing have also affected residents of the other communities bordering the park: Elfin Cove, Excursion Inlet, Gustavus, Pelican.

32. For example, after it was found that the seal population of Glacier Bay was too large to be adversely affected by Indian hunting, NPS emphasis shifted to conflict with tourism. Catton (1993a) summarizes the recent record on the emphasis of tourism rather than subsistence, "'Passengers on the Park cruise boat express great interest at seeing these animals," a 1966 report on seal hunting stated. 'They are visibly shaken when they learn that the Hoonah are allowed to kill them within the Monument Boundaries. (NPS 1966).'" See also NPS 1984.

33. Note that our sample included relatively few households who were active in the 1920s. There are enough cases from the late 1930s and early 1940s to make comparisons useful.

34. Non-Glacier Bay units show no clear trend with use levels in most units. There has been no comparable general decline in use in other units.

35. Excursion River and Sawmill Bay have traditionally been associated with a single Tlingit clan and may have been used mainly by members and affines of that clan. This may account for somewhat lower use of that unit. Cape Spencer/Lituya Bay also has a specific clan association and is distant from Hoonah.

36. In addition to banning all forms of hunting, including traditional seal hunting, NPS prohibited fishing with nets for subsistence, and gathering of seagull eggs. Since 1980 small boats, including those of the Huna Tlingit, have been required to get permits before entering Glacier Bay during June through August. Rod and reel fishing and berry picking have not been prohibited and may account for some of the more recent use of Glacier Bay waters by Hoonah residents.

37. Survey question in both the 1986 and 1993 surveys simply asked about harvests when access to subsistence resources was unrestricted; we did not specify a particular year when subsistence use began to be discouraged. As we have seen, hunting and trapping on land was prohibited or actively discouraged during the 1940s. Seal hunting discouraged through the 1960s (refer to the *New Annie* boarding) and prohibited in about 1974.

38. These data from the 1986 and 1993 surveys do not indicate the years when GBNP was used.

39. Excluding one high harvester, this mean drops to 5.3 seals per hunter. Elsewhere we have noted that a small number of hunters typically supply a community's need for seals (Wolfe et al 1993). Our research data show that a harvest of nine seals (or five seals) per hunter is not particularly large.

40. This is down somewhat from the 1985 estimate, probably for statistical rather than real reasons.

41. Questions concerning navigational servitude could affect Huna use of Glacier Bay in addition to questions raised in the recent criminal trial concerning the MMPA, the Native American Religious Freedom Act, state jurisdiction over the waters of Glacier Bay.

42. This position was maintained by NPS staff in numerous public meetings held in Hoonah and Juneau 1990-1994.

43. See for example statements by Huna tribal members in the Judge Byrnes hearings, 1991 (Byrnes 1991).

Tlingit and Euro-American Toponymies in Glacier Bay

by

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Abstract

Tlingits and Euro-Americans have applied different place names to areas within Glacier Bay National Park and Preserve in Southeast Alaska. As potent descriptive symbols place names provide important clues to the natural and cultural history of Glacier Bay. A comparison of Tlingit and Euro-American toponymies in terms of linguistic structure, geographic referents, and semantic content reveals significant differences between the two cultures' perceptions and interactions with the landscape. The Tlingit toponymy is heavily oriented toward the marine and shoreline geography and laden with semantic references to biological and topographical elements of those environments. Both name sets are concerned with history, but Tlingit avoids biographical naming, the predominant pattern in English. Despite their endurance, Tlingit toponyms have become increasingly fragile due to language loss and cultural change. Efforts should be made to conserve the Tlingit toponymy so that the rich knowledge base contained therein will remain a vital part of Glacier Bay.

KEY WORDS. Tlingit, geography, place names, history, language, anthropology, Glacier Bay.

Nomina si nescis, Perit cognito rerum ("If you don't know the names, your knowledge of things perishes").
-Linnaeus 1737

To whom do we owe the name of Glacier Bay? According to the colorful essayist and travel writer Eliza Scidmore, US Navy Commander Lester A. Beardslee, who captained the ship *Favorite* into the uncharted bay in 1880, is responsible. As she tells it:

> *By his own personal insistence and a determined stand made at the Coast Survey office, Captain Beardslee had his very apt name of Glacier bay retained on official charts instead of giving it the name of some inconsequent and now forgotten statesman whom it seemed officially desirable to flatter at the time. All Alaska tourists owe it to Captain Beardslee that this reserve of such unparalleled scenic grandeur is not vulgarized by some great misnomer (1896).*

Beardslee's appellation was certainly apt, but was it inspired by a Tlingit toponym? The Commander communicated with Huna Tlingits[1] residing in the area during his visit and credits their input in the development of the first sketch of the bay (1882). Undoubtedly, in the course of his contacts with the Tlingit, he learned, as John Muir had in 1879, that the Tlingit name for the main bay was *Sít'eeti G̱eeyí*, or "Bay in Place of the Glacier."[2] Was something lost in the translation? Perhaps we will never know.

In fact, Huna Tlingits had hundreds of names for places within Glacier Bay National Park, though few have survived on contemporary maps. Of the more than 200 official place names in Glacier Bay, only two are direct transcriptions from Tlingit. Recent research conducted by the Division of Subsistence in conjunction with the Huna Traditional Tribal Council has documented more than 100 Tlingit place names within the park boundaries.[3] This paper compares Tlingit and Euro-American toponymies in Glacier Bay in terms of

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their linguistic structure, geographic referents, and semantic content.[4] I argue that, as potent descriptive symbols, place names provide important clues to the natural and cultural history of Glacier Bay as viewed by both cultures. As linguistic artifacts representative of an integrated domain of human knowledge, toponyms also provide a basis for comparing interpretations of the landscape across cultures. Analysis of Tlingit and Euro-American toponymies in Glacier Bay shows significant differences in the two cultures' conceptions of and ways of being in the environment. Tlingit toponyms are oriented toward the marine environment and semantic associations allude mainly to key biological and topographic elements of the land and seascape, many of which were critical to subsistence, habitation, and navigation. Other names evoke events of the mytho-historical past, thus creating a living history that can be read on the contemporary landscape. However, Tlingit avoids biographical naming, which, as Scidmore cynically suggests, is the most prominent semantic association in the immigrant Euro-American toponymy.

Language and Naming

Every culture uses names to describe, differentiate, and distill the surrounding universe. Place naming, in particular, is motivated by the desire to distinguish meaningful, bounded spaces from space in general. How naming systems develop is a function of language and culture as well as the environment. Cognitive anthropological research has shown convincingly that, while language and culture are not so arbitrary as to actually constitute the environment--as the extreme form of the Sapir-Whorf or linguistic relativity hypothesis suggests--they do play a powerful role in shaping our perceptions of the landscape. Thus, cultures inhabiting the same terrain may conceive of and act on the environment in very different ways.

