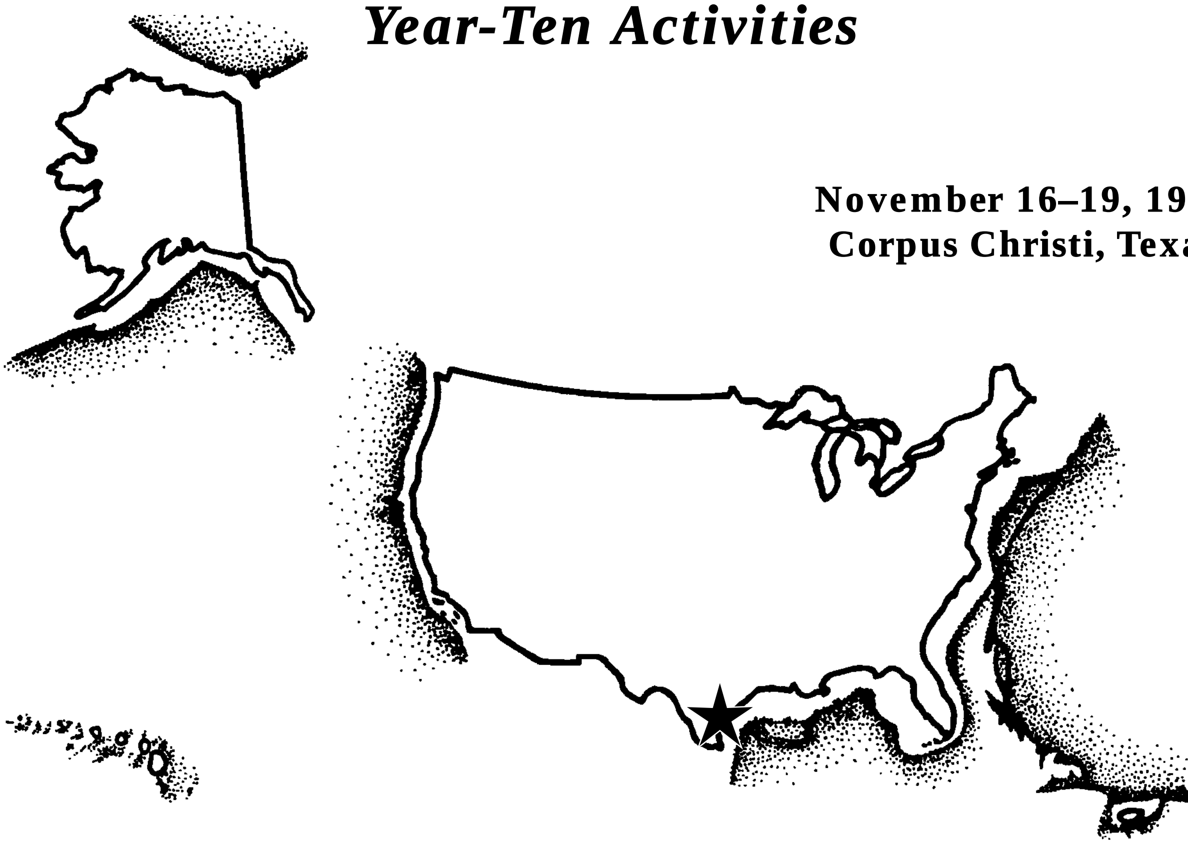
Proceedings

Fourth Symposium on

Studies Related to Continental Margins—A Summary of Year-Nine and Year-Ten Activities

November 16–19, 1997
Corpus Christi, Texas



George Dellagiarino, Lynda A. Miller, and Susann Doenges

Editors

sponsored by

Minerals Management Service
U.S. Department of the Interior

and

Continental Margins Committee
Association of American State Geologists

hosted by

Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
Austin, Texas 78713-8924

1998

Proceedings

Fourth Symposium on

Studies Related to Continental Margins— A Summary of Year-Nine and Year-Ten Activities

George Dellagiarino, Lynda A. Miller, and Susann Doenges

Editors

sponsored by

Minerals Management Service
U.S. Department of the Interior

and

Continental Margins Committee
Association of American State Geologists

hosted by

Bureau of Economic Geology
Noel Tyler, Director
The University of Texas at Austin
Austin, Texas 78713-8924

November 16–19, 1997
Corpus Christi, Texas

1998

MMS Introduction

The Minerals Management Service (MMS) has the major responsibility for administering the Department of the Interior's role in activities associated with mineral resource development on the Federal Outer Continental Shelf (OCS). These activities relate to the inventorying, leasing, exploration, development, production, and royalty management of these mineral resources. These activities, in turn, are overseen through resource evaluation and assessment functions, leasing management, environmental review, regulation of operations, inspection and enforcement programs, collection and distribution of revenues, and related public liaison and planning functions for OCS lands.

The Continental Margins Program was established through the MMS Resource Evaluation Program, whose primary function is to investigate the mineral potential of the OCS and to assure the receipt of fair market value for these resources. In this regard, MMS is fortunate to have entered into a useful and productive relationship with the Association of American State Geologists (AASG) through both the Continental Margins Program and the peer review of two MMS National OCS Assessments. As a result of the cooperative agreement between the MMS and Continental Margins Committee of the AASG and the participating State Geological Surveys, projects related to both petroleum as well as strategic mineral resources and environmental geology have provided useful information to both MMS and the participating States. Many of these projects have been in direct support of task forces and other activities and programs that MMS has entered into with various coastal States. Opportunities to collect, analyze, and share geological, geophysical, and engineering information regarding nearshore resources and offshore areas assist both the coastal States as well as the Federal Government in managing resources, protecting the environment, and planning for the future.

This fourth Continental Margins Symposium offered State participants the opportunity to present and discuss results of the final projects completed under the cooperative agreement as well as providing a sampling of MMS, industry, and other outside activities in particular coastal and offshore areas. We appreciate the participation of the coastal State Geological Surveys in the Continental Margins Program as well as the industry and outside representation at this symposium. With many similar challenges and opportunities, MMS is committed to close ties with the AASG and we look forward to a continued excellent working relationship in the future.

Carolita U. Kallaur
Associate Director for Offshore Minerals Management
Minerals Management Service

AASG Introduction

In the fall of 1998, the Continental Margins Program will draw to a close 15 years of a highly successful Federal-State collaboration to investigate a variety of marine-environmental and natural resource issues of great importance to the nation. This model program of Federal-State collaboration was funded by the Minerals Management Service (MMS), administered by the Texas Bureau of Economic Geology for the Association of American State Geologists (AASG), and involved State Geological Surveys, Federal agencies, public and private universities, and private-sector consultants. In a typical year, 20 to 23 coastal States used the limited funding provided by this program to leverage projects and other funding into a cost-effective, productive national program. Recognizing the integrated character of marine systems, the program funded projects that ranged from the coastal environment to offshore continental margins. Nearly 400 deliverables were produced and resulted in a variety of publications (listed in the appendix at the end of this volume). In addition, four national symposia were held, the proceedings from one of which were published in a special issue of the journal *Marine Geology*. The MMS utilized the expertise of the coastal States to supplement its own knowledge in investigating a range of issues that facilitated the leasing of offshore hydrocarbon resources, evaluation of marine mineral resources, and enhancing the ability of the State and the Federal governments to protect the environment. Examples include the evaluation of offshore sand resources that many coastal States need for beach replenishment and other coastal environmental restoration projects as well as geologic framework studies in areas of hydrocarbon potential. The program also provided support for the Federal marine minerals program as well as data relevant to the evaluation of oil and gas resources, and made innovative use of digital information technologies for improved and expanded access to data and results.

In addition to the scientific and technical advances that have resulted from this collaboration, the program has served as a vehicle for State-Federal communication and joint action on issues of mutual concern and has demonstrated that Federal funding can be used to leverage and strengthen State coastal programs that are in the national interest. The successes that the Continental Margins Program achieved along our nation’s coastlines and in the offshore marine environment have established it as a model for future programs of State and Federal cooperation and collaboration.

Noel Tyler
Director, Bureau of Economic Geology, and
Chair, Continental Margins Committee,
Association of American State Geologists

Contents

U.S. Minerals Management Service (MMS) Prelease Geological and Geophysical (G&G) Data Acquisition: A 20-Year Retrospective, 1976–1996[1]

George Dellagiarino

U.S. Department of the Interior, Minerals Management Service,
Resource Evaluation Division, MS 4070, 381 Elden Street, Herndon, VA 20170

Abstract

Since 1976, the Minerals Management Service (MMS) has administered its prelease geological and geophysical (G&G) data acquisition program through Title 30, Part 251, of the Code of Federal Regulations that govern permitting, acquisitions, and data release. Leading indicators of offshore oil and gas activity are the number of permits issued to industry, associated mileage, and expenditures.

Over the last 20 years, permit activity has indicated that most of the oil and gas surveying has been in the Gulf of Mexico, where 80 percent of all permits have been issued, followed by Alaska (10 percent), the Pacific (7 percent), and the Atlantic (3 percent). These statistics correlate with the dominant position of the central and western Gulf of Mexico areas in oil and gas activity. More than 95 percent of all permits were issued for geophysical exploration, mostly for two-dimensional (2-D) common-depth-point (CDP) seismic data. However, over the last 10 years, permits for three-dimensional (3-D) seismic data have averaged 25 percent of all geophysical permits and, by 1996, made up approximately half of all geophysical permits offshore-wide.

Between 1976 and the early 1990's, industry shot approximately 500,000 line-miles of 2-D CDP data each year on the Outer Continental Shelf (OCS). Of that total, MMS had acquired approximately 50,000 line-miles annually. In the 1990's, parallel with industry, MMS had increased its acquisition of 3-D seismic data in concert with the development and use of interactive workstations. The majority of 2-D and 3-D data have been acquired in the Gulf of Mexico by a ratio of 2:1 over Alaska, the next largest data inventory.

With regard to MMS expenditures for G&G data, from 1976 through the 1980's, Alaska, having more offshore area than the other three regions combined, had the largest portion. However, in the 1990's, the vast majority of expenditures have been in the Gulf of Mexico.

Over the years, permit totals, mileage acquired, and expenditures for data reflect trends of oil and gas pricing, limitations of offshore moratoria, and a shift of industry emphasis to foreign theaters.

Introduction

The Minerals Management Service (MMS), through its Resource Evaluation Program (REP), administers the provisions of the OCS Lands Act for geological and geophysical (G&G) data acquisition through regulations found under Title 30 of the Code of Federal Regulations (CFR). The regulations, which have been in effect since 1976, govern permitting, data acquisitions, reimbursement, and proprietary terms on the Outer Continental Shelf (OCS).

The primary source of the G&G data and information used by the REP is the oil and gas industry. Although the MMS does not perform any direct data collection activities, it does issue permits to industry for collecting prelease G&G data. Data from prelease permits constitute approximately 90 percent of the MMS database. Permittees and lessees collecting data

[1]Excerpted from Dellagiarino, George, Fulton, Patricia, and Zinzer, David, 1997, Geological and Geophysical Data Acquisition: A 20-Year Retrospective, 1976–1996: Minerals Management Service OCS Report MMS 97-0035, 39 p.

in their normal conduct of business are reimbursed for only the cost of data reproduction. However, if industry has collected data in areas not under MMS jurisdiction, e.g., State waters or adjacent foreign waters, and MMS selects such data, MMS pays the significantly higher "market price" for obtaining such data.

Geophysical Data Surveys

A large percentage of the geophysical data in the MMS inventory is two-dimensional (2-D) common-depth-point (CDP) seismic information, high-resolution data (HRD), gravity data, and magnetic data.

The most recent component in our data inventory is three-dimensional (3-D) seismic data. Whereas the main use of this information may still be in reservoir development, the evolution of 3-D seismic data and information, in conjunction with interactive computer workstations, has made it possible to more closely define and assess the potential for oil and gas occurrence on the OCS, especially with regard to subsalt prospects.

As a result of speculative surveys over much of the Gulf of Mexico shelf, acquisition costs to natural gas and oil companies have been decreasing. Recent innovations have made this information usable on workstations, whereas in the past, supercomputers were needed. This "cutting edge" technology is rapidly affecting exploration techniques and success rates.

Geological Data Collection

There are two major components to our geological data inventory: (1) bottom sampling and shallow coring and (2) deep stratigraphic tests. Bottom samples are obtained by dropping a weighted tube to the ocean floor and recovering it with an attached wire line or by dredging while shallow coring is performed by conventional rotary drilling equipment.

A deep stratigraphic test is defined in the regulations as drilling that involves the penetration into the sea bottom of more than 50 feet (15.2 meters) of consolidated rock or a total of more than 500 feet (152 meters). Also known as Continental Offshore Stratigraphic Test (COST) wells, they are not necessarily designed to discover oil and gas but, rather, to obtain information about the nature of the subsurface rocks or drilling conditions in a particular offshore area.

Originally, deep stratigraphic tests were only allowed to be drilled offstructure. Regulations governing onstructure drilling became effective in January 1980. To date, however, no onstructure deep stratigraphic tests have been drilled. One possible explanation might be that in a frontier area where industry is trying to determine drilling conditions and costs, an onstructure test may not provide better information on variables such as porosity, permeability, and water saturation if the stratigraphic section has been deformed by the geologic structure. Despite this limitation, three wells encountered hydrocarbon shows—the Atlantic COST B-3 well, the Point Conception No. 1 well in the Pacific, and the Norton COST No. 2 well in Alaska.

Analysis of Present MMS Data Coverage on the OCS

Mileage

A leading indicator of the amount of OCS oil and gas activity is the number and associated mileage of prelease exploration permits that MMS issues to industry each year. Between 1968 and the early 1990's, industry shot and recorded approximately 500,000 line miles of CDP data each year on the OCS. Of that data, the MMS selected and acquired approximately 50,000 line miles of those CDP data each year for the REP. Since the early 1990's, and in parallel with industry, the MMS has increased its acquisition of 3-D seismic data in concert with the development and use of interactive workstations. Table 1 summarizes MMS data acquisitions through 1996. HRD information was used for shallow hazards analysis, and gravity and magnetic data were used for basin definition in the early years of the REP.

G&G Exploration Permits

As mentioned, the number of permits issued each calendar year by the MMS and the areas for which the permits are issued are leading indicators of oil and gas activity on the OCS. Table 2 presents the statistics of G&G exploration permitting for the OCS since 1960, with a differentiation between geological permits and geophysical permits from 1969 to 1996. The Gulf of Mexico has issued 80 percent of all permits and is followed by the Alaska Region with 10 percent, the Pacific Region with 7 percent, and the now-defunct Atlantic Region with about 3 percent. These statistics correlate extremely well with the dominant position of the Central and Western Gulf of Mexico Planning Areas in OCS oil and gas activities.

Table 1. Summary of geological and geophysical data acquisition by data type and region, FY 1968–1996.

Data type	Region	Mileage*
CDP	Alaska	439,524
	Atlantic	189,858
	Gulf of Mexico	739,829
	Pacific	132,841
	Total	1,502,052
High resolution	Alaska	59,855
	Atlantic	49,509
	Gulf of Mexico	145,768
	Pacific	30,582
	Total	285,714
CDP interpretations	Alaska	84,683
	Atlantic	44,801
	Gulf of Mexico	139,418
	Pacific	42,365
	Total	311,267
Gravity and magnetics	Alaska	370,849
	Atlantic	15,783
	Gulf of Mexico	75,942
	Pacific	110,150
	Total	572,724
3-D seismic	Alaska	0
	Atlantic	0
	Gulf of Mexico	6,267 bl
	Pacific	12 bl
	Total	6,279 bl
Deep stratigraphic tests	Alaska	14
	Atlantic	5
	Gulf of Mexico	3
	Pacific	2
	Total	24

* 3-D seismic is measured in blocks, and deep stratigraphic test units are wells drilled.
bl = Blocks

Table 2. Total number of permits issued for geological and geophysical exploration.

Year	A	B	C	D	E	F
1960–68	2,353	---	---	---	---	---
1969	258	249	9	0	0	0
1970	213	203	10	0	0	0
1971	210	205	5	0	0	0
1972	220	210	10	0	0	0
1973	339	321	18	0	0	0
1974	357	345	12	2	0	0
1975	510	487	23	3	0	0
1976	420	400	20	7	0	0
1977	452	436	16	4	0	0
1978	342	329	13	2	0	0
1979	276	265	11	0	0	0
1980	318	302	16	1	0	0
1981	394	383	11	0	0	0
1982	502	490	12	3	0	0
1983	574	542	32	1	16	0
1984	543	518	25	0	18	0
1985	398	382	16	0	38	0
1986	211	207	4	0	32	0
1987	298	282	16	0	42	0
1988	313	289	24	0	45	0
1989	249	237	12	1	47	0
1990	251	241	9	0	57	1
1991	170	156	12	0	45	2
1992	141	137	3	0	53	1
1993	147	135	11	0	70	1
1994	133	117	16	0	53	0
1995	104	92	11	0	50	1
1996	136	120	16	0	59	0
Total	10,832	8,080	393	24	625	6

A = Total number of geological and geophysical permits
B = Number of geophysical permits
C = Number of geological permits
D = Number of geological permits issued for deep stratigraphic tests
E = Number of geophysical permits issued for 3-D seismic data
F = Number of permits issued for strategic (nonenergy) minerals
Dashed lines = Individual breakouts not established

Figures may vary 1–2%.

It should be noted that since 1969, more than 95 percent of the permits issued were for geophysical exploration. Although the total number of 3-D permits issued is rather small (7 percent) when compared with the total geophysical permits issued, over the past 10 years, 3-D permits have averaged 25 percent of all geophysical permits, and by 1995 made up 54 percent of the total geophysical permits issued bureauwide. Permits for deep stratigraphic test wells account for about 6 percent of the geological permits.

The overall trends in permitting for all the Regions are similar and reflect fluctuations in the price and supply of petroleum, shifts in industry emphasis, and areas under moratoria.

Expenditures

The MMS records financial and procurement transactions by fiscal year. Table 3 shows the total expenditures for G&G data. Alaska had the largest portion of the expenditures, 40 percent, followed closely by the Gulf of Mexico with 36 percent. Alaska has more than twice the offshore area of the other three Regions combined and, thus, has the largest portion of the expenditures. The Pacific Region has the smallest slice of the expenditures for G&G data because parts of the Pacific OCS have been under moratoria since the 1980's.

The Gulf of Mexico Region's dominant role with the offshore industry is apparent by its acquisition of the majority of the data before 1976 and since 1990.

Comparisons with Industry

Industry acquires substantially more data than MMS. This is particularly true for the Gulf of Mexico and Pacific Regions. However, of the data shot by industry in the Alaska OCS, MMS has acquired approximately 90 percent. Alaska is a large frontier area with limited data coverage by industry, a fact that necessitates MMS to acquire as much of these data as feasible.

The MMS acquired more data in the Atlantic Region than industry in 1976 and 1983. Before 1976, the MMS database was limited because industry had shown very little interest in leasing this frontier area, although industry had been acquiring geophysical data. During the period 1976 to 1984, MMS not only acquired most of the industry data but purchased much of the pre-1976 data. Since 1985, there has been less activity, reflecting a decrease in industry interest.

Some of the reasons MMS does not acquire all the data held by industry are as follows:

- Redundancy of data and difference in data quality between companies
- Budgetary constraints
- Personnel limitations for data management

In conclusion, totals for mileage acquired, permits issued, and expenditures reflect the overall trends of oil and gas pricing, limitations of areas due to offshore moratoria, and shift of industry emphasis to foreign theaters.

Table 3. Summary of geological and geophysical data acquisition expenditures by data type and region, FY 1968–1996.

Data type	Expenditures ($)*
Alaska	
CDP seismic	40,555,456
High resolution	11,125,798
CDP interpretations	439,793
Gravity and magnetics	1,026,956
3-D seismic	0
Total	53,148,003
Atlantic	
CDP seismic	7,791,438
High resolution	9,751,232
CDP interpretations	55,274
Gravity and magnetics	2,902
3-D seismic	0
Total	17,600,846
Gulf of Mexico	
CDP seismic	31,015,469
High resolution	12,729,139
CDP interpretations	856,526
Gravity and magnetics	514,734
3-D seismic	2,304,194
Total	47,420,062
Pacific	
CDP seismic	9,553,194
High resolution	3,696,394
CDP interpretations	72,175
Gravity and magnetics	534,363
3-D seismic	10,452
Total	13,866,578

*MMS has had additional expenditures through its G&G data acquisition budget for other general purchases such as field tapes, special processing, navigation tapes, interpretive hardware and software for evaluation purposes, geological studies.

Figures may vary 1–2%.

Bibliography

Dellagiarino, George, 1986, Offshore Resource Evaluation Program: background and functions: U.S. Department of the Interior, Minerals Management Service, OCS Report MMS 85-0091, 42 p.

__________ 1991, The Offshore Deep Stratigraphic Test Well Program: U.S. Department of the Interior, Minerals Management Service, OCS Report MMS 90-0028, 36 p.

Dellagiarino, George, Fulton, Patricia, and Zinzer, David, 1991, Geologic and geophysical data acquisition, Outer Continental Shelf through fiscal year 1990: U.S. Department of the Interior, Minerals Management Service, OCS Report MMS 91-0092, 67 p.

Fulton, Patricia, 1991, Permitting process for oil, gas, and sulphur on the Outer Continental Shelf: U.S. Department of the Interior, Minerals Management Service, OCS Report MMS 91-0059, 97 p.

Robinson, E. S., and Coruh, C., 1988, Basic exploration geophysics: John Wiley & Sons, 562 p.

Society of Exploration Geophysicists, 1994, The Leading Edge: Tulsa, Oklahoma, v. 13, no. 8, August 1994.

Wood, L. C., 1982, Imaging the subsurface, *in* Concepts and techniques in oil and gas exploration: Tulsa, Oklahoma, Society of Exploration Geophysicists, 289 p.

Use of Federal Sand for Beach Nourishment and Shore Protection Projects

Anthony Giordano and John Rowland

U.S. Department of the Interior, Minerals Management Service,
Division of International Activities and Marine Minerals, 381 Elden Street, Herndon, VA 20170

Abstract

Coastal shoreline protection and beach nourishment are significant issues for coastal States along the Atlantic and Gulf coasts. In some areas, there is a critical need to identify suitable sources of sand for possible use in public works projects for coastal protection. The continental shelf contains large resources of sand and gravel that could be used to support such projects. The U.S. Department of the Interior's (DOI) Minerals Management Service (MMS) provides policy direction and guidance for development of the resources located on the Federal portion of the continental shelf. This paper highlights the MMS's Sand Program, focusing on its cooperative resource and environmental studies with several coastal States, significant milestones and accomplishments, and anticipated activities in 1998 and beyond.

Management of sand resources on the Federal portion of the continental shelf has been made easier by a Federal-State partnership concept. Using this cooperative concept, joint projects are being conducted to investigate offshore sand resources, potential sites, extraction methods, and related environmental conditions. The MMS has procedures for negotiating sand agreements under the Outer Continental Shelf Lands Act (OCSLA) and ensuring that the resources are developed in an environmentally sound manner. The authority to negotiate with project sponsors, an important recent change in the OCSLA, also resides with the MMS. This 1992 change in OCSLA facilitates the use of Outer Continental Shelf (OCS) resources for public projects. Further, the MMS is authorized to assess a fee based on the value of the resource and the public interest served.

The MMS has worked with local sponsors and authorized the use of OCS sand for two projects. However, additional resource and environmental projects, as well as negotiated agreements, are anticipated within the near future with States and local governments along the Atlantic and Gulf coasts.

Introduction

The U.S. Department of the Interior's (DOI) Minerals Management Service (MMS) provides policy direction and guidance for the development of mineral resources from the continental shelf. The Marine Minerals Program of MMS is in the Division of International Activities and Marine Minerals (INTERMAR). The Division provides policy direction and guidance for the development of marine nonenergy mineral resources on the continental shelf. The MMS program does not promote any particular approach for managing the coast; rather, it focuses on assisting State and local communities if a choice is made to use Federal sand for beach nourishment programs or projects.

To accomplish this mission, MMS and 10 coastal States along the east and gulf coasts are joined in cooperative agreements focused on investigations of offshore sand deposits. INTERMAR, through these agreements, evaluates geologic and environmental information to assess sand resources in Federal waters that could be suitable for use in public works projects for coastal protection, as well as in the aggregate industry. The geologic and engineering properties of the deposit material are studied to ascertain the quality and quantity of the sand, and the feasibility of extraction. The site is examined to determine possible environmental issues related to potential use. As a result, sponsors of beach projects in Maryland, Virginia, South Carolina, North Carolina, and Louisiana are planning to use sand sources in five beach nourishment projects. To support these efforts, MMS sponsors studies to examine questions related to dredging sand from specific areas.

Resource and Environmental Cooperative Studies

The cooperative studies between coastal States and INTERMAR scientists are focused toward evaluations of selected offshore sand resource targets to determine the quantity and quality of sand, gravel, and shell material. The State of Alabama has contributed matching funds throughout the history of the project. Investigators collect and analyze data obtained from high-resolution shallow seismic surveys, surface sediment, and shallow core sampling. In many cases, a geologic model of the deposit is developed pertinent to use of the sand resource. Alabama, Virginia, North Carolina, Delaware, Maryland, and New Jersey are each participating in cooperative studies in Federal waters adjacent to their coasts. Concurrent efforts are under way that complement the resource studies but are focused on environmental questions associated with dredging of sand from the sand resources.

The Geological Survey of Alabama and the University of Alabama are concluding a 3-year project to model the geosystem of offshore and south of Dauphin Island. Since establishing the cooperative in 1993, the MMS has invested nearly $230,000 into geologic assessments of sand resource sites on the continental shelf offshore of the State. The MMS and the State have maintained a 50-50 cost-sharing arrangement throughout the history of the cooperative agreements. In previous years, scientists and engineers completed an evaluation of the sand resource deposit located in Federal waters south of Dauphin Island, Alabama, referred to as Target Site #4. An estimated 30 million cubic yards (yd^3) of the material forms a submarine ridge. Results of several sediment tests indicate that the shelly sand material located in the east-central portion of Target Site #4 has a high degree of compatibility with material required for Dauphin Island beach nourishment. Engineering analysis results suggest that southeastern Dauphin Island shoreline could be restored to the 1955 position by application of about 2.4 million yd^3 of this material. The resource appears to contain sufficient sand for several future projects.

A related environmental study, "Environmental Studies Relative to the Impacts of Dredging for Beach Nourishment Offshore Alabama," was initiated to address questions raised by the potential for dredging sand from offshore of Alabama for the beach nourishment use. This study, funded at nearly $500,000, collected information at five sites that will be used to assess the potential for adverse impacts prior to any dredging. This study should be completed in 1999.

The Florida Geological Survey, in cooperation with the MMS, is continuing geologic assessments of possible borrow sites offshore of Brevard County. This agreement, established in 1994, has identified sites that if proven viable could be used as sources of sand for projects along the east-central coast of Florida within the next 5-year period. Since 1994, the MMS has invested nearly $315,000 into work efforts of the agreement. The State of Florida has contributed matching funds. The cooperative investigation continues, with current work including the acquisition and analysis of geological and geophysical data pertinent to lateral extent, thickness, and quality of the sand bodies located within a 250-square-mile area offshore of southern Brevard County, Florida. Sediment for 11 cores was analyzed, as well as subbottom profiles and surface sediment samples.

An MMS-sponsored study, "Synthesis of Hard Mineral Resources on the Florida Panhandle Shelf: Spatial Distribution, Subsurface Evaluation, and Sediment Budget," is expected to yield information about mineral resources, geologic framework, and sediment dynamics offshore of Mobile Bay, Alabama, to Choctawhatchee, Florida. The completion of the final report is scheduled for late 1998. The "East Florida Shelf Benthic Repopulation Study" was completed in 1997 to support the negotiated agreement with the City of Jacksonville, Florida, and the U.S. Army Corps of Engineers (USACE) funded a study to examine the effects of a dredging operation within borrow area on the local macro-infauna.

As a followup to the Ship Shoal modeling study, a 3-year field study is under way to examine the wave climate, wave-current interactions, bottom boundary layer dynamics, and the sediment transport characteristic of the Ship Shoal area landward of the Isles Dernieres. The results from this project should enhance the confidence in the results obtained from the model and assist preparation of an environmental impact statement relative to mining of Ship Shoal. "Environmental Studies Wave Climate and Bottom Boundary Layer Dynamics with Implications for Offshore Sand Mining and Barrier Island Replenishment, South-Central Louisiana" is another follow-on study to the Ship Shoal modeling project. This 3-year study focuses on evaluation of wave climate, wave-current interactions, bottom boundary layer dynamics, and sediment transport leeward of Ship Shoal. The results anticipated during 1999 should further strengthen confidence in the model as it relates to the mining of Ship Shoal.

Currently, we are working with the States of New Jersey, Delaware, and Maryland on a project to describe offshore sand resource sites. The Maryland and Delaware Geological Surveys are coordinating a project to obtain vibracores within the offshore area from Ocean City, Maryland, to Indian River Inlet, Delaware. In June 1997, the MMS awarded a contract to a group of scientists to model the wave climate and benthic populations in that offshore area. The New Jersey Geological Survey is completing an archeological survey of a sand shoal area offshore of Avalon, New Jersey. Sand deposits offshore of Avalon evaluated during past years were found suitable for use in beach nourishment projects. Plans are to drill as many as 30 vibracores at four offshore sites between Atlantic City, New Jersey, and Manasquan, New Jersey. These sites contain shoals that have potential as sources of "emergency" nourishment sand. The sand would be used for a rapid response to erosion caused by severe storms.

Six sand resource sites have been identified offshore of New Jersey, and a promising area offshore Maryland/Delaware has also been evaluated. An environmental study examining the potential impacts of dredging sand from offshore of New Jersey for beach nourishment was begun in 1997. A similar study that focused on the offshore Maryland-Delaware was also initiated during that year.

Activity with the State of North Carolina continues to delineate sand resources for possible nourishment of coastal Dare County in the year 2002. Related environmental studies are under way offshore of North Carolina in 1998. The cooperative effort with North Carolina continues toward an evaluation of the resources offshore of Dare County. This area covers more than 400 square miles extending from Oregon Inlet to Duck Island, North Carolina. Efforts continue to develop a seismic stratigraphic characterization of that area. Data are needed to identify sand resources for maintenance of the beach system along Route 12 on the Outer Banks. MMS began a 32-month cooperative study with the State in late 1997 titled "Environmental Studies Relative to the Impacts of Dredging for Beach Nourishment, Offshore North Carolina," which involves wave modeling and collection of biological data at two offshore sand sites.

Our cooperative agreement with South Carolina continues as we work to identify sand resources for future beach nourishment projects and to evaluate biological resources associated with the resource sites. This year's work is a continuation of a multiphased mapping effort of the area offshore of Hilton Head, South Carolina. Information obtained from this project will be used to identify sand deposits compatible with use as nourishment material.

The Commonwealth of Virginia through the Virginia Institute of Marine Science has evaluated several offshore sand sites through the MMS and Virginia cooperative agreement. Since established in 1992, the MMS has contributed nearly $364,000, and the Commonwealth has contributed an equal amount to the geologic studies and resource assessments. The results obtained from this investment have been significant and have already proven valuable. Sandbridge Shoal was judged to have the highest potential as a source of sand for coastal restoration projects. Reserves of the shoal are estimated to be as much as 40 million yd^3 of sand. In 1996, sand from this shoal was used to nourish the beach and construct a berm at the U.S. Navy's Combat Training Facility at Dam Neck to protect against potentially damaging impacts of hurricanes. Recently, the Norfolk District of the USACE requested a Memorandum of Agreement (MOA) with the MMS while the City of Virginia Beach is negotiating with the MMS for a noncompetitive lease. An environmental assessment of the proposed project was completed during the fall of 1997. Information obtained from the study completed in December 1997 titled "Environmental Studies Relative to Potential Sand Mining in the Vicinity of the City of Virginia Beach, Virginia" was used to address questions related to mining sand offshore of Virginia.

The MMS awarded a contract for the study titled "Investigation of Benthic and Surface Plumes Associated with Marine Aggregate Production in the United Kingdom" in August 1994. Scientists associated with the study are examining the degree to which disturbed sediment persists within the near-bottom and surface water layers during dredging operations. The initial data collection and analysis focused on the effects on benthic and water column organisms. Completion of the multiyear and multifaceted project is anticipated in the near future.

Although not currently funded, a cooperative agreement with the Bureau of Economic Geology at The University of Texas at Austin completed geologic evaluations and engineering feasibility studies of the Heald and Sabine Banks offshore of Galveston, Texas. The volume of sand, including muddy and shelly, estimated for the Heald Bank is nearly 600 million yd^3. The dimensions of the sand body are enormous with a sand layer 3 feet thick extending over a 64-square-mile surface area. The volume of sand, including muddy and shelly, estimated for Sabine Bank is about 1.6 billion yd^3 on the basis of a sand layer 10 feet thick over a 135-square-mile area. Analysis results reveal that Heald Bank sediment is appropriate for restoration of regional shorelines.

The cooperative agreement with the State of Mississippi operates through the Marine Minerals Technology Center (MMTC) at the University of Mississippi. Efforts continue to conduct engineering research related to marine exploration systems. MMTC accomplishments have been significant and instrumental in identification and assessment of sand and shell deposits in various offshore environments.

Accomplishments and Milestones

In October 1996, the President signed the "Marine Mineral Resources Research Act of 1996" reauthorizing the current Marine Minerals Research Center (MMRC) of the Minerals Institute Program, which was established in 1984. The Act authorizes the Secretary of the DOI to designate three program divisions for marine minerals research: (1) the Continental Shelf, (2) Deep Ocean Basin, and (3) Arctic Cold-Water Region Divisions. The Secretary delegated MMRC budgetary oversight to the MMS. Subsequently, MMS recommended selection of the Universities of Mississippi and Hawaii, giving priority to their program accomplishments since it was established in 1984. The University of Alaska, Fairbanks, was chosen as the location for the third division because of the University's experience with and proximity to cold-water environments.

A major legislative milestone was achieved in 1994 that helps the MMS ensure that sufficient quantities of sand continue to be available for beneficial projects for the public. In October 1994, the U.S. Congress amended the Outer Continental Shelf Lands Act (OCSLA) (P.L. 103-426). This amendment removed procedural obstacles for obtaining OCS sand and authorized negotiation of agreements for rights to use OCS sand, gravel, and shell for certain uses for a fee to be determined by the Secretary of the DOI. The Secretary delegated the authority to the MMS. State and local governments and other Federal agencies can negotiate with the MMS for use of sand for public works projects such as shore protection, wetlands restoration, and Federally funded authorized projects. Development of policy guidelines for fees for access and use of offshore Federal sand for public works projects is a significant step to ensure that the public receives fair value for the use of public resources. The guidelines for fee determination balance resource value with public benefits from use of OCS sand, so that assessments are fair and will not prevent an otherwise acceptable project. The MMS/OCS Policy Committee passed a resolution approving fee guideline recommendations on October 30, 1997. The MMS will use these guidelines in negotiating agreements in section 8(k)(2) of the OCSLA.

In 1996, beach-quality sand from the Sandbridge Shoal located in Federal waters offshore of Virginia was used to nourish the Dam Neck Naval Facility oceanfront beach. An MOA with the U.S. Navy resulted in construction of a beach and berm to protect the Navy's Combat Fleet Training Facility coastal facility valued at more than $95 million. This project was the first conveyance of Federal sand for use in a beach nourishment project designed to protect Federal coastal assets. Table 1 provides a listing of recently completed public works projects that used sand from the Federal OCS for beach nourishment and hurricane protection projects.

Table 1. Public works beach restoration projects using sand from Federal OCS.

Public works project (type of agreement)	Completion year	Sand volume (yd^3)
U.S. Navy's Combat Fleet Training Center Dam Neck, Virginia (Memorandum of Agreement)	1996	972,000
Myrtle Beach, North Carolina (Negotiated Agreement)	1998	557,000
Duvall County, Florida (Negotiated Agreement)	1995	1,240,000

Anticipated Activities

Within 2 years, we anticipate additional use of Federal sand for authorized projects for public coastal beach nourishment and hurricane protection in coastal areas of Sandbridge, Virginia, and Myrtle Beach, South Carolina. In May 1997, the Norfolk District of the USACE requested the MMS to initiate work with them to develop an MOA for a proposed shoreline protection project for the Sandbridge Beach section of Virginia Beach, Virginia. A negotiated agreement with the City of Virginia Beach for the Sandbridge beach project was completed in early 1998. The project plan calls for the use of as much as 1.5 million yd^3 of sand from Sandbridge Shoal for placement on the eroding coastline. This shoal is the same sand resource used for the 1996 beach nourishment project at the U.S. Navy's coastal facility. Recently, INTERMAR made projections for the sand volumes anticipated within 2 years on the basis of available information related to projects in planning or preparatory stages. Demand for sand by Federal, State, and local governments for beach nourishment will not be continuous and market-driven. Table 2 lists the coastal sites where the INTERMAR staff anticipates that sand from the Outer Continental Shelf will be used for beach restoration projects during 1998 and 1999. However, implementation of the projects as projected will depend upon completion of feasibility plans, governmental budget approvals, and negotiated agreement granting authority for a one-time removal of a specified amount of sand. Revenues or fees will be collected at the time of the negotiated agreement, whereas the sand is removed and placed on the beach within a few months of the agreement.

Horry County, South Carolina, requested negotiations for OCS sand resources for use in a Federally funded beach restoration project at Myrtle Beach, South Carolina. The MMS and the USACE finalized the MOA opening the way for negotiations. Federal sand is anticipated to be used as the material to restore the shoreline south of Myrtle Beach. The negotiated agreement for the noncompetitive lease of the sand is expected in the near future, although the project is not expected to begin until 1998 or later.

We also expect to negotiate an agreement in 1998 with the National Park Service to use Federal sand to restore a portion of Assateague Island. The sand will come from Great Gull Bank shoal, 4 to 6 miles offshore of Assateague Island, Maryland. This resource was evaluated by the Maryland Geological Survey in cooperation with the MMS.

The Commonwealth of Puerto Rico and INTERMAR began discussions in 1997 that could lead to cooperative assessments of sand resources located in Federal waters offshore of that island. Puerto Rico has several areas of coastal erosion and a shortage of inland sand resources of suitable quality for beach nourishment.

Table 2. Sites of anticipated restoration project using Federal sand.

1998	1999
Myrtle Beach, South Carolina	Isles Dernieres, Louisiana
Virginia Beach, Virginia (Sandbridge Beach section)	Virginia Beach, Virginia (Resort Strip Section)
	Assateague, Maryland

Further Information

Additional information may be obtained from the MMS's Marine Minerals Program Web site at www.mms.gov/intermar/marineac.htm or by contacting the staff of the Division of International Activities and Marine Minerals at (703)787-1300.

Northstar—Geology, Exploration History, and Development Status, Beaufort Sea, Alaska

Jerry Siok

BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, AK 99519-6612

Abstract

Exploration for oil at Northstar has been long and costly. Northstar leases were first acquired in 1979 at a joint state & federal sale by Shell Oil, Amerada Hess and Texas Eastern. The Northstar Unit is 6 miles offshore and about 4 miles northeast of the Point McIntyre Field. Oil was first discovered in Shell's Seal Island #1 in 1983. Five additional appraisal wells were drilled (1983–86) from 2 man-made gravel islands in 40 feet of water. Early engineering estimates put the cost of development at $1.6 billion. In February 1995, BP Exploration (Alaska) acquired a 98% interest in the Northstar Unit from Amerada Hess and Shell Oil. When developed by BP, Northstar will be the first oil produced from Federal Leases in Alaska. To date, the oil industry has invested in excess of $140 million in exploration and appraisal operations. An additional $90 million was spent on lease bonus bids.

The giant Prudhoe Bay and Kuparuk Fields lie along the Barrow Arch. This arch is bounded to the North by a rift margin that deepens into the present-day offshore region. Northstar is located among a series of down-stepping faults off this northern rift margin of the Prudhoe/Kuparuk high. The structure is a gently south-dipping northwest-trending faulted anticline. The crest of the structure is located near 10,850 feet subsea. The primary reservoir is the Ivishak Formation (325 feet thick) of the Sadlerochit Group. This is the same primary reservoir at Prudhoe Bay, approximately 12 miles to the South. At Northstar the Ivishak is a high-energy, coarse-grained conglomeratic facies of the Ivishak Formation. The primary lithology is a pebbly chert to quartz conglomerate with occasional sandstone. This very high net to gross reservoir appears to contain no regionally continuous permeability barriers. Cementation has reduced primary porosity to less than 15%. Accurate porosity estimates are difficult to make due to the coarse-grained nature of the lithology and the presence of kaolinite and microporous chert. Permeability is highly variable, but averages 10 to 100 mDarcies. Oil is a very light and volatile 42° API crude with approximately 2100 cubic feet of gas per stock tank barrel of oil. This oil is very different from the heavier oils (26°) found to the South in Prudhoe Bay. Estimated recoverable oil reserves range from 100 to 160 million barrels.

A free-standing drilling rig is required at Northstar because the reserves are beyond extend reach drilling techniques from shore-based facilities. The current development plan is to expand the existing Seal Island to about 5 acres. This is significantly less than Endicott's 40-acre island. The proposed drilling and production island will be accessed by summer barges and winter ice roads. Oil, gas and water will be processed at a stand-alone facility and then sent to shore via a subsurface pipeline. Northstar will have the first Arctic subsea pipeline in Alaska to transport oil to shore facilities (TAPS). Preliminary tests in Spring 1996 were very successful in demonstrating the technology to successfully bury a subsea pipeline safely in the Arctic.

Development of Aggregate Resources in Pacific Tropical Islands

Michael J. Cruickshank

Director, Marine Minerals Technology Center,
University of Hawaii, 811 Olomehani St., Honolulu, HI 96813

Abstract

Small tropical Pacific islands suffer from a common problem of acquiring and maintaining an adequate supply of sand and aggregate for infrastructure development, coastal protection and beach maintenance. This is most critical in countries where atolls predominate, such as the Federated States of Micronesia, and the Republic of Marshall Islands, but presents difficulties in even the largest and most highly developed island communities such as Hawaii and American Samoa. Recent studies by the Marine Minerals Technology Center and others have indicated a Pacific-wide sea-level stillstand about 40,000 years ago which resulted in the formation of coastal terraces with significant sand beaches at depths of about 70 m. It is proposed that such deposits, in water depths of 50 to 100 m and seaward of the reefs, will serve as resources for sustainable development. Exploration should result in the discovery, throughout the region, of sand deposits containing tens to hundreds of millions of cubic yards of clean sand close to shore. These large deposits should be amenable to dredging by advanced technology at low unit cost. Stockpiles located appropriately throughout the region, integrated with a bulk transportation service, could supply projected needs at a cost which would be affordable to each community.

