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Impact Study of Vessel Effects on the Marine and Nearshore Zone, Glacier Bay, Alaska

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James Wuebben[1], Lewis E. Hunter[1], Daniel E. Lawson[2] and Susan R. Bigl[1]

[1] U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road, Hanover, NH 03755

[2] U.S. Army Cold Regions Research and Engineering Laboratory
P.O. Box 5646, Building 724, Fort Richardson, AK 99505

Prepared for
National Park Service
Glacier Bay National Park and Preserve
P.O. Box 140
Gustavus, AK 99826

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NOMENCLATURE

a'	coefficient dependent on bank composition
a	exponent, -0.6 for a jet influence by a channel bottom
a_s	cross-section of ship
A	coefficient that is function of m_n and m_o
A_1	cross-sectional area prior to constriction
A_2	cross-sectional area within constriction
A_c	cross-sectional area of channel
A_j	coefficient dependent on degree of jet limitation
b	a coefficient related to the formation of shoals from eroded sediment
b_n	width of developing shelf per unit time
B	shelf width
B_D	increased width of shelf as water level decreases
B_H	shelf width at a time instant
$\bar{c}$	cohesion intercept
$\bar{c}_d$	degree of consolidation
c_u	degree of underconsolidation
C	non-dimensional constant
C_f	$0.075/(\log u_v L_s/\nu - 2)^2$
d	water depth
d_1	depth prior to constriction
d_2	depth within constriction
d_c	water depth at the cliff base
d_D	decrease in water level
d_e	water depth at which erosion starts
d_p	water depth from propeller axis to channel bed
d_s	draft of boat
d_{swl}	water depth at still-water level (SWL)
D	propeller diameter
D_g	grain diameter
D_o	diameter of the orbital wave
e_i	wave energy for winds of bearing α'
E	total wave energy density
E_i	available wave energy for winds of bearing α'
E_w	available wave energy

f_r	resistive force of cliff material
f_w	erosive force of waves
$f(x)$	function concerning distribution of internal forces
F	function related to propeller diameter $=(\pi D^2)/4$
F_e	total erosive force of waves
F_s	safety factor
Fr	Froude number
g	acceleration due to gravity
G_s	specific gravity of the riprap particles
h_b	average bank height
H	wave height
H_b	breaker height
H_{bw}	bow wave height
H_c	wave height at cliff base
H_{crit}	critical wave height to initiate erosion
H_i	height of wave group i
H_{max}	maximum wave height
H_o	offshore wave height
H_s	near ship wave height
H_{sig}	significant wave height
H_w	generated wave height
i	seepage gradient
i_θ	sediment transport per unit width
I_l	total transport length
k	coefficient
K	constant with units of length over time
K'	dimensionless parameter
K_b	coefficient of bank height, expressed as $h_b \cdot a$
K_e	wash-out coefficient
K_f	coefficient
K_T	thrust coefficient
K_w	coefficient
L_b	ship's beam
L_E	entrance length, distance from bow to parallel midbody
L_f	fetch length
L_{fe}	effective fetch length

L_o	offshore wave length
L_s	ship length
L_w	wave length
m	weight of the stable riprap particle
m_n	coefficient related to nearshore slope
m_o	coefficient related to slope at outer edge of shelf
$M_i(\theta_F)$	$\cos\theta_i\left[1+\frac{\tan\theta_i\tan\bar{\phi}}{F_s}\right]$
M_R	moment of shear strength along failure arc
M_D	moment of weight of failure mass
n	ratio of wave group and wave phase velocities
n_e	effective stress
N_E	effective normal force
p	pore pressure
p_e	excess pore pressure
p_i	excess pore pressure at the base of slice i
$p_{O\,e}$	effective overburden pressure
$p_{O\,m}$	maximum overburden pressure
P	standard wave power function $=Eu_pn$
Q	discharge
r	perpendicular distance from jet centerline
R	coefficient relating to sediment erosion resistance
R_T	total open water resistance
S	wetted surface area
s	shear strength
S_c	compressive strength of cliff face
S_s	shear strength of stratified sediments
t	length of time interval under consideration
t_e	time interval for erosion
t_i	duration of waves of height H_i
t_{sig}	significant wave period, seconds
T	wave period
u_1	velocity prior to constriction
u_2	velocity within constriction
u_j	initial jet velocity

u_l	longshore current
u_m	maximum braking wave orbital velocity
u_o	orbital velocity
u_os	wave motion speed relative to bed
u_p	wave phase velocity
$u_\mathrm{s,max}$	velocity of bottom scour from propeller wash
u_t	critical velocity to initiate motion
u_v	ship velocity
u_w	wind velocity
$u_\mathrm{x,max}$	centerline velocity at distance x_c
u_xcr	velocity at distance x_c from propeller and distance r from jet centerline
u_θ	transport current
U_l	total transporting current
w	width of wind fetch
w_i	weight of slice i
W	total volume of eroded shore material
W'	incremental volume sediment loss over time interval t
x	distance of cliff retreat
x_b	distance from boat
x_c	centerline distance
x_i	internal forces on slice i
x_j	horizontal distance from jet
X	stable shelf width
Y	stable shelf height
z	depth within sediments
z_p	vertical depth to failure plane

Greek

α	angle between the breaking wave crest and shoreline
α'	wind bearing with respect to shoreline
β	nearshore bottom slope/angle of the beach face
γ	total unit weight
γ'	submerged unit weight of soil
γ_b	buoyant unit weight of bluff material
γ_w	specific weight of water
δ_i	frequency of occurrence of waves with height H_i

ε	resistance of shore material to erosion
η	water level rise or wave set-up
θ	transport direction
θ_F	failure arc
λ	scale factor in force equation
ν	kinematic viscosity of water
ρ	water density
ρ_s	grain density
σ	normal stress on the shear surface
Σ	normal force
φ	screw rpm
τ	shear force
$\bar{\phi}$	effective angle of internal friction
ψ	angle off jet centerline
ω	force exerted by waves

EXECUTIVE SUMMARY

Cruise boat visitation in Glacier Bay has risen over 171% in the last decade. This increase followed one of over 144% in the previous decade. At the same time, there has been a marked increase in tour boat, private boat, and backcountry access, the latter being primarily through the use of kayaks. Current vessel quotas for the Park allow more than 500 cruise boats and nearly 500 tour boats to enter between mid-April and the end of September.

Since the primary access to the Park is via the fjords, vessel and visitor impacts will mainly be concentrated on the marine and coastal ecosystems of the inland waterways. The Park Service must balance visitation quotas with its mandate to protect ecosystem productivity and diversity, a crucial challenge for Resource Management. The physical impact of vessels is one of these issues and the subject of this report.

In this report, we evaluate the physical environments that may be impacted, assess the natural physical processes of those environments, examine the potential physical impacts from vessels, define basic data gaps required to evaluate physical impacts that are occurring in the Park, and provide recommendations on future studies necessary to fill the data gaps and assess vessel impacts. This information will provide resource managers and biological researchers with the data required to evaluate ecosystem impacts of vessels and ultimately develop management strategies to meet Park goals.

An analysis of the physical impacts caused by vessels or any other anthropogenic disturbance must consider the wide range of oceanographic, geologic, hydrologic, glaciologic and climatic regimes found in the Park. These regimes interact to control circulation, fresh and ocean water mixing, sediment and nutrient influx, basin configuration, seafloor morphology and sedimentation patterns. These interrelated factors control system dynamics and biological activity in the marine and coastal ecosystems.

The physical environments of Glacier Bay are extremely varied and defy a simple characterization and classification. Highly varied natural conditions include the open waters at the mouth of Glacier Bay; deep basins within the main Bay; numerous unglaciated fjords, bays, and coves throughout the Bay; and large glaciated areas at the heads of the major fjords. Climate across this vast region is highly variable and plays an important role in driving the physical environment and related ecosystems. Climatic parameters affect biological communities, nutrient availability and other parameters critical to habitation, species distribution and abundance. Glaciers, in their role as freshwater and sediment sources, are also key factors affecting biologic activity in the upper reaches of the Bay. Currents, upwellings and mixing zones are important to the marine environment throughout the Bay, but are especially critical to controlling nutrient flux and biologic productivity in the main part of Glacier Bay and its tributary fjords, inlets and coves.

In our analysis, the natural physical processes in potential vessel impact areas can be considered in terms of three environments: 1) shore zone (i.e. bluff, beach, intertidal, nearshore), 2) shallower offshore areas and fjord slopes, and 3) deep water offshore areas of the inlets and fjords. In addition, impacts are also possible within the atmospheric environment and at the interface between the marine waters and the air.

Although the intertidal zone is currently the focus of inventory mapping by Park researchers, as a whole, the physical processes and physical factors of the shore zone have not been studied. Under natural conditions, high-energy wave processes regularly modify and impact the shore zone, but these natural impacts vary temporally and spatially depending on wind patterns and the characteristics of the site being impacted (i.e. shore geometry, orientation and composition). Erosion and deposition patterns will vary in response to the length of fetch, wind speed and wind direction, which determine the amount of wave buildup and the incident angle that waves impinge the shore. Shore zones composed of non-cohesive or of interstratified non-cohesive and cohesive sediments and exposed to the direct impacts of waves will be more susceptible to erosion than those composed of competent bedrock or those covered by boulders. Shore zones in isolated bays or inlets where wave and current energy are limited in strength are also less likely to be subject to erosion.

Processes of the submerged area of the shore zone include wind waves, nearshore currents, ground water flow, slope failure, sediment gravity flow (e.g. turbidity currents, debris flows), and tidal ebb and flood currents. Exposed beaches and bluffs are also affected by: overland flow (sheet, rill and gully), slope failures, gravitational sediment flows, storm and wind waves, tidal flooding, freeze-thaw processes and ground water flow and piping. Multiple interrelated factors determine when and where erosion and deposition take place. Critical parameters are local bathymetry and water depth, configuration of the shore zone profile, extent and type of terrestrial and aquatic vegetation, type of terrain, thickness and composition of sediment, and exposure to wave energy or oceanic currents, and weather.

The shore zone can be exposed to high-energy events as a result of vessel passage. Vessel-generated processes that are similar to natural processes include waves, currents, turbulence and surface mixing. The amplitude, frequency, and duration of waves and currents will likely vary from natural counterparts but there are few studies to define those differences. Although we have identified that vessel traffic can impact physical systems, there are few observations and little quantitative data on vessel impacts within Glacier Bay; studies of vessel impacts elsewhere are therefore examined in terms of the Glacier Bay environment.

In addition, there are insufficient data to assess whether vessel-generated waves and currents can produce significant impacts over large areas of the Bay. A large part of the Glacier Bay coast consists of coarse gravelly beaches or bedrock bluffs that are regularly exposed to high energy storm waves. It is unlikely that short duration vessel-generated waves would have any significant long-term effect on such beach segments. However, in areas where beaches and bluffs are composed of interstratified sand, silt and clay, or of uniform, non-cohesive sand and gravel, vessel-generated waves may significantly modify the shore zone. Here, erosional and depositional patterns may be altered. Undercutting of cohesive sediments by waves and currents may induce a fall or topple failure of bluff slopes. Where slopes are unstable, ship-generated waves or currents may induce failure by slumping, flow or a retrogressive combination of failure mechanisms both above and below the water line. In addition, vessels can generate air, water and noise (aquatic, air) pollution, marine litter, and other visual impacts. There is also the potential for accidents that may generate petroleum, sewage and spills of other hazardous substances. Current structure and velocity, processes that critically affect a spill and determine appropriate response actions, remain poorly defined in Glacier Bay.

Vessel passage through confined channels (i.e., where the shoreline or bottom is close enough to be influenced by ship-generated water movements), such as entrances to restricted bays, coves or inlets, may also cause hydraulic effects in the nearshore and offshore zones. Changes in the pattern and magnitude of water motion may result from ship-generated waves, propeller wash, and drawdown and surge. These changes in flow can, if large enough, cause erosion of the shore zone or scour of the fjord bottom in shallower offshore areas. Increases in turbulence and mixing of the water column may increase suspended sediments, alter water quality parameters, and affect ecological and physiological processes of populations as well as individuals. Turbulence can impact phytoplankton, marine snow, algae and other suspended particles while dispersing solutes and increasing mixing at the air:water interface. Circulation changes may affect nutrient supply and light availability, while scour of the bed will affect grazing by zooplankton and scavengers. Mixing and turbulence can alter larval transport and dispersal patterns. Ship-generated increases in suspended solids may in turn affect benthos, aquatic plants, fish and birds.

The deepwater marine environment of Glacier Bay may be affected by vessel passage, but quantifying the impacts of vessel passage on marine ecosystems is limited by the absence of data on the physical processes active here. Offshore as well as nearshore circulation patterns are poorly known. The extremely high tidal range is well documented, but its role in deep and shallow water circulation is not understood. The range and timing of ebb and flood are known only from predictive models based on few data in the Park. There are virtually no data at the heads of the East and West Arms, nor in many of the restricted bays, coves and inlets throughout the Park. The magnitude of tidal current velocities during ebb and flood, and its seasonal variability are important to understanding biotic community habitation and abundance, as well as larval transport.

Water quality parameters have only recently been examined on a regional basis, but the well-known temperature, salinity and turbidity gradient from the heads of the glaciated fjords to the mouth of the lower bay is without sufficient measurements to delineate it and its seasonal variability. This gradient is potentially critical to understanding the dynamics of marine ecosystems throughout Glacier Bay.

The magnitude and significance of potential vessel-generated impacts depend on a number of local conditions at the site of vessel passage. These include bathymetry, tidal elevation and range, shore material engineering properties, ice conditions, substrate or bottom composition, ground water state, shore zone profile geometry, vegetation cover and composition, weather, and nature and activity of other natural agents such as water currents, suspended sediment transport and wind waves. Because of these factors, the timing of vessel passage is in many instances critical to determining the physical changes that may result from it. In addition, factors that determine the amount of energy expended by a particular vessel will affect how much potential impact may occur. These include the distance of passage from the shoreline, vessel speed, hull shape and size, prop dimensions and shape, draft, and similar factors determining the nature of currents, turbulence and waves generated during passage.

Our preliminary conclusions based on the limited data on the natural processes and physical impacts of vessels, especially within Glacier Bay and similar fjord environments, are:

- Shore zones are not sufficiently characterized in terms of physical processes and factors to determine what impacts vessels may be having on the physical environment of Glacier Bay.

- The deepwater marine environment of Glacier Bay is not sufficiently characterized in terms of physical processes and factors to determine how vessels may affect physical or marine biotic activity.
- Historic data documenting the effects of private boats, commercial fishing, cruise ship or tour boats are extremely limited and a critical data gap to defining the potential impacts of increased usage of Park waters by vessels.
- Basic information and baseline data on the natural physical processes and factors of the deepwater marine and shore zone of Glacier Bay, are virtually unavailable. Basic climatic, oceanographic, hydrologic and geologic data are required to effectively analyze, model and predict vessel impacts on Park resources. This lack of data is a critical gap to understanding vessel impacts on marine ecosystems.
- The physical effects of vessels on the fjord environment and particularly on Glacier Bay have received little study to date. Again, this is a major data gap.
- In order to assess how vessels, whether they be cruise ships, tour boats, commercial fishing vessels, or pleasure craft, impact the natural environment, field investigations are required of various marine and shore zone environments. These analyses must be contrasted with similar analyses where physical and biological systems are not impacted. At the present time, one can only speculate on how such vessels may be affecting the physical environment. In addition, basic physical parameters for the Park, including that of climate, are lacking but required for nearly any biological or physical investigation.

A multi-disciplinary monitoring program is required to document and quantitatively evaluate the effects of vessel traffic on marine and coastal ecosystems. This program needs to address basic regional- and local-scale gaps in knowledge. Investigations should monitor the effects of waves, currents, and acoustic noise at the site level, while examining oceanographic parameters on a larger scale in areas with high vessel use. Ecosystems, biota, and physical zones that are susceptible to disturbance need to be identified and monitored. Individual segments of the shore zone need to be examined independently to evaluate unique conditions in terms of fetch, shoreline orientation, composition and onshore/offshore profile and configuration. Foreshore and offshore areas need to be characterized by side-scan sonar and acoustic bottom profiling to define substrate conditions and related parameters. Beaches with a limited fetch, with an orientation oblique to incident wave directions, and composed of bedrock are not likely to be impacted significantly by vessel waves; however, marine mammals and benthic communities may be affected and these need to be evaluated separately.

In the abiotic system, most impacts will be focused on bluffs, beaches, and intertidal zones in restricted waters and along open waterways where vessel-generated waves are common. Protected shore zones that are in equilibrium with lower energy conditions may be unstable when exposed to periodic, high-intensity wave events generated by nearshore vessel traffic. In the latter case, shore erosion and littoral transport of sediment particles may coincide with the breaking of large, vessel-generated waves. Undercutting of unconsolidated bluffs may result. Currents generated by vessel traffic will most likely be limited to the waters immediately surrounding the vessel, so that distance from the shoreline and vessel speed are critical factors. Minimal littoral currents may also be generated by vessel waves. Unfortunately, the long-term effects of these anthropogenic disturbances to the natural environment are also unknown and thus their effects need to be monitored in terms of the ambient background conditions of the physical systems in the Park.

IMPACT STUDY OF VESSEL EFFECTS ON THE MARINE AND NEARSHORE ZONE, GLACIER BAY, ALASKA

JAMES WUEBBEN[1], LEWIS E. HUNTER[1], DANIEL E. LAWSON[2] and SUSAN R. BIGL[1]

[1] U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road, Hanover, NH 03755

[2] U.S. Army Cold Regions Research and Engineering Laboratory
P.O. Box 5646, Building 724, Fort Richardson, AK 99505

INTRODUCTION

Glacier Bay National Park and Preserve is a vast holding of land and water in southeast Alaska that contains many diverse as well as dynamic marine and terrestrial ecosystems (Fig. 1). More than 500 cruise ships and tour boats enter Glacier Bay National Park each year and up to 468 private vessels are allowed to access the Park during the peak mid-summer season. In addition, commercial fishing occurs within the Park's boundaries during particular seasons and these visits have historically been exempt from vessel regulations. Vessel traffic represents the primary means of transportation to and within the Park by visitors, most of whom never leave their vessels to step on shore either within the Bay proper or in Bartlett Cove at the Park's headquarters. Potential impacts to the Park by such visitation as a whole are therefore focused towards the marine and coastal environments and their ecosystems.

Recent regulation changes have increased quotas for vessel entries into Glacier Bay, presenting the National Park Service with a dilemma. The Park Service is mandated to protect the productivity and diversity of the ecosystems under its supervision, but it must also allow for usage and visitation. In developing an adaptive ecosystem management plan, the Park Service must evaluate the potential impacts that land and water use practices might have on these fragile ecosystems.

The diversity and dynamics of the Glacier Bay ecosystems are largely controlled by the region's physical setting and recent history of deglaciation. Active glaciers, which are in a constant state of flux, remain at the heads of many large fjords and smaller alpine valleys and represent major elements contributing to the region's biosphere. These glaciers release a large volume of fresh, sediment-laden water that creates brackish, nutrient-enriched waters in the fjords, supporting a large, productive, and diverse marine ecosystem. Their activity in the upper reaches of Glacier Bay result in a significant gradient in certain marine parameters, including water temperature, salinity, and turbidity, which ultimately affect biotic diversity and habitat. Intertidal and terrestrial communities that feed off of the glacially regulated marine system are similarly productive.

In this report, we review basic information on the Park's physical environment, and assess the potential impacts of vessel traffic on the marine waters and coastal environment. We review these potential impacts on the physical environment in relation to the natural processes common in Glacier Bay. Our analysis of the literature on vessel impacts revealed few directly applicable studies in an open-water or unconfined marine environment. Studies of vessel effects have concentrated on more restricted freshwater environments, including the Great Lakes of North America, their associated connecting channels, and the Mississippi River. Thus, these effects need to be assessed with respect to Glacier Bay ecosystems, as well as with respect to sustained or increased vessel use in the Park. We present matrices to show these relationships and identify critical data gaps. In addition, because there are only limited data available on the physical systems of the marine and shore zone environments, we develop a study plan to address key gaps in our understanding of the natural setting. Baseline data are essential to evaluating the impacts of vessels on the physical and biological systems of the Park.

BACKGROUND

Glacier Bay was designated a National Monument in 1925 to preserve the glacial environment and plant communities for public enjoyment, scientific study, and historic interest. In 1939, Franklin D. Roosevelt expanded the boundaries to include the ice-covered areas of the upper bay and increased the area of the lower bay to preserve brown bear habitat and coastal forest (Kauffmann 1954). In the Alaska National Interest Lands Conservation Act (ANILCA) of 1980, the monument's designation was changed to Glacier Bay National Park and Preserve and its boundaries were extended north to Dry Bay and the Alsek and Tatshenshini Rivers (Fig. 1). The total area now covers more than 1.3 million hectares, with some 243,500 hectares of marine waters. The United Nations Educational, Scientific, and Cultural Organization (UNESCO) named the park an International Biosphere Reserve in 1986; in 1992, it was also listed as a World Heritage Site. These international designations are in recognition of the natural and cultural significance of the area. The dual status shows that the international community is aware of the uniqueness of this dynamic glacial landscape and its diverse ecosystems, and recognizes the need for site preservation.

As one of 47 Biosphere Reserves in the United States, the Park staff are required to develop adaptive management practices that balance visitation with biodiversity within the framework of the ecosystem, cultural values, and socioeconomic development. Protected "Wilderness Areas" are reserved to conserve and monitor minimally disturbed ecosystems, while other "Managed Use Areas" are sites of research, educational activities, public recreation, and economic activities. Managed uses may include restricted commercial and subsistence fishing, and recreational visitation (e.g., backcountry use, private vessel traffic, and tour boat and cruise ship access).

GLACIER BAY ECOSYSTEMS AND HUMAN OCCUPATION

The terrestrial environment of Glacier Bay is reasonably well known because of a long history of pioneering plant succession studies (e.g., Cooper 1923, 1926; Lawrence 1951; Schoenike 1957; Lawrence et al. 1967) and glacier monitoring (e.g. Muir 1895; Reid 1892, 1896; Cooper 1937; Field 1947, 1964; Goldthwait 1986; McKenzie 1976; Powell 1984; Hunter 1994). Less-well studied, but a prime tourist attraction, is the terrestrial wildlife, including wolf, bear, wolverine, river otter, lynx, deer, moose, sheep, and mountain goat. Freshwater fish include dolly varden, cut-throat trout, and three-spined stickleback.

The marine ecosystem is also widely recognized for its diversity, a diversity that reflects the complex and dynamic fjord environment of the Park. It supports a variety of marine mammals (harbor seal, Stellar sea lion, sea otter, Orca whale, and the endangered humpback whale), and has traditionally been an important site for the fishing industry of southeast Alaska, where over 200 fish species (including salmon, halibut, herring, cod, and sandlance) and shellfish (king, Dungeness, and tanner crab) are found. Sharing the marine and terrestrial ecosystems are 210 recorded bird species (e.g., bald and golden eagle, marbled murrelet, trumpeter swan, and the endangered peregrine falcon; USA 1991). Of these, at least 65 species are migratory seabirds, many of which breed and nest along the rocky shores and stony beaches just above the intertidal zone.

The diversity of ecosystems in the Park reflect in part its geological diversity and topography, and resulting complex spatial and temporal patterns in temperature and precipitation (e.g., Hunter and Powell 1995). Elevation ranges from as high as 4,670 m at the top of Mount Fairweather to a depth of more than 500 m below sea level in the main Bay. Arctic, subarctic, alpine, and temperate rain forests occur within this region. A wide range of coastal, estuarine, and inlet environments characterize the Outer Coast and inland waterways regions.

Human occupation of Park land dates back to about 10,000 years BP (Howell, personal communication, 1999). Recent occupation during the 18th and 19th century includes Tlingit settlements in the vicinity of Excursion Inlet and Point Couverden, and Listi villages in the Dundas River and Dry Bay areas (NPS 1984). Twenty-one seasonal food gathering camps have also been identified in the Park and Preserve. Non-native settlements associated with mining, fur-trading, logging, commercial fishing, and pioneering were common in the early to mid-Twentieth Century (cf., Bohn 1967). Unfortunately, the damp climate and rapidly growing vegetation of the region have obliterated most of these settlements. A few historic structures remain, including the Harbeson cabin (1930s to 1940s) and a cannery complex (from 1898) in Dundas Bay, and the Cape Spencer lighthouse (NPS 1984). Historic sites, such as John Muir’s cabin near Muir Point or the Ibach cabin at the mouth of Reid Inlet, are either overgrown by vegetation or in a state of disrepair.

PHYSICAL ENVIRONMENT

Glacier Bay National Park and Preserve’s physiography is characterized by high mountain ranges (Fairweather and Alsek ranges, and Takhinsha Mountains) that are dissected by numerous large glacial valleys. These valleys form a fjord network that was filled by large tidewater glaciers as recently as the late 18th Century (Field 1947; Bohn 1967; Goldthwait 1986). Within the interior region of the Park east of the Fairweather Range, the two largest fjords are locally referred to as the “East Arm” (Muir Inlet) and the “West Arm” (upper main Bay, Tarr Inlet). Both the East and West arms are regularly visited by cruise ships, tour boats, private boats, kayaks, and commercial fishing boats. Several tributary inlets branch off of these “Arms,” ten of which form deep fjords (Hale and Wright 1979). Glaciers with tidewater margins currently remain at the heads of McBride, Tarr, Johns Hopkins, and Reid inlets, with ice in Muir Inlet retreating out of tidewater only within the last decade (Hunter et al. 1996b; Hunter and Lawson 1998). Glaciers like Rendu, Carroll, and Tyeen periodically surge and approach tidewater. Numerous other glaciers occupy terrestrial valleys and generate large amounts of meltwater that flows into the fjords throughout the Park.

The fjords have average depths from 200–250 m, with a maximum depth of 510 m in the upper Bay south of Russell Island (Pickard 1967; Fig. 1). In cross section, these fjords exhibit the typical catenary (U-shaped) profile that is characteristic of formerly glaciated valleys (Fig. 2). However, the centers of many fjords are filled with over 100 m of glacial sediments (Fig. 2; Carlson et al. 1983; Molnia et al. 1984; Seramur et al. 1997). Entrance sills, shallower areas at the mouths of inlets, bays, and fjords, are common features (Syvitski et al. 1987; Fig. 3). Examples include the sill at the mouth of Glacier Bay and at Muir Inlet, where water depths are only 69 and 62 m, respectively (Matthews 1981). The sill at the mouth of Glacier Bay is a terminal moraine last occupied in the early 1700’s, while that in Muir Inlet is a recessional moraine deposited at the grounding line of Muir Glacier between 1880 and 1899 (Reid 1892; Field 1947). Sills are also located at the mouths of McBride, Reid, and Wachusett inlets, Berg Bay, and other smaller coves and bays, such as North Fingers Bay (Fig. 1).

The historic record of physical activity and environmental change in Glacier Bay includes the best-documented glacial retreat in the Northern Hemisphere, spanning the last two centuries

(Cooper 1937; Field 1947, 1964; Goldthwait 1986; McKenzie 1976; Powell 1984; Hunter 1994). Since Vancouver first observed Glacier Bay in 1794, the main trunk glaciers have retreated more than 100 km. Tidewater glacial recession is continuing in McBride Inlet, while Grand Pacific, Lamplugh, and Reid glaciers appear to be thinning and slowly receding from relatively stable positions (Hunter and Lawson 1998).

Shore zone

The physical character of the shore zone is widely diverse and has not yet been mapped in detail. Recent inventory mapping of coastal resources by the National Park Service (Sharman, personal communication, 1999) is the first attempt at classifying the characteristics of the intertidal zone and developing baseline data to guide future management decisions. This inventory is critical to monitoring future changes in the physical or biological environments. However, this program is still in the early stages and is likely to take another 3 to 4 years to complete.

The Beach Erosion Board (1933) established a standard terminology for describing the shore zone (Fig. 4). The shoreline is the demarcation between water and land, whereas the shore zone is the transitional area between shallow water and dry land. Morphologically, the shore zone consists of several elements that have specific erosional or depositional processes active within them. Individual profiles will vary from the idealized case in Figure 4; in general, one or more of the segments are present, but may be truncated (e.g., the backshore along coastal bluffs) or exaggerated (e.g., the backshore and foreshore along active deltas at the heads of fjords).

Shore zones in Glacier Bay vary from gently sloping mudflats to near vertical bedrock walls and coastal bluffs that extend for some 30 to 50 m above the intertidal zone. Shore zone deposits range from coarse, bouldery sediment near ice margins and along exposed shorelines to silt and sand in restricted bays and inlets (Fig 5). Bluffs abutting the shoreline at high tide are composed mainly of glacial and fluvial deposits, as well as marine sediments that have been raised above the tides by isostatic rebound since deglaciation. The seasonality of the region's climate produces changes in many of the beach's attributes, as do large storms that may occur at any time of the year.

Hydrology

The hydrology of Glacier Bay is largely dictated by glacier and snow melt, and surface water runoff during and following precipitation events. Tidewater and terrestrial glaciers discharge large amounts of freshwater into the heads of the major fjords, producing a longitudinal gradient of increasing salinity in the downfjord direction and freshwater lenses near the fjord heads (Pickard 1967). Although this gradient is known to exist, there are few measurements to quantify its magnitude, seasonal or spatial variability, or its importance to marine biology.

The discharge of meltwater from glaciers begins seasonally in late April to early May and increases until late August or early September. Cessation of melt appears to take place in late September or early October. Most glacial rivers exhibit two peaks in discharge, one in spring and one at the peak of summer melt (e.g., Lawson 1993). Non-glacial streams fed by snow melt and surface runoff typically begin to flow between March and April and likely peak in June or early July. Large precipitation events from storms can occur anytime, generating large volumes of overland flow and flooding conditions. Storms cause significant erosion and sediment discharge into fjords where vegetation is sparse or absent following recent deglaciation (e.g., Cowan et al.

1988). These slopes are commonly covered by steep gullies where water flows only during precipitation events. However, the hydrology of glacial and non-glacial streams in the Park is virtually unknown and poorly understood.

Tides and circulation

Tidal range in Glacier Bay is extreme and therefore tidal dynamics are critical to shore zone development. Semidiurnal fluctuations of nearly 8 m occur during spring tide events in the fall and winter. Tidal fluctuations result in perceptible movement of the waterline during flood and ebb, and result in drastic changes in shoreline configuration between high and low tidal stages. Tidal exchange during storm events can expose large sections of coastal reaches to extreme tidal energy and wave-related erosion. The magnitude of tidal ranges within the upper reaches of the East and West arms and in smaller inlets and bays are relatively unknown and are predicted from circulation models based on relationships to known benchmarks. Circulation patterns associated with tides and other currents are similarly poorly documented or unstudied.

Glacier Bay forms, like fjords in general (Syvitski et al. 1987), a large estuary that is open to the south into Icy Strait (Matthews 1981). It is subject to open circulation during tidal exchange, with an estimated mean tidal current of 80 cm/sec over the Glacier Bay sill and 26 cm/sec over the Muir Inlet sill. Matthews (1981) concluded that Glacier Bay deep water is renewed by saline intrusions over the sill at Icy Strait between November and April and that tidally induced internal waves at depth cause mixing below 60 m. In addition, Muir, Reid, and other inlets having sills at their entrances are estuaries with open circulation during tidal exchange (e.g., Fig. 3).

Circulation of surface waters depends strongly on the level of stratification and fresh water influx to each fjord. Because this stratification may be highly seasonal, partial to complete mixing is possible (Syvitski et al. 1987). Tidal currents, wind, surface cooling due to ice, bathymetry and shoreline configuration, stream discharge, glacial melt influx and other factors will mix the water column to varying degrees. Significant spatial and temporal variability may result in each fjord, as well as between fjords (e.g., McClimans 1978, 1979; Farmer and Osborne 1976; Farmer and Freeland 1983). Some poorly known aspects of water mass exchanges in Glacier Bay include the effects of fresh water influx from tributary streams and glaciers, wind-driven and tidal circulation patterns, and current velocities throughout the water column of the majority of fjords.

Climate

With the exception of temperature and precipitation data at Bartlett Cove, meteorological data within the Park are sparse (limited to seasonal data sets from remote field camps; e.g., Goldthwait et al. 1966). Anecdotal evidence suggests the East Arm receives greater precipitation than the West Arm, but there are insufficient measurements to define the amounts of precipitation each receives. Climatic data are generally insufficient to develop simple, seasonal trends in meteorologic parameters, like air temperature and precipitation. As such, this is a deficiency for any ecosystem analyses.

A preliminary climate model proposed by Hunter and Powell (1995) demonstrated that storm tracks are deflected by the Fairweather Mountains and tend to enter Glacier Bay from the south. Snowlines dip generally southward toward the prevailing moisture source. Precipitation is believed to increase rapidly with elevation according to the adiabatic lapse rate based on studies in the St. Elias Range (Marcus and LaBelle 1970; Marcus 1974). However, there are virtually no data to determine if this relationship holds within the Park.

Ice

Ice is common in the fjords of Glacier Bay, either as sea ice in winter or icebergs year-round. Sea ice forms from frazil ice during calm conditions and subfreezing air temperatures (e.g., Ashton 1986). Growth produces fast ice and pan ice. Fast ice is sea ice that is often attached to the shoreline and can extend up to several kilometers from the coast (Jackson 1997). Pan ice consists of large flat plates that are generally thin and free floating. Pans usually collide, causing the edges to thicken and form relatively thick rims that may harden above the waterline. Pan ice can form when snowfall coincides with calm, subfreezing air conditions. A layer of slush and freshwater forms on the fjord surface and freezes. Tidal currents and wind waves cause the slush layer to break and drift as pans. In the upper reaches of fjords, freshwater discharged at glacier margins may form an ice cover from the growth of frazil ice, or in some cases, from snow forming ice crystals that aggregate and freeze. Meltwater from snow, but perhaps more commonly groundwater, comprises the freshwater discharging from glaciers in winter (Lawson 1993).

Seasonal sea ice is common at the heads of Muir, Reid, Johns Hopkins, Rendu, and other inlets. The orientation and configuration of these fjords often protect the surface water from strong winds. Icebergs collected in front of glaciers provide windbreaks that reduce surface disturbance by wind, cool the surface water as they melt, and develop a thin freshwater lens at the surface through melting. P. Hooge (personal communication, 1999) reported that sea ice in Tarr Inlet extended to Russell Island during the 1998-99 winter. The authors have seen extensive fast ice in Muir, Johns Hopkins and Reid Inlets, as well as smaller coves and bays (Fig. 6). Note that when complete ice covers develop, circulation patterns, as well as temperature and salinity profiles, are changed (Lewis and Walker 1970; Gade et al. 1974; Lewis and Perkin 1982). Boats disrupting an ice cover repeatedly could alter such seasonal circulation patterns.

Ice at the shore commonly breaks or is shoved onto the beach because of the high tidal ranges. An open area may be present here during high tide. Once formed, a stable ice cover of sufficient thickness is not easily broken up by storms. A flexible hinge zone of tidal cracks may form in a narrow band along the shoreline in such cases (e.g., Lake and Walker 1976). There have, however, been no systematic studies of sea ice formation or pan ice distribution within the Park.

Sea ice, frazil, and snow slush can dampen swells and wind waves, and protect beaches when shorefast (e.g., Lawson 1985). Storm and extreme high tides can lift shorefast ice with beach sediments frozen to it, transporting them some distance offshore or onshore. Waves generated by vessels could have the same effect. Currently, cruise ships do not frequent the Park during winter and such impacts will be limited to commercial fishing boats.

Icebergs occur year-round near the heads of fjords with calving tidewater glaciers. Margerie and Johns Hopkins glaciers annually discharge up to a few cubic kilometers of ice; lesser amounts enter the fjords from Riggs, McBride, Reid, Lamplugh, and Grand Pacific glaciers (e.g., Brown et al. 1982; Hunter et al. 1996a). Icebergs range in size from a few cubic meters (brash ice) to several thousand cubic meters. The latter can be traced for several days as they slowly drift downfjord distances of up to 40 km or more (Luthy, personal communication, 1999; Gottler 1992).

Drifting patterns and melting rates of icebergs depend on prevailing wind and tidal currents, and air and water temperatures. No study has attempted to determine what these patterns are in Glacier Bay. Icebergs are a known hazard to vessel traffic, often limiting access to glacier margins by smaller pleasure and tour boats. The larger cruise ships entering Glacier Bay are relatively unaffected by their presence because of the relatively small size of the icebergs; however, much larger icebergs could pose a significant hazard to even large vessels (e.g., Meier et al. 1980).

PHYSICAL PROCESSES

Wind waves

The following discussion provides a detailed description of processes associated with wind waves, especially their dissipation of energy within the shore zone. Waves are among the most important geomorphic processes shaping and maintaining the beach and nearshore zones (e.g., Komar 1998). Anthropogenic waves, such as bow and stern waves generated by vessel traffic, or even power boat-generated waves, are similar to wind waves and can expend sufficient energy to modify shore zones (e.g., Simons and Li 1982). Glacier Bay has over 965 km of shoreline that are continuously exposed to wave and tidal action. Some of these sections are also regularly exposed to vessel-generated waves, particularly those shores along the main bay and Tarr Inlet, which are oriented parallel to the cruise and tour boat routes (Fig. 7).

Once a wave reaches the shore zone, the source of the wave is not relevant to how the wave energy is expended. However two basic differences exist between the two types of waves: duration and character. The duration of time that the beach may be exposed to wind waves may be hours to days in length, whereas vessel-generated waves may last minutes to perhaps an hour.

In addition, the character of vessel waves (frequency, height, form) may differ depending on the source (e.g., Bhowmik 1976, 1978). In order to evaluate potential effects within the shore zone created by vessel traffic, it is important to have an understanding of the natural process.