One way that the Tlingit language influences environmental perceptions is by its emphasis on activity and motion. Tlingit is a language rich in verbs and, as such, often defines the landscape in terms of its actions. Actions are attributed not only to what English speakers would define as animate objects or beings, but also to inanimate ones, such as glaciers (especially in Glacier Bay!), rocks, and trees, indeed the earth itself (de Laguna 1972). In addition to this "enlivening" influence of the Tlingit verb, the Tlingit system of affixing directionals, possessives, relational nouns, and other specifiers to the verb enables the speaker to describe complex actions with a precision and brevity that is hard to match in English.

To understand how this works, let us return to the English and Tlingit names for Glacier Bay, which, although similar in their geographic referents, convey quite different meanings. The English name is a classic binomial compound, consisting of a generic physical feature of the landscape (bay) with a specifier, in this case a noun (glacier), preceding it. Almost all the English names in the park conform to this pattern. The Tlingit toponym also is typical in its construction. Like the English, the Tlingit includes the generic (*g̲eeyí* or "bay"), but the specifier is not a simple adjective or noun, as is commonplace in English; rather it is a relational noun phrase indicating not only action in time (*eetí*, "taking the place of") but also relative location (the glacier, *sit'*, versus the bay). This place name reflects well the capacity of the Tlingit verb to communicate a complex idea in a minimum of space.

More intriguing than its grammatical construction, however, is the idea that the Tlingit toponym conveys. While the English name implies only the presence of glaciers, the Tlingit name denotes a historical, geographic process--a process of glacial recession and the consequent formation of a bay in its place. Unlike the English name, the Tlingit toponym clues us into important geological and hydrographic events that have occurred in this place. The Tlingit names for Johns Hopkins Inlet, *Tsalx̲aan T'éide Wool'éex'i Yé* ("The Inlet that Broke Towards Behind Mount Fairweather") and Hugh Miller Inlet, *Anax̲ K̲uyaawal'ix'i Yé* ("Where the Glacier Ice Broke Through") are other examples of this kind of action-oriented naming, describing a process which has occurred or is occurring over time.

Geographic Referents: What is Named

What is named in Glacier Bay? Certain geographic features, such as bays, streams, islands, peaks, and points have perceptual salience across cultures. Like English, Tlingit has generic terms for all of these features. But perceptual salience itself does not guarantee that a place will be named. While we may judge our geographic knowledge to be incomplete as long as there are blank areas or unnamed features on the map, Tlingits tend to name only specific features of interest to them, such as productive hunting, fishing, and gathering locales, refuges, and key navigational landmarks, while the places in between remain a "relatively undifferentiated landscape" (de Laguna 1960). Especially among societies without written records, where names and other knowledge were passed down through oral tradition, cultural interests influenced not only the selection of sites to be named but also whether or not the names are retained in the collective memory. As a result, some important differences are evident between what features are named in English versus Tlingit.

Table 1 illustrates the frequency with which key geographic features are named in Tlingit and English. Several differences are noteworthy concerning what is named. Mountains are the most commonly named feature in the English toponymy, comprising 25 percent of the name set. Not only are individual mountains named but also mountain ranges. In contrast, mountains are named only five percent of the time in Tlingit.[5] Toponymic loss is probably one factor contributing to the paucity of mountain names in our Tlingit sample; our Huna consultants suggested that additional peaks, particularly in the Fairweather Range, did possess Tlingit names, but that they could not recall them. But otherwise it seems that the majority of mountains did not inspire names unless they possessed other significant characteristics. Most were relatively inaccessible and contained few harvestable resources of value to Tlingits.

Table 1. Geographical Referents in Glacier Bay Place Names.

Geographical Feature	% Tlingit Names	% English Names
Bays	20	20
Cliffs	2	0
Glaciers	5	18
Habitation Sites	12	0
Islands	13	9
Lakes	2	4
Mountains	5	25
Passages/Straits	3	1
Peninsulas	2	1
Points	8	8
Rocks	3	3
Slides	2	0
Streams	19	8
Valleys	1	1

Those peaks that are named are typically valued for other reasons than subsistence. For example, Mount Fairweather, or *Tsalx̱aan*, is named not only for its utility as a landmark, but also for its reliability as a weather indicator, for the mythological events that occurred there, and for the powerful beings who were believed to dwell in its midst. *Tsalx̱aan* is today an important crest symbol to the T'ak̲deintaan clan, one of several Tlingit social groups that inhabited Glacier Bay. Another named peak, *Loolx̱ooshaa* ("Mountain Amidst the Fireweed"), located above Excursion Inlet, is remembered among the Wooshkeetaan clan as a refuge site for indigenous inhabitants during the Flood, another watershed event in the Tlingit geographic history of Southeast Alaska. Yet, a mountain need not be prominent to be named. For example, *L'awsha Shakee Aan*, or "Town on Top of the Glacial Sand Dunes," refers to the cutbanks that once dominated the landscape around Bartlett Cove and are associated with perhaps the earliest human settlement in Glacier Bay. The frequency of these land forms between Point Gustavus and the Beardslee Islands led to the whole area being dubbed *L'awshaayi*, or "Glacial Sand Mountains."

As befits a maritime culture, hydrographic and shoreline features figure more prominently than inland landmarks in the Tlingit toponymy. Bays, streams, and islands are the geographic features most frequently named. Although most of these features also have English names, they constitute a smaller percentage of the English name set. For Tlingits, bays and streams had cultural value not only as outstanding geographical landmarks but also as subsistence resource areas and habitation sites.

The most productive bays and streams were owned and defended in addition to being named. Localized Tlingit clans laid exclusive claim to wealthy, defensible pockets of natural resources, especially salmon fishing streams. Berg Creek, or *Chookanhéeni* ("Straw Grass Creek"), is a case in point. A productive sockeye and coho fishery and sheltered habitation site, this area was claimed by the Chookaneidi clan. The Chookaneidi not only occupied and possessed this bay, but also took their name from it. Indeed, the derivation of clan and house names from the landscape was a common practice among the Tlingit. The Asáank'i, a Tlingit group that Lieutenant C.E.S. Wood (1882) observed seal hunting near Hugh Miller Inlet in 1877, hailed from Freshwater Bay on northeast Chichagof Island and took their name from that place. The name K̲uyeik̲'.ádi, belonging to a now defunct clan perhaps related to the modern T'ak̲deintaan or Lukaax̱.ádi, can be translated as "People of Excursion Inlet" (Emmons [n.d.]). A group called the T'ikanaa, or "People of the Pacific Side" at one time may have occupied Taylor Bay (*T'ixaa*) and parts of the outer coast. And finally, the T'ak̲deintaan, a clan still well represented in Hoonah, apparently took their name from a small island in Lituya Bay which they used as a hunting camp. In addition to clans, individuals too were named for places. In this way place names were linked to identity, property, and other important aspects of social life. Only members of the possessing clan were free to interpret the geography and history--including the toponymy--of their territory, which they did through oratory, songs, dances, regalia and other visual art, as well as through the very act of place naming.