Integrated Reservoir Management for the Long Term—The Carpinteria Offshore Field

E. M. Whitney and R. P. Kendall

Los Alamos National Laboratory, Earth and Environmental Sciences Division, Geoanalysis Group EES-5, P.O. Box 1663, MS-F665, Los Alamos, NM 87545

M. R. Brickey

Minerals Management Service

S. E. Coombs

Coombs & Associates

C. A. Duda and V. K. Duda

California State Lands Commission

Abstract

The Carpinteria offshore field, Santa Barbara, California, has produced more than 100 million barrels of oil to date. This mature field has continued operations in an economically and politically challenging environment that finally resulted in the abandonment of the field's California State leases by the lease holder. The abandoned leases, together with adjoining Federal leases, are now operated by an independent producer. Los Alamos National Laboratory has joined with that independent operator, Pacific Operators Offshore, and with the State Lands Commission of California and the Minerals Management Service in a unique collaborative effort to redevelop the mature field. This project is a part of a larger umbrella project, the Advanced Reservoir Management project (ARM), that is designed to demonstrate the worth of advanced computational tools and state-of-the-art methods for independent oil and gas producers. The Carpinteria Reservoir Redevelopment project takes a long-term view of reservoir management; as a result, our management plan includes a continuing investment in time and technology to better understand the reservoir. In particular, we have completed an extensive reservoir characterization and geological modeling effort that has created a self-consistent model, satisfying geophysical, geological, and engineering data constraints. We have begun the engineering-intensive flow simulation phase of the project using the current geological description of the reservoir and are confident that our careful efforts in geological modeling will result in a reasonable reservoir flow model.

Dynamic documents exist that are used by participants to stay abreast of developments on the project. These World Wide Web (www) pages may be viewed at http://ees.lanl.gov/EES5/arm/pooi. Other sites of interest that describe the nature of the agencies and companies involved in the project are at http://ees.lanl.gov/EES5/, http://www.mms.gov/omm/pacific/index.html, http://www.slc.ca.gov, and http://www.pacops.com.

Introduction

The Carpinteria offshore field, Santa Barbara, California (fig. 1), was discovered in 1964 and has been developed over three decades with deviated drilling from five platforms. The field has produced more than 100 million barrels of oil to date. This mature field is analogous to other nearby offshore fields, and efforts to redevelop it therefore have great implications for those fields.

The 3-mile coastal waters boundary between Federal and State leases cuts through the Carpinteria

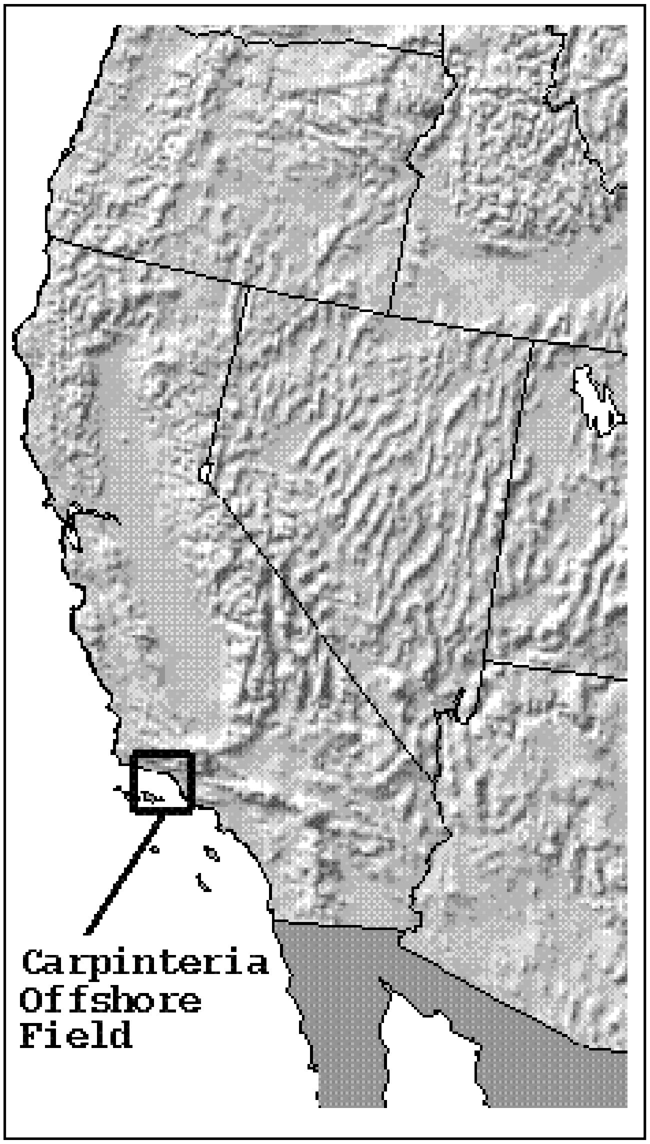


Figure 1. The Carpinteria offshore field is located near Santa Barbara, California, and is divided into California State and Federal leases by the 3-mile coastal waters limit.

field, so that of the five leases on the field, three belong to the State, and two are Federal. Over the years, various companies have operated the leases, a situation that has resulted in a disjointed production strategy for the reservoir as a whole.

Twenty-nine productive intervals have been identified and mapped in the Carpinteria reservoir, and production from these intervals has been commingled to a large degree on individual leases throughout the history of the field. In recent years, increased water cuts and sand production from unconsolidated strata, accompanied by lower production, reduced the profitability of the field and contributed to a decision by the operator to abandon the California State leases. Two of the abandoned State leases and the adjoining Federal lease are now operated by an independent producer, Pacific Operators Offshore, Inc. (POOI).

In the course of abandonment by the previous operator in 1966, all wells on the two production platforms in the State leases were plugged and abandoned, and the platforms were removed. The State leases are thus unreachable by drilling, except from platforms in Federal leases. Plans for redeveloping the reservoir include options for high-angle extended-reach drilling to recover oil from various parts of the reservoir, including the otherwise inaccessible State leases.

In 1993, when POOI acquired the leases, the conceptual model of the field was confusing. This confusion was the result of multiple interpretations of geological and engineering data by a variety of operators. No field-wide reservoir interpretation was available to POOI that integrated geological, geophysical, engineering (well test), and production data.

POOI recognized that to understand such a complex geological environment, advanced modeling and visualization technologies would be required that would permit the building of a coherent model of the reservoir sands and would permit that model to be viewed in three dimensions. This model would be viewed and manipulated to reveal its surfaces, its volumes, and its distribution of rock and fluid properties.

The long-term reservoir management plans for the Carpinteria field will make use of reservoir simulation as a guide for production operations in the field. To conduct meaningful reservoir simulation studies, and thereby meet the needs of the operator and the management plan, a credible reservoir model was needed. The construction of the model is the subject of this paper.

The Advanced Reservoir Management Project

These advanced technologies were offered to independent oil and gas producers by the U.S. Department of Energy (DOE) as part of the Advanced Reservoir Management project (ARM) at Los Alamos National Laboratory (LANL). POOI recognized this opportunity and joined in a Cooperative Research and Development Agreement (CRADA) with LANL. POOI also sought the participation of the royalty owners in the field, the California State Lands Commission (CSLC) and the Minerals Management Service (MMS) of the U.S. Department of the Interior. These agencies joined POOI and LANL to form the Carpinteria Offshore Field Redevelopment project.

The Carpinteria project is the first collaboration of its kind of which authors are aware. It brings together Federal and State agencies, an industry partner, and a national laboratory in a combined effort to understand, and thereby guide, the redevelopment and management of a mature offshore field. Additionally, the participants retained the consulting services of other organizations to fill out the technical competency of the team—Coombs and Associates, for petrophysical and well log analysis, and R. G. Heck and Associates, for specialized geological interpretations.

The impetus for collaboration on the Carpinteria project varies among organizations. POOI is interested in increased revenues from improved production. The California State Lands Commission and the Minerals Management Service are interested in continuing royalty revenues from the Carpinteria field and in understanding the implications that redevelopment has for the many other similar offshore fields. Los Alamos National Laboratory and the Department of Energy are committed to supporting domestic independent oil and gas producers as they improve reservoir management practices by applying available technology (http://ees.lanl.gov/EES5/arm).

The Virtual Enterprise

The Carpinteria project depends on the "virtual enterprise" model to tap the resources of its many participants. Simply stated, the virtual enterprise is the combination of efforts of individuals and companies that join together to accomplish a common goal. The individuals and companies that work together in the virtual enterprise may be, as in the case of the Carpinteria project, geographically dispersed, yet they interact in a common workplace every day. This common workplace is the union of computers and networks at each of the remote locations where the individuals and companies reside.

The importance of the virtual enterprise to independent oil and gas producers cannot be overstated. It enables any independent producer to enlist widely dispersed technical resources and expertise to solve a specific problem inexpensively and in a well-coordinated way. It provides the independent producer access to technical resources equivalent to those in a major oil company. Recent successes with virtual enterprise teams have helped other independent operators solve complex problems (Murphy and others, 1996; Voskanian and others, 1996).

In the case of the Carpinteria project, the management of this enterprise is distributed among the various participants. But it need not be so. An independent producing company may develop and centrally manage a virtual enterprise with known and trusted subcontractors and consultants. The foundation for such an enterprise is the company's association with these consultants; networked computers make available the common "virtual office" where they can work together (fig. 2).

In the Carpinteria project, no one of the participants has the expertise and equipment to carry out a project of this scale alone; instead, each has unique resources that benefit the overall project. The project depends on a coordination of these widely distributed resources. The situation is complicated by the fact that management, too, is dispersed among the organizations. The project management has therefore depended on conference-call meetings, E-mail, electronic file transfers, and the World Wide Web to create this coordination of resources, to direct the project, to monitor progress, and to receive feedback.

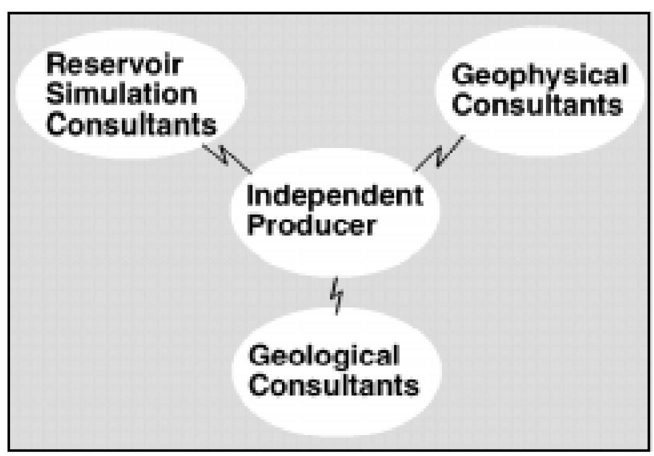


Figure 2. The virtual enterprise provides a small independent producer access to technical resources that previously were available only to major oil companies.

Project Planning and Preparations

There are four main segments in the reservoir management scheme for the Carpinteria Reservoir—geological modeling, geostatistical modeling, engineering modeling, and project integration. The task diagram shows various subtasks within these main segments (fig. 3). Early in the life of the project, a consensus was reached by the management of the various participants about commitment of resources to the project.

Data Review and Analysis

An initial review of available data revealed multiple well log traces from slightly more than 200 wells, cross sections, and geological maps from previous studies of the reservoir, comments on the depositional history of the field, and engineering and production data (fig. 4).

Geological Modeling

Well Log Analysis

Coombs and Associates obtained hard copies of all well logs, digitized the several thousand traces, and formatted this large data set in a series of standard format files. The vectorized forms of the well log traces were then transformed into reservoir property logs (porosity, permeability, and water saturation) for the 200 wells. All of this raw data and calculated information, and additional information on reservoir description and performance, are part of a distributed database that is being compiled by MMS and CSLC to be archived in commercially available databases for later use.

Well Log Correlation

Initial well correlations were made from the paper SP and GR logs, and paper cross sections were generated to guide preliminary rough correlating work. The initial correlations were refined on visually intuitive multiple-well-log display panels in a computer-aided design (CAD) package. The data for these CAD displays were generated with script files in a commercially available spreadsheet program. The script extracts SP and GR picks from the database where they are stored and writes these data to files for display by the CAD package. This method was used to create display panels that showed as many as 20 digitized correlation logs at a time. More importantly, the display panels were projected on a computer monitor, where it was possible to alter the scale, position, or color of any trace, which significantly reduced the time required to make and to quality-control the correlations. Iterations of selecting marker picks, entering the picks in the database, and visually reviewing the results in display panels proved invaluable in ensuring the quality of the resulting data set.

All well directional surveys were used to compute true vertical depth logs, and true stratigraphic thickness logs were prepared by integrating dipmeter and dip from contour maps. These corrected logs allow well log traces to be correlated without the distorting effects of well deviation or structural dip.

The *x*, *y*, and *z* locations of all picks in all wells were calculated from directional surveys and measured depth logs. Well marker picks were then mapped in a commercial mapping package over the areal extent of the Carpinteria field. The resulting 31 maps were imported into a 3-D visualization package and examined for errors. This quality-control step proved invaluable for understanding the limitations of the mapping and for identifying data errors. It also highlighted the need to better define stratigraphic volumes by mapping well marker picks of sand bottoms. Accordingly, the same process of correlating and checking quality (with CAD displays) was repeated for bottoms of productive intervals, and the same mapping and 3-D visualization quality-control effort was again employed to assure that all surfaces honored all available data.

Database Generation

As mentioned previously, geological and engineering data are stored in three different commercial databases. Commercial software was chosen for the project to guarantee availability, flexibility, and long-term support for the database products in our reservoir management software suite. The first database serves as a repository for digitized well log traces. The second, an industry-oriented database solution, houses production and completion information, as well as fluid property tables and other engineering data. The third contains marker picks and directional survey data. There has been a continuing process of database archiving and quality control of reservoir information; errors and omissions are corrected in the database, and new data are added. In this way, the most recent data are always available for construction of successive reservoir model generations.

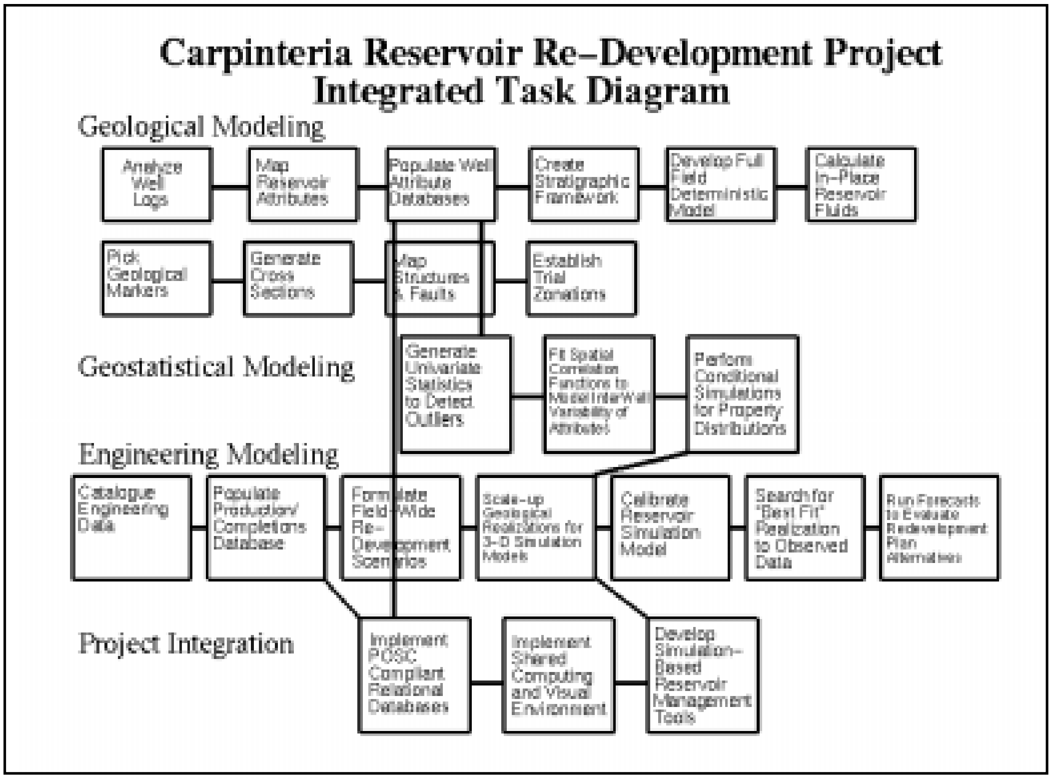


Figure 3. Integrated outline for the Carpinteria project. The many tasks are distributed among the project participants.

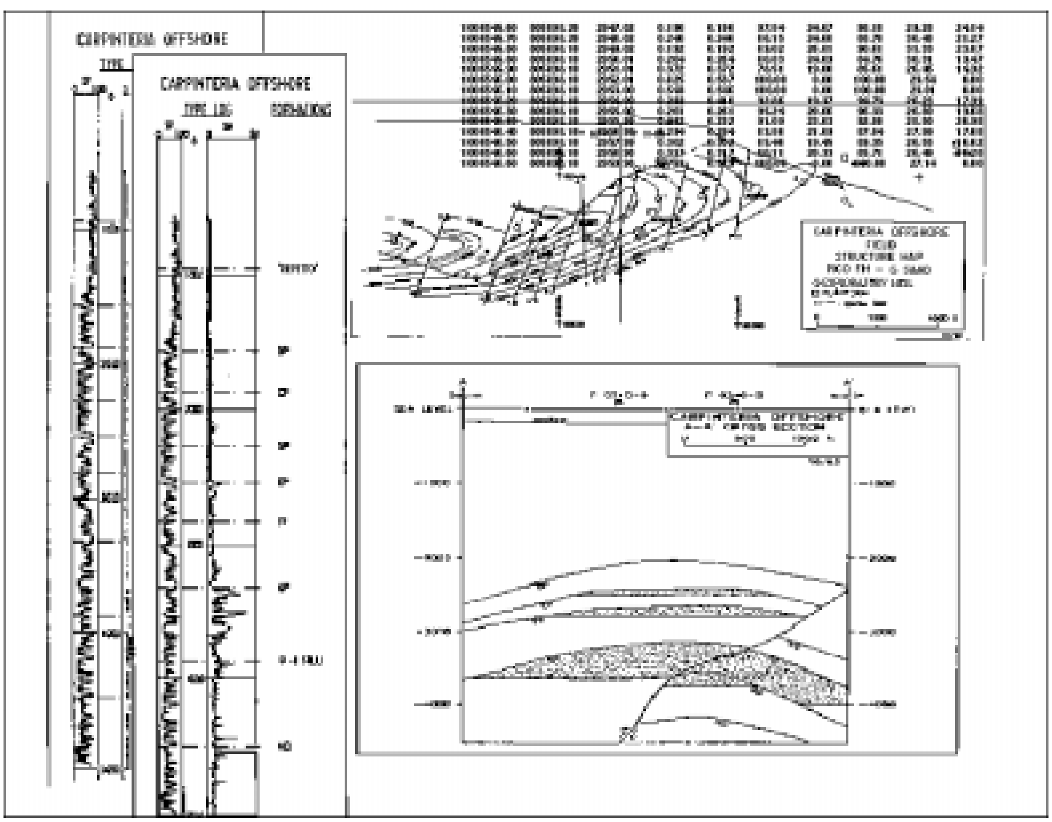


Figure 4. An initial review of data revealed well logs, cross sections, structural maps, engineering and production data, and some commentary on depositional history.

Oil-Water Contacts Interpretation

The Carpinteria field has multiple oil-water contacts. For the most part, individual lithologically defined zones appear to be hydraulically isolated from others. This complicates the calculation of oil-in-place volumetrics.

It was first thought that oil-water contacts would be identified from distributions of saturation in a 3-D geological model. However, it became evident that saturation was not a simple function of depth below sea level but that water contacts in correlated layers occurred at successively greater depths to the east.

This unforeseen variation in saturations indicated that oil-water contacts might be tilted in the field, and it was decided that a careful determination of oil-water contacts would be needed in all wells. These contacts in individual wells picked from calculated logs did not exist for many of the wells in the eastern (State leases) portion of the field. Oil-water contacts there were picked from SP, GR, and resistivity logs. These picks were compared with those from calculated logs for consistency.

These new picks confirmed that the oil-water contacts are not horizontal but incline approximately 5 degrees down plunge to the east on lease P-0116 and about 2 degrees to the east on State leases on the field. With this interpretation in mind, the picks were mapped and gridded in three dimensions, and the resulting surfaces were conservatively extrapolated to their intersection with tops of stratigraphic units (fig. 5).

A careful examination of the intersections of these extrapolations with structural surfaces and a visual review of the distribution of wells that are fully oil or water saturated led to editing and remapping of the oil-water contact surfaces. This remapping ensured not only that all oil-water contact picks were honored but also that the intersection of the oil-water contact surface and top of stratigraphy (correlated surface) honored the saturation state of wells in a given zone.

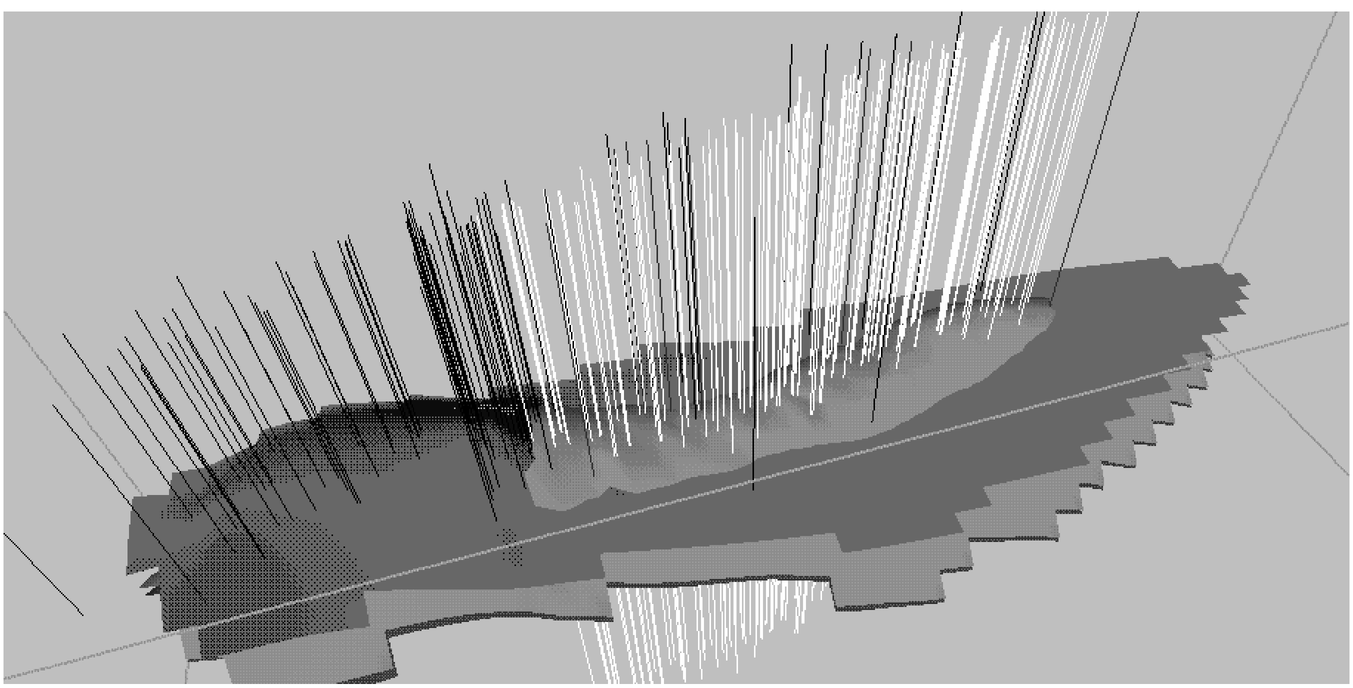


Figure 5. Oil-water contact surface in the E1 sand (extrapolated beyond stratigraphy for visual effect), showing fully saturated wells (white) with water-oil contact in the E1 (gray) and wells that are water saturated in the E1 (black).

Structural and Fault Mapping

It is recognized that faulting in the field plays an important role in the static distribution of fluids and in flow behavior of the reservoir. It has been a goal of the project to capture important faulting effects not only in the interpretive geological model but also in the engineering flow model. The Hobson thrust fault has been identified in previous work, and its faulting interpretation was supported by missing section and repeated section analysis in well logs. Although other significant anomalies in contour maps were identified in early work on the project, no further evidence of any other faults existed at the time, and so the first several generations of the geological model included only the Hobson fault (figs. 6 and 7).

Previous geological studies included many interpreted faults that explained multiple well-to-well production anomalies but that had not been detected by well penetrations. These production anomalies are currently interpreted to be the result of a tilted oil-water contact. This interpretation rests on three lines of reasoning. First, the careful process of picking oil-water contacts in all wells has shown such a tilted interface. Second, if there were many small faults, it is unlikely that they would remain undetected in the more than 200 wells that have been drilled in the field. Third, nearby reservoirs that are tectonically related to the Carpinteria field have not been shown to exhibit such faulting.

R. G. Heck and Associates have been retained to study other significant faults in the field and have recently described several faults consistent with anomalies in structure maps, five of which explain large offsets in the oil-water contacts that are apparently unrelated to the overall tilted trend. Evidence of these few faults is found in missing and repeated section intervals in true stratigraphic thickness logs from Coombs and Associates. The latest geological model, which is the basis for the reservoir flow modeling, includes six of these faults.

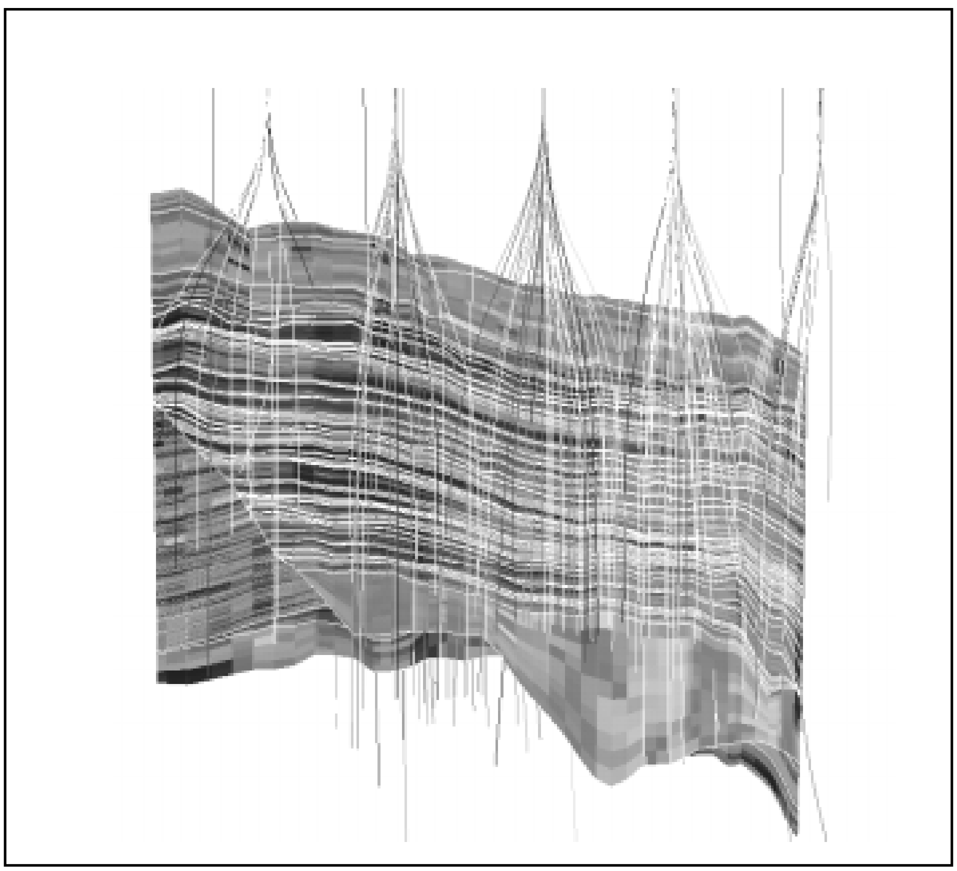


Figure 6. East-west cross section of the Carpinteria field. Hobson thrust is visible on the left.

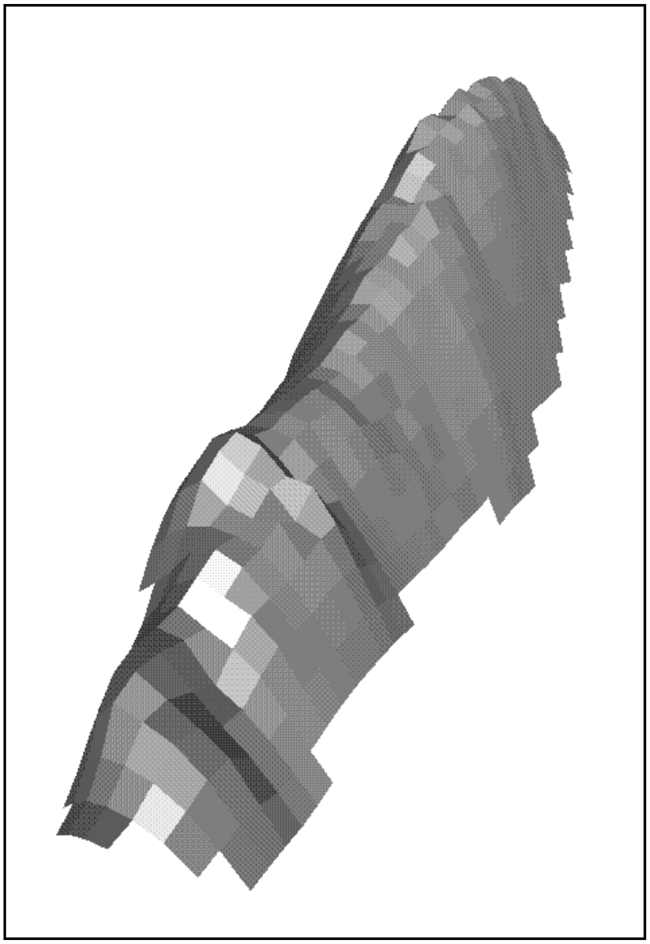


Figure 7. Stratigraphic slice of the Carpinteria reservoir computational framework: top of C1 sand.

Framework Grid Construction and Attribute Distribution

A 3-D gridded structural framework has been constructed that is the basis for computational modeling of both static and dynamic phenomena. The grids for this 3-D geological framework are required to be orthogonal in the *x* and *y* directions, and each must be locked to the same *x*, *y* points. However, all nodes are permitted to vary vertically, and in this way, 3-D surfaces are created that follow stratigraphic boundaries.

The 3-D grid volume was constructed of the 29 tops and bottoms of pay zone intervals; that is, the 58 bounding surface grids are from the structural mapping work of the CSLC and MMS. In addition, oil-water contact surfaces for each of the zones were incorporated in the model. Because zone top and zone bottom surfaces guide the correlation of properties between wells, the process of matching well marker picks to these surfaces at the wells is extremely important; this was the motivation for repeated quality control and remapping.

Each stratigraphic model unit between a top and bottom grid is mathematically subdivided into grid cell layers that are used to project bedding patterns within that zone. The process of vertically subdividing units results in a highly refined grid; several million cells are required to capture heterogeneity in the many layers of the many zones in the reservoir.

The calculated coordinates (*x*, *y*, true vertical depth) for the paths of all wells are incorporated into the framework grid, and all intersections of well paths and grid cells are calculated internally. Reservoir properties, calculated from wireline log traces, are tied directly to the well path at the resolution of the well log data.

These reservoir attributes are then distributed throughout the volume of the 3-D model (fig. 8). We used an inverse-distance-squared weighting for the interpolation of all properties during this first phase of model construction. We recognize the weaknesses of this deterministic approach and plan to remedy this problem by applying spatial statistical methods of distribution in an improved model.

Volumetrics Calculations

Calculation of original oil in place was conducted on the model. Only saturation of mobile oil in individual zones was included in the calculation. The model volumetric calculations were compared with standard engineering/production calculations conducted by POOI. Together, these volumetric calculations contributed to a recent decision to proceed with redevelopment of the field.

Visual Data Quality Control

The geological modeling software packages used on this project, and many similar packages that are available commercially, permit displays of 3-D data sets to be zoom scaled and dynamically viewed from any direction. Such software also permits the creation of 2-D exhibits, which ultimately leads to a reduction in the time and effort associated with mapping and cross-section generation. Many helpful displays of the model were created (arbitrary vertical cross sections, stratigraphic sections, 3-D property volumes, etc.) We found this sophisticated display capability to be

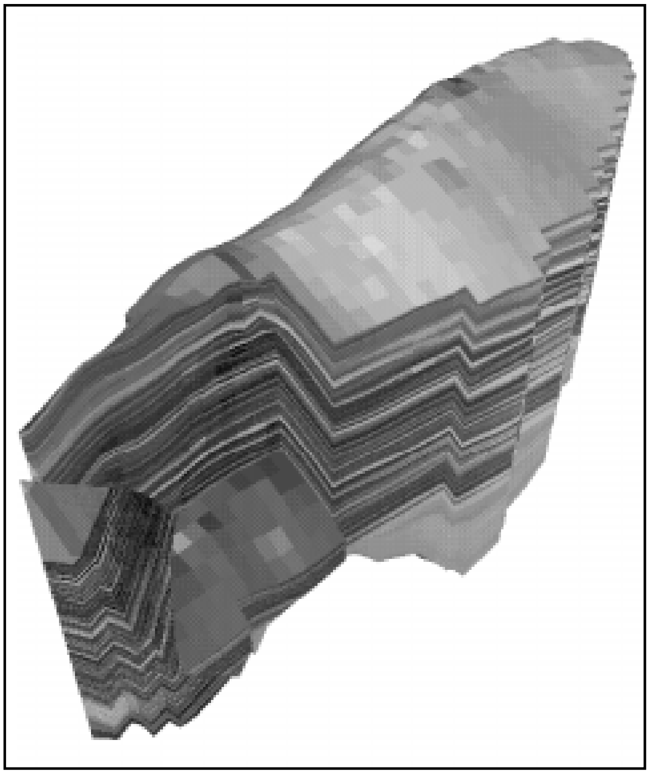


Figure 8. Three-dimensional computational framework model, from southwest, showing distribution of attribute "shale fraction." Hobson thrust divides stratigraphy on the west.

extremely useful in reviewing contoured data, visualizing intersections between structural surfaces, recognizing thickness changes between multiple surfaces, and visualizing the relationship between fault planes, surfaces, and deviated well traces.

Reservoir Simulator Initialization and Grid Upscaling Considerations

A meeting was held upon completion of the first completely populated model of the field, and geology, engineering, and operational concerns for modeling were addressed. A key point of discussion was the extent to which this geological model might be upscaled for flow simulation studies. On the one hand, computing speeds required that the flow model be limited in size. On the other hand, preserving the 3-D heterogeneity of the geological model is certainly important if we are to closely mimic flow behavior in the flow model.

An initial coarsening of the grid that preserved lithologic variability was still too large for flow simulation. A second grid upscaling yielded a smaller grid but resulted in averaged units that were deemed lithologically and hydraulically different. A decision was made first to proceed with another upscaled grid that merged cells of similar porosity and later to address upscaling issues again as a part of planned spatial statistical studies.

The geological model was exported for flow simulation, imported into a commercial reservoir flow simulation package, and initialized. This process was supported by an integrated geomodeling/reservoir simulation software platform, which helped us avoid the complexities of data reformatting that often accompany any data export/import operations.

A gridding module within this integrated environment permitted upscaling on the basis of various averaging schemes. The current upscaled model was generated by vertically averaging together regions of similar porosity. The areal resolution of the model was not changed and resulted in a grid that has more than one well intersecting some of the grid blocks. This was not deemed an insurmountable problem, and it was decided that lumped production would be used for those grid cells with more than a single well.

The history-matching phase of the reservoir simulation studies has not yet begun, as it has been decided that a new generation of the geological model should first be exported. This new generation model will include five faults that are thought to be important in governing flow behavior in the reservoir.

Geostatistical Modeling

To date, the geological modeling work has depended on deterministic interpolation schemes to fill the volume of the model's 3-D grid structure. There is a weakness in this approach: by making the assumption that properties may be interpolated from well to well, we have overlooked important information about the way in which the data vary from well to well.

An improvement would be to employ some similarity-dissimilarity analysis that quantifies correlation lengths between wells and that reproduces in the final model the statistical character of our sample data.

The best way to employ this analysis is to examine lateral continuity in a single stratigraphic unit. We do this naturally when we visually correlate features between well log traces. When a feature appears in one log but not in another, we must decide how far to correlate the feature between the logs. Although this exercise is subjective, we have effectively determined a correlation length for the given attribute. However, we would probably not expect to use the same correlation length for the given attribute in any other direction. Instead, we would search for another well log in the new direction and again examine the similarity-dissimilarity between those two logs. Extending this methodology to a large, spatially distributed data set, we would like to examine the correlation between each well and every other well in the collection. This is an extremely time-consuming exercise and one that is difficult to do rigorously.

A preliminary study was made of spatial correlations of attributes in the reservoir data. The purpose of the study was to determine whether sufficient lateral continuity exists in individual units to make geostatistical estimation and simulation approaches worthwhile. The “F” zone was chosen as the region of interest for this study.

Empirical variograms of the calculated properties data suggest fairly good correlation over distances of at least 500 feet in the “F” zone. In this first analysis, the empirical variograms show spikes at small lags that might be eliminated in a more careful analysis of outliers. At a depth of 3,000 feet, the distance between wells exceeds 500 feet for only 10 percent of the wells. Thus, within the field, at least in the depth range of 2,500 to 4,000 feet, there will usually be data within 200 or 300 feet of any point that we wish to estimate. Given this density of data, the empirical variograms suggest that improvements in the distribution of properties between wells can be expected if geostatistical methods for estimation and simulation are used.

Conclusions

Integrated reservoir management approaches have already provided a valid option for redeveloping the complex Carpinteria field (geomodeling and well planning) and will yield more benefits as fluid movement in the reservoir is studied.

Geological/engineering reservoir modeling pays off in the long term, as it enables the operator to evaluate alternate development scenarios, but it requires an up-front investment. This investment may be managed as a virtual enterprise, making world-class expertise available to independent operators.

The use of geological modeling tools requires extensive data preparation and quality control, as the tools do not observe, define, or correct data errors. However, these tools ultimately offer a valuable visual approach to data quality control and understanding.

Closely integrated geological and engineering modeling leads to a self-consistent reservoir model that honors all available data, including interpretive data, and more closely approximates reality, making it useful as a predictive tool. Well planning and design in an alternating water-oil stratigraphy environment is greatly enhanced by the use of a visual geomodeling environment. It is especially helpful in avoiding interference between wellbores and in steering to significant accumulations of hydrocarbons.

A preliminary scoping study has motivated the application of geostatistical methods to describe the distribution of reservoir properties in the model. Flow simulation modeling depends on such a model and will help guide the long-term management of this mature reservoir.

Acknowledgments

The authors wish to acknowledge the following Federal and State agencies that have funded this work: the U.S. Department of Energy, the Minerals Management Service of the U.S. Department of the Interior, and the California State Lands Commission. The authors also wish to acknowledge the contributions of R. G. Heck and Associates in developing the faulting interpretations for the Carpinteria field.

References

Murphy, M. B., and others, 1996, Advanced oil recovery from slope basin clastic reservoirs, Nash Draw Brushy Canyon pool, Eddy County, NM: First Annual Report to the U.S. Department of Energy, DOE Cooperative Agreement No. DE-FC-95BC14941.

Voskanian, M. M., and others, 1996, A simulation based reservoir management program: Society of Petroleum Engineers Western Regional Meeting, Anchorage, Alaska, May 22–24. SPE Paper No. 35703.

Geology and Exploration of the Manteo Prospect off North Carolina

Keith L. Meekins

U.S. Department of the Interior, Minerals Management Service, Headquarters, 381 Elden Street, Herndon, VA 20170

Abstract

The Manteo Prospect is located about 45 miles northeast of Cape Hatteras, North Carolina. It is a high-risk prospect with world-class potential. The 21-lease unit was approved by the Minerals Management Service (MMS) in May 1990. A suspension of operations (SOO) was issued in October 1992 by the MMS. Chevron was approved for an exploration permit for Block 510 while Mobil's plan for Block 467 was under appeal.

The Baltimore Canyon Trough and the Carolina Trough are the two large and deep sedimentary basins of the Atlantic Continental Margin. The Manteo unit is at the juncture of these two sedimentary basins.

The Manteo Prospect is interpreted as a reef with its overlying structural high on the seaward edge of a carbonate platform. The structure is approximately 30 miles long and 3 to 5 miles wide. The initial exploration well will be located at the highest point on the structure. Potential source rocks for the prospect are euxinic basinal shales and black micrite as well as interior lagoonal shales associated with the reef. The geothermal gradient projected from wells in the Baltimore Canyon Trough indicates that thermally mature sediments would be encountered below 12,000 feet in the vicinity of the Manteo Prospect. Mobil estimated that the Manteo Prospect may contain as much as 5 trillion cubic feet of dry natural gas.

A meeting was held between the State of North Carolina, MMS, and Chevron in February 1997 to discuss the proposal for the Manteo Prospect. An additional meeting held in September concentrated on drilling technology. A well could be drilled on Block 467 or Block 510 during the year 2000. Chevron has not decided which type of drilling vessel will be employed. The potential shorebase for operations is Morehead City, North Carolina.

Introduction

The Manteo Prospect is located about 45 miles northeast of Cape Hatteras, North Carolina. It is a high-risk prospect with world-class potential. Unitization of 21 lease blocks was approved by the Minerals Management Service (MMS) in May 1990 and resulted in the Manteo exploration unit. Originally, eight oil companies were participating in this unit—Mobil, Chevron, Amerada Hess, Conoco, Marathon, Oxy USA, Union, and Shell. All but 2 of the 21 blocks were leased in Sale 56, which took place in August 1981. The remaining two blocks were leased in Sale 78 held in 1983. Total bonuses for the unit exceeded $300 million, with Mobil bidding the highest value for a Sale 56 lease, more than $100 million for Block 467. The initial lease term was 10 years, but the leases were extended because of a suspension of operations (SOO) issued in October 1992 by the MMS pursuant to the regulations in 30 CFR 250.10.

Chevron received approval for an exploration permit in July 1982 to drill Block 510. In July 1988, Mobil discussed with MMS a seven-well exploration program in water depths ranging from 2,130 to 3,800 feet. The initial proposed wildcat was planned for mid-1993 on the crest of the prospect in Block 467. However, the plan of exploration was not approved, and a decision on Mobil's appeal has not been made by the Secretary of Commerce. Additionally, on July 14, 1997, the Court of Federal Appeals determined that Mobil and

Marathon were entitled to restitution of all their bonuses paid for five leases off North Carolina, of which four are part of the Manteo Unit including Block 467. The Federal Government has appealed this decision. The appeal brief is due in early December 1997.

Regional Geology

The Baltimore Canyon Trough and the Carolina Trough are the two large and deep sedimentary basins of the Atlantic continental margin. The margin consists of a wedge of Mesozoic and Cenozoic sediments overlying a zone of deeply buried fault blocks and grabens. These sediments are more than 40,000 feet thick in the deep basins and are separated by the breakup unconformity. The sedimentary wedge has been tested by 32 wildcats and 2 stratigraphic test (COST) wells in the Baltimore Canyon Trough. The Carolina Trough is untested. The Manteo exploration unit is at the juncture of these two sedimentary basins (fig. 1).

Manteo Geology and Hydrocarbon Potential

A thick Jurassic–Early Cretaceous carbonate trend exists as a buried ridge beneath the seaward margin of both the Baltimore Canyon and Carolina Troughs. This ridge is prominent below the Manteo Unit and is interpreted as a reef on the seaward edge of a carbonate platform. This reef with its overlying structural high is the Manteo exploration target. The reef was tested farther north in the Baltimore Canyon Trough in 1983–84. Shell Offshore Inc. found good reservoir facies but no significant oil or gas.