Net erosion by wind waves depends primarily upon: 1) wind velocity, duration, and effective fetch, 2) nearshore and offshore bathymetry (slope configuration and angle), 3) shoreline configuration, 4) water level, and 5) foreshore, beach, and bluff composition (Kachugin 1966; Wiebe and Drennan 1973; Edil and Vallejo 1980). Because these conditions vary widely, erosion and deposition of sediments by wave activity can vary greatly along adjacent lengths of shore.

The effect of waves on the beach, foreshore, and onshore environment is typically two-fold. First, waves breaking upon the backshore or bluffs causes erosion by applying a variety of forces to the sediments (e.g. Sunamura 1977; Robinson 1977; McGreal 1979) and causing cyclic loading that can progressively increase pore pressures, reduce shear strength (e.g., Seed and Rahman 1977), thereby increasing sediment erodibility. Secondly, swash run-up may cause erosion and abrasion (e.g., McGreal 1979). Sediment eroded and entrained by wave generated currents is added to the littoral transport system and moved either off or along the shore. Deposition of this sediment in nearshore waters is important in developing the equilibrium profile. Offshore bathymetry determines wave refraction patterns and hence variation in the dissipation of wave energy and the development of longshore and rip currents.

The large expanse of water in Glacier Bay is particularly favorable to wave generation when storms track to the south and produce southerly or southeasterly winds. There are large open-water areas, such as the lower bay, with long southeast to northwest fetches where waves can build when exposed to persistent storm-generated winds. This is especially true during the fall and winter, when prevailing winds tend to shift to a more southerly direction and can generate large storm waves (Hunter and Powell 1995). When winds oppose tidal currents, conditions are amplified and high-energy erosional forces can be exerted within the intertidal and beach zones. Currently, there are only anecdotal accounts of the heights that wind waves reach during storms, with waves reported in excess of 2 m in the lower bay during some storm events. However, there are generally no baseline data on natural wave conditions and variability, nor measurements of wind waves or vessel waves under calm or storm conditions.

Erosion and oversteepening of foreshore sediments, especially on the highly unstable sediment of deltas and alluvial fans, can induce subaqueous failures and sediment flows. Extreme storm waves may attack onshore bluffs as well; depending on their composition, significant undercutting of slopes can lead to slope instability and failure in any of several modes.

Wave mechanics

Wind waves are the principal source of energy input to the littoral zone, although where vessel traffic is frequent, vessel generated waves may represent an important energy source and process in causing changes in the shore zone. This may be especially true in restricted inlets and bays where fetch is limited and the equilibrium profile of the nearshore zone has adjusted to these lower natural wave energy levels.

Internal waves, those occurring between water masses of differing density (e.g., in the thermocline) are basin-scale motions whose causes are only partly understood (Mortimer 1971; Roberts 1975; Garrett and Munk 1979; Imberger and Hamblin 1982; Imberger 1998). Such internal waves are common features in fjord environments (Syvitski et al. 1987; Fig 8a), rippled patterns in Figure 8b may be indicative of their activity in the Park. Laboratory and theoretical studies show that internal waves can break and thereby create turbulence and entrain sediment in shallower water above bottom slopes or rises (Southard and Cacchione 1972; Gibson 1998; Fedorov and Melville 1998). Entrance sills such as at the mouth of Muir Inlet may be subject to such forces. Internal waves moving over sloping beds can generate a turbulent benthic boundary layer, which can result in vertical transport of heat and mass, including biologically important materials (e.g., Lemckert and Imberger 1998)

Wind wave character and mechanics

The generation and mechanics of orbital motion and sediment transport by wind waves are extremely complex because of the many natural variables. Thus, many theories have been proposed, each assuming an idealized wave form, motion, and specific boundary conditions. The Shore Protection Manual (USACERC 1984) provides a particularly good discussion of coastal engineering, including techniques for estimating wave properties and interactions with the coastal zone. Nearshore sediment entrainment and movement by waves, current generation by wind waves, and related longshore sediment transport are, however, still only understood in mainly a qualitative sense (Horikawa 1981; Komar 1998).

The interaction of waves with nearshore and coastal sediments, and the propagation of littoral currents, are particularly important for shore zone development, including erosion and sedimentation. Waves are generally described in terms of the wavelength spectra, wave height, and period (Fig. 9). Statistical evaluation of these spectra define the significant wave height (H_{sig}) and the significant wave period (t_{sig}) (Allen 1982). Wave height (H_{sig}) is the average height of the highest one-third of the waves measured over a given period of time, and t_{sig} is the average period of these highest waves. These variables are significant because they relate to wave energy and the potential force that can be applied to the shore zone. Since wave energy is proportional to the square of wave height, H_{sig} measures the modal energy of a particular series of waves (Allen 1982).

The character and intensity of wind waves approaching the shore zone generally depend on 1) wind speed and direction, 2) storm/wind duration, 3) the effective fetch, and 4) water depth (e.g. Bhowmik 1976; USACERC 1984; Muir Wood; Fleming 1981). The longer and harder the wind blows, the larger are the waves and the longer is the time period for decay after the wind dies. Fetch governs the water surface area affected by wind action and, thus, the time for wind energy to be converted into wave energy. It also limits the period and height of waves generated, which is affected by landforms adjacent to the basin as well as basin geometry (e.g. Saville 1954, USACERC 1984). Long-period waves require a long fetch. In fetchs of equal length, the narrower fetch will result in lower wave heights than do open waters (Ippen 1966). Wave heights and periods are similarly dampened in shallow water.

As waves approach the shore, they are increasingly affected by bottom configuration. When water depth reaches about one-half their deep-water wavelength, the wavelength and velocity both decrease and wave height increases (e.g., Eagleson 1956). This change in wave profile results from a disruption of the orbital motion within the wave (Fig. 10). Eventually, the waves become oversteepened and break (Wiegel 1964; Collins 1976; Le Mehauté 1976). This occurs roughly when wave height equals the water depth. Breaking occurs because the velocity of water in the crest exceeds the phase velocity of the wave form (the rate at which the crest is moving forward) (e.g., Wiegel 1964; Galvin 1968, 1972; Collins 1976; Cokelet 1977).

Four types of breaking waves are generally recognized, although they actually represent a continuum responding to beach slope and wave steepness (Fig. 11). Spilling breakers gradually peak until the crest becomes unstable and cascades down as turbulent "white water" (bubbles and foam). In plunging breakers, the shoreward face of the wave becomes vertical, curls over, and plunges downward, striking the surface as an intact mass of water. Surging breakers collapse downward, with the wave surging up the beach face. Collapsing breakers, intermediate between the plunging and surging types, result when the wave overturns below the crest within the forward face, the location being marked by white water (Galvin 1968; Cokelet 1977).

Breaker type depends on the initial wave energy flux, and, thus, offshore wave steepness (H_o/L_o), and on the rate of energy flux input from shoaling, hence, the beach slope (Cokelet 1977). Plunging breakers tend to occur on steeper beaches from waves of intermediate steepness, surging breakers occur on high-gradient beaches with waves of low steepness, and spilling waves occur on beaches of very low slope from waves of high steepness (Wiegel 1964; Fig. 12). On a steep beach, waves steepen rapidly near shore and often produce plunging breakers that collapse and dissipate energy in the narrow, turbulent surf zone (Huntley and Bowen 1975). On shallow beaches, breaker form develops more slowly and waves undergo a steady transformation to a steep, "bore-like" frontal wave that dissipates the energy over a much wider zone. In a fjord setting where water depths plunge rapidly near the shore zone (and other factors being equal), plunging and spilling breakers may be expected.

Sediment entrainment and transport by waves

Sediment transport in the offshore zone is induced by the orbital motions of waves as a combination of bed load and suspended load (e.g., Inman and Bowen 1963; Dingler and Inman

1976; Fig. 13). The initiation of sediment motion and the depth of wave influence are dependent on wave size and period, and sediment properties (e.g. Hakanson 1977). Depths of motion induced by waves of a particular period can be significant; as an extreme for ocean waves with a period of 15 seconds, depths of 100 m or more are possible (Komar and Miller 1975a). In addition, near shore wind-wave induced unidirectional currents may further influence the net offshore transport rate.

Inside the surf zone, turbulence caused by breaking waves suspends bed materials and initiates motion of sediments on the bed (e.g., Eagleson 1959; Eagleson and Dean 1961). Transport takes place both as bed load in a thin layer close to the sea floor and as suspended load within the water column. Komar (1976) states that bed load transport dominates over suspended load transport on beaches, and also that only material that is coarse enough to remain in bed load will remain on the beach. Suspended fine-grained particles get preferentially transported from the beach in nearshore currents.

Komar and Miller (1973) proposed an empirical relationship to estimate sediment motion induced by waves for grains of cohesionless material less than 0.5 mm in diameter. They estimated:

$$\frac{\rho u_{\mathrm{t}}^{2}}{(\rho_{\mathrm{s}} - \rho) g D_{\mathrm{g}}} = 0.21 \left(\frac{D_{\mathrm{o}}}{\mathrm{D}_{\mathrm{g}}} \right)^{1/2} \qquad (1)$$

where u_{t} = critical velocity to initiate motion

D_{o} = diameter of the orbital wave motion

ρ = water density

ρ_{s} = grain density

D_{g} = grain diameter

g = acceleration of gravity

and where the critical velocity and wave characteristics are related by:

$$u_{\mathrm{t}} = \frac{\pi H}{T \sin d\left(2\pi d/L_{\mathrm{w}}\right)} \qquad (2)$$

where H = wave height
d = water depth
L_{w} = wave length
T = wave period.

For coarse sand and larger grain sizes (> 0.5 mm diameter), the empirical relationship changes to:

$$\frac{\rho u_{\mathrm{t}}^{2}}{\left(\rho_{\mathrm{s}} - \rho\right) g D_{\mathrm{g}}} = 0.46\pi \left(\frac{D_{\mathrm{o}}}{\mathrm{D}_{\mathrm{g}}}\right)^{1/4} \qquad (3)$$

Komar and Miller (1975a,b) evaluated the sediment mobilization threshold under various wave conditions, including those shown on graphs based upon eq 1 and 3 (Fig. 14). They found that for a particular grain diameter, several combinations of T and u_{t} are possible: as the value of T grows, the greater u_{t} is. As indicated by the relationship for u_{t} in eq 2, many combinations of water depth and wave height can produce the required u_{t}. Komar and Miller (1975a) and Madsen and Grant (1976) also concluded that the initiation of movement of cohesionless particles under oscillatory, unsteady flow could be estimated using the empirical relationship of Shields (1936), where movement is initiated by a critical tractive force exerted by currents at the bed. Grant and Madsen (1979) suggested that when waves and currents combine, the resulting bottom shear stresses are altered by turbulence at the bed interface and differ from the stress expected for either waves or currents alone. A resistance to flow essentially results that is based on an apparent bottom roughness factor. Turbulence at the bed is greater when currents move in the same direction as the wind waves (Kemp and Simons 1982), which increases the bed shear stress while decreasing current velocities. Additional flume studies by Kemp and Simons (1983) suggested that waves propagating against a current had similar effects on turbulence and velocity near the bed. The depth to which waves initiate sediment movement can also be estimated with eq 1 and 3 (Komar and Miller 1975a). Figure 15 illustrates this effect for different grain sizes of bed material, assuming a wave generated in an ocean with a period of 15 seconds.

The concentration of suspended sediment in waves at their breaking point is high, with the amount varying mainly with breaker type (Fairchild 1972; Kana 1978, 1979). Internally, sediment concentration decreases exponentially above the bed, with coarse bed material intermittently entrained in water near the bed under certain wave conditions (Fig. 13; Muir Wood and Fleming 1981). Kana (1979) analyzed natural waves and found that plunging breakers, like those we would expect along steep fjord shores, entrain one order of magnitude more sediment than spilling breakers. Plunging breakers are particularly important in scouring beach sediments because they develop large, near-vertical velocity vectors at impact (e.g., Adeyemo 1971; Cokelet 1977; Allen 1982a). Sediments scoured by plunging breakers are normally moved as part of the swash and backswash of water across the foreshore because of the inertia from the breaking waves. Suspended fines and coarser particles rolled up the beach face may be entrained within nearshore currents.

During breaking and run-up of waves, distinct and significant variations take place in the water table of the beach sediments (e.g., Grant 1948; Waddell 1973, 1976; Chappell et al. 1979; Kondratjev 1966). Under swash and backswash, oscillations in groundwater create a zone that is periodically saturated or unsaturated. Under unsaturated conditions, water flows into beach sediments and localized deposition is favored. When saturated, infiltration cannot occur, and previously deposited sediment can be eroded. This is particularly important on sandy or coarser beaches because infiltration adds to the effects of gravity and friction in causing cessation of the swash motion. Kondratjev (1966) suggested that pressure variations on the bottom because of oscillatory wave motion may induce water flow into pore spaces and energy dissipation. In coarse-grained gravel beaches, he estimated inflow to pore spaces to absorb half the available energy and used this concept to explain the lower angles of slope in run-up areas of beaches composed of finer-grained material and the higher slope angles on coarse-grained beaches.

Chappell et al. (1979) concluded that rises in the water table in sediments beneath and landward of the beach face, which are covered by steadily rising water levels from tides, takes place as a slow wave of diminishing amplitude and increasing time lag. Under a rising water table, pressure waves propagating into the water table from breaking waves can induce slumping by initiating liquefaction of sand (e.g., Fig. 16). Lowering the water table induces sand deposition and also reduces the tendency for such liquefaction. Chappell et al. concluded that this factor is important in beach failure and slumping when water levels rise during storms.

Models of shore zone development and erosion

The attack of water on beach and bluff sediments has usually been quantitatively related to the dissipation of energy from waves and related currents in the nearshore zone (e.g., Rossmann and Seibel 1977; Miller 1976; Kondratjev 1966; Kachugin 1966; Quigley and Gélinas 1976; Sunamura 1977, 1982a and b; Black 1980; Carter et al. 1981), although the relationship of wave energy to the rate and amount of bluff erosion has not yet been satisfactorily established (Edil and Vallejo 1980). No analyses have quantitatively defined the importance of wind waves as an erosional process in relation to other processes that cause coastal retreat. However, wave-generated currents caused by strong onshore winds can transport sediment as suspended and bed loads after its mobilization by waves. Erosion ceases after the shelf reaches a width B, over which all available wave energy will be dissipated before reaching the backshore and bluff zone (Fig. 17).

The morphology of the stable shelf is defined empirically by Kondratjev (1966) as

$$X = AY^2 + \frac{1}{m_\mathrm{n}}Y \qquad (4)$$

$$\text{where} \qquad A = \frac{m_\mathrm{n} - m_\mathrm{o}}{20m_\mathrm{n} \cdot m_\mathrm{o}} \qquad (5)$$

and m_n is related to the slope of the shelf near the shoreline, and m_o is related to the slope at the outer edge of the shelf where wave action ceases. Values for m_n and m_o are given by Kondratjev. Variable Y is shelf height between the water's edge and depth d_e, at which erosion starts, and is dependent upon wavelength, wave amplitude, and the nature of the shelf sediments (Fig. 17). Variable X is the stable shelf width.

The width of the shelf B_H at some time t is therefore defined by

$$B_\mathrm{H} = A{d_\mathrm{e}}^2 + \frac{1}{m_\mathrm{n}}d_\mathrm{e}\,. \qquad (6)$$

If the water level decreases, this modifies B_H by

$$B_\mathrm{D} = d_\mathrm{D}\left(2Ad_\mathrm{e} + \frac{1}{m_\mathrm{n}}\right) \qquad (7)$$

where B_D is the increase in width of the shelf and d_D the decrease in water level height on the shore face. Thus, total shelf width would be

$$B = B_\mathrm{H} + B_\mathrm{D}\,. \qquad (8)$$

Kondratjev (1966) further expands his concept to include wave action, by assuming wave action is the only erosive force, and its resultant dispersal of energy transports the eroded material. This equation is

$$W = W'\left(1 - 1^{-Rt_e}\right) \qquad (9)$$

which relates W, total volume of shore material eroded, to the incremental loss in volume of sediment W', over a given interval of time, t_e, where R depends upon the resistance of shore sediments to erosion determined by various iterations of the following equation,

$$\Delta t = \frac{\varepsilon B_H - W'}{\overline{N}} \ln \frac{B_H - b_n}{B_H - b_{n+1}} \quad . \qquad (10)$$

This equation accounts for the volumetric loss of shore material W' over a given time interval Δt and in response to a total wave energy $\overline{N}$ per unit length of shore. The variables b_n and b_{n+1} indicate the width of the developing shelf at the beginning and end of the time interval under consideration. The variable ε is the resistance of shore materials to erosion by wave action. By varying $\overline{N}$ for various water levels, the total volume of eroded material and the volumetric loss W can be determined. Thus, in eq 9, t_e would equal $\Sigma\Delta t$.

Kachugin (1966) has empirically related the quantity of material eroded W to available wave energy E_w by

$$W = E_w \cdot K_e \cdot K_b \cdot t^b \qquad (11)$$

where K_e = wash-out coefficient

K_b = a coefficient of bank height, expressed as $h_b \cdot a'$

h_b = average bank height

a' = coefficient dependent upon bank composition

b = coefficient related to the formation of shoals from the eroded sediment, which varies with the dimensions and dispersal of eroded sediment in the foreshore.

E_w is determined by wave climate studies and two simple relationships

$$E_i = e_i \sin(\alpha') \tag{12}$$

where e_i is the wave energy for winds of a given bearing α' with respect to the shoreline, and

$$E_w = E_1 + E_2 + E_3 \cdots + E_i \ . \tag{13}$$

The parameter *a'* also varies with K_e; values are given by Kachugin (1966). Variations in bank height with time are used to account for water level fluctuations. Thus, *W* is the volume of eroded sediment per unit length of the shore under the total energy of waves attacking the shore zone.

K_e is essentially a measure of the erodibility of bank materials under the action of waves. Readily eroded sediment, such as sand and sandy loam, have larger washout coefficients than much less erodible cohesive sediment such as clay and clayey silt. Kachugin (1966) presents empirical estimates of K_e for different sediment types.

As with Kondratjev's (1966) concept, Kachugin's model assumes that eroded sediment is moved offshore a distance determined by the strength of the unidirectional nearshore currents and, thus, wave energy. Longshore currents are equally important in moving washout material away from the eroding shore. Bars develop at a certain distance offshore, their location controlled by these factors (Kachugin 1966). Coarser sediment is assumed to be deposited in nearshore shoals that are continually reworked by waves.

Once *W* is calculated, the quantity of eroded sediment is used to estimate the width of the zones from which shore material is eroded over fixed time periods. Kachugin (1966) used characteristic beach profiles for average bank heights along the shore reaches of interest to estimate graphically the expected shore zone modifications.

According to Sunamura (1977, 1982a,b), long-term rates of sea cliff erosion are quantitatively related to the erosive force of waves. Based upon laboratory wave tank experiments that were confirmed by previous field and laboratory data, this proportional relationship is expressed as

$$\frac{\partial x}{\partial t} \propto F_{\mathrm{e}} = \ln\left(\frac{f_{\mathrm{w}}}{f_{\mathrm{r}}}\right) \tag{14}$$

where $\partial x/\partial t$ is the erosion rate and F_{e} the erosive force of waves. F_{e} is defined as being proportional to $\ln\left(f_{\mathrm{w}}/f_{\mathrm{r}}\right)$, where f_{w} is the erosive force of waves and f_{r} is the resisting force of the cliff material.

Resistance of rocks to wave erosion is obviously controlled by their mechanical properties and structural features, such as joints or stratification, which can act as planes of weakness. Weathering coupled with wave action will reduce their effective strength or erosive resistance with time. Sunamura (1977) concluded that erosion of rock cliffs by breaking waves and by waves during runup could be expressed by

$$\frac{\partial x}{\partial t} \propto \left(\ln\left(\frac{\rho\, gH_c}{S_{\mathrm{c}}}\right) + C\right) \tag{15}$$

where S_{c} = compressive strength of cliff face rocks
ρ = density of water
H_{c} = wave height at the cliff base
g = gravitational acceleration
C = a non-dimensional constant.

Both C and the proportionality factor are defined by field data.

Sunamura (1982a) slightly modified this equation to account for short-term recession of bluffs composed of sedimentary rocks over a given time interval, so that

$$\frac{\partial x}{\partial t} = K\left(C + \ln \frac{\rho\, gH_c}{S_{\mathrm{c}}} \right) \qquad (16)$$

where K is a constant with units of length over time. Integration of eq 16 defines x, the total distance of cliff retreat with time. Thus,

$$x = K\left(C + \ln \frac{\rho\, gH_c}{S_{\mathrm{c}}} \right)t \qquad (17)$$

can be used to estimate the distance of bluffline recession or coastal retreat. Furthermore, the critical wave height to initiate erosion H_{crit} is defined as

$$H_{\mathrm{crit}} = S_{\mathrm{c}} e^{-\mathrm{C}} / \rho g\ . \qquad (18)$$

Because variability in wave height with time at a location can be expressed as a frequency distribution, cliff retreat caused by a given group of waves of height H_{i} is

$$x_{\mathrm{i}} = K\left(C + \ln \frac{\rho\, gH_{\mathrm{i}}}{S_{\mathrm{c}}} \right)t_{\mathrm{i}} \qquad (19)$$

where $t_{\mathrm{i}} = \delta_{\mathrm{i}}\, t$

t_{i} = duration of waves of height H_{i}

δ_{i} = frequency of occurrence of waves with height H_{i}

t = length of time interval under consideration.

δ_{i} is simply the number of occurrences of waves of H_{i} divided by the total number of occurrences of all waves during the time interval.

Under field conditions, the critical wave height H_{i} is not immediately known. Therefore, the total distance of bluffline recession can be initially expressed as a summation of the erosion caused by each wave height impinging on the bluff. If H_{j} is arbitrarily assumed to represent the critical wave height at a location and the waves of a height less than H_{j} are assumed not to cause erosion, the length of recession is

$$x = \sum_{\mathrm{i=j}}^{\mathrm{n}} x_{\mathrm{i}} = \sum_{\mathrm{i=j}}^{\mathrm{n}} K\left(C + \ln \frac{\rho\, gH_{\mathrm{i}}}{S_{\mathrm{c}}} \right)\delta_{\mathrm{i}} t \qquad (20)$$

where n is the largest observed wave height. By repetitively solving this equation with field data for each H_{i}, the values of C and K can be computed for

$$K = x / t \sum_{\mathrm{i=j}}^{\mathrm{n}} \left(C + \ln \frac{\rho\, gH_{\mathrm{i}}}{S_{\mathrm{c}}} \right)\delta_{\mathrm{i}} \qquad (21)$$

and

$$C = -\ln \frac{\rho\, gH_{\mathrm{i}}}{S_{\mathrm{c}}} \qquad (22)$$

from eq 20 and 16, respectively.

In practice, data on wave heights at the cliff base are not always available. Offshore wave height, however, can be used to estimate H_{c} with the empirical relationship

$$\frac{H_c}{d_c} = 0.78, \qquad \text{with } d_{\mathrm{c}} = d_{\mathrm{swl}} + \eta \qquad (23)$$

where d_{c} = water depth at the cliff base

d_{swl} = water depth at still-water level (SWL)
η = water level rise or wave set-up (Fig. 18).

An empirical relationship gives η as:

$$\eta = -(3.95 \tan \beta + 0.015) d_{\mathrm{swl}} / (1.63 \tan \beta + 0.048) H_{\mathrm{b}} \qquad (24)$$

where tan β is nearshore bottom slope and H_{b} is breaker height (Fig. 18). H_{b} can be estimated from offshore wave height H_{o} and wave length L_{o} by:

$$H_{\mathrm{b}} = 0.563 H_{\mathrm{o}} \big/ (H_{\mathrm{o}} / L_{\mathrm{o}})^{1/5} \qquad (25)$$

While Sunamura developed these equations for eroding cliffs composed of sedimentary rock, the compressive strength S_c, which represents the mechanical strength of the bluff material, could be replaced with tensile strength or shear strength because these indices are closely related and not independent of one another (Sunamura 1982a). Thus, it seems reasonable that substituting a shear strength S_s for S_c may be representative of erosion of bluffs composed of homogeneous, unconsolidated material. Furthermore, bluffs composed of stratified sediments with highly variable structure and composition could be represented by either a smallest value for the weakest material under wave attack, or as a summational effect by solving eq 20 several times to simulate the variability in response of the individual strata.

Sunamura's (1982a) field observations indicated that eq 16 and 17 adequately represented cliff erosion rates and coastal retreat at two sites in Japan where toe erosion resulted from waves activities. These bluffs were not subject to large-scale mass movements or other erosional processes to any great degree. At each site, the larger, but less common, waves caused most cliff erosion while smaller waves were important only in removing erosional products that had fallen to the cliff base. His data also showed that recession rates of beach sediment are apparently related directly to the occurrence frequency of waves above the critical height that caused erosion.

Bhowmik (1976, 1978) presented an equation for estimating significant wave height (H_{sig}) and applied it in analyzing the stability of riprap used for bank protection against wind waves. At a bank location, wave conditions are evaluated with a time series analysis for estimating changes in wave height with time. Bhowmik derived the equation

$$\frac{gH_{\mathrm{sig}}}{u_{\mathrm{w}}^{2}} = 3.23\times10^{-3}\left(\frac{gL_{\mathrm{fe}}}{u_{\mathrm{w}}^{2}}\right)^{0.435} \qquad (26)$$

to determine the significant wave height when the wind velocity u_w, effective fetch length (L_{fe}), and wind direction are known. ($L_{fe} = 1.054\, w^{0.6}\, L_f^{0.4}$ where w is width and L_f is fetch length). The parameter g is acceleration due to gravity. This equation is based on relationships proposed by Sibul (1955), Saville (1954), and Saville et al. (1962), and was tested with field data collected in the Carlyle Lake impoundment in Illinois.

Bhowmik (1978) also analyzed the stablity of single riprap particles against the forces generated by breaking waves (Fig. 19). After analyzing the forces acting on particles, he derived the equation

$$m = \frac{kH^3 G_s}{\gamma_w{}^2 (G_s - 1)^3 (\cos\beta - \sin\beta)^3} \tag{27}$$

where m = weight of the stable riprap particle

k = coefficient (values defined in Bhowmik 1978)

G_s = specific gravity of the riprap particles

γ_w = specific weight of water

β = angle of the beach face

H = wave height.

This expression makes the reasonable assumption that the depth of water at which the wave breaks equals the wave height. Hudson (1959) also made an analysis of wave forces and derived a similar relationship.

Bhowmik (1978) presents a nomograph based upon eq 27 for estimating the median size particle that is stable under existing wave conditions. He indicates that an estimate of bank width needing stabilization must be calculated and this estimate depends upon expected low water level and maximum high water level plus freeboard. Freeboard, the highest effective location of wave action (Saville et al. 1962), depends upon wave height, wave runup, and tide.

Nearshore currents

Waves entering shallow water undergo refraction, which causes their crests to become nearly parallel to the shoreline by the time the waves reach the beach (Fig. 20; e.g., Bretschneider 1966). However, where deep waters lie close to the shore, the waves may impinge on the beach at widely divergent angles from the shoreline trend and induce longshore currents that can transport sediment (Komar and Inman 1970; Longuet-Higgins 1970a,b) and cause erosion of the shoreface. As waves approach the shore, bottom topography influences refraction and reflection patterns (e.g., Munk and Traylor 1947). Waves refract and flow lines diverge over deeper water areas, whereas they converge over shallows where wave energy is greater because of increases in wave height (Fig. 21). Intense areas of erosion and shoreline recession may, thus, be correlated to wave convergence over nearshore shallows (e.g., Maresca 1975). Hence, shore zone morphology is partially controlled by offshore bathymetry (Fico 1978; Fig. 22).

Sediment transport by currents

Longshore currents are the primary process transporting sediment in the littoral zone; however, such transport varies with wave energy, steepness, and angle of approach (Inman and Bagnold 1963). Generally, total net transport results from the orbital velocity of incoming waves (which places beach sediments in motion) and the longshore, rip, and currents normal to the shoreline (such as those generated locally by the wind) that transport sediment along the shore or directly into offshore regions (Bagnold 1963; Komar and Inman 1970; Komar 1971; Fig. 23). Total net transport is approximately proportional to wind stress and current velocity; therefore, the rate of movement is maximum near the breaker line, and decreases shoreward. Movement caused by combined waves and currents has been described by Komar (1971) as a zig-zag motion (Fig. 24). Each incoming wave drives particles up the beach at an oblique angle, determined by the approaching wave, with the return flow (backswash) driven by gravity that moves the particle to its original level on the shore.

According to Bagnold (1963), the orbital motion of waves moves sediment back and forth after initially suspending it into the water column. Net transport, however, only results from the unidirectional currents that are present. Thus,

$$i_\theta = K'\omega \frac{u_\theta}{u_o} \tag{28}$$

indicates the sediment transport per unit width i_θ occurring in the direction θ under a current u_θ, where u_o is orbital velocity, K' a dimensionless parameter, and ω represents the force exerted by the waves (Fig. 25). Thus ω/u_o is the stress exerted by the waves. To estimate total sediment transport for breaking waves, Inman and Bagnold (1963) applied this relationship by assuming that the wave energy flux per wave crest ($P \cos \alpha$) is lost in initiating sediment motion. Thus, the stress applied to the beach sediments is proportional to $P \cos \alpha/u_{os}$, where u_{os} is wave motion speed relative to the bed and is proportional to u_o before the wave breaks in the surf zone. For a location with a longshore current of velocity u_l, total transport I_l (e.g., Komar 1976) is as follows:

$$I_l = K' P \cos\alpha \frac{u_l}{u_{os}} \tag{29}$$

where P = standard wave power function = Eu_pn
E = total wave energy density
u_p = wave phase velocity
n = ratio of wave group and wave phase velocities
α = angle between the breaking wave crest and the shoreline.

Komar and Inman (1970) indicated that for K' values of 0.28 and $u_{os} = u_m$ (the maximum orbital velocity under the breaking wave), eq 29 gave a reasonably good prediction of littoral sediment transport for wave and current interaction. Also, by using wave parameters based on hindcasting techniques of waves generated by storms, littoral transport rates can be grossly estimated (e.g., USACERC 1984).

Onshore/offshore sediment movement

The interactions among wave-induced oscillatory motions, unidirectional currents, and onshore-offshore sediment movement create changes in the equilibrium profile of the beach and shore zone. McGreal (1979) concluded that short-lived, temporal variations in erosion rates were largely explained by changes in beach-profile configuration and elevation, while along-shore changes were related to geographical aspects. Weischar and Wood (1983) found that longer-term shifts in beach profile could be correlated directly with wind and water level changes.

Variations in shore profiles are associated with changes in storm activity and wave intensity (e.g., Shepard 1950b; Bascom 1954; Aubrey 1979) caused by intense wave activity during a single storm (e.g., Davis et al. 1972; Hayes and Boothroyd 1969; Fig. 26). Summer and winter profiles result from annual variations in shore processes associated with shifts in storm tracks. Other parameters clearly related to onshore or offshore shifts in sediment are wave height and period (e.g., Shepard and LaFond 1940; Shepard 1950a,b; Bascom 1954; Gorsline 1966). Onshore-offshore shifts in sediment may result from currents generated by coastal winds (e.g., King and Williams 1949; Shepard and LaFond 1940; King 1953; Seibold 1963; Weishar and Wood 1983) and by tides (e.g., Strahler 1966; Duncan 1964).

Offshore moving sediment is usually deposited in one or more longshore bars with troughs on their shoreward side (e.g., Evans 1940; Shepard 1950a; King and Williams 1949; Davis et al. 1972). Bars migrate onshore during non-storm periods (e.g., Davis and Fox 1972) with their location and size being controlled by breaker position, wave height and wave steepness (e.g., Keulegan 1948; Felder and Fisher 1980). Plunging breakers appear most conducive to bar development (Shepard 1950a), with the deeper waves generating larger bars (Keulegan 1948).

Shore zone instability and failure

Fjords, including nearshore areas and beaches, are commonly subject to massive subaerial and subaqueous slope failures (Syvitski et al. 1987). In recently deglaciated areas, vegetation is often insufficient to stabilize sediments, commonly resulting in creep and other forms of gravitational failure (Fig. 27). At the margins of active tidewater glaciers, such as Johns Hopkins or Margerie Glaciers, or along active deltas where streams discharge sediment-laden water into the fjord, sediments become highly oversaturated and oversteepened, making them unstable and subject to failure. Hunter et al. (1996a, b) and Powell et al. (1991) have observed these conditions in both Muir and Tarr Inlets.

Sediments transported downslope to the shore zone remain highly erodible by streams, waves and other oceanic currents. In addition, oversteepening caused by rapid deposition at the shoreline can produce unstable slopes, which can fail in response to several factors. Deltas and alluvial fans are well known for generating submarine mass movements (e.g. Prior et al. 1982; Bornhold 1983; Syvitski and Farrow 1983 Syvitski et al. 1987; Fig. 28). In other areas, sediments deposited on the sidewalls of fjords are often quasi-stable and subject to subaqueous failure (e.g., Terzaghi 1956; Prior et al. 1981; Powell et al. 1991; Farrow et al. 1983). Such instabilities in shore zone materials need to be considered in determining vessel impacts where failure can result from many processes that cause a loss in strength or reduction in resistance. In addition, an unstable substrate disrupts benthic organisms and the repetitive failure and movement of submarine sediments inhibits habitation (e.g., Chapter 6, Syvitski et al. 1987).

Subaerial and intertidal failures

The nearshore and onshore areas in Glacier Bay are highly variable. No single type exists. Near-vertical faces with deep water adjacent to them contrast with low angle, gently sloping materials that extend 100 m or more offshore (Fig. 5). Bedrock or sediments can compose these vertical slopes. Cohesive sediments, such as marine clays and silts, and non-cohesive sediments, such as fluvial gravels and sands are present, typically being interstratified with one another. Diamictons, or till, are glacial deposits with a variable mix of clay- to boulder-size materials, and they may be cohesive or non-cohesive and heavily compacted (e.g., submarine or subglacial tills) or loose (e.g., ice-marginal and subaerial tills). Boulder fields are also common along the shore areas (Fig. 5). Some of these originate from supraglacial moraines deposited from retreating glaciers, whereas others are lags from diamictons, the fines having been winnowed out by waves and currents.

Our observations throughout the Park reveal that many sections of the shore are undergoing failure or appear to be poised to fail. Failure introduces sediment into nearshore as well as offshore zones, locally increasing turbidity and disturbing the substrate for benthic organisms. In highly unstable materials, a stable substrate may not develop.

The importance of these observations is that natural and anthropogenic forces can induce failure of bluff, beach, and nearshore sediments. A vessel may create instability through a variety of processes. These include ship wave undercutting of bluffs, vibrations (acoustic, process-generated) that induce movement by decreasing sediment resistance, or flooding of intertidal areas by wave surge at low tide that can alter the ground water table and saturate sediments.

The rapid and sometimes extensive recession of bluffs and beaches result from a loss of stability and the failure of these sediments (Fig. 27). Such failure can occur in concert with the failure of materials below the waterline. Most studies to date have analyzed the failure and movement of natural slopes and bluffs along rivers and lakes. The results of these studies are generally applicable to the problem of shore zone stability and instability in fjords.

Stability

In general, every mass of sediment beneath a sloping ground surface or within vertically cut faces has the tendency to move downward under the influence of gravity. The resistance of the soil mass to the force of gravity determines the immediate stability of a slope; if it counteracts this force, the slope is considered stable. As defined by Casagrande (1936),

> "Stability of a soil mass refers to the equilibrium of all external and internal forces with the resistance of the soil, including the force of gravity, seepage pressures, and any possible artificial disturbances due to construction activities, etc., as well as the effects of earthquakes. Stability does not refer to the amount of deformation which these forces produce, as long as the shearing resistance of the soil is not utilized to its ultimate limit.
>
> The stability of a mass of soil is not an individual property of the material like the specific gravity, permeability, compressibility or angle of internal friction, which can be measured on a sample of the soil and expressed by a single quantity. It is a combined effect of one or several of such individual properties and of numerous other factors, particularly the character of the forces to which the soil mass may

> be exposed, its dimensions, various local conditions, and possibly other factors which are not sufficiently known …”

Thus the loss of stability or the creation of an unstable condition can result from processes that either modify the balance between the external and internal forces, or that alter the properties and hence shear strength of the materials themselves.

Because numerous and often complexly related factors can determine the stability of a particular slope, it remains extremely difficult to predict the stability or failure of natural slopes (Peck 1967). Thus, methods of stability analysis (e.g. Morgenstern and Sangrey 1978) require the careful and deliberate use of sound engineering and geological judgment in their application. Geologically complex situations remain largely beyond the scope of such analyses and a need still exists for basic scientific knowledge of the causes, mechanisms and critical, controlling factors of failures under natural conditions (Skempton and Hutchinson 1969, Patton and Deere 1971).

Loss of stability

The loss of stability and cause of slope movements in the nearshore, beach, and bluff zones can result from: 1) changes in material properties by degradational processes that reduce the strength of sediments, and 2) external disturbances or erosional processes, such as the undercutting of the bluff by waves or currents, that reduce the resistance of the sediment mass to the force of gravity (e.g. Kachugin 1970). Water generally appears to be the most important agent altering material properties and reducing the shearing resistance of natural slopes (Cedergren 1977). The mechanics of failure depend upon the size, geometry and structure of the bluff or beach slope and the engineering properties of the bluff material (Thorne 1982). It is important to recognize that these factors are not static, but will change with time, season, and exposure (Vallejo 1977).

Along river banks, degradational and erosional processes are mainly fluvial entrainment at the bluff toe and interactive processes of weakening and weathering of the intact bank material (Thorne 1978, 1982, Hooke 1979, 1980). River bed degradation may also result in an effective oversteepening of an adjacent bank slope (Patrick et al. 1982). Along the Great Lakes' shores, similar bluff degradational processes are active (Edil and Vallejo 1977, 1980), but the principal erosional process at the bluff toe is wave action (e.g., Chieruzzi and Baker 1958, Hadley 1976, Hadley et al. 1977a,b, Vallejo 1977, Quigley et al. 1978, Edil and Vallejo 1980, Birkemeier 1981). Both situations provide analogs for bluff failures in reservoirs.