Glacial history undoubtedly has also played a role in the distribution of names. Our mapping shows a significantly higher density of names near the mouth of Glacier Bay than at the present head of the bay, which was inaccessible as recently as 130 years ago. Tlingit oral history and the western scientific literature both highlight the significant glacial recession that has occurred in the bay over the past several centuries. Tlingit traditions also note the rapid advance of a single large glacier to the mouth of the bay prior to the modern glacial retreat, an advance that destroyed their main settlement at Bartlett Cove, *L'awsha Shakee Aan* ("Town on Top of the Glacial Sand Dunes"). Prior to this glacial advance, Glacier Bay possessed a different toponym, *S'é Shuyee*, meaning "End of the Glacial Mud." Tlingit history traces this name to an earlier epoch when the bay was "a great valley" with a single, muddy river flowing through it (Hall 1962). Here again, the Tlingit names provide clues as to the natural history and evolution of the region.

What's in a Name? Semantic Referents

Analysis of the linguistic structure and topographical distribution of place names provides a partial glimpse of how cultures perceive their environment. A semantic analysis helps to complete the picture by tracing out other references contained in toponyms besides generic topographical features. The typology in Table 2 provides one basis for comparing semantic referents in Tlingit and English place names in Glacier Bay National Park.

The first category, biological references, includes animals, plants, and anatomical and mythological allusions. Animals are evident in 29 percent of Tlingit place names, referring to 19 different species of fish and wildlife. In English, animals are evoked in six percent of names, referring to 10 different species of wildlife but no fish. The majority of these associations in both languages are metonymic, meaning that the animals characterize the places by their presence there, usually in abundance. For example, Goose Cove was a name suggested by W.S. Cooper who observed there "a number of young wild geese, who still unable to fly, were flapping over the water" (Orth 1971). I also include references to human populations in this category. The English name Tlingit Point is a metonymic association referring to Hoonah seal hunters who camped there. Similarly, the Tlingit called Tidal Inlet *Gus'k'iyee Kwáan Geeyí* ("Under the Clouds People Bay") perhaps because of the presence of whites at that place. The Tlingit names for Bartlett River, *Gathéeni* ("Sockeye Creek", and for Beartrack River, *Gathéeni Tlein* or "Big Sockeye Creek"), reflect not only the concentration of this species at these locations but also the Tlingit cultural interest in these fish. Indeed, sockeye salmon (*Oncorhynchus nerka*) were among the most coveted of resources due to their attributes as a food source (high oil content) and their narrow distribution compared to other salmon (Langdon 1989, Thornton, et al. 1992). Consequently, sockeye streams were highly valued, carefully guarded, and often named for this key resource. On the other hand, the lack of references to fish in the English name set is indicative of a bias toward upland resources, especially those which are easily viewed.

Metonomy also characterizes plant references in both languages. In the English toponymy, Strawberry Island is an example of a metonymic plant association based on abundance. *Chookanhéeni* ("Straw Grass Creek"--Berg Creek), *Keishísh Aani* ("Alder Country"--uplands between Bartlett Cove and Point Gustavus), and *Wudzidugu Yé* ("Place Wooded with Cottonwoods"--Geikie Inlet) are examples of this pattern in Tlingit. Interestingly, the Tlingit name for Strawberry Island was *L'eiw X'áat'i*, or "Glacial Sand Island," indicative of the island's habitat at an earlier stage of succession, perhaps prior to the presence of significant patches of strawberries. The relative dearth of plant names in both toponymies may be a reflection of glacial scouring and the lack of culturally significant plants in Glacier Bay as compared to other habitats. Although 12 percent of the Tlingit toponymy includes references to plants, many of these are repetitive. Analysis of other Tlingit place-name data indicates that plant references are more common than in Glacier Bay, though still a minority in relation to animal associations. The same is probably true for other English toponymies.

Not all plant and animal references are metonymic. Some associations may hearken back to a mythological or historical event. *Kuts'een Gil'i*, or "Rat Cliff", refers not to an abundance of ordinary rats at the cliff below Spokane Cove, but rather to a single extraordinary rodent of epic proportions that once, long ago, kidnapped a young Tlingit maiden to be his wife. The villainous varmint eventually had to be subdued by the young woman's brothers in a

Table 2. Semantic Referents in Glacier Bay Place Names.

Semantic Category	% Tlingit Names	% English Names
Biological	43	9
Animal	29	6
Plant	12	1
Mythological	5	0
Anatomical	7	1
Topographical	59	25
Hydrographic	42	11
Terrestrial	16	13
Biographical	1	50
Habitation Sites	12	0
Historical	13	9

violent battle at the site (Lilly White 1993, personal communication). There are also names commemorating the wanderings and misadventures of the creator/trickster Raven. "Dribble Creek" (*X̲'as'tuhéen*) identifies a small stream created by the drops of water that spilled from Raven's mouth as he fled from Petrel after stealing his water (Sam Hanlon 1993, personal communication). A site where Raven was active on the Alsek River is dubbed *Yéil Aaludaawdligoowu Yé*, "Place Where Raven Wiped his Beak" (Nora Dauenhauer, personal communication). Such toponymic references serve as historical citations on the landscape, bringing events of the past into the present for new generations to behold. Mythological animal and plant references comprise five percent of the Tlingit toponymy in Glacier Bay.

Another set of references found in place names are those that refer to the body. Anatomical associations are common in place naming and other referencing systems because the body is in fact our most basic environment and instrument of measure (Johnson 1987; Lakoff 1987). Place names such as *Yáay Shaak'ú* ("Whale's Little Head"--Point Carolus) display a metaphoric association, positing an analogy between a geographic feature and an anatomical feature based on visual resemblance. Even generic topographical references may be couched in terms of the body. In Tlingit a word often used to describe a point of land is *lutú*, which means nose or nostril, as in *Ltu.áa* ("Inside the Nose Lake"), or Lituya Bay in English. Body references characterize seven percent of the Tlingit place names in Glacier Bay. Anatomical metaphors are also invoked in the English toponymy (e.g., Dicks Arm) but less frequently.

A second major category of semantic references consists of topographical associations. Topographical references may be divided into two basic categories: hydrographic, those alluding to aquatic or shoreline features, and terrestrial, those referring to upland features of the landscape. Topographical references other than generics make up 59 percent of the Tlingit name set and 25 percent of the English. Significantly, 42 percent of all Tlingit place names contain hydrographic references, another reflection of the culture's maritime orientation. The majority of non-generic Euro-American topographical referents, in contrast, are associated with upland features.