A near top Jurassic horizon identified in the nearest deep well (Esso Hatteras Light No. 1, T.D. 10,054 feet) onshore at Cape Hatteras marks the top of the prospective interval and was tied to the Manteo Prospect seismic grid. No oil or gas shows were recorded in this well. Seismic surveys were conducted in the Manteo area in the late 1970’s and early 1980’s by Digicon and Petty Ray. The structure map on this horizon shows a large north-northeast-trending structure approximately 30 miles long and 3 to 5 miles wide (fig. 2). The top of the reservoir is estimated at a depth of 11,300 feet and closes on the 12,700-foot contour, giving 1,400 feet vertical relief.

A proposed exploration well on Block 467 will be located at the highest point on the structure and is expected to penetrate reservoir rocks composed of reefal boundstones and grainstones. Primary porosity is thought to have been enhanced by a period of subaerial weathering during the early Cretaceous. Following this period of exposure, the reef was buried by a thick wedge of Cretaceous and Recent fine-grained sediments that formed an effective seal over this combination structural/stratigraphic trap. The stratigraphic depth section of the Manteo Prospect is shown in fig. 3.

Potential source rocks for the Manteo Prospect are euxinic basinal shales and black micrite as well as interior lagoonal shales associated with the shelf-edge reef. An Early Cretaceous shale is thought to be widespread in the deep ocean basin and was encountered in the JOIDES No. 105 research hole drilled about 300 miles to the east of the prospect. The geothermal gradient projected from wells in the Baltimore Canyon Trough indicates that thermally mature sediments would be encountered below 12,000 feet in the vicinity of the Manteo Prospect. Geochemical analyses of the Early Cretaceous shale as well as lagoonal shales encountered in Atlantic OCS exploration wells indicate that any hydrocarbon source rock for this prospect would be far more likely to generate gas rather than oil. Faults and unconformities in the vicinity of the prospect would provide vertical and horizontal migration paths for the hydrocarbons.

Mobil estimated that the Manteo Prospect may contain as much as 5 trillion cubic feet (Tcf) of dry natural gas. This estimate would place the prospect on the border between a major (1–5 Tcf) and a giant (5–50 Tcf) field. The MMS geologists concluded that while optimistic, that amount of gas could be present given the size and reservoir characteristics of the prospect.

Chevron’s Proposal

In February 1997, a meeting was held in North Carolina between the State, MMS, and Chevron to discuss the proposal for the Manteo Prospect. An additional presentation made in September concentrated on deep-water drilling technology.

Chevron plans to drill an exploratory well on Block 467, similar to the Mobil proposal for a well on Block 510. The two sites are about 9,000 feet apart. Because of the expense of drilling the Manteo Prospect, if it is a dry hole, the company will not drill any other wells. The well will be drilled to a depth of at least 14,000 feet and 2,500 feet of water using nonpollutant drilling muds composed of seawater and enhanced

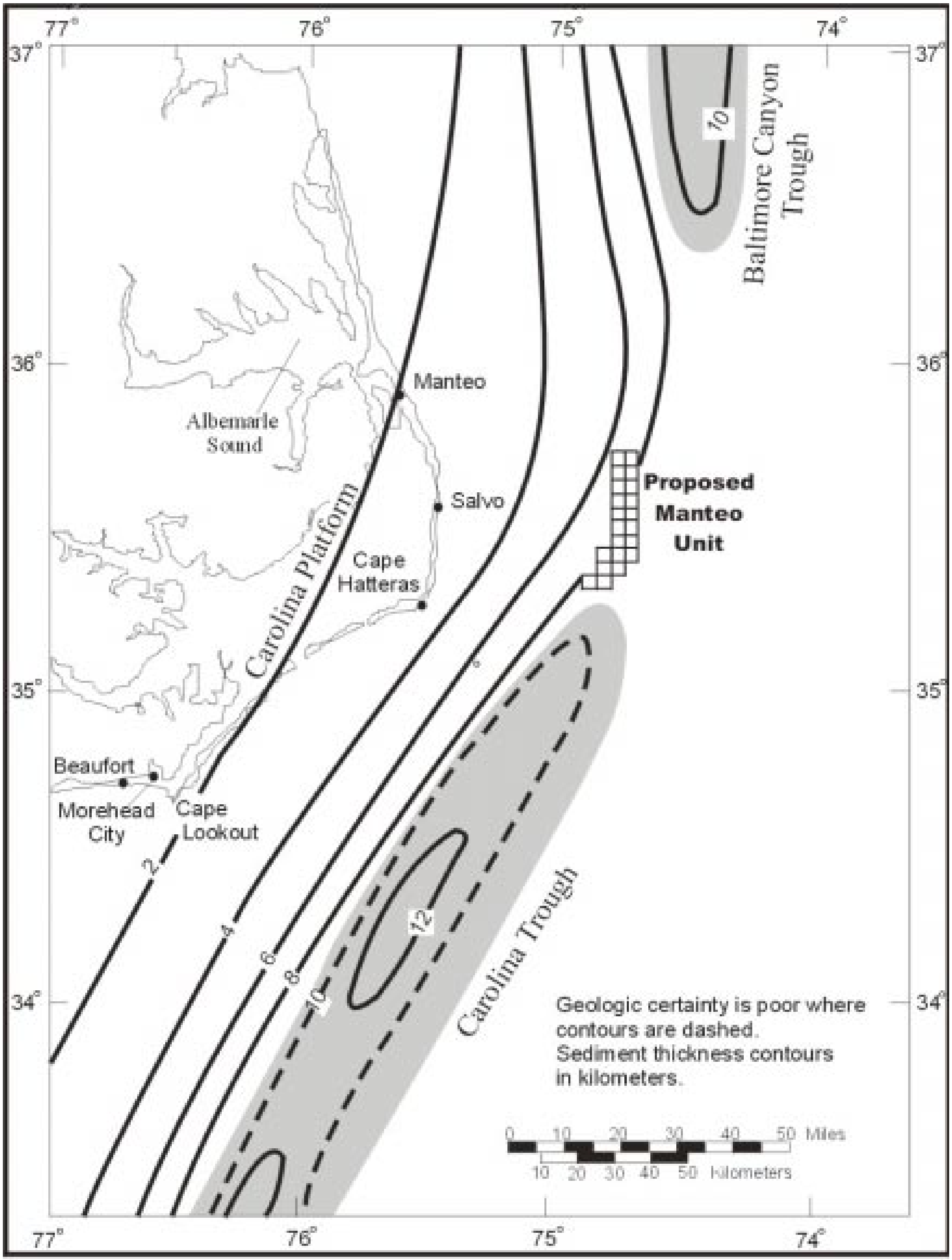


Figure 1. Location of the Manteo Unit on the arch between the Baltimore Canyon Trough to the north and the Carolina Trough to the south.

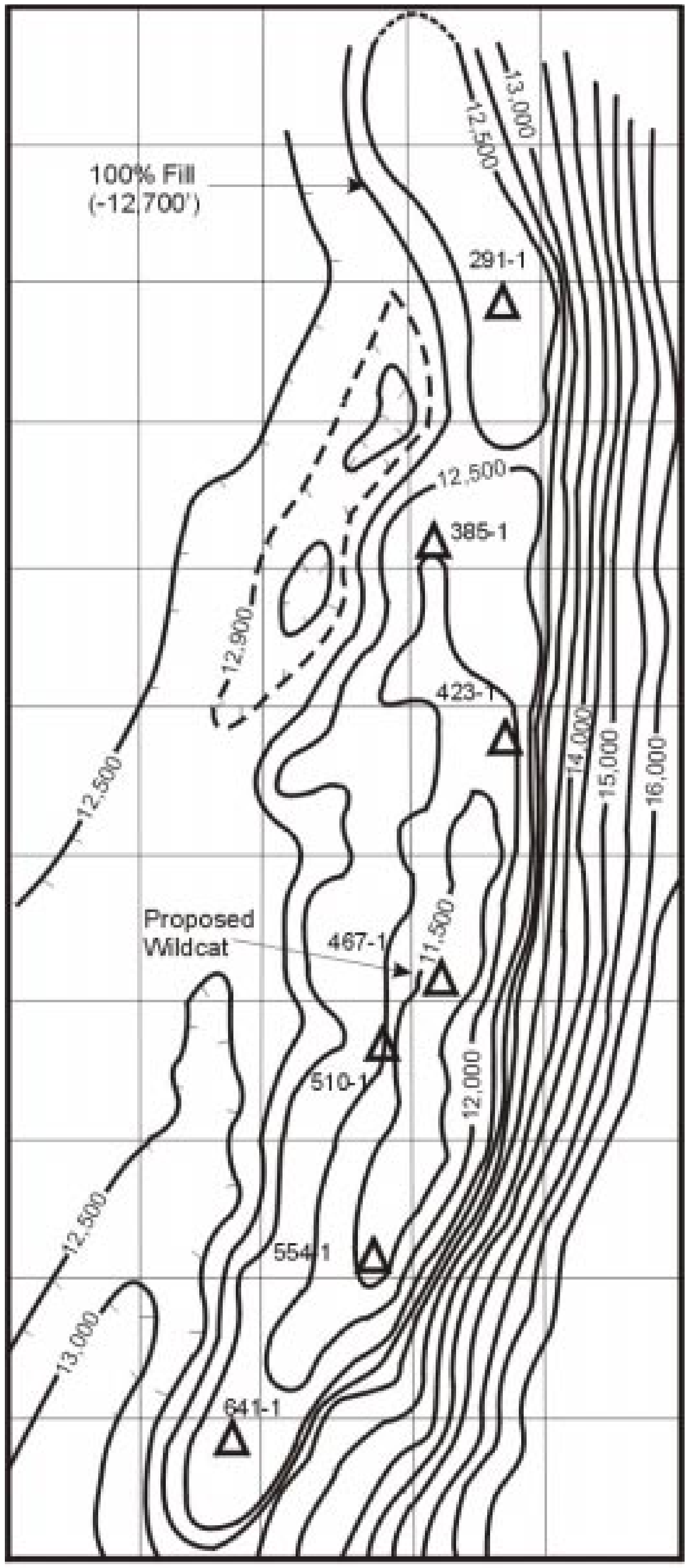


Figure 2. Manteo Prospect near top of Jurassic with proposed wildcat and future wells.

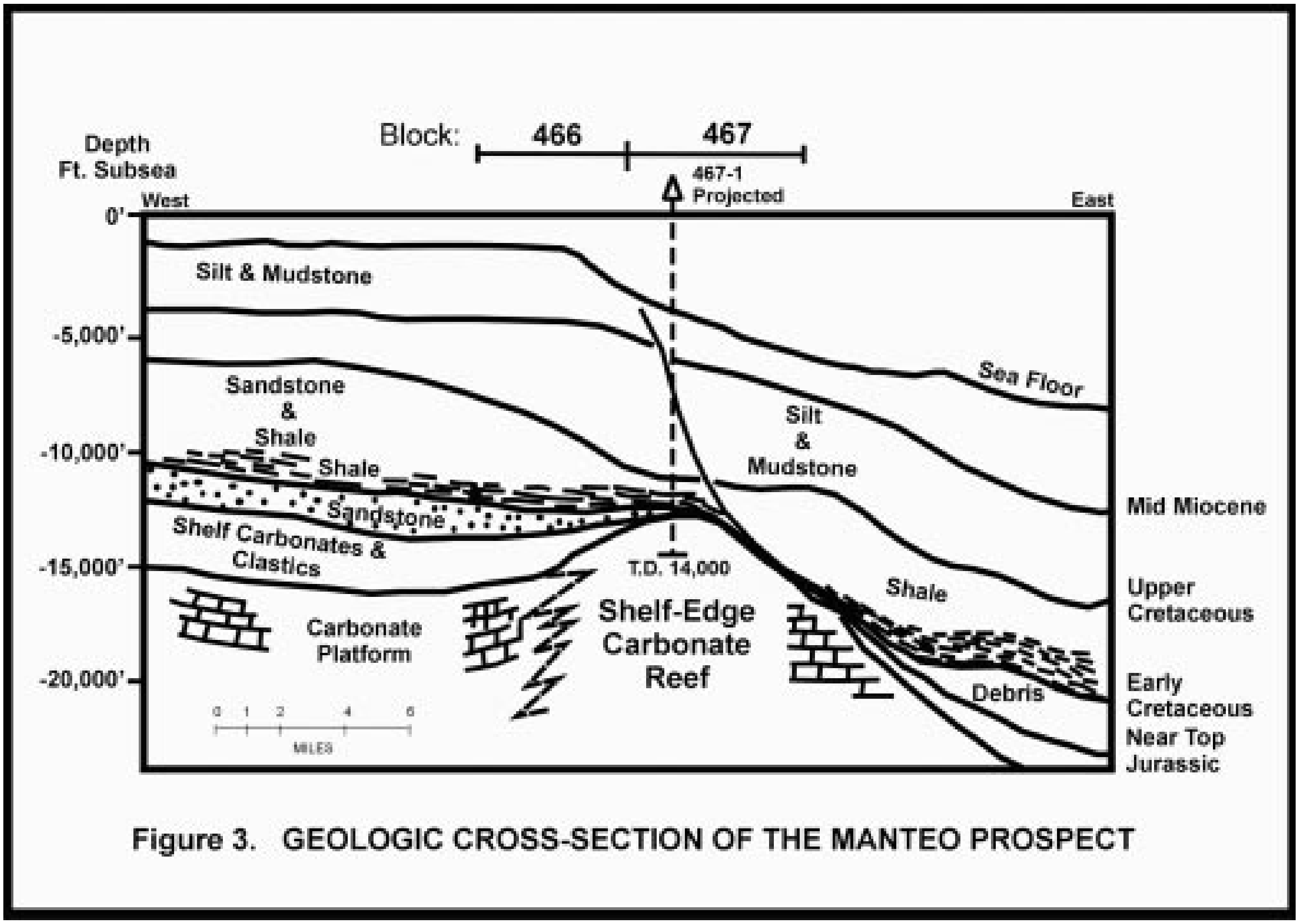


Figure 3. Geologic cross section of the Manteo Prospect.

polymer muds. Fields in corresponding water depths have been explored and developed in the Gulf of Mexico (table 1). Furthermore, Chevron has experience drilling in deep water and high-current environments. The company hasn't decided which drilling vessel will be employed. Either a dynamically positioned drillship or moored semisubmersible will be used to drill the well. Chevron hopes to drill during the year 2000, depending on rig availability and permitting. It is estimated to take 100 to 115 days to complete the well. The potential shorebase for operations is Morehead City, North Carolina. No decisions have been made about transportation, processing, or landfall for any hydrocarbons that might be discovered and produced. The company believes that the first well could test 600 million barrels of oil equivalent (about 3.36 billion cubic feet of gas). However, Chevron estimates that there is only a 7-percent chance of finding hydrocarbons and only a 2-percent chance of their being commercial.

In early November 1997 the Governor of North Carolina issued an executive order stating that Chevron must strive to avoid injuring environmentally sensitive areas and must repair any damage the company inflicts. A spokesman for Chevron said that he thought that is something they would want to do anyway.

Table 1. Deep-water fields in the Gulf of Mexico in water depths greater than 2,500 feet.

Project name	Area	Block	Depth (ft)/(m)	Operator
Coulomb	MC	657	7520/2292	Shell Offshore
King's Peak	DC	133	6530/1990	Amoco
(no prospect name)	AV	575	6220/1896	BP Exploration
Mensa(SS)	MC	731*	5376/1639	Shell Offshore
Diana	EB	945	4645/1416	Exxon Corporation
Fuji	GC	506	4243/1293	Texaco
Ursa	MC	854	4020/1225	Shell Offshore
Vancouver	GC	254	3780/1152	Shell Offshore
(no prospect name)	VK	688	3737/1139	Shell Offshore
Gemini	MC	292	3393/1034	Texaco
Allegheny	GC	254	3225/983	Enserch Exploration
Ram Powell	VK	956*	3218/981	Shell Offshore
Marlin	VK	915	3200/975	Amoco
Mars (TLP) (SS)	MC	807*	2940/967	Shell Offshore
Auger (TLP)	GB	426*	2861/872	Shell Offshore
Brutus (SS)	GC	158	2841/866	Shell Offshore
Troika	GC	244	2672/814	BP Exploration
Genesis (SPAR)	GC	205	2600/792	Chevron
Bison	GC	166	2518/767	Exxon Corporation

FPS = Floating Platform System; TLP = Tension Leg Platform; SS = Subseas System;
SPAR = unit consisting of single point buoy tanker loading and mooring platform with storage tank

AV = Atwater Valley; DC = Desoto Canyon; EB = East Breaks; GB = Garden Banks; GC = Green Canyon;
MC = Mississippi Canyon; VK = Viosca Knoll
*Producing discovery

Non-Energy Resources, Connecticut Coastal Waters, Year-Nine and -Ten Activities

Ralph S. Lewis, Mary L. DiGiacomo-Cohen, Nancy Friedrich Neff, and Richard Hyde

Connecticut Department of Environmental Protection, Long Island Sound Resource Center, UCONN-Avery Point, 1084 Shennecossett Road, Groton, CT 06340-6097

Abstract

The Connecticut effort in year nine of the Continental Margins Program concentrated on a 13.6 square-mile area south of the Housatonic River. This area was chosen for a side-scan sonar survey because it lies on and adjacent to the bathymetric expressions of two fairly large, subcropping, potential sources of coarse material. Previous seismic work in the area indicated that outcrops or subcrops of these potential source deposits could be delineated using their bathymetric expression. Owing to the limited resolution of the seismic data, a correlation between bottom type and underlying source deposits could not be made with the seismics alone. Results from the November 1993 side-scan survey show that although the source deposits have discernible bathymetric expressions, they are not cropping out as much as expected. As a result, bottom type is not necessarily determined by subcropping deposits in this particular area.

Year-ten work was concentrated in Fishers Island Sound, where three areas of potential interest for near-shore gravel resources had previously been identified. These areas were surveyed, during the spring of 1996, using the RoxAnn Seabed Classification System. A small video camera and a Van Veen grab sampler were used to calibrate and verify the RoxAnn data. Although previous sampling had indicated the presence of gravel or gravelly sediment in all of the survey areas, the RoxAnn results showed less gravel than anticipated. Vibrant eelgrass beds and other habitat indicators were detected in all of the survey areas. Given the variable sediment results, and the high habitat potential of the areas surveyed, the likelihood of developing a sand and gravel supply from the near shore of Fishers Island Sound appears quite low.

Surficial Sediments along the Inner Continental Shelf of Maine

Joseph T. Kelley, Stephen M. Dickson

Maine Geological Survey, 22 State House Station, Augusta, ME 04333-0022

Abstract

Through ten years of support from the Minerals Management Service–Association of American State Geologists' Continental Margins Program we have mapped along the Maine coast, seaward to the 100 m isobath. In all, 1,773 bottom sample stations were occupied, 3,358 km of side scan sonar and 5,011 km of seismic reflection profiles were gathered. On the basis of these data, a surficial sediment map was created for the Maine inner continental shelf during the Year 8 project, and cores and seismic data were collected to evaluate sand thickness during Years 9 and 10.

Sand covers only 8% of the Maine shelf, and is concentrated seaward of beaches off southern Maine in water depths less than 60 m. Sand occurs in three depositional settings: (1) in shoreface deposits dynamically connected to contemporary beaches; (2) in submerged deltas associated with lower sea-level positions; and (3) in submerged lowstand shoreline positions between 50 and 60 m.

Seismic profiles over the shoreface off Saco Bay, Wells Embayment and off the Kennebec River mouth each imaged a wedge-shaped acoustic unit which tapered off between 20 and 30 m. Cores determined that this was sand that was underlain by a variable but thin (commonly < 1 m) deposit of estuarine muddy sand and a thick deposit of glacial-marine mud. Off Saco Bay, more than 55 million m^3 of sand exists in the shoreface, compared with about 22 million m^3 on the adjacent beach and dunes.

Seaward of the Kennebec River, a large delta deposited between 13 ka and the present time holds more than 300 million m^3 of sand and gravel. The best sorted sand is on the surface nearshore, with increasing amounts of gravel offshore and mud beneath the surficial sand sheet. Bedforms indicate that the surficial sand is moved by waves to at least 55 m depth.

Seaward of the Penobscot River, no significant sand or gravel was encountered. Muddy estuarine sediments overlie muddy glacial-marine sediment throughout the area offshore area of this river. No satisfactory explanation is offered for lack of a sandy delta seaward of Maine's largest river.

Lowstand-shoreline deposits were cored in many places in Saco Bay and off the Kennebec River mouth. Datable materials from cores indicated that the lowstand occurred around 10.5 ka off the Kennebec. Cores did not penetrate glacial-marine sediment in the lowstand deposits, and seismic profiles were ambiguous about the vertical extent of sand in these units. For these reasons, no total thickness of sand was determined from the lowstand deposits, but given the area of the surficial sand, the volume is probably in the hundreds of millions of m^3.

Ten Years of Studies on Maryland's Inner Continental Margin and Coastal Bays

Randall T. Kerhin, Robert Conkwright, and Darlene Wells

Maryland Geological Survey, Kenneth N. Weaver Building, 2300 St. Paul Street, Baltimore, MD 21218

Abstract

During the past several years of the Association of American State Geologists–Minerals Management Service Continental Margins Program, the Maryland Geological Survey has mapped the surficial sediments (Kerhin and Williams, 1987; Kerhin and Toscano, 1988; Kerhin, 1989), geological framework (Toscano and Kerhin, 1990; Toscano et al., 1989; Toscano and York, 1992; Wells, 1994), and heavy mineral concentrations (Wulff 1991) by investigating the sedimentological, paleontological, stratigraphical, and geophysical character of the inner continental shelf (AASG–MMS Years 1–7). In the eighth and ninth years, the studies were expanded to include the coastal bays of Assawoman, Isle of Wight, Sinepuxent, and Chincoteague. These coastal bays mark the leading edge of the present transgression and overlie sedimentary sequences that link the onshore to the offshore geology and its sand resources.

Shallow, high-resolution subbottom profiles reveal several paleochannel systems in each of the major streams, St. Martin River, Greys Creek, and Roy Creek, that drain into the coastal bays. Extensions of these paleochannels have been identified in the subbottom records offshore of Fenwick Island (Ocean City, Maryland). A vibracore in the Roy Creek paleochannel penetrated a peat layer within the channel that yielded a radiocarbon date of 5,570 +/- 70 yr. Reconstruction of the paleodrainage systems offshore of the Fenwick Island and in the coastal bays suggests that a paleo-interfluve corresponding to the early Holocene drainage divide separated the Delaware River system from the St. Martin River, which is projected to flow into the Susquehanna River system.

The sediments in the coastal bays are predominately sand along the edges of the bay shoreline, becoming finer (clayey silts) toward the middle. Trace metal data indicate that anthropogenic activities have a greater influence on trace metal distribution, particularly copper and zinc, in the northern bays than in the southern bays.

Introduction

The inner continental shelf of Maryland (fig. 1) has been extensively studied in terms of ongoing nearshore processes and resulting seafloor morphology. Most of the previous research had been devoted to linear sand ridges genesis and evolution, whereas less attention had been paid to the underlying stratigraphic sequence and its relationship to late Quaternary sea-level fluctuations. Much of the previous knowledge of the Maryland shelf, both morphological and stratigraphic, has been advanced by studies investigating the linear ridges system as source of sand and gravel.

Because the linear sand ridges have been the focus of studies for potential sand resources, significant portions of the Maryland Shelf have not been mapped or evaluated as to the subsurface geology, additional potential sand resources, or economic value of the mineral resources. This paper is a summary of 10 years of activity, sponsored by the Association of American State Geologists and the Minerals Management Service, that investigated the subsurface geology, surficial sediments, and economic potential of the minerals. Years 1 to 4 mapped the near-surface Quaternary geology, establishing the geologic framework on which to base the economic evaluations. Years 5 and 6 identified the heavy mineral potential of the surficial and subsurface sediments. Years 7 to 9 continued the framework studies in areas near the Maryland–Delaware line and in the coastal bays behind the barrier

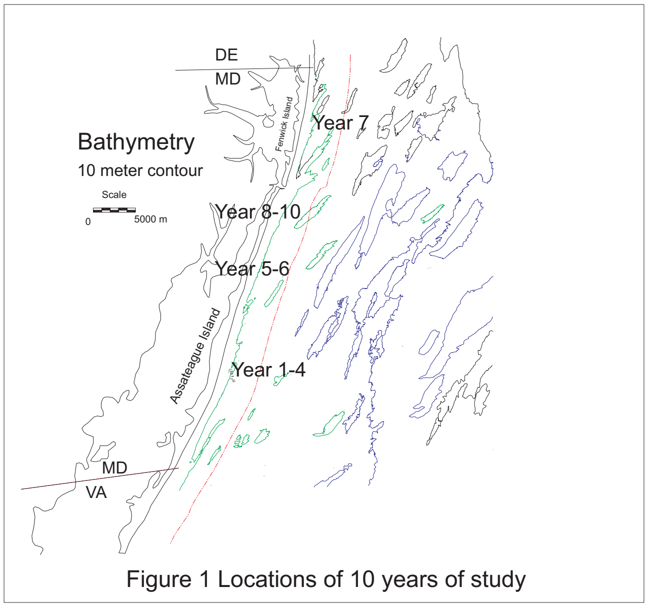


Figure 1. Location of Maryland's inner continental margin.

islands. Year 10 was spent developing a core repository and database for the all the vibracores collected in 10 years of effort. Also included in the core repository were vibracores taken by various State and Federal agencies working on the sand resources of the Maryland shelf.

Years 1 to 4—Quaternary Stratigraphy

Five distinct stratigraphic units are identified for the Maryland inner shelf from high-resolution seismic-reflection profiles, vibracores, amino acid racemization age determinations, and paleontology. The lowermost unit, T1 (Tertiary), lies below ~21 meters (MSL) at the shoreface and is characterized by steep internal reflectors and extensive channeling near its top. Unit T1 is truncated by a persistent high-amplitude, essentially horizontal reflector (horizon M1), which is coincident with the Tertiary-Quaternary unconformity immediately onshore. Overlying M1 are approximately 10 meters of units (Q1–Q2) of concordant strata with parallel to subparallel bedding. Horizon M2, a less prominent reflector, is associated with channeling and sand bodies on the same scale as modern shelf shoals. The 6-meter section above M2 consists of a dewatered fossiliferous clayey silt (Q2), estimated from amino acid racemization data to be of last interglacial, oxygen-isotope stage 5 (128–75 ka) age. This mud sequence contains at least four distinct paleoclimatic zones as defined by ostracode assemblages, each representing particular paleoclimatic-oceanographic conditions. A warmer-than-present sand zone (Zone 1) occurs below -22 meters MSL, a colder-than-present zone (Zone 2) occurs from -22 to -20 meters MSL, and a cool zone (Zone 3) occurs above -20 meters. A fourth zone (Zone 4), representing a warm interval, is tentatively identified above Zone 3; this zone appears to become more prominent southward in the study area. All ostracode assemblages from unit Q2 were representative of normal marine salinities, indicating an open-shelf depositional environment. The Q2 mud is interpreted as a regressive, shallow shelf deposit of oxygen-isotope substages 5d–c, with warmer climate sand below representing the transgressive portion of substage 5e.

Unit Q1, below horizon M2, consists of shelly sands at its top meters and is interpreted to represent remnants of transgressive shelf sands of pre-Illinoisan (possibly oxygen-isotope stages 7 and/or 9) age. Incised into units Q2 and Q1 and numerous paleochannels, unit Q3 fills an extensive ancestral channel and tributary system, marked by reflectors M3 and M1, traceable to the present St. Martin River estuary, that was incised into the shelf during the most recent Pleistocene (Wisconsin) glaciation (oxygen-isotope stages 4, 3, and 2). Iron-stained gravels and fluvial sandy silts barren of microfauna have been cored in this unit. The channels cut during the Wisconsin probably contain continuous fluvial-estuarine tidal-channel-fill sequences representing the oxygen-isotope stage 2-1 transition. The cored, upper portions of these channel fills contain radiocarbon-dated early Holocene (unit Q4) estuarine deposits. Transgressive, leading-edge coastal deposits (lowland swamps) of unit Q4 cut into and overlap portions of unit Q2 and have degrees of preservation below the shoreface ravinement unconformity that are demonstrably related to rates of sea-level rise and pretransgression topography. No Holocene back-barrier remnants were found within a distance of 40 km from shore or between depths of -12 and -22 meters MSL. Modern trailing-edge transgressive shelf shoals (unit Q5) discontinuously cap the sequence.

These data indicate that oxygen-isotope substages 5d–a represent a unique, relatively high, sea-level stand of sufficient duration (40 ka) to deposit a thick regressive shelf mud. The Holocene transgression is represented only by remnants in truncated channels or by relict facies preserved far offshore owing to initially high rates of sea-level rise. From approximately 7,000 yr BP to the present, the Holocene depositional record has mostly been obliterated by shoreface ravinement processes in connection with a slow rate of sea-level rise.

Preservation of late Holocene transgressive deposits of barrier island systems seaward of barrier strandlines on the mid-Atlantic coastal plain should thus be rare and topographically confined. Remnants of trailing-edge shelf sands are most likely the only transgressive deposits preserved on the shelf during intervals of slow sea-level rise. Major preserved shelf sequences are more likely to be seaward-thickening, finer grained sediments deposited during lone, low-energy, regressive phases of interglaciations. Consequently the mud sequence of unit Q2 is probably unique, at least in terms of the Pleistocene glacial/interglacial record on the mid-Atlantic continental shelf.

Years 5 and 6—Economic Minerals

The fifth and sixth years reported on the economic minerals of the surficial and cored sediments. The purposes of this phase of the project were to initiate work on a database for heavy mineral (HM) assemblages in continental shelf sediments off the Delmarva Peninsula and to fit these data into a regional study being done by adjacent states along the Atlantic coast.

A total of 30 vibracores from two different surveys of the same study area off the Maryland Inner Continental Shelf were split into 105 smaller segments. Mineral types and abundances, weight percent of general size fractions, and HM content were analyzed and calculated for each of these segments. Individual mineral species analyzed for are, in decreasing order of abundance, ilmenite, garnet, pyroboles, zircon, epidote, leucoxene, aluminosilicates, staurolite, rutile, magnetite, monazite, and tourmaline, the first three composing an average of 58.92 percent of total heavy minerals (THM). Segments were then combined to yield data for each entire core. THM content for the segments ranges from 0.15 to 2.67 weight percent, with values for the cores showing a narrower range of 0.16 to 1.80 weight percent (average = 0.85 weight percent). These results are lower than those shown in similar studies in New Jersey, New York, and South Carolina but tend to be slightly higher than results from studies in Florida. Weight percent of economic heavy minerals (EHM) ranges from 0.05 to 0.67 for the segments, whereas the cores show a range of 0.06 to 0.54 weight percent EHM. However, this EHM portion accounts for 15.00 to 41.14 percent of the THM for each segment and 18.24 to 39.27 percent for the cores (averaging = 30.6 percent) (table 1).

The New Jersey Geological Survey presents a model that predicts high concentrations of THM and EHM in areas of high textural and chemical maturity, high zircon-tourmaline-rutile (ZTR) index, and low labile heavy minerals (LHM) index, suggesting near-shore, midshelf environments. Cumulative data for both years of this study reveal strong positive relationships between THM and EHM with ZTR and LHM, with the year 5 cores showing a more consistent pattern. The ZTR minerals make up only 2.83 percent of the THM content but 8.5 percent of the total EHM, whereas the labile minerals composed 34.77 percent of the THM content but none of the EHM. Therefore, a high ZTR index might reflect the EHM content, but a high LHM index will not have any correlation with it. Similarly, increases in LHM content will only be shown in higher THM, and not in EHM. The New Jersey samples are apparently higher in ilmenite-leucoxene aluminosilicates or ZTR minerals.

The samples were magnetically subdivided into six fractions, and the percentage of the total EHM was calculated for each magnetic fraction. The 203–205 magnetic fractions represent both the most magnetic fractions and the highest percentage of the total EHM, reflecting the high amounts of ilmenite in the samples. The 206–207 fractions had generally low amounts of the total EHM.

Two mineralogic maturity indices (ZTR and LHM) were compiled in an attempt to correlate the THM and EHM abundances with position offshore, sediment type, and the indices themselves. Data from this study, when combined with those from similar studies along the Atlantic Coast, should provide a large enough database for predictive value.

HM concentrations calculated for the combined segments of lithologic similarity range from 0.15 to 4.74 weight percent. However, HM concentrations using the combined data for each entire core have a narrower range from 0.15 to 1.50 weight percent. These results are lower than those shown in similar studies in New Jersey, New York, and South Carolina, but they tend to be slightly higher than results from studies in Florida. Comparisons at this stage with other studies

Table 1. Mineral abundances of different indices (in weight percent).

Index	Mineral	Year 4	Year 5	Years 4 and 5
LHM	magnetite	0.01	0.17	0.10
	garnet	16.36	21.75	19.44
	pyrobole	22.18	10.72	15.64
	epidote	4.38	1.24	2.59
ZTR	zircon	2.44	3.07	2.80
	tourmaline	0.02	0.00	0.00
	rutile	0.43	0.00	0.19
EHM	ilmenite	19.86	26.84	23.85
	leucoxene	1.15	3.36	2.41
	rutile	0.43	0.00	0.19
	zircon	2.44	3.07	2.80
	monazite	0.00	0.04	0.02
	ky-and-sill	2.10	1.20	1.59

must take into consideration that the weight percentage of recovered HM in each sample is calculated using only the spiral heavy concentrate and does not represent a total recovered HM percentage.

Year 7—Quaternary Framework Off Ocean City, Maryland

For the seventh year of the MMS–AASG Continental Margins program, the Maryland Geological Survey reexamined geophysical records and lithological data collected in the nearshore off Ocean City, Maryland. More than 300 kilometers of high-resolution seismic profile records and lithological logs and textural data from 163 vibracores were reexamined. The seismic profiles and vibracores, collected primarily in the vicinity of nine shoals in the study area, were originally analyzed by the U.S. Army Corps of Engineers to locate and assess beach fill borrow areas for the Ocean City Beach Replenishment Project.

Information and textural data from more than 500 sediment samples taken from the 163 vibracores were systematically compiled and correlated with seismic records. The textural data from sediment samples, most of which represent modern shoal sands, show that the shallow shelf sediments consist primarily of medium to fine sand. The mean grain size of the samples tends to decrease with depth below mean sea level. Sediments become coarser in the northerly and offshore direction. Although gravel is not a major component in the sediment, vibracores collected in the northern study area contained higher gravel contents.

Vibracores penetrated at least three distinct depositional units seen in seismic records that correlate closely with those identified by previous studies (years 1–4). The oldest unit penetrated by the cores is Pleistocene in age, assumed to be equivalent to oxygen isotope stage 5 (Q2) depositional unit. Seismic profiles show this unit extending throughout the study area and exposed along the sea floor in the intershoal trough areas. A persistent reflector, interpreted to be the M2 horizon that defines the lower boundary for the Q2 unit, is mapped between -26 and -16 meters. The Pleistocene unit is heterogeneous in texture, ranging from sequences of interbedded green to gray muddy sands and fine sand, to gravelly sands, and appears to coarsen in the northerly direction. The Q2 sediments sampled in the vicinity are coarser than Q2 sediment elsewhere. Most the cores penetrated poorly sorted medium sands with gravel below the projected A1 horizon. This coarser fraction may represent a facies change in the Q2 unit. Toscano and others (1989) reported a lower (basal) sand facies within the Q2 unit, interpreted to be an early stage 5 (5e) transgressive sequence. Toscano (1992) hypothesized this sandy facies represents trailing-edge shelf sand ridges correlative to the stage 5e barrier islands (including Ironshire Formation and Bethany Paralic Unit) deposited at the peak interglacial sea level. The lower Q2 facies is stratigraphically above the M2 horizon, which becomes increasingly shallow northwestward. Therefore, lower Q2 unit sediments are more likely to be penetrated by the vibracores collected in the northern part of the study area. Additional analyses (including ostracode studies) of the Corps' vibracores may permit dating these sandy Q2 sediments.

Incised into and overlying the Q2 unit, the Q4 depositional unit is found to be fairly extensive, but restricted to the nearshore zone (landward of the -10-meter isobathymetric contour). A ^{14}C date of 5737 +/-70 yr B.P. (5730-yr halflife) was obtained from a peat sample at -14.32 m National Geodetic Vertical Datum (NGVD) from core 4-31. This radiocarbon date is consistent with the sea-level curve for the Delmarva coast. These Q4 deposits are interpreted to be largely leading-edge paralic sediments (lagoonal, fringing marsh) and appear to be with an earlier fluvial channel thought to be extensions of Roy and Dirickson Creeks. There is evidence that paralic deposits are fairly widespread beneath the shoreface. Orientation and geometry of the channels and their relative position to other offshore channels (mapped by Toscano and others, 1989) suggest that they were part of a tributary system of the ancestral St. Martin River. The confluences of the tributaries with the St. Martin River were located to the south. Maximum depths of the channels within the study area are -26 meters. Most of the paleochannels are fairly shallow when compared with the ancestral channels of Indian River and Love/ Herring Creeks, mapped along Delaware. Thalweg depths of these Delaware paleochannels exceed 40 meters within 5 kilometers of the present shoreline. These deeply incised channels are most likely a result of headward erosion stemming away from the Delaware River. During Wisconsinan time, the Delaware River had a much lower base level owing to increased discharge of glacial meltwater. Conversely, gradients of Greys and Roy Creeks were probably less severe because they flowed southeast across a more gently sloping shelf. As a result these tributaries generally have shallower thalweg depths and broader channels.

As the Holocene transgression continued, the fluvial channels became flooded and estuarine sediments were deposited. Continued sea-level rise resulted in the estuarine facies expanding upward and outward from the central channels. Back-barrier bays similar to the present-day Isle of Wight and Assawoman Bays may have formed. Continued transgression to present-day levels eventually exposed the Q4 deposits to shoreface erosion. If sea level continues to rise at the present rate, shoreface erosion is expected to scour much of the Holocene sediments except for those preserved in the deeper fluvial channels. Toscano and others (1989) found no evidence of widespread leading-edge Holocene lithosomes between 5 and 13 kilometers from shore, except for those preserved as fill in paleochannels. They attributed this lack of preserved leading-edge Holocene deposits to the slowing rate of sea-level rise between 7 and 2 ka, which resulted in deeper shoreface scour and the removal of the back-barrier deposits.

The exact location where the St. Martin paleochannel crosses under Fenwick Island remains unresolved. On the basis of onshore well data, Toscano and others (1989) projected that the channel extends under the southern end of Ocean City just north of the inlet. However, additional seismic data have not confirmed this location. A combination of shallow waters depth, relatively hard sea floor (that is, sandy bottom), and extensive sandy shoals in this area contributes to the attenuation of most acoustic signals. The St. Martin paleochannel may not be discernible in the records with currently available acoustical profiling equipment.

Years 8 and 9—Sediments in the Coastal Bays

For the eighth year of the program, the Maryland Geological Survey conducted a sedimentological and geochemical study of the sediments of Isle of Wight and Assawoman Bays. The objectives of the study were to delineate the shallow stratigraphic sequence of the coastal bays, relating the stratigraphy to late Quaternary sea-level fluctuations, and to document the geochemical character of the shallow sediments, providing preliminary base-line data for comparison for future studies.

Thirty-three kilometers of 7 kHz seismic profile surveys and 11 sediment cores were collected. Surficial sediments grab samples were collected at three other stations. The cores were X-rayed, described, and sampled at various intervals. A total of 96 sediment samples were analyzed for texture (sand, silt, clay contents), water content, total nitrogen, carbon, and sulfur concentrations, and six metals: Cr, Cu, Fe, Mn, Ni, and Zn.

Seismic records feature several shallow paleochannels defined by a very strong reflector. Depths to the reflector were mapped, allowing the structure of a pretransgression surface beneath the bays to be contoured. The surface reveals a simple paleodrainage system that is traceable to the present tributaries. Maximum depths of the paleochannels are approximately 8 meters below mean sea level. Thalweg depths, particularly for the St. Martin paleochannel, are much shallower than previously projected on the basis of well log and bridge boring data.

Concentrations for nitrogen, carbon, and sulfur for most of the sediments are within ranges expected for marine sediments and are comparable with those found in the Chesapeake Bay and other Atlantic coast estuaries. Nitrogen contents range from 0 to 1.39 percent, averaging 0.22 percent; carbon contents range from 0.02 to 30 percent, averaging 2.8 percent; and sulfur contents range from 0 to 5.28 percent, averaging 1.05 percent. Nitrogen, carbon, and sulfur contents are strongly related to the texture of the coastal bay sediments, higher values being associated with finer grained sediments.

Metal concentrations are within the ranges of other coastal bays not subject to heavy industry. The behavior of the metals was determined by two methods. The first method utilized enrichment factors referenced to average continental crust (Taylor, 1964). Enrichment factor values for Cu, Mn, and Ni are less than 1 for most of the sediments, suggesting that the reference material used may not represent the coastal bay sediments. Nevertheless, enrichment factors indicate that the upper 20 to 30 cm of sediment column is enriched with Cr, Cu, Ni, and Zn compared with sediments deeper than 30 cm. The metal concentrations in the deeper sediments are interpreted to represent historical or background levels.

The second technique employed to assess metal concentrations in the sediments correlated metal content with the grain-size composition. Sediment deeper than 30 cm were used to obtain the relationship between texture and metal contents to determine background metal concentrations. Background levels were calculated for all samples and compared with measured levels, obtaining variation factors. Variation factors showed the same trends in the behavior of Cu and Zn as did the enrichment factors.

On the basis of the textural analyses of 171 surficial sediment samples, the average textural composition of the bay bottom sediments is 54 percent sand, 28 percent silt and 18 percent clay. The sand to mud (sand + clay components) ratio is nearly 1:1. Sand sediments (that is, sand > 75 percent), which cover approximately 44 percent of the bottom of the two bays, are found primarily along the eastern side of the bays. The sands range in thickness from several centimeters to more than 8 meters, gradually thinning toward the west. Clayey silts, which cover approximately 14 percent of the study area, are found in the tributaries and in isolated pockets associated with marshy shorelines. Silty clays are restricted to upstream areas of the tributaries. Silty sand, sandy silt, and sand-silt-clay are found in isolated pockets along marshy shorelines and along the boundaries between sand and clayey silts. On the basis of seismic data collected during the previous year's study, the clayey silt deposits are estimated to be as much as 5 meters thick in the area east of the mouth of St. Martin River (due south of Isle of Wight Bay). This area corresponds to the thalweg of the St. Martin paleochannel.

Total carbon contents measured in the surficial sediments range from 0 to 9.86 percent with a mean value of 2.08 percent. Correlation analysis reveals strong associations between carbon content and percent water ($r = 0.89$), and carbon content and clay ($r = 0.88$), indicating that carbon content is associated with the fine-grained fraction. In general, the carbon content distribution closely follows the sediment distribution. The highest carbon values (>7 percent) were obtained from silty clay sediments collected in the upstream areas of Roy and Greys Creeks and St. Martin River.

Nitrogen contents in surficial sediments range from 0 to 0.59 percent, and average 0.16 percent. The highest nitrogen contents are associated with silty clays found in upstream areas of the tributaries (St. Martin River, Greys Creek, and Roy Creek). Nitrogen content of the sediments is strongly associated with carbon content ($r = 0.915$), reflecting the fact that nitrogen comes primarily from organic geopolymers found in the sediment. N/C values are generally low (mean = 0.065) for sediments in the tributaries and along the marsh island areas between Greys Creek and Roy Creek, suggesting that nitrogen in sediments comes primarily from terrestrial organic material, probably as cellulose plant tissue. N/C values are higher, averaging 0.177, for the sediments collected in the central portions of Isle of Wight and Assawoman Bays. In these areas plankton is most likely the primary source of nitrogen in sediments.