Bluff stability may be modified by undercutting and formation of a cavity or niche at its base by waves and nearshore wind-driven currents, especially during storms (e.g. Kachugin 1970, Reid 1984). Fluctuating water levels allow the height of this niche to be greater than the wave height, assuming sufficient stability exists in the overlying sediments to allow for niche growth. Generally sands or other cohesionless materials tend to slough from a face almost immediately (e.g. Fisk 1952, cover photo). Gradual reduction in stability of cohesive sediments by toe erosion may result in failure by slip or flow (e.g. Hutchinson 1983). Cohesive sediments may resist failure sufficiently to allow blocks of material to be cantilevered over the water surface until some critical distance is reached at which the overlying material fails and the block falls (e.g. Thorne 1978, Birkemeier 1981). Joints, fissures or other near-vertical discontinuities may act as planes of weakness along which failure may take place before the material itself losses its stability (e.g. Deere 1957).

Sheet flow, rill erosion and gullying are important in physically removing sediment from the bluff face and can result in the loss of stability in the remaining particles or blocks of sediment between the rills or gullies. These processes affect soil moisture and ground water flow conditions (e.g. Vallejo 1977). Raindrop impact and creep have similar effects. Wind may also winnow out finer sediments when bluff materials are dry, thereby freeing coarser particles to fall to the base of the bluff. In composite banks, layers of cohesionless materials may selectively fail, causing each overlying cohesive layer to be cantilevered over cavities formerly filled with the cohesionless materials. Locally, removal of bluff sediments by erosional processes reduces overburden pressures and may allow stress relief and spalling in fissured or jointed consolidated sediments. For each of these processes, their overall impact will depend upon-factors such as slope angle, extent of the vegetation cover, soil moisture content, material types and properties, and local climate (e.g. Carson 1971, Bodenko et al. 1978, Thorne 1980, Edil and Haas 1980).

Internal changes in the strength of bluff sediments can result from several processes not always evident at the bluff surface. Of primary importance are changes in soil moisture, pore pressures and seepage pressures. Seepage, in general, reduces slope stability. Zaslavsky and Sinai (1981) have concluded that seepage may actually predominate in causing surface erosion, including that within rills. These changes can be brought about by a rise in the water table, as when the water level rises due to the flood tide or storm surges.

Movement of water through bluff materials can leach out soluble chemicals or clay particles, thereby reducing their shear strength with time (e.g. Terzaghi and Peck 1967, Kachugin 1970). Leaching may be especially important in loss of stability of sensitive or “quick” clays (e.g., Smalley 1976, Carson 1977). “Quick” clays are those deposited slowly in marine waters and their structure makes them highly sensitive to vibrations from any number of sources. It is unknown if such materials exist in the Park, but their existence is probable.

Similarly, seepage pressures due to ground water flow out of bluff faces may reduce their effective stress. Piping can wash out near-surface sediments within the bluff face, thereby undermining other material within the face (e.g. Deere 1957, Kachugin 1970, Edil and Vallejo 1980). Reduction in shear strength sufficient to cause failure may be confined within fracture zones or individual strata as pore water pressure rises and may result in slip along or within such effective planes or zones of weakness (e.g. Casagrande 1936, Terzaghi 1950).

Freezing of water within pores or fissures heaves soil particles apart, physically loosening or detaching the sediments and reducing strength derived from both particle interlocking and cohesion (Wolman 1959, Corte 1969). Thawing of ice-rich sediments can produce saturated or oversaturated materials that are near failure, with excess pore pressures generated just above the thawing interface (e.g., McRoberts and Morgenstern 1974a). Simple alternating wetting and drying may also cause the loosening and slaking of exposed bluff materials. Bluffs composed of interstratified cohesive and cohesionless sediments exhibit much more complex behavior because individual layers may be more susceptible to internal changes in strength than the sediment mass as a whole. Given the climate in Glacier Bay, repetative periods of freezing and thawing as well as wetting and drying are likely agents affecting slope stability.

Types of movement

The types of failure will obviously vary with the configuration and physical properties of the bluff or beach as well as the forces tending to cause failure. Slope movements range from those in which single particles, aggregates or blocks of material undergo failure and free fall, to those involving the *en masse* flow of saturated, remolded material (Fig. 29). The mechanisms involved in the movements are often complex. Because of the apparent continuum between many of the slope processes, distinguishing individual types of movement can be somewhat difficult.

Several classifications separating failure modes exist; no matter which is chosen, they all are somewhat arbitrary because of the gradational nature of the processes and the variability inherent in materials composing slopes. A widely accepted classification proposed by Varnes (1958, 1978) provides a useful format for describing the basic types of movement.

The primary types of slope movement include falls, topples, slides, lateral spreads and flows, and complex types involving two or more of these (e.g. slides leading to flows). Briefly these movements are as follows:

1. Falls – A material mass is detached from a steep slope or cliff and descends primarily through the air to the slope's base by free fall, leaping, bounding or rolling.

2. Topples – Large blocks or segments of the slope undergo a forward rotation about a pivot point, following an upslope tensional fracturing and failure due to the force of gravity, caused by forces exerted by adjacent sediments or by a wedging force in cracks. Forward rotation culminates with a fall or perhaps slide to the slope's base.

3. Slides – Sediments move downslope under the force of gravity by slip along one or several discrete surfaces or within a thin zone at the base of the moving material. Two types are recognized. Rotational slides or slumps rotate down and out along a surface that is roughly concave upward. Translational slides move down a more or less planar surface such as defined by joints or bedding planes, without a rotary motion. These types are also called slab slides. Transitional forms between these end-members are common, with sliding surfaces often controlled by geologic discontinuities.

4. Lateral spreads – The dominant mode of movement involves a lateral extension of the slope sediments accommodated at the upslope end by a shear or tensile fracture. Fine-grained

sediments, particularly sensitive silt or clay that loses most or all shear strength on disturbance or remolding, exhibit lateral spreading, usually as a progressive failure. Thus a slump along a shore initiates progressive failure that extends retrogressively landward into the bluff. Lateral spreads range gradationally between block slides and flows.

5. Flows – In a general sense, flows are sediment/water mixtures that move downslope under the force of gravity. They appear to be continuously deforming and without distinct slip surfaces. Rates of movement may range from almost imperceptible to extremely rapid. Flow characteristics, including rate, style and form, can vary continuously and appear related to the water content. They may occur subaerially or subaqueously, but exhibit different mechanisms and form.

6. Complex – Complex flows are slope movements involving two or more of the principal types of movement listed above, leading to one another during the course of movement, or simultaneously occurring within different parts of the same moving mass (Fig. 30). Slides leading to lateral spreads or flows are fairly common types described in the literature.

Mechanics of subaerial and intertidal failures

The mechanics of each type of movement are complex and remain poorly understood, particularly in regard to flows, lateral spreads and progressive or retrogressive slides and flows. The importance of understanding the mechanics is that it allows us to assess the factors determining when, where, and what can lead to failure.

Thorne (1978, 1982) and Thorne and Tovey (1981) have analyzed the mechanics of failure for slope movements that occur along actively eroding riverbanks, both those being undercut by currents and those removed from the immediate effects of currents, using fundamental soil mechanics theory and the concept of effective stress. These analyses can be adapted to bluffs composed of sediment in Glacier Bay.

Basic conditions

Thorne (1978, 1982) considers three classes of bluffs and slopes based upon their general composition: cohesive, cohesionless or composite (consisting of interbedded cohesive and cohesionless sediments). In each case, stability is assumed to depend upon a balance between motive and resistive forces associated with the most critical mechanism of failure. These mechanisms can vary with the size, geometry, structure and engineering properties of the bank, external forces and climatic conditions. Vallejo (1977) applied slope stability theory in a similar manner to analyze bluff stability and failure of Lake Michigan bluffs and shore zones, which, given the dimensions and typically glacial origin for shore zone materials, is applicable to Glacier Bay.

For both cohesive and non-cohesive materials, the shear strength is given by the revised Coulomb equation in terms of effective stress (Terzaghi and Peck 1967):

$$s = (\sigma - p)\tan\bar{\phi} + \bar{c} \tag{30}$$

where s = shear strength

p = pore pressure

σ = normal stress on the shear surface

$\bar{\phi}$ = effective angle of internal friction

$\bar{c}$ = cohesion intercept.

In the case of noncohesive materials, $c = 0$ and drops out of the equation. Shear strength parameters are usually defined through testing.

For noncohesive materials under drained conditions, the pore water pressure is negligible and $p = 0$. Stability of a slope of an infinite length then depends upon the angle of slope and angle of internal friction. A factor of safety F_s can be defined by

$$F_s = \frac{\tan \beta}{\tan \phi} \qquad (31)$$

where β is the slope angle. The limiting case occurs where $\beta = \phi$ and the slope is at the point of failure. F_s greater than one indicates stability.

Failure of drained noncohesive banks takes place when either the friction angle is reduced to less than the slope angle, or the materials are effectively oversteepened so that $\beta > \phi$. The latter case exemplifies the undercutting of bluff materials by currents or waves, while the former reduction in ϕ can result from weakening and weathering of the slope-forming sediments (e.g. Deere and Patton 1971). These processes reduce the packing density and hence friction angle of the material. Most failures in homogeneous, noncohesive banks involve the fall of individual grains, or result from shallow slips along planar surfaces because the shear strength of these materials will usually increase with depth faster than shear stress (Thorne 1982; Fig. 31).

Under undrained conditions, pore water pressures may be important in determining shear strength. The limiting slope angle is then given by

$$\tan \alpha = \frac{\left(\gamma\, z_{\mathrm{p}} \cos^2 \beta - u\right) \tan \overline{\phi}}{\gamma\, z_{\mathrm{p}} \cos^2 \beta} \qquad (32)$$

where γ is the bulk unit weight of the bluff material, and z_{p} is the vertical depth to the failure plane (Carson and Kirkby 1972). Thus, where positive pore pressures are present, the limiting slope angle will be less than the angle of internal friction. Such positive pore pressures can develop, for example, when submerged materials are uncovered by rapid drawdown. Under partially saturated conditions, the pore water pressure term is negative and imparts an apparent cohesion due to capillary effects (Lambe and Whitman 1969). For sand or coarser well-sorted sediments, this apparent cohesion can be considered negligible.

The effect of flowing ground water upon slope stability can often be approximated by assuming that flow is parallel to the slope. Where appropriate data can be measured, however, construction of a flow net based upon the pore water pressures is a more accurate representation and clearly needed in slopes with geological complexities (Cedergren 1977).

Calculations may also be performed based upon an analysis of the forces acting on an element within an infinite slope (i.e. thickness of unstable, failing material is small compared to the height of the slope). For forces in equilibrium

$$\frac{\tau}{\overline{N}_{\mathrm{E}}} = \tan \overline{\phi} = \frac{\gamma}{\gamma_{\mathrm{b}}} \tan i \qquad (33)$$

where $\overline{\phi}$ = friction angle based on effective stress

τ = shear force

$\overline{N}_{\mathrm{E}}$ = effective normal force

γ = total unit weight

γ_{b} = buoyant unit weight

i = seepage gradient.

Since $\gamma_{\mathrm{b}}/\gamma$ of clean sand is about ½, the maximum possible stable slope under these conditions is about ½ $\overline{\phi}$ Thus in an infinite slope composed of homogeneous sand with the above conditions, seepage reduces the maximum stable slope angle to about half that for sand that is dry. or is completely submerged and without ground water flow (Lambe and Whitman 1969).

Thorne (1978) observed failures that were similar to those of non-cohesive, drained bluffs but that resulted from increases in pore water pressure such as at the base of high slopes after a heavy rain, during snowmelt and runoff, or after a rapid drawdown in the water level.

Shallow slips and individual grain failures were common. He also commented on the importance of high seepage pressures. They can cause piping by physically removing the sediment at the bank face where water emerges, or create excess hydrostatic pressures at locations where water percolates upward at the base of a slope and exceeds the effective weight of the overlying sediments.

Rotational and plane slip failures

The classic rotational slide on a circular failure surface has been analyzed in a number of ways, the commonly used methods often being the conventional method of slices described by Taylor (1948) and Bishop's simplified method of slices (Bishop 1955). The method of slices is applicable for analyzing long-term stability of natural slopes where failure eventually results from longer-term changes in strength parameters or pore water pressure and where the critical height approaches the actual height of the slope (Fig. 32a). Effective strength parameters are therefore used in these analyses so that measurements of pore water pressures are needed.

Bishop's (1955) method of slices appears accurate for most purposes and is commonly used (Morgenstern and Sangrey 1978). For the method of slices, the normal stress acting at a point on the failure arc is assumed to be determined mainly by the weight of soil overlying it. For a particular slope, the mass of material above the circular failure plane is divided into a series of vertical slices (Fig. 33) and the equilibrium of each slice, based upon the forces acting on it, is defined. Because of the number of unknown factors involved, simplifying assumptions are made. For Bishop's method, the forces acting on the sides of any slice are assumed to act horizontally.

For the method of slices, a safety factor F_s is defined as a ratio of restoring moments to disturbing moments about the center of the failure arc:

$$F_s = \frac{\text{Moment of shear strength along failure arc}}{\text{Moment of weight of failure mass}} = \frac{M_R}{M_D} \qquad (34)$$

The factor of safety for Bishop's method is given by:

$$F_s = \sum_{i=1}^{i=n} \frac{\left[\bar{c}\,\Delta x_i + \left(w_i - p_i\ \Delta x_i\right)\tan\bar{\phi}\right]\left[1/M_i\left(\theta_F\right)\right]}{\sum_{i=1}^{i=n} w_i \sin\theta_i} \qquad (35)$$

where

$$M_i\left(\theta_F\right) = \cos\theta_i\left[1 + \frac{\tan\theta_i\,\tan\bar{\phi}}{F_s}\right] \qquad (36)$$

w_i is the weight of slice i, x_i the internal forces on slice i, and p_i the pore water pressure at the base of slice i. F_s is solved in an iterative manner, but the values converge rapidly. Several possible locations of the critical slip circle must be tried because there is no way to define its location based upon these relationships. Bishop and Morgenstern (1960) and Morgenstern (1963) developed stability charts, the latter for undrained conditions, to predict the worst case.

In slopes where noncircular slip surfaces of irregular shape and unknown geometry are anticipated, such as in bluffs of layered cohesive sediments, heavily fissured materials or stratified sediments with individual layers or zones of low strength, techniques such as defined by Morgenstern and Price (1965) are more appropriate. Morgenstern and Price's technique also employs the method of slices but accounts for all boundary and equilibrium conditions. To make the analysis statistically determinate, the shear and normal forces τ and Σ acting on each slice are assumed to be related by the expression

$$\tau = \lambda\ \ f(x)\Sigma \qquad (37)$$

where λ is a scale factor determined by the solution and $f(x)$ is an arbitrary function concerning the distribution of the internal forces. For each solution, the choice of $f(x)$ is limited by conditions of physical admissibility, which require that no tension be developed in the sediments above the failure plane and that the failure criterion as defined not be violated. To solve these equations requires extensive iterative calculations best suited for a computer. The reader is referred to the original reference and Morgenstern and Price (1967) for a discussion of the numerical method for solving the equations.

The stability of bluffs composed of interstratified cohesive and cohesionless sediments is often much more difficult to analyze. Geologic controls on where failure may take place are exceedingly important and thus the location and shape of the failure plane are much harder to define. While many bluffs exhibit repetitive sequences of alluvial sediments (e.g. Fisk 1952; Brunsden and Kesel 1973; Thorne and Tovey 1981; Turnbull et al. 1966), sediments composing shore zones in northern regions are also commonly a complex of glacial, periglacial, colluvial, and lacustrine deposits. Their geologic history will influence and complicate stability calculations for eroding bluff faces (e.g. Deere and Peck 1958). Sterrett and Edil (1982) have discussed the application of Bishop's method (1955) and its problems to bluffs composed of glacial deposits with complex ground water flow systems.

Because noncircular rotational slip failure surfaces often occur because of various geologic discontinuities in composite bluffs or banks (Fig. 34). Static analyses discussed above for the cohesive or cohesionless cases apply to individual strata, but the problem of analyzing composite bluffs requires identification of where the actual failure plane is likely to be located. A trial-and-error technique must be applied to composite slopes because the critical failure surface may occur within one layer or between several layers of multilayered (stratified) bluffs. The simpler case occur where a single weak layer lies within the slope but the point of intersection of the failure plane and this layer are unknown. Noncircular failure surfaces may be analyzed by the methods of Morgenstern and Price (1965), Sarma (1979), or Baker and Garber (1978), but field experience and testing are still needed to determine the accuracy of each method for natural slopes.

Plane slip failures are apparently common in slopes of high bluffs with multiple thin cohesive layers and low bluffs in general (Thorne et al. 1981; Thorne 1982; Chieruzzi and Baker 1958; Carter 1976; Birkemeier 1981).

Fall and topple failures

Thorne (1978) and Thorne and Tovey (1981) discuss the failure mechanisms of vertical slopes developed in cohesive sediments that are underlain by cohesionless sediments. Erosion of these underlying cohesionless sediments can generate an overhanging or cantilevered block of the cohesive material.

Three principal modes of failure were recognized as resulting from continued expansion of the niche or cavity or weakening of the overlying sediments by wetting or cracking (Fig. 35). A shear failure can occur by downward displacement of an overhanging block along a vertical plane “AB” when the shear stress due to weight of the block overcomes the shear strength of the sediment along that plane (Fig. 35a). In a beam failure (Fig. 35b), a block rotates forward about a horizontal axis. At this axis, forces are neutral; while above the axis, the block is in tension and below it in compression. Once the moment of the weight of the block about the neutral axis overcomes the resistive moments of the soil's strength in tension and in compression, failure takes place. In the final case (Fig. 35c), a tensile failure occurs across a horizontal plane within the overhanging block and it falls when the tensile stress of the failed block overcomes the tensile strength of the sediment.

Beam failures were the types of failure most commonly observed by Thorne and Tovey (1981). Shear failures generally occur in cohesionless sands or where root systems in bank vegetation provided little strength to the overhanging block. Tensile failures commonly take place after vertical cracks develop along planes of weakness within the cantilevered material. Failure then occurs along horizontal planes of weakness or zones of minimum tensile strength within the block of material. Desiccation after exposure of the sediment to the air is also important to crack generation.

Lateral spreads and retrogressive failures

Laterally spreading slope movements typically form in fine-grained sediments on shallow slopes and occur rather rapidly with little warning (Varnes 1978). Sensitive silt and clay quickly lose shear strength upon disturbance and remolding and are unique types of materials characterized by spreads, and commonly occur in marine deposits (e.g., Bjerrum 1955; Crawford and Eden 1967; Cabrera and Smalley 1973; Mitchell and Markell 1974; Mitchell and Klugman 1979). Such silts and clays have properties that cause them to be particularly sensitive, although controversy remains as to which properties are more important and how they actually alter or produce sensitive materials (e.g., Smalley 1976; Kerr 1979, Gillott; 1979, Moon 1979).

Failures may take place gradually over tens of years and are progressive, starting at one location and spreading laterally into previously undisturbed sediments (Fig. 36). The initial failure may involve a distinct rotation, but quite often the principal movement is one of translation (e.g., Thomson and Hayley 1975; Haug et al. 1977; Bjerrum 1971; Carson 1977). Many of the reported progressive failures in coastal bluffs start initially as a single slip failure and then spread landward into undisturbed sediments. Progressive or retrogressive failures commonly move along a noncircular failure surface that has had its peak or maximum shear strength reduced by large strains applied by previous downslope failures (Fig. 37) (Bjerrum 1967, 1971; Bishop 1967; Carson 1977). Each successive slip provides material that laterally supports upslope blocks (Fig. 38). In other situations, failure and remolding are rapid so that most material in the slope loses its structure and the entire area flows almost immediately (Skempton and Hutchinson 1969).

The mechanisms of these retrogressive failures are poorly understood. Bjerrum (1967, 1971) concluded that such failures in overconsolidated clays are preceded by the development of a continuous sliding surface. This surface forms by progressive failure that reduces the undrained shear strength on it to its residual value. Failure analyses of progressive or retrogressive lateral spread indicate that the average shear stress causing failure is smaller than the shear strength of the failed material, but it is typically similar in magnitude to the residual stress of that material.

Conditions required for developing a continuous failure surface with only residual strength are 1) an internal discontinuity or external disturbance where failure can first take place and 2) material properties and behavior such that a) local internal shear stresses must exceed the peak shear strength of the material, b) local differential strain must exceed the strain at which the material will fail for the failure surface to advance, and c) a rapid and large decrease in shear strength must result with strain after failure, so that shear resistance in the failed zone does not obstruct movement of upslope materials (Bjerrum 1967). Pore pressures and weathering processes acting over time are often required to reduce or eliminate properties controlling the shear strength of clays.

Bjerrum (1967) described a progressive failure in a partly weathered coastal clay bluff. This analysis is applicable in a general way to rocks with foliation or bedding planes that have a similar orientation (Fig. 39). Weathering occurs to some depth z, so that internal stresses (P_L) parallel to the surface are increased, water content has increased and shear strength has decreased to this depth (Fig. 39a). Toe erosion at the slope's base (Fig. 39b) develops a steep slope and removes lateral support. Lateral stresses in the weathering zone are then transmitted to the lower unweathered clay by shear stress on the plane "SS" (Fig. 39). These shear stresses combine with the shear stress from gravity to exceed the peak shear strength of the clay so that a slip failure on plane "SS" takes place and initiates the progressive failure.

After the slip plane has formed (to point "P" in Fig. 39c), further movement depends on the inclination of the slope. Shear strength on the slip plane is reduced to its residual value because it has moved. Further movement away from the remaining mass requires a slope angle sufficient for the gravitational force to be greater than the residual shear strength (Fig 39c). Lateral stresses on plane "PP_1" are therefore reduced. Once these stresses are sufficiently reduced, shear stresses in the clay due to gravity at the leading edge of the slip surface (P_L) and the lateral stresses on the plane "AA_1" will exceed the peak shear strength, thereby initiating a second failure. Progressive development of the slip surface continues in the upslope direction.

Flow failures

The mobilization, movement and deposition of subaerial and subaqueous flows are complex and only partly understood. The sediment gravity flow or sediment flow process has importance to shore erosion as a failure mechanism that is distinct from failure along a singular planar or circular surface, and as a downslope transport process which carries sediments ranging in size from clay to boulders into nearshore and offshore areas, possibly generating subaqueous flows or turbidity currents once within the water (e.g., Morgenstern 1967; Andresen and Bjerrum

1967; Hampton 1972). Flow failures of coastal bluffs have been identified at a number of locations (e.g., Sharpe 1938; Varnes 1958; Chieruzzi and Baker 1958; Jones et al. 1961; Hutchinson 1983; Kachugin 1970; Bjerrum 1971; McGreal and Craig 1977; Edil and Vallejo 1977; Heller 1981; Syvitski et al 1987). Commonly sediment gravity flows are a part of complex or progressive failures with, for example, slip failures or liquefaction preceding and initiating remolding prior to flow (e.g., numerous examples in Varnes 1978 and Skempton and Hutchinson 1969).

Several different types of flows have been identified. Mudflows, debris flows, earth flows, and slurries are types of flow failures. Each flow type has physical characteristics and apparent mechanisms of grain support and transport that distinguish them, yet they appear to actually represent a continuum of gradational forms. In mostly fine-grained materials, for example, they may exhibit behavior ranging from a very slow-moving, viscous, plastically deforming mass to a liquefied, fluid-like flow (e.g., Middleton and Hampton 1976; Youd 1973; Carter 1975; Lawson 1979, 1982; Lowe 1979). Rates of movement can vary from centimeters per day to centimeters per second. As with lateral spreads, flows are commonly observed on slopes of 10° or less.

The mechanics of flow mobilization, the ability of certain flows to transport up to boulder size particles, and the mechanics of movement remain to be fully explained; recent theoretical and empirical treatments have significantly improved our understanding of the sediment flow process (e.g., Johnson 1970; Hampton 1972; Rodine and Johnson 1976; Keefer 1977; Takahashi 1981; Lawson 1982). Observations and especially quantitative analyses of active subaerial flows and their properties have been strictly limited to date because of their general occurrence as singular, one-time events (e.g., Blackwelder 1928; Sharp and Nobles 1953; Curry 1966; Johnson and Rahn 1970; Johnson 1970; Rodine 1974; Pierson 1980). Lawson (1979, 1982) recently made detailed, repetitive measurements in the glacial environment where conditions are suitable for nearly continuous generation of subaerial flows during the summer.

The factors which apparently interact to produce conditions necessary for flow generation appear to be 1) rate and duration of precipitation, 2) geotechnical properties of slope material, including permeability and its variability with depth, 3) slope angle, 4) excess pore water pressures, 5) freeze-thaw activity, 6) slope aspect, 7) seepage pressures and ground water flow patterns, 8) snowmelt runoff, 9) vegetation cover, 10) thermal state of the material and 11) stratigraphy of slope materials.

Of primary importance to the character of the sediment flow as well as to the initiation of movement is the initial process that directly causes loss of strength or remolding of the material, thereby reducing its shear strength and resistance to movement under the force of gravity. This process may involve, for example, reduction in cohesion or internal friction because of excess pore water pressures or leaching, the physical disaggregation and remolding of the sediments, or the disruption of particle contacts by earthquake motions. Water is inherently involved in loss of shear strength, especially when fine-grained cohesive sediment is a major component (e.g., Blackwelder 1928; Sharp and Nobles 1953; Curry 1966; Crozier 1969; Rodine 1974; Keefer 1977; Lawson 1979, 1982).

As movement takes place, various factors including changes in slope angle, turbulent mixing, addition of water and other factors may further reduce its strength. Deposition generally requires the opposite condition: an increase in the strength or resistance to flow offered by the material (e.g., lowered slope angle). Within the shore zone, slow flows may undergo deposition at the base of the bluff, while more fluid and rapid flows may move directly into the nearshore and offshore zones.

A particular case of significance to coastal bluff erosion is surface flow resulting from thawing of frozen materials in the spring (Edil and Vallejo 1977; Sterrett 1980; Reid 1984). Thawing causes melting of ice formed during freeze-up in the fall and winter. This meltwater can fully saturate or oversaturate the sediment, thereby reducing its shear strength. In addition, excess pore pressures may be generated under proper conditions above the still-frozen sediment, further reducing the strength of the materials (McRoberts and Morgenstern 1974a,b; McRoberts 1978). Thin flows of a few centimeters thickness characterize steeper slopes; thicker flows occur on lower angle slopes. Flow on frozen beaches has also been observed.

Submarine failures

Submarine slumping, from offshore and nearshore regions, including deltas, off coastal shores and in fjords has been described (e.g. Shepard 1955; Terzaghi 1956; Moore 1961; Morgenstern 1967; Coleman and Garrison 1977; Prior and Coleman 1978; Pickrill and Irwin 1983; Bea et al. 1983; Svyitski et al 1987). Slope failures include localized minor slumps of fine-grained sediments mantling otherwise stable materials of relatively steep slope, intermittent slumping of recently deposited clays on gentle slopes, and movements encompassing a wide area of slope with flow and lateral spreading of fine-grained cohesionless material after failure by localized subsidence and translational motions (Terzaghi 1956). Liquefaction of bed materials by excess pore pressure from waves is also a possible failure mode (e.g. Gill and Nataraja 1983). Complex progressive failures similar to those described by Bjerrum (1967) or Skempton and Hutchinson (1969) were postulated to occur in shallow (5-to 25-m) water off the Mississippi

Delta by Prior and Coleman (1978); the postulated movements and mechanisms are illustrated in Figure 40.

Slopes in areas of submarine slumping are often low in angle (<10°) and have been reported as low as l° to 3° (e.g. Shepard 1955). Sediments involved in failures on low angle slopes typically are normally consolidated or underconsolidated and fine-grained. Underconsolidated materials can originate by recent and rapid rates of deposition (Terzaghi 1956), producing material that is readily erodible and subject to failure by flow (Einsele et al. 1974).

Morgenstern (1967) analyzed the stability of subaqueous materials by using the limit equilibrium concept in terms of effective stress for drained and undrained failures, and considering the simple case of an infinite slope with slips along one or many closely spaced planes paralleling the slope surface. He also considers a third case termed collapse slumping for failure of metastable, underconsolidated sediments. This latter type results from failure initially under drained conditions but the deformations associated with failure cause a large and sudden increase in pore pressures. This increase, in turn, reduces shearing resistance and accelerates the moving sediment mass. Drained failures are probably limited to coarse-grained (sand, gravel) materials on steep slopes. Undrained failures are probably typical of underconsolidated materials or those where stresses are induced by rapid deposition or erosion.

Additionally, Morgenstern (1967) considers the effects of underconsolidation on undrained strength, which he deduced should be proportional to the average degree of consolidation. Thus,

$$\left(\frac{c_{\mathrm{u}}}{p_{\mathrm{O\,m}}}\right)\overline{c_{\mathrm{d}}} = N_{\mathrm{E}}\,\overline{c_{\mathrm{d}}} \qquad (38)$$

where c_{u} is the degree of underconsolidation, $\overline{c_{\mathrm{d}}}$ the average degree of consolidation, $p_{\mathrm{O\,m}}$ the maximum effective overburden pressure, and N_E, the effective normal force as follows

$$N_E = \frac{c_u}{p_{Om}}. \qquad (39)$$

This relationship rests on the assumption that effective overburden pressure p_{Oe} at any time during consolidation when excess pore pressures exist is given by

$$p_{Oe} = \gamma' z - p_e = \gamma' z\left(1 - \frac{n_e}{\gamma'}\right) \qquad (40)$$

where p_e is excess pore pressure, γ' submerged unit weight of soil, n_e effective stress, and z is depth. Excess pore pressure can be estimated as varying linearly with depth:

$$p_e = n_e\, z. \qquad (41)$$

Substituting in eq 40 gives

$$p_{Oe} = \gamma' z\left(1 - \frac{n_e}{\gamma'}\right). \qquad (42)$$

This relationship shows that excess pore pressures can develop in material undergoing an increase in height due to deposition (Terzaghi 1956). The pore pressure values depend upon rate of sedimentation, height of the deposit, and coefficient of consolidation for the material. At any depth in the material, p_e will reduce the effective stress and undrained strength of the material. Clearly, failure conditions can develop at some depth over time when consolidation does not keep pace with rates of sedimentation.

Factors that might lead to subaqueous slope failures remain speculative, but several situations may be conducive to failure. First, oversteepening of nearshore sediments in slopes can result from erosion by wind waves and currents. This may be particularly true when the combined effects of erosion and wave-generated pore pressures in submerged sediments are at a maximum during storms (e.g. Henkel 1970; Suhayada et al. 1976; Tsui and Helfrich 1983).

Similarly, the failure of bluff slopes and the deposition of this sediment mass upon subaqueous slopes could increase the overburden sufficiently to produce an unstable condition in slopes of low angle. This situation is analogous to that described by Hutchinson and Bhandari (1971) for undrained loading of subaerial slopes (Fig. 41).

Rapidly eroding and receding shores can introduce a large quantity of sediment into the water column, increasing turbidity locally. If it is deposited rapidly on nearshore slopes, a metastable condition may exist and collapse slumping as described by Morgenstern (1967) may result from additional sedimentation. Slides in shallow water may result from rapid drawdown during extreme low tides, the direct action of waves pounding nearshore sediments, or strong currents, particularly in shallow areas where erosion can take place. Lowering of water level during ebb tide may shift the location of sedimentation by streams onto outer delta slopes leading to oversteepening and deep- or shallow-seated failures of the delta front (e.g. Pickrill and Irwin 1983). Because of unfavorable environmental conditions, observations and measurement of subaqueous failures remain to be done.

Submarine failures can also generate or result in subaqueous retrogressive flow slides, debris flows, turbidity currents, liquefaction followed by debris flow, grain flows and others (e.g. Terzaghi 1956; Morgenstern 1967; Andresen and Bjerrum 1967; Hampton 1972; Carter 1975; Lowe 1976; and Middleton and Hampton 1976). Movement is initiated when the loss of strength or resistance to shearing occurs, such as may result from temporary increases in pore pressures, shock (from earthquakes or perhaps sudden mass loading), effective oversteepening of sediments in slope, or perhaps fluidization resulting from upward flow of ground water through the bottom sediments (Carter 1975).

Factors affecting stability

Factors that are critical to the stability of subaerial and submarine slopes include: 1) ground water conditions, 2) stratigraphy with respect to bluff and shoreline orientation, 3) presence of potential "weak" layers or surfaces, 4) intensity and type of toe zone erosional processes, 5) intensity and type of bluff face erosional or degradational processes, 6). slope geometry (mainly height, length, angle, and aspect), 7) geotechnical properties of the sediments and their variabilty within composite slopes, 8) nearshore bottom topography, 9) climate/weather, and 10) frozen or unfrozen condition.

Field and theoretical analyses have suggested that the water content is usually critical in determining or modifying the shear strength of slope materials and thus their frictional and cohesive resistance to the force of gravity. As saturation increases, the simple increase in the mass of slope materials effectively increases the applied shear stress (e.g., Terzaghi 1950). The horizontal movement of water generates seepage pressures that generally reduce stability. Concentrated flow within single layers or along fracture planes will locally reduce the effective stress and lead to slippage (e.g., Rodgers and Selby 1980; Sterrett 1980). High ground water flow conditions can result in springs issuing at a bluff face that may in turn cause piping and undermining of overlying sediments (e.g., Hadley 1976; Hagerty et al. 1981; Hopkins et al. 1975).

Seepage into submerged sediments may actually increase the stability of these materials in accordance with the average hydraulic gradient (e.g., Burgi and Karaki 1971; Thomson and Morgenstern 1977), and decrease their erodibility. In part this may result from deposition of suspended silt within pore spaces as water enters them (Harrison 1968; Harrison and Clayton 1970). Conversely, outflow may increase their erodibility by decreasing the effective cohesion and hence shear strength (Terzaghi and Peck 1967), possibly leading to heaving and failure (Terzaghi 1929). Outflow can similarly increase a materials erodibility by currents (e.g. Clayton et al. 1966).

Weather-related factors may be equally important in affecting stability and sediment strength. These include rate and duration of rainfall, rate and volume of snowmelt, and extended periods without rainfall. Drying periods followed by wetting during heavy precipitation may result directly in sloughing (Quigley et al. 1978; Kachugin 1970). Continued flow of ground water may also leach chemical constituents from sediments and thereby reduce strength (e.g., Kachugin 1970).

The ground water flow regime is thus critical to analysis of shore zone stability and should be defined by field measurement, as the actual flow pattern may deviate significantly from a typically assumed parallel-to-slope flow regime or from an assumed hydrostatic condition (Patton and Hendron 1974; Cedergren 1977; Hodge and Freeze 1977; Lafleur and Lefebvre 1980; Fig. 42). Regional geology (stratigraphy and associated regional ground water flow pattern) may be critical to defining the actual, more localized pore pressure distribution in a slope. Slope materials may undergo progressive changes in strength over months and years by leaching, piping or other ground water processes and cause an unexpected failure.

The principle factors causing an increase in stress are:

- Removal of lateral support by wave and current erosion, previous slope failures, and surficial degradation by weathering, wetting and drying or frost action.
- Surcharge on slopes due to weight of precipitation, failed material from an upslope position, seepage pressures or vegetation.

- Earthquake shocks, human-induced vibrations, and acoustic shocks.

- Removal of underlying support by wave and current undercutting, subaerial weathering, wetting and drying, frost action, piping, or failure of underlying materials.

- Lateral pressures as may result from water in cracks, ice formation in cracks or soil pores, or mobilization of residual stress.

The factors reducing material strength include:

- Inherent characteristics of material, such as composition, internal structure, geologic discontinuities such as bedding planes, joints or fractures, massive materials on weak beds, alternating permeable and impermeable strata, and slope orientation.

- Weathering and related physical and chemical reactions that may include physical disintegration by frost or thermal expansion, hydration of clay minerals, cation exchange in clay minerals, drying and cracking of clays, or solution of cementing agents.

- Changes in intergranular forces due to changes in water content and excess pore pressures within sediment or fractures and other discontinuities.

- Structural changes caused by fissuring of clays, spalling with removal of surficial materials, disturbance or remolding of fine-grained materials, burrowing animals, and growing tree roots.

VESSEL REGULATIONS AND USE

Traffic regulations

Concern over significant reduction in the number of humpback whales feeding in Glacier Bay in the late 1970s led to the first vessel regulations for the Park being issued in 1980 (e.g., 45 FR 32228; 45 FR 32234; 45 FR 85471). The intent of this and more recent regulations (NPS 1995) is to reduce behavioral alterations in marine mammals by reducing vessel overcrowding and noise generation in sensitive areas. The Park's initial strategy was to restrict the number of daily vessel entries and set seasonal quotas to allow some visitation while trying to reduce ecosystem impacts. More recently, additional regulations have been implemented that require lower vessel speeds (10-knot maximum) to reduce noise levels in areas where humpback whales frequently visit (NPS 1995; Fig. 43). Outside of these "whale waters," cruise ships and tour boats will travel at approximately 17 to 20 knots. Use of motorized vessels is also restricted in designated wilderness areas and requires a written waiver for access. Other environmentally sensitive areas are closed during critical breeding, pupping, or molting periods to reduce impacts to harbor seals, sea lions, and sea birds.

The present quotas for vessels entering Glacier Bay are divided into four categories: cruise ships, tour vessels, charter vessels, and private vessels (Table 1, GBNPP Concessions Office 1998). Cruise ships are motorized vessels weighing over 2,000 tons gross (International Convention System) and carrying commercial passengers (Fig. 44). Cruise ships entering the Park range in size from 87 to 279 m long and 3 thousand to 78 thousand tons gross weight (Table 2). Tour and charter vessels carry commercial passengers and both are under 2,000 tons gross weight (Fig. 45 and 46). Tour vessels carry more than 49 passengers, range from 24 to 78 m long and operate at regularly scheduled times. Nearly all have a single-hull design. Two exceptions are the *Executive Explorer* and *Spirit of Adventure* (Fig. 47), which have double catamaran-type hulls. Charter vessels carry up to 49 passengers and are available for hire on an unscheduled basis. Private vessels are any motor vessel used for recreation that is not engaged in commercial transport of passengers, commercial fishing, or official government business.