While these two major semantic categories account for more than 90 percent of Tlingit place names, less than 35 percent of the English toponyms contain non-generic biological or topographical referents. This is because the preeminent category in the English toponymy, as Scidmore cynically suggests, is biographical naming. English place names refer to explorers (e.g., La Perouse Glacier, Dixon Entrance, Muir Inlet), scientists (e.g., Geikie Inlet, Reid Glacier, Adams Inlet), missionaries (e.g., Young Island, Brady Glacier), entrepreneurs (e.g., Bartlett Cove, Willoughby Island, Ibach Point), inventors (e.g., Wilbur Mountain, of the Wright brothers), surveyors (e.g., Riggs Glacier, Lars Island, Netland Island), Treasurers of the British Navy (Dundas Bay), and a host of other characters, many of whom never came within a thousand miles of Glacier Bay. Even Scidmore herself, despite her implicit condemnation of biographical naming, was honored with a glacier and a bay. Tlingits were not left out either. In addition to Hoonah Glacier, which recognizes the whole group, individual Tlingits also were honored. Sitka Charley (Charley Glacier) and Tyeen (Tyeen Glacier), members Muir's expedition, were memorialized in glaciers (although not until years after their pioneering voyage), as were the Hoonah leader Kasohto (Kahsoto Glacier) and the Chilkat leader Koh Klux (Kloh-Kutz Glacier).

Ironically, such honorific naming practices probably would have been deemed inappropriate in Tlingit. Indeed, biographical naming is virtually absent from the Tlingit toponymy.[6] Rather than naming places after people, as was the Euro-American tradition, the Tlingit custom was more commonly to name people after places. This difference in naming practices is undoubtedly linked to larger cultural attitudes toward the landscape. In the Euro-American perspective the individual was the basic social unit, the discoverer and possessor of the landscape. In the process of colonizing America it was natural for European explorers to honor their patrons, cohorts, and countrymen with place names both as a means of paying tribute and of marking the land as their own. Many places were named prior to any significant interaction with the landscape and thus probably could not have included biological and topographical referents worthy of distinction. Similarly, the tradition of naming objects for intellectual forebears is very strong in Western science. In Tlingit, on the other hand, clans and house groups were the key social units, and property, political power, and identity were concentrated at those levels. Tlingit scientific discoveries concerning the environment tended to be memorialized in toponyms with biological and topographical references to the landscapes from which the people derived their living. In these and other ways, cultural differences have contributed to different patterns in place naming.

Another divergence in Tlingit and Euro-American naming patterns concerns habitation sites. Twelve percent of the Tlingit names mark dwelling sites, including villages, camps, and forts, whereas we find no such references in English. The lack of references in English is not surprising considering that Euro-American habitation sites are often biographically named (e.g., Bartlett Cove, Gustavus, Juneau) and that permanent settlements came late to Glacier Bay and were outlawed following the park's creation. In Tlingit the affix *aan* denotes a village, and *noow* defines a fort or refuge. Forts were strategically important in the context of intra- and inter-ethnic warfare dating back at least to the protohistoric period (Moss and Erlandson 1992). Place names that include these habitation references provide archeological clues to early settlements and refuges in Glacier Bay and elsewhere in Tlingit country. Ackerman (1968) successfully located some of these named sites within the park--based in part on interviews with knowledgeable Huna Tlingits--but other named sites with semantic references to habitation have yet to be investigated.

Conclusions

A quarter of a century ago, In his book *Glacier Bay: The Land and the Silence*, David Bohn (1967) reflected soulfully on Beardslee's naming of Glacier ,Bay, marking it as the beginning of the end for the indigenous toponomy:

> *At least as far as the white man was concerned, the bay of glaciers was no longer nameless. Of course, it never had been nameless for the Hoonah, but as is usually the case white men found it difficult to explore new country and bother about native names. And while Glacier Bay National Monument has probably fared better in place names than other areas, it seems very unfortunate a good many native words are not today on the maps. Among over two hundred place names covering a land and water area of 4400 square miles, there is exactly one Indian name surviving, and that is Lituya Bay. Other Indian names have been added, about seven of them, one of which--Sitakaday Narrows--is misspelled from John Muir's original rendition of Sitadakay. What happened to the Hoonah names for Taylor and Dundas Bay and the Grand Pacific Glacier, for example, all of which were intimately known to these people? As far as I know, they are lost as are the native words for all the other inlets and glaciers in Glacier Bay. For perhaps five hundred to a thousand years of Indian history to be represented by several place names in two hundred, speaks rather poorly for the white man, but that is certainly nothing new.*

Fortunately, many of these names, including those for Taylor Bay (*T'ix'aa*), Dundas Bay (*L'istee*), and Grand Pacific Glacier (*Sit' Tlein*), have not been lost. Though missing from the cartography, they have survived in the culture, minds, and hearts of Huna Tlingits. As a result of this cooperative project with the Huna Traditional Tribal Council, a significant portion of Tlingit toponyms in Glacier Bay are now transcribed and mapped. That the names have not been lost is testimony to the vitality of Tlingit culture in this area.

There are good reasons for consulting the Tlingit toponymy as source of scientific information about Glacier Bay. This knowledge base represents many centuries of direct experience with the landscape and provides important clues as to the natural and ethnological history of the area which can aide and complement western scientific inquiry. The explorer Glave, who traversed the northwestern part of Glacier Bay Preserve a century ago, encouraged the study and retention of Native names for this very reason (see Cruikshank 1981). Indeed, many observers have been impressed by the rich content of Tlingit names. As one put it:

> *It would be difficult to exaggerate the importance of naming among the Tlingit. In a culture where everything is related to everything else and nothing was spiritually meaningless, names not only classified, they defined social roles, conferred mythic significance, and they were often lovely (Carpenter 1977).*

Unfortunately, while Tlingit place names have showed remarkable endurance to date, as linguistic artifacts of a moribund language, they are actually very fragile. What is more, unlike other domains of knowledge that are widely shared (plant and animal names, for example), toponymic knowledge tends to be highly localized. We cannot ask just any Tlingit speaker about the geography of Glacier Bay; we must consult the smaller circle of experts who are descendants of Glacier Bay, who know this place because they belong to it. Thus, the conservation of indigenous place names would seem to be a matter of some urgency. For, as Linneaus said, "If you don't know the names, your knowledge of things perishes."

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[1] "Huna Tlingits" refers to those groups that traditionally inhabited Icy Strait, Cross Sound, and the outer coast between Cape Spencer and Lituya Bay and later became consolidated at the village of Hoonah in Port Frederick.

[2] Muir was told by his Huna informants "that the main bay was called *Sit-a-da-kay,* or Ice Bay" (Muir 1895:235), but this is both a poor transcription and translation of the indigenous name. A variation of the name recorded by Muir, Sitakaday [Narrows], appears on modern USGS maps, apparently a misspelling of Muir's original rendering.

[3] This ongoing mapping project was undertaken jointly by the Huna Traditional Tribal Council of Elders and the Alaska Department of Fish and Game, Division of Subsistence. Place names were gathered from interviews with Huna elders. Nora Dauenhauer of Sealaska Heritage Foundation and Jeff Leer of the Alaska Native Language Center assisted with transcription and translation of the Tlingit.

[4] The Euro-American toponymy is based on a sample of 204 English names drawn from Orth's (1971) *Dictionary of Alaska Place Names*.