Total sulfur contents of the surficial sediments of the coastal bays range from 0 to 3.16 percent about a mean of 0.63 percent. Distribution pattern for sulfur contents are similar to those for nitrogen and carbon. Sulfur content is greatly influenced by sediment texture. Correlation analyses show a strong association between sulfur and clay content ($r = 0.91$) and water content ($r = 0.88$). Silty clays collected in the tributaries yielded the highest sulfur contents, ranging from 1.41 to 3.16 percent. The ratio of carbon to sulfur (C/S) averages 3.56 ± 1.32 for all samples. This value is much higher than the C/S ratio of 2.8 ($\pm$ 1.5) for modern marine sediments reported by Berner and Raiswell (1984). The higher C/S values may reflect the origin and nature of the carbon contained in the sediments. A significant portion of the total carbon measured in many of the coastal bay sediments may be nonreactive carbon, perhaps in the form of plant material or inorganic carbon secretions in worm tubes.

Correlations between metal contents and carbon, nitrogen, and sulfur contents are moderate to strong ($r > 0.7$). The highest correlations are between Fe and Cr ($r = 0.984$), Fe and Mn ($r = 0.956$), and Cr and Zn ($r = 0.953$). There are also high correlations between clay content and Cr, Fe, and Ni, and between water content and all six metals. These metals typically are associated with clay minerals either as they are components of the mineral lattice structure or are absorbed onto clay surfaces. Because of the strong relationship between metal content and grain size, several techniques were used to normalize the metal data so the comparisons could be made between the different sediment types.

One technique correlated metal content with the grain-size composition. Metal concentrations in sediments below 30 centimeters in the sediment column were interpreted to represent the historical norms for the coastal bays. These deeper sediments were used to obtain the relationship between grain size and metal contents to determine background metal concentrations. Background levels were calculated for all surficial samples on the basis of grain size and compared with the measured metal levels. Variation from background levels were then mapped.

Variation levels for Cr, Fe, and Mn are not significant for most areas within the two bays; that is, variation level values fall within the normal dispersion of background level values. On the other hand, variation levels for Cu and Zn indicate that the surficial sediments contain twice the amount of Cu and Zn detected in background levels (historical levels). Mapping of variation levels for Zn and Cu revealed distribution patterns that reflect anthropogenic influences within the two bays. High variation levels of both Cu and Zn are seen in the St. Martin River and in isolated pockets adjacent to developments and marinas. The developed shorelines contain dead-end canals and narrow boat slips, and thus by design, they have poor water circulation, which contributes to the accumulation of these metals. Likewise, the St. Martin River acts as a sink for these metals as well as other pollutants, owing in part to the fine-grained nature of the sediments. The variation levels for metals also reflect the relatively high pollutant input into the St. Martin River compared with that of other tributaries.

Year 10—Core Repository

For the 10th year agreement, the Maryland Geological Survey established a core repository for vibracores collected on the inner continental shelf. Included in this repository are the vibracores collected for the AASG–MMS Continental Margins Program, the Ocean City Beach Replenishment Project, Assateague Island Restoration Project, and several other related projects. More than 270 vibracores are currently in the repository at the Matapeake Facility, Kent Island, Maryland. The inventory of cores is linked to a database containing pertinent information regarding the cores and the projects obtaining the cores. Each core is entered with a core identification code and project code. Core identification codes are based on the original numbering scheme assigned by the originating agency. Horizontal coordinates are in latitude and longitude, NAD 83.

List of Publications for AASG–MMS Continental Margins Program

Years 1 to 4

Berner, R. A., and Raiswell, R., 1984, C/S method for distinguishing freshwater from marine sedimentary rocks: Geology, v. 12, p. 365–368.

Kerhin, R. T., and M. A. Toscano, 1988, Non-energy mineral and surficial geology of the continental margin of Maryland, *in* Hunt, M. C., Ratcliff, D. C., Doenges, S., and Condon, C., eds., Proceedings, First Symposium on Studies Related to Continental Margins—a summary of year-one and year-two activities: U.S. Department of the Interior, Minerals Management Service, and Association of American State Geologists, Continental Margins Committee, p. 180–195.

Kerhin, R. T., and S. J. Williams, 1987, Surficial sediments and later Quaternary sedimentary framework of the Maryland continental shelf: Proceedings, Coastal Sediments ’87, American Society of Civil Engineers, New Orleans, Louisiana, v. II, p. 2126–2140.

Kerhin R.T., 1989, Non-energy minerals and surficial geology of the continental margin of Maryland: Marine Geology, v. 90, p. 95–102.

Taylor, S. R., 1964, The abundance of chemical elements in the continental crusts—a new table: Geochim. Cosmochim. Acta, vol. 28, p. 283–294.

Toscano, M.A., 1989, Comments on “Late Pleistocene barrier island sequence along the southern Delmarva Peninsula: Implications for middle Wisconsin sea level”: Geology, v. 17, p. 85–86.

__________ 1992, Record of oxygen isotope stage 5 on the Maryland inner shelf and Atlantic Coastal Plain—a post transgressive-highstand regime, *in* Fletcher, C., and Wehmiller, J., eds., Quaternary coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication No. 48, p. 89–100.

Toscano, M. A., and Kerhin, R. T., 1988, Late Quaternary stratigraphy of the inner continental shelf of Maryland: Maryland Geological Survey, Open-File Report 50, 55 p.

__________ 1990, Subbottom structure and stratigraphy of the inner continental shelf of Maryland, *in* Hunt, M. C., Doenges, S., and Stubbs, G. S., eds., Proceedings, Second Symposium on Studies Related to Continental Margins—a summary of year-three and year-four activities: U.S. Department of the Interior, Minerals Management Service and Association of American State Geologists, Continental Margins Committee, p. 124–142.

Toscano, M. A., Kerhin, R. T., York, L. L., Cronin, T. M., and Williams, S. J., 1989, Quaternary stratigraphy of the inner continental shelf of Maryland: Maryland Geological Survey Report of Investigations, No. 50, 116 p.

Toscano, M. A., and York, L. L., 1992, Quaternary stratigraphy and sea-level history of the U.S. middle Atlantic Coastal Plain: Quaternary Science Reviews, v. 11, p. 301–328.

Years 5 and 6

Wulff, A., 1991, Heavy mineral abundances on the continental shelf of Maryland: Maryland Geological Survey Open-File Report, 34 p.

Wulff, A., and Brooks, J., 1990, Sieve analyses and heavy mineral concentrations of the sand taken from the inner continental shelf of Maryland: Maryland Geological Survey Open-File Report, 37 p.

Wulff, A., Kerhin, R., and Reger, J., 1990, Heavy mineral abundances on the continental shelf of Maryland: Maryland Geological Survey Open-File Report, 15 p.

Year 7

Wells, D. V., 1994, Non-energy resources and shallow geological framework of the inner continental margin off Ocean City, Maryland: Maryland Geological Survey Open-File Report 16, 97 p.

Years 8 and 9

Wells, D. V., Conkwright, R., Hill, J., and Park, J., 1994, The surficial sediments of Assawoman Bay and Isle of Wight in Maryland: physical and chemical characteristics: Maryland Geological Survey Open-File Report 94-2, 99 p.

Wells, D. V., Conkwright, R., and Park, J., 1994, Geochemistry and geophysical framework of the shallow sediment of Assawoman Bay and Isle of Wight in Maryland: Maryland Geological Survey Open-File Report No. 15, 125 p.

Year 10

Wells, D.V., and Conkwright, R., 1996, Physical inventory and repository of vibracores collected on Maryland's continental shelf: Maryland Geological Survey Open-File Report 96-6, 65 p.

Assessment of Offshore New Jersey Sources of Beach Replenishment Sand by Diversified Application of Geologic and Geophysical Methods

J. S. Waldner, D. W. Hall, Jane Uptegrove

New Jersey Geological Survey, CN 427, Trenton, NJ 08625

R. E. Sheridan, G. M. Ashley

Rutgers University, Department of Geological Sciences, Wright-Rieman Laboratories, Busch Campus, Piscataway, NJ 08855

Dominic Esker

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149

Abstract

Beach replenishment serves the dual purpose of maintaining a source of tourism and recreation while protecting life and property. For New Jersey, sources for beach sand supply are increasingly found offshore. To meet present and future needs, geologic and geophysical techniques can be used to improve the identification, volume estimation, and determination of suitability, thereby making the mining and managing of this resource more effective.

Current research has improved both data collection and interpretation of seismic surveys and vibracore analysis for projects investigating sand ridges offshore of New Jersey. The New Jersey Geological Survey in cooperation with Rutgers University is evaluating the capabilities of digital seismic data (in addition to analog data) to analyze sand ridges. The printing density of analog systems limits the dynamic range to about 24 decibels. Digital acquisition systems with dynamic ranges above 100 decibels can permit enhanced seismic profiles by trace static correction, deconvolution, automatic gain scaling, horizontal stacking and digital filtering. Problems common to analog data, such as wave-motion effects of surface sources, water-bottom reverberation, and bubble-pulse-width can be addressed by processing.

More than 160 line miles of digital high-resolution continuous profiling seismic data have been collected at sand ridges off Avalon, Beach Haven and Barnegat Inlet. Digital multi-channel data collection has recently been employed to map sand resources within the Port of New York/ New Jersey expanded dredge-spoil site located 3 miles offshore of Sandy Hook, New Jersey. Multi-channel data processing can reduce multiples, improve signal-to-noise calculations, enable source deconvolution, and generate sediment acoustic velocities and acoustic impedance analysis. Synthetic seismograms based on empirical relationships among grain size distribution, density, and velocity from vibracores are used to calculate proxy values for density and velocity. The seismograms are then correlated to the digital seismic profile to confirm reflected events. They are particularly useful where individual reflection events cannot be detected but a waveform generated by several thin lithologic units can be recognized.

Progress in application of geologic and geophysical methods provides advantages in detailed sediment analysis and volumetric estimation of offshore sand ridges. New techniques for current and ongoing beach replenishment projects not only expand our knowledge of the geologic processes involved in sand ridge origin and development, but also improve our assessment of these valuable resources. These reconnaissance studies provide extensive data to the engineer regarding the suitability and quantity of sand and can optimize placement and analysis of vibracore samples.

Seismic Reflection and Vibracoring Studies of the Continental Shelf Offshore Central and Western Long Island, New York

William M. Kelly

New York State Geological Survey, Cultural Education Center, Albany, NY 12230

James R. Albanese

Department of Earth Sciences, State University College, Oneonta, NY 13820

Nicholas K. Coch

Department of Geology, Queens College (CUNY), Flushing, NY 11367

Aidan A. Harsch

Marine Sciences Research Center, State University of New York, Stony Brook, NY 11794

Abstract

The ridge and swale topography on the continental shelf south of Fire Island, New York, is characterized by northeast-trending linear shoals that are shore attached and shore oblique on the inner shelf and isolated and shore parallel on the middle shelf. High-resolution seismic reflection profiles show that the ridges and swales occur independent of, and are not controlled by, the presence of internal structures (for example, filled tidal inlet channels, paleobarrier strata) or underlying structure (for example, high-relief Cretaceous unconformity). Grab samples of surficial sediments on the shelf south of Fire Island average 98 percent sand. Locally, benthic fauna increase silt and clay content through fecal pellet production or increase the content of gravel-size material by contribution of their fragmented shell remains. Surficial sand on the ridges is unimodal at 0.33 millimeters (medium sand, about 50 mesh), and surficial sand in troughs is bimodal at 0.33 millimeters and 0.15 millimeters (fine sand, about 100 mesh). In addition to seismic studies, 26 vibracores were recovered from the continental shelf in State and Federal waters from south of Rockaway and Long Beaches, Long Island, New York. Stratigraphic and sedimentological data gleaned from these cores were used to outline the geologic framework in the study area. A variety of sedimentary features were noted in the cores, including burrow-mottled sections of sand in a finer silty-sand, rhythmic lamination of sand and silty-sand that reflect cyclic changes in sediment transport, layers of shell hash and shells that probably represent tempestites, and changes from dark color to light color in the sediments that probably represent changes in the oxidation-reduction conditions in the area with time. The stratigraphic units identified are an upper, generally oxidized, nearshore facies, an underlying fine- to medium-sand and silty-clay unit considered to be an estuarine facies, and a lower, coarse-grained, deeply oxidized, cross-laminated pre-Holocene unit. Grain-size analysis shows that medium- to fine-grained sand makes up most (68 to 99 percent) of the surficial sediments. Gravel exists in trace amounts up to 19 percent. Silt ranges between 3 and 42 percent, and clay ranges from 1 to 10 percent.

Sedimentological Features

The nearshore continental shelf is one of the most dynamic sedimentary environments on Earth. Sediments there reflect not only sedimentological and anthropogenic input from the adjacent land but also the effects of sea-level change, coastal storms and strong current, and wave action. This study involves sedimentological analysis of vibracores taken on the nearshore continental shelf south of Rockaway Beach and Long Beach, New York, and grab samples recovered on the nearshore and middle continental shelf south of Fire Island, New York. A total of 26 vibracores, which range in length from 66 to 309 centimeters, and 44 grab samples were taken in the study areas. Locations of the samples are shown in figure 1. This report summarizes the results of analysis of the cores and grab samples in terms of grain-size analyses, representative lithologies in major stratigraphic units, descriptions of sedimentary features that provide environmental information, and an overall view of changes in sedimentation in the study area with time.

Coring operations were carried out on the *R.V. Walford* of the New Jersey Marine Sciences Consortium. Cores were obtained using a Rossfelder P-1 and P-3 vibracorers with a 3-inch PVC liner inserted in a 10-foot coring tube. However, some coring operations were carried out under adverse sea conditions, and in some cases bad weather limited the length of core that could be obtained at many of the sites. One half of the core was retained for bulk grain-size and mineral analysis by the New York State Geological Survey, and the other half was made available for sedimentological studies, including estimated grain size, color, sedimentary features, and the nature of contacts between layers. Each of the layers in the cores was then photographed in color. A channel sample was obtained along one side of each major unit, and samples were taken every 5 centimeters along the other side of the core.

Grab sampling of the uppermost sediments was conducted aboard the *R.V. Onrust* of the S.U.N.Y. Marine Sciences Research Center with a Shipek grab sampler. Subsamples of approximately 150 grams were kept from each grab and used for grain-size and shape

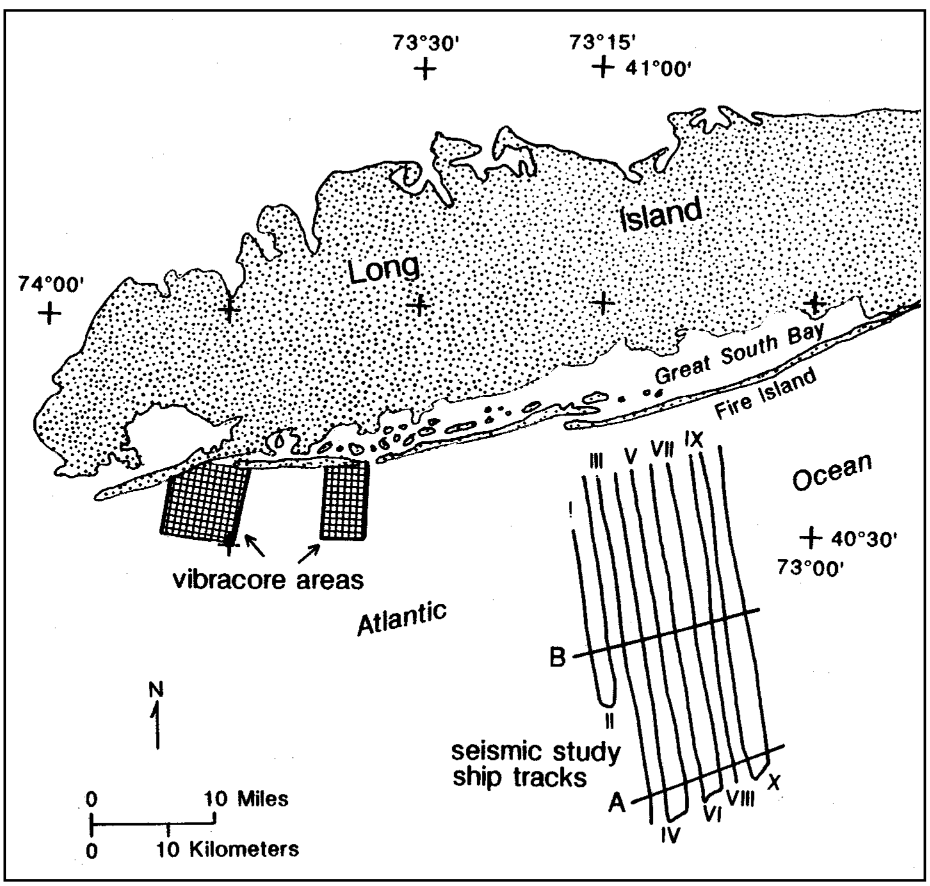


Figure 1. Locations of study areas.

analysis. Locations of the samples were chosen from the graphic seismic records, and positions were determined using a Raytheon Model DE-719B precision survey fathometer and the ship's Loran-C unit. Distances offshore from Fire Island, New York, of the sampling locations were determined directly from the ship's radar. Sampling locations were on crests and in troughs. Forty-four grab samples (21 crests, 19 troughs, and 4 flanks) were obtained; grain-size analysis was performed on 36 of the samples, and shape analysis was performed on 35 samples. Complete details of the sedimentological analysis methods used for the core samples are contained in Coch and others (1997a, b) and, for the grab samples, in Harsch and others (1997).

Sedimentary features of the cores

A variety of sedimentary features were noted in the cores, including burrowed-mottled sections of sand in a finer grained silty sand, rhythmic lamination of sand and silty sand that reflect cyclic changes in sediment transport, layers of shell hash and shells that probably represent tempestites, and changes from dark to light color in the sediments that probably represent changes in the oxidation-reduction conditions within the sediments with time. The most notable feature was a sharp contact at the base of core no. 10 that may represent the Pleistocene-Holocene boundary. The section above the boundary is dark gray and fine grained, whereas the section below is reddish brown and has cross-laminations suggestive of an outwash origin. This stratigraphic contact occurs at a depth of 120 centimeters below the sediment interface at that site. Longer cores taken in other parts of the study area did not contain a contact marked by such profound color/grain-size changes. This suggests that the top of the Pleistocene sequence has an irregular topography and the thickness of the Holocene sequence may be quite variable.

Sediment characteristics of the cores

Core descriptions and sedimentological studies show an overall downward coarsening in the cores. In general, the upper parts of the cores are fine-grained sand, whereas the lower parts are medium sand. Within each of these two major units are subdivisions bounded by smaller changes and gravel and shell-hash layers that may represent storm scouring. These shell-hash layers appear at roughly the same level in several cores and possibly could be used for correlation. The overall decrease in grain size upward in most of the core sections may represent a change in sediment source with time. The lower part of the cores is coarser and may represent local reworking of the underlying outwash. The upper part may represent the finer portion of outwash-derived sediment with an eastern provenance and transported into the area by the predominant east-to-west littoral drift that acts along the south shore of Long Island.

Grain-size analysis of the cores

Grain-size analysis was carried out at the New York State Geological Survey. Average grain-size data for each of the cores is illustrated in figure 2. The grain-size fractions chosen for this analysis are ones commonly specified for construction aggregates by the New York State Department of Transportation (NYSDOT, 1985).

Figure 2 shows that the dominant sediment size in the material cored for this study was fine-grained and very fine grained sand. The coarser fractions of the samples were largely shell material with minor quartz gravel. It should be noted that in the dry sieving of these large samples, agglomerated fine sand/mud balls often did not disaggregate completely. Therefore, some material retained on the intermediate-size (#16-#50) sieves was actually aggregates of grains rather than individual grains. This bias causes a small apparent increase in overall grain size. Few lithic clasts are present in the gravel fraction. The analysis of the surface of each core, for comparison to the grab samples, shows that sand makes up most (68 to 99 percent) of the surficial sediments. Gravel exists in trace amounts up to 19 percent, silt ranges between 3 and 42 percent, and clay ranges from 1 to 10 percent.

Grain-size analysis of the grab samples

Results of the grain-size analysis indicated that ridge crests in the study area contain an average of 98.5 percent sand by weight with a very slight decrease in sand percentage as distance from shore increases. Ridge troughs contain an average of 97.1 percent sand, with no apparent trend as distance from shore increase (fig. 3). Ridge crests are composed of medium sand, about 45 to 50 mesh. Sand of similar size occurs in the ridge troughs with the addition of a significant component of fine sand of approximately 100 mesh.

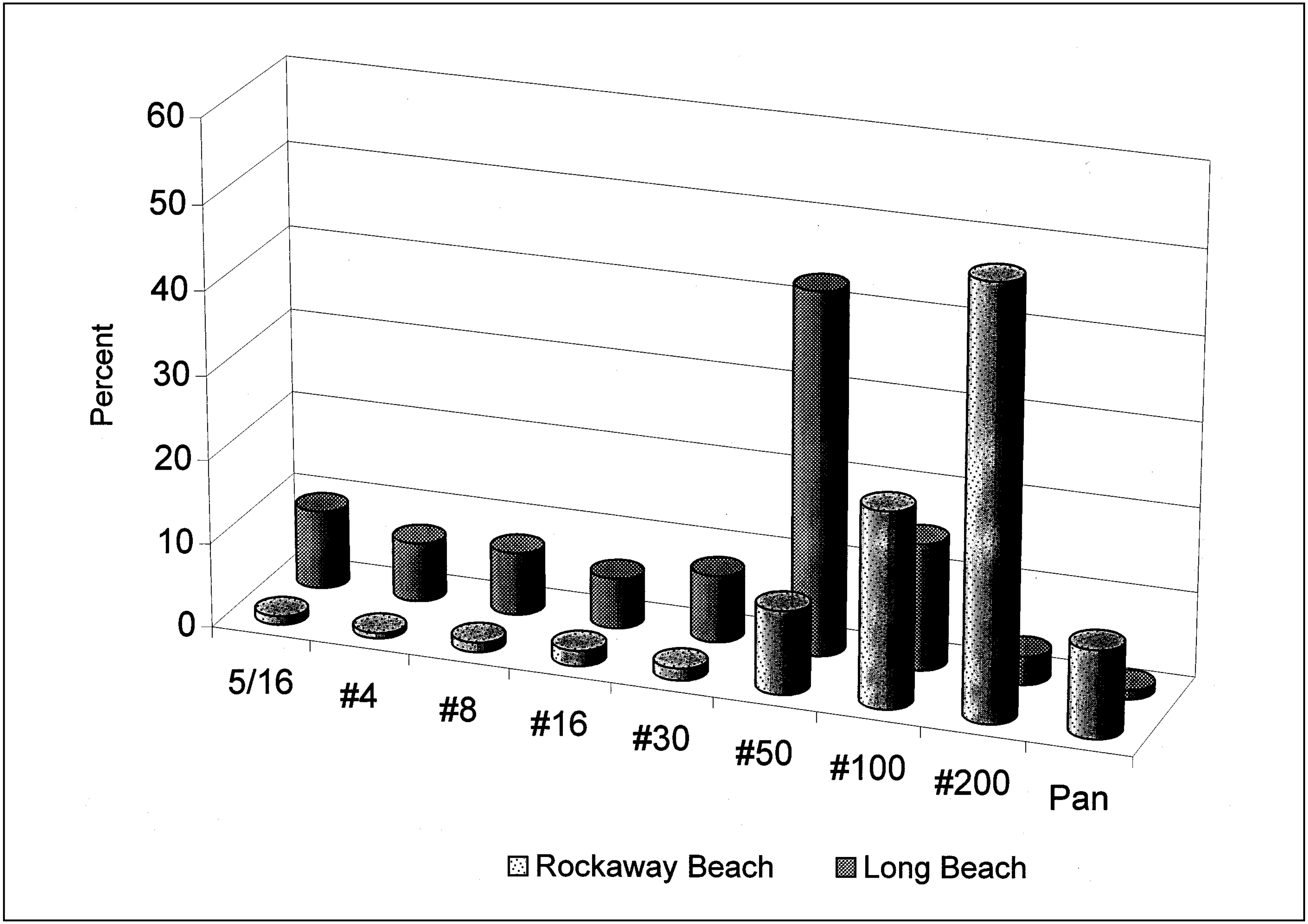


Figure 2. Average vibracore grain sizes.

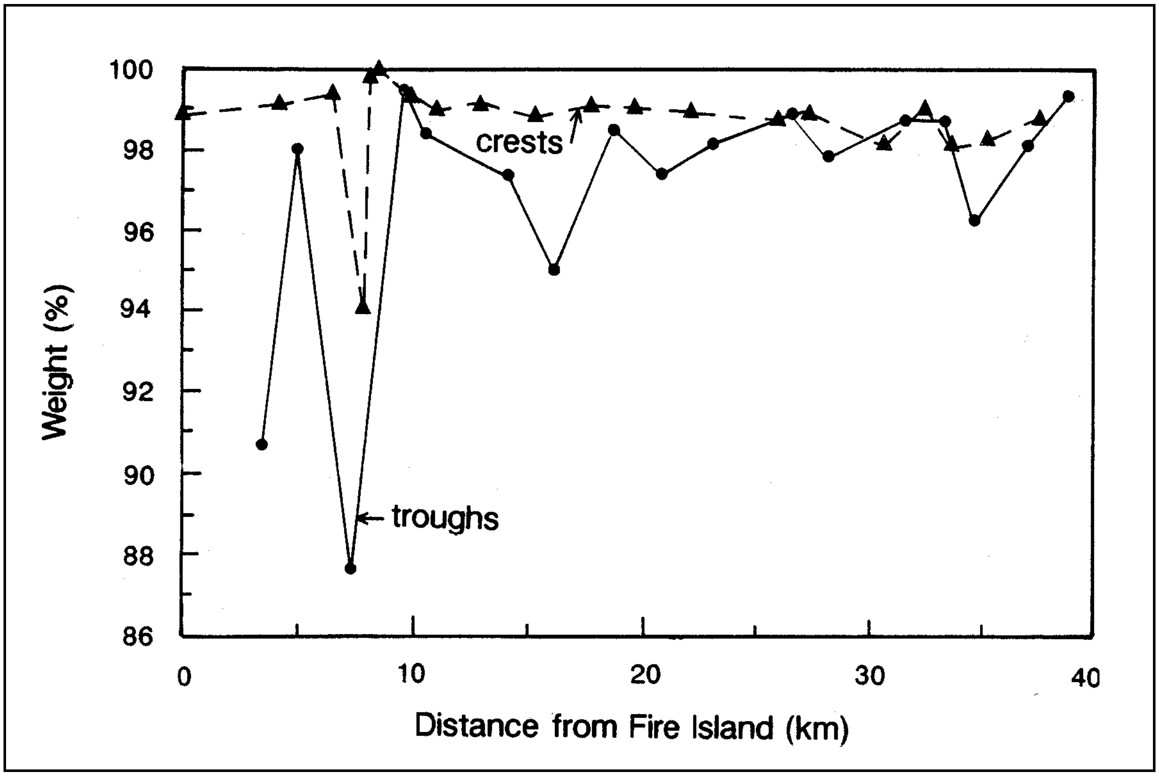


Figure 3. Percent sand in crests and troughs south of Fire Island.

Average silt and clay content is 0.5 and 0.8 percent, respectively, for ridge crests, and gravel content remained relatively uniform with increasing distance from shore and averaged 0.3 percent. Shell fragments may have collected in the trough. Average gravel and silt content in troughs is 1.2 and 0.8 percent higher, respectively, than on crests. Clay content in troughs remains relatively uniform with increased distance from shore and averages 0.9 percent of the sample. Average amount of gravel, sand, silt, and clay of ridge flanks, and ridge crests sampled is approximately the same.

Results of the rapid sediment analysis of the sand fraction revealed that the mode for all crests and all troughs is approximately 0.33 millimeters. Ridge troughs appeared to be polymodal with one population of grains that had similar size distributions as the crests and a separate population consisting of finer particles (0.15 millimeters) (fig. 4).

Subsurface Stratigraphy

Subsurface stratigraphic units interpreted from vibracores

Analysis of data from 26 vibracores taken on the nearshore shelf of western Long Island since 1992 has provided valuable clues to temporal variation in sedimentation. Examination of the vibracores indicates that there are significant changes with depth in the characteristics of stratigraphic units. These variations include changes in grain size, color, shell content and character, organic content, and types of sedimentary sequences. Sedimentary structures that have been identified are cross laminae, mottling, flaser bedding, rhythmic lamination, graded laminae, and shell hash and gravel lag laminae. Determination of the sedimentary environments associated with each set of sedimentary characteristics will allow the determination of the succession of sedimentary environments with time. The vibracore locations and composite section south of Rockaway Beach are shown in figures 5a and 5b, and the vibracore locations and composite stratigraphic section south of Long Beach are shown in figures 6a and 6b.

Three major stratigraphic units have been tentatively defined. The uppermost unit is composed of fine sands with generally oxidized colors. This unit was assigned to a nearshore facies. Underlying the nearshore unit is a fine to medium sand and silty clay unit with darker colors. This unit has been assigned to an estuarine facies. The nearshore and estuarine facies are almost everywhere clearly separated by a coarse-

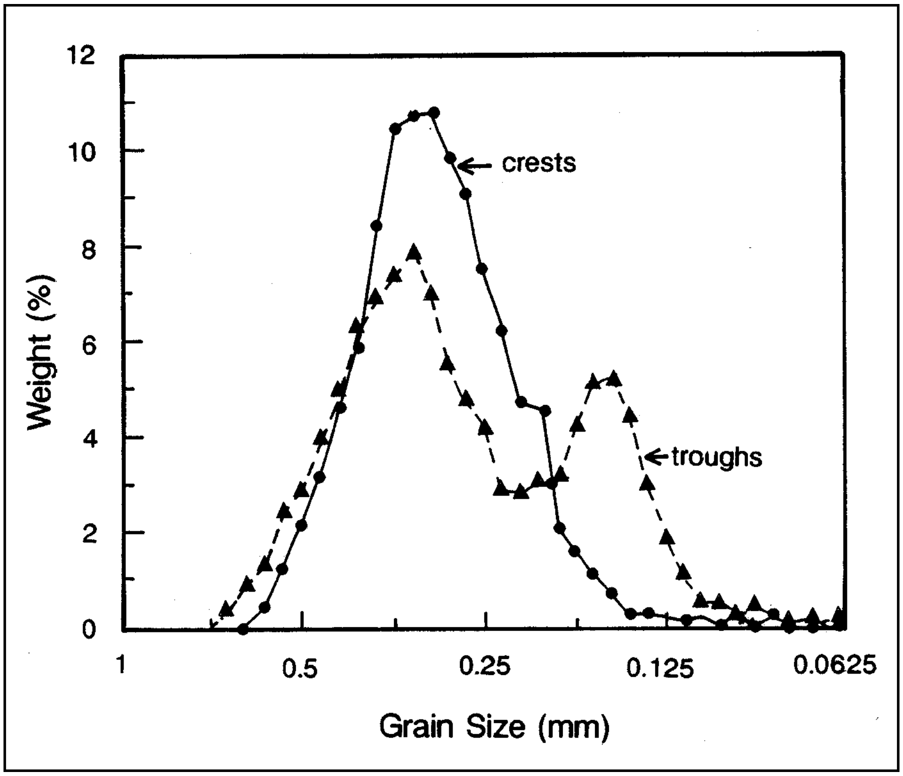


Figure 4. Grain-size distributions of grab samples from ridges and troughs.

grained gravel, shell, or shell hash unit that is interpreted as a lag deposit from reworking. The coarseness, strong oxidation (oranges and yellows), and cross laminations (fine and coarse) in this unit strongly suggest a continental origin. It is inferred that this site was a high point on an old erosion surface. The pre-Holocene unit may be Pleistocene outwash, or it may represent Tertiary or Cretaceous coastal plain deposits.

The following generalizations can be made from the composite sections (figs. 5b and 6b).

1. An erosional surface cut into the pre-Holocene sediment sequence is an irregular topography upon which deposition occurred during Holocene sea-level rise.
2. The nature of the unconformable contact between the Holocene and older units varies in character over the area. The gentle southward dip of Cenozoic and Cretaceous units may account for this phenomenon. The Holocene units may overlie truncated Cretaceous units nearshore and truncated Cenozoic units farther offshore (southward).
3. The thickness of the Holocene section varies considerably over the area. It appears that the Holocene sand section is thicker in the western part of the study area.
4. The Holocene section everywhere is composed of two parts, separated in most places by a thin lag deposit that indicates reworking of the top of the lower unit before deposition of the upper one. The Holocene surface sands are underlain by finer grained units that are probably of about the same age. This conclusion is based on the lack of any evidence of weathering that would suggest subaerial exposure.

Examination of these cores has shown that it is difficult to distinguish between surface layers and those presumably lying below. In many places, surface sands sharply overlie distinctly finer, darker sediments. In the absence of fossil data, it would be tempting to ascribe this to an unconformity. However, the possibility exists that both are Holocene in age. Analysis of foraminiferans recovered from cores taken earlier in this program shows that all of the sediments examined were Holocene (Hill and others, 1994). The upper unit may indicate a surface sand sheet that overlapped back-barrier deposits when a former barrier island system was submerged after a pause in Holocene sea-level rise.

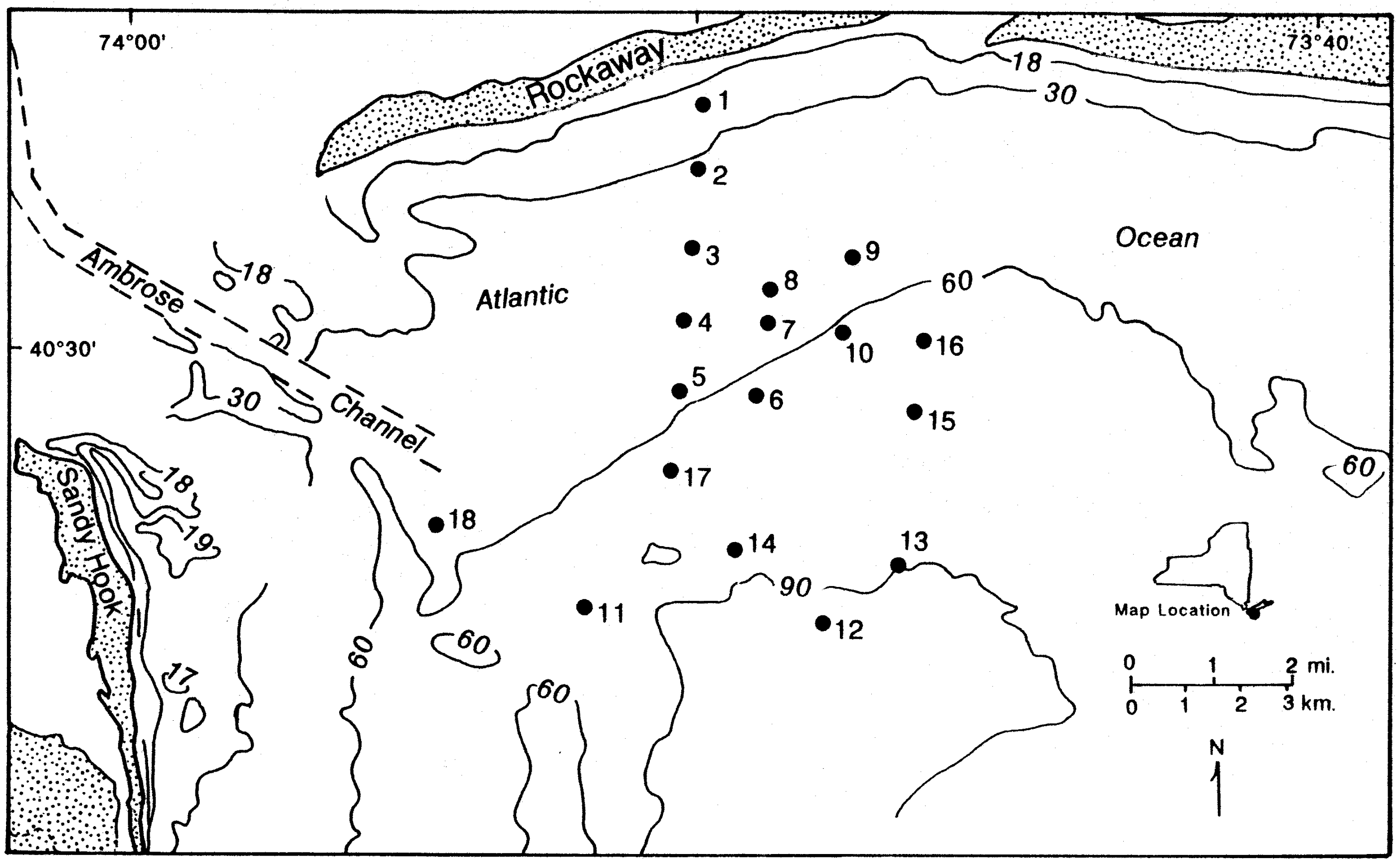


Figure 5a. Vibracore locations south of Rockaway Beach.

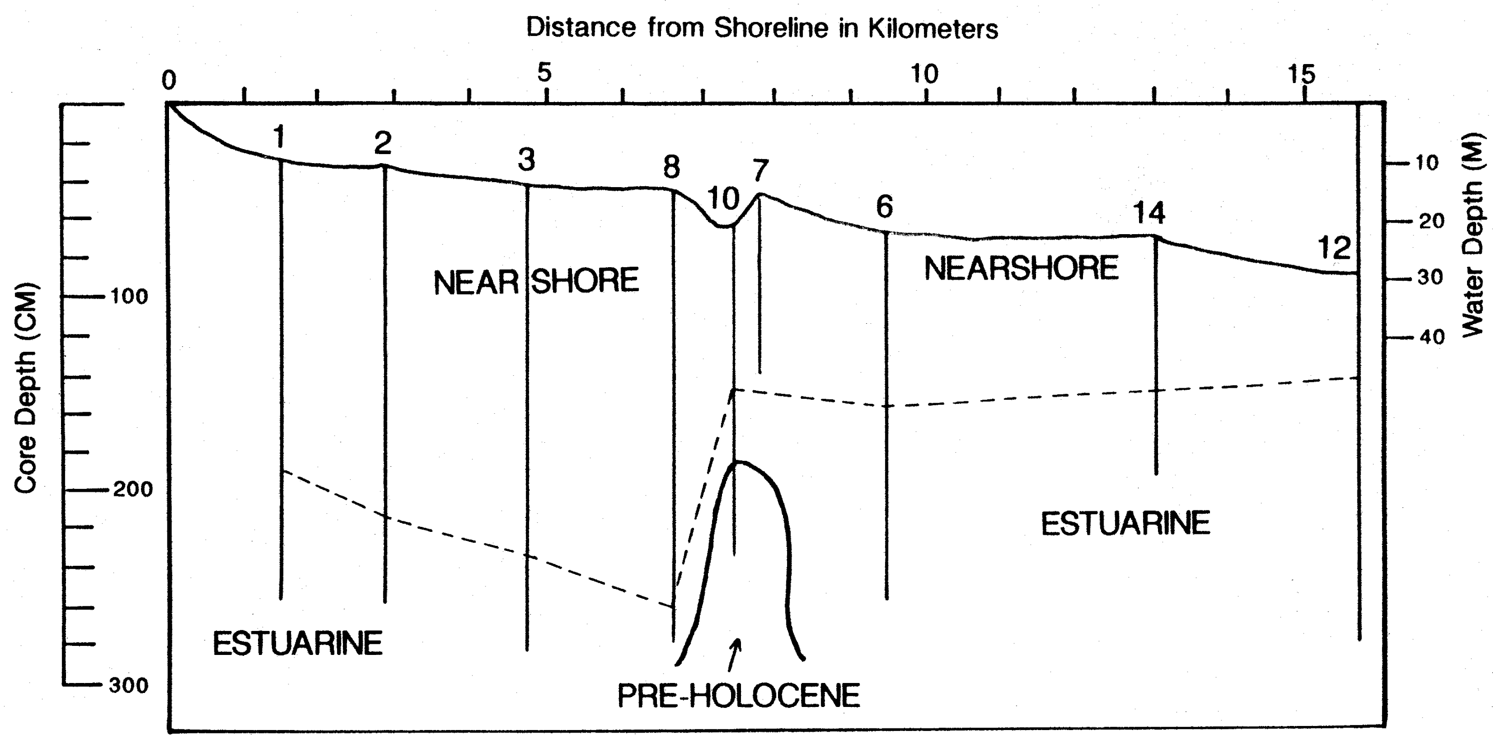


Figure 5b. Stratigraphic section south of Rockaway Beach.

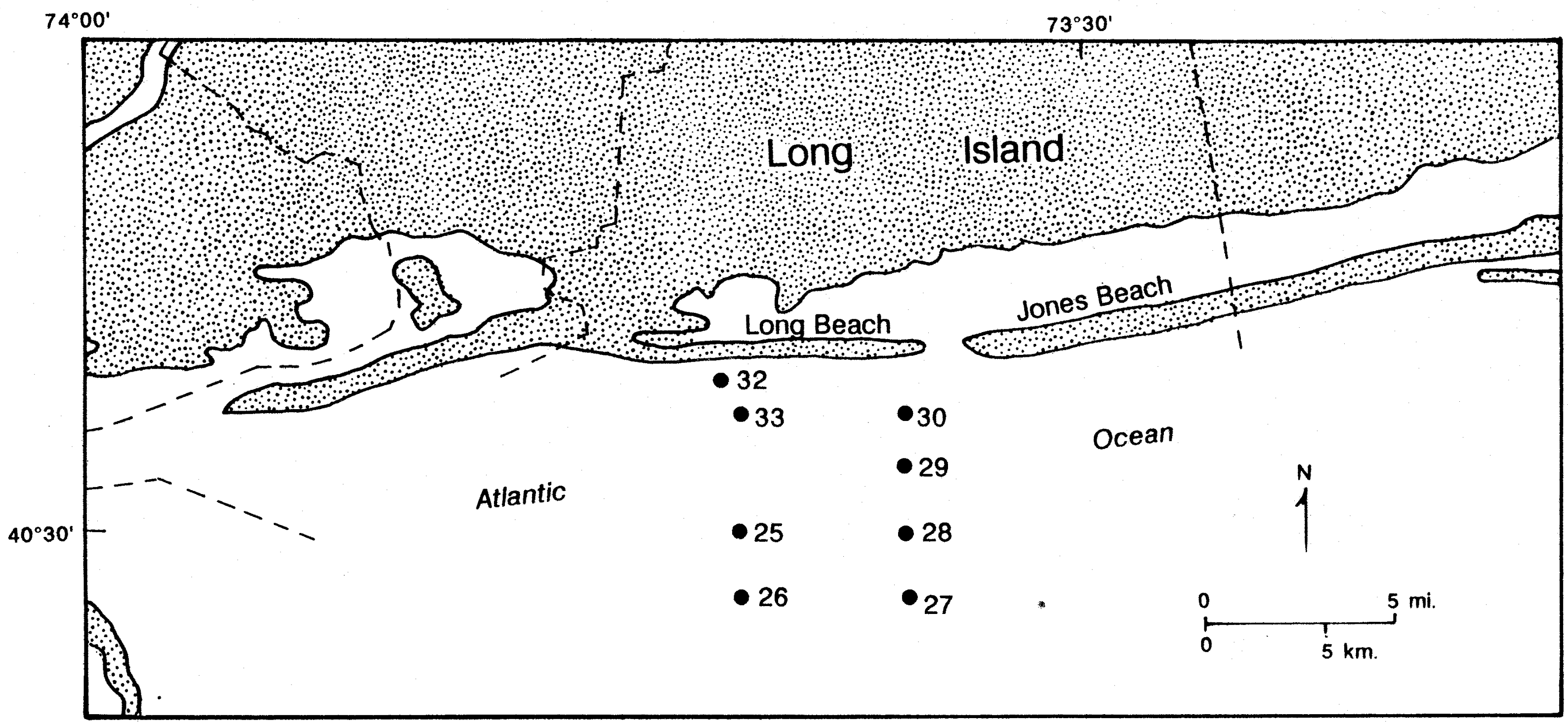


Figure 6a. Vibracore locations section south Long Beach.