Stack emissions from vessels operating in the Park are regulated by the state of Alaska, which has the authority to establish air quality standards under the Federal Clean Air Act. State air quality regulations for marine vessels (18 AAC 50.100) apply to visible emissions from any marine vessel, excluding condensed water vapor. Those regulations say that emissions may not reduce visibility through exhaust effluent greater than 20 percent for a period, or periods, aggregating more than 3 minutes in any hour while underway, at berth, or at anchor. State opacity standards, effective July 21, 1991 for marine vessels, match those standards already in effect in West Coast states. Before the 1991 rule, air emission standards limited vessels to producing smoke of 40% opacity for no more than 3 minutes per hour.

Vessel use

Glacier Bay is a major tourist destination and one of the highlights of the Inland Waterway system in southeast Alaska, where marine vessels are the primary means of transportation to sites of interest. There is a continually growing demand for park visitation and pressure to increase the number of vessel entries. Legislative mandate tasks the National Park Service to protect the Park resources, such as scenery, natural and historic objects, and wildlife, including endangered species like the humpback whale, Steller sea lion and bald eagle. Management practices have to allow ecological processes to continue unimpaired; however, this must be balanced by marine and terrestrial visitation that may impact marine and terrestrial ecosystems. These issues present an enormous management challenge to balance protection requirements with visitation use (NPS 1995).

During the 1997 and 1998 seasons, 28 different cruise ships and 15 tour vessels visited Glacier Bay regularly (Table 3). While the visits during the 1 June–31 August peak period were at or below the authorized number (Table 1), total visits for the year were higher due to the extended off-season from mid-April to the end of September.

Entries by the large cruise ships have been increasing since the early 1980s. The 1984 vessel regulations allowed for a 20% increase over 1976 levels (NPS 1995). By 1988, there had been a 144% increase in the number of passengers brought into the Park by large cruise vessels (81,115 in 1980 to 198,023 in 1988). In 1998, some 339,058 passengers viewed the Park from large cruise vessels, representing a 171% increase since 1988 (GBNPP Concessions Office 1998).

The route taken by nearly all cruise ships is to enter Glacier Bay and head towards the "West Arm" following an approximately mid-channel course (Fig. 7). The first cruise ship of the day typically heads straight towards upper Tarr Inlet, passing by a Kittiwake colony on the west side of the inlet prior to crossing in front of Margerie and Grand Pacific glaciers. Commonly, the vessel stops to view the glaciers for up to an hour prior to turning and heading downbay. On the route out, most ships tour past Lamplugh Glacier and may turn around at Jaw Point where they can view Johns Hopkins Glacier. These vessels then follow the same general mid-channel course as they prepare to leave Glacier Bay. To reduce congestion at the head of the fjords, the second cruise vessel of the day often reverses the pattern and visits the Lamplugh Glacier and John Hopkins Inlet areas first.

Smaller tour boats and charters have more leeway in the paths they follow while visiting the Park (Fig. 7). Most follow the same general course as the large cruise vessels, except that they travel closer to shore while trying to view wildlife. The *Executive Explorer*, and other multi-day tour vessels, travel even more slowly and closer to shore to view the shorelines of both arms of the Bay and visit sites like North Sandy Cove and Tidal Inlet (Fig. 1).

For several years, the *Spirit of Adventure* has been the designated camper pick-up and drop-off vessel for the Park concession. During its daily run, it typically stops several times at designated drop off points to offload and load kayakers and back country users. To accomplish this, the captain drives the bow of the vessel up onto shore. Camper drop-offs have been at Sebree Island, Blue Mouse Cove, Queen Inlet, Geikie Inlet, and other sites (Fig. 48). An additional boat (*Crystal Fjords*) began operation during summer 1999 to drop-off and pick-up campers at Ripple Cove, south side of Geikie, west side of Rendu Inlet entrance, mainland east of Garforth Island, and just south of York Creek.

PHYSICAL EFFECTS OF VESSEL PASSAGE

The entry of vessels and their passage through Glacier Bay affect the marine and near-shore environments in many ways. Several of the potential physical impacts are listed in Table 4. Vessel traffic produces waves, changes velocity fields around the hull and prop, introduces noises to the marine and subaerial environments, and can generate pollutants. In most cases the potential impact zones are poorly defined and their impacts in Glacier Bay have been deduced largely from other studies, such as those evaluating the effects of vessel traffic on the Great Lakes and connecting waterways. In order to evaluate vessel effects, we need to understand ambient background conditions controlled by natural processes, which in turn set the general physical and biological framework of the Park’s ecosystem (Table 5).

As stated above, among the most detailed studies of vessel impacts on nearshore and aquatic environments are those conducted on the Great Lakes, its connecting waterways, and the upper Mississippi and Illinois waterways. These studies have shown that vessel passage through confined waterways may result in changes in water flow dynamics and other parameters that can influence marine and coastal ecosystems. Flow changes are created primarily by bow and stern waves, propeller wash, and drawdown and surge (a lowering then rising of water elevation caused by the passage of a vessel). In terms of vessel traffic, a confined waterway is one in which the shoreline or bottom is close enough to influence ship-generated water movements. These changes in water flow can, if large enough, move particulate materials (both on the shoreline and sea floor), resulting in possible physical effects (e.g., shore erosion, transport of sediment, increased turbidity), shore structure damage, and related chemical or biological effects. The size and significance of these various effects depends on a number of local conditions, such as bathymetry and channel geometry, water level, soil conditions, ice conditions, shore zone composition and geometry, ambient water currents, and presence of other natural agents such as waves.

Vessels entering Glacier Bay range in size from tour boats to cruise ships (Table 2). The primary region where confined conditions may exist for cruise ships entering Glacier Bay is located just south of Sitakaday Narrows (Fig. 1), where water depths are relatively shallow (50-80 m). However, tour boats entering Bartlett Cove, Sandy Cove, or other narrow and shallow areas might encounter confined conditions where their passage might exceed threshold conditions and locally influence hydraulic parameters.

As a starting point, we will review the physical effects of vessel passage on waterway hydraulics because they form a common basis for potential damage mechanisms discussed later. Most research on vessel movement to date has focused on reducing the resistance to ship motion and increasing maneuverability. Resistance to motion results from frictional drag along the hull, wave drag due to the energy expended in generating waves, and losses related to the generation of turbulence during vessel passage.

Ship waves

Wave impacts are poorly defined in Glacier Bay. However, back country users frequently experience adverse conditions related to cruise boat passage that generate waves ranging from short-lived swells in the open water to breaking waves along the shore that toss kayaks and open skiffs onto the rocky beaches. Sustained waves of equal magnitude generated by storms are common; however, kayakers and small boat operators typically stay off the water during such events, so their effects on Park visitors are treated as part of the “Park experience.” An example is provided by Mathews (personal communication), who monitored Steller sea lions being temporarily displaced by cruise boat wakes. This displacement was short lived; however, shortly after this incident Mathews observed the close passage of a boat and some kayaks which displaced the sea lions for a much longer time. The difference in displacement times are likely because vessel waves mimic a natural process (wind waves) and the sea lions do not associate them with their anthropogenic source; however, the boat and kayak represented a direct invasion of their space and a potential threat.

When a ship sails in open water, a system of diverging and transverse waves develops. Diverging waves are those that form the familiar V-shaped wave pattern, starting at the bow of a ship; transverse waves form a less noticeable wave train that follows the vessel and is oriented normal to the sailing line. As these waves propagate, their amplitude decays. According to Sorenson (1973), transverse waves decay more rapidly and diverging waves become dominant with distance from the sailing line.

Owing to the decay of the waves as they propagate away from the ship and the interaction between these dissimilar wave sets, the generated wave heights are a strong function of position. Maximum wave heights, called cusps, occur where the crests of the two wave types intersect, reinforcing one another. In deep water, these waves form a constant pattern and meet to form a locus of cusps at an angle of about 19° 28’ to the sailing line. This angle becomes greater in shallow water. The wave heights at these cusp locations decrease inversely, proportional to about the cube root of the distance from the disturbance. Except in very shallow water, this decay is caused primarily by the distribution of energy along the crest of the wave (Sorenson 1973).

When a wave propagates through water with depth that is less than about half its wavelength, the wave begins to ‘feel’ the bottom (see above discussions). According to Sorenson (1973), this begins when the Froude number (Fr) reaches a value of 0.56. When the Fr is greater than about 0.7, noticeable changes occur in a vessel-generated wave system (Sorenson 1997). As Fr increases from 0.7 to 1, wave heights rise at an increasing rate and transverse waves become relatively more prominent. This is a result of the diverging wave angle, and the cusp locus angle increases from the deep-water value of 19° 28’ to 90° when Fr equals 1. In a constricted channel, vessels that cannot plane are unable to achieve velocities corresponding to a Froude number greater than 0.95 (PIANC 1987).

In terms of the analysis of vessel-generated waves, Sorenson (1973) states:

> “…. the analytical approaches for calculating the water surface patterns of waves generated by a given hull form have not yet been perfected. Wave patterns can be calculated with reasonable accuracy for hulls of very simplified form moving in deep water at not too great a speed. As the hull geometry becomes more complex and the water motion increases, the methods become much less satisfactory.”

Unfortunately, the state of the art for ship wave prediction has not improved significantly since that was written. In particular, little information is available to deal with nearshore wave prediction and the ability of those waves to cause sediment transport or shore zone erosion. A review of literature has located information useful in assessing the relative effect of vessel size on ship generated waves, but the actual wave heights calculated by the different relations vary widely.

The height of ship-generated waves is primarily a function of vessel speed (Gates and Herbich 1977a). Table 6 gives the heights H_{max} of waves generated by boats with displacements from 3 to 5420 tons. These data were derived from measurements in the Oakland Estuary. Note the small range of wave heights generated at equivalent speeds by vessels of very different sizes and types in water about 10.7 m deep. Ashton (1974) developed Figure 49 from the data presented by Sorenson (1973). Although this figure ignores depth and draft effects, there is remarkably little scatter. The figure shows the strong relation between the maximum wave height 30.5 m (100 ft) from the sailing line $H_{\mathrm{max},100}$ and ship velocity u_{v}.

In fact, Ofuya (1970), in his study of ship waves on the Great Lakes connecting channels, concluded that the essential parameters influencing wave height were ship speed and distance from the sailing line. He was unable to factor out the effects of vessel size or hull geometry because of the small variations caused by variables other than vessel speed. Ofuya also cited the results of wave data collection at three sites on the St. Clair River and one each on the Detroit and St. Lawrence Rivers. For gauges located in 1.5–7.6 m of water, very few waves were measured in excess of 18 cm, and then only when the local speed limit was significantly exceeded.

One method of estimating the height of a ship-generated bow wave in deep water is presented in Saunders (1957):

$$H_{\mathrm{bw}} = K_{\mathrm{w}} \frac{L_{\mathrm{b}}}{L_{\mathrm{E}}} \cdot \frac{u_{\mathrm{v}}^{2}}{2g} \cdot 0.3048 \qquad (43)$$

where H_{bw} = height of the water surface at the bow (m)

K_w = coefficient

L_b = ship beam (m)

L_E =entrance length, or the distance from the bow to the parallel midbody (m)

u_v= ship velocity (m/s)

g = acceleration due to gravity (m/s^2).

According to Helwig (1966), the bow and stern of a ship are responsible for most of a ships wave making ability, and ships with equivalent bow and stern geometries but differing parallel midbody lengths will produce waves of the same magnitude. For vessels with long, parallel midbodies, K_w is relatively constant at 1.133. Since we do not have sufficient information on entrance lengths for the various vessel classes, we will use $L_E/L_s = 0.416 - 0.000235L_s$, where L_s is the overall vessel length (Gates and Herbich 1977a). Equation 43 would then allow us to illustrate the relative waves generated by at least the larger ships entering Glacier Bay.

While the magnitude of the wave heights calculated with eq 30 should not be considered accurate for Glacier Bay, they do indicate that vessel speed can be much more important than vessel size and geometry for the range of ship sizes considered here. Also, these calculated wave heights are near-ship waves. Since bow waves decay in approximately inverse proportion to the cube root of the distance from the sailing line, the wave heights and the differences between wave heights will be reduced significantly as the wave propagate away from the ship.

Another important consideration is the water depth. This has been treated by using the ratio of water depth to ship draft (Johnson 1958). As the depth d becomes shallower relative to the draft d_s, wave heights change. However, this is most important in the case of deeply loaded vessels.

For channels that are not only shallow, but also restricted laterally, wave heights can change due to hydrodynamic interaction with the channel. An empirical relation for estimating the near-ship wave heights (H_s) in a restricted channel was presented by Balanin and Bykov (1965):

$$H_{\mathrm{s}} = 0.3048 \cdot \frac{2.5 u_{\mathrm{v}}^{2}}{2g}\left[1-\left(1-\frac{1}{\left(4.2+\left(A_{\mathrm{c}}/a_{\mathrm{s}}\right)\right)^{0.5}}\right)\left(\frac{A_{\mathrm{c}}/a_{\mathrm{s}}-1}{A_{\mathrm{c}}/a_{\mathrm{s}}}\right)^{2}\right] \qquad (44)$$

where A_c is the cross-sectional area of the channel and a_s is the cross section of the ship. Although this equation ignores the effects of hull geometry, it does provide a means for evaluating the influence of a restricted channel on wave heights. Sorenson (1997) suggests that the above equation is only applicable to channels of fairly restricted width.

A comparison of wave heights between this method and that of Saunders discussed earlier reveals that, at low blockage ratios (a_s/ A_c), the calculated wave heights agree reasonably well, but as ships occupy a larger portion of the channel cross section, wave heights increase markedly. Although a number of other wave equations were also reviewed, each was developed for specific site conditions. There is no strong justification for selecting one over another, except that the Balanin-Bykov approach allows us to examine the effect of vessel size in restricted channels.

Another equation for estimating maximum wave height is given by Hochstein (U.S. Army Corps of Engineers, 1980):

$$H_{\max} = 0.0416 u_{\mathrm{v}}^{2}\left(d_{\mathrm{s}}/L_{\mathrm{s}}\right)^{0.5}\left(1-L_{\mathrm{b}} d_{\mathrm{s}}/A_{\mathrm{c}}\right)^{-2.5} \qquad (45)$$

where:

$H_{\max}$ = maximum wave height

L_s = length of the vessel

All other variables are as defined before. The main difference between this and the Balanin-Bykov relation, other than their form, is the inclusion of the vessel's length.

Bhomik (1975, 1976), using data collected on Carlyle Lake in Illinois, as well as information from Das (1969), developed an equation for waves generated by recreational boats:

$$\left(H_{\max}/d_s\right)^2 = 0.139u_s^{1.174}\left(x_b / L_s\right)^{-0.915} \tag{46}$$

where $H_{\max}$ is the maximum wave height in meters, d_s is the draft of the boat in meters, u_v is the speed of the boat in m/s, x_b is the distance from the boat in meters, and L_s is the length of the boat in m.

Sorenson (1997) reviews nine different wave prediction equations (Balanin and Bykov 1965; USACE 1980; Bhowmik 1975; Gates and Herbich 1977b; Bhowmik et al. 1982; Blaauw et al. 1985; PIANC 1987; Sorenson and Weggel 1984; Bhowmik et al. 1991). Of these, only Bhowmik (1991) addresses recreational craft. However, the prediction of vessel-generated wave height depends on many factors that impede the accuracy of these relationships. Sorenson (1997) suggests that the three models of most general application are those of Gates and Herbich (1977b), PIANC (1987), and Weggel and Sorenson (1986). Of those, he felt that the Weggel and Sorenson (1986) model is the more general, since it includes most of the dependent factors, but is limited in the manner in which it includes vessel hull form effects.

In summary, it appears that the effect of vessel size on nearshore wave heights should be small except for shorelines very close to the ship track. In the absence of appropriate field data for verification or perhaps calibration, any magnitudes calculated are subject to question. Certainly the effect of vessel class as defined by overall length is meaningless. Numerous authors (such as Carruthers 1966; Helwig 1966; Brebner et al. 1966) have concluded that ship length has very little effect on wave height. According to Sorenson (1973), a ship’s wave-making capability depends primarily on the speed of the ship, and to a lesser extent, on the hull form, draft and water depth below the keel.

Although the beam of ships tends to increase with ship length, this is not a unique relation and a ship in a lower length class may in fact be wider. In addition, since the hull geometry depends more on the intended use of the ship than its length, there is no direct relation between vessel class and the parameters important to a ship's wave-making capability as described by Ofuya (1970). However, he was unable to factor out the effects of vessel size owing to the small amount of scatter caused by factors other than vessel speed.

Although equations are available for predicting ship-generated wave heights and their subsequent decay in open water, none adequately address situations involving shallow water or confined or irregularly shaped channels accompanied by complex flow distributions. Without site-specific field data to calibrate and check the calculated values, any projections made must be considered approximate. However, the available theories clearly show that vessel speed is by far the most important variable controlling the magnitude of ship waves generated, followed by the distance to the shoreline, which governs their decay.

Propeller wash

During vessel passage, the bottom and sides of a channel may be subjected to a propeller-driven water jet if water is sufficiently shallow. There has been very little study of sediment transport or other effects of prop wash, and there were no data available for Glacier Bay. However, the velocities within the jet are indeed high, as demonstrated by Fuehrer and Romisch

(1977) who cite an equation by Robakiewicz that estimates the initial jet velocity, u_j, induced by a screw:

$$u_{\mathrm{j}} = \varphi D \left[\frac{2K_{\mathrm{T}} D^2}{F} \right]^{1/2} \qquad (47)$$

where φ = screw rpm

D = propeller diameter

K_T = thrust coefficient (0.25 - 0.50)

$F = \pi D^2/4$.

According to Fuebrer and Romisch (1977), this jet spread would be about 12 to 13° relative to the jet centerline, and they propose a relation for velocity along the centerline of

$$\left(u_{\mathrm{x,max}} / u_j \right) = A_{\mathrm{j}} \left(x_{\mathrm{j}} / D \right)^a \qquad (48)$$

where $u_{x,max}$ = centerline velocity at distance x_j

x_j = horizontal distance from jet

$a = -0.6$ for a jet influenced by a channel bottom

A_j = coefficient dependent on degree of jet limitation.

The coefficient A_j is dependent on water depth, and distance from the prop axis to the bed. No general relation for A_j is available, but they did give an example for the case where the ratio of distance from propeller axis to the channel bed, d_p, divided by the propeller diameter, D, was 3.72. This example is reproduced in Figure 50.

Assuming a Gaussian distribution of velocities within the jet, Fuehrer and Romisch (1977) propose that the radial velocity distribution can be described as:

$$\left(u_{\mathrm{x_c r}} / u_{\mathrm{x_c,max}} \right) = e^{-22.2 \left(r / x_{\mathrm{c}} \right)^2} \qquad (49)$$

where $u_{x_c r}$ is the velocity at a distance x_c from the prop and a distance r from the jet centerline. They further state that the maximum bed velocity will occur at a distance of:

$$\frac{x_c}{D} = \frac{h_p \tan \psi}{D} \tag{50}$$

behind the ship, where $\psi = 13°$ for their case. Based on these simplified equations and empirical correction factors, they present a relation for bottom scour velocity as shown in Figure 51. The general range of velocities found by Fuehrer and Romisch (1977) in their model studies was 6 to 7.9 m/s, and values calculated by Liou and Herbich (1976) were 5.7 m/s for the tanker *Texas California* running at 33.3 km/hr at a draft/depth ratio of 0.83.

Several things should be noted about the calculations above. They are simplified equations and assumed that the ship was operating at full speed in a shallow channel. A primary problem in quantitatively addressing the effects of propeller wash is a lack of information on propeller characteristics and operating speeds. The required thrust to propel a vessel is that required to overcome the resistance to motion, which is primarily composed of skin friction along the wetted surface of the ship and wave-making resistance. The total open water resistance, R_T, has been described by Comstock (1967) as:

$$R_T = \frac{K_f \gamma L_b H_w^{\ 2}}{2} + \left(C_{f_i} + \Delta C_f\right) \frac{\rho S u_v^{\ 2}}{2} \tag{51}$$

where K_f = a coefficient

γ = specific weight of water

L_b = ship's beam

H_w = generated wave height

$C_f = 0.075/(\log u_v L_s/\nu - 2)^2$

ρ = density of water

S = wetted surface area
u_v= ship velocity
L_s = ship length
ν = kinematic viscosity of water

From eq 51 it can be observed that ship length enters into the frictional drag on a ship's hull through its contribution to the wetted surface area of the ship, but it has little effect on the wave-making resistance. In contrast, the skin friction varies as the square of the velocity. Thus, a change in ship length from 183 to 305 m would increase the frictional resistance by about 67%, while a modest increase in ship speed from 12.9 to 16.1 km/h would increase the resistance by 56%. A further complication arises in assessing required horsepower when a ship enters shallow water or a restricted channel because of the added resistance to motion caused by interaction with channel boundaries (Comstock 1967).

In a study of the effect of vessel size on ship-related damage, Wuebben (1983) selected empirical relations based on their ability to deal with the variation in propeller jet velocity for locations with limited depth or lateral confinement. Lacking any calibration data from the Great Lakes system under study, he was unable to provide site-specific, quantitative predictions, but did conclude that fully loaded commercial vessels are easily capable of scouring the channel bed throughout the dredged portions of the connecting channels. He also found that vessel speed was by far the most important factor determining the magnitude of prop wash, followed by cross-sectional area and hull geometry. For confined channels, hydraulic interaction with the channel boundaries requires a higher propeller thrust to maintain open-water speed, increasing the damage potential.

Hochstein and Adams (1985b, 1986) modified their existing prop wash numerical model for application to the St. Marys River by incorporating appropriate ship and site characteristics and transferring other necessary information from earlier studies on the Kanawha and Ohio Rivers in West Virginia and Ohio. They concluded that prop wash effects could not be effectively separated from backwater (drawdown) influences, so they considered both simultaneously. Through a combination of basic theory and empiricism, they provided a quasi-two-dimensional prediction of vessel effects. The "quasi" prefix is used since the two-dimensional predictions are premised on empirically assumed distributions of ambient and ship-affected velocities. Without collecting appropriate field data (which they recommended), the performance of these assumed distributions in the complex, dredged channel portions of the river cannot be accurately assessed. However, the model was verified against all available Great Lakes connecting channel data.

In their study of propeller erosion at the Corpus Chrisi ship canal, Liou and Herbich (1976, 1977) concluded that the ratio of ship draft to water depth is the predominant factor affecting sediment movement caused by propeller wash. They found that little movement occurred for $d_p/d_s > 2$. For deeper drafts relative to depth, $d_p/d_s < 1$, very large bottom velocities occurred that were capable of moving most naturally occurring sediment sizes. For comparison, cruise ships running through the Sitakaday Narrows with a draft of 5 to 8 m, where channel depths are as low as 51 m, the draft to depth ratio only reaches about 10 to 6.67. Tour boats entering South Sandy Cove can reach a draft to depth ratio of about 10, while those entering North Sandy Cove reach a ratio of 2. Therefore, under most situations, water depth is too great under normal vessel routes for prop effects to influence the sea floor in Glacier Bay. The primary exception will be the daily drop-off vessel that makes frequent shore landings. It is likely under these conditions that prop wash may cause localized scour and sediment resuspension.

Drawdown and surge

Although ship waves and other hydrodynamic effects of vessel passage have been studied in terms of vessel maneuverability and power requirements, the effects of vessel passage on natural flow patterns and distribution, and other environmental factors, are not yet understood. When a vessel is in motion, even in deep water, the water level in the vicinity of the ship is lowered and the ship with it (called vessel squat). For the same ship, this effect increases as the vessel speed increases or as the water depth decreases. When a ship enters confined water, there is a considerable change in flow patterns about the hull. The water passing beneath the hull must pass at a faster rate than in deep water, and as a result there is a pressure drop beneath the vessel, which increases vessel squat. In a channel that is restricted laterally, this effect is further exaggerated. These effects can occur independently when a channel is restricted laterally or vertically and unrestricted in the other direction.

In considering the design of canals and harbor entrances, squat has been of concern primarily in terms of grounding and loss of control of the vessel. However, for sediment resuspension and shore zone erosion studies, water elevation fluctuation along the shore is of greater significance. Generally, the drop in water elevation is the greatest around the vessel and decreases with increasing distance away. It is, therefore, reasonable to assume that the drawdown at the stream banks is less than the squat; however, both the squat and drawdown are generally assumed to be equal to simplify the physical process into one-dimensional flow for analytical analysis (Gates and Herbich 1977a; Schijf and Jansen 1953; Kaa 1978).

However, there is another problem associated with the water level drop caused by the movement of a ship in confined waterways. The water level drop becomes, in effect, a trough extending from the ship to the shore and moves along the channel at the same velocity as the ship. As the ship size or speed increases, this moving trough deepens. For the restricted channel sections, such as rivers or canals, this effect might be envisioned as a channel constriction such as a bridge pier. Applying the conservation of energy principle to subcritical flow in an open channel, as the flow passes through a channel constriction, the water surface will drop as the flow passes through the constricted portion of the channel.

The phenomenon of nearshore drawdown and surge may be explained in terms of the moving trough. In sufficiently deep water, the moving trough appears as a fluctuation of the elevation of the water surface. To an observer in a shallow or nearshore area, where the depressed water level approaches or reaches the shore zone, the water appears to recede as the ship passes. This is followed by an uprush and finally a return to the normal level after the vessel-induced surface waves are damped. In addition to the temporary dewatering of shallow areas during vessel passage, drawdown can also cause a pumping action at the mouths of narrow off-channel inlets to backwaters and side channels (Stewart et al. 1997).

While the analysis of these hydraulic effects is discussed in more detail in the following sections, one method for determining whether a waterway is sufficiently restricted to affect vessel motion and the hydraulic effects of vessel passage is the use of the blockage ratio. This ratio is obtained by dividing the cross-sectional area of the waterway by the maximum submerged cross section of the vessel. For blockage ratios above 20, the vessel does not significantly influence water movement (Bhowmik et al. 1991). For many areas of Glacier Bay, the blockage ratio is well above this level; therefore, under most conditions, such effects should not be of concern. For example, the largest cruise ships like *Dawn Princess* (Table 2) in the Sitakaday Narrows will have a blockage ratio greater than 500, while the *World Discoverer* will have a ratio greater than 1700. Similarly, the *Spirit of Adventure* entering North or South Sandy

Cove will have a blockage ratio of about 130 and 520, respectively. Potential impacts might occur where these ships pass near shore or the mouths of inlets where the drawdown effects might extend to shore.

Most analytical and predictive work on drawdown employed a one-dimensional approach applying the conservation of energy principle to subcritical flow in an open channel. Under these conditions, the energy relation (neglecting losses) takes the form of

$$\frac{u_1^2}{2g} + d_1 = \frac{u_2^2}{2g} + d_2 \qquad (52)$$

where u_1 and d_1 = velocity and depth prior to the constriction
u_2 and d_2 = velocity and depth within the constricted passage
g = acceleration due to gravity.

This is combined with the continuity relation:

$$Q = A_1 u_1 = A_2 u_2 \qquad (53)$$

where Q is the discharge and A_1 and A_2 are areas available for flow before and within the constriction, respectively. Before eq 52 and 53 can be applied in this form, the unsteady flow with the passage of a ship should be converted to steady flow by adding a velocity vector to the flow sections that is equal but opposite to the vessel speed.

For long, parallel-midbody ships, vessel length is insignificant in determining drawdown (McNown 1976). Further, length does not enter into the calculations used here. The primary ship dimensions important in determining drawdown are the beam and draft of the ship. For shorter vessels, field data collection becomes even more critical.

Wuebben (1981, 1983) and Wuebben et al. (1984) developed such a one-dimensional treatment to allow an assessment of vessel size on drawdown and resulting sediment transport potential. For the long, parallel-midbody commercial vessels common on the Great Lakes, vessel length is relatively insignificant in determining drawdown. For illustration, Wuebben et al. (1984) considered the relative importance of the major variables by examining the deviations they cause from a base case. That case was a ship with a 7.6-m draft and 30.5-m beam traveling in a rectangular channel 10.7 m deep and 610 m wide. The ship velocity relative to the water was 3.66 m/s. This case is plotted as the central point on Figure 52.

Figure 52 shows that, other things being equal, the effect of increasing channel depth is roughly equivalent to increasing the vessel draft. Figure 52 also indicates that an increase in draft is more important than an equivalent increase in beam. This is simply a matter of geometry. A 0.3-m change in draft occurs over the entire width of the ship (which is at least twice the draft for the ships considered). A 0.3-m increase in beam would only add to the submerged area of the ship over the current operating draft. It is also evident from Figure 52 that vessel speed is by far the most important parameter in determining drawdown.

Although a multi-dimensional treatment would provide more detail, especially in regard to water velocities, there are insufficient data to calibrate or validate an expanded treatment. If the waterway cross section is not symmetrical or the ship passes closer to one shore, the one-dimensional results can be improved by assuming that no water crosses the sailing line, so that the section may be split into separate pieces for calculation (Wuebben 1983; Hodek et al. 1986). For highly non-uniform flow distributions or complex channel shapes, empirical cross-section shape factors can also be included, but these are highly site specific and cannot be reliably transferred elsewhere (Wuebben 1983). The distribution of velocities and sediment transport potential across a river cross section cannot be directly considered, however. Previous work has generally used the existing field data base to develop shore and shore structure damage criteria that can be empirically correlated to one-dimensional modeling (Wuebben 1981, 1983, Wuebben et al. 1984, Hodek et al. 1986).

Hochstein and Adams (1985b) adapted a model that considers drawdown and the effects of propeller wash on the St. Marys River. A subsequent report (Hochstein and Adams 1986) added treatment of ship-generated waves. Their model is attractive for assessing environmental effects in that it makes quantitative predictions of the distribution of water velocity, suspended solids, and bed load across a river cross section based on prop wash, waves, and drawdown. The numerical formulation they employed is a quasi-two-dimensional treatment in that it conducts hydraulic calculations in one dimension and then superimposes assumed distributions for the cross-channel variations of both ambient and ship-influenced flow variables.

While in simple channel shapes this approach may provide useful additional detail, extension to the complex channel shapes and flow distributions is uncertain. However, the Hochstein and Adams model provided an improved basis for comparison of various vessel frequency scenarios. This model was subsequently modified by personnel from the Detroit District to allow input of measured ambient velocity distributions, but the hydraulic calculations remained one dimensional. Treating ship effects in two dimensions is important because of significant variation in ship-induced water velocities across a channel cross section. This variation must be accounted for in predicting magnitudes of sediment transport, turbidity, and impacts on biological systems.

Data from a prior study on the Kanawha River in West Virginia were compared with predicted values, but the results are not presented in two-dimensional form (Hochstein and

Adams 1985a). Lacking a complete, two-dimensional set of field data on the variation of ship-induced water velocities and sediment movement on the St. Marys River (which they strongly recommended obtaining), the performance of the model cannot be definitely assessed. It was, however, calibrated against the available one-dimensional data on ship-generated drawdown and waves. The model was also applied to channels in Duluth–Superior Harbor (D. Williams, personal communication) and resulted in predictions of sediment suspension of the same order of magnitude as the field data of Stortz and Sydor (1980).

Erosion and sediment resuspension

Erosion and sediment transport may be caused in shallow waters and along the shore zone by vessel-induced drawdown and surge, and the breaking of waves. Both processes can introduce energy that exceeds the shear strength of the material at the fjord floor or along the shore zone, causing sediment to be put into motion and redistributed.

Drawdown as an erosional force

The potential for shore damage from drawdown is a direct function of the ship-induced change in hydraulic conditions that can initiate sediment transport or increase transport rates. For sediment transport to take place, near-bottom or nearshore water velocities must overcome a sediment particle’s resistance to motion. Since the drawdown and surge mechanism usually sets up water velocities in opposite directions, their effects tend to cancel. However, natural currents or a sloped bottom can combine with vessel effects to cause a net sediment transport upstream or downstream and offshore.

Hodek et al. (1986) and Liston and McNabb (1986) made field measurements of turbidity and light extinction profiles under both ambient and ship-influenced conditions on the St. Marys River. According to Hodek et al. (1986), during open-water periods, turbidity develops because of wind-driven waves acting on clay bluffs and the nearshore riverbed. For waves on the order of 15.2 cm or more in height, they observed that a high level of turbidity may develop, extending from the shore to the navigation channel. Turbidity did not increase during ship passage when wind-driven waves were present, but if wind-driven waves were absent, that nearshore turbidity did increase with the passage of each vessel.

Ideally, the potential for sediment movement requires analysis of the bed shear stress developed by drawdown-induced water movements. In many practical problems, the determination of the shear stress presents a major difficulty. As discussed earlier, the drawdown-induced water movements are three-dimensional and unsteady, making normal shear stress calculation methods (such as energy slope or velocity profile slope) meaningless. For this reason, velocity is often accepted as the most important factor in assessing channel stability or instability for various vessels. A maximum acceptable velocity at which there will be no scouring can be developed, but the accuracy of such a simplified approach is limited.

Direct observations of vessel impacts

Bhowmik (1978) also quantitatively analyzed waves generated by small power boats, as these waves have been cited as possibly important in causing erosion (e.g. Palmer 1973; Williams et al. 1979; Simons and Li 1982). His analysis of these data followed that described above for estimating significant wave height.

Bhowmik found that boat-generated waves do not show periodic variations, that they are nonstationary in nature, and that wave heights are only partly accounted for by a Rayleigh distribution. As might be expected, waves generated by boats close to shore initially produced a peak wave of large amplitude that was followed by small amplitude waves. Waves from boats farther offshore had smaller amplitudes and smoother forms near shore, apparently because of frictional resistance and energy dissipation. In terms of erosion, a much larger amount of wave energy must be dissipated in the beach zone over a shorter time for waves produced by boats closer to shore than farther away. Bhowmik (1976) suggested that banning small boats from within 100 ft of the shoreline would minimize erosion caused by boat waves. The empirical equation based upon field data for the wave height of boat-generated waves is given by eq 46.

Assessing Damage Criterion

A major problem in setting damage criteria is in defining levels of ship-induced effects that are either undesirable or unacceptable. Realistically, ships cannot be required to cause no sediment motion, even if it were possible to accurately predict the transient, ship-induced threshold of motion in the large, irregularly shaped channels of the Park. Small sediment dislocations should not necessarily be considered damaging, particularly since natural currents, waves, and other factors are often more significant. However, ships can cause large water-level fluctuations and currents that would cause unacceptable levels of sediment transport, shore zone erosion or other environmental damage, as well as affecting recreation and personal safety. Between these extremes, the increase in significance of ship effects is gradual, so it is difficult to define a precise threshold where the effects become unacceptable. In contrast, properly developed and enforced speed limits could effectively eliminate any potential hazards.

In developing a damage criterion for vessel-induced drawdown, Wuebben et al. (1984) adapted non-scouring velocity criteria from the open-channel-flow literature for the various classes of soils found in the Great Lakes connecting channels. Since drawdown is the ship effect that can be predicted with the best accuracy, these scour criteria were then correlated to field data on the maximum ship-induced velocities caused by given levels of drawdown. This allowed the use of a one-dimensional drawdown model to compare the significance of various channel, vessel size, and speed scenarios and to predict reaches where the erosion potential was high.

Hodek et al. (1986) based their damage criteria on the level of drawdown and velocity disturbance, the magnitude of surge, soil conditions, and shore geometry. They also indicated that in the winter the development of shorefast, grounded ice would serve as a barrier to shore zone damage. In developing their criteria, they used data on ship-induced velocities as well as the results of 34 measurements of directional sediment transport. This allowed quantitative prediction of net transport and direction for sand-sized materials, but their actual damage criteria were largely qualitative. Their basis for prediction of cohesive sediment transport is unclear. They classified the potential for damage into three categories. None to light damage refers to inconsequential movement; moderate damage implies light transport as bedload; and severe damage is defined as a condition where sediment is suspended and soils sustaining shallow-rooted organics may be displaced. They concluded that damage could be effectively minimized by controlling vessel speed.

Acoustics

The effects of waves in the shore zone are among the most obvious impacts that can be readily tied to vessel operations; however, the operation of generators, gasoline and diesel engines, public announcement (PA) systems, and other machinery generate large amounts of acoustic noise that is transmitted both underwater and through the air. These noises do not generally represent a direct physical hazard to the surrounding environment or ecosystems; however, exposure can cause biotic responses and repeated exposure may produce long-term behavioral changes (i.e., shifting of feeding grounds).

Underwater

Although we do not fully understand the effects of underwater noise on marine mammals, we do know that the acoustic environment is very important to these animals and that man-made noise is most likely a pollutant of their environment (NRC 1994). Many mammals vocalize during socialization, feeding, or breeding, and some mammals produce sounds for echolocation (Popper and Edds-Watson 1997). These sounds are emitted over a very broad frequency range, from less than 100 Hz to tens of kHz or higher. Thus, underwater noise at nearly any frequency may interfere with marine mammal activities. Frequencies below 1 kHz appear to be particularly important to whales (Heaney and Clark 1999). However, an assessment of noise effects on marine mammals is complicated by our inability to monitor the response of the animals, since most of their activities, and their changes in response to noise, occur underwater where we cannot observe them.

In Glacier Bay, both ambient and man-made noise sources may affect marine mammal activities. Wenz (1962) published a compilation of ambient noise sources as a function of frequency in the open ocean. According to this report, natural sources including wind, precipitation, and sea surface noise are important for frequencies above 100 Hz. Natural sources producing sound below 100 Hz are mostly sea ice noise (down to about 10 Hz) and earthquakes

(100 Hz and below). In the mid-frequency range of 10 Hz to 1 kHz, ship traffic and industrial noise are the most important ambient noise sources. Dyer (1997) also presents an overview of underwater ambient noise sources.