[5] Interestingly, although the Fairweather and Wrangell-Saint Elias ranges are not explicitly named in Tlingit, the most prominent among them, including Mount Fairweather and Mount Saint Elias, do have Tlingit names, and many of their diminutive neighbors are conceived of as being related to them, in this case as children of the larger, parental peaks.

[6] Only the name of a fort on Lars Island (*X̲atadáa Noowú*, "Hanging Weasals at the Mouth Fort") can be linked directly to a personal title, and in this case the title itself seems to have been derived from a historical event.

Presentation of the Huna Tlingits
Third Glacier Bay Science Symposium
Bartlett Cove, September 15, 1993

The Huna Traditional Tribal Council was invited to participate in the symposium as part of the social science session. Representatives of the two major clans that traditionally inhabited and utilized Glacier Bay, the Chookaneidí and the T'akdeintaan, traveled from Hoonah to make presentations on their historic and cultural ties to the park's lands and resources. This paper is an edited transcript of their oral presentation. (Note: Amy Marvin's presentation was made in Tlingit and translated into English by Kenny Grant.)

KEY WORDS: Tlingit, oral history, social life and customs, Glacier Bay, Hoonah, possessory rights.

Speakers: Wanda Culp (Chookaneidí), Richard Sheakley (T'akdeintaan), Wilbur James (Chookaneidí), Kenny Grant (T'akdeintaan), Mary Rudolph (Chookaneidí), Amy Marvin (Chookaneidí)

Wanda Culp (Moderator): I would like to welcome all of you to our homeland, *S'é Shuyee*, otherwise known as Glacier Bay. We are here tonight representing the Huna Traditional Tribal Council of Elders. The Council of Elders is made up of six tribal spokesmen for the Tlingit clans that reside in Hoonah and traditionally lived in this area since time immemorial. Two of our tribal leaders are here to make presentations along with our matriarch, the eldest of our Chookaneidí clan--she's the grandmother of our Chookaneidí people. The Chookaneidí people hail originally from this area and the other clan that borders the outside waters here is the T'akdeintaan. We have the spokesman from the T'akdeintaan here: he is Richard Sheakley. He will speak first and following him will be Wilbur James, who is the spokesman for the Chookaneidí, and following him will be our matriarch, Amy Marvin, and her daughter and grandchildren will be introduced. My Tlingit name is *Kashudahaa.* I am Chookaneidí also. So the two primary clans that lived forever in Glacier Bay are represented here tonight and will be speaking to you.

I will now introduce Richard Sheakley; he is the T'akdeintaan leader and the President of the Huna Traditional Tribal Council of Elders.

Richard Sheakley: Thank you, Wanda. My name is Richard Sheakley. I am of the Raven Tribe, the T'akdeintaan tribe. My Tlingit name is *Neeyeilk'*. That was my grandpa's name; it was passed down to me--that is a Tlingit custom. I want to tell you about these hats over here. These are Mount Fairweather Lady hats. I will tell you about them later. Next we have the Mount Fairweather Wolf-Dog hat. Why it came about is that many years ago--we don't know how many hundreds of years ago--we used to stay in Lituya Bay. We used to cross into Johns Hopkins Inlet. Then in springtime they used to go over the glacier to Lituya Bay--that's a long hike from Johns Hopkins. Why this hat came about is (it's a long story but I'm going to cut it short) because one man there in Lituya Bay quarreled with his family, and they condemned him. They left him up the mountain to die, up on Mount Fairweather. After a couple of weeks it started to freeze up there. They knew he was dying already. He was sitting in one place one night when that wolf came out of the glacier and jumped on him, and he fainted. When he woke up he was warm. The same place he was sitting, that dog was gone because that was a wolf. And he was sitting there, night time, freezing weather--you can imagine that Mount Fairweather is cold. And he was up, not at the top, but about halfway up when he saw a lady come out of there. He said, "What are you doing there? Come on over here." And by gosh he got up and he started going for that lady. Pretty soon he got close to her, and she said, "No, no; you stay where you are. Take a snow bath first because you're too dirty." He said that was the prettiest girl he'd ever seen. And that saved him. That wolf and that lady gave him some kind of a spirit and he warmed up. And he kept following that dog over to Lituya Bay and that's where he became an Indian good luck doctor you call it.[1]

That's how these hats came about. The only time I bring them out of the trunk is when somebody dies and when I really feel sorrowful, especially when something happens to a relative of my dad, like Amy Marvin here--she's the niece of my dad. Now if something happens to Amy, I got bring these hats out on the Eagle side. That's the way it works. That's what you call a Tlingit respect. Well so much for that hat right now; that is a good story behind that hat. I'm just cutting it short because I got other speakers behind me.

People want to know why we claim Glacier Bay. Why do we claim Glacier Bay? They say the white man discovered Glacier Bay. They didn't discover anything. We've been here thousands of years, and these hats can tell it. How many times they have been rebuilt; one gets rotten and then they build a new one. But it gets into thousands and thousands of dollars to replace the old one. And the Eagle tribe has to burn up what is left of the old ones.

So, as I said, people are asking, "Why are they claiming Glacier Bay when they are staying in Hoonah?" Amy will tell that story after a while. I'll tell you why we claim it. It's because this used to be called our ice box, even up to now. Every year the laws are restricting us from shooting anything over here. Sure there's all kinds of foods on the islands where we're staying, but this is a special place. The glacier's cold water is what makes the difference in the fish. The glacier's cold air is what makes the berries juicier and tastier. That's the reason why we always come here. Lots of boats from outside--like Kake, Sitka, Angoon and Klawock--used to come here to pick berries. Now we're being shut out. Why? Out of our own homeland! In the first place, we never went to war with the United States like the State-side Indians did. We're a different kind of people, we're not Indians. We called them Gunana [the Interior Indians]. We're called Tlingits [shows how Tlingit is spelled and pronounced]. We've been Tlingits for thousands of years--that's why we claim Glacier Bay, and we do not want to give it up. [Pointing to the Mount Fairweather hat] Here is our deed for Glacier Bay, our proven deed, the Mount Fairweather hat. It's been our deed for hundreds of years.

This is all I am going to say for now. Thank you.

Wanda Culp: We'll back up a little bit here and let you know that we're also represented equally, balanced with the Eagles and Ravens in presence here. The Tlingit people are divided into the Eagle and Raven tribes, and the Chookaneidís that you see here--myself, Mary, and Wilbur--we're on the Eagle side. Kenny Grant is our interpreter; he's on the Raven side. Wilbur "Jumbo" James, he's the spokesman and head of the Chookaneidí people. He will be speaking next.

Wilbur James: *Gunalcheesh. Gunalcheesh.* Thank you. Thank you. My name is *Shadahéix̱* and my home is *Chookanhéeni*, just a little ways up across in Berg Bay. The first seven years of my life were spent here. All through my lifetime, in a limited manner, we have utilized the resources of Glacier Bay. We claim complete ownership because of our history. Right here where we're at--in Tlingit this place is called "Mountain Village." Before the last major ice advanced there was a high glacial moraine that created a mountain next to here. This is the base of it. The name of this place is still known among us [*L'awshaa Shakee Aan*]. The Park Service and Alaska Department of Fish and Game are working hand-in-hand to produce a place map--a map showing all the Tlingit area and all the Tlingit names. If time permits and funding is available, we can tell stories of each particular place and why its name was given.