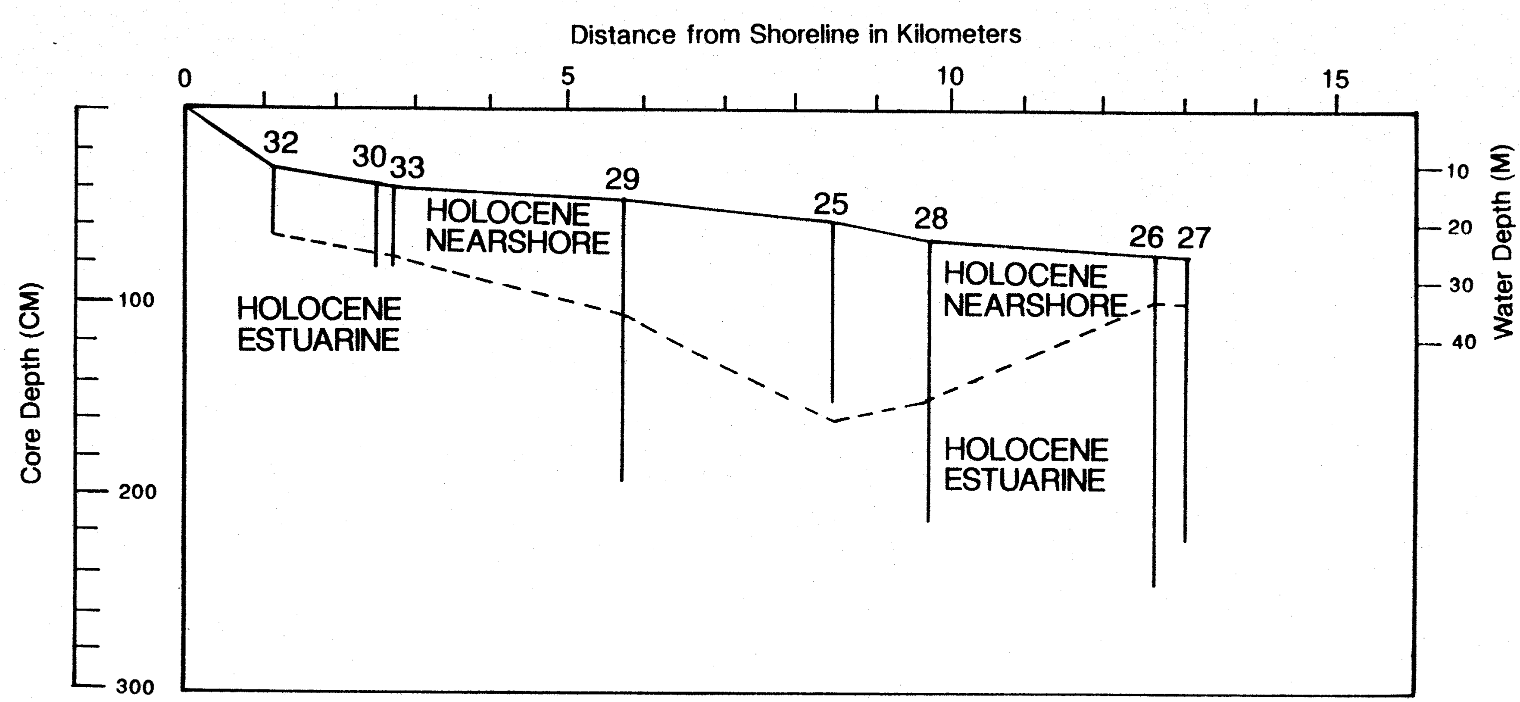


Figure 6b. Stratigraphic section south Long Beach.

Subsurface stratigraphic units interpreted from seismic surveys

Seismic survey tracks of this study were concentrated from about the 3-nautical-mile limit to the 40-meter isobath, approximately 42 kilometers offshore. Continuous high-resolution seismic reflection profiles covering 350 kilometers on the shelf were made perpendicular to shore (roughly north to south), and seismic reflection profiles over 50 kilometers across the shelf were collected parallel to shore (roughly east to west) (see fig. 1).

An isopach map of the study area was prepared to depict the thickness of the Pleistocene-Holocene sediment blanket (fig. 7). The isopachs shown in figure 7 indicate that the Pleistocene-Holocene sediment blanket is of relatively uniform thickness in the north of the study area and more variable in the south. In the north, thickness of the blanket appears to reflect the ridge and swale topography, and in the south, it appears to reflect a deposit that infills a deeply eroded channel in the underlying Upper Cretaceous strata. The channel extends from approximately 27 kilometers offshore to the edge of the study area almost 42 kilometers

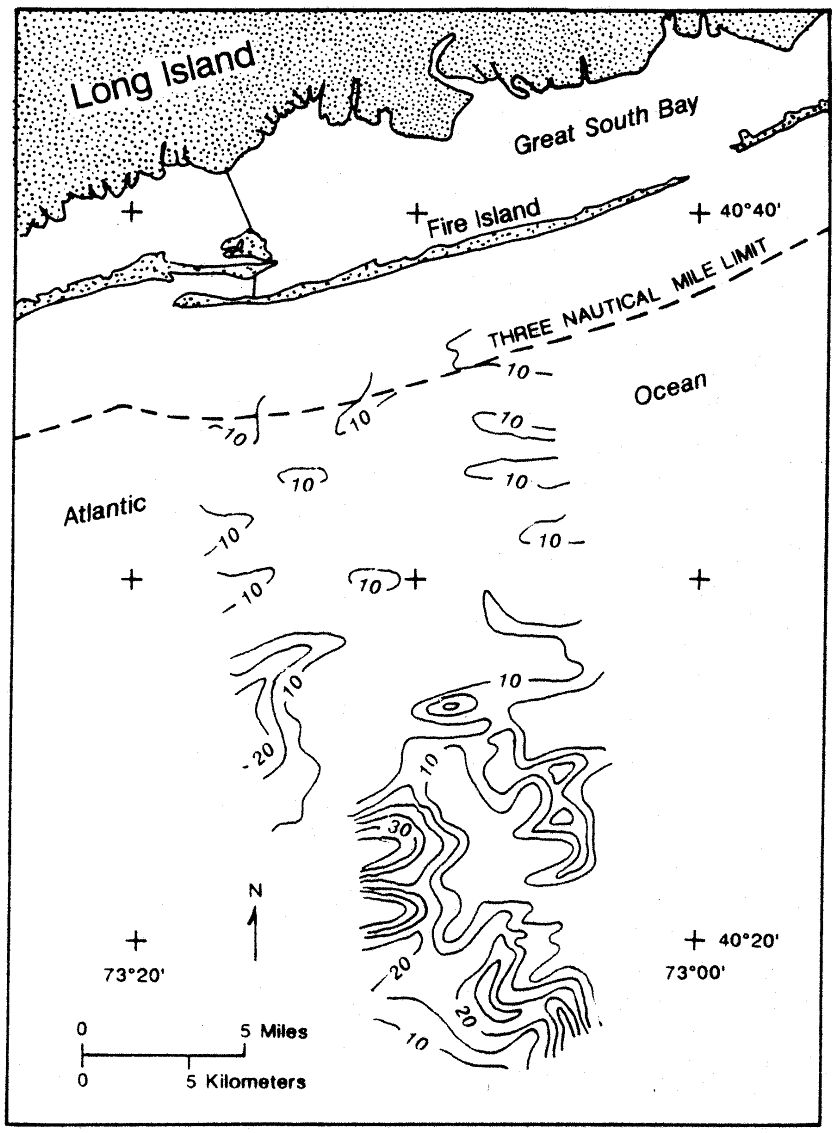


Figure 7. Isopach map of sediment thickness.

offshore. The 2- to 4-kilometer-wide deposit is roughly shore parallel with less eroded Cretaceous strata in the center of the deposit approximately 25 to 35 kilometers offshore. Where underlying Cretaceous strata were most deeply eroded, infilled sediments exceeded 50 meters in thickness (fig. 7).

In the widely separated positions on seismic profiles where the Pleistocene-Holocene contact was discernible, channel-shaped indentations exist in the Pleistocene-Holocene layer (fig. 8) that are similar to those described by Panageotou and Leatherman (1986). These are likely relict tidal inlet–filled channels. Although too few of these indentations were distinguishable seismically to map their extent, they are of a much smaller scale than the ridges and do not appear to affect ridge and swale morphology as they are found as relict features within the ridge sediments.

Possible evidence of the paleobarrier inferred by Sanders and Kumar (1975) and Panageotou and Leatherman (1986) was distinguishable offshore of Fire Island on seismic Line V. Figure 9 shows a seismic reflection profile with a lens-shaped, buried barrierlike deposit with its seaward face occurring approximately 7 kilometers offshore and approximately 35 meters

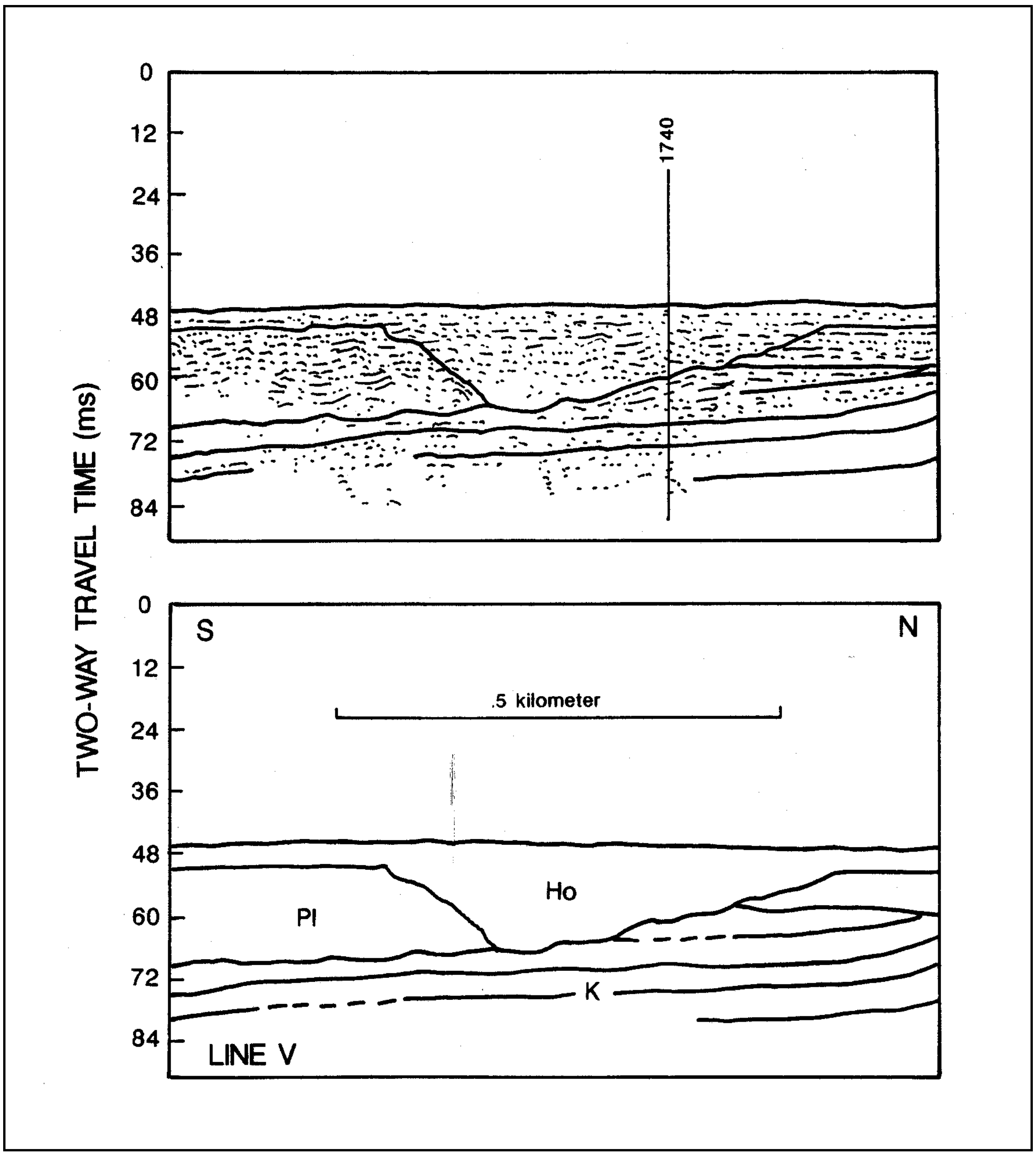


Figure 8. Seismogram of channel in the Pleistocene-Holocene layer.

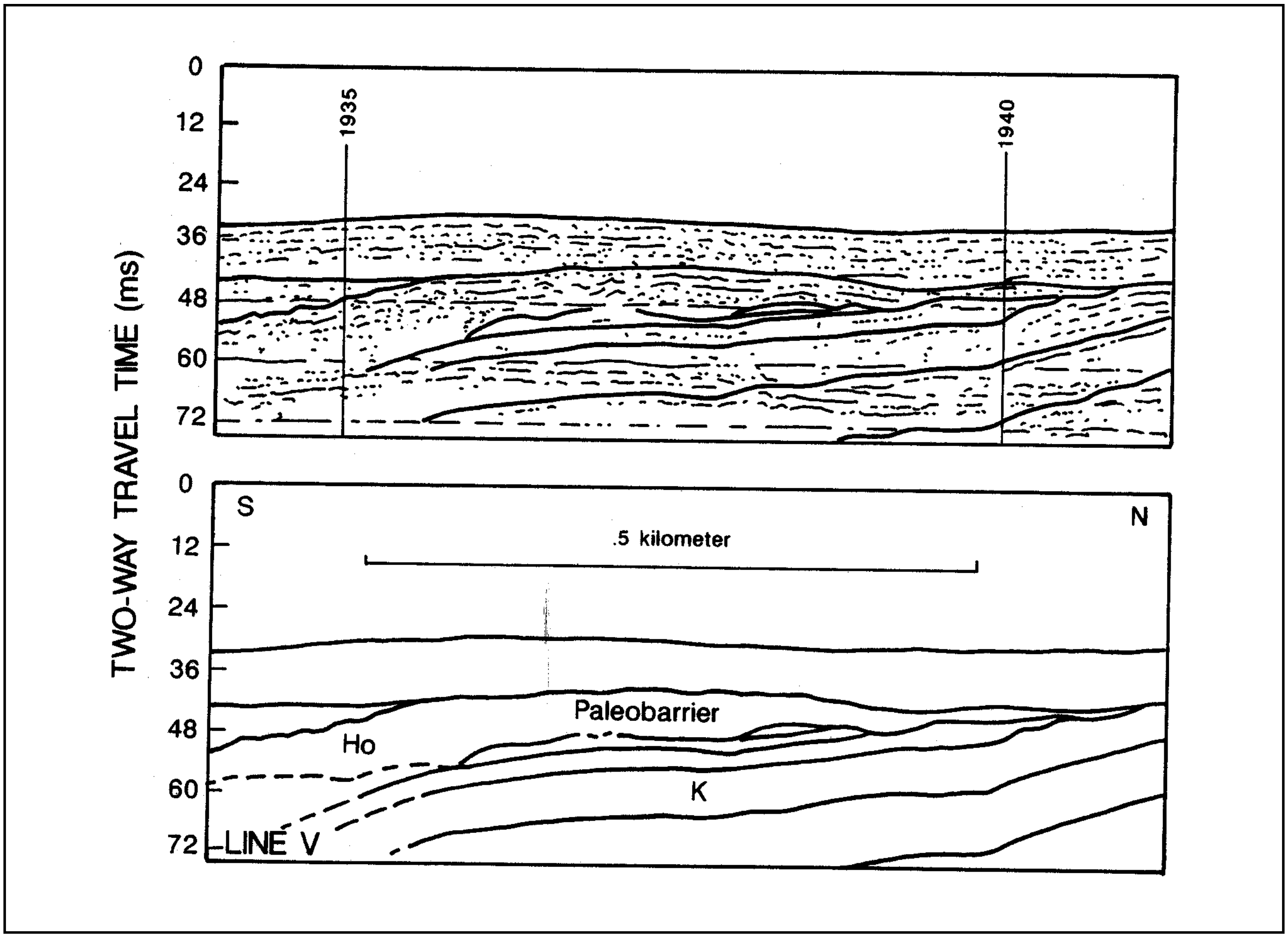


Figure 9. Seismogram of buried barrier bar.

below present sea level. Extent of the structure is unknown because the deposit lies at the edge of the seismic survey. No subsurface features controlled the locations, sizes, shapes, or orientations of the ridges, and the locations, morphologies, and orientations were unaffected by the relief of the underlying Cretaceous unconformity.

Conclusions

Stratigraphic analysis of the vibracores taken in this program enables an attempt to reconstruct of the paleoenvironmental succession along the western part of the south shore of Long Island. These two sections suggest that Holocene nearshore sands overlie the uppermost part of a Holocene estuarine sequence. In some cores, the contact is indicated by a gravel lag at the base of the sand, or by clasts of estuarine clay reworked into the base of the shelf sands. Some of the deeper cores provide more details of the fine-grained unit under the sands. The compact nature of this layer and features such as flaser bedding indicate that it is of estuarine origin.

The succession of environments is reconstructed as follows. Pre-Pleistocene exposure and erosion of older sediments created an irregular topography. Holocene sea-level rose as deglaciation of the area proceeded. Sea-level rise paused, and a barrier island system evolved somewhere east of the present sample area. Estuarine deposits were deposited westward of the former barrier. Sea-level rise resumed and drowned or destroyed the older barrier system. Nearshore sediments were deposited as the shoreline transgressed westward to the present shoreline position. A modern barrier island and bay shoreline was established as sea level stabilized near its present position about 5,000 years B.P.

Ridge crests and troughs can be identified by their separate grain-size distributions. Although crest as well as trough surficial sediments dominantly consist of medium sand, trough sediments are characterized by a bimodal distribution with an additional mode of fine sand. This mode is probably due to deposition in troughs of reworked backbarrier sands.

References

Coch, N. K, Kelly, W. M., Albanese, J. R., 1997a, Sedimentological analysis of vibracores from the nearshore shelf south of Rockaway Beach, Queens County, New York: New York State Geological Survey Open-File Report, 8d184.

Coch, N. K, Kelly, W. M., Albanese, J. R., 1997b, Analysis of vibracores recovered south of Rockaway Beach, Queens County, New York—clues to modern sediment dynamics and Holocene stratigraphic development: New York State Geological Survey Open-File Report, 8d185.

Harsch, A. A., Kelly, W. M., and Albanese, J. R., 1997, Seismic reflection profiles and the nature of sand ridges on the continental shelf south of Fire Island, Suffolk County, New York: New York State Geological Survey Open-File Report 4d 307.

Hill, H., Albanese, J. R., and Kelly, W. M., 1994, Foraminifera populations as indicators of sedimentary environments in the New York Bight: Geological Society of America, Abstracts with Programs, v. 26, no. 3, p. 23.

New York State Department of Transportation, 1985, Standard specifications, construction and materials: Office of Engineering, Albany, New York.

Panageotou, W., and Leatherman, S. P., 1986, Holocene-Pleistocene stratigraphy of the inner shelf off Fire Island, New York: implications for barrier-island migration: Journal of Sedimentary Petrology, v. 56, p. 528–537.

Sanders, J. E., and Kumar, N., 1975, Evidence of shoreface retreat and in-place “drowning” during Holocene submergence of barriers, shelf off Fire Island, New York: Geological Society of America Bulletin, v. 86, p. 65–76.

Submarine Sand Resources, Southeastern Virginia—Contributions from Year Nine and Year Ten of Virginia's Continental Margins Program

Carl H. Hobbs III and C. Scott Hardaway, Jr.

Virginia Institute of Marine Science, College of William & Mary, P.O. Box 1346, Gloucester Point, VA 23062-1346

C. R. Berquist, Jr.

College of William & Mary, Department of Geology, Virginia Division of Mineral Resources, P.O. Box 8795, Williamsburg, VA 23187-8795

Abstract

Virginia's Year-Nine and Year-Ten funds from the Continental Shelf Program were used to supplement other work funded by the Minerals Management Service in an ongoing Cooperative Agreement focused on the area offshore of southeastern Virginia. Year-Nine and Year-Ten funds facilitated interpretation of subbottom profiles and the analysis of sediment samples from cores and grabs.

On Virginia's sediment-starved continental shelf, deposits of material potentially suitable for use as beach nourishment or, perhaps, as construction aggregate occur in three stratigraphic settings, each with specific characteristics of morphology, grain-size gradients, likelihood of discovery, and physical ease of exploitation. All must be verified with a careful program of coring. Modern shoals generally are easier to identify, prove, and access than either filled channels or lenticular facies. Shoals usually are identifiable on nautical charts and characteristically have a definite lower boundary that can be seen in subbottom profiles. In most cases, the base of the shoal coincides with the level of the surrounding sea floor. Filled channels are readily identifiable on subbottom profiles but may have a narrow, sinuous form and steep lateral gradients in sediment properties. Buried lenticular facies of good-quality sand usually are found only fortuitously. As the lateral and often vertical gradients in geotechnical properties usually are low, the lenticular facies can be mined with a lesser concern for the consequences of violating the deposit's limits than with the other two types of deposit.

There are three types of filled paleochannels in the study area: (1) Relatively near surface, generally small, roughly shore normal channels most likely mark the migration of tidal inlets across the shelf during the most recent transgression. (2) Small, relatively wide and relatively shallow generally shore parallel channels may be filled back-barrier or lagoonal channels. (3) Larger channels trending across the shelf probably result from riverine flow.

The complexity of the seismo-stratigraphy of the Quaternary deposits on southeastern Virginia's inner continental shelf is a result of series of high-frequency (fifth-order, 10–20,000 y), low-amplitude (20–30 m) variations in sea level that occurred during the last highstand, roughly 80,000 to 130,000 B.P. The evidence of the small oscillations in sea level is best seen in the regions that were between the shoreline and wave base, today's inner shelf; however, the very low rates of deposition on the shelf make it difficult to correlate specific reflectors or beds or, at times, to distinguish between fifth- and fourth-order changes.

Results for the continuing studies already have been used in the determination to mine several hundred thousand cubic meters of sand from Sandbridge Shoal for use on a Navy-owned facility and in consideration of mining greater quantities of sand from Sandbridge and other shoals for use in the local beach nourishment and hurricane protection efforts.

Introduction

The inner continental shelf offshore of southeastern Virginia (fig. 1) is a focus of both applied and academic studies. Increasing demands for large quantities of sand to nourish the region's valuable beaches have resulted in surveys designed to identify potential sand sources. This work has facilitated the collection of data that enhance the understanding of the area's Quaternary geological history. It is the intent of this paper to provide a means for the characterization of the sand resources and to provide an updated interpretation of the stratigraphic record.

Portions of this paper have been presented in the dissertation of one of the authors (Hobbs, 1997) and in various contract reports (Hardaway and others, 1995; Hobbs, 1996, among others) or meeting presentations (Hobbs and Hardaway, 1996; Hobbs and others, 1997, among others).

Previous Work

Shepard (1932) depicted the sediments offshore of southeastern Virginia as being "shells, sand & gravel," "gravel," near the Virginia–North Carolina border, and "shells & sand" near the mouth of Chesapeake Bay. Shepard based the portrayal on information recorded on navigation charts augmented by examination of samples collected by the United States Coast Survey but provided no indication of the number or spacing of samples. Milliman and others (1972) and Milliman (1972), using a grid of grab samples with an 18-km (10-n-mi) spacing, mentioned a plume of very fine sand with coarse silt extending seaward from Chesapeake Bay and a band of arkosic sediments in the sand portion also extending outward from the bay. With 10 or so samples within the present study area, the reports described the nearshore subarkosic to arkosic fine-grained sediments and sands as being derived from modern, nearshore, fluvial sources and the similarly composed materials found farther offshore as relict fluvial sediments. Amato (1994), in describing the sand and gravel resources of the Atlantic Continental Shelf, provided a summary and review of earlier works and included maps showing the distribution of sediment types. As is the nature of a compilation and review, his work basically echoes the above-referenced studies but does specifically consider the sediments as a resource.

Swift, Shideler, and their co-workers (Shideler and others, 1972; Shideler and Swift, 1972; Swift and others, 1970; 1971; 1972a,b; 1977) performed a series of studies of the Virginia continental shelf. Shideler and others (1972) proposed a standard stratigraphic section for the area, which most subsequent workers have used. The standard section consists of a sequence of four stratigraphic units, termed units A, B, C, and D, separated by major reflectors.

Oaks and others (1974) described the terrestrial, post-Miocene geology of southeastern Virginia (more recent interpretations [Johnson and others, 1985] consider the same sequence to be post-Pliocene). Oaks and others (1974) discussed 10 stratigraphic units that were formed during "6 distinct periods of submergence" and "6 important periods of emergence." The major sea-level lows occurred before the Sedley, Moorings, Windsor, Great Bridge, Londonbridge, and modern units. Johnson and Berquist (1989) summarized the stratigraphic nomenclature used since 1928 in studies of Virginia's coastal plain. Table 1 compares Johnson and Berquist's (1989) terminology, modified with the inclusion of the Chowan Formation from Johnson and others (1985), with the stratigraphy discussed by Oaks and others (1974).

Toscano and others (1989) and Toscano (1992) discussed the Quaternary history of inner continental shelf offshore of Maryland and the inner shelf of the mid-Atlantic. One facet of these studies that has specific bearing to the inner shelf off southeastern Virginia is the set of small-scale fluctuations of sea level, -23 to +6 m, during Oxygen Isotope Stage 5, roughly 75,000 to 130,000 years B.P. This period corresponds to the North American Sangamon (Richmond and Fullerton, 1986). These oscillations, three highs and two intervening lows within 23 m of today's sea level, should be evident on the inner shelf. Those sections of the shelf less than 20 m in depth would have been exposed and the areas at slightly greater depth would have been subjected to shallow-water wave and current energy. Toscano and York (1992) presented a correlation chart for middle Atlantic coastal plain and inner shelf strata. Their work suggests some of the problems of interpretation and correlation. Specifically, the correlation shows "unit C" (Shideler and others, 1972) as existing across major regressions; that is, unit C continues in time through the formation of the Exmore and Eastville (and by extension, Belle Haven [Oertel and Foyle, 1995]) paleochannels. This lack of differentiation in unit C possibly results from the inability of Shideler and others' (1972) equipment to image or resolve some reflectors.

Chen (1992) and Chen and others (1995), using some of the same data as used for the present paper, described a set of filled channels on Virginia's inner

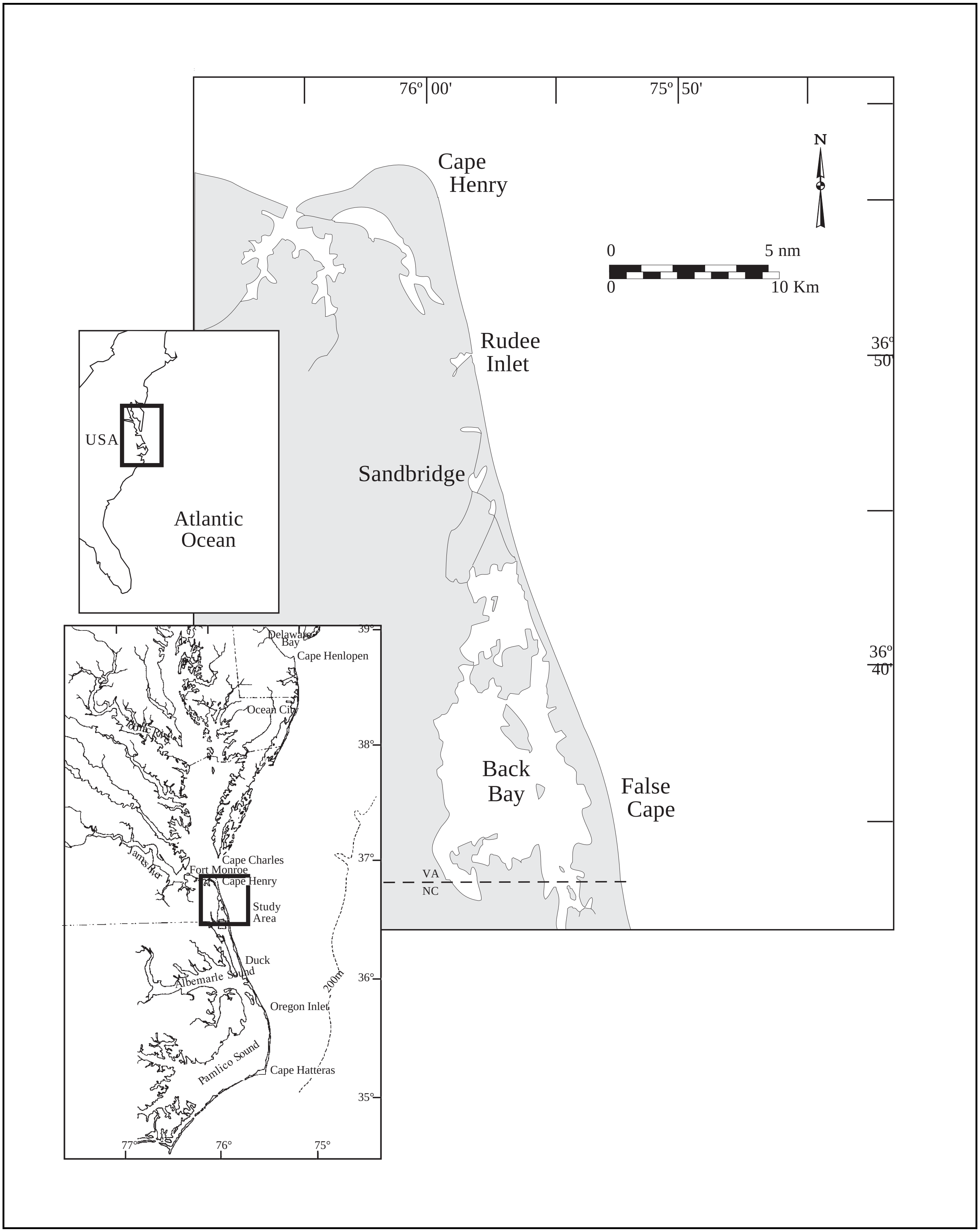


Figure 1. Map depicting the location and extent of the study area.

Table 1. Comparison of nomenclature for the stratigraphy of Virginia's coastal plain.

	Oaks and Coch (1973) Oaks and others (1974)	Johnson and Berquist (1989) Johnson and others (1985)		
HOLOCENE	Unnamed Holocene and Dismal Swamp peat	Unnamed Holocene deposits		HOLOCENE
	Sandbridge Fm.	T	Poquoson Mbr.	
		a F		
	Londonbridge Fm.	b m	Lynnhaven Mbr.	
		b		
	Kempsville Fm.		Sedgefield Mbr.	
	Norfolk Fm.			
PLEISTOCENE		Shirley Fm.		PLEISTOCENE
	Great Bridge Fm.			
		Chuckatuck Fm.		
	Windsor Fm.	Charles City Fm.		
		Windsor Fm. (restricted)		
PLEISTOCENE AND/OR	"Moorings" unit	"Moorings" unit		
PLIOCENE	Bacons Castle Fm.	Bacons Castle Fm.		
				PLIOCENE
		Chowan River Fm.		
	Sedley Fm.	Yorktown Fm.		
MIOCENE				
	Yorktown Fm.	Eastover Fm.		MIOCENE

shelf and attempted to correlate them to the Cape Charles, Exmore, and Eastville paleochannels in Chesapeake Bay of Colman and Hobbs (1987, 1988), Colman and Mixon (1988), and Colman and others (1990). Foyle (1994) and Oertel and Foyle (1995) furthered the understanding of the regional channel systems with the recognition of the Belle Haven paleochannel.

Kimball and Dame (1989), Dame (1990), and Kimball and others (1991) investigated some of the sand resources potentially available within the present study area and provided an initial description and geological history of Sandbridge Shoal. Hardaway and others (1995) and Hobbs (1996) continued the series of studies of the region's sand resources.

Methods

This study is based upon approximately 1,100 km (595 n mi) of high-resolution, 3.5 kHz, seismic-reflection profiles obtained with an analog DataSonics system and printed upon either or both an EPC 4800 or 3202 graphics recorders. Loran-C was used to obtain position information for the earlier profiles, and GPS was used for the more recent. Fixes generally were logged at 2-minute intervals. This data set was augmented by two sets of cores. The first were 9-cm-diameter (3.5-in) vibracores of up to 6 m (20 ft) length collected in the summer of 1987. The second group of cores were 7.5-cm-diameter (3-in) vibracores up to 9 m (30 ft) length that were acquired in the spring of 1994. Additionally, we collected and determined the granule:sand:silt:clay ratios of a set of 380 grab samples of the surface sediments.

Results and Discussion

Plots of the granulometric analyses of the surficial samples indicate that the region is dominated by coarser sediments, most of the samples being in excess of 90 or 95 percent sand. Only 5 of the 380 samples would not plot as “sand” on Shepard’s (1954) ternary classification. The sands usually are coarser than 2 phi with the finer sands occurring generally south of False Cape and in a large area adjacent to the mouth of Chesapeake Bay. Fine-grained sediments occur very near shore near locations where marsh or lagoonal sediments crop out through the beach.

The subbottom profiles depict a set of thin, sometimes discontinuous strata above a widespread sharp reflector that most likely is Shideler and others’ (1972) reflector 1 that is assumed to mark the bottom of the Pleistocene record. The Pleistocene strata are cut by and overlay filled channels of various orientations and scales. A large fragment of wood from 3.7 m below the sea floor (approximately 15.2 m below sea level) in a core almost directly offshore from Rudee Inlet had a carbon-14 date of 9,440 $^{+}$/- 50 yr BP. The wood was at the base of a coarse-sand channel fill immediately above a thick, fine-grained muddy section. The upper portion of the seismic profiles contains many closely spaced, difficult-to-correlate reflectors. The subbottom profiles also display shoals, corresponding to Shideler and others’ (1972) Unit D, atop an older substrate.

Conclusions

Although the surficial sediments within the study area are dominantly sands, their textures are more varied than has been indicated by previous studies. The density of the sample grid used in this study allowed identification of a degree of spatial variability that was not afforded by the earlier studies. The patterns of distribution indicate that Chesapeake Bay probably is the source of a plume of generally finer grained sediments extending from the bay mouth, that isolated patches of much finer grained materials very near shore are related to outcrops of older marsh or back-barrier sediments similar to those exposed along some of the shoreline, and that small offshore areas of differing sediments may indicate either outcrops of older materials or topographically controlled local deposits of modern sediment.

The Pleistocene history of the inner continental shelf of southeastern Virginia and the resulting stratigraphy are more complex than has been suggested by the previous literature. The impact of the Exmore, Belle Haven, and Eastville channel-forming events on the stratigraphy, especially submarine Unit C, has not been fully understood. Similarly the several high-frequency, low-amplitude fluctuations in sea level during Oxygen Isotope Stage 5 have resulted in a complex pattern of thin yet regionally continuous seismostratigraphic units that most likely echo the lithostratigraphy. These fifth-order stratigraphic sequences are difficult to discern in the relatively sediment starved shelf. Furthermore, because the individual sequences are so thin, drainage channels are likely to cut several strata.

There are three distinct types of filled paleochannels within the inner continental shelf. Relatively near surface, generally small, roughly shore normal channels, such as seen near Rudee Inlet, are most likely the courses of tidal inlet channels, in this instance dating from the last lowstand of sea level. Small, relatively wide and relatively shallow, generally shore parallel channels, some of which are evident in the records, may be back-barrier or lagoonal channels. The third type of channel results from riverine flow.

There are substantial resources of sand on the inner continental shelf of Virginia. The deposits occur in three distinct stratigraphic settings (table 2). The most easily discernible type of deposit is the discrete, surficial shoal, as exemplified by Sandbridge Shoal. Shoals are well-defined topographic features on the surface of the inner shelf. In the seismic records they have clear bottom boundaries. After the grain-size characteristics of such deposits are verified by coring, the physical process of mining should be relatively straightforward: dredge the shoal to the depth of the bottom contact.

Filled channels, such as those offshore of Rudee Inlet, are another class of deposit. The fluvial sands filling the channels can be a very clean, high-quality sand suitable for use in beach restoration or nourishment and in construction aggregate. Although there is

Table 2. Inner shelf sand bodies.

	Shoal	Filled channel	Gradational
Visibility	On surface	Buried	Buried
Lateral limits		Sharp	Undefined
Top	Sea floor	Varied	Varied
Bottom	Sharp	Usually sharp	Varied
Seismic definition	Good	Good	Poor
How found	Bathymetry	Seismics Geology	Serendipity Geology (?)
How proved	Coring through bottom reflector	Coring	Coring
Dredging	"Easy" Remove shoal to predetermined depth	"Difficult" Stay within channel	"Very Easy" Stay within broad vertical and horizontal limits

no surface expression of the deposit, the extent of the deposit is fairly clear in subbottom profiles. Mining the filled channels is more difficult than the surficial shoals. Overburden would have to be removed or mixed with the more desirable channel fill. The lateral extent of the deposit is small relative to its length, and the boundaries are sharp. Dredging requires careful mapping of the lateral and vertical limits of the deposit through seismic profiling and coring and careful control of the dredge.

The third type of sand deposit, a lenticular facies, is the most difficult to find. A bed may grade from sediments of unacceptable quality for use to acceptable quality and back to unacceptable. There is no surface expression of the deposit, the top of which could be buried or could be the sea floor. There are no reliable indicators in the seismic records. This class of deposit is discovered serendipitously and only by coring. However, once the deposit is discovered and defined, the process of mining is relatively easy. Changes in sediment type are apt to be gradual with the result that the limits of the area to be dredged are set arbitrarily on the basis of sedimentary characteristics determined by analysis of core samples.

Acknowledgments

We thank our co-workers and acknowledge the substantial funding provided by the Minerals Management Service (MMS) during the course of our efforts. MMS provided funding both through the Continental Margins Program of the Association of American State Geologists and with direct support in cooperative agreements and contracts. B. S. Drucker and T. J. Rowland of MMS and S. S. Johnson of the Virginia Division of Mineral Resources provided encouragement and advice. R. A. Gammisch, and D. A. Milligan of the Virginia Institute of Marine Science assisted in the field and office. Captain L. D. Ward of the *R/V Bay Eagle* contributed substantially to the acquisition of the seismic data. S. M. Kimball and J. K. Dame II participated in early portions of our MMS-funded study of the inner continental shelf offshore of southeastern Virginia. J. R. Woolsey, Jr., and the other members of co-author Hobbs' dissertation committee at the University of Mississippi provided suggestions and comments which improved that document and, thus, this paper.

References

Amato, R. V., 1994, Sand and gravel maps of the Atlantic Continental Shelf with explanatory text: U.S. Department of the Interior, Minerals Management Service, Office of International Activities and Marine Minerals, OCS Monograph MMS 93-0037, 35.

Chen, Z.-Q., 1992, An investigation of the late Pleistocene paleochannel systems in the Continental Shelf, south of the Chesapeake Bay mouth: College of William & Mary, School of Marine Science, Virginia Institute of Marine Science, Gloucester Point, Virginia, unpublished Master's thesis, 100 p.

Chen, Z.-Q., Hobbs, C. H., III, Wehmiller, J. F., and Kimball, S. M., 1995, Late Quaternary paleochannel systems on the continental shelf, south of the Chesapeake Bay entrance: Journal of Coastal Research, 11(3):605-614.

Colman, S. M., Halka, J. P., Hobbs, C. H., III, Mixon, R. B., and Foster, D. S., 1990, Ancient channels of the Susquehanna River beneath Chesapeake Bay and the Delmarva Peninsula: Geological Society of America Bulletin, 102:1268-1279.

Colman, S. M., and Hobbs, C. H., III, 1987, Quaternary geology of the southern Virginia part of the Chesapeake Bay: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1948-A.

___________ 1988, Quaternary geology of the northern Virginia part of the Chesapeake Bay: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1948-B.

Colman, S. M., and Mixon, R. B., 1988, The record of major Quaternary sea-level changes in a large Coastal Plain estuary, Chesapeake Bay, eastern United States: Palaeogeography, Palaeoclimatology, Palaeoecology, 68:99-116.

Dame, J. K., II, 1990, Origin of a solitary sand shoal offshore of Sandbridge Beach, Virginia: College of William & Mary, School of Marine Science, Virginia Institute of Marine Science, Gloucester Point, Virginia, unpublished Master's thesis, 94 p.

Foyle, A. M., 1994, Quaternary seismic stratigraphy of the inner shelf and coastal zone, Southern Delmarva Peninsula, Virginia: Old Dominion University, Norfolk, Virginia, unpublished Ph.D. dissertation, 492 p.

Hardaway, C. S., Hobbs, C. H., III, and Milligan, D. A,. 1995, Investigations of offshore beach sands: Virginia Beach and Sandbridge, Virginia: Virginia Institute of Marine Science, Gloucester Point, Virginia, contract report, 16 p.

Hobbs, C. H., III, 1996, Investigations of isolated sand shoals and associated deposits, Virginia inner shelf, Virginia Institute of Marine Science, Gloucester Point, Virginia, contract report, 11 p.

Hobbs, C. H., III, 1997, The sediments and shallow stratigraphy of a portion of the continental shelf of southeastern Virginia: The University of Mississippi, unpublished Ph.D. dissertation, 177 p.

Hobbs, C. H., III, and Hardaway, C. S., 1996, Sand from Virginia's inner continental shelf (abs.): 29th Underwater Mining Institute, Washington, D.C.

Hobbs, C. H., III, Maa, J. P.-Y., and Hardaway, C. S., 1997, Investigations of southeastern Virginia's sand resources (abs.). Geological Society of America 32nd Annual Meeting, Northeastern Section, 29(1):52-53.

Johnson, G. H., and Berquist, C. R., Jr., 1989, Geology and mineral resources of the Brandon and Norge Quadrangles, Virginia: Virginia Division of Mineral Resources, Charlottesville, Publication 87, 28 p.

Johnson, G. H., Peebles, P. C., Otte, L. J., and Smith, B. J., 1985, The Late Cenozoic geology of southeastern Virginia and the Great Dismal Swamp: American Association of Petroleum Geologists Eastern Section, Field Trip 1, Guidebook, 68 p.

Kimball, S. M., and Dame, J. K., 1989, Geotechnical evaluation of sand resources on the inner shelf of southern Virginia: College of William & Mary, Virginia Institute of Marine Science, Gloucester Point, Virginia, final report to the City of Virginia Beach, two volumes.

Kimball, S. M., Dame, J. K., II, and Hobbs, C. H., III, 1991, Investigation of isolated sand shoals on the inner shelf of southern Virginia: College of William & Mary, Virginia Institute of Marine Science, School of Marine Science, Gloucester Point, Virginia, Project Report, 73 p.