Other natural sounds, believed to be caused by the proximity of glaciers, have been noted Miles and Malme (1988). Low frequency sounds (below about 500 Hz, with some resonant lines near 63 Hz) were recorded and attributed to seismic waves generated by glacier motion. In addition, close to the glaciers, very loud broadband noise from about 200 Hz to more than 1 kHz was also noted and attributed to bubble effervescence from the fresh water ice calving into the bay and the formation of bubbles as dissolved oxygen comes out of saturation. The signal levels of both of these noise sources will change in response to changes in glacier conditions (surges or response to climate change).

Ship-generated noise is probably the most important man-made noise in Glacier Bay. The noise is generated by propellers, machinery vibrations within the ship, flow along the hull, and sounds within the ship below the waterline, as discussed in Collier (1997). The spectrum of noise produced by ships is complex, with both broad band (cavitation, flow noise) and narrow band (propeller, machinery) sources. In Glacier Bay, where the ships are very close, the spectra will be much broader than those shown by Wenz (1962), who included the filtering effect of long range propagation through the ocean in his presentation.

Malme et al. (1982, 1983) present noise spectra for specific ships measured in Glacier Bay. These studies showed that diesel-powered ships were the noisiest, with signal levels 10 – 15 dB above even the larger steam turbine powered ships.

Air

Airborne noise pollution is also common with passage of a vessel; however, no monitoring has been conducted in the area to define noise levels. Sounds generated by the large cruise ships and tour boats, such as various engine and mechanical noises and their outside PA systems are audible for several kilometers and can commonly be heard on the beach by back country users. Private vessels and small boats with outboard motors also generate sounds that are audible for several kilometers.

Pollution

With the presence of all these vessels in Glacier Bay and increased backcountry use, it is impossible to prevent at least minimal levels of both water and air pollution. The following types of pollution might be expected: minor fuel spills, bilge pumping and leaks, inboard and outboard exhaust emissions (both within and above the water), larger scale stack emissions from tour and cruise boats, and marine litter, including anything that happens to fall overboard and lost fishing gear.

Water

The water quality of Glacier Bay is generally considered pristine; however, it is susceptible to pollution from petroleum spills, wastewater discharge, ballast water dumping, and marine debris disposal. There are frequent small spills at a vessel fueling and underground petroleum storage facility at Bartlett Cove (NPS 1995). The fueling facility is used by all classes of vessels discussed, except cruise ships. It has a capacity of 18,000 gallons of gasoline and 70,500 gallons of diesel fuel and is located above the intertidal zone near the public dock. Fuel is delivered to Bartlett Cove about every three weeks in the summer and a total of three or four times during the winter. An estimated 45,000 gallons of fuel is delivered during an average shipment.

Federal regulations mandate that all vessels be equipped with an approved marine sanitation device to prevent the dumping of sewage into the water; however, enforcement of this regulation is difficult. In the developed portion of the Park near the public dock, human waste is discharged into Bartlett Cove through a sewage outfall pipe. Human waste is also introduced by backcountry users who are instructed to use the intertidal zone. In previous years, some camper drop-off points have been forced to move because of the accumulation of human waste in the intertidal zone.

Marine debris

Marine debris is a common type of litter found within the Park that can create nautical hazards to vessels and marine animals. It also degrades the aesthetic beauty of the water and coastal zone. As well as being an entanglement or ingestion hazard for marine mammals, fish, and seabirds, terrestrial animals such as bears regularly eat the debris. Debris can be introduced into the marine environments from a number of sources.

Polasky (1992) conducted a limited study of marine debris within the Park. Most of the marine debris consisted of lost or tangled commercial fishing gear, assorted human refuse (bottles, jars, cans, etc.) that fell overboard, and various building or other industrial materials that either floated in from Icy Strait or came from the collapse and movement of settlers/miners cabins and associated infrastructure. Within Glacier Bay, most debris is concentrated on beaches of the lower bay, south of Willoughby Island. Most beach debris within Glacier Bay proper consists of "generic" boat garbage (NPS 1995). The highest concentrations of marine debris in the Park accumulate on windward beaches of the exposed outer coast between Cape Spencer and Dry Bay. Some of this debris originates from commercial fishing and merchant fleet operations, while other amounts consist of debris washed off of large container ships crossing the Gulf of Alaska.

Air

Glacier Bay National Park and Preserve is classified as a Class II area under the Clean Air Act, with neither an ambient air quality monitoring system nor a model of air resource impacts (NPS 1985). The air quality is generally pristine. However, temperature inversions occur about 83% of the time on clear days and 29% on overcast days (Benson et al. 1978). This is significant because stack emissions become trapped at the thermal boundary and stagnate, forming a yellowing-gray cloud that can persist for several hours (Fig. 53). Vequist (1989) reported that 25 of 77 cruise ships monitored between 1986 and 1987 produced visible plumes that lasted longer than 10 minutes, with the average plume lasting 41 minutes. Benson et al. (1978) determined that thermal mixing of the inversions is minimal, with lapse rates as great as 3.6°C/100 m up to about 200 m above sea level. With low average wind speeds (~4.4 mph in Muir Inlet), these thermal layers are common features of the Glacier Bay ecosystem. As a result, Benson concluded that Glacier Bay has an extremely low tolerance for air pollution.

Emissions from the cruise ships and tour boats include nitrogen, sulfur, carbon compounds, soot, ash, and steam. The Park has tried to ensure that emissions are reduced by requesting ships to use higher-grade fuels while in protected waters. However, all vessels operating in the Park and using fossil fuels as an energy source will produce perceptible emissions at some time.

Other forms of air pollution include lower levels of exhaust emissions produced by tour boats, private vessels, and smaller boats with outboard motors. No systematic studies have been conducted of these vessels, but their influences are generally more localized and at lower levels than the larger vessels.

PHYSICAL FACTORS AFFECTING VESSEL IMPACTS

The range of impacts vessels may have on the physical environment and may in turn on the biological environments of intertidal, nearshore and deeper water marine areas is dependent on a number of interrelated factors. Some factors such as tides are continually changing and the energy expended on the environment by vessels and its net effect will vary as a result. In addition, various attributes of vessels and their operations as discussed previously will affect the interplay between vessel-generated physical processes and natural ones. This discussion attempts to elucidate the nature of some of the more important factors and how they modulate or enhance the physical effects of vessel passage.

One of the principle factors affecting shore zone impacts are tides, and in particular, their range and elevation when vessel waves or currents are generated. At extreme high tide for example, waves may impinge directly on bluff and upper beach sediments. A high tide with a storm surge can result in extreme run-up of waves and breaking high on the shore and bluffs if they are present. At extreme low tide, intertidal zones are subject to the breaking action of waves.

Beach, bluff and nearshore composition, and specifically whether materials are bedrock or sediments, fine- or coarse-grained, cohesive or non-cohesive, uniform or stratified, stable or near a state of failure are important considerations as to how shore zones will respond. The configuration of the above-waterline and below-waterline slope affects wave intensity at the shoreline, as well as in the foreshore region. As tide ebbs or floods, these properties may change. Shoreline configuration and lateral changes in shore zone properties are also critical to vessel effects along a given reach of shore.

The extent of vegetation at the high tide and storm tide elevations, as well as the extent of colonization of intertidal and nearshore zones will modulate wave and current intensity, as well as the strength and erodibility of shore zone materials. Well developed root systems bind soils, while a complete cover of vegetation reduces the intensity and direct impacts of waves, rain or other forces.

Ground and surface water are factors affecting shore zones and nearshore zones. Ground water flow creates pore pressures that affect sediment stability and erodibility. When tides are ebbing, ground water flows out of intertidal and beach sediments, reducing their resistance to erosional and gravitational forces. During flooding tides, water enters sediments, potentially increasing surface resistance. Thus the action of waves and currents may differ depending on ground water conditions.

Similarly during heavy rains, surface flow erodes sediments and weakens them. This increases their susceptibility to waves and currents. Ground water levels also rise and beach and intertidal sediments may be affected by small seeps and piping of sediments. Both conditions increase the likelihood of erosion or a failure by some flow mechanism.

Surface streams can generate a significant influx of suspended sediments to nearshore environments. Rapid deposition during storm events, especially in areas of sparse vegetation, can produce nearshore materials susceptible to failure. Vessels may increase turbulence to the flow field, cause suspended sediment redistribution and initiate slope failures through wave energy or currents that impinge recent deltaic or alluvial fan deposits.

Thus not only are certain physical conditions important to determining how vessels may affect shore and nearshore zones, but the timing of vessel passage relative to tidal stage and storms may be critical as well.

In offshore areas, it is difficult without minimal data to summarize how timing may affect the level or nature of impact. Certainly disruption of sediment or algal blooms by vessel passage can occur. Noise-generation may be dampened during storms. Currents vary with tidal cycle and elevation, and may be altered by wind waves in shallower and restricted areas. Unfortunately current structure of most fjords and bays in the Park are not known and speculation on the likely effects would serve no purpose. The nature of vessel impacts under the various oceanographic conditions of the Park region remain to be determined.

BIOLOGICAL EFFECTS

Biologic effects outside of changes in behavioral patterns caused by vessel traffic are difficult to define. Both benthic and pelagic organisms may be affected by physical alterations of the water column by vessel activity. Such effects as increased turbidity caused by prop wash or bow and stern waves, or the addition of focused turbulence in the flow field caused by a vessel passage, can affect ecological and physical processes on large and small scales (e.g., MacIntyre 1998).

Turbulence can affect populations as well as individual organisms. Phytoplankton, particles and solutes can be dispersed (e.g., Lewis et al. 1984, 1986; Yamazaki and Kamykowski

1991), with subsequent effects on nutrient supply, light availability, sediment resuspension, and substrate disruption affecting zooplankton and larvae (MacIntyre 1993, 1998). Particle flocculation rates may also be altered. Turbulence can redistribute marine snow causing localized accumulations that may alter the oceanic community structure and chemical cycling (MacIntyre et al. 1995a). Eddies reaching the benthic boundary layer disturb settling of larvae and the number of those metamorphosing to adults (e.g. Eckman 1983; Pawlik and Butman 1993). At the micro scale, a turbulent flow field also affects algae, marine snow and solutes, potentially increasing aggregation of particles and organisms such as zooplankton and their prey (Rothschild and Osborn 1988; Denman and Gargett 1995; MacIntyre 1998). Turbulent eddies at the air-water interface move dissolved gases to the boundary, affecting rates of gas flux across it (MacIntyre et al. 1995b).

Although an analysis of the biological effects caused by the physical impacts of vessels is beyond the scope of this report, we include in this section some information that we encountered while conducting our literature analysis. A limited number of studies studies conducted in the Great Lakes Region, for example, provide some insight on what we might expect in Glacier Bay. However, we must keep in mind the large-scale differences in system dynamics and the large sediment sources at the heads of many inlets that dictate background conditions not found in the Great Lakes.

Liston and McNabb (1986) collected baseline water quality data at seven stations in both shipping and non-shipping channels along the St. Marys River during periods without winter navigation. Variables considered include temperature, pH, dissolved oxygen, turbidity, and sedimentation rates. In their study, they found that temperature, pH, and dissolved oxygen were not affected by winter navigation. Turbidity was a more significant concern because of the biological importance of water clarity and light penetration for photosynthesis. Further, turbidity can directly impact invertebrates and fish by fouling gill mechanisms, which in turn can affect circulation, respiration, excretion, and salt balance.

Sletten (1986) conducted a two-year study of the water quality effects of extended season operations on the St. Clair-Detroit River System. Included were documentation of background water quality, sedimentation rate data, and water quality variations with time during vessel passages. The background water quality information was primarily summarized from existing databases supplemented by a limited amount of new measurements. The primary emphasis in the analysis of these data was to locate extreme values of total suspended solids and turbidity for comparison with vessel passage events. Other variables examined were pH, temperature, and dissolved oxygen. The average turbidity was found to vary from 8.7 JTU* in the winter to 7.3 JTU in the summer, but temporal variations within a season were large. Mean values of suspended solids, pH, and dissolved oxygen did not vary significantly between seasons.

Ship passages were monitored at two sites, one on each river. The Detroit River site had 24 passages sampled, equally split during August 1983 and April, August, and December 1984. The St. Clair River site had 18 passages sampled, evenly split among the three 1984 observations. April and December were considered winter, while August constituted summer. Water samples were collected at intervals following the passage of the bow for periods of 30 or 60 minutes, providing a time record of water quality variations. Although levels of turbidity and suspended solids were found to vary following vessel passage, all maximum values recorded were significantly less than natural variations in background levels. No significant correlation

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* Values given in Jackson Turbidity Unit, which are roughly equal to Nephelometric Turbidity Units (NTU)

between ship size, speed, or season of passage, and measured changes in water quality parameters were detected.

Possible reasons cited for the lack of correlation were that none exist, that correlations exist but are too complex for analysis, and that the samplers were not located properly. However, Sletten used linear regression with single ship variables (draft, displacement, or speed) to examine correlation. Correlation on this basis would require equal effects for large and small ships if they traveled at the same speed, or equal effects for a single ship traveling at different speeds. A lumped parameter reflecting both ship speed and size would be more appropriate. Further, the data show that the elapsed time from ship passage to the maximum recorded parameter values ranged as high as 60 minutes, which was the maximum period of sample collection. While vessel passage effects can persist for a relatively long time, it is curious that maximum values were often found as much as an hour after the event, probably indicating other causes. Hodek et al. (1986) found that spatial variations in turbidity were large, even under ambient conditions on the St. Marys River, and that the maximum levels of ship-generated turbidity were near the shore. Sletten's sampling was conducted at the edge of the navigation channel, where Hodek's observations showed the least change and where fluctuations due to other causes would be more significant.

Hodek et al. (1986) conducted a field investigation of ship-generated turbidity on the St. Marys River. They provided the results of 95 measurements of turbidity and 85 light extinction profiles under both ambient and ship-influenced conditions. Ambient turbidities during open-water conditions were typically in the range of 5–30 JTU, although numerous points were higher and the maximum reading was 380. Measurements during open-water vessel passages typically ranged from 6 to 30 JTU, with a maximum of 53. They found that a common source of turbidity was the clay shore zones common along the river and that wind-driven waves of 15 cm or more in height could generate a high level of turbidity extending from the shore to the navigation channel. Under those conditions, no effect of vessel passage could be discerned. Several of the sites used to monitor other vessel effects examined in their study were sufficiently turbid throughout all field periods that it was impossible to see the riverbed. Their major findings were:

- The nearshore zones have more turbidity than the navigation channel, both with an ice cover and no vessel traffic and with open-water and vessel passages.
- Navigation channel turbidity was less in March than in May or June.
- In general, near-shore turbidity decreased with the removal of the ice cover.
- The turbidity in offshore areas of Lake Munuscong (but away from the channel) was least with an ice cover and most in June.
- Sites on Lake Nicolet showed a decrease in turbidity after ice-out.
- The Charlotte River is a major contributor of sediments causing turbidity.

Finally, vessel-induced turbidity was observed to be slight near the channel and highest near the shore, indicating that ship waves and drawdown and surge were generally more significant than propeller wash.

Poe et al. (1980) also measured light extinction on the St. Marys River during the winter of 1978-79 during a period with winter navigation. They chose two river areas for study, and they selected what they considered to be high- and low-impact data collection sites in each of these areas based on a perceived difference in the potential for vessel passage effects. The basis for determining the level of vessel impact potential is not clear, nor are differences in site conditions apart from vessel effects explained.

All measurements were collected during or immediately following vessel passage except for those made during March. Observations in March had no vessel passages and were considered a “control” condition. All measurements were taken through the ice, but by the April field period the ice cover had become fragmented. They found that light penetration was generally lower in February than in March or April and that light penetration was greater at their low-impact sites than at the high ones.

Based on records of ship passage, they felt vessel traffic may have been responsible for the higher turbidity in February, but only one site was monitored during February, and all March and April measurements (except one) were collected at three other sites. It is questionable whether a comparison of samples collected at different sites on different dates can be used to infer navigation-induced turbidity. Further, the single March “control” measurement taken at the same site as the February measurements was less than the maximum light penetration recorded during February.

They also suggested that the greater light penetration at their low-impact sites supported the claim of ship-induced turbidity. However, their data from their March control period show this same relation between sites, suggesting natural variations may have contributed. Further, since Hodek et al. (1986) found turbidity levels to vary significantly with location (even for essentially simultaneous samples at a single site), drawing conclusions on ship effects by direct comparison of turbidity levels at sites more than 915 m apart is tenuous. Interestingly, penetration was greater in April than in March despite heavier vessel traffic. They felt that this may be attributable to the fragmentation of the solid ice cover in April.

Jude et al. (1986) considered it highly probable that vessel passage could result in increased benthic drift, and based on visual observations they speculated that upbound vessels would have the greatest impact on drift density. In reviewing their data, however, they were unable to demonstrate detectable increases in the density of drifting benthos ascribable to vessel traffic. Noting the windy conditions prevalent during data collection, they concluded that ship passage had not significantly altered the already disturbed system.

While considering the distance that disrupted benthos might be expected to travel in the St. Marys River before resettlement, Jude et al. (1986) speculated that a great proportion resettle within a short distance, with only a small fraction consumed or destroyed by drifting activity. Since the period of ship disturbance is very short-lived in comparison with wind events, which could last for hours or days, they concluded that ship-induced drift would resettle more quickly than wind-induced drift. On that basis, they felt that drift induced by windy weather has a greater overall, river-wide effect on drift than individual, though frequent, ice-free ship passages.

Schloesser and Manny (1989) concluded that vessel passage affects the composition and reduces the density of sumbersed macrophytes via vessel-induced disruptions of prevailing water current patterns. Those disruptions may erode substrates beneficial to macrophyte growth, uproot them, or fragment plant stems. Stewart et al. (1997) felt that in shallow water locations, high wave forces may penetrate to the bottom and heavily damage, or possibly completely uproot, submersed aquatic plants.

Canopy forming plants species with leaves and branches projecting from the shoots will probably be damaged by waves more than species with individual, ribbon-like leaves arising from basal rosettes Stewart et al. (1997).

Kimber and Barko (1994) conducted a literature review of the effects of waves on aquatic plants. They noted that aquatic plants can be affected by waves generated by tides, wind, or vessel traffic because of their location in littoral, shoreline, or rocky intertidal zones. Waves can act directly by uprooting or fragmenting plants, or indirectly through resuspension of sediments.

Resuspended sediments can influence aquatic plants by affecting substrate, decreasing light availability, scouring of leaves, or stimulating phytoplankton and periphyton blooms.

The potential effects of suspended solids included siltation of spawning beds, decreased productivity, reduced food availability, clogging of gills, reduced respiration, and changes in behavior. Liston and McNabb (1986) mentioned that high turbidity is generally recognized as an acute stress that fish can tolerate for short periods of time and that they may migrate away from it. As discussed earlier in this report, there has not been substantive documentation of large or persistent increases in turbidity during ship passage on the Great Lakes connecting channels. Liston and McNabb (1986) also cited documentation where several species of fish were exposed to very high levels of suspended solids (as high as 20,000 ppm) and turbidity (up to 500 NTU) without abnormal behavior or apparent harm.

These levels are far in excess of those observed by Poe et al. (1980), Sletten (1986), or Hodek et al. (1986) for ship passages on the St. Marys, St. Clair, and Detroit Rivers. Liston and McNabb (1986) found ambient turbidity levels at their sites on the St. Marys River to range from 1.3 to 45.5 NTU during the summer and 0.5 to 2.3 NTU in the winter. For ship passages monitored during the open-water season, no reading exceeded 11.8 NTU. The measurements of Hodek et al. (1986) on the St. Marys River showed typical ambient turbidity levels of 5–30 JTU, with a maximum reading of 380. During vessel passages their measurements typically ranged from 6 to 30 JTU, with a maximum of 53. On the Detroit and St. Clair Rivers, Sletten (1986) reviewed the Environmental Protection Agency STORET database and estimated that mean turbidities varied from 7.3 JTU in the summer to 8.7 in the winter. Sletten also monitored turbidity during 42 ship passages and found maximum levels ranging from 2.3 to 73 JTU. The maximum turbidity measured during his “winter” field periods (April and December 1984) was 7

JTU. Liston and McNabb (1986) concluded that suspended solids levels in the St. Marys River would cause no direct harm to the fishery unless catastrophic increases in sediment load occur.

Increases in turbidity or suspended solids were cited as potential causes of damage for benthos, aquatic plants, fish and birds, but no significant damage was documented. Further, the data do not suggest large or persistent changes in these parameters, and ambient variations were found to equal or exceed vessel passage values. There was some evidence that benthic drift rates might be higher for navigation in ice, but the magnitude and significance of this increase could not be determined. Two studies showed that macrobenthos densities were not significantly affected by navigation in ice. Similarly, the possibility of damage to emergent vegetation by the movement of ice frozen about rootstocks was discussed but not observed. The ice movements could be caused by either vessel-induced water level fluctuations or ice breakup in the spring.

For fish the major effects were considered to be increases in suspended solids and damage to aquatic vegetation. Direct damage to fish by ships was largely discounted since the vast majority of fish were found to be outside the navigation channel. Those fish found in the channel were generally winter-active and could presumably avoid impacts during vessel passage. The major effect of winter navigation on waterfowl appeared to be flushing during vessel passage, but this occurred mainly in April in the St. Marys River, after the traditional shipping season had resumed. Its physiological significance is unclear. Other concerns were centered around changes in open-water areas, but it does not appear that the critical areas described would be significantly affected by vessel passage.

OIL AND HAZARDOUS SUBSTANCE SPILLS

The general effects of a spill on an aquatic environment could vary by impact and degree. These include:

- Direct kill of organisms through coating and asphyxiation;
- Direct kill through contact poisoning of organisms;
- Direct kill through exposure to water-soluble toxic components of oil at some distance in space and time from the accident;
- Destruction of the generally more sensitive species;
- Destruction of the generally more sensitive juvenile forms of organisms;
- Incorporation of sublethal amounts of oil and oil products into organisms, resulting in reduced resistance to infection and other stresses (the principle cause of death in birds surviving the immediate exposure to oil);
- Destruction of food values through the incorporation of oil and oil products into fisheries resources; and
- Incorporation of carcinogens into aquatic food chain and human food resources.

Oil and greases could have a devastating effect upon waterfowl as well as life within the water; the problems for waterfowl are compounded by low water temperatures. Therefore, of the living resources, waterfowl appear to be potentially the most vulnerable to the effects of an oil spill. The specific impacts of spills on the freshwater environment have been summarized on the basis of laboratory and field studies and on observations during four actual spills (Baca et al. 1986):

- Algae. Phytoplankton was relatively unaffected by spilled oil except in certain laboratory cultures and in exposures to certain components of oils. Filamentous and benthic algae showed some impacts but were generally resistant or recovered quickly. Blue-green algae frequently increased following spills.

- Macrophyte vegetation. Submerged species or the submerged portions of emergent species were generally not impacted. However, emergent species or those at the edge of the water (typically marsh) were affected or killed by surface oiling.
- Invertebrates. Results of laboratory studies established toxicity levels, but impacts in real spills have been minimal or short-lived. The most impacted groups have been insects moving at the air/water interface.
- Fish. Toxicity studies have established levels, and field experience shows serious impacts caused by spills in some cases. Larvae and fry have generally been more sensitive than adults. Tainting of flesh in adults is another impact. Oiling of lines and gear and impacts on fishing are other factors to consider.
- Birds. Historically, the most noticeable impacts have been on this group. Toxic effects can be caused through ingestion, absorption, or transfer to eggs and chicks. Surficial oiling has been most deleterious, causing problems with heat regulation and buoyancy.
- Mammals. Similar to birds, impacts are related to surface oiling, which causes a loss in insulative properties of the fur. Mortality can also be caused by ingestion.

Generally, spills in water are handled with absorbing agents, skimming by vacuum, skimming by pumping or burning, and herding agents.

Alaska Clean Seas, a nonprofit organization sponsored by 15 oil companies, is devoted to oil spill response in most offshore areas of Alaska. This organization has sponsored research and development of better oil spill cleanup equipment and techniques. In addition, it provides manuals, training, and equipment for oil spill containment, disposal, and mitigation.

CONCLUSIONS

Glacier Bay National Park and Preserve is an internationally recognized site for the preservation of both marine and terrestrial ecosystems. The National Park Service is mandated to manage and protect this area for future generations, while also allowing for ongoing visitation and research activities. However, most of these activities introduce some level of environmental impact, which the Park Service needs to address. Risk assessments are also needed to evaluate the likely potential health hazards (e.g., oil spills) and management practices to mitigate such events.

The nearly constant pressure placed on the Park Service to increase visitation to Glacier Bay has resulted in a 170% increase in the number of people visiting the Park on large cruise ships over the past decade. Along with cruise ship increases, entries of tour, charter, and private boats have increased. In addition, Glacier Bay is a major destination for back country users whose primary means of transportation is kayak. Therefore, marine visitation represents the area of greatest growth in Park activities and corresponds to the most likely source of potential impacts to Glacier Bay ecosystems. As such, we have identified the most obvious physical impacts that might be related to vessel traffic and also their corresponding natural processes that govern ambient background conditions (Table 7).

Vessel-generated waves are known to actively modify shore zones along large lakes and connecting channels where shipping traffic is heavy; however, their importance in Glacier Bay is not clear. The energy within a vessel-generated wave is proportional to the speed of the vessel and is subject to hull design (Table 7a). Like wind waves, the height and frequency of these waves transforms into erosive energy when they encounter the shore. However, the coastal environment in Glacier Bay is frequently subject to natural high-energy events (storms) and many of the beaches are extremely coarse grained, or even composed of bedrock (Fig. 5). Under such conditions, it is likely that short-lived vessel waves will have only limited ability to modify the shore zone. In contrast, other shore zones are composed of highly erodable materials or of materials subject to failure, and waves and currents could cause erosion, sediment resuspension, or lead to instability and failure. Similarly, changes in fjord currents associated with vessel passage will be short lived and these disturbances are in many cases minimal in comparison to littoral and tidal currents associated with tidal exchanges of 5 to 7 m. But again, in certain situation such as shallow water or along sediment bluffs, changes can result.

There is little documentation of natural variations or ship-generated wave characterization. Slightly more information has been collected to define air and water pollution levels. Water quality can be affected by fuel leaks and refueling spills, sewage outflow, engine emissions, and the illegal discharge of marine toilets (Table 7). There are no natural processes that are similar to these anthropogenic sources of pollution; however, natural processes may be important in breaking down and remediating the contaminants. Air quality is often noticeably affected by cruise ship traffic where stack emissions are trapped by a thermal inversion layer within the narrow fjords. These emissions tend to leave a yellowish cloud that can reside over the fjord for several hours before it dissipates, resulting in reduced visibility. Because Glacier Bay is pristine, such emissions are especially evident and can affect visitors.

Noise is another common feature associated with vessel traffic that can have negative effects on marine and terrestrial ecosystems as well as Park visitors (Table 7). These noise sources, which are transient and often within the audible range of marine organisms, can initiate behavioral responses. Ambient acoustic noise is also common however (Table 7b) and overlaps with various vessel-generated sounds.

Our preliminary conclusions based on the limited data on the natural processes of Glacier Bay and on the physical impacts of vessels, especially within Glacier Bay and similar fjord environments follow:

- Shore zones are not sufficiently characterized in terms of physical processes and factors to determine what impacts vessels may be having on the physical environment in Glacier Bay.
- The deep water marine environment of Glacier Bay is not sufficiently characterized in terms of physical processes and factors to determine how vessels may affect physical or marine biotic activity.
- Historic data documenting the effects of private boats, commercial fishing, cruise ship or tour boats are extremely limited and a critical data gap to defining the potential impacts of increased usage of Park waters by vessels.
- Basic information and baseline data on the natural physical processes and factors of the marine environment, including the intertidal and shore zones of Glacier Bay, are virtually unavailable. Basic meteorologic, oceanographic, hydrologic and geologic data are required to effectively analyze, model, or predict vessel impacts on Park resources. This lack of data is also a critical gap to understanding vessel impacts on ecosystems.
- The physical effects of vessels on the fjord environment and particularly on Glacier Bay have received little study to date. Again, this is a major data gap.
- In order to assess how vessels, whether they be cruise ships, tour boats, commercial fishing vessels, or pleasure craft, impact the natural environment, field investigations are required of various marine and shore zone environments. These analyses must be contrasted with similar analyses where physical and biological systems are not impacted. At the present time, one can only speculate on how such vessels may be affecting the physical environment. In addition, basic physical parameters for the Park, including that of climate, are lacking but required for nearly any biological or physical investigation.

Because many of the natural processes and vessel-generated impacts described in Table 7 have not been quantitatively monitored in the field, statements and assumptions therein must be treated as qualitative and designed to demonstrate levels of knowledge while identifying data gaps. To address these data gaps, we propose that field monitoring should be carried out so that future management decisions can be based on quantitative and defensible data.

In the next section, we outline a study plan to examine the natural and anthropogenic physical processes and impacts, and address the most severe data gaps. Such a program needs to be undertaken considering the size of the Park region, extremes in fjord bathymetry and substrate, length of impacted shoreline, extreme diversity of terrain and landforms, highly variable geologic material types, and spatially and temporally variable meteorologic conditions.

REQUIREMENTS FOR FUTURE SYSTEMS AND IMPACT MONITORING

A multi-disciplinary monitoring program is required to document and quantitatively evaluate the effects of vessel traffic on marine and coastal ecosystems. This program needs to address basic regional and local scale gaps in knowledge. Monitoring needs to investigate the effects of waves, currents, and acoustic noise at the site level, while examining oceanographic parameters in high vessel use areas on a larger scale. Ecosystems, biota, and physical zones that are susceptible to disturbance need to be identified and monitored. Individual segments of the shore zone need to be examined independently to evaluate unique conditions in terms of fetch, beach orientation, intertidal zone extent, textural composition, and slope profiles. Foreshore and offshore areas need to be characterized by side-scan sonar and acoustic bottom profiling to define substrate conditions and related parameters. Beaches with a limited fetch, with an orientation oblique to incident wave directions, and composed of bedrock are not likely to be impacted significantly by vessel waves; however, marine mammals and benthic communities may be affected and these effects will need to be evaluated separately (B. Mathews, personal communication, 1999).

In the abiotic system, most of the impacts will be focused on bluffs, beaches, and intertidal zones in restricted waters along open waterways in the main bay where vessel-generated waves are common. Protected shore zones that are in equilibrium with lower energy conditions may be unstable when exposed to periodic, high-intensity wave events generated by nearshore vessel traffic. In the latter case, shore erosion and littoral transport of sediment particles may coincide with the breaking of large, vessel-generated waves. Undercutting of unconsolidated bluffs may result. Currents generated by vessel traffic will most likely be limited to the waters immediately surrounding the vessel, so that distance from the shoreline and vessel speed are critical factors. Minimal littoral currents may also be generated by vessel waves. Unfortunately, neither the short- or long-term effects of these anthropogenic disturbances to the natural environment are known and thus their effects need to be monitored in terms of the ambient background conditions of the physical systems in the Park.

Impacts to shore zone biotic communities are likely to be behavioral. Shorebirds and marine mammals are temporarily displaced by waves; however, this displacement is generally short unless it coincides with a human visit or the appearance of a predator (e.g., brown bear). It is not known whether these animals habitualize under these disturbances or relocate if disturbance thresholds are routinely exceeded.

Coastal surveys

Evaluating the effects of vessel traffic on marine and coastal ecosystems requires that natural baseline conditions be monitored and understood. We suggest that a series of coastal surveys be performed throughout the Park to attain baseline information on their physical attributes. Important parameters to be identified include orientation of the coastal section, material type (texture, composition, etc.), shore profiles, exposure to wind waves and currents, frequently occurring wave characteristics, and nature of the biotic ecosystems. The Park's on-going Coastal Resource Inventory and Mapping Program (L. Sharman, personal communication, 1999) is already mapping some of these parameters and this database should be consulted before fieldwork begins.

The initial study should include defining shoreline orientation and evaluating exposure to incident waves, both vessel- and wind-generated. A Geographic Information System (GIS) should be used to divide coastal segments based on their beach orientation. Wave propagation direction can be determined from known vessel traffic patterns. The shoreline segments that are susceptible to incident waves related to up-bay and down-bay vessel traffic can then be identified. Storm-generated waves will be more diverse; however, an analysis of storm trends (especially in the fall and winter) will reveal average wind conditions that generate wind waves. These analyses will provide critical information on which beaches and shore are most likely to be exposed to vessel- and wind-generated waves, when these conditions exist, and how frequently and prolonged such an exposure might last. In addition, conducting these analyses should aid in determining critical locations for climate stations that can measure wind velocity and direction. These data are required for determining ambient wave conditions.

Shore zones with a high exposure to waves should be investigated by skiff and on-site surveys. Such surveys will augment the Park's coastal surveys, or provide critical baseline data where such surveys are in advance of the Park's mapping and inventory. These shore zones need to be described in terms of their geological composition (i.e., sediment type and size, soils, bedrock exposures), beach and offshore profiles, stream proximity, off-shore currents, vegetation cover, and biotic communities (intertidal species, nesting shorebirds, mammal visitation). The nearshore, foreshore and immediate offshore areas should be evaluated in terms of bathymetry and substrate types. Data from such inventories need to be archived in a spatial database for developing GIS coverages and to aid in selecting places for site-specific monitoring programs.

Waves

Waves are generated by all vessels operating in Glacier Bay and are their most direct effect (Wuebben 1995). The wavelength and amplitude of these waves dictate the amount of energy available to be expended on the shore when these waves break. The height of these waves is primarily a function of vessel speed (Gates and Herbich 1977a; Wuebben et al. 1984), and to a lesser degree, hull design (Ofuya 1970). The interaction of waves with nearshore and coastal sediments, and the propagation of littoral currents are important factors controlling shore erosion, beach stability, and sediment transport. Hydraulic turbulence in the surf zone causes resuspension of particles and littoral transport, which may alter the intertidal zone substrate (e.g., by winnowing fine-grained sediments).

The height and frequency of waves of both vessel and wind origin must be measured. These parameters are important because wave energy is proportional to the square of wave height (Allen 1982), and therefore represents the available force that can be applied to a shore zone. Wave burst information can be acquired using a SBE Seagauge wave and tide gauge, or similar device. We suggest using the device over discrete time intervals such as a high-tide cycle when vessel traffic is also likely. The instrument should be set to continuously monitor tidal and wave bursts over a 4 to 8 hour period. An observer should record vessel traffic, vessel type, approximate speed, and distance from shore. Such measurements should be conducted over several tide cycles through each season and at all monitoring site.

Turbidity and littoral transport

Waves resuspend fine-grained particles and cause littoral transport of sand and gravel along and from shore. These wave effects can be monitored by performing repeat profile transects, installing sediment traps and secchi disks, and monitoring index-stone movement. Automated water samplers (e.g., ISCO or sucking turbidity meters) can also be used to sample suspended sediment in the water column (e.g., Lawson et al. 1996). Such a sampling program needs to monitor net transport and deposition in the swash, nearshore, and offshore zones.

Long-term effects can be monitored through repeat measuring of shore profiles. Profiles should be measured at several sites to characterize variation in shore zone geometry and to define profiles in protected and exposed sites, shores with different textural characteristics (grain size), and different orientations relative to incident wave angles. Profiles should be collected at least twice a year (early spring, late summer). Representative control sites in areas away from the influence of vessel traffic need to be included to record natural process dynamics so that comparisons can be made against disturbed shores. Beach slopes can be simply measured by hand leveling along a transect and recording the transect location with a GPS recorder. These transects can be extended 100-200 m offshore using an echo sounder. An understanding of the shore profile is critical for evaluating wave behavior and deformation of the oscillatory motion of the water as a wave impinges on the shore.

Sediment traps should be installed as bottom traps offshore and suspended in the water column to record sediment transport. These traps need to measure multidirectional sediment transport. Such a trap may consist of four containers oriented to collect sediment moving either laterally along the slope, or vertically up and down the swash zone. These traps will acquire qualitative data on net sediment transport and should be deployed during normal conditions to obtain baseline sediment transport data and just prior to vessel wave events.

Sediment traps should also be installed on the shoreface just below the low tide line to measure nearshore transport. These should be installed by divers in the spring and visited periodically throughout the year. One method to use are flat plates about 30 cm^2, the top set even with the bottom surface. Sedimentation measurements can be made by inserting a millimeter ruler into the sediment until refusal is met by encountering the underlying plate, then reading the sediment height on the ruler (e.g., Lawson et al. 1996). At least three measurements should be taken at each site to account for natural variability in deposition.

One or two camper drop-off sites should be investigated in detail to define daily and seasonal impacts. This should include establishing sediment traps along transects in the swash zone and below the tide line. The center of these transects should approximate the landing area where the drop-off vessel comes to shore to drop-off and pick-up passengers. Prop wash associated with the this maneuver, especially when backing away from the shore, likely creates considerable disturbance to the benthic environment and causes intensified sediment erosion, transport and deposition.

Currents

Currents at selected sites should be monitored to characterize natural background conditions and to determine limits on natural conditions. Both electromagnetic current meters and Acoustic Doppler Profilers (ADP) can be deployed in place or used from onboard ship to define current patterns across trafficked areas. Initial surveys of the current velocity and direction should focus on defining the overall pattern and then focus on biologically sensitive areas for a more detailed analysis. Restricted inlets and fjords frequented by fishing and tour boats should also be evaluated. Currents are generated by shifting tides, storms, and nearby streams and control long-term site conditions. The degree to which vessel waves and generated currents affect the nearshore environment depends on background conditions. Beaches and shore faces in equilibrium with prolonged exposure to high-energy wind waves and tidal currents are likely to be coarse and stony and only minimally affected by anthropogenic waves. However, shore zones along more restricted inlets where fetch is minimal may be heavily impacted by vessel traffic.