Concerning the coming of the white man, the first white man to really take an interest in Glacier Bay as a park was John Muir--a true lover of beauty and a lover of wild natural beauty. In fact he was quite a bit eccentric, that gentlemen. We have stories of him. Our people fed him, clothed him, and guided him, and literally kept him alive. When he wanted to do something, nothing would stop him. He would go do it regardless of the weather or anything. And we knew how much he loved this whole area and that he wished to explore every square inch of it, which he probably did through the years.

Our claim for Glacier Bay is in part due to [a letter transmitted by] the Director of the National Park Service in 1990 wherein he states that:

> *Indian tribes must have the opportunity to participate fully in the National Historic Preservation Program, but on terms that respect their cultural values, traditions, and sovereignty. The report suggests that responding to the needs of Indian tribes highlights a more general development in historic preservation--the concern of the cultural environment as a whole including both historical properties and cultural traditions. What can be learned from the development has broad applicability beyond tribal concerns and should lead to improvements in procedures, standards, and guidelines.*

> *We in the National Park Service welcome the opportunity to broaden our perspectives on preservation issues and look forward to working with all interested parties to implement the recommendations contained in* *Keepers of the Treasures.* *(National Park Service 1990)*

All of Glacier Bay is a treasure. There is no one who loves and values his own homeland more than a Tlingit. We are very proud of this, our home. We wish to always retain it, always keep its beauty, free of unregulated exploitation or anything detrimental to the area. We need our preservation because of what was stated previously, and we wish to participate fully in anything that concerns Glacier Bay because it is our traditional homeland. Thank you very much.

Wanda Culp: I'd like to introduce another T'ak̲deintaan, Mr. Kenny Grant.

Kenny Grant: Thank you. In our culture the protocol is when anyone addresses an audience he always recognizes the top or head person, and I really don't know who is the head of this program. I would like to take this opportunity to thank those who are responsible for inviting our participation in this symposium. My name, to begin with, is Kenny Grant like Wanda says, but we're also known by our own names. My name is *X'ul x̲aa.* I belong to the Raven tribe, the T'ak̲deintaan clan. I can't really repeat what our clan grandfather has said here--only to restate the fact that the T'ak̲deintaan did in fact occupy the outside coast. In our ways certain tribes adopted, or were custodians, and took care of certain things. The creature that we took care of out there was the sea otter. And the canoe that you see out here [on display below the lodge] was a sea otter canoe in which our people hunted and utilized the sea otter. But a lot of you are from the academic community; I know I've seen the word scientist in this symposium and I know a lot of you have read the documentation regarding Glacier Bay. One [book] in particular that I can refer you to is by Krause, who came to Hoonah. It's called *Journey to the Tlingits* (see Krause and Krause 1993) and he in fact recorded that Huna people were living where they are now on the other side of the northern tip of Chichagof Island. But he states also that, during early spring, the different clans left to go to their various camps. The Raven clan, T'ak̲deintaan, went to the outer coast out towards Lituya Bay, up towards Yakutat. Chookaneidí came here to Glacier Bay, and they know about their story, and you'll hear more about it a little later. And the Wooshkeetaan went over into Excursion Inlet. And the Kaagwaantaan went over to Ground Hog Bay. The Kaagwaantaan, the Wooshkeetaan, and the Chookaneidí all belong under the Eagle moiety, and T'ak̲deintaan, we're Ravens. We do have sub clans, too, but that's the way it's broken down.

I had an experience recently of meeting a Russian. Maybe some of you have met or read about the group of Russians that recreated the journey of Vitus Bering. Anybody read about it? Anyway, one of the persons that was on there--I had the privilege of giving him shelter, and in turn he gave me stories of their journey in recreating Bering and Chirikov's journey (Dmitiri Saramov, personal communication). He came upon one portion that I thought very interesting. I have heard versions of it before, but I'll tell you, when Bering and Chirikov set out in 1741 into the new world, they came and ventured out into what we now know as Alaska. Somewhere along the way a storm separated them and Bering continued his way and Chirikov continued his way. It happened that Chirikov ended up in a place. And this person that was telling me the story said he himself went to the library (I think it was in Leningrad) and he himself read the journals of Chirikov--and I mean the actual journals. The place that Chirikov landed he recorded at 58 degrees, 20 minutes. I had no idea where it was, but I know we're close to 58. Well this Russian and I went down to the boat, and nowadays we have these magic boxes--we punch the numbers into a plotter which is a computer. I punched in 58 degrees 20 minutes and, low and behold, it was right from the land from which our clan grandfather and myself claim. And the name of the place is *G̲aanax̲áa*, and that's the house I come from, *G̲aanax̲áa Hít*, and that is our hat right here. The story goes on that Chirikov sent some men ashore just to explore and, low and behold, the men did not return. Evidently they were massacred. (I know there's another story like this, but it's up in Lituya Bay, but this is from a specific area that we claim.) He sent another party ashore to see what happened to the first party, and they didn't return. In the third party, Chirikov himself went ashore with them, and he just barely escaped. He was wounded, and they returned to their home. It's a pretty interesting story.

The other story that I have I heard from my grandparents, also from my Dad, and I heard it from a relative whose name is George Carteeti. This is a really good story--I'm sure that some of you can relate to it. It has something to do with trickery. A lot of you have heard about the trinkets and gadgets and such that were traded with the natives. This story is exactly the same thing that happened to us. And I'm going to teach you a little bit of Tlingit--if you care to learn--since you're academically oriented. I'll teach you a Tlingit word: the word is *taal.* Anyone can say *taal* [repeated by the audience]. What it is is a container, a tray, *taal.* When the Russians came to Lituya Bay they brought this tray that we call *taal*, the Russian tray. They served food. They served rice, and our people, not knowing what rice was, thought it was maggots (the price of ignorance). And they served it with sugar too, and our people hadn't tasted it before. And this was the very first contact with our people in this specific area, Lituya Bay. Well, they had a big feast and everybody was happy. And they proceeded to trade for furs, etc., for things that they could take back to their homeland. What had happened in this case was that the *taal* that they traded was made of lead.

When the Russians had gone and our people were happy so they built a fire and they were going to cook with this Russian *taal*, and it melted. Our people, you know, took upon this phrase: when somebody tricks you or does something and you really believe in it and it fails, they say, "*Taal yax̱ woonei.*" Okay, let's try it [audience repeats]. Now there is a reason for this story. It has good meaning because a lot of us have big expectations over things, and it fails for some reason or other because somebody tricked you. I hope now--with this audience I don't know if I'm speaking to the wrong forum but for history's sake I hope--that our relationship with the National Park Service does not go like the *taal yax̱ woonei*. You understand that. Anyway, that is a little bit of the history, and I didn't mean to take so much time. Thank you.