Milliman, J. D., 1972, Atlantic continental shelf and slope of the United States—petrology of the sand fraction of sediments, northern New Jersey to southern Florida: U.S. Geological Survey Professional Paper 529-J, 40 p.

Milliman, J. D., Pilkey, O. H., and Ross, D. A., 1972, Sediments of the continental margin off the eastern United States: Geological Society of America Bulletin, 83(5):1315-1334.

Oaks, R. Q., and Coch, N. K., 1973, Post-Miocene stratigraphy and morphology, southeastern Virginia: Virginia Division of Mineral Resources Bulletin 82, 135 p.

Oaks, R. Q., Jr., Coch, N. K., Sanders, J. E., and Flint, R. F., 1974, Post-Miocene shorelines and sea levels, southeastern Virginia, *in* Oaks, R. Q., Jr., and DuBar, J. R., Post-Miocene stratigraphy central and southern Atlantic coastal plain: Utah State University Press, p. 53–87.

Oertel, G. F., and Foyle, A. M., 1995, Drainage displacement by sea-level fluctuation at the outer margin of the Chesapeake Seaway: Journal of Coastal Research, 11(3):583-604.

Richmond, G. M., and Fullerton, D. S., 1986, Introduction to Quaternary glaciations in the United States of America: Quaternary Science Reviews, 5:3-10.

Shepard, F. P., 1932, Sediments of the continental shelves: Geological Society of America Bulletin, 43(12):1017-1040.

Shepard, F. P., 1954, Nomenclature based on sand-silt-clay ratios: an interim report: Journal of Sedimentary Petrology, 24:151-158.

Shideler, G. L., and Swift, D. J. P., 1972, Seismic reconnaissance of post-Miocene deposits, middle Atlantic continental shelf—Cape Henry, Virginia to Cape Hatteras, North Carolina: Marine Geology, 12:165-185.

Shideler, G. L., Swift, D. J. P., Johnson, G. H., and Holliday, B. W., 1972, Late Quaternary stratigraphy of the inner Virginia continental shelf; a proposed standard section: Geological Society of America Bulletin, 83(6):1787-1804.

Swift, D. J. P., Dill, C. E., Jr., and McHone, J., 1971, Hydraulic fractionation of heavy mineral suites on an unconsolidated retreating coast: Journal of Sedimentary Petrology, 41(3):683-690.

Swift, D. J. P., Holliday, B., Avignone, N., and Shideler, G., 1972a, Anatomy of a shore face ridge system, False Cape, Virginia: Marine Geology, 12:59-84.

Swift, D. J. P., Kofoed, J. W., Saulsbury, F. P., and Sears, P., 1972b, Holocene evolution of the shelf surface, central and southern shelf of North America, *in* Swift, D. J. P., Duane, D. B., and Pilkey, O. H., eds., Shelf sediment transport processes and pattern: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 499–574.

Swift, D. J. P., Nelsen, T., McHone, J., Holliday, B., Palmer, H., and Shideler, G., 1977, Holocene evolution of the inner shelf of southern Virginia: Journal of Sedimentary Petrology, 47(4):1454-1474.

Swift, D. J. P., Shideler, G. L., Avignone, N. F., Holliday, B. W., and Dill, C. E., Jr., 1970, Quaternary sedimentation on the inner Atlantic shelf between Cape Henry and Cape Hatteras: A preliminary report. Maritime Sediments, 6:5-11.

Toscano, M. A., 1992, Record of oxygen isotope Stage 5 on the Maryland inner shelf and Atlantic coastal plain, a post-transgressive-highstand regime, *in* Fletcher, C. H., III, and Wehmiller, J. F., eds., Quaternary coasts of the United States: Marine and Lacustrine Systems, SEPM Special Publication 48, p. 89–99.

Toscano, M. A., Kerhin, R. T., York, L. L., Cronin, T. M., and Williams, S. J., 1989, Quaternary stratigraphy of the inner continental shelf of Maryland: Maryland Geological Survey, Baltimore, Maryland, Report of Investigations No. 5, 116 p.

Toscano, M. A., and York, L. L., 1992, Quaternary stratigraphy and sea-level history of the U.S. middle Atlantic coastal plain: Quaternary Science Reviews, 11:301-328.

Sedimentology of the New Hampshire Inner Continental Shelf Based on Subbottom Seismics, Side-Scan Sonar, Bathymetry, and Bottom Samples

Larry G. Ward

Department of Earth Sciences, Jackson Estuarine Laboratory, 85 Adams Point Road, Durham, NH 03824, (603 862-2175); lgward@christa.unh.edu

Francis S. Birch

Department of Earth Sciences, University of New Hampshire, Durham, NH 03824

Abstract

Typical of glaciated environments, the inner continental shelf of New Hampshire is composed of bedrock outcrops, remnants of glacial deposits (for example, drumlins), sand and gravel deposits, as well as muddier sediments farther offshore. A number of previous studies have defined the general trends of the New Hampshire inner shelf from the coarser deposits nearer the shore to the muddier outer basins. Most recently, a seismic survey (~150 kilometers of side-scan sonar and subbottom seismic profiles), as well as bottom sediment sampling (~74 stations), has provided a detailed bottom map of the southern New Hampshire shelf area (landward of the 30-meter contour). The surficial sediments within this area range from very fine sand to gravel. Bedrock outcrops are common. The seismic survey indicated several large sand deposits exceeding 6 to 8 meters in thickness that occur relatively close to the coast. These sedimentary units, which are within 3 kilometers of the shoreline, are composed of fine to medium sands. Examination of the general morphology and depositional setting indicates at least some of these features are probably relic ebb tidal delta shoals. However, a large eroding drumlin occurs between two of the sand bodies and may represent the source of these deposits. Additional work is needed to verify the origin of these sediment bodies.

Introduction

The New Hampshire inner continental shelf is extremely complex, largely owing to the bedrock structure, repeated glaciations, and major sea-level fluctuations during the Quaternary (for example, a major transgression, regression, and another transgression in the last ~13,000 years; Belknap and others, 1987, Kelley and others, 1995). Consequently, the New Hampshire shelf is heterogeneous, characterized by extensive bedrock outcrops as well as a large range of sedimentary material from boulders to mud. The sedimentary deposits on the inner continental shelf of New Hampshire from approximately 1 to 25 kilometers from shore were originally mapped and described by Birch (1984a, 1984b) using subbottom seismics, side-scan sonar, and magnetics. On the basis of seismic characteristics, Birch (1984b) defined four sedimentary units: glacial till (Unit 1), ice-rafted, glacial-marine deposits of the Presumpscott Formation (Unit 2), offshore Holocene mud (Unit 3), and Holocene sand (Unit 4). In some locations, the sand and gravel deposits form mounds or wedges ranging in size from very small to as much as 5 kilometers long by 3 kilometers wide and as much as 15 meters thick (Birch 1986a, 1986b). A series of these features is found along the 30-meter depth contour running from off Hampton Beach to near the Isles of Shoals and just south of the Piscataqua River entrance. A second group is found in shallower water and appears to be an extension of beach deposits.

The characteristics of the sedimentary deposits on the New Hampshire shelf were described by a number of Minerals Management Service Continental Margins Program activities, including vibracoring of sand and gravel deposits, surficial sediment grab sampling, as well as tidal current and sediment transport studies (Anderson 1987, Birch 1986a, Birch 1986b, Birch 1988, Ward 1989, 1990, 1994, Ward and Anderson 1990, Ward and Birch 1993, 1996). This paper presents the results of the most recent activities, a high-resolution mapping of the inner 5 to 10 kilometers of the southern New Hampshire shelf from Little Boars Head to near the entrance to the Merrimack River (fig. 1; Ward and Birch 1993, 1996). This work included an extensive subbottom seismic and side-scan sonar survey, as well as the collection and grain-size analyses of bottom sediments (fig. 2).

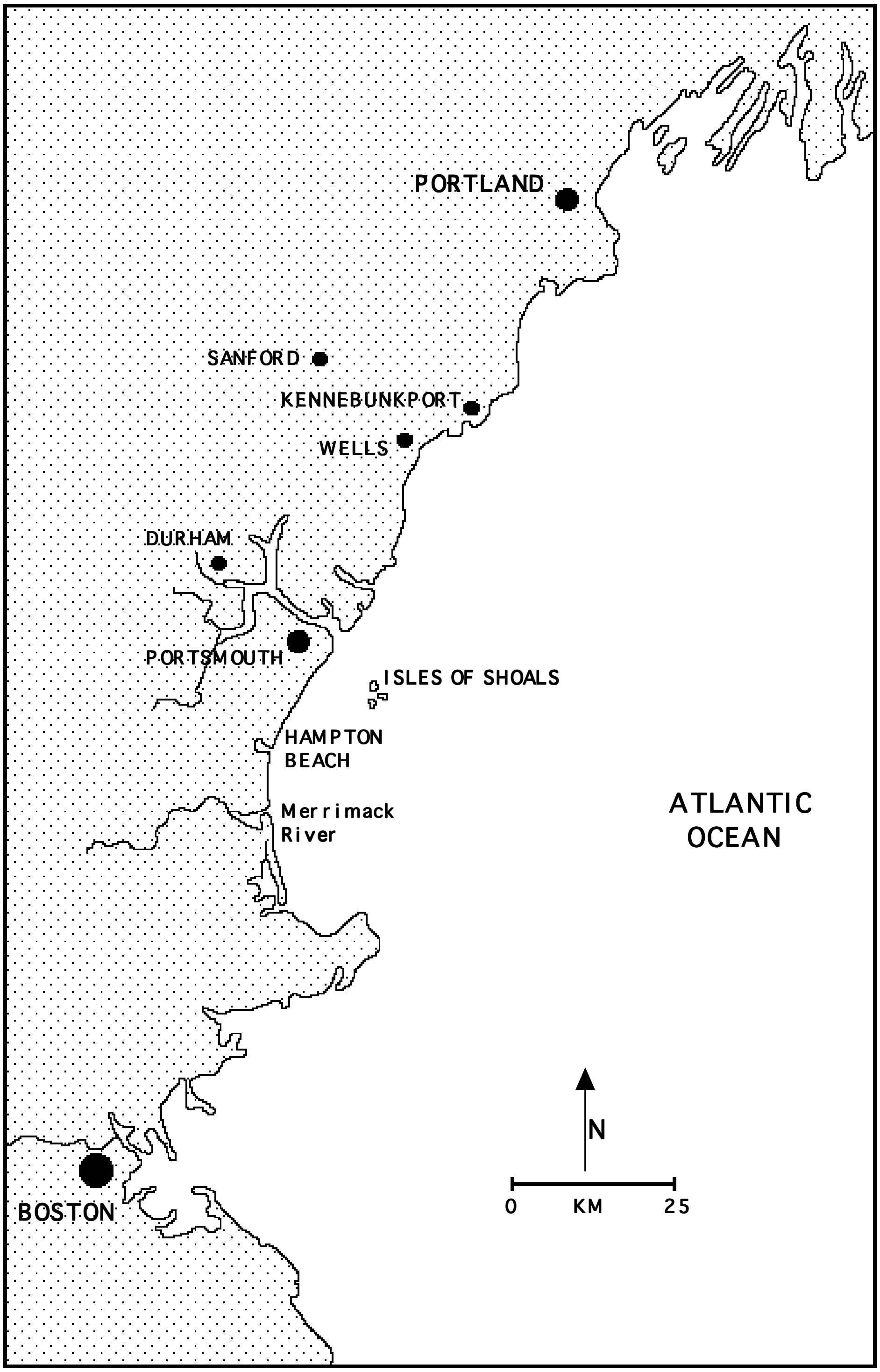


Figure 1. Location map of the study area. The seismic survey and bottom sampling were conducted from Little Boars Head (located ~6 kilometers north of Hampton Beach) to the Merrimack River.

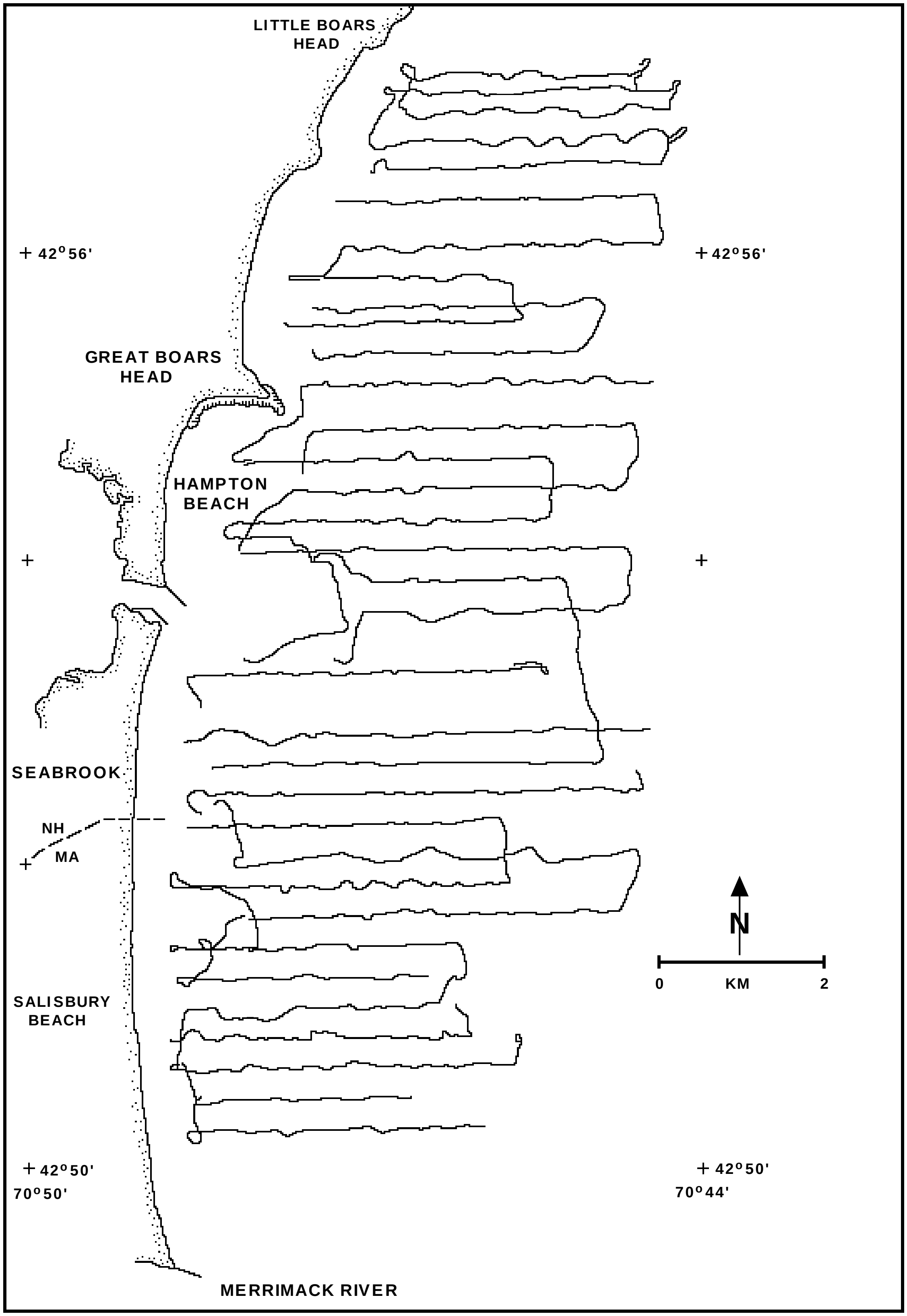


Figure 2. Shiptracks for the seismic survey conducted on the inner New Hampshire shelf. Seventy-four stations located approximately along the shiptracks were sampled for bottom samples.

Methods

A geophysical survey was conducted utilizing an ORE Model 140 subbottom seismic system broadcasting at a frequency of 3.5 kHz with variable power, as well as a side-scan sonar system composed of a dual-frequency Klein Digital Recorder (Model 595) and a Klein Dual-Frequency Towfish (Model 422S-101HF). The side-scan unit operated at 100 and 500 kHz simultaneously and recorded the bottom backscatter on thermal paper. A bathymetric survey was conducted using a dual-frequency (24 kHz and 200 kHz), survey-quality ODOM Hydrographic Systems Fathometer (ODOM Echotrac Model DF-3200 Control Unit and dual-frequency transducer Model 210-33/9-19). The data acquisition system (SAIC INDAS) allowed synchronous annotation of the side-scan record and the echo sounder record with time, depth, and location. Precision location was provided by a UHF navigation system composed of a master transponder (Del Norte Model 547) and a digital distance measuring unit (Del Norte 547). The range accuracy was several meters.

The seismic survey covered a grid of shore-normal transects that extended from within a few hundred meters of shore (~7-meter depth contour) to approximately 5 to 7 kilometers offshore (fig. 2). The transects were spaced a maximum of 0.3 to 0.5 kilometers apart. The subbottom and side-scan sonar records were visually interpreted. Isopach maps of sand and gravel deposits were developed by hand-contouring.

Surficial sediment sampling was conducted aboard the *R/V Jere A. Chase* (Loran C navigation) and the *R/V Gulf Challenger* (GPS navigation) using a Shipek grab sampler. Seventy-four stations were sampled: sediment was recovered from 50 stations, and bedrock cropped out at the other 24 stations. All samples recovered were analyzed for textural characteristics utilizing the methods outlined in Folk (1980) for sieve and pipette analyses.

Results and Discussion

In general, the northern New Hampshire inner shelf tends to be dominated by rocky and gravely bottoms (Mills 1977, Birch 1984b), although a belt of sand extends into the Piscataqua River (Ward 1995). Bedrock and gravel deposits are still common along the southern New Hampshire shelf landward of outcropping bedrock; however, more extensive sand deposits associated with the Merrimack River occur (Ward and Birch 1993, 1996). The muddier offshore deposits (Flight 1972), which typically lie in water depths greater than 70 to 80 meters, are often separated from the coarser inner shelf sediments by outcropping bedrock.

The surficial sediments collected during this study from the southern New Hampshire inner shelf ranged from very fine sand to gravel (3.93 to -2.95 phi, fig. 3). The sediments were well sorted to extremely poorly sorted (0.37 to 3.88 phi). The sands tended to be negatively skewed and the gravels positively skewed. Where the large sand (shoals) deposits were sampled, the sediments were fine to medium sands. Birch (1986a) reported that the mean grain size of the surficial sediment on a large aggregate deposit off North Hampton Beach (described as the southern sand body) ranged from 2 to 3 phi, or within the fine sand interval. Although the southern sand body was not relocated during this survey, the reported textural characteristics appear to be similar to the deposits identified here.

The seismic survey showed the study area has extensive bedrock outcrops or outcrops covered with a thin veneer of sediment. Birch (1984a) mapped the bedrock just seaward of the present study area largely on the basis of subbottom seismic and magnetometer surveys. He described a 5- to 7-kilometers-wide belt of bedrock along the New Hampshire coast that extended from Hampton Beach to the Piscataqua River that was interpreted as an extension of the Rye Formation. These tightly folded gneisses, schists, and amphibolites, which trended northeast–southwest, were usually found within 40 meters of present sea level and had less than 20 meters of relief.

The results of the present survey are consistent with those reported by Birch. Extensive bedrock outcrops, presumably of the Rye Formation, extend in a northeast–southwest direction from less than 1 kilometer from shore to the seaward limit (~7 kilometers) of the study area (fig. 4). Bedrock outcrops are common onshore along the New Hampshire coastline. South of Salisbury Beach, the bedrock on the inner shelf appears to be buried, owing largely to the sediments provided by the Merrimack River delta complex. Sediment thickness often exceeds 60 meters in this area (Birch 1984a).

Several relatively large sediment deposits greater than 6 meters in thickness, presumably consisting largely of sand, were identified from the seismic survey lying landward of the outcropping bedrock between Little Boars Head and the Merrimack River (fig. 4). One of the sand bodies is located just north of the

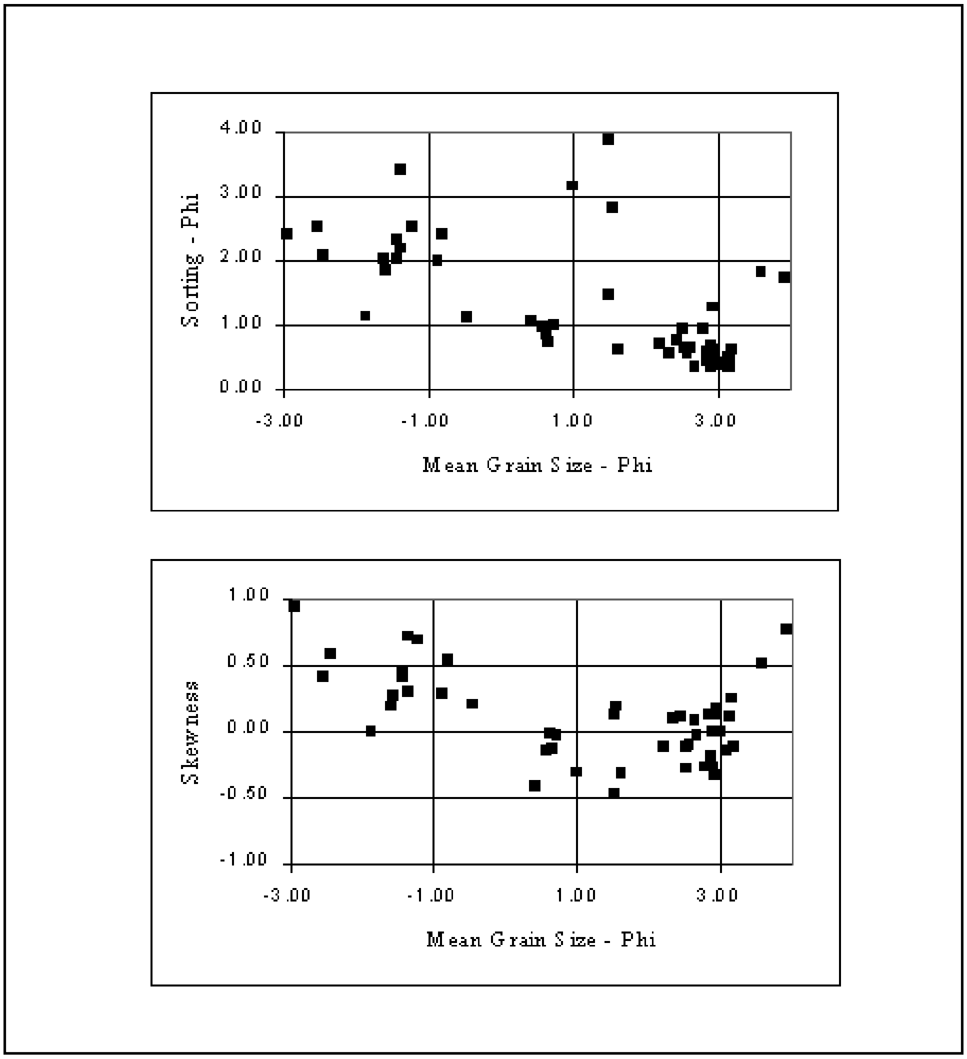


Figure 3. Bivariate plots of grain-size characteristics of bottom samples collected along the inner shelf area off southern New Hampshire.

Merrimack River entrance and is related to the ebb tidal delta complex and jetties stabilizing the channel. Similarly, a sand body adjacent to Hampton Inlet is part of that inlet's shoals. However, two northern sand deposits that approach 2 kilometers in their longest dimension and exceed 8 meters in thickness are not found near any currently active inlets. The present coastal geomorphology, however, does not preclude the existence of relic tidal channels or river systems at these sites. Inspection of the general geomorphic characteristics of the sand bodies leads to the interpretation that these are relic ebb tidal delta complexes. The two large sand deposits, however, are located adjacent to Great Boars Head, a large drumlin. Thus, these two sediment bodies may be related to the erosion of this drumlin. Additional studies are required to verify the origin of these deposits.

Acknowledgments

The work presented in this paper was funded by the Minerals Management Service Continental Shelf Program. The seismic and bathymetric survey of the southern New Hampshire inner shelf was conducted in conjunction with the Coastal Geology Group from Woods Hole Oceanographic Institution (WHOI). Wayne Spencer from WHOI oversaw boat, navigation, and equipment operations and also edited and corrected the bathymetric data at WHOI. The following students and technicians participated in the field and laboratory work: James Jefferson and Philip Pope aided in the field work and conducted the sedimentologic analyses; Chris Hartman helped with the seismic interpretations; and Sandra Weiss prepared the illustrations and the isopach map.

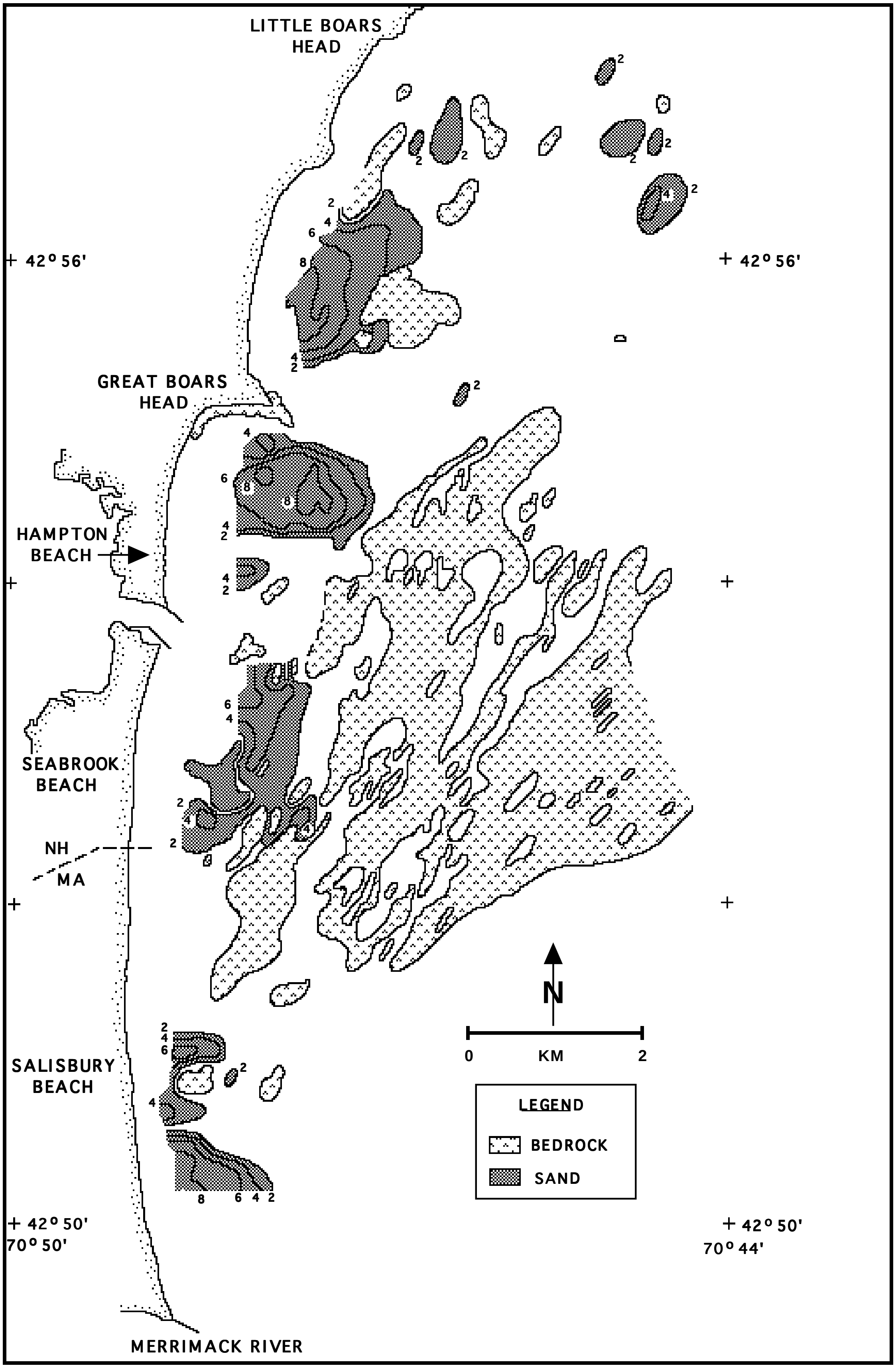


Figure 4. Isopach map of sand deposits mapped along the southern New Hampshire inner shelf. Contours are in meters.

References

Anderson, F. E., 1987, Distribution and concentration of heavy minerals over an aggregate body on the inner continental shelf of New Hampshire: U.S. Department of the Interior, Minerals Management Service Continental Margins Program, Cooperative Agreement #14-12-0001-30296, 30 p.

Belknap, D. F., Anderson, B. G., Anderson, R. S., Anderson, W. G., Borns, H. W., Jr., Jacobson, G. W., Kelley, J. T., Shipp, R. C., Smith, D. C., Stuckenrath, R., Jr., Thompson, W. W., and Tyler, D. A., 1987, Late Quaternary sea level changes in Maine, *in* Nummedal, D., Pilkey, O. H., and Howard, J. D., eds., Sea-level fluctuation and coastal evolution: Tulsa, Oklahoma, Society of Economic Paleontologists Mineralogists Special Publication 41, p. 71–85.

Birch, F. S., 1984a, Geophysical survey of bedrock on the inner continental shelf of New Hampshire: Northeastern Geology 6:92-101.

Birch, F. S., 1984b, A geophysical survey of sedimentary deposits on the inner continental shelf of New Hampshire: Northeastern Geology 6:207-221.

Birch, F. S., 1986a, Evaluation of sand and gravel on the inner continental shelf of New Hampshire: U.S. Department of the Interior, Minerals Management Service Continental Margins Program, Cooperative Agreement #14-12-0001-30115, 14 p.

Birch, F. S., 1986b, Vibracores from the inner continental shelf of New Hampshire: U.S. Department of the Interior, Minerals Management Service Continental Margins Program, Cooperative Agreement #14-12-30115, 54 p.

Birch, F. S., 1988, Sediments of the inner continental shelf: first- and second-year projects in New Hampshire, *in* Hunt, M. C., Ratcliff, D. C., Doenges, S., and Condon, C., eds., Proceedings of the First Symposium on the Studies Related to Continental Margins—a summary of year-one and year-two activities: U.S. Department of the Interior, Minerals Management Service Continental Margins Program and Association of American State Geologists Continental Margins Committee, p. 242–251.

Kelley, J. T., Gehrels, W. R., and Belknap, D. F., 1995, Late Holocene relative sea level rise and the geologic development of tidal marshes at Wells, Maine, U.S.A.: Journal of Coastal Research, 11:136-153.

Flight, W. R., 1972, The Holocene sedimentary history of Jeffreys Basins: University of New Hampshire, Durham, M.S. thesis, 173 p.

Folk, R. L., 1980, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing Company, 185 p.

Mills, T. E., 1977, Inner continental shelf sediments off New Hampshire, University of New Hampshire, Durham, M.S. thesis, 64 p.

Ward, L. G., 1989, Sedimentological characteristics of vibracores taken in sand and gravel deposits on the inner continental shelf of New Hampshire: U.S. Department of the Interior, Minerals Management Service Continental Margins Program, Cooperative Agreement 14-12-0001-30316, 22 p.

Ward, L. G., 1990, A pilot study to evaluate the sedimentary environment of an offshore aggregate deposit on the inner continental shelf of New Hampshire: U.S. Department of the Interior, Minerals Management Service Continental Margins Program, Cooperative Agreement MMS#14-12-0001-30387, 45 p.

Ward, L. G., 1994, Nearbottom currents and sediment transport on the inner continental shelf of New Hampshire, *in* Dellagiarino, G., Masterson, A. R., and Miller, L. A., eds., Studies related to continental margins—a summary of year-five and year-six activities: U.S. Department of the Interior Minerals Management Service Continental Margins Program and Association of American State Geologists Continental Margins Committee, p. 150–156.

Ward, L. G., 1995, Sedimentolgy of the lower Great Bay/ Piscataqua River Estuary: Department of the Navy, NCCOSC RDTE Division Report, San Diego, California, 102 p.

Ward, L. G., and Anderson, F. E., 1990, Sedimentology of sand deposits from the inner continental shelf of New Hampshire, *in* Hunt, M. C., Doenges, S., and Stubbs, G.S., eds., Studies related to continental margins—a summary of year-three and year-four activities: U.S. Department of the Interior Mineral Management Service Continental Margins Program and Association of American State Geologists Continental Margins Committee, p. 194–198.

Ward, L. G., and Birch, F. S., 1993, Subbottom seismic, side-scan sonar, and bathymetric survey of the inner continental shelf of (southern) New Hampshire: Final Report Cooperative Agreement 14-35-0001-30534, U.S. Department of the Interior, Minerals Management Service, 11 p.

Ward, L. G., and Birch, F. S., 1996, Surficial sediment distribution map of the inner continental shelf off southern New Hampshire based on side-scan sonar and bottom samples: Final Report Cooperative Agreement 14-35-0001-30731, U.S. Department of the Interior, Minerals Management Service.

Stratigraphic Framework and Heavy Minerals of the Continental Shelf of Onslow and Long Bays, North Carolina

Charles W. Hoffman

North Carolina Geological Survey, Coastal Plain Office,
4100-A Reedy Creek Road, Raleigh, NC 27607-6411

Andrew E. Grosz

U.S. Geological Survey, 954 National Center, Reston, VA 20171

John G. Nickerson

North Carolina Geological Survey, Coastal Plain Office

Abstract

One hundred fourteen vibracores from the Atlantic Continental Shelf offshore of southeastern North Carolina were opened, described, and processed over several contract years (Years 6 through 9) of the Minerals Management Service–Association of American State Geologists Continental Margins program. Reports for Years 9 and 10 of the program compiled the results of the work and assembled the data for release as an interactive CD-ROM report, respectively.

The Continental Shelf of Onslow and Long Bays consists predominantly of outcropping Cretaceous through late Tertiary geologic units. Nearshore these units are covered and incised by late Tertiary and Quaternary units. From oldest to youngest, formally recognized geologic units mapped as part of this study are the Late Cretaceous Peedee Formation—a muddy, fine- to medium-grained quartz sand with trace amounts of glauconite and phosphate; the Paleocene Beaufort Formation—a muddy, fine- to medium-grained glauconitic quartz sand with locally occurring turritelid-mold biosparudite; the middle Eocene Castle Hayne Formation—a sandy bryozoan biomicrudite and biosparrudite; the Oligocene River Bend Formation—a sandy molluscan-mold biosparrudite; and the Miocene Pungo River Formation—a medium-grained, poorly sorted slightly shelly phosphatic sand. Informal units include a very widespread, unnamed fine- to very fine grained, well-sorted, dolomitic muddy quartz sand that is biostratigraphically equivalent to the Oligocene River Bend Formation; several large valley-fill lithosomes composed of biomicrudite, biomicrite, and biosparrudite of Plio/Pleistocene age; muddy, shelly sands and silty clays of Pliocene, Pleistocene, or mixed Plio/Pleistocene age; and loose, slightly shelly, medium- to coarse-grained sands assigned a Holocene age.

Heavy minerals (S.G.>2.96) comprise an average of 0.54 weight percent (on a bulk-sample basis) of the sediments in 306 samples derived from the 114 vibracores. Heavy-mineral content ranges from <0.01 to 3.69 weight percent. The economic heavy mineral content (EHM = ilmenite + zircon + rutile + aluminosilicates + leucoxene [altered ilmenite] + monazite) of the bulk samples averages 0.26 weight percent in a range of <0.01 to 1.70 weight percent. As a percentage of the heavy-mineral concentrate, the average EHM value is 45.78 percent in a range of 0.27 to 68.60 percent.

The distribution of heavy minerals offshore of southeastern North Carolina is controlled by the lithostratigraphic framework. The unnamed Oligocene sand unit has the highest heavy-mineral content, averaging 0.86 weight percent on a bulk sample basis. The remaining geologic units and their heavy-mineral content (in decreasing order of abundance) are Beaufort (0.64 percent), Holocene sand (0.60 percent), Plio-Pleistocene muddy sand and silty clay (0.59 percent), Peedee (0.42 percent), River Bend (0.34 percent), Plio-Pleistocene carbonate (0.12 percent), and Castle Hayne (0.08 percent). The heavy-mineral assemblage is fairly consistent throughout the different units. Significantly smaller percentages of heavy minerals correlate with increased amounts of $CaCO_3$ in the sediments.

The sediments analyzed in this study have significantly lower overall heavy-mineral content, as well as lower EHM content than sediments that are known to host commercially important heavy-mineral deposits in the southeastern United States. The potential for economic deposits of heavy minerals in the area of this study, therefore, appears to be limited.

Introduction

This report presents data developed in the course of a multiyear project sponsored by the U.S. Department of the Interior Minerals Management Service (MMS) in cooperation with the Continental Margins Committee of the Association of American State Geologists (AASG). Beginning with Year 6 of the program, the North Carolina Geological Survey, working cooperatively with the U.S. Geological Survey and North Carolina State University, processed a set of 114 vibracores taken on the Continental Shelf off southeastern North Carolina (fig. 1). The focus of this program was the study of the stratigraphy and heavy-mineral resource potential of the Atlantic Continental Shelf in the region of Cape Fear, a cuspate foreland.

The vibracores were collected in 1972 by the U.S. Army Corps of Engineers Coastal Engineering Research Center (CERC) and were reported on by Meisburger (1977, 1979). These cores remained largely intact following the CERC work and were provided for study to the North Carolina Geological Survey (NCGS) in 1990 by Andrew E. Grosz of the U.S. Geological Survey. Under the MMS-AASG cooperative agreement, the NCGS also subcontracted for the collection and analysis of new, as well as the work-up of existing, shallow, high-resolution seismic reflection data for the study area (fig. 1). This work was conducted by Stephen W. Snyder of North Carolina State University. A seismic stratigraphic framework for part of the region was presented in Snyder and others (1994).

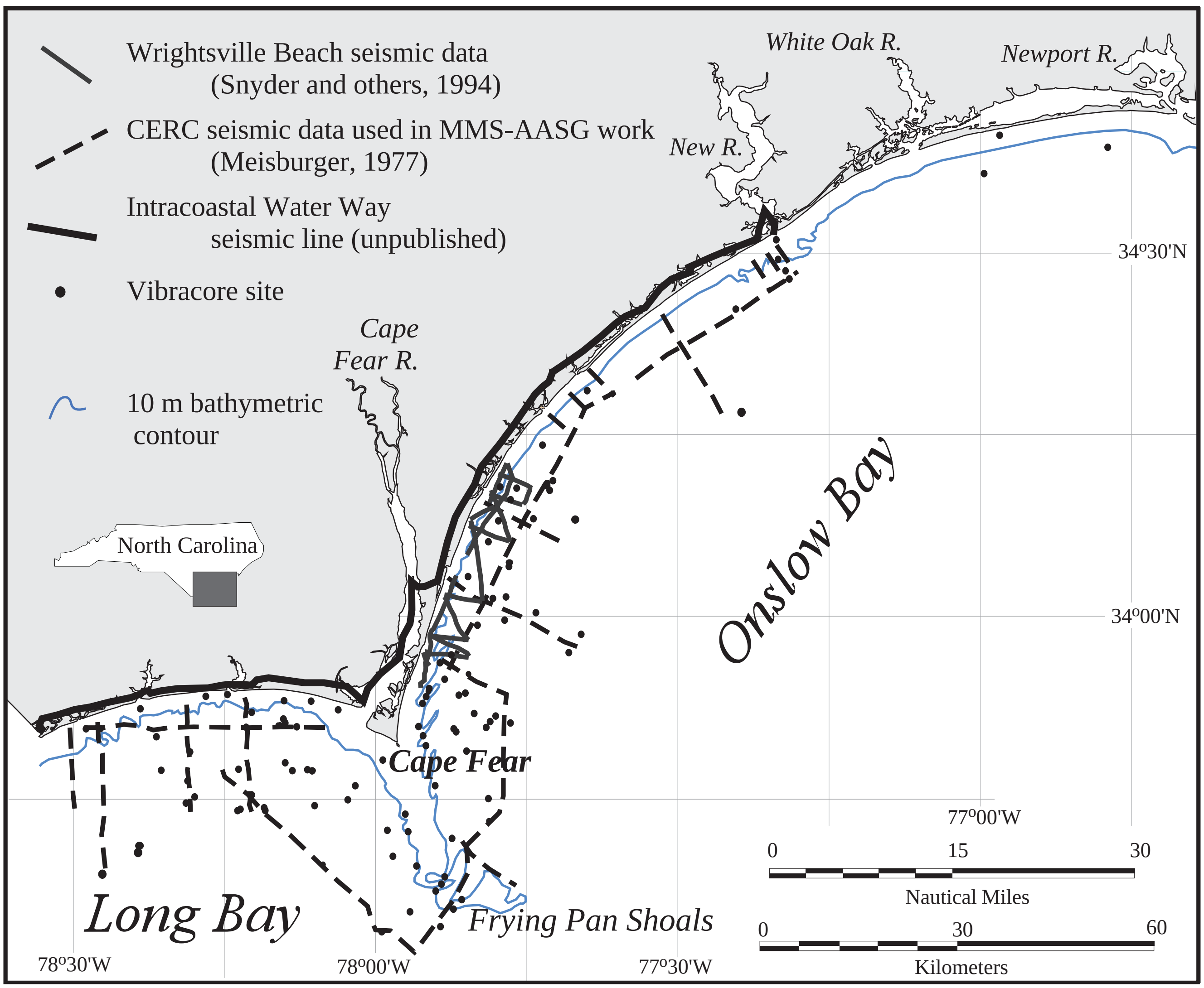


Figure 1. The project study area showing MMS-AASG project data in the Continental Shelf of Onslow and Long Bays, North Carolina.

The vibracores were opened and processed over several contract-years (Years 6 through 9 of the MMS-AASG program). The results and description of the analytical methods were published in a series of NCGS open-file reports (Hoffman and others, 1991; Nickerson and others, 1993; Nickerson and others, 1994). The vibracore data, along with images and descriptions of the vibracores, were compiled and published on a compact disk (CD) by Hoffman (1997).