In more restricted navigable channels, as found in the waterways of the Great Lakes, measurable velocity fields are induced by the passage of vessels (e.g., USACE 1974; Wuebben et al. 1978). This requires that the vessel width and draft account for a sizable portion of the channel cross section. Such conditions are unlikely in the larger channels and bays found in Glacier Bay. To confirm this, limited numerical modeling could be performed for select channel cross sections representing areas where waterways are relatively restricted using hull dimensions of a few of the ships that enter Glacier Bay (Table 4). These data would provide constraints on vessel effects on velocity fields in the fjords.

Acoustics

Acoustic measurements were last done in Glacier Bay in the early 1980’s. Since then, ship traffic in the Bay has increased dramatically, with different types of ships present, including newer, more powerful cruise boats, and the tourist season has been extended to include the spring and fall. New ambient noise measurements will show how the acoustic environment and background noise levels in Glacier Bay have changed over the last 15 years. An acoustic array should be established in a busy vessel area and noise records correlated with vessel passage.

As the earlier measurements have shown, the relationship between ship size and the radiated sound level is not a simple one. The type of engine and hull details are important factors contributing to the sound produced by each ship, and measurements are needed to determine these levels. The smaller ships might required more maneuvering than the larger cruise ships, and, therefore, produce a wide range of sounds associated with turns, acceleration, and deceleration. We need to determine what sounds are produced by this maneuvering. These effects may be quantified by additional measurements. Specific measurements can be designed and conducted to verify and determine the importance of glacier-produced noise specific to Glacier Bay, including the calving and effervescence of fresh water ice and the production and transmission of seismic waves into the Bay from basal sliding.

Site selection

Site selection is critical because the regional size, the length of coastline, and ecosystem diversity of Glacier Bay must necessarily limit the number of sites that can be effectively monitored and characterized. Several parameters need to be considered when selecting a limited number of sites that can adequately represent the diverse geologic and oceanographic conditions, wave exposure, climate, weather patterns and similar factors. A Geographic Information System will be an essential tool for prescreening potential monitoring sites before fieldwork is begun. This prescreening needs to include shoreline orientation and potential incident-wave propagation directions to limit the number of segments and to group according to their potential exposures. Coastal sites affected by natural processes should be contrasted by those impacted by vessels. Available coverages of shore conditions and characteristics from the Park’s coastal inventory and mapping should be included. Final site selection will depend on available funding, time, and integration of data from skiff surveys.

Some potential sites of interest for monitoring smaller vessel and medium sized cruise boat’s physical impacts include Bartlett Cove, the Russell cut, Whidbey Passage, lower Muir Inlet, Tidal Inlet, proposed drop-off points, and smaller coves or inlets (e.g., Reid, Sandy Cove, Fingers Bay). Bartlett Cove is an ideal location for part of the study because of permitting restrictions that require private vessel operators to check in at the Backcountry Office, while commercial vessels make short dock visits to allow passengers to visit the Glacier Bay Lodge. Acoustic and wave instrumentation should be placed near the mouth of Bartlett Cove. Vessels passing this point tend to have accelerated to, or are in the process of accelerating to, Whale Water cruising speeds. Because vessels congregate in this area, they can be visually identified while their acoustic and wave patterns are observed. Monitoring closer to the Bartlett Cove dock would be inappropriate because vessels operate at a low idle and produce a minimal wake.

Lower Muir Inlet and Tidal Inlet are potential areas for examining tour boat effects, especially of catamaran style hulls, on the shore zone and fjords. Tour boats travel relatively close to shore at higher speeds and therefore have a higher potential for impact than does a cruise ship. The Russell Island cut and Whidbey Passage are also ideal locations to characterize small vessel patterns because of their restricted waters.

Larger cruise ships do not generally frequent the above mentioned sites. Waves and acoustic signatures of these vessels need to be monitored either on the more exposed sides of the islands, or along shoreline segments of the upper main bay, or both. The site should be selected to allow easy identification and tracking of vessels as well as where a relatively uniform bathymetry and shoreline configuration exist. Monitoring can also be conducted from smaller vessels that can wait for passing cruise ships at fixed distances from standard travel routes, as these vessels tend not to travel near the shoreline.

Monitoring around drop-off/pick-up points are of particular interest because they are sites where a medium-sized vessel cruises near shore at high speed before it slows and turns into the beach. The captain of the vessel then throttles up the motors (i.e., increase prop wash) to drive the bow onto shore, and subsequently to pull away offshore. These repeated maneuvers can cause localized, intense disturbance at the sea floor. Scour of the substrate and intertidal zone and sediment redistribution are likely results that need to be monitored.

Basic data requirements

In addition to specific site measurements and analyses, certain data are basic requirements for both physical and biological investigations in the Park. These include meteorologic data, with a minimum of three climate stations at sea level required in the East and West Arms and central Bay area. Stations should measure air temperature, barometric pressure, snow depth, precipitation, solar radiation (incoming, outgoing), and wind speed and direction. Climate stations should be supplemented by simple precipitation and air temperature sensors at sites across the Park to establish regional gradients and storm tracks.

Tide gauges should be installed in the upper reaches of the Bay, as well as in restricted coves or bays. Water levels should be recorded at 10- to 15-min. intervals. All sites must be precisely surveyed.

Remote monitoring of water quality parameters at various depths within fjords of the East and West Arms will provide information on seasonal characteristics of fjord waters. Water temperature, salinity, turbidity, chlorophyll A, current velocity, dissolved oxygen, and pH/Eh should be monitored. If funding permits, such oceanographic stations could transmit data via satellite to appropriate offices. Sites should be chosen to encompass the important variability within fjord systems including glacial sources. Moored sediment traps should augment the analyses of suspended sediments in the water column.

Current structure should be defined for the principal fjords and lower Bay. Monitoring from the Nunatak, or similar boat, should be done on a series of transects that are repeatedly surveyed during each season at high, slack, and low tides. These data are basic oceanographic parameters unknown for all but small parts of Glacier Bay, yet essential to understanding the physical and marine ecosystems.

Water temperature, salinity, and suspended sediment gradients within individual fjords and the Bay as a whole should be defined. These gradients are basic background oceanographic data like current structure, required for understanding the physical system and marine ecosystem and any impacts to it. This survey could be conducted in conjunction with the current analyses.

Risk assessment

Finally, field data on natural and vessel processes need to be evaluated in terms of risk or the susceptibility of the physical environment to impacts from vessels of different types considering their routes of travel. Using the GIS, shore zones and offshore areas should be evaluated in terms of degree of susceptibility as natural conditions vary. From this analysis, potential restrictions on vessel usage (timing, speed, distance offshore, location, etc.) could be defined to minimize impacts. Management could then determine what practices to follow to maximize resource preservation by combining this evaluation of physical impacts with that resulting from the biological and ecosystem analysis of vessel impacts.

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Table 1. Authorized limits on vessel services in Glacier Bay National Park.

Vessel category	*Vessels per day*	*Total entries (June 1 – Aug 31)*	*Total use days (June 1 – Aug 31)*
Cruise ship	2 (Jan 1 – Dec 31)	139	139
Tour vessel	3 (Jan 1 – Dec 31)	276	276
Charter vessel	6 (June 1 – Aug 31)	312	552
Private vessel	25 (June 1 – Aug 31)	468	1971

Table 2. Size and capacity specifications for vessels entering GBNPP (Ward 1999; D. Nemeth, personal communication, 1999).

	Dimensions (m)			*Passenger*	*Gross*	*Horse*	*Speed*		
Ship	*Length*	*Beam*	*Draft*	*Capacity*	*tonnage*	*Power*	*(knots)*	*Screws*	*Rudder*
a. Cruise Ship									
Rhapsody of the Seas	279	32	8	2000	78491	- - -	- - -	2	- - -
Dawn Princess	261	32	8	1950	77000	24599	20	2	Single
Sun Princess	261	32	8	1950	77000	18000	19	2	- - -
Galaxy	264	32	8	1896	76522	- - -	22	2	Single
Mercury	264	32	7	1908	76522	60000	- - -	2	- - -
Legend of the Seas	264	32	8	1804	70950	- - -	- - -	2	Single
Crown Princess	245	32	8	1590	69845	22250	21	2	Single
Regal Princess	245	32	8	1590	69845	32640	20	2	Single
Star Princess	245	32	8	1490	63524	53000	22	2	Single
Maasdam	219	31	8	1266	55451	- - -	- - -	2	Single
Ryndam	219	31	8	1266	55451	- - -	- - -	2	Single
Statendam	219	31	8	1266	55451	- - -	- - -	2	Single
Veendam	219	31	8	1266	55451	- - -	- - -	2	- - -
Westerdam	243	29	7	1494	53872	- - -	22	2	Twin
Norwegian Wind	230	29	7	1748	50760	- - -	- - -	2	- - -
Crystal Symphony	237	30	8	960	50202	- - -	- - -	2	- - -
Crystal Harmony	241	30	8	960	48621	- - -	- - -	2	Single
Horizon	208	29	7	1354	46811	- - -	- - -	2	Single
Sky Princess	240	28	8	1200	43692	32200	19	2	Single
Tropicale	205	27	7	1022	36674	- - -	- - -	2	Single
Nieuw Amsterdam	215	27	8	1214	33930	29368	23	2	Single
Noordam	215	27	8	1214	33930	29368	23	2	Single
Universe Explorer	188	26	8	740	23879	- - -	- - -	2	Single
Seabourn Legend	134	19	5	204	9975	- - -	- - -	2	- - -
Hanseatic	123	18	5	188	8378	- - -	- - -	2	Single
World Discoverer	88	15	5	138	3153	4800	13	1	Twin

Table 2. Size and capacity specifications for vessels entering GBNPP (cont.).

Boat	*Dimensions (m)* *Length*	*Beam*	*Draft*	*Passenger capacity*	*Gross tonnage*	*Horse power*	*Speed (knots)*	*Screws*	*Rudder*
b. Tour Vessels									
Yorktown Clipper	78.3	13.1	2.4	138	97	1800	- - -	2	- - -
Spirit of Endeavor	63.1	11.3	- - -	107	99	- - -	13	0	Single
Spirit of '98	58.5	12.2	- - -	99	96	- - -	13	0	Single
Wilderness Discoverer	51.5	11.6	1.8	86	95	1000	12	2	Twin
Spirit of Glacier Bay	50.6	11.3	- - -	84	97	- - -	13	- - -	- - -
Spirit of Discovery	50.6	11.3	- - -	84	94	- - -	13	- - -	- - -
Wilderness Adventurer	47.9	11.6	1.8	74	89	680	10	2	Twin
Sea Lion	46.3	- - -	- - -	70	99	- - -	12	- - -	Single
Sea Bird	46.3	- - -	- - -	70	96	- - -	12	- - -	Single
Spirit of Alaska	43.6	8.5	- - -	82	97	- - -	12	- - -	- - -
Wilderness Explorer	34.1	6.71	- - -	36	98	- - -	9	- - -	Single
Executive Explorer	29.9	11.3	- - -	49	98	- - -	18	- - -	- - -
Spirit of Adventure	26.2	9.75	2.4	250	98	2600	30	2	Twin
St. Gregory	23.8	8.5	0.6	150	91	2200	- - -	4	- - -

Table 3. Commercial visits to Glacier Bay National Park during 1997 and 1998 (D. Nemeth, personal communication, 1999).

Company	*Vessel*	*1997 Visits*	*1998 Visits*
a. Cruise Ships			
Carnival Cruises	Tropicale	1	
Celebrity Cruises	Galaxy	8	9
	Horizon	7	
	Mercury		5
Crystal Cruises	Crystal Harmony	4	8
	Crystal Symphony	1	
Cunard	Crown Majesty	9	
Discovery Shipping (Society)	World Discoverer	1	1
Hanseatic Cruises	Hanseatic	1	1
Holland America Line	Maasdam		20
	Nieuw Amsterdam	18	20
	Noordam	6	3
	Ryndam	16	9
	Statendam	19	9
	Veendam	20	
	Westerdam		20
Kloster Cruise Limited	Norwegian Wind (aka Windward)	13	1
Princess Cruises	Crown Princess	18	1
	Dawn Princess	16	18
	Regal Princess	19	18
	Sky Princess	2	
	Star Princess	3	
	Sun Princess	18	18
Royal Caribbean International	Legend of the Seas	9	4
	Rhapsody of the Sea		11
Seabourn Cruise Line	Seabourn Legend	1	
World Explorer	Universe Explorer	7	7
	Total for season*	217	183
	Total (1 June - 31Aug)	139	115

*Vessel entries occurred 26 Apr - 30 Sep 1997; 8 May - 27 Sep 1998.

Table 3. Commercial visits to Glacier Bay National Park during 1997 and 1998 (cont.).

Company	*Vessel*	*1997 Visits*	*1998 Visits*
b. Tour Vessels			
Alaska Tours & Cruises	Spirit of Alaska	20	2
	Spirit of Columbia		20
	Spirit of Discovery	40	22
	Spirit of Endeavour	22	22
	Spirit of Glacier Bay	2	2
	Spirit of Ninety-Eight	5	24
Clipper Cruise Line	Yorktown Clipper	11	10
Glacier Bay Park Concession	Wilderness Adventurer	25	25
	Wilderness Explorer	45	26
	Spirit of Adventure	83	116
	St. Gregory	57	
	Executive Explorer	24	23
	Wilderness Discoverer		24
Special Expeditions	Sea Bird	14	14
	Sea Lion	14	12
	Total for season*	362	342
	Total (1 June - 31Aug)	235	247

*Vessel entries occurred 12 Apr - 29 Sep 1997; 17 Apr - 24 Sep 1998.

Table 6. Selected Ship-Generated Wave Heights (after Sorenson 1973).

					Distance from sailing line	
					100 ft	*500 ft*
Vessel	*Length (m)*	*Beam (m)*	*Draft (m)*	*Displacement (tons)*	*Height (m)*	*Height (m)*
Cabin cruiser	7.0	2.5	0.5	3	0.3	0.2
Coast guard cutter	12.2	3.0	1.1	10	0.5	0.3
Tugboat	13.7	4.0	1.8	29	0.5	0.3
Fishing boat	19.5	3.9	0.9	35	0.5	0.2
Fireboat	30.5	8.5	3.2	343	0.5	0.3

Table 7. Summary of physical processes and impacts.

A. Vessel Generated

Type	*Parameter*	*Impact Zone*	*Controlling Factors*	*Physical Impacts*	*Weakness of Data as Applied to GBNP*
Vessel Waves	-Height -Shape -Frequency	-Offshore -Intertidal	-Vessel speed -Hull design -Shore profile	-Periodic, short-term exposure to wave energy -Shore zone scour and erosion -Sediment resuspension and transport -Bluff/nearshore failures	No background data
Velocity Changes and Currents	-Vessel wake and hull effects -Littoral currents	-Offshore -Nearshore	-Vessel speed -Hull design -Propulsion characteristics -Channel cross-section -Ambient velocities	-Periodic, short-term disturbance of water column -Shore zone scour and erosion -Sediment resuspension and transport -Offshore turbulence and surface water mixing -Slope failures	No background data
Pollution					
Water Quality	-Fuel spills -Sewage outfall -Leaks -Engine emissions	-Offshore -Intertidal	-Vessel maintenance -Engine type -Accidents	-Water quality and habitat degradation -Increased water opacity -Wildlife health hazard (ingestion, absorption)	Little quantitative documentation
Aquatic Noise	-Frequency -Magnitude	-Intertidal -Nearshore -Offshore	-Temperature -Salinity -Sediment type/ bedrock (hardness) -Vessel type and distance	-Behavioral response of marine animals	From published data by Malme et al. 1982, Baker and Herman 1983. No signatures for newer vessels.
Air Quality	-Composition -Opacity	-Atmosphere	-Vessel emissions -Thermal inversion -Wind	-Air quality degradation -Increased opacity -Prolonged exposure risk/health hazard (inhalation)	Little quantitative documentation
Air Noise	-Frequency -Magnitude	-Terrestrial -Intertidal -Nearshore -Offshore	-Weather Temperature Cloud cover Relative humidity -Vessel type and distance -PA system configuration and volume	-Wilderness disturbance -Behavioral response (birds/terrestrial mammals)	No background data
Visitor Impacts	-Human waste -Marine litter -Camper litter -Trafficing	-Terrestrial -Intertidal	-Overboard loss of equipment -Intensity of visitation -Type of use	-Wildlife health hazard (absorption/ingestion/physical) -Ecosystem degradation -Visual impact (visible litter)	Little quantitative documentation

Table 7. Summary of physical processes and impacts (cont.).

B. Natural

Type	*Parameter*	*Impact Zone*	*Controlling Factors*	*Physical Impacts*	*Weakness of Data as Applied to GBNP*
Waves	-Height -Shape -Frequency	-Offshore -Intertidal	-Shore profile -Wind speed, direction and fetch	-Long-term exposure to wave energy -Shore zone scour and erosion -Sediment resuspension and transport -Bluff/nearshore failures	No background data
Currents	-Littoral currents -Tidal currents	-Offshore -Nearshore	-Tidal exchange -Wind conditions/storms -Fjord geometry -Side channel inputs -Glacial discharges	-Disturbance of water column -Shore zone scour and erosion -Sediment resuspension and transport -Offshore turbulence and surface water mixing -Slope failures	No background data
Ambient Noise					
-Aquatic	-Frequency -Magnitude	-Intertidal -Nearshore -Offshore	-Temperature -Salinity -Sediment type/ bedrock (hardness) -Wind speed -Wave intensity -Proximity to calving and icebergs -Biologic activity	-Limited behavioral response of marine animals	From published data by Malme et al. 1982, Baker and Herman 1983. No signatures for newer vessels.
-Air	-Frequency -Magnitude	-Terrestrial -Intertidal -Nearshore -Offshore	-Weather Temperature Cloud cover Relative humidity -Proximity to calving and icebergs -Wave intensity	-Limited wilderness disturbance -Behavioral response (birds/terrestrial mammals)	No background data
Ice Movement					
-Pan/Fast ice	-Thickness -Location of formation	-Intertidal -Nearshore -Offshore	-Weather Temperature Precipitation type Wind speed; direction -Fjord geometry -proximity to shore	-Shore and nearshore scour (plucking) -Ice rafting (sediment transport/redistribution) -Dampens waves (reduces wave erosion) -Reduces light penetration in photic zone -Reduces near surface mixing	Little quantitative documentation
-Iceberg	-Concentration -Drift velocity -Size	-Intertidal -Nearshore -Offshore	-Calving rate -Proximity to glacier -Oceanographic currents -Wind speed; direction -Water, air temperature	-Shore and nearshore scour -Iceberg rafting (sediment transport/redistribution) -May dampen waves if concenration great enough -Freshwater input to surface water -Physical hazard (breakup and collapse) -Slope failures	Documentation at heads of Muir, McBride, Tarr, and Johns Hopkins

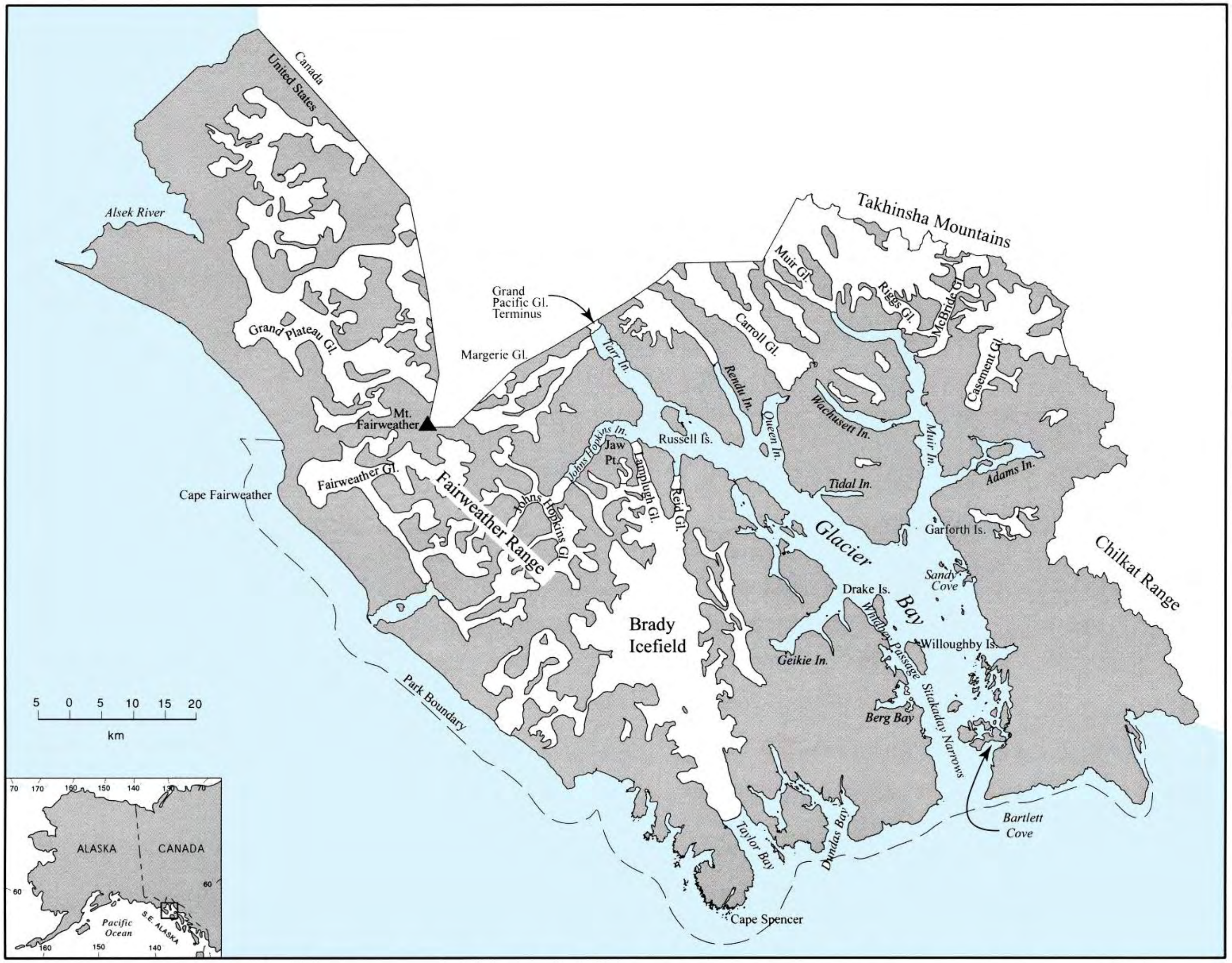
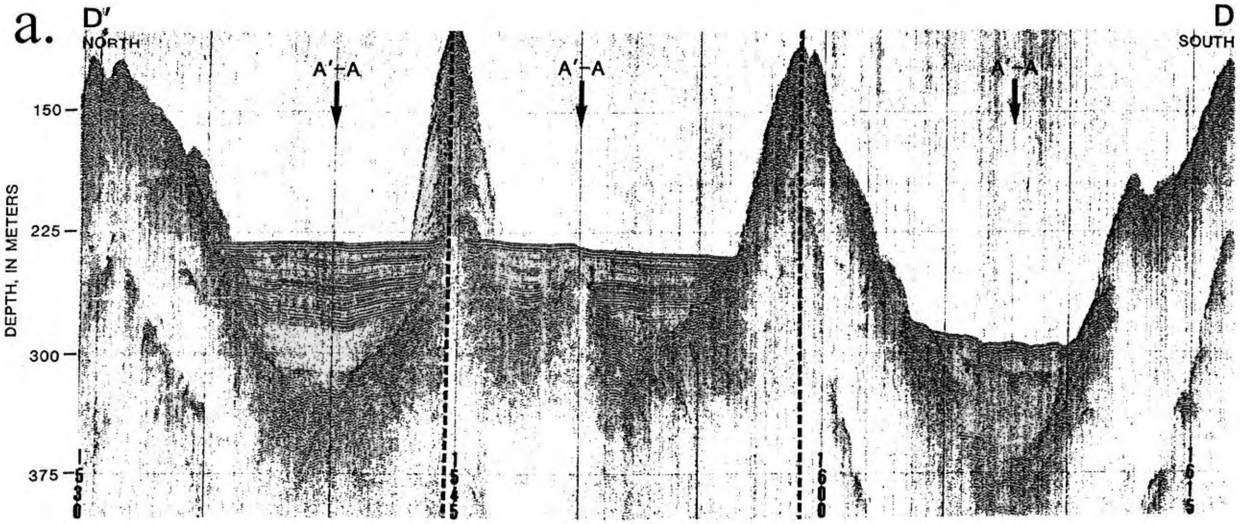


Figure 1. Map of Glacier Bay National Park and Preserve showing select geographic features.

a.



b.

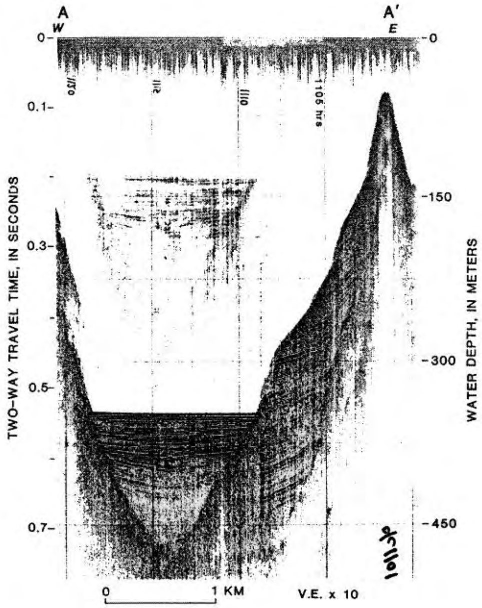


Figure 2. Seismic profiles from Muir and Tarr inlets. (a) Zig-zag lines from lower Muir Inlet showing a sedimentary fill of generally flat-lying beds that is up to 70 m thick. (b) Approximately 110 m of flay-lying sediment in lower Tarr Inlet. Location of transect lines shown in Figure 1. Profiles are from (a) Molnia et al. (1984) and (b) Carlson et al. (1983).

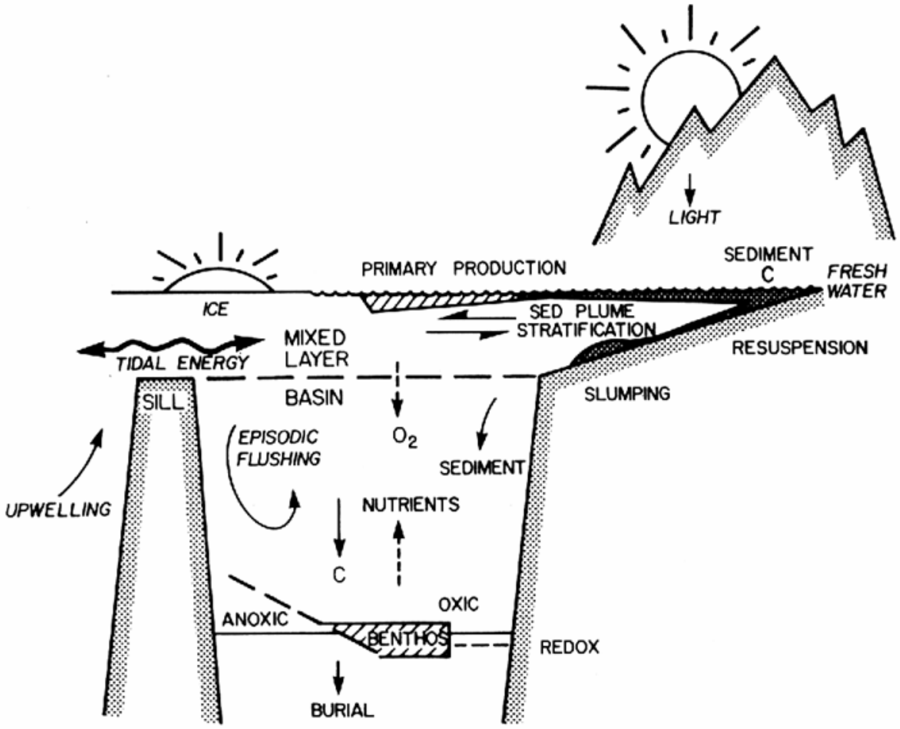


Figure 3. Diagram showing generic fjord profile with sill and interrelationship of physical, geological, biological, and chemical processes (from Syvitski et al. 1987).

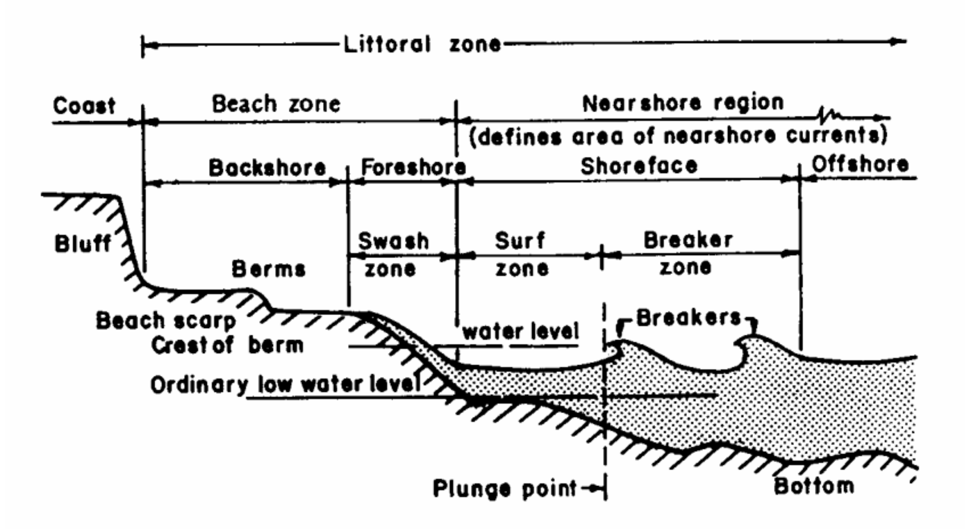


Figure 4. Schematic representation and terminology of the typical shore zone profile (after USACERC 1984).

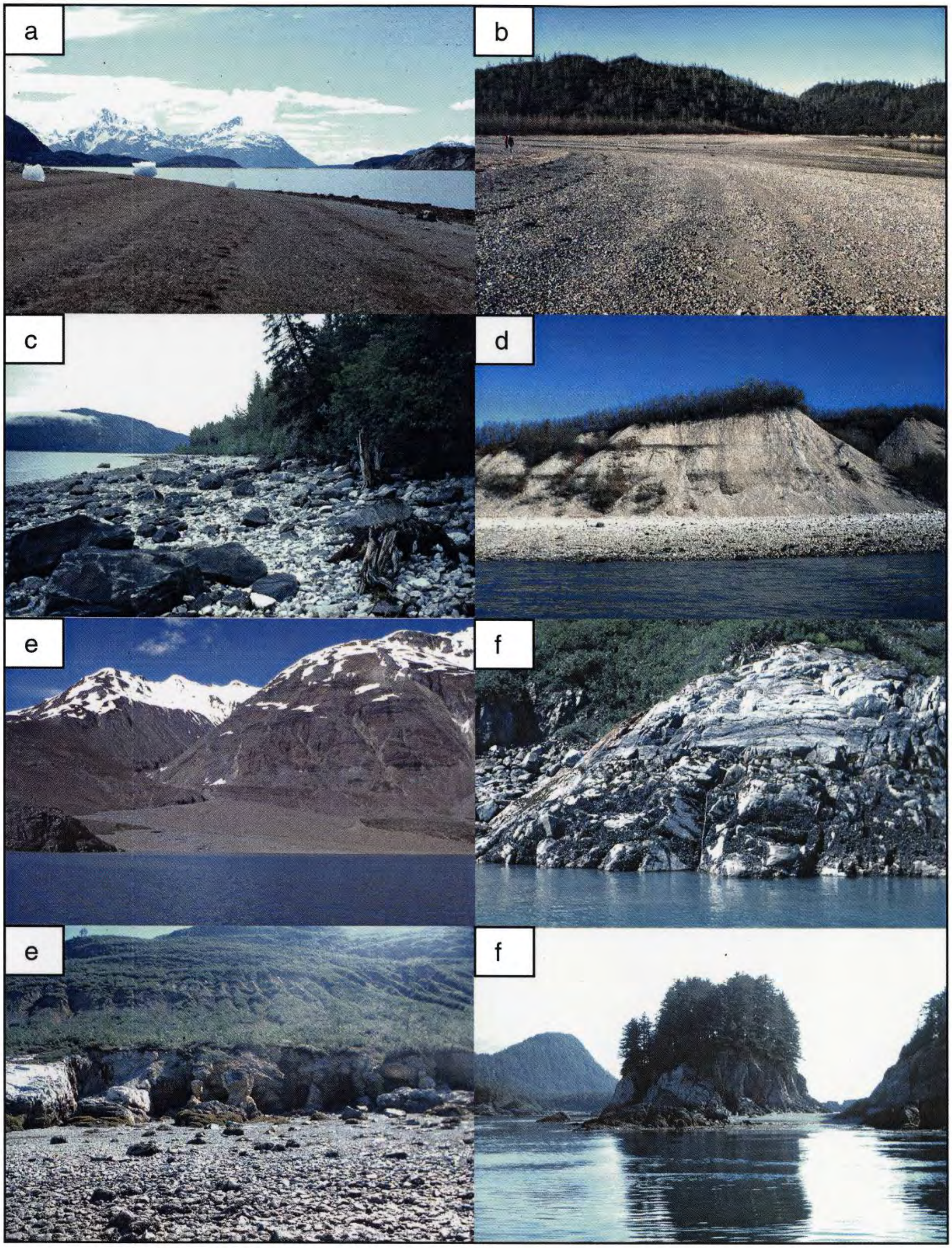


Figure 5. Examples of beaches and shore zones in Glacier Bay. a) sandy beach in upper Muir Inlet, b) gravel berm near Berg Bay, c) boulder beach on Drake Island, d) sand and gravel bluffs in Wachusett Inlet, e) gravel alluvial fan in upper Muir Inlet, f) beadrock shore zone near Reid Inlet, g) weathered and eroded bedrock cliffs and gravel beach in Reid Inlet, and h) bedrock stack near Cape Spencer.

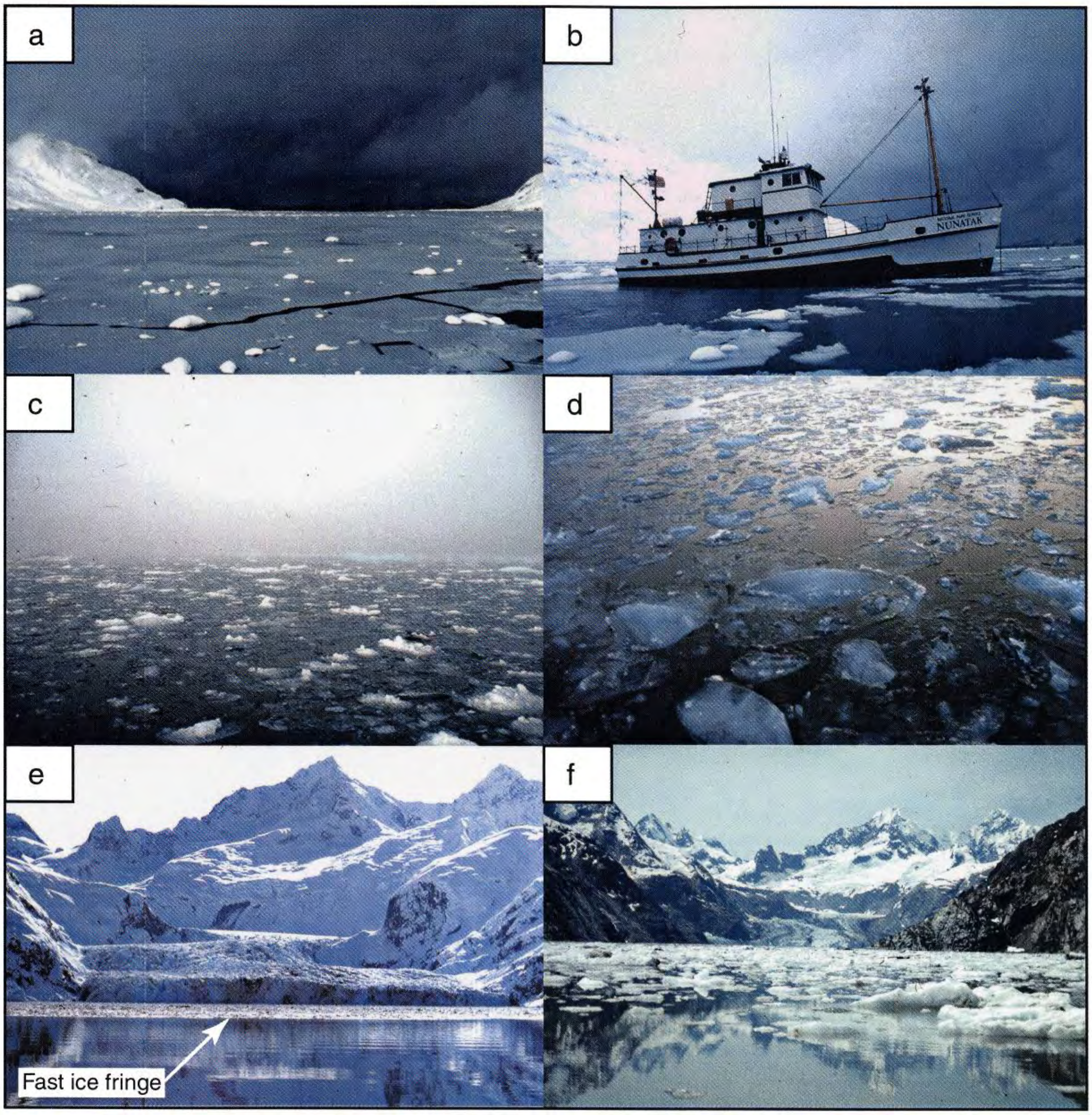


Figure 6. Examples of ice types commonly found in Glacier Bay. a) slush layer covering mouth of Tarr Inlet during early phase of fast ice formation, b) broken slush and ice pans in Reid Inlet, c and d) small ice pans, e) fringe of fast ice located near Jaw Point in Johns Hopkins Inlet, and f) concentration of small to medium sized icebergs in Johns Hopkins Inlet.