Wanda Culp: Thank you, Kenny. The next person I'd like to introduce is a clan sister, Mary Rudolph.

Mary Rudolph: Yes, my birth name is *Jina haag*, My European name is Mary Rudolph. I have four generations here with me tonight: my mother, who is 83 years old, my daughter and my grandchildren. So four Chookaneidí generations stand here. My mother is the one that taught us our history. I think our practicing our traditional culture way of food and different things kind of ended with me. This is my grandchildren's first visit to Glacier Bay. They have been very excited as we have been sharing a little history of the history of Glacier Bay as our ancestors did for generations. The respect that was shown in our tribal houses was such that there was never any stepping on anybody else's boundary line. This is one of the things I share with my grandchildren.

A lot of our history--our songs, and the things that are told to us as Chookaneidís--always stems back to Glacier Bay. There has never been any doubt in my mother's mind that this is still her home, and this is still part of her life that nothing or anybody is ever going to take away from her. She is really happy to be a part of this science symposium tonight. We appreciate the effort that was put in by the people who got us to come over here. We had one elderly lady who said, "I gave up on Glacier Bay a long time ago." But today, now, I feel like it's coming back to me, and thank goodness it's part of our lives again now before I die. This is what all this means to us.

I know a lot of times our stories and everything that intertwines seems like folklore--but for us it's our history. One of the things I used strongly was the Bible. I know my stepfather, who passed away in 1978, spoke strongly about how we were intertwined with the Bible. He couldn't understand why our stories were similar to those of the Bible. The things I read in the Bible--I realize that our history is that strong for us. Our food and the things that we have are not something that we violate.

To be here now with my mother and to be part of this gathering and to get to meet some of you here--as one of our clansmen would say: "Welcome to our home." Thank you.

Wanda Culp: Now I would like to introduce our *Naa Tlaa* (Clan Mother). She's the grandmother of the Chookaneidí clan, our matriarch, Amy Marvin (Tlingit name, *K̲ooteen*).

Amy Marvin: (speaks in Tlingit). *Gunalcheesh...*

Kenny Grant (Translator): It is a great honor to be able to translate for her. The traditions and the protocol amongst our people, as it is carried out through out the generations, say that the story that she'll tell, I don't have the right to it [i.e., it belongs exclusively to the Chookaneidí clan]. But she's given me permission to translate for her, which I thank her for.

She opens up by saying, "Thank you, *Aanyátx'u sáani.*" Actually she's calling you "Children of the Land." What she's doing is giving you a high status, and she thanks you for this opportunity to come here and speak to you.

Amy Marvin (translated by Kenny Grant): The people who knew this story about Glacier Bay that I'm going to tell you just passed away recently. But I traveled over to Sitka to learn the story, and this is the one I am going to tell you tonight.[2] This is the place my mom and dad use to come, right here at Glacier Bay. We stayed here even during school months, which was the least of our worries, that is the reason why I can't speak English too good which always makes me feel bad. I do speak a little English sometimes, but this is not the appropriate time. It's hard for me, when I'm talking about Glacier Bay. [Holding up a photograph of relatives] This is my grandmother, she was elderly, and this is my mother. This is me and this is the oldest sister; I'm standing by my brothers. This is their story that I remember in my mind. The hat here before you, the Eagle, I'm holding for my grandchildren. But if anything should happen to it, the mother will take care of it. It was brought from Haines. I used to live up the bay in a place called

Nana, and the house, we all come from a clan house called *Nana Hít*. There was nothing but glacial silt here and the water that ran through it. It was very difficult for my grandparents to tell this story--it always brought tears to their eyes. I experienced that difficulty when I was getting ready to come over here today. I have that same feeling.

I'm going to tell you a story of their clan and the things that happened to them. It begins with the story of young lady [*Kaasteen*] who is going into maturity, becoming a young lady. A young lady that is going to become a woman is put in the back of the village, that was the custom. And this young woman did something which caused the glacier to move--you might call it an insult, the spirit of the glacier was insulted. So the glacier moved and it came down and wrecked the house. And when they were leaving, of course everybody was sad. This is the song I remember, the one we're going to sing. As they were leaving, they stopped right there at the edge and they watched. As they were watching, the house - the one the girl was sitting in - started to go down into the ice, and that was when the mother started crying. She didn't stop. Again, as they came near Pleasant Island [*Wanachích*], another Chookaneidí stood up on the boat again.

We composed two songs, our sorrow songs. And when we have problems, when were thinking of our family that are deceased, and we're going to repay the kindness that was shown by the Raven tribe, that is when we use these songs. I'm really praying that I can perform for you and have the strength; I'll pray the Lord will be with me. Come and stand by me Chookanshába [female members of the clan] and you come too Chookaneidí [male members]. This is the first song, then we will do the second song when we came to Pleasant Island.

First Song

Ahaa haa hei hei
ahaa haa hei heiiiy
ahaa haa hei heiiy
aa haa hei hei
ahaa haa hei

Won't my house
be pitiful
won't my house
be pitiful
when I leave on foot?
hee hee aahaaa
hee hee aa
ahaa, haa, hei, hei, hi.aa aaa

(Repeat first verse and vocables.)

Won't my land
be pitiful
won't my land
be pitiful
when I leave by boat?
hee hee aahaa
hee hee aa
ahaa, haa, hei, hei, hi, aaa

(Repeat second verse and vocables.)

hooooo, hoo, hoo

When they were going to sing the second song, he said to turn the canoes around to face Glacier Bay (these were open canoes--they were not covered).

Then my grandparents sang another song.

Second Song

Ahaa haa aa haa
hei hei aa hei hei
ahaa haaa aaa haa
yei hei hayoo
aa yei hei
aa haa haa

My land,
will I ever
see it again?
shei aanaa haa hayoo
aahaa yei hei hei hayoo
aanaa aaa haa haa
haa haa yei hei hayoo
aahaa haa haa haa

(Repeat first verse and vocables.)

My house,
will I ever
see it again?
shei aanaa hayoo
aahaa yei hei hei hayoo
aahaa aaa haa

(Repeat second verse and vocables.)

a haa haa haa
hooooo hoo hoo.

I heard my great grandchildren singing, and I am proud that they out-sang me.

We ate all kinds of foods here in Glacier Bay. We picked from the soils, the ground, and also from the beaches. The old people never dressed warm and they never got sick. In that day we never thought of stores because there was no such thing as stores. I just finished my 83rd year and I'm really surprised. I have been teaching my grandchildren and great grandchildren the ways that I learned. My granddaughter called from Juneau and wanted very badly to make it but couldn't because one of her daughters was sick.

Thank you for inviting me and for allowing me to take part in this. I feel good looking amongst you and seeing you. Maybe some of you are relatives.

Kenny Grant: In our way it is always a custom to respond with a thank you. In our way when you say thank you you say *Gunalchéesh*. Okay [audience repeats].