Stratigraphy

The Continental Shelf of Onslow and Long Bays consists predominantly of outcropping Cretaceous through late Tertiary geologic units (fig. 2). Nearshore they are covered and incised by late Tertiary and Quaternary units. Snyder and others (1994) and Nickerson and others (1994) each described the distribution and characteristics of geologic units that occur within the Cape Fear region on the basis of data developed from the vibracore data set. The stratigraphic framework of the region was constructed from a variety of data developed through the MMS-AASG Continental Margins projects, including lithologic descriptions and photographs of the vibracores; foraminiferal biostratigraphic analysis performed on 19 project cores by Larry Zarra, former geologist with NCGS, and summarized in Hoffman and others (1991); limited molluscan biostratigraphic analysis provided by L. W. Ward, Virginia Museum of Natural History (Nickerson and others, 1994); additional biostratigraphic work per-

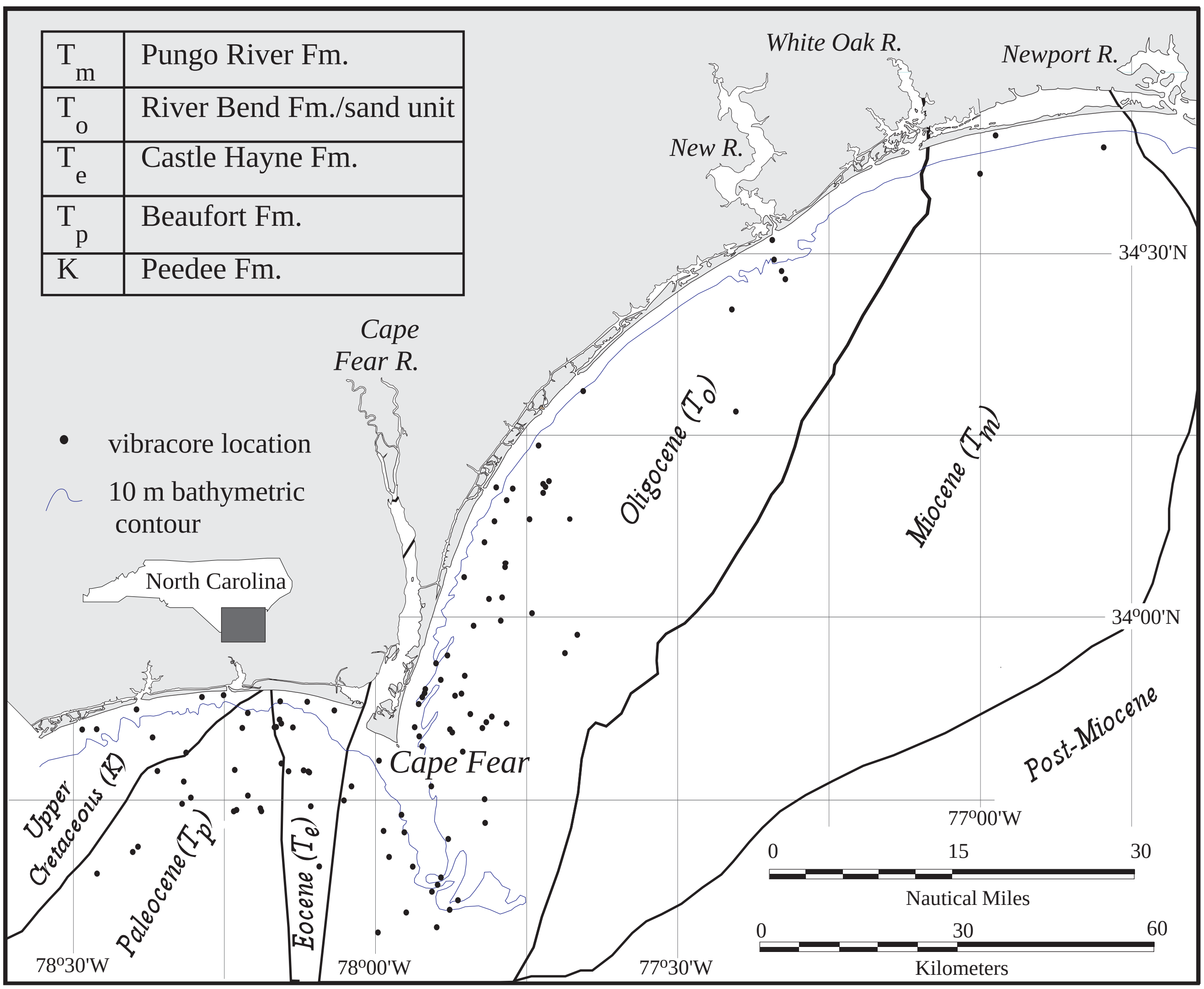


Figure 2. Generalized geologic map of Onslow and Long Bays, North Carolina. (Miocene geology from Snyder and others, 1993).

formed by Mary Watson of the NCGS (Nickerson and others, 1994); and seismic sequence analysis of several data sets by S. W. Snyder.

The oldest unit encountered, the Peedee Formation of Late Cretaceous age, crops out in northwestern and north-central Long Bay. This unit is characteristically a muddy, fine- to medium-grained quartz sand with trace amounts of glauconite and phosphate. Zarra (unpublished data) assigned samples from this unit to the *Gansserina gansseri* planktic Zone, which is Maastrichtian (Upper Cretaceous). This unit has been traced through the subbottom via seismic records into southern Onslow Bay as seismic sequence K_{pd} of Snyder and others (1994).

The Paleocene Beaufort Formation consists of muddy, fine- to medium-grained glauconitic quartz sand with locally occurring turritelid-mold biosparrudite. This unit is identified on the basis of lithologies that correlate with Paleocene-age sediments reported by Harris and Laws (1994) from vibracores in Long Bay; the presence of *Flabellum*, a coral commonly recognized as a Paleocene indicator; similar lithologies described from onshore boreholes by Zarra (1991); and stratigraphic identifications made by Meisburger (1979) on some of these cores. Paleocene strata were reported to crop out in Long Bay by Meisburger (1979).

The middle Eocene Castle Hayne Formation crops out in northern Long Bay and consists of a sandy bryozoan biomicrudite to biosparrudite. Zarra (unpublished data) identified two diagnostic Castle Hayne foraminifera in one core, *Eponides carolinensis* and *Siphonina danvillensis*, and another one contained the middle Eocene megafossil *Pecten membranosus*. Snyder and others (1994) showed that the Castle Hayne Formation, in southern Onslow Bay, is thin and discontinuous and occupies channels cut into the underlying Peedee strata (fig. 3).

Oligocene-age deposits are represented by the molluscan-mold biosparrudite of the River Bend Formation, and an unnamed fine- to very fine grained,

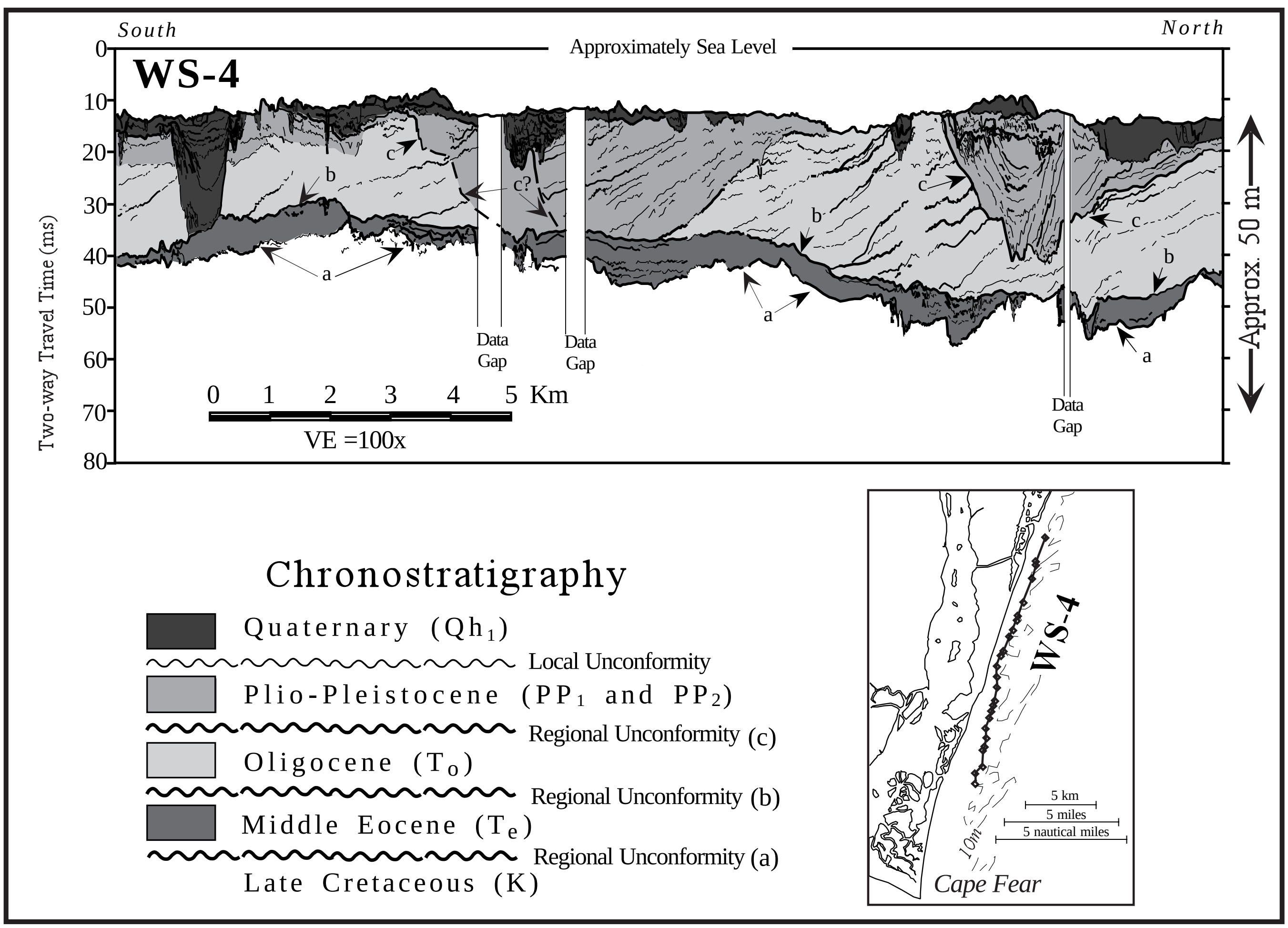


Figure 3. Seismic cross-section from off the southeastern coast of North Carolina showing several of the geologic units defined and mapped under the MMS-AASG Continental Margins program.

well-sorted, dolomitic, muddy quartz sand unit. The River Bend Formation crops out in the New River Inlet area and extends slightly to the south. The unnamed sand unit, determined to be biostratigraphically equivalent to the River Bend Formation, is widespread in southwestern Onslow Bay (Zarra, unpublished data cited in Hoffman and others, 1991).

A single core in northern Onslow Bay penetrated the Miocene Pungo River Formation. The lithology consists of medium-grained, poorly sorted, slightly shelly phosphatic sand. Zarra (unpublished data) noted the presence of a middle to upper Miocene benthic index species, *Virgulinella miocenica*, and stated that the age could be in the range of planktic Zone N9 to N11. The limited number of samples precluded this unit from being included in heavy mineral statistical summaries.

Several large valley-fill lithosomes delineated by seismic data in southern and south-central Onslow Bay (PP_{vf} unit of Snyder and others, 1994; PP_1 in this report) have been confirmed through vibracore data to be composed of biomicrudite, biomicrite, and biosparrudite. These deposits commonly contain pieces of bryozoans, barnacle plates, abraded fragments of molluscan shells, and a mixture of Pliocene and Pleistocene microfaunas and macrofaunas. The PP_1 unit occupies four northwest-southeast-trending paleovalleys greater than 3 kilometers wide and cut more than 15 meters deep into the Oligocene section (fig. 3).

Muddy, shelly sands and silty clays of Pliocene, Pleistocene, or mixed Plio/Pleistocene age are informally referred to herein as the PP_2 unit. Within this range of lithologies, the unit exhibits a high degree of variability throughout the study area. Thirty-two cores encountered outcropping PP_2 strata. Zarra (unpublished data) recognized *Globigerina woodi* and *Globigerina eamesi*, both of which became extinct in the Pliocene, in one core within this unit. Other PP_2 samples carry a clearly Pleistocene fauna (for example, *Carolinapecten eboreus* or *Chama gardneri*). Another sample from this unit contained both Pliocene and Pleistocene faunas (*Mulinia congesta* and *Mulinia lateralis*).

The PP_2 unit is considered to be approximately correlative with two lithosomes identified from shallow, high-resolution seismic data by Snyder and others (1994): the lower shoreface, a seaward extension of the modern shoreface, and paleofluvial channel-fill deposits, which consist of distinct channel-fill deposits that can be traced locally onto the shelf.

Loose, slightly shelly, medium- to coarse-grained quartz sands present at the sediment-water interface along the inner shelf are interpreted to represent the youngest unit in the area. It is preliminarily assigned a Holocene age and informally referred to as "Qh_1." Shells with original pigment remaining are characteristic of this unit. This unit most likely represents the two shoal lithosomes (linear shoreface-attached shoals and inner shelf sand shoals) of Snyder and others (1994) and is most prevalent in the Frying Pan Shoals area.

Heavy Minerals

Summary heavy-mineral data are given in tables 1 and 2. Average total heavy mineral (THM) content of the 306 vibracore samples derived from the 114 vibracores, expressed as a weight percentage of the bulk sample, is 0.54 in a range of <0.01 to 3.69 weight percent with a standard deviation of 0.50 weight percent.

The abundance of heavy minerals varies systematically among the lithostratigraphic units (fig. 4). The unnamed Oligocene sand unit has the highest heavy-

Table 1. Summary statistics on the distribution of heavy minerals by stratigraphic unit. Heavy-mineral values are expressed as a weight percent of the bulk samples.

Straigraphic Unit	**Qh1**	**PP1**	**PP2**	**Oligocene sand**	**River Bend**	**Castle Hayne**	**Beaufort**	**Peedee**
n	37	51	96	50	6	6	6	8
average	0.60%	0.10%	0.59%	0.87%	0.34%	0.08%	0.64%	0.42%
maximum	1.35%	0.69%	3.58%	3.69%	0.47%	0.18%	1.10%	0.95%
minimum	0.08%	0.00%	0.01%	0.12%	0.18%	0.02%	0.23%	0.16%
st. dev.	0.35%	0.12%	0.46%	0.63%	0.11%	0.05%	0.36%	0.29%

Table 2. Summary statistics on the distribution of the principal heavy-mineral species expressed as a percentage of the heavy-mineral concentrate.

mineral	MAG	ILM	GAR	STA	EPI	PYR	SIK	TOU	LEU
n	143	298	294	302	299	225	298	296	284
average	<.01%	0.14%	0.02%	0.06%	0.09%	0.04%	0.02%	0.03%	0.02%
maximum	0.03%	1.10%	0.20%	1.06%	0.49%	0.44%	0.34%	0.26%	0.13%
minimum	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%
st. dev.	<.01%	0.14%	0.02%	0.09%	0.10%	0.07%	0.03%	0.04%	0.02%

	RUT	ZIR	MON	PHO	GLA	SUL	CAR	OTH
n	304	295	35	269	38	191	85	275
average	0.03%	0.04%	0.00%	0.02%	0.01%	0.06%	0.03%	0.02%
maximum	0.19%	0.43%	0.03%	0.34%	0.11%	0.90%	0.39%	0.24%
minimum	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%	<.01%
st. dev.	0.03%	0.04%	0.01%	0.03%	0.02%	0.13%	0.06%	0.03%

Key to abbreviations: MAG/magnetite, ILM/ilmenite, GAR/garnet, STA/staurolite, EPI/epidote, PYR/pyroboles (pyroxene+amphibole), SIK/aluminosilicates (sillimanite+kyanite+andalusite), TOU/tourmaline, LEU/leucoxene, RUT/rutile, ZIR/zircon, MON/monazite, PHO/phosphate, GLA/glauconite, SUL/sulphides, CAR/carbonate (shells), OTH/others.

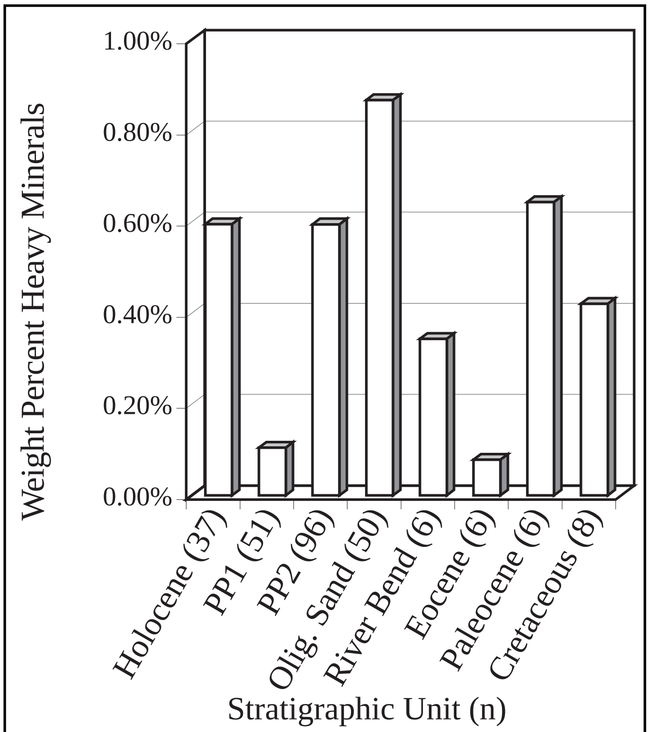


Figure 4. Plot of the distribution of heavy minerals (on a bulk sample basis) within the major stratigraphic units of the study area (n = number of samples).

mineral content, averaging 0.86 weight percent on a bulk sample basis. Other units with higher-than-average heavy-mineral content are the Beaufort Formation (0.64 percent), Holocene sand—Qh_1 (0.60 percent), and the Plio-Pleistocene muddy sand and silty clay—PP_2 (0.59 percent). The units containing lower-than-average heavy-mineral concentrations include the Peedee Formation (0.42 percent), River Bend Formation (0.34 percent), Plio-Pleistocence carbonate—PP_1 (0.12 percent), and Castle Hayne Formation (0.08 percent).

A plot of heavy-mineral content versus calcium carbonate content (Fig. 5) shows an inverse relationship. Indeed the four units with less-than-average heavy-mineral content are the four units with the highest average $CaCO_3$ content (>45 average weight percent). No particular relationship between heavy-mineral content and mean grain size is evident (fig. 6) over the 216 siliciclastic samples for which mean grain size was determined.

The heavy-mineral suite (fig. 7) remains fairly consistent throughout the different stratigraphic units, especially with respect to the primary heavy minerals. Variability is highest in phosphate, carbonate (typically phosphatized shells), and sulphides (typically marcasite

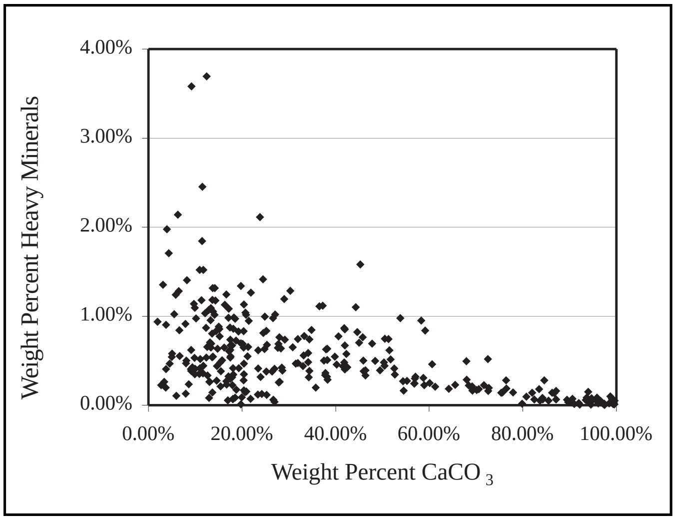


Figure 5. Plot of weight percent heavy minerals (on a bulk sample basis) versus calcium carbonate content

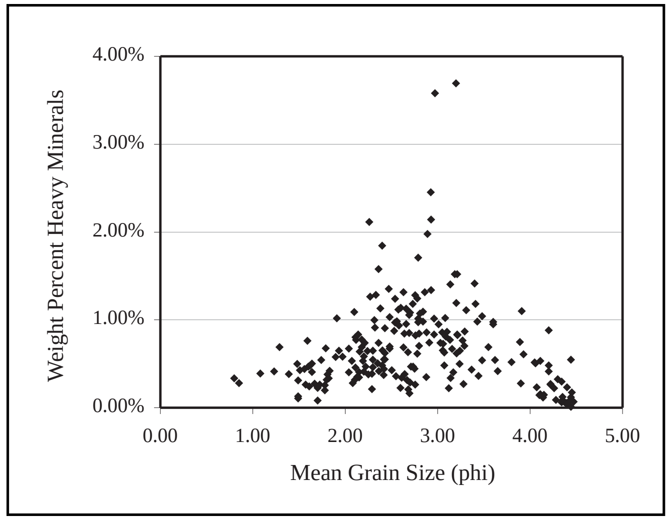


Figure 6. Plot of the weight percent heavy minerals (on a bulk sample basis) versus grain size (216 samples).

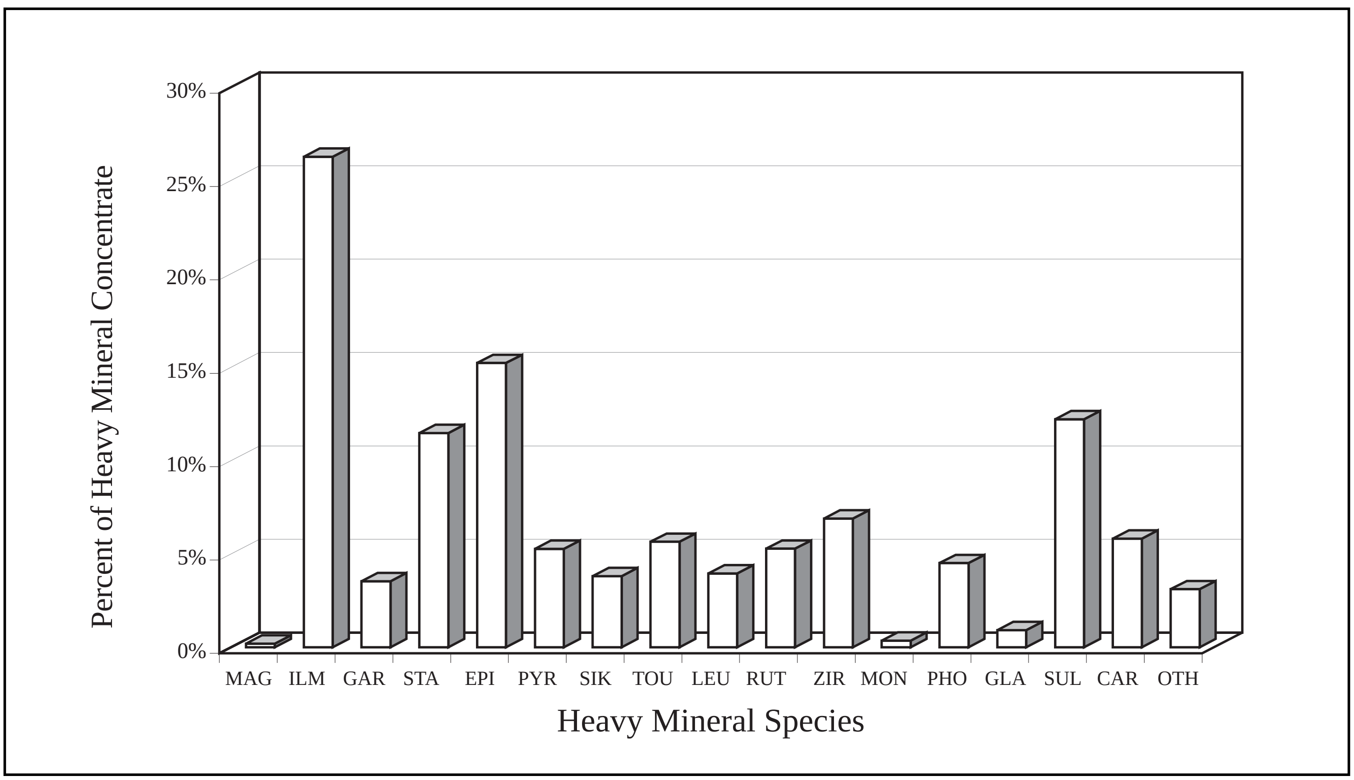


Figure 7. Plot showing the heavy mineral content by species for the 306 samples of the study area. Key to abbreviations: MAG/magnetite, ILM/ilmenite, GAR/garnet, STA/staurolite, EPI/epidote, PYR/pyroboles (pyroxene + amphibole), SIK/ aluminosilicates (sillimanite + kyanite + andalusite), TOU/tourmaline, LEU/leucoxene, RUT/rutile, ZIR/zircon, MON/monazite, PHO/phosphate, GLA/glauconite, SUL/sulphides, CAR/carbonate (shells), OTH/others.

and pyrite replacement growths in shells). The average sulphide value of more than 12 percent of the heavy-mineral concentrate is a statistical anomaly in that these minerals occur predominantly in carbonate units that have very low heavy-mineral abundances. When present they account for a relatively large percentage of the heavy-mineral concentrate. Also, when a given mineral species is absent or not detected, that sample is not figured into the calculation of the average value. Thus, when sulphides are present, they typically comprise a high percentage, and when not present they are not counted toward the average.

The average economic heavy mineral (EHM = ilmenite + zircon + rutile + aluminosilicates + leucoxene [altered ilmenite] + monazite) content of the heavy-mineral concentrates is 45.78 weight percent. Ilmenite is the most abundant mineral of the EHM suite, constituting an average of 26.60 weight percent of the heavy-mineral concentrates. The remainder of the average EHM content contains 8.77 weight percent zircon with 4.47 weight percent rutile, 4.27 weight percent aluminosilicates, 3.04 weight percent leucoxene, and 0.19 weight percent monazite. Other minerals having lesser economic significance include staurolite, tourmaline, and garnet with average weight percentages of 11.31, 4.48, and 3.42, respectively.

The sediments analyzed in this study have significantly lower overall heavy-mineral contents, as well as lower EHM contents than sediments that are known to host commercially important heavy-mineral deposits in the southeastern United States. The potential for economic deposits of heavy minerals in the area of this study, therefore, appears to be limited.

CD-ROM Publication

North Carolina's MMS-AASG Continental Margins project for Year 10 was to compile the data developed through the four previous project years and release it in an electronic format. The multiple years of work generated a very large database of color vibracore images (approximately 1,200 photographs), descriptions (114 cores), and analytical data (several laboratory notebooks). Traditional printed publication methods are cost prohibitive in terms of publishing such a database in its entirety. The advent of relatively inexpensive compact disk (CD) writers along with the simplification of converting standard text and image files to hypertext markup language (HTML) presented a feasible method whereby such a large amount of information could be economically packaged and distributed as a North Carolina Geological Survey publication—namely as an open-file report on CD.

The product was set up just as a World Wide Web site would be—a series of linked graphics, text, and spreadsheet files (fig. 8). This approach enabled the user to use commonly available software, namely an Internet browser, to "launch" the report and move through the files interactively. Included in the publication were

- maps illustrating vibracore locations and the regional geologic framework
- color images (at two sizes) of all 114 vibracores
- lithologic descriptions of the vibracores
- tabulated data providing basic information (length, water depth, latitude, longitude), stratigraphic and sedimentological data (stratigraphic unit, mean grain size, and weight percent heavy minerals), and weight percent heavy minerals by species for each of the vibracores.

The bulk of the text and spreadsheet information was readily available in electronic format through the efforts made to publish prior years' reports. The core images existed as 4 × 6 inch color prints with each print showing an approximately 30-cm segment of the 4-inch-diameter (~10-cm) split vibracore. The photos were scanned on a flatbed scanner attached to a desktop PC. Scanning resolution was 450 dots (pixels) per inch (dpi) at 50 percent of the original size. This created a high-resolution "archive" image that is typically 1,800 × 2,700 pixels and uses 13.5 MB of storage memory when saved in a tagged image file format (TIFF). (In retrospect, the scanning resolution was higher than necessary. A lower resolution of 300 dpi would have been sufficient.) To be more practical in terms of file size, these images were then resampled to 300 dpi to yield files that are 1,200 × 1,800 pixels and use 6 MB of storage memory.

The 300-dpi individual file segments were then electronically pasted together in an image-processing application and laid out as composite core images in a 4,500 × 2,175 pixel image template (still at 300 dpi). Core segments were arranged in horizontal strips about 1.5 m long with the top of the core being in the top left of the image. The 300-dpi TIFF images vary in size, and range from 1.3 to 16.7 MB. Final image processing consisted of saving each composite to JPEG format—one 600 × 290 pixel image at 300 dpi and one 3,000 × 1,450 pixel image at 200 dpi for "full-screen" and "zoomed-in" views, respectively. These JPEG files vary in size depending on core length. The full-screen images are mainly in the 50 to 70 KB size in a range of 13 to 78 KB. The larger image files are about

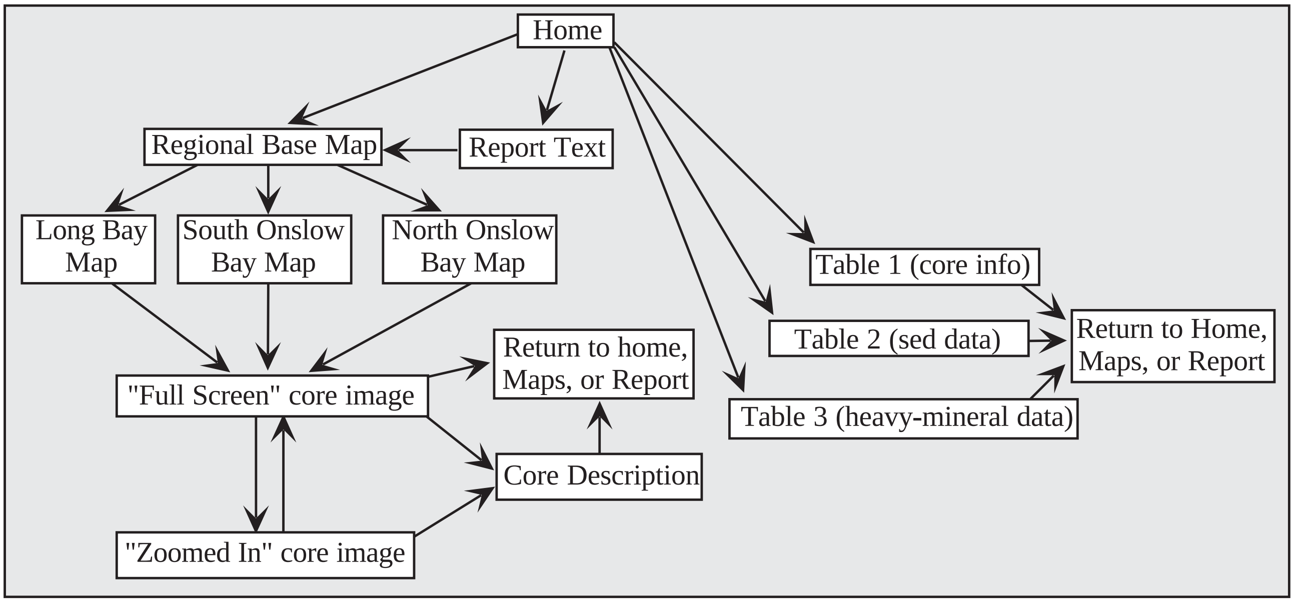


Figure 8. NCGS Open-File Report 97-4 “site map.” Arrows indicate links between the various files shown in the diagram.

15 times the size of the their smaller counterparts and range up to about 1 MB in size.

The smaller image size (full-screen view) was selected so that the image would display in a browser window on a monitor set to a 800 × 600 pixel screen size. This provides a reasonable overview of the core’s texture and lithology and allows recognition of significant discontinuities. To view in more detail, the larger file dimensions were set so that a single core diameter approximately fills the browser window. With scrolling, the user can work through the core and see specific features in detail. Because a tape measure was registered to the core and incorporated into each original photograph, the images show core depth. When used in conjunction with descriptive information, the images are a powerful information transfer tool.

Map graphics were constructed in a standard graphics application and saved as GIF images for use in the CD publication. Client side-image mapping, an HTML 3.0 extension that involves defining pixel locations and linking them to a respective file, was used to link core locations on the base maps to core image files. Thus, the user can point and click on a core location and bring up the core image. From there, the enlarged core image or the description for that core can be called. Headers on each screen allow returning to any of the main links in the “site.”

The total size of the open-file report, along with a number of data files written in native and text formats so users can copy and edit them, is about 95 MB. As this represents less than 20 percent of a CD’s capacity, considerably more robust data sets can be produced in this manner.

Acknowledgments

Numerous former NCGS employees and NCSU grad students not mentioned above contributed in various ways through the five years of project work. They include: Patricia Gallagher, Richard Dentzman, Charles Brockman, Wenfeng Li, Robert Brooks, and Michelle Hayes. The manuscript benefited from reviews by Jeffrey Reid, Charles Gardner, and Bronwyn Kelly.

References

Harris, W. B., and Laws, R. A., 1994, Paleogene sediments on the axis of the Cape Fear Arch, Long Bay, North Carolina: Southeastern Geology, v. 34, p. 189–199.

Hoffman, C. W., 1997, Stratigraphic and heavy-mineral data from Continental Shelf vibracores: Cape Fear cuspate foreland region, North Carolina: North Carolina Geological Survey Open-File Report 97-4, 1 compact disk.

Hoffman, C. W., Gallagher, P. E., and Zarra, L., 1991, Stratigraphic framework and heavy-mineral resource potential of the inner Continental Shelf, Cape Fear area, North Carolina: first interim progress report: North Carolina Geological Survey Open-File Report 91-3, 31 p.

Meisburger, E. P., 1977, Sand resources of the inner Continental Shelf of the Cape Fear region, North Carolina: U.S. Army Corps of Engineers, Coastal Engineering Research Center Technical Paper 77-11, 20 p.

Meisburger, E. P., 1979, Reconnaissance geology of the inner Continental Shelf, Cape Fear region, North Carolina: U.S. Army Corps of Engineers, Coastal Engineering Research Center Technical Paper 79-3, 135 p.

Nickerson, J. G., Li, Wenfeng, and Watson, M. E., 1993, Heavy-mineral data for selected vibracores from the southern inner Continental Shelf of North Carolina: North Carolina Geological Survey Open-File Report 93-37, 41 p.

Nickerson, J. G., Li, Wenfeng, Watson, M. E., and Dentzman, R. C., 1994, Mineralogy of vibracore heavy-mineral concentrates and preliminary stratigraphic framework of the southern inner Continental Shelf of North Carolina: North Carolina Geological Survey Open-File Report 94-2, 29 p.

Snyder, S. W., Hoffman, C. W., and Riggs, S. R., 1994, Seismic stratigraphic framework of the inner Continental Shelf: Mason Inlet to New Inlet, North Carolina: North Carolina Geological Survey Bulletin 96, 75 p.

Snyder, S. W., Hine, A. E., Riggs, S. R., and Snyder, S. W., 1993, Miocene geology of the Continental Shelf: Onslow Bay, North Carolina: North Carolina Geological Survey Map 3, 1 sheet, scale 1:430,000.

Zarra, Larry, 1991, Subsurface stratigraphic framework for Cenozoic strata in Brunswick and New Hanover Counties, North Carolina: North Carolina Geological Survey Information Circular 27, 1 sheet.

Connecting Onshore and Offshore Near-Surface Geology: Delaware's Sand Inventory Project

Kelvin W. Ramsey, Robert R. Jordan, John H. Talley

Delaware Geological Survey, University of Delaware, Newark, DE 19716-7501

Abstract

Beginning in 1988, the Delaware Geological Survey began a program to inventory on-land sand resources suitable for beach nourishment. The inventory included an assessment of the native beach textures using existing data and developing parameters of what would be considered suitable sand textures for Delaware's Atlantic beaches. An assessment of the economics of on-land sand resources was also conducted, and it was determined that the cost of the sand was competitive with offshore dredging costs. In addition, the sand resources were put into a geologic context for purposes of predicting which depositional environments and lithostratigraphic units were most likely to produce suitable sand resources. The results of the work identified several suitable on-land sand resource areas in the Omar and Beaverdam formations that were deposited in barrier-tidal delta and fluvial-estuarine environments, respectively. The identified on-land resource areas have not been utilized due to difficulties of truck transport and development pressures in the resource areas.

The Delaware Geological Survey's participation in years 8, 9, and 10 of the Continental Margins Program was developed to extend the known resource areas onshore to offshore Delaware in order to determine potential offshore sand resources for beach nourishment. Years 8 and 9 were primarily involved in the collection of all available data on the offshore geology. These data included all seismic lines, surface grab samples, and cores. The data were filtered for those that had reliable locations and geologic information that could be used for geologic investigations. Year 10 completed the investigations onshore by construction of a geologic cross-section from data along the coast of Delaware from Cape Henlopen to Fenwick. This cross-section identified the geologic units and potential sand resource bodies as found immediately along the coast. These units and resources are currently being extended offshore and tied to known and potential sand resources as a part of the continuing cooperative effort between the Delaware Geological Survey and the Minerals Management Service's INTERMAR office as sand resources are identified in Federal waters off Delaware.

Offshore sand resources are found in the Pliocene Beaverdam formation offshore where overlying Quaternary units have been stripped, in the tidal delta complexes of several Quaternary units likely equivalent to the onshore Omar formation, and in late Pleistocene and Holocene-age shoal complexes. Onshore lithostratigraphic units can be traced offshore and show another reason for continued geologic mapping both onshore and offshore.

Baseline Sediment Trace Metals Investigation: Steinhatchee River Estuary, Florida, Northeast Gulf of Mexico

Candace A. Trimble, Ronald W. Hoenstine, and A. Brad Highley

Florida Geological Survey, 903 W. Tenn. St., Tallahassee, FL 32304-7700

Joseph F. Donoghue and Paul C. Ragland

Geology Dept., Florida State University, Tallahassee, FL 32306

Abstract

This Florida Geological Survey/U.S. Department of the Interior, Minerals Management Service Cooperative Study provides baseline data for major and trace metal concentrations in the sediments of the Steinhatchee River Estuary. These data are intended to provide a benchmark for comparison with future metal concentration data measurements.

The Steinhatchee River estuary is a relatively pristine bay located within the Big Bend Wildlife Management Area on the North Central Florida Gulf of Mexico coastline. The river flows 55 kilometers through woodlands and planted pines before emptying into the Gulf at Deadman Harbor. Water quality in the estuary is excellent at present. There is minimal development within the watershed. The estuary is part of an extensive system of marshes that formed along the Florida Gulf coast during the Holocene marine transgression. Sediment accretion rate measurements range from 1.4 to 4.1 mm/yr on the basis of lead-210 measurements.

Seventy-nine short cores were collected from 66 sample locations, representing four lithofacies: clay- and organic-rich sands, organic-rich sands, clean quartz sands, and oyster bioherms. Samples were analyzed for texture, total organic matter, total carbon, total nitrogen, clay mineralogy, and major and trace metal content. Following these analyses, metal concentrations were normalized against geochemical reference elements (aluminum and iron) and against total weight percent organic matter. Metals were also normalized granulometrically against total weight percent fines (<0.062 mm).

Concentrations were determined by inductively coupled plasma–atomic emission spectrometry (ICP-AES) for all metals except mercury. Mercury concentrations were determined by cold-flameless atomic absorption spectrometry (AAS). Granulometric measurements were made by sieve and pipette analyses. Organic matter was determined by two methods: weight loss on ignition and elemental analysis (by Carlo-Erba Furnace) of carbon and nitrogen. X-ray diffraction was used to determine clay mineralogy.

Trace metal concentrations were best correlated when normalized with respect to sediment aluminum concentrations. Normalizations indicate that most major and trace metal concentrations fall within 95 percent prediction limits of the expected value. This finding suggests that little significant metal contamination occurred within this system prior to 1994 sediment sampling. Exceptions include lead, mercury, copper, zinc, potassium, and phosphorous. Lead and mercury are elements that generally enter this watershed through atmospheric deposition; thus, anomalous levels of these metals are not necessarily associated with activities within the watershed of the Steinhatchee River estuary. Anomalous concentrations of other metals such as zinc, copper, and phosphorous probably do originate within the Steinhatchee watershed. Copper failed to correlate well with any geochemical or granulometric normalizer, and this condition was not limited to a single facies or area within the estuary. This finding may indicate copper contamination in the system. Increased zinc and copper levels may be attributed to marine paints. Phosphorous levels also appeared to be elevated in a few locations in the two marsh facies sampled. This may be due to nutrient loading from two small communities, Jena and Steinhatchee, or from the application of this element in fertilizer to reduce moisture stress to young planted pines on tree farms within the watershed.

Historical Perspective

The Minerals Management Service and the Florida Geological Survey began cooperating in offshore and estuarine investigations along the Florida coastline during the mid-1980's when a series of sand and gravel and heavy mineral resource studies were carried out on the Gulf of Mexico and Atlantic continental shelves. Starting in 1985 and lasting until 1988 the area of the Northwest Florida coast between Pensacola and Apalachee Bay was investigated to locate promising resources. Between 1988 and 1993, a similar series of investigations were carried out along the Atlantic Coast covering an area that stretched from the Georgia border to Miami, Florida. In the 10th year of the program investigations were focused closer to shore in an investigation of baseline trace metal concentrations for the Steinhatchee River estuary.

Introduction

There are two principal sources of metals in estuarine sediments: the weathering of rocks and minerals that are naturally present in the watersheds, and pollution (Drever, 1988). Pollution by the addition of substances not found in nature is easily quantified by the direct measurement of concentrations of the substance in waters and sediments. Trace-metal contamination is not so easily quantified. Direct measurement of element concentration does not distinguish between anthropogenic contamination and naturally occurring concentrations of the same component.

Initially, investigators simply compared metal concentrations in surface sediments to the concentration of the same metal found deeper in the sediment column. If higher concentrations were found in surface sediments than in older, deeper sediments, it was assumed these greater recent concentrations indicated trace-metal pollution (Trefrey and Presley, 1976; Rule, 1986). This method was fairly effective, but it consumed large amounts of time by requiring workers to collect and analyze cores deep enough to establish time segments and their relationships to sediment-metal levels (Trefrey and Presley, 1976; Rule, 1986).

Concentrations of naturally occurring metals vary greatly among natural environments (Schropp and others, 1990). It is nevertheless important to be able to compare natural systems significantly different from each other when attempting to assess pollution of these systems by specific trace metals. This requirement led workers to search for ways to compare metal concentrations using both physical and geochemical characteristics of sediments, "normalizing" the concentration of the metal of interest.

Normalization is accomplished by graphical and/ or mathematical comparison of the trace-metal concentration in a particular sediment to the concentration of some conservative element that is also present in the system (Klinkhammer and Bender, 1981; Horowitz, 1985). This element, often referred to as a reference element, acts as a proxy for both mineralogic and grain-size variability. The elements most frequently used in this manner include aluminum, iron, cesium, and lithium, which are usually structurally combined with one or more trace-metal carriers (Horowitz, 1985; Rule, 1986; Windom and others, 1989; Schropp and others, 1990; Loring, 1990 and 1991; Trimble, 1997; Trimble and others, 1997). Trivariate regression has also been successfully employed as a trace-metal normalization method (Donoghue and others, in press).

Windom and others (1989) measured trace-metal concentrations in 450 samples of estuarine and coastal sediments from the southeastern United States. These samples were collected in areas remote from population centers and other sources of contamination. Trace-metal concentrations from these samples were directly compared with aluminum concentrations. They found that most trace metals covaried significantly with aluminum. Their work, along with the work of Schropp and others (1990), strongly supports the usefulness of geochemical normalization of trace-metal concentrations to aluminum in estuarine and similar sediments.

Study Area

The Steinhatchee River estuary lies within, and serves as a boundary between, the Big Bend Wildlife Management Area (Taylor County, Florida) and the Jena Wildlife Management Area (Dixie County, Florida) to the south (fig. 1). The Steinhatchee River flows from Mallory Swamp, near Mayo, for approximately 55 kilometers before emptying into Deadman Bay. The Steinhatchee River estuary, a small bay, is part of an extensive system of marshes along the Florida Big Bend coastline that developed during the Holocene marine transgression. The bay and its contributing watershed are relatively undeveloped, with no large manufacturing or other heavy industry. The greatest development lies along the lower reaches of the Steinhatchee River, where the towns of Steinhatchee and Jena lie along the banks near the river's mouth.