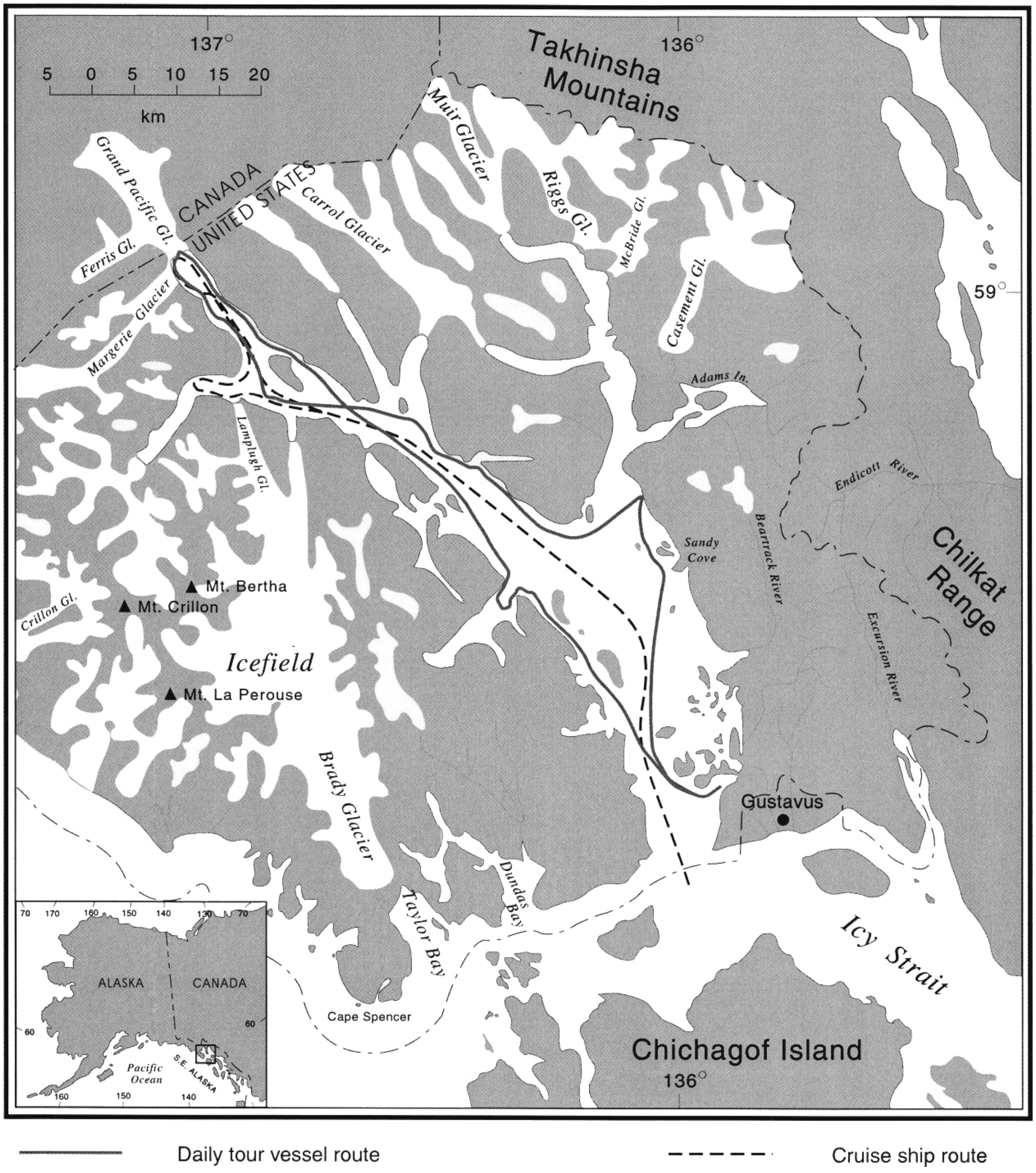


Figure 7. Cruise ship and daily tour boat routes. Refer to Figure 1 for site names.

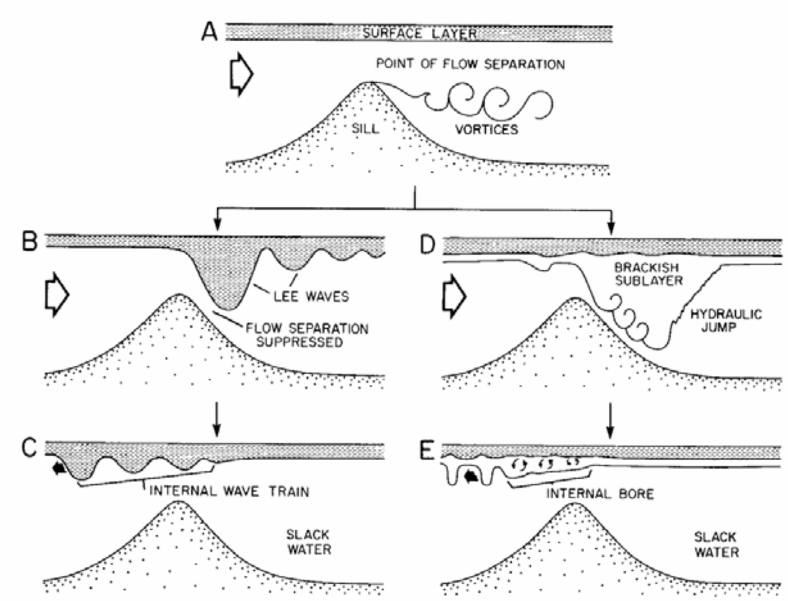


Figure 8a. Dynamics of mixing over Knight Inlet sill, BC (from Syvitski 1987, after Farmer and Freeland 1983). A) Increased tidal velocity may result in flow separation followed by: B) and C) the generation of lee waves and an internal wave train when tide slacks; or D) and E) the generation of a hydraulic jump and an internal bore when the tide slacks.

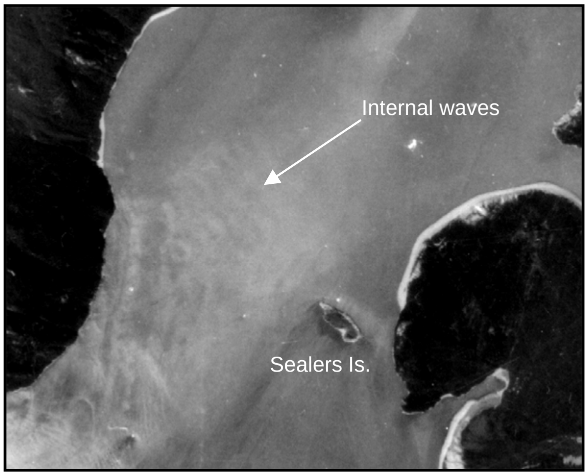


Figure 8b. Internal waves in Muir Inlet just northwest of Sealers Island and north of the mouth of Wachusett Inlet.

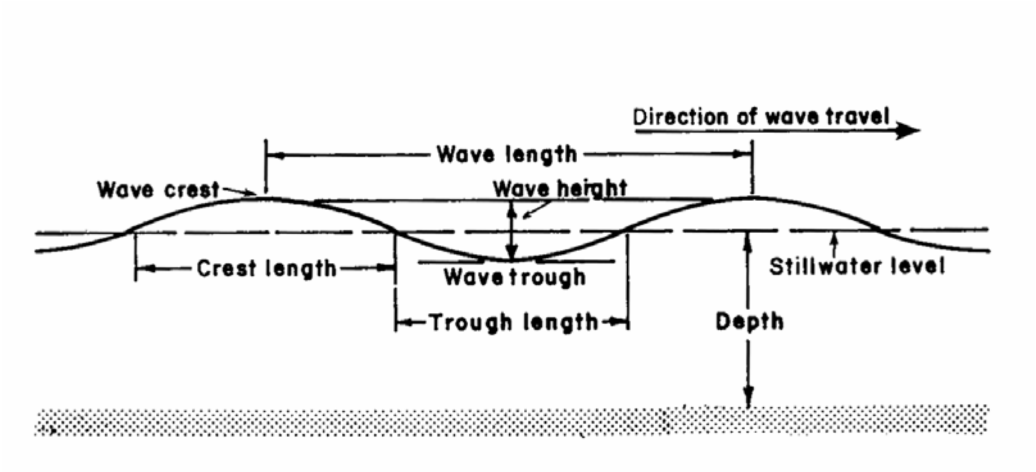


Figure 9. Definition of terms describing characteristics of oscillatory wind waves in deep water.

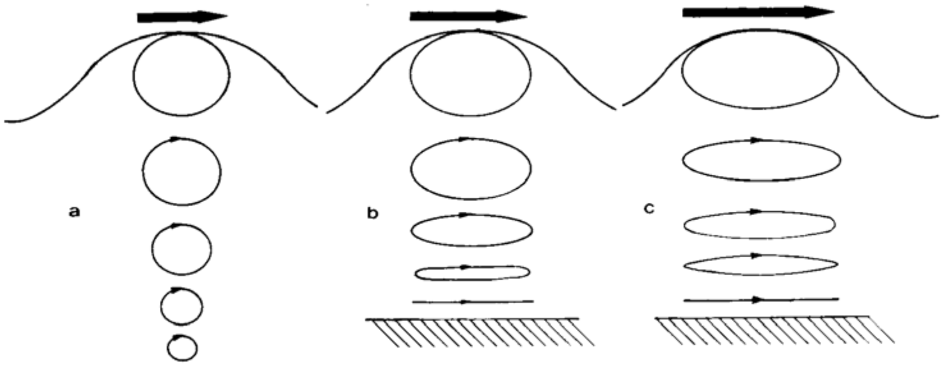
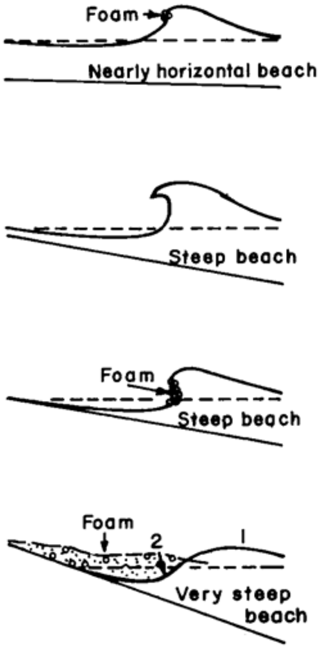


Figure 10. Orbital motion of water particles beneath surface waves in different depths of water. a) deep water, b) water of intermediate depth, c) shallow water (after Allen 1982).



a. spilling breaker.

b. plunging breaker.

c. collapsing breaker.

d. surging breaker.

Figure 11. Four types of breaking waves.

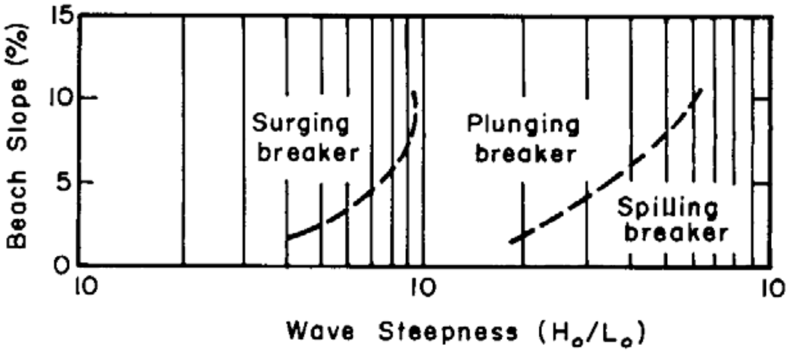


Figure 12. Type of breaking wave as a function of wave steepness and beach slope (after Wiegel 1964).

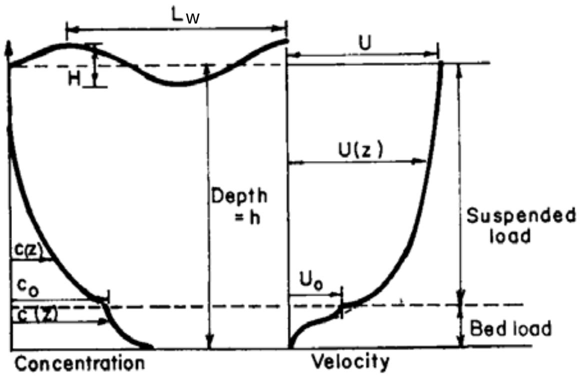


Figure 13. Relative concentration (c) of sediment in suspended load and bed load and orbital velocity (U) as a function of depth beneath a wave (after Muir Wood and Fleming 1981).

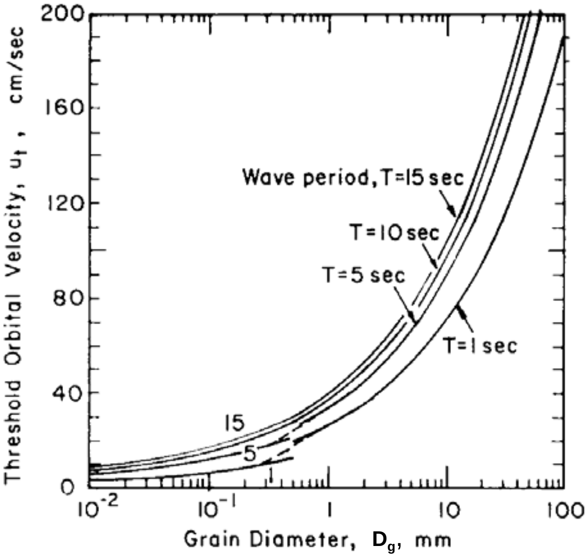


Figure 14. Threshold of sediment motion by waves estimated for cohesionless material of a given diameter D_g and density of 2.65 g/cm^3 (quartz) (from Komar and Miller 1985a). Equations in text define relationship to wave height and water depth.

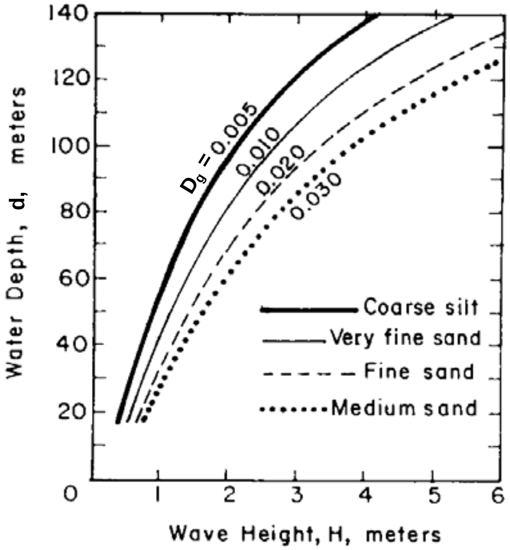


Figure 15. Water depth at which sediments are mobilized by surface waves of period T = 15 seconds (from Komar and Miller 1975a).

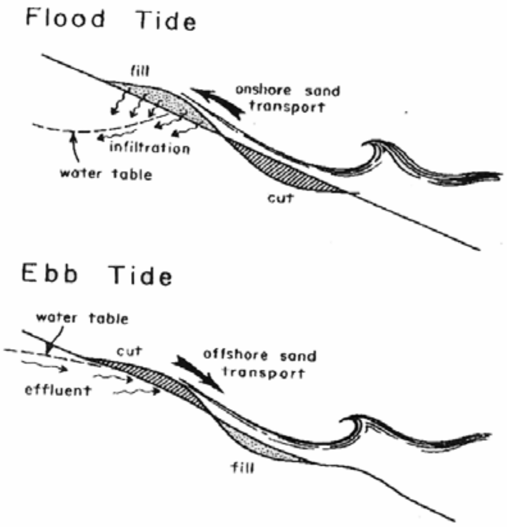


Figure 16. Water table effects on the cut and fill of the beach profile during flood and ebb tides (from Komar 1998).

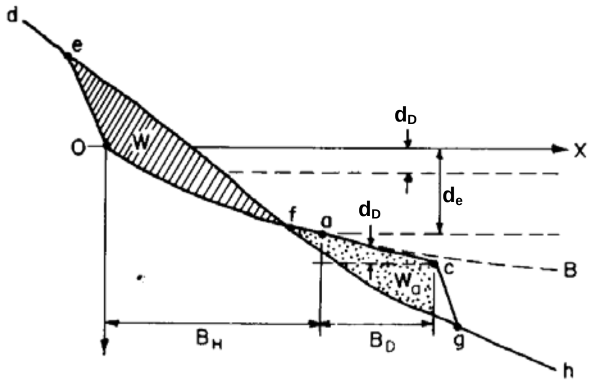


Figure 17. Kondratjev's (1966) conceptual stable shelf model. Parameters defined in the text.

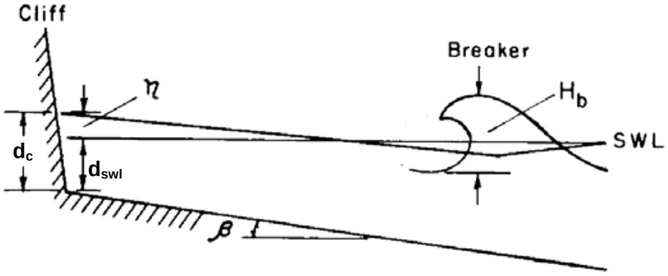
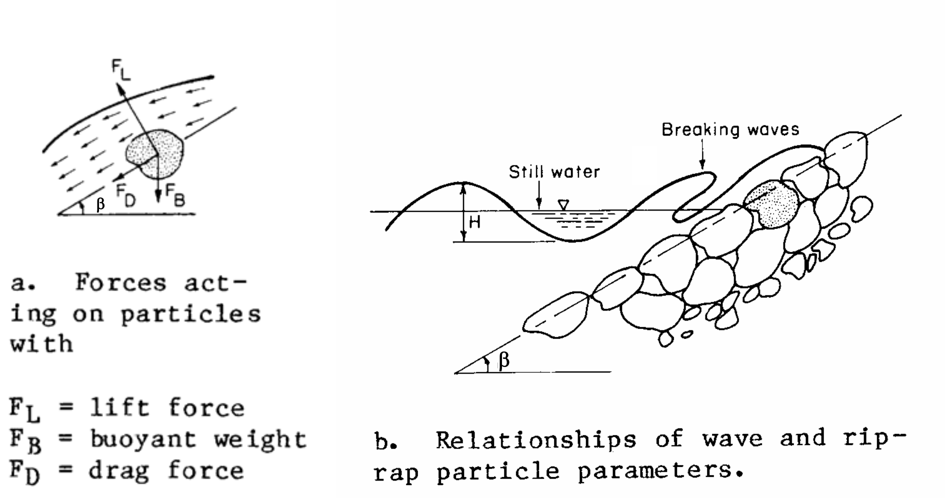


Figure 18. Definition of parameters in Sunamura's (1982) theoretical calculations.



a. Forces acting on particles with

F_L = lift force
F_B = buoyant weight
F_D = drag force

b. Relationships of wave and riprap particle parameters.

Figure 19. Stability of riprap particles as determined by Bhowmik (1978).

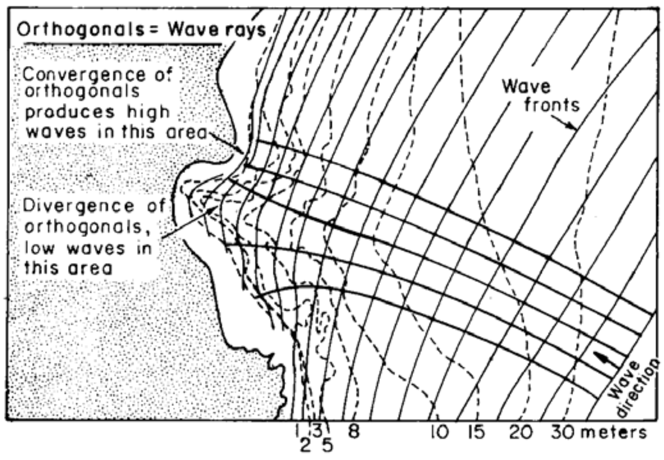


Figure 20. Idealized relationship between monochromatic waves, depth contours, and shoreline configuration (after Goldsmith et al. 1977).

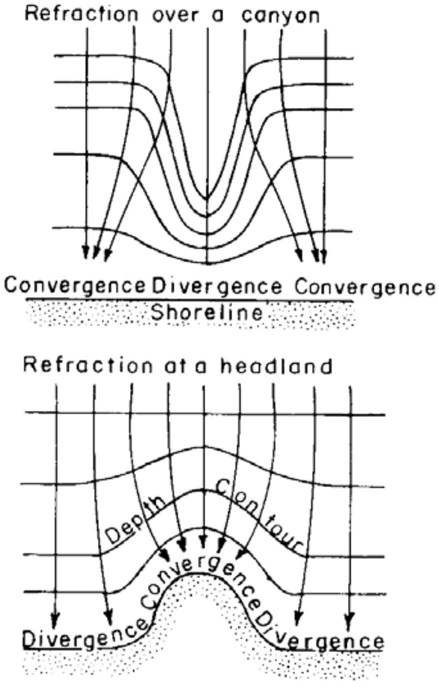
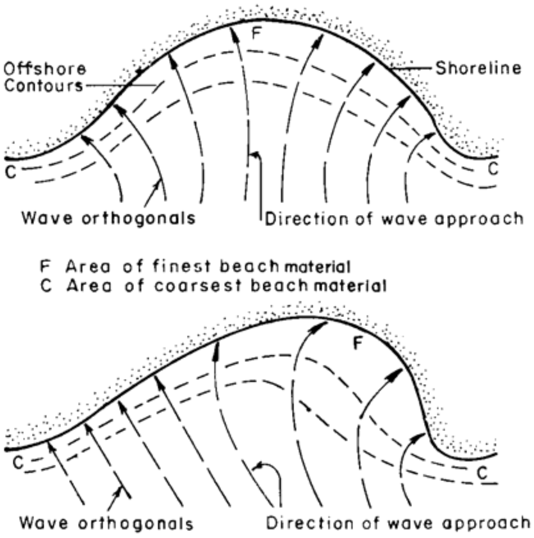


Figure 21. Refraction of wave crests in response to changes in water depth near the shoreline. Wave energy is greatest in areas of wave ray convergence, least in areas of divergence (after Komar 1976).



a. Bay facing directly into prevailing winds.

b. Bay facing obliquely into prevailing winds.

Figure 22. Bay form and shoreline configuration in relation to prevailing waves (after Muir Wood and Fleming 1981). Mean grain size of beach material reflects differences in wave intensity with convergence or divergence.

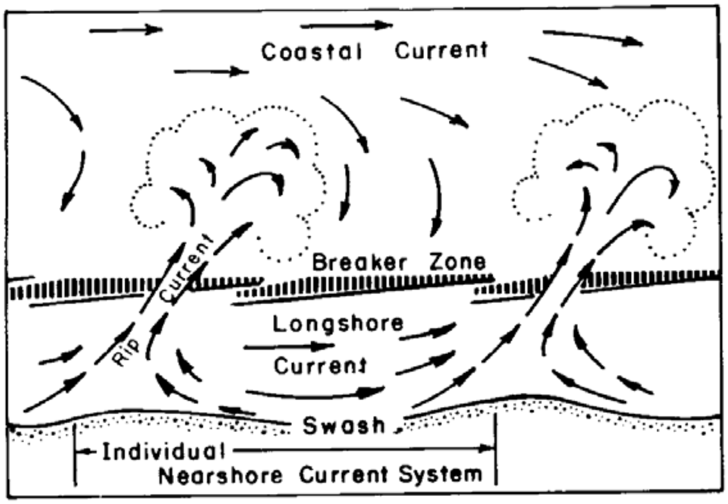


Figure 23. Diagram of nearshore current systems illustrating the wave-induced longshore and rip currents along a shoreline with a protuberance (after Komar 1971).

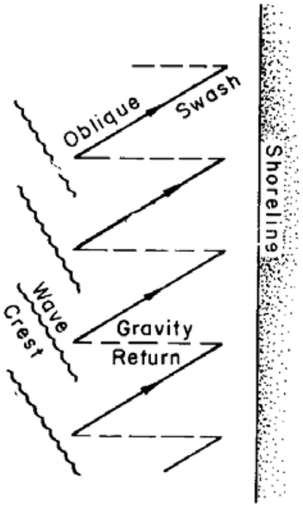


Figure 24. Conceptualized zigzag motion of sediment along a beach face under wave swash (after Komar 1971).

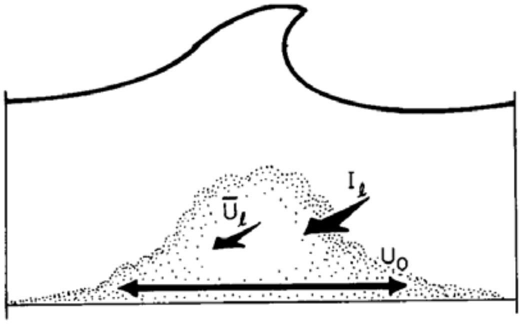


Figure 25. Schematic representation of net sand transport by waves I_l as the result of the orbital velocity u_o of the waves placing particles in motion and the current U_l transporting them (after Komar 1976).

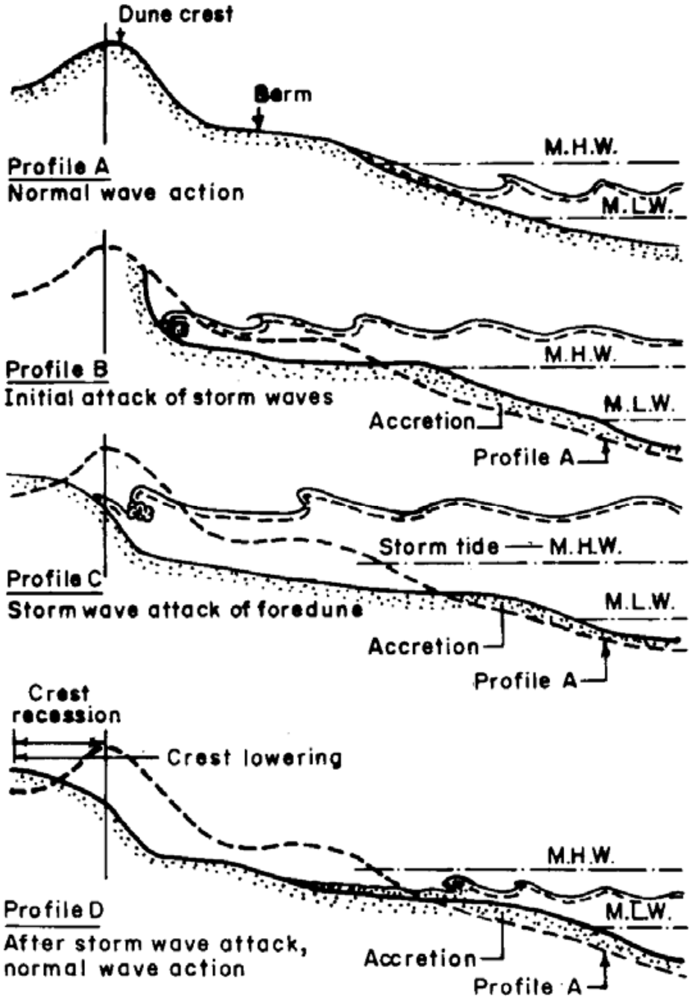


Figure 26. Idealized changes in shore profile resulting from a single storm-generated wave attack (after USACERC 1984). (MHW - mean high water level; MLW - mean low water level).

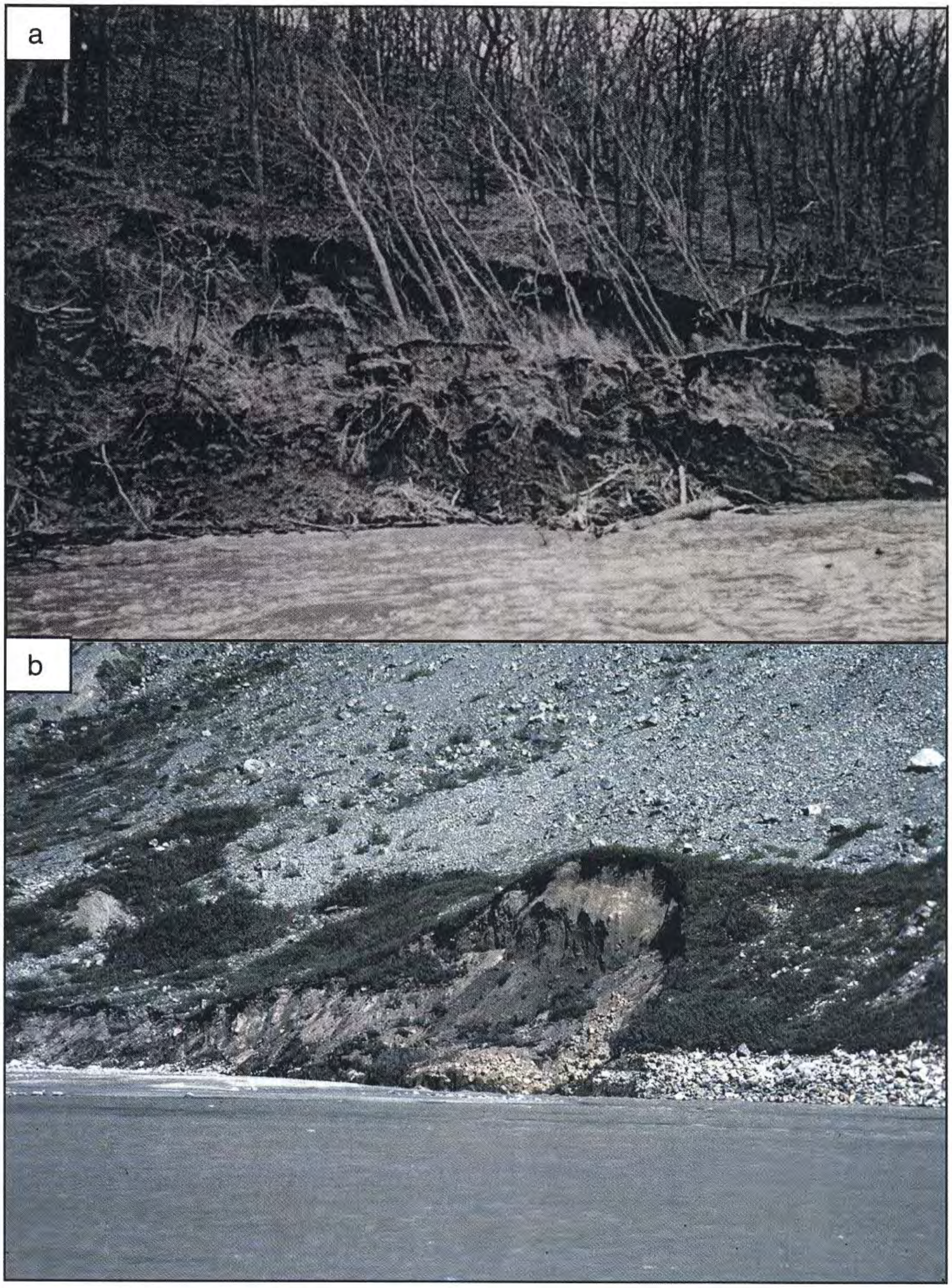


Figure 27. Slope failure. a) rotational slip failure in bank materials causing extensive bluff recession (from Lawson 1985, b) undercutting and bluff failure along margin of Grand Pacific delta that coincided with the generation of sediment gravity flows in Tarr Inlet (cf. Hunter 1994).

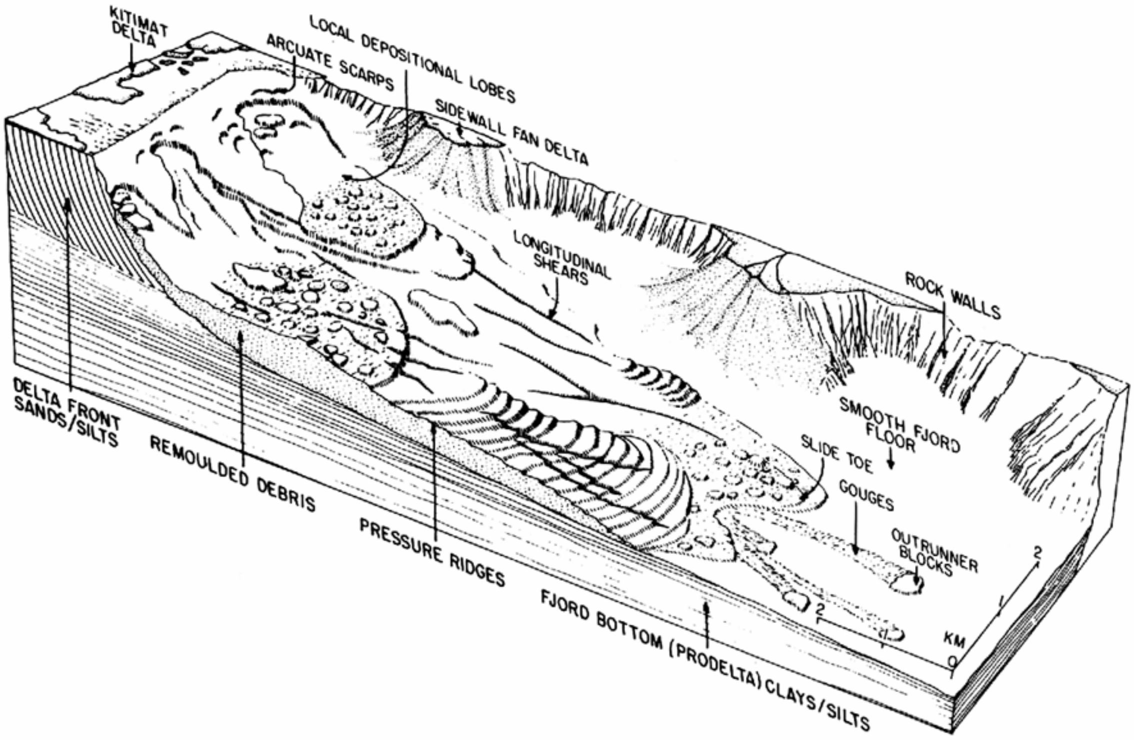


Figure 28. Diagram showing sediment failures on delta front at the head of Kitimat Arm, B.C. showing diverse surface morphologies (from Syvitski et al. 1987; after Prior et al. 1983)

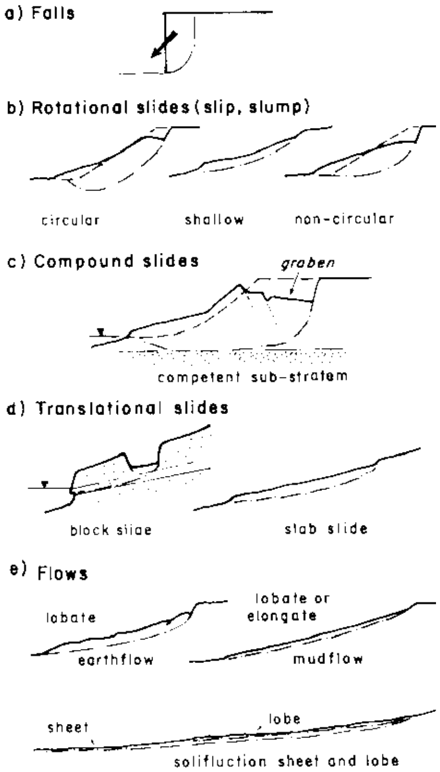


Figure 29. Cross-sectional profiles of some basic types of slope failures as defined by Skempton and Hutchinson (1969) for clay slopes. Failure surfaces shown by dashed and dotted lines.

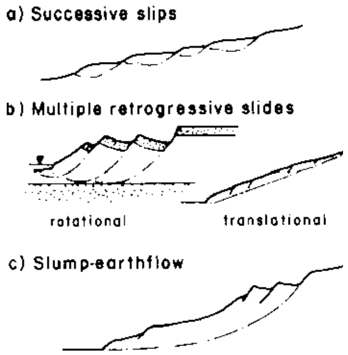


Figure 30. Examples of common, complex slope movements that may affect unconsolitated glacial and fluvial deposits in the shore zone (from Lawson 1985).

Figure 31. Bluff consisting of mostly non-cohesive sand and gravel undergoing failure by individual grain falls and shallow, localized slips. Material accumulates at the base as talus deposit, which protects the slope from further undercutting and failure until removed by waves and currents.

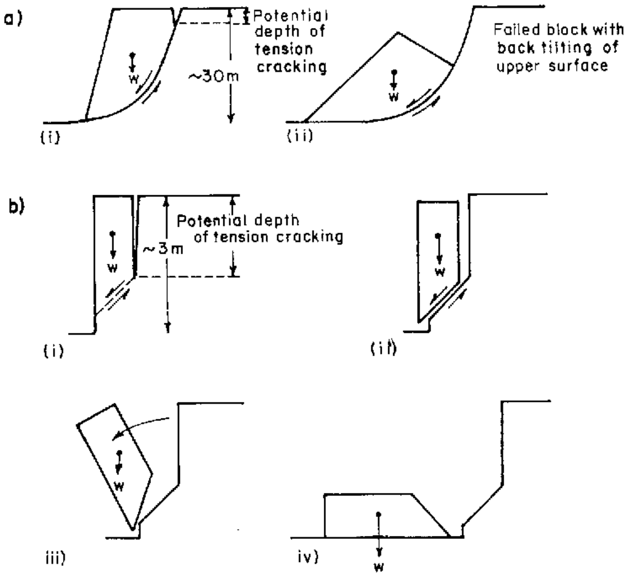
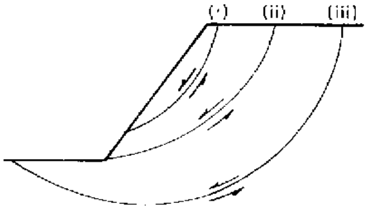
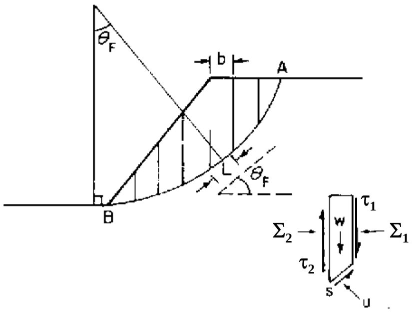


Figure 32. Progression of rotational slip failure in high bank with steep face (a), and plane slip or toppling failure (b) in bluff that is low in height with steep to vertical face (after Thorne and Tovey 1981).