I would just like to make one point. I was translating for her, and the story belongs to them, so I'm really nervous when I do it. It's their story and that's the way our people are. These three hats, there is no question they belong to Richard and I and our clan and this one (the Eagle hat) belongs to the Chookaneidí. And the stories that they have belong to them. But I just wanted to let you know that the story that she told was a very heavy, heavy story. It's one that she mentioned earlier was difficult for her to do because their tribal member clan woman was left behind here in Glacier Bay when the ice was coming down and wrecking the houses. And when they were leaving they were all heartbroken of course--they were leaving on the canoe. And when they got out here they composed that first song. And I think you can imagine the weightiness of it. I mean can you imagine leaving your relative behind? There's a long story that goes with it, and they'll tell it--it doesn't belong to me. But that's the gist of that story, and it is really, really heavy. And I know you really appreciate that story, so thank you very much.

Wanda Culp: I'd like to close out the evening with a few thoughts here. What you have seen here tonight is just a small, small part of the rich, rich culture that people hold and the rich, rich culture that we are striving very hard to protect and to keep alive for our great, great grandchildren. Our people knew how to live in this area--this beautiful, wonderful area--and also knew how to utilize the resources to the very utmost. The scientists, I know you look very long and hard at the remnants, the ones that were here. But when you think of Glacier Bay and the presentation you saw here tonight, also think of us as a living culture. We've got a lot of history that we would like to generate, and let it be known that our history is entrenched into Glacier Bay. There's no separating us from this country.

When we had our household everyday dishes and such, we used shells from the beach, or shells for spoons. When we used the mountain goat, the horn was used for ladles; the wool was used for clothing. I heard elders talk about when they would get a mountain goat up in the mountains and butcher it, they would use the stomach to cook with. So there was nothing left behind. Everything we use was made from the animals and what we get off the earth. We don't leave a lot behind. We respect everything that we use, and we don't waste anything. There is a lot that could be learned from our living culture, and we would be here and willing at any time to provide whatever information we could to help fill in the gaps in your research and in your efforts to meet your goals here.

Very quickly, I would like to thank the Friends of Glacier Bay and Greg Streveler. Thank you very much for making us feel welcome and comfortable--I would like you to come and meet our group personally. I want to thank another T'ak̲deintaan, *K̲ashadaheix̲*, Dan Sharclane, our cameraman. And thank you Department of Fish and Game, Division of Subsistence for all your support and help.

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1. *Íx̱t'* in Tlingit meaning "medicine man," "spirit man," or "shaman."

2. This is an abbreviated version of the story. For a longer version of the story, as told by Amy Marvin, see Dauenhauer and Dauenhauer (1987:260-291).

Closing Remarks

Enlarging the Substance and Spirit of the Glacier Bay Symposium

by

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This symposium, like past ones, is heavy on biological and physical sciences; light on the socio-cultural and humanistic. There is good historical reason for this: The interaction of physical and biological forces in this dynamic environment attracted the early scientists here, it moved them to get the parkland set aside as a natural laboratory, and their and their successors' work constitute the great bulk of the science done here.

Resolutions of the first and second symposia to broaden and deepen the spectrum of interests represented at these gatherings have foundered on this historical momentum and simple time constraints, and, with particular reference to this symposium, on a recent series of critical science developments--both locally and in the larger national and international science picture. The park has greatly expanded its science research capabilities over the past two years--fueled in good part by the fisheries studies. The National Academy of Sciences report, "Science and the National Parks," and complementary National Science Foundation initiatives for northern-area research programs have opened vistas of opportunity for parks like Glacier Bay. Secretary of Interior Babbitt's reinstitution of a National Biological Survey (Service) is in part reciprocal to these opportunities and to evermore palpable indications of global change. Thus great flux is in the air, and a park like this, and the scientists who work here in an established nexus of biological and physical sciences, do tend to run with their strength to meet these opportunities--knowing that the searchlight sweeps by, then moves on. So the emphasis for this symposium and its workshops focuses on making Glacier Bay a model "park for science" so it can benefit from and contribute to these moving targets of opportunity.

Given all this, for those of us who helped plan the symposium, this nearly exclusive--however inevitable--focus, has been uncomfortable. We tried to lengthen the meeting to accommodate other interests. But five days plus travel we found was too long for most of you very busy people. And there were other problems.

In sum, the current construct of the Glacier Bay Symposium cannot satisfy the spectrum of interests and values that this park generates among a broad, informed, and committed public. In particular, socio-cultural elements have been add-ons and insertions. They have not been fully integrated into the mainline of symposium business and discourse.

We must find a construct that does this . . . and not only because it's **morally** right to do so. Practically speaking, if we cannot truly integrate human concerns--socio-economic, cultural, esthetic, philosophical, and political--into these symposia, then our ecosystem management aspirations are doomed. If we cannot develop the full spectrum of scientific and human values of this park with these broader-interest constituencies already committed to it, then we shall surely fail in our communications and rationales with the greater uninformed and uncommitted public, which will eventually determine the fate of this park and other protected lands. This is that great public evermore driven to desperation by the closing vice of population/resource disparity. In hard times the politics of scarcity determines. So, there must be generally understood and accepted values across the board in our society if parklands and other protected lands are to survive without armed guards, already standard in many parts of the world. At the grand strategic level, ecosystem management begins here.

Then let us agree that we are not just doing others a favor by opening up these meetings. We need these folks who see and can communicate big pictures to the big public out

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there. And they need both science and philosophy to give weight and substance to their communications.

How do we do it?

A few suggestions to be worked over and given practical form in the final work session Sunday:

1. Let us open up the park's Science Advisory Board to a broader spectrum. Science, after all, like all human activities, is culturally driven and determined. If you doubt that, think how many switches in emphasis and approach you have made in grant applications over the last 25 years.

2. If we lack time to **develop** broader themes and spectra of interest during these symposia, let us have intervening theme and workshop meetings, based on an agenda that covers the many fields of Glacier Bay interest beyond physical and biological sciences.

3. Attendees at such theme/workshop sessions would be weighted toward the selected theme, but would include representatives from other disciplines and interests--scientific, sociological, and humanistic--thus encouraging the desired integrative discourse.

4. The colloquy resulting from these workshops--their multidisciplinary and multi-value exploration of ideas and complementing interests--would allow the oncoming symposium to seek synthesis and integration, rather than be a scene of disparate bits and pieces struggling to be heard.

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The goal of all this--a continuing process through the years--would be mature discourse, a mosaic of patterned purpose, a hierarchy of values and actions in this park. If the Glacier Bay Symposium is to become a productive institution over the long haul, it must reach for those larger, inclusive ideas that order individual effort through the blending of disciplines and interests. Scientists and humanists have to recognize and utilize each others' complementing powers so the composition can be whole.

In making whole our composition here, I take you back again to Dave Bohn's universal thought on Katmai: "I want Katmai to be a place where the advancement of wisdom is practiced." If we can't do that here and in the other chosen places, where can we do it?

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