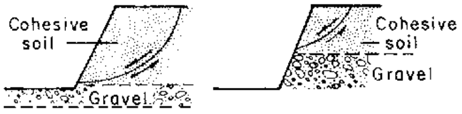


a. Failure arcs indicated for (i) thin slope failure, (ii) toe failure, and (iii) base failure.

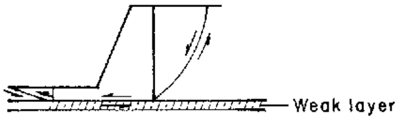


b. Stability analysis of a slip circle by the method of slices with restoring and disturbing forces resolved for a single slice *i* shown on the lower right. τ represents internal forces and Σ external forces.

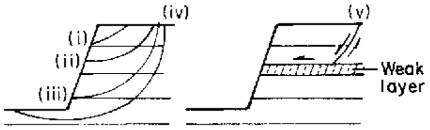
Figure 33. Rotational slip failures in cohesive slope materials (after Thorne 1982).



a. Rotational slip failures, with slip at gravel bed interface; examples in Glacier Bay are marine silt overlying fluvial gravels.



b. Composite slip surfaces due to weak layer.



c. Multiple possible failure planes within multilayered bluff sequence of differing strengths and containing a single weaker layer that overrides the influence of other possible failure planes.

Figure 34. Examples of possible rotational slip failures in high composite bluffs (after Thorne 1982). Bedding planes, weak horizons and other discontinuities may act as failure planes.

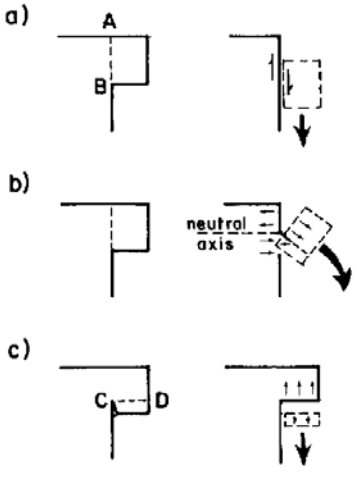


Figure 35. Principal modes of failure of cohesive sediments that are cantilevered by erosion of underlying cohesionless sediment (after Thorne and Lewin 1979). Shear (a), beam (b) and tensile (c) failures.

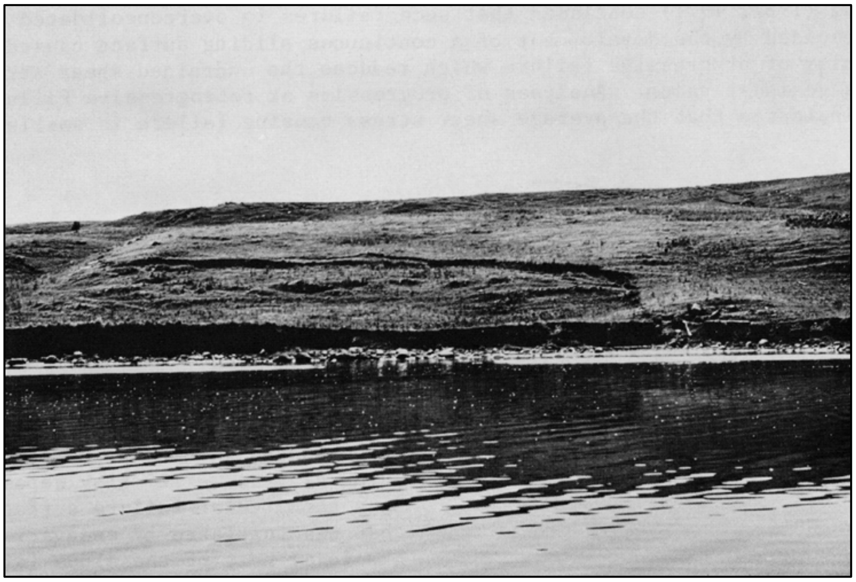


Figure 36. Progressive slump-flow failure of low bluff and adjacent, landward sediments on Lake Ashtabula, ND, apparently initiated by toe erosion at higher water level.

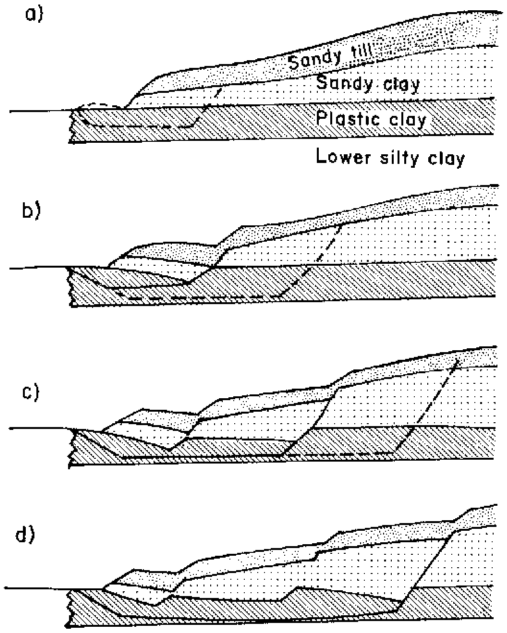


Figure 37. Sketch of the progressive slip failure of stratified unconsolidated glacial deposits overlying clay and silty clay deposits on a noncircular failure surface that was initiated by excavation of the lower part of the slope (after Bjerrum 1967). Each successive failure moved along the same lower surface; the actual sequence developed gradually over 80 years and consisted of many more such slip failures.

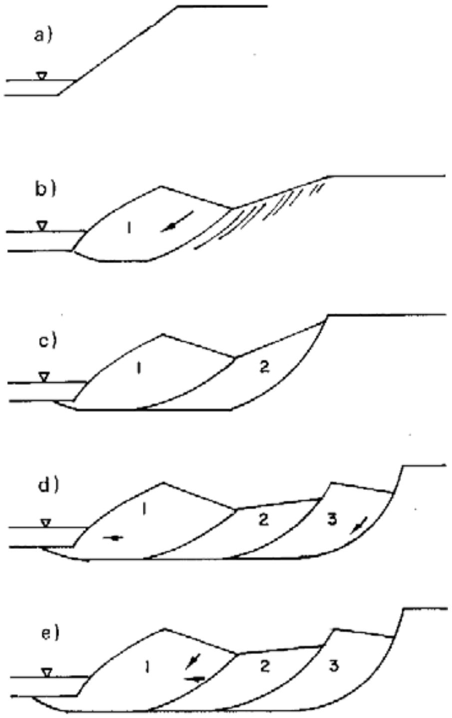


Figure 38. Example of retrogressive slope failure due to toe erosion along a river as determined by Haug et al. (1977): a) undisturbed slope, b) rotational failure and pulling down of the upslope scarp, c) rotational failure of block 2, d) horizontal movement of block 1, allowing block 2 to settle and block 3 to fail, and e) additional rotation and translation of block 1 with blocks 2 and 3 further settling.

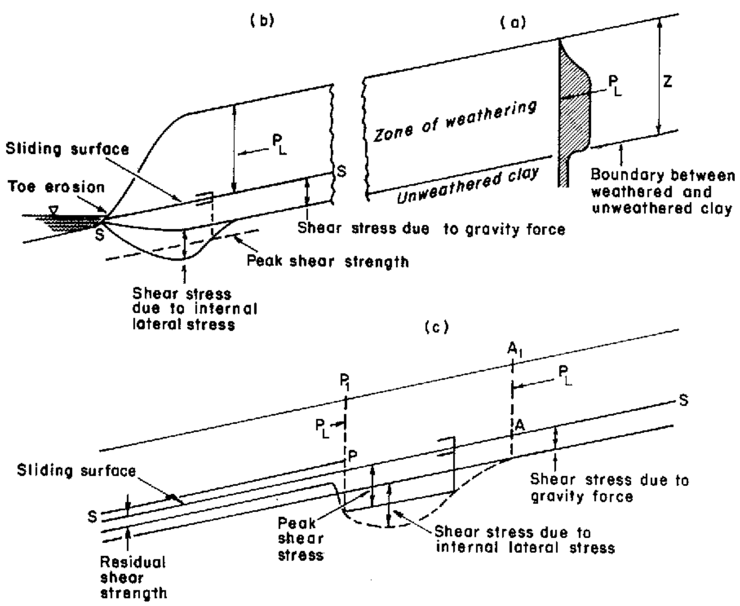


Figure 39. Example of a progressive slope failure in weathered clay in a coastal bluff (after Bjerrum 1967).

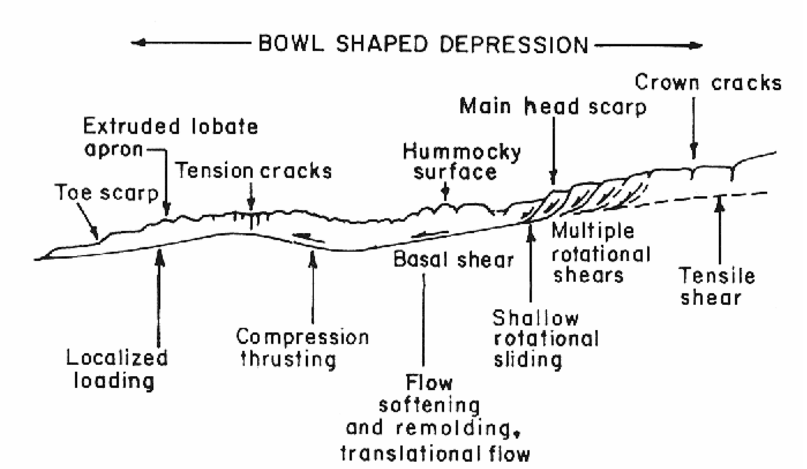


Figure 40. Postulated movement mechanisms and configuration of subaqueous, progressive failures in shallow water off a delta (after Prior and Coleman 1978).

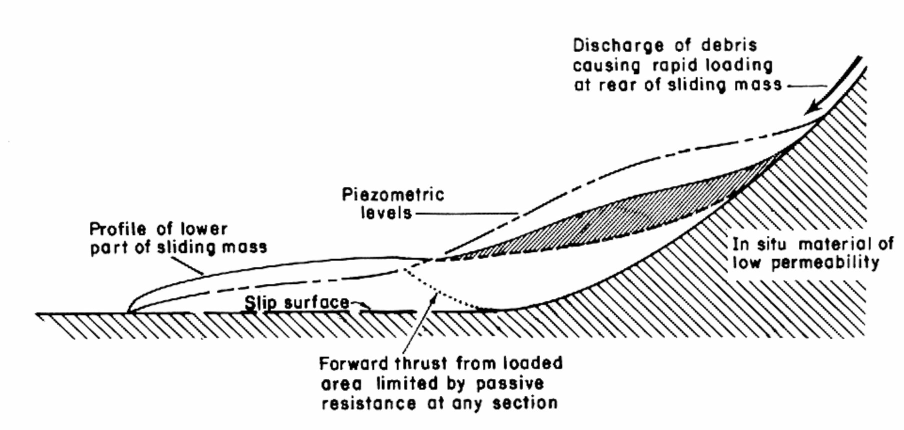


Figure 41. Common development and movement of slopes caused by undrained loading (after Hutchinson and Bhandari 1971).

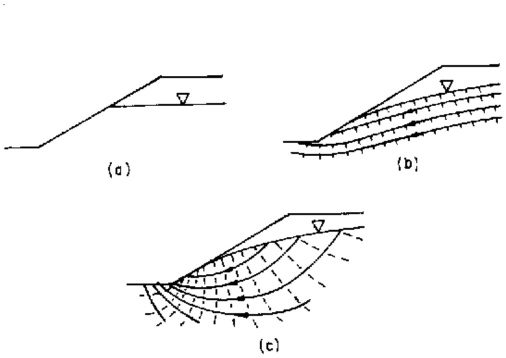


Figure 42. Ground water flow systems in slopes: a) static case typically assumed in slope stability analyses, and b) commonly assumed, but incorrect, parallel to slope flow pattern.. Actual flow system in homogeneous isotropic materials c) should be used in predicting pore pressure distributions along potential slip surfaces. Flow systems in nonhomogeneous and anisotropic materials are more complex than shown (after Patton and Hendron 1974).

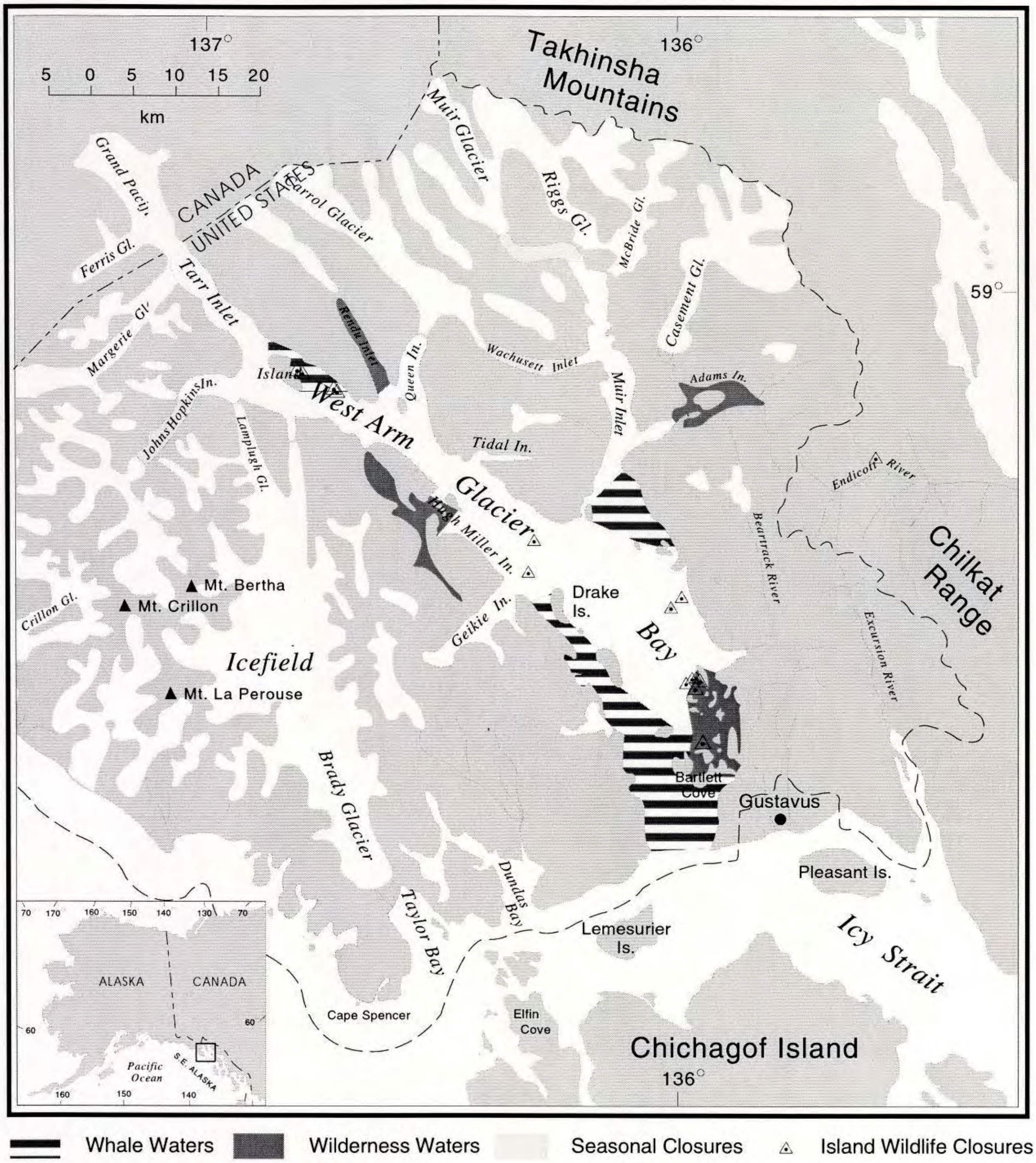


Figure 43. Restricted waters and seasonal closure sites.

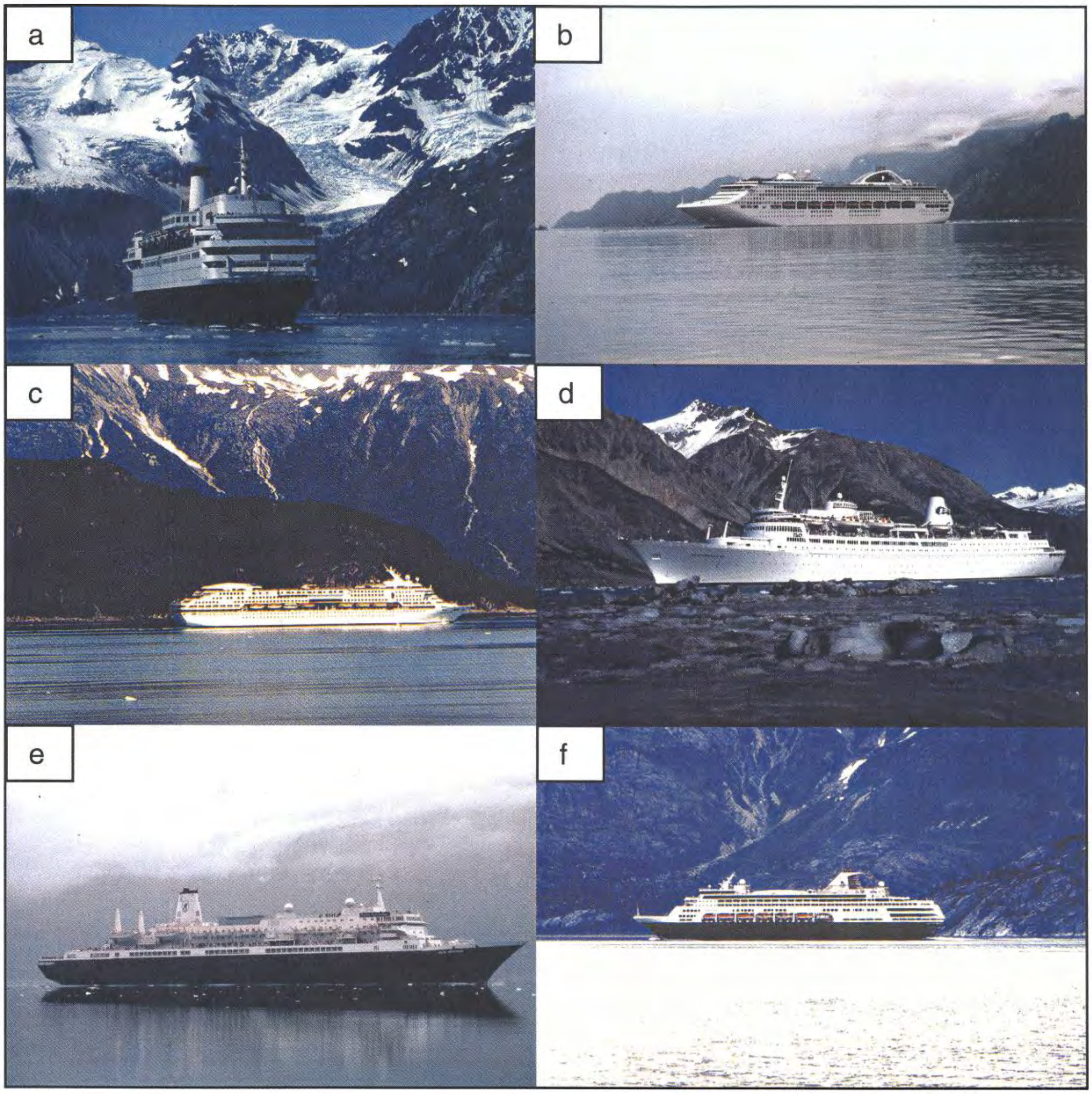


Figure 44. Examples of cruise ships in Glacier Bay. a) *Westerdam* at mouth of Johns Hopkins Inlet, b) *Sun Princess* in front of Lamplugh Glacier, C) *Crystal Harmony* in upper Glacier Bay, d) *Sea Princess* in Tarr Inlet, e) *Nieuw Amsterdam* in Tarr Inlet and f) *Legend of the Sea* in upper Glacier Bay.

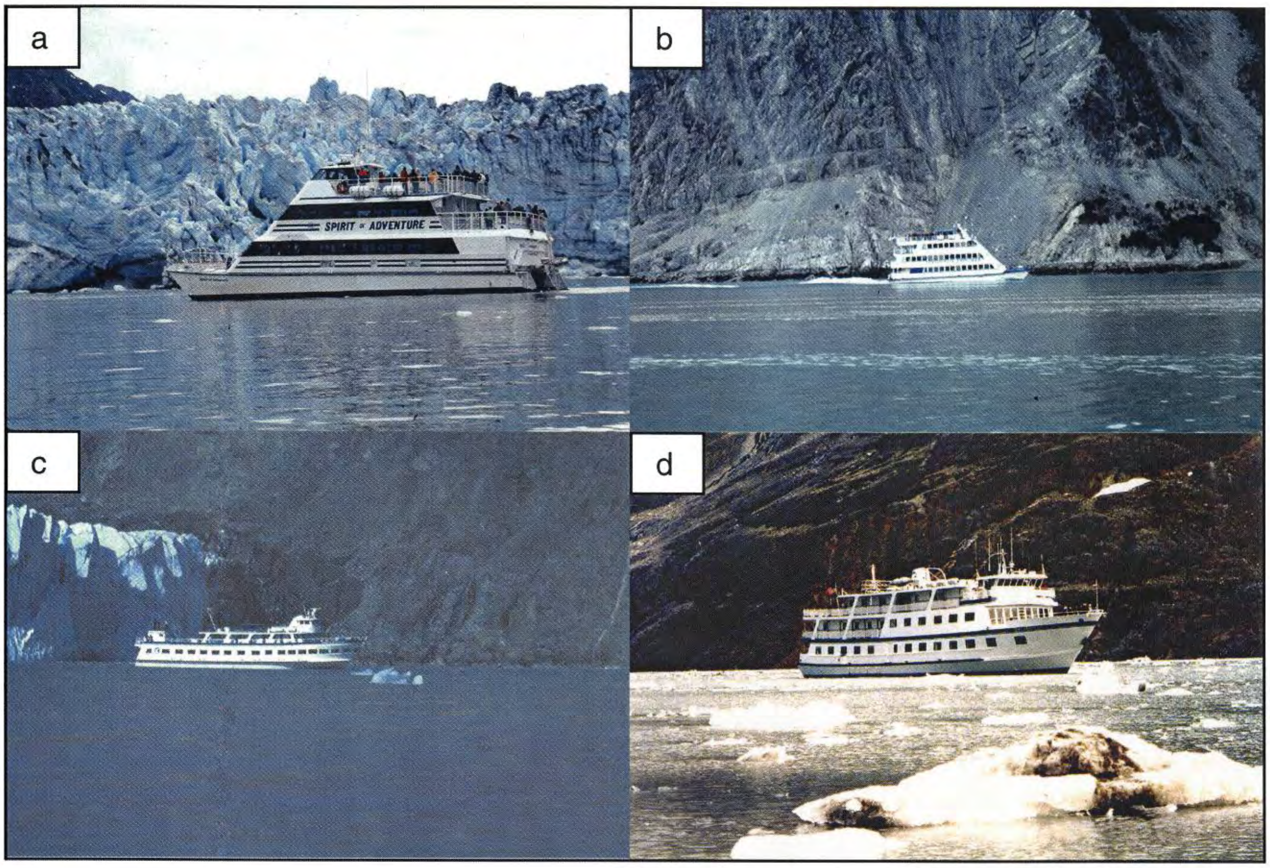


Figure 45. Examples of tour boats. a) *Spirit of Adventure*, b) *Executive Explorer*, c) *Spirit of Glacier Bay* and d) *Spirit of Discovery*.

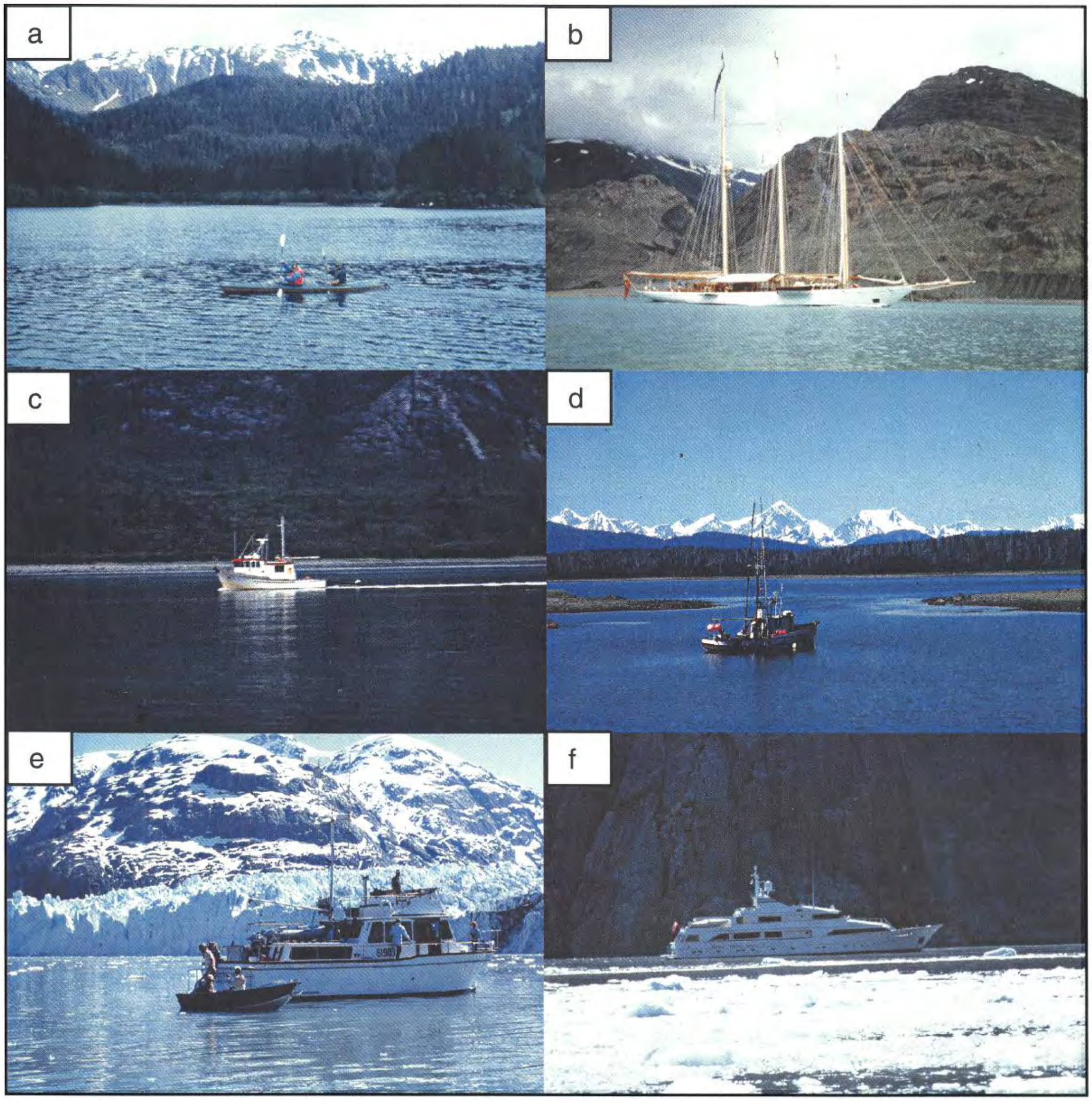


Figure 46. Examples of private and charter boats. a) kayak, b) sailing yacht, c and d) fishing vessels, e) small charter and f) power yacht.

Figure 47. Example of a catamaran hull (*Spirit of Adventure*).

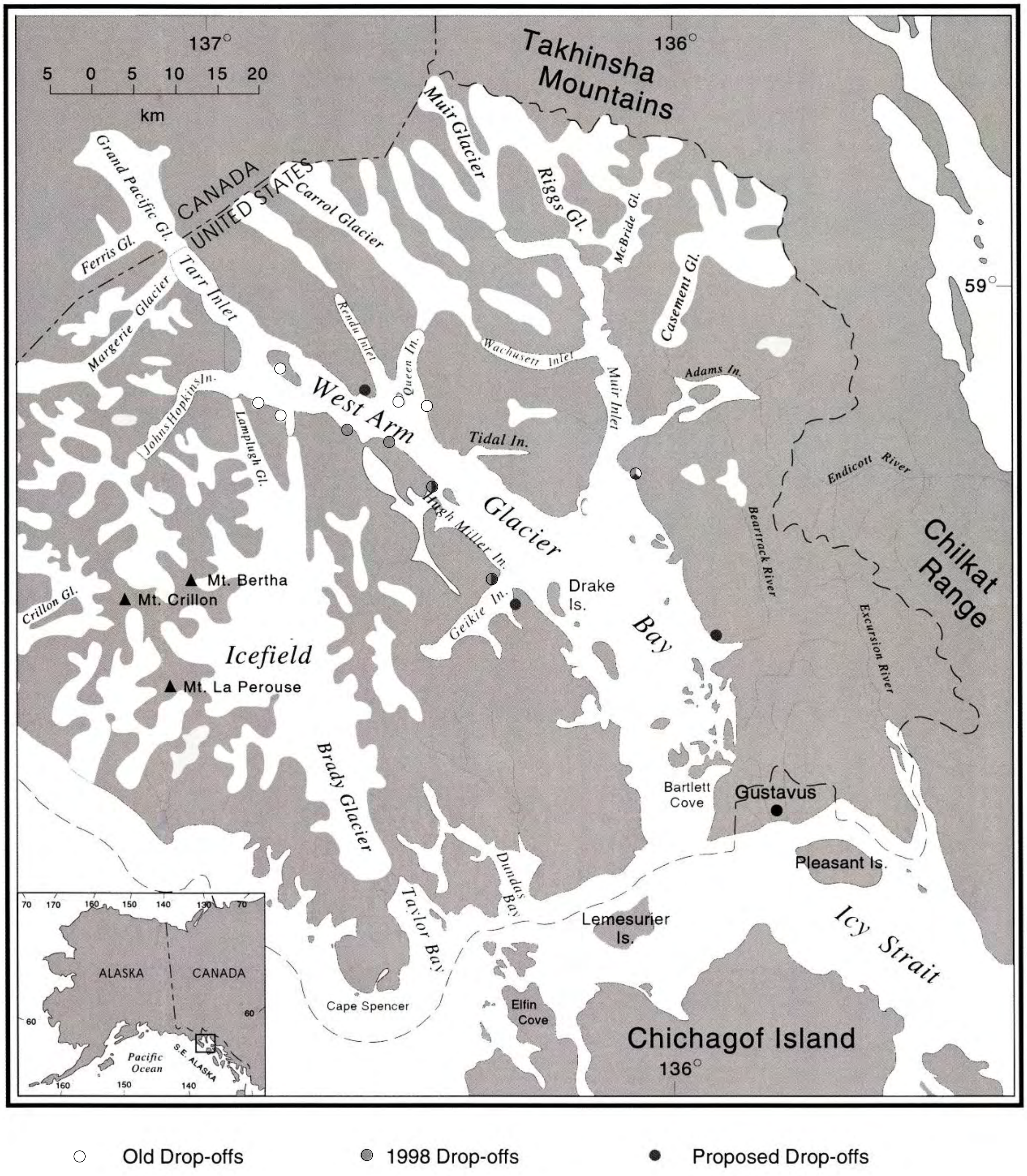


Figure 48. Kayak and backcountry user drop-off locations. Split symbols refer to multi-year use.

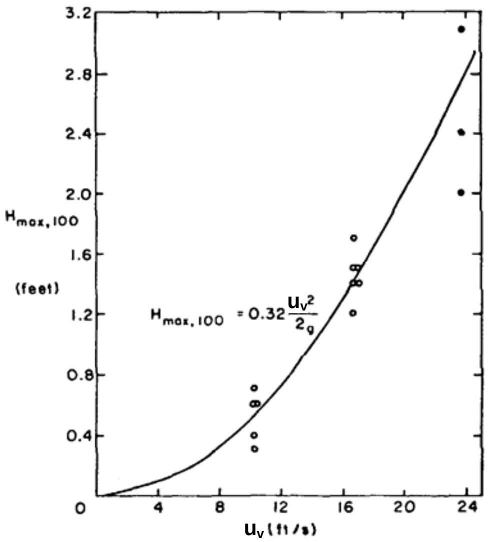


Figure 49. Relationship between ship velocity and maximum wave height at a distance of 100 ft from the sailing line (from Ashton 1984, after Sorenson 1973).

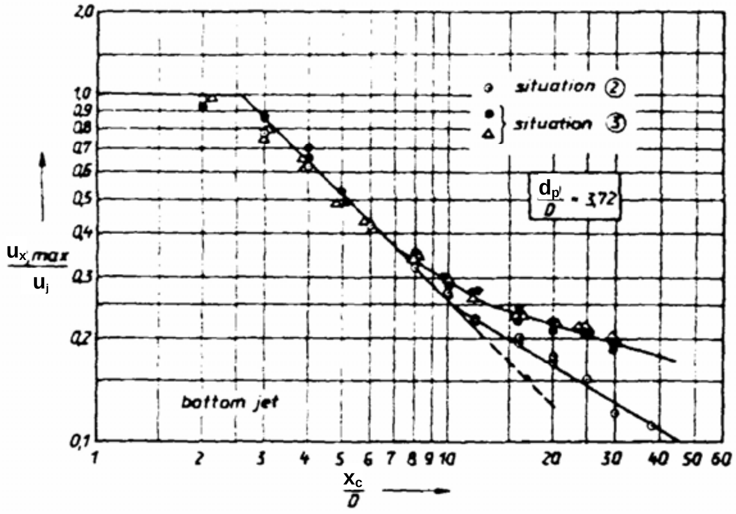


Figure 50. Relation between propeller-driven jet velocity and the relative distance from the jet (from Fuehrer and Romisch 1977).

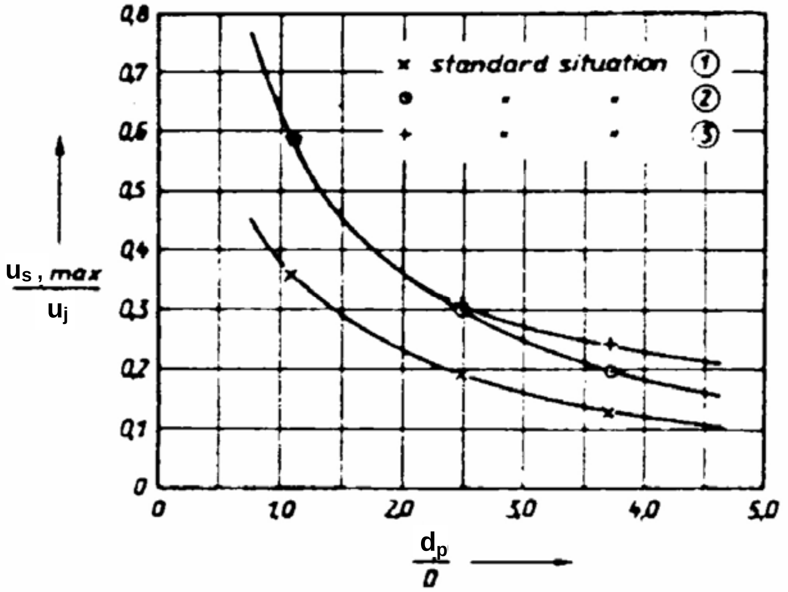


Figure 51. Relation between bottom scour, $u_{s,max}$, from propeller-driven jet velocity and the channel depth below the propeller (from Fuehrer and Romisch 1977).

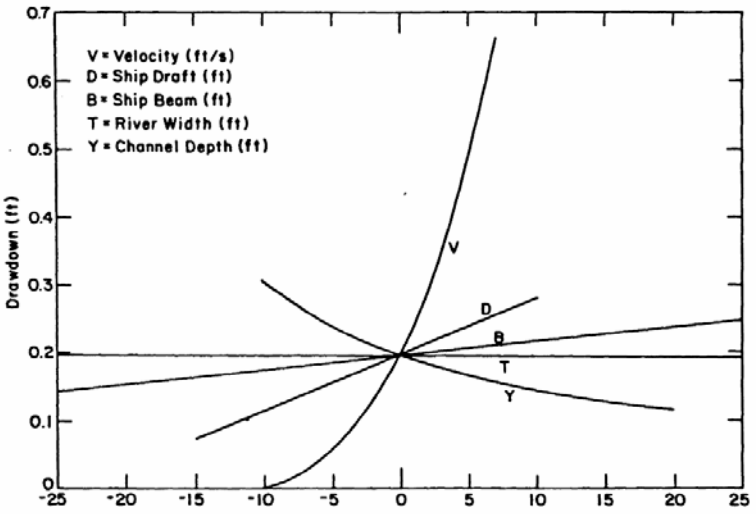


Figure 52. Relative importance of major vessel variables on drawdown and resulting sediment transport potential (from Wuebben et al. 1984).