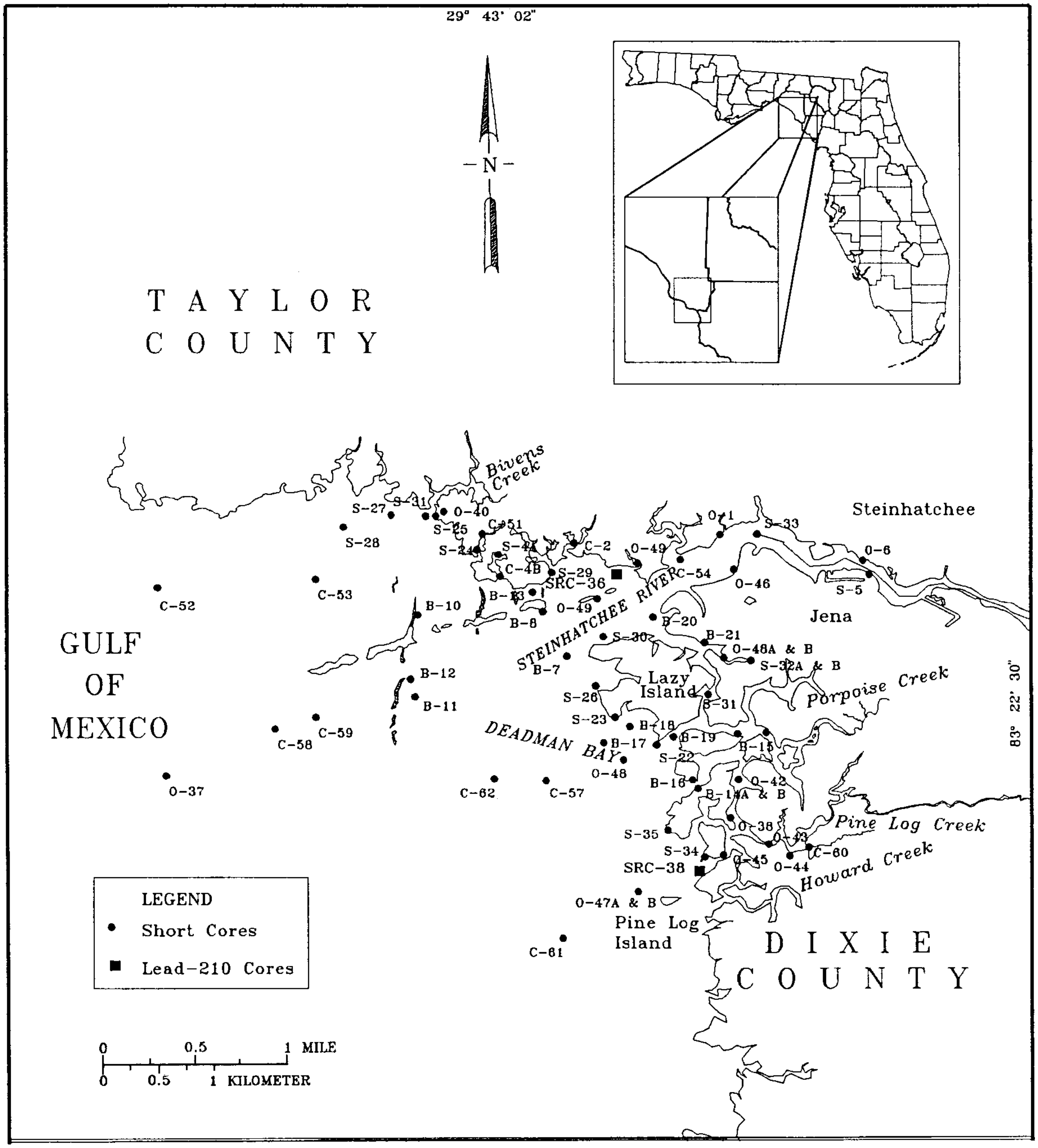


Figure 1. Steinhatchee River estuary study area and sample site map.

Sediment accumulation rates, measured by lead-210 dating of two cores, range from 1.4 mm/yr north of Pine Log Creek (SRC-38) to 4.1 mm/yr (SRC-36) near the river mouth (Hoenstine and others, 1993). These data are consistent with rates established elsewhere along Florida's Gulf of Mexico coastline (Hoenstine and others, 1993; Highley, 1995; Hendrickson, 1997).

Bay sediments are composed of the four lithofacies sampled in this study. The open-grass flats and beach berms are principally composed of clean quartz sands with minor amounts of shell material. Two similar facies are found in the salt marshes of the estuary: clay- and organic-rich sands and organic-rich sands. Lastly, oyster bioherms are common in the mouth of the Steinhatchee River and across the channels and mouths of the many small creeks and distributary channels present throughout the estuary.

Methods

Sample Collection and Handling. In June and July of 1994, estuarine sediment samples were collected at 79 locations from four lithofacies: (1) clay- and organic-rich sands, (2) organic-rich sands, (3) quartz sands, and (4) oyster bioherms. Prior to sample collection, all available data were analyzed to select sampling stations. These sites were then plotted on a U.S. Geological Survey 7.5-minute quadrangle to ensure diversity of sites and adequate coverage of the estuary. A Trimble Global Positioning System data recorder was used to locate sites precisely during sampling. These positions were later transferred to a site map using Autocad (fig. 1).

Short cores (15 to 45 cm) were collected in acid-washed plastic tubes of cellulose acetate butyrate plastic. After sampling, these were placed in dry ice and field-frozen to preserve stratification. Samples were thawed upright and extruded and dried. A detailed discussion of protocols used to minimize metal contamination of samples during collection and processing may be found in Lauenstine and Cantillo (1993). Samples were homogenized and then split by the cone and quarter method (Ingram, 1971) prior to further analyses.

Granulometry and Total Organic Matter. Total fine fraction (silt plus clay-size, <0.062 mm), total clay fraction (<.002 mm), and total organic matter were determined by the following methods: (1) wet sieving to separate fine (<0.062 mm) and coarse (>0.062 mm) fractions (Galehouse, 1971); (2) organic matter loss on ignition in an electric furnace at 550°C for 2 hours to determine weight percent organic matter (Gross, 1971); dry sieving to divide the coarse fraction into sand (2 to 0.062 mm) and gravel (>2 mm) size fractions (Ingram, 1971); and particle settling with pipette analysis to determine total clay fractions (Galehouse, 1971). Total carbon (C) and total nitrogen (N) were determined by elemental analysis utilizing using a Carlo Erba elemental analyzer (model 1106).

Clay mineralogy. Clay mineralogy was evaluated by X-ray diffraction (Gibbs, 1971; Moore and Reynolds, 1989) using a Philips X-ray diffractometer, model APD 1700. Qualitative analyses of peak height were used to establish predominant mineralogy. Samples were then glycolated in a vacuum oven for a minimum of 8 hours and then scanned for indications of smectite-related low-angle peak shifts (Moore and Reynolds, 1989).

Metals. Prior to analyses all splits were hand-ground to silt size using an acid-washed glass or agate mortar and pestle. They were then weighed into clean glass vials and shipped to a commercial laboratory for analysis. All 79 samples plus 14 blind duplicates and 4 blind standards were totally digested by $HClO_4$-HNO_3-HCl-HF at 200°C (Loring and Rantala, 1988). The samples were analyzed for 35 metals by ICP-AES. Mercury analyses were by cold, flameless AAS (Potts, 1987).

Concentrations of 23 of the 35 metals were measured at levels above detection limits (Potts, 1987) These metals include aluminum, antimony, arsenic, barium, calcium, chromium, copper, iron, lanthanum, lead, magnesium, manganese, mercury, nickel, phosphorous, potassium, sodium, strontium, titanium, vanadium, zinc, and zirconium.

Quality control results indicate that most elements measured were within acceptable limits of precision with coefficients of variation less than 20 percent. Accuracy measurements were based upon recovery of elements from a standard reference material, National Institute of Standards and Technology–Standard Reference Material–2704, Buffalo River Sediment. Accuracy was generally good. Most metals were within 10 percent of the certified value, with a few notable exceptions. The exceptions include arsenic, antimony, chromium, titanium, and vanadium. The problem with the arsenic data is probably due to volatilization during sample digestion. The remaining three metals are present in resistate mineral lattices and seem to indicate incomplete sediment digestion.

Results

Granulometry, organic matter, and mineralogy. Two lithofacies are dominated by sand, organic-rich sands, and quartz sands. Clay- and organic-rich sands are dominated by finer material (silt and clay) and would perhaps be better labeled as clay and organic-rich muds. Finally, oyster bioherms are generally shell dominated with varying amounts of sand, silt, and clay (table 1).

Organic matter content was extremely variable and tended to be highest in the clay- and organic-rich sands, followed by organic-rich sands, and lowest in the quartz sands. In the oyster bioherms organic matter content depended upon location with respect to channels. For sites at which oyster bars were located in a relatively

Table 1. Grain size, organic matter, carbon, and nitrogen for the four lithofacies ranges and mean weight percents.

Lithofacies	**Large shell > 2mm**		**Sand 2.0-0.0625mm**		**Silt 0.0625-0.002mm**		**Clay <0.002 mm**		**Organic matter**	
	Range %	Mean %	Range %	Mean %	Range %	Mean %	Range %	Mean %	Range %	Mean %
Clay- and organic-rich sands	0-15.5	4.5	9.0-80.3	47.4	10.9-55.6	48.5	5.5-32.9	18.2	8.5-51.2	25.1
Organic-rich sands	0-1.3	0.3	24.9-97.1	75.9	0.3-51.3	10.0	1.6-21.8	5.6	1.4-33.2	8.8
Quartz sands	0-6.7	1.2	67.8-98.1	93.1	0-11.7	2.2	0.3-7.2	3.4	0.7-4.8	2.7
Oyster bioherms	3.1-82.9	40.7	14.0-90.0	54.6	0-9.4	4.0	0-12.3	4.0	3.0-35.5	12.9

swift channel, shell and sands gathered were relatively clean. However, those located in slowly flowing marsh channels or creeks contained substantially more organic matter (table 1).

Terrigenous clays were generally absent from most of the estuary samples and seldom exceeded 5 percent. In the clay- and organic-rich facies, terrigenous clay averaged only 18 percent. Fine-sediment constituents included organic matter and silt-sized quartz and carbonates. Low quartz, aragonite, and calcite were the most abundant sediment minerals. Aluminosilicate clays were primarily found to be illite and kaolinite. The presence of minor amounts of calcium montmorillonite was indicated by diffraction peaks and by the low-angle diffraction peak shift in two of the sediment samples: B12 and S32A (fig. 1).

Metal data and normalizations. Following procedures established by Windom and others (1989), simple linear correlation was used to evaluate metal concentrations and graphically display the results of the normalizations. Initially, 66 sites were sampled and the data analyzed as stated above. Sample results from 13 of the sites suggested the presence of unnaturally high concentrations of four metals: lead, mercury, arsenic, and zinc. These sites were resampled, and these data were combined with results from initial tests. Regression lines and >95 percent prediction limits were established for 21 of the 23 metals with respect to the following geochemical normalizers: aluminum, iron, organic matter, and carbon (table 2). The same procedure was followed for 21 metals with respect to total fines (<0.062 mm) and total clay (<0.002 mm) for the purpose of granulometric normalization.

Most metals correlated well with both aluminum concentration and total weight percent fines (<0.062 mm). Copper did not correlate well with any normalizer but gave similar correlation coefficients for normalization to aluminum, organic matter, percent carbon, and total fines. Sixteen metals covaried well with aluminum concentration, whereas only 13 covaried with total fines, or total organic matter. In nearly every instance, normalization to aluminum concentration following total digestion was superior to the other methods used (table 2). Normalization of metal concentration to aluminum concentration proved superior to granulometric normalizations and normalizations to total organic matter, total carbon, and total nitrogen. The one exception to this is copper, which was only slightly better correlated with respect to total fines than with respect to aluminum.

In general, the Steinhatchee River and estuary appeared relatively pollution free. Lead contamination was minor with anthropogenically augmented levels suspected at only two sites in the estuary (fig. 2). Mercury concentrations were also generally low, with three exceptions that are high enough and far enough outside prediction limits that they appear to indicate mercury enrichment at sites O-42, O-44, and B18 (figs. 1 and 2 and table 2). Unlike most other metals, these anomalous lead and mercury concentrations are not necessarily correlated with local pollution, but they may indicate atmospheric deposition, perhaps from distant sites. The remaining metal anomalies cannot thus be explained and may be attributed to activity within the watershed of the Steinhatchee River and its estuary. Zinc concentrations exceeded prediction limits at two sites (C-2 and B-13), which would be anticipated in a sample set of this size (n = 79). Total zinc concentrations at these two sites are still fairly low, at 10 and 7 ppm, respectively. However, because these locations are quite close to the developed areas of the estuary or in the river channel itself, they may well be

Table 2. Linear correlations and regression coefficients for selected metal with aluminum, *carbon, and **total fines, 95% significance. N = 79, F = 77.

Element	r	y-intercept	m
Arsenic	0.244	1.010	0.167
Barium	0.617	1.390	0.340
Copper	0.660	0.530	0.394
* Copper	0.590	0.072	0.400
** Copper	0.680	-0.181	0.440
Chromium	0.961	1.419	0.778
Iron	0.950	0.030	0.783
Lanthanum	0.852	0.830	0.640
Lead	0.545	0.806	0.330
Mercury	0.843	1.780	0.703
** Mercury	0.820	0.560	0.750
Manganese	0.564	1.886	0.451
Nickel	0.831	0.790	0.625
Phosphorus	0.789	-1.419	0.610
Potassium	0.921	-0.900	0.785
Titanium	0.9170	0.019	0.039
Vanadium	0.958	1.330	0.900
Zinc	0.853	1.069	0.502

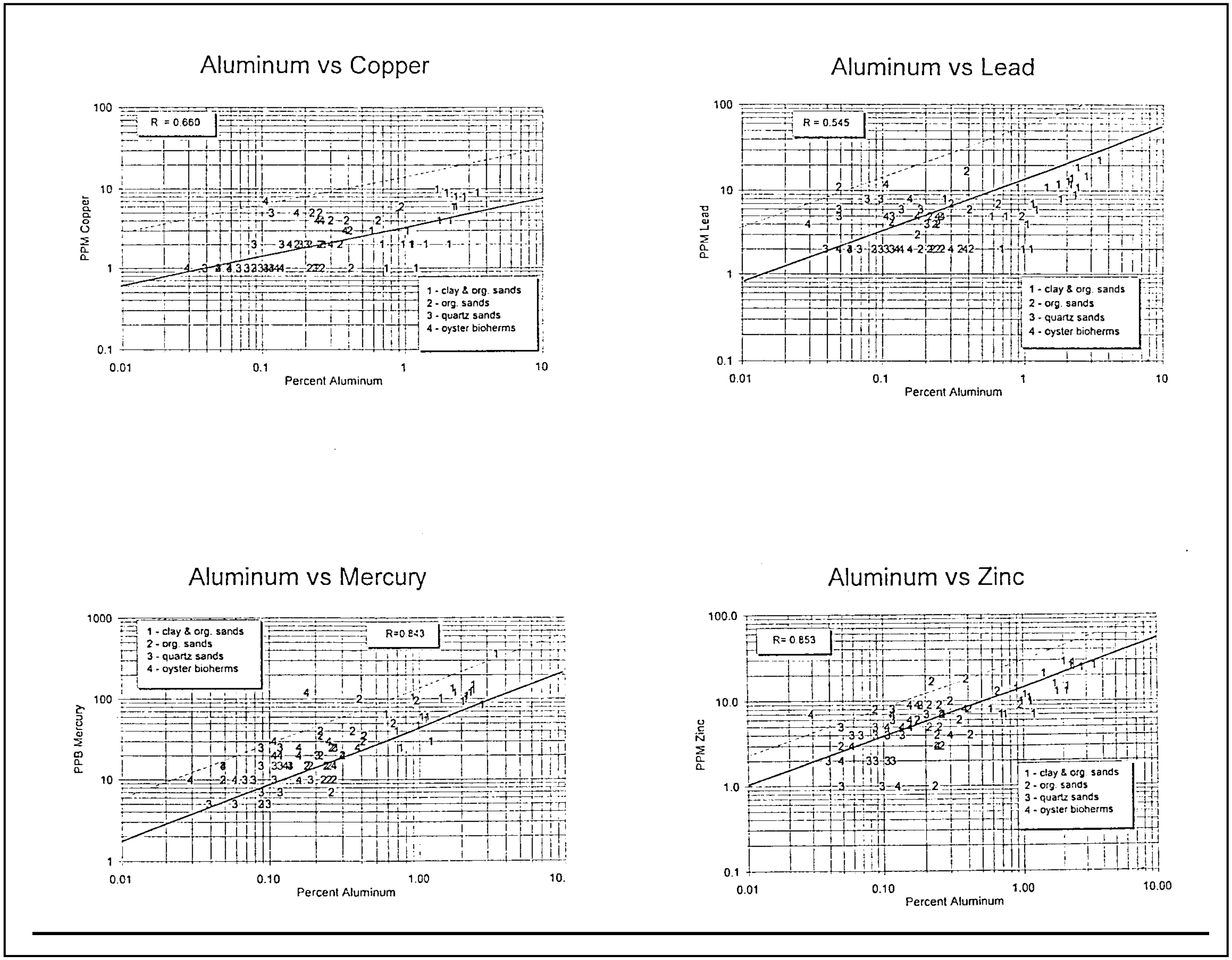


Figure 2. Selected scatterplots for metal:aluminum correlations: copper, lead, mercury, and zinc, with >95 percent prediction limits (dashed lines) and linear regression lines (solid lines) shown (n = 79).

indicative of human activities in the system. Concentrations of two major elements, phosphorous and potassium, exhibited concentrations above prediction limits in a few sites within the bay. Although anomalously high concentrations of phosphorous are probably the result of erosion of phosphatic clays from sediments overlying the Ocala Limestone (Rupert, 1991), one must not disregard the possibility of phosphorous influx from nonpoint sources such as runoff from the towns of Jena and Steinhatchee. It is difficult to attribute elevated potassium concentrations to natural causes. High concentrations of this metal may be related to nutrient contamination from nonpoint sources such as those described above, or from silviculture operations, which often apply potassium and phosphorous to reduce moisture stress on young pine seedlings when planted in extremely wet flatwoods.

Conclusions

To date, the Steinhatchee Estuary has experienced little metal contamination prior to establishing these baseline data. Few sites show metal concentrations indicative of pollution when normalized against weight percent aluminum, organic matter, carbon, or total fines. The sites that appear anomalous are in heavily trafficked areas of the bay and probably do indicate slight amounts of metal pollution. Finally, these data establish baseline data for the Steinhatchee River estuary against which future changes in the estuary may be measured.

References

Donoghue, J. F,. Ragland, P. C., Chen, Z., and Trimble, C. A., *in press*, Standardization of metal concentrations in sediments using regression residuals: an example from a large lake in north Florida: Environ. Geol.

Drever, J. I., 1988, The geochemistry of natural waters (2d ed.): Englewood Cliffs, Prentice-Hall, 437 p.

Galehouse, J. S., 1971, Sedimentation analysis, *in* Carver, R. E., ed., Procedures in sedimentary petrology: p. 69.

Gibbs, R., 1971, X-ray diffraction mounts, *in* Carver, R. E., ed., Procedures in sedimentary petrology: p. 531.

Gross, M. G., 1971, Carbon determination, *in* Carver, R. E., ed., Procedures in sedimentary petrology: p. 573.

Hendrickson, J. C., 1997, Coastal wetland response to rising sea level: quantification of short- and long-term accretion and subsidence, Northeast Gulf of Mexico: Florida State University, unpublished Master's thesis.

Highley, A. B., 1995, Recent sediments of the Aucilla River estuary and the northern Big Bend coast, Florida: Florida State University, Master's thesis.

Hoenstine, R., Garret, C., Hertler, H., and Highley, B., 1993, Florida Big Bend coastal wetlands study, second annual report: Florida Department of Environmental Protection, Florida Geological Survey, 25 p.

Horowitz, A. J., 1985, A primer on trace-metal sediment chemistry: U.S. Geological Survey, Water-Supply Paper 2277, 66 p.

Ingram, R. L., 1971, *in* Carver, R. E., ed., Procedures in sedimentary petrology: p. 531.

Klinkhammer, G. P., and Bender, M. L., 1981, Trace metal distributions in the Hudson River Estuary: Estuarine and Coastal Marine Science, v. 12, no. 6, p. 629–643.

Lauenstine, G., and Cantillo, A., 1993, Sampling and analytical methods of the National Status and Trends Program: NOAA Tech. Mem. NOS-ORCA 71, v. I.

Loring, D. H., 1990, Lithium—a new approach for the granulometric normalization of trace metal data: Marine Chem, no. 29, p. 155–168.

__________ 1991, Normalization of heavy-metal data from estuarine and coastal sediments: ICES, Jour. of Marine Sci., no. 48, p. 13–28.

Loring, D. H., and Rantala, R. T. T., 1988, An intercalibration exercise for trace metals in marine sediments: Marine Chem, no. 24, p. 13–28.

Moore, D. M., and Reynolds, R. C., 1989, X-ray diffraction and identification and analysis of clay minerals: Oxford, Oxford Press, 332 p.

Potts, P. J., 1987, A handbook of silicate rock analysis: London, Blackie, p. 15–46; 106–197.

Rule, J. F., 1986, Assessment of trace metal geochemistry of Hampton Roads Harbor and lower Chesapeake Bay area sediments: Envir. Geol. Water Sci., v. 8, p. 209–219.

Rupert, F., 1991, The geomorphology and geology of Dixie County, Florida: Florida Geol. Survey, OFR 45, 6 p.

Schropp, S., Lewis, F., Windom, H., Ryan, J., Calder, F., and Burney, L., 1990, Interpretation of metal concentrations in estuarine sediments of Florida using aluminum as a reference element: Estuaries, v. 13, p. 227–235.

Trefrey, J., and Presley, B., 1976, Heavy metal transport from the Mississippi River to the Gulf of Mexico, *in* Windom and Duce, eds., Marine pollutant transfer: Lexington, Mass., Heath & Co., 391 p.

Trimble, C. A., 1997, Cation exchange capacity and normalization of trace metal concentrations in bottom sediments of the Steinhatchee River estuary, Florida: Florida State University, Master's thesis.

Trimble, C. A., Hoenstine, R. W., Highley, A. B. , Donoghue, J. F. and Ragland, P. C., 1997, Baseline investigation of estuarine sediment metals for the Steinhatchee River area of the Florida Big Bend: Environ. Geosci., v. 4, p. 95–103.

Windom, H., Schropp, S., Calder, F., Ryan, J., Smith, R., Burney, L., Lewis, F., and Rawlinson, C., 1989, Natural trace metal concentrations in estuarine and coastal marine sediments of the southeastern United States: Environ. Sci. and Tech., v. 23, p. 314–320.

The Continental Margins Program in Georgia

Mark D. Cocker and Earl A. Shapiro

Georgia Geologic Survey, Room 400, 19 Martin Luther King, Jr., Dr., SW, Atlanta, GA 30334

Abstract

From 1984 to 1993, the Georgia Geologic Survey (GGS) participated in the Minerals Management Service–funded Continental Margins Program. Geological and geophysical data acquisition focused on offshore stratigraphic framework studies, phosphate-bearing Miocene-age strata, distribution of heavy minerals, near-surface alternative sources of ground water, and development of a PC-based Coastal Geographic Information System (GIS). Seven GGS publications document results of those investigations. In addition to those publications, direct benefits of the GGS's participation include an impetus to the GGS's investigations of economic minerals on the Georgia coast, establishment of a GIS that included computer hardware and software, and seeds for additional investigations through the information and training acquired as a result of the Continental Margins Program. These additional investigations are quite varied in scope, and many were made possible because of GIS expertise gained as a result of the Continental Margins Program. Future investigations will also reap the benefits of the Continental Margins Program.

Introduction

The Georgia Geologic Survey (GGS) has participated in Years One through Nine of the Minerals Management Service's (MMS) Continental Margins Program (CMP) from 1984 through 1993 (table 1). The CMP supported geologic framework and petroleum-related studies, critical and strategic minerals studies, and environmental studies. Initial phases of the CMP coincided with the GGS's Accelerated Economic Minerals Program that was designed to improve the base of geologic information on Georgia's mineral resources. Cocker and O'Connor (1996) summarized the different aspects of the Accelerated Economic Minerals Program and listed nearly 100 publications resulting from that program. The CMP provided an impetus and aid to economic minerals investigations that concerned coastal Georgia. During the early 1990's, emphasis of the GGS shifted toward environmental investigations, and the Year-Nine study reflects that shift (table 1). Kellam and Henry (1986, 1987), Henry and Kellam (1988), Bonn and Simonson (1991), Kellam and others (1992), O'Connell (1991), Cocker (1993a), and Hughes and Henry (1995) documented results of these investigations.

Transferring data from different scale or projection maps has been a formidable task and not often attempted. Accessibility of GIS technology to small-sized users such as state geologic surveys significantly decreased the magnitude of the task and has allowed the integration of the various offshore studies with each other and with onshore investigations. Selected data generated by the earlier CMP and Accelerated Economic Minerals Program investigations were incorporated into a coastal GIS (Cocker, 1993a).

The purpose of this paper is to discuss the initial studies on phosphate deposits, their stratigraphy, and potential impact of their development, as well as urban growth on critical coastal aquifers. Also discussed are the heavy mineral investigations, development of a GIS, and the impact of data and techniques generated during the CMP on subsequent investigations in Georgia.

Table 1. Summary of Georgia Geologic Survey's participation in Continental Margins Program.

Year		Investigation
1	1984	Geologic mapping of the phosphate-bearing strata of the Outer Continental Shelf area off Georgia.
2	1985	Correlation of drilling and core information with a seismic database for Miocene-age strata of the Continental Shelf area off of Georgia.
3	1986	Preparation of a Georgia Geologic Survey Bulletin on the phosphate-bearing, Miocene-age strata of the Continental Shelf area off of Georgia.
4	1987	Preparation of a Georgia Geologic Survey Bulletin on the distribution of heavy mineral sands in a tide-dominated delta, as a possible exploration model: Phase I.
5	1988	Preparation of a Georgia Geologic Survey Bulletin on the distribution of heavy mineral sands in a tide-dominated delta, as a possible exploration model:Phase II.
6	1989	Development of a personal computer–compatible Geographic Information System for the coastal area and Continental Shelf of Georgia.
7	1990	Creation of databases for the Georgia Coastal Geographic Information System.
8	1991	Addition of other databases into the Georgia Coastal Geographic Information System.
9	1992	Compilation and review of information on shallow aquifers (the Surficial and Brunswick aquifers) in Glynn and Camden Counties.

Continental Margins Program

Phosphates

The Waycross Basin in the eastern part of the Georgia Coastal Plain and on the adjacent Continental Shelf was a large depocenter for Miocene-age phosphate deposits (fig. 1). The bulk of the phosphate is in the Tybee Phosphorite Member of the Hawthorne Group. The offshore phosphate investigations evaluated approximately 2,000 miles of seismic tracklines off the Georgia coast as well as cores and cuttings from both onshore and offshore wells and borings. Offshore stratigraphy was correlated to the better known onshore stratigraphy (Kellam and Henry, 1986; Henry and Kellam, 1988). Stratigraphic profiles, structure contour maps, and isopach maps of several Neogene formations were constructed and include bounding contacts for phosphate-bearing Middle Miocene strata. These projects identified potential sites for detailed exploration for offshore phosphates. The geological and geophysical data provide important information regarding the relation of these phosphates to the Floridan aquifer (the principal artesian aquifer) and the confining unit between the phosphate-bearing strata and the aquifer.

Aquifers

Groundwater in the coastal area of Georgia is a critical resource important to Georgia as well as adjacent parts of Florida and South Carolina. The principal aquifer system (also referred to as the principal artesian aquifer) is the Floridan aquifer. Wells that tap this aquifer supply nearly all municipal, agricultural, and industrial users in coastal Georgia. Large ground-water withdrawals affect the Floridan aquifer around major pumping centers by lowering ground-water levels and by consequent contamination of fresh water by brackish water. The stretch of coast between Savannah, Georgia, and Jacksonville, Florida (fig. 1) is growing rapidly in population and accompanying industrial and agricultural development, and will continue to place additional pressure on the principal artesian aquifer. Alternative sources of ground water, principally for irrigation, need to be investigated for relief of water demands. Breaching of the principal artesian aquifer during phosphate mining may result in salt-water contamination of the aquifer.

The principal artesian aquifer is located in Eocene- to Oligocene-age sediments. Shallower aquifers in coastal Georgia include the Lower and Upper Brunswick aquifers and the Surficial aquifer (fig. 2). These aquifers are located in Miocene- and Holocene-age sediments. A preliminary study involved a literature review and compilation of previously gathered hydrogeologic data for the shallower aquifers in Glynn and Camden Counties (Hughes and Henry, 1995). In Glynn and Camden Counties, the cities of St. Marys and Brunswick, and the Kings Bay Naval Submarine Base are experiencing rapid population and industrial growth. A hydrogeologic database obtained from 279 wells for the shallow aquifers and from 416 deeper

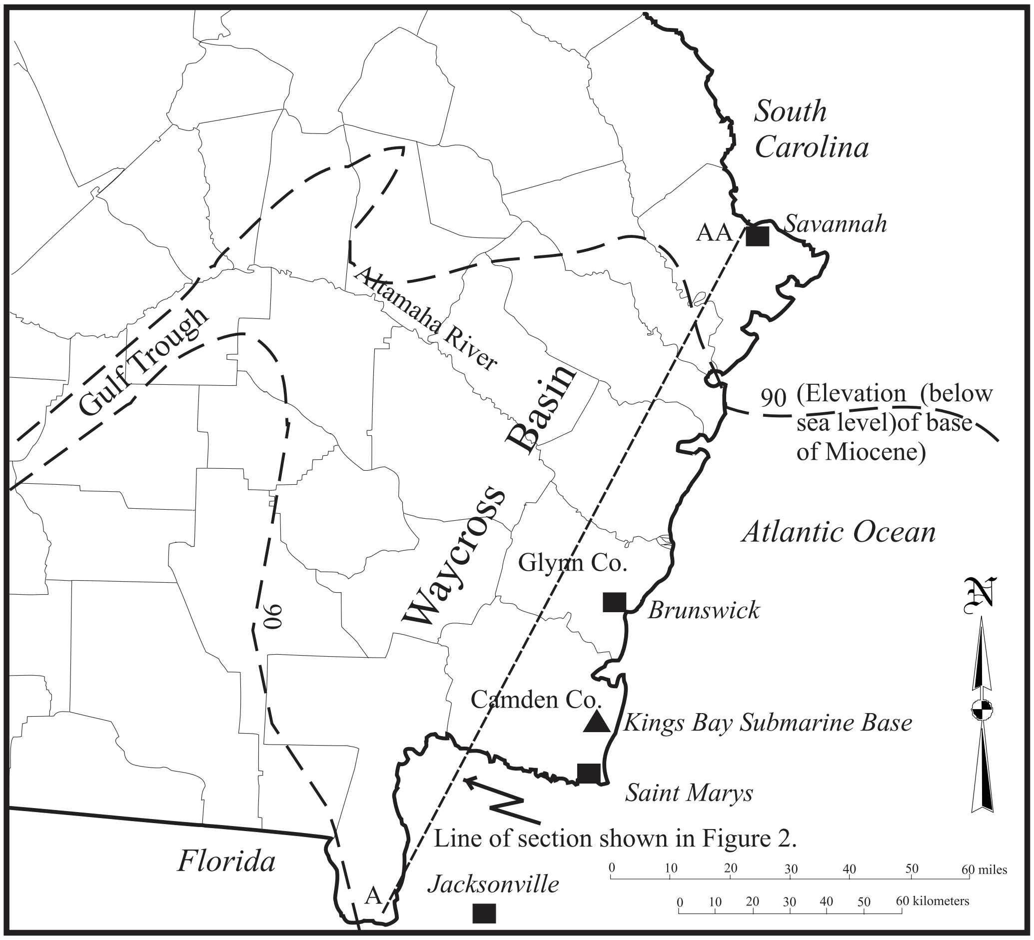


Figure 1. Location of Waycross basin, coastal aquifer study, and line of section (A-AA) shown in figure 2. Basin location from Popenoe (1991).

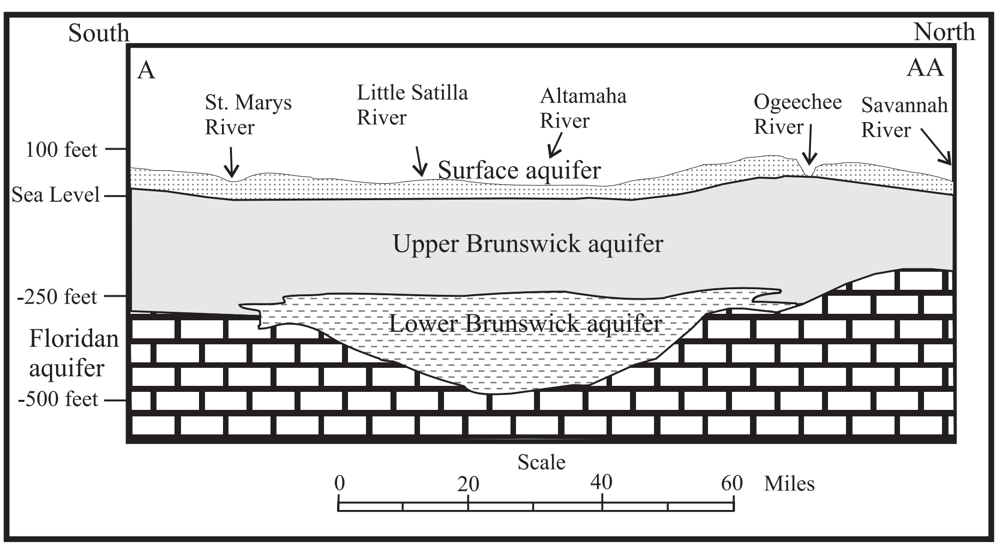


Figure 2. North-south section (A-AA in fig. 1) showing relation of coastal aquifers. Modified from Watson (1979).

wells served as a starting point for an investigation of alternatives to the Floridan aquifer in coastal Georgia (McDowell and Steele, in review).

Heavy Minerals

The coastal area of southeastern Georgia lies within a major heavy-mineral–bearing province that extends from Florida into New Jersey. The northern Florida–southeastern Georgia district is the principal domestic source of titanium oxides. The heavy-mineral deposits in southeastern Georgia and northern Florida are spatially and genetically related to beach and barrier island environments that are principally Pleistocene in age. Heavy minerals are also currently being transported by the major river systems and deposited in delta systems along the coast.

The focus of the CMP was on the distribution and mineralogy of heavy minerals in modern depositional environments of the Altamaha River delta, the Altamaha Sound, and the surrounding tidal inlet-barrier island complex (fig. 3). Sampling included more than 200 surface samples and 30 vibracores from nearshore sandbars. Bonn and Simonson (1991) and Kellam and others (1992) showed that heavy minerals are concentrated in intertidal sand bars relative to shallow subtidal shelf environments. Heavy minerals are further concentrated in onshore depositional environments, such as dunes, washovers, and storm ridges. Ilmenite, rutile, leucoxene, monazite, and zircon are the principal economic heavy minerals along the modern Georgia coast, and these minerals make up 44 percent of the heavy-mineral suite. With the aid of the GIS sample locations on the Altamaha delta and Altamaha Sound (Bonn and Simonson, 1991; Kellam and others, 1992),

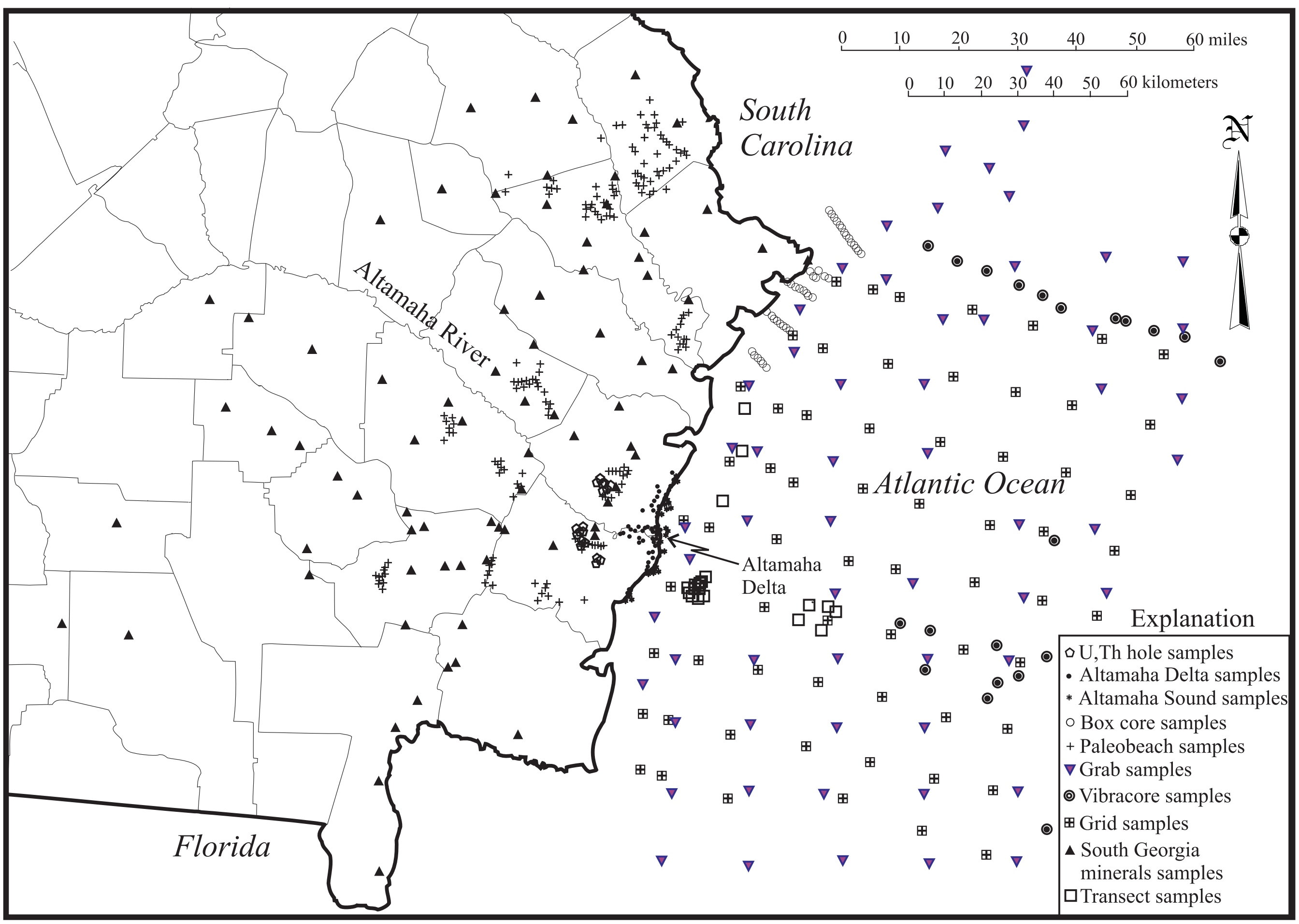


Figure 3. Locations of heavy mineral samples in the Lower Coastal Plain of Georgia and offshore Georgia. Modified from Cocker (1993a).

and other studies dating back to the 1960's, offshore Pleistocene and Recent shorelines (Kellam and others, 1991) on the Continental Shelf were plotted on the same map (Cocker, 1993a), and spatial relations between the data could be analyzed.

Geographic Information System (GIS)

Decreasing costs and increasing capabilities of computer hardware and software during the late 1980's and early 1990's spurred growth and use of GIS technology in geological and environmental sciences. A computer-based GIS system is critical to spatially relate and analyze the various databases with a wide variety of data sources, data types, areas of coverage, and map scales. Funding by the MMS provided the opportunity to incorporate the databases into a PC-based GIS. Principal computer hardware that formed the heart of the GIS included an IBM 386 15MHz, a Hewlett Packard Draft Pro pen plotter, and a Calcomp digitizer. The GIS software purchased for the computer is ESRI's PC ARC/INFO (O'Connell, 1991).

Databases from offshore Georgia incorporated into the Coastal GIS include locations and analyses from coreholes, boxcores, vibracores, seismic tracklines, structure contour and isopach maps of Tertiary and Quaternary sediments, hardgrounds, bathymetry, and 10 heavy-mineral investigations. Databases from onshore Georgia incorporated into the Coastal GIS include locations of mines, drill cores, auger holes, five heavy-mineral investigations, geology, soils, and land use (Cocker, 1993a).

Interesting relationships apparent during preliminary evaluation of the GIS databases (Cocker, 1993a) included the possible relation of hardgrounds to fluvial erosion during Pleistocene sea-level lowering, location of environmentally sensitive hardgrounds relative to potentially minable areas of offshore Middle Miocene–age phosphatic sediments, identification of gaps in sample coverage, and correlation of data from nine different heavy-mineral investigations (fig. 4).

Additional Investigations

A number of additional studies were conducted in concert with or as a result of the CMP and were also funded by the MMS. These studies include the distribution of heavy minerals on the Continental Shelf off Georgia (Zellars-Williams, 1988; Grosz, 1993), the shallow seismic stratigraphy of the Continental Shelf and Slope off Georgia (Popenoe, 1992), and the geology, stratigraphy, and chemistry of phosphatic drill cores from the Continental Shelf off Georgia (Mannheim, 1992) and onshore Georgia (Herring and others, 1992).

Cocker (1993b, 1993c) developed a comprehensive model of heavy mineral deposit formation based on analysis of several databases. Labile mineral concentrations were found to increase from the oldest onshore deposits to the farthest offshore samples. Highest labile mineral concentrations and total heavy minerals were found in the youngest onshore deposits. Southwesterly longshore currents appear to transport clastic sediments remobilized from deltaic deposits as suggested by the spatial distribution of heavy minerals relative to the deltas and by the location of the heavy-mineral deposits in the Georgia and Florida Coastal Plain.

Distribution patterns for rare earth elements, particularly cerium and lanthanum, and titanium represent the presence of monazite and titanium oxides (rutile, ilmenite, and leucoxene) and display similar distribution patterns. Cocker (1997a, in press) redefined earlier known heavy-mineral belts in northern Georgia and identified new belts and areas in the Upper Coastal Plain (fig. 4) that may be prospective for mineral exploration. Cocker used GIS techniques to identify rock units that contain the highest concentrations of heavy minerals. In the Piedmont, these rock units are dominantly metamorphosed clastic sediments such as schists, metaquartzites, metagraywackes, and biotite gneisses. In the Upper Coastal Plain, clastic strata of Cretaceous and Early Tertiary age contain the highest concentrations of rare earth elements and titanium and correlate with the limited studies of heavy minerals in the Upper Coastal Plain. The concentrations of heavy minerals in the Piedmont and Upper Coastal Plain heavy-mineral belts appear to represent paleoplacer deposits in former beach deposits. The concentration of heavy-mineral deposits in the southeastern Georgia and north Florida Coastal Plain appears to result from multiple episodes of weathering, transportation, and concentration (Bonn and Simonson, 1991; Kellam and others, 1991, 1992; Cocker, 1993b, 1993c).

A program to develop river basin management plans for each of the major river basins within Georgia relied, in part, on documentation of the background geochemistry and geochemical relations to rock units within Georgia. Using GIS experience from the CMP, Cocker (1996a, 1996b, 1996c, 1997b, 1998a, 1998b) documented and analyzed the background geochemistry of stream sediments and rock units within several major river basins from data gathered by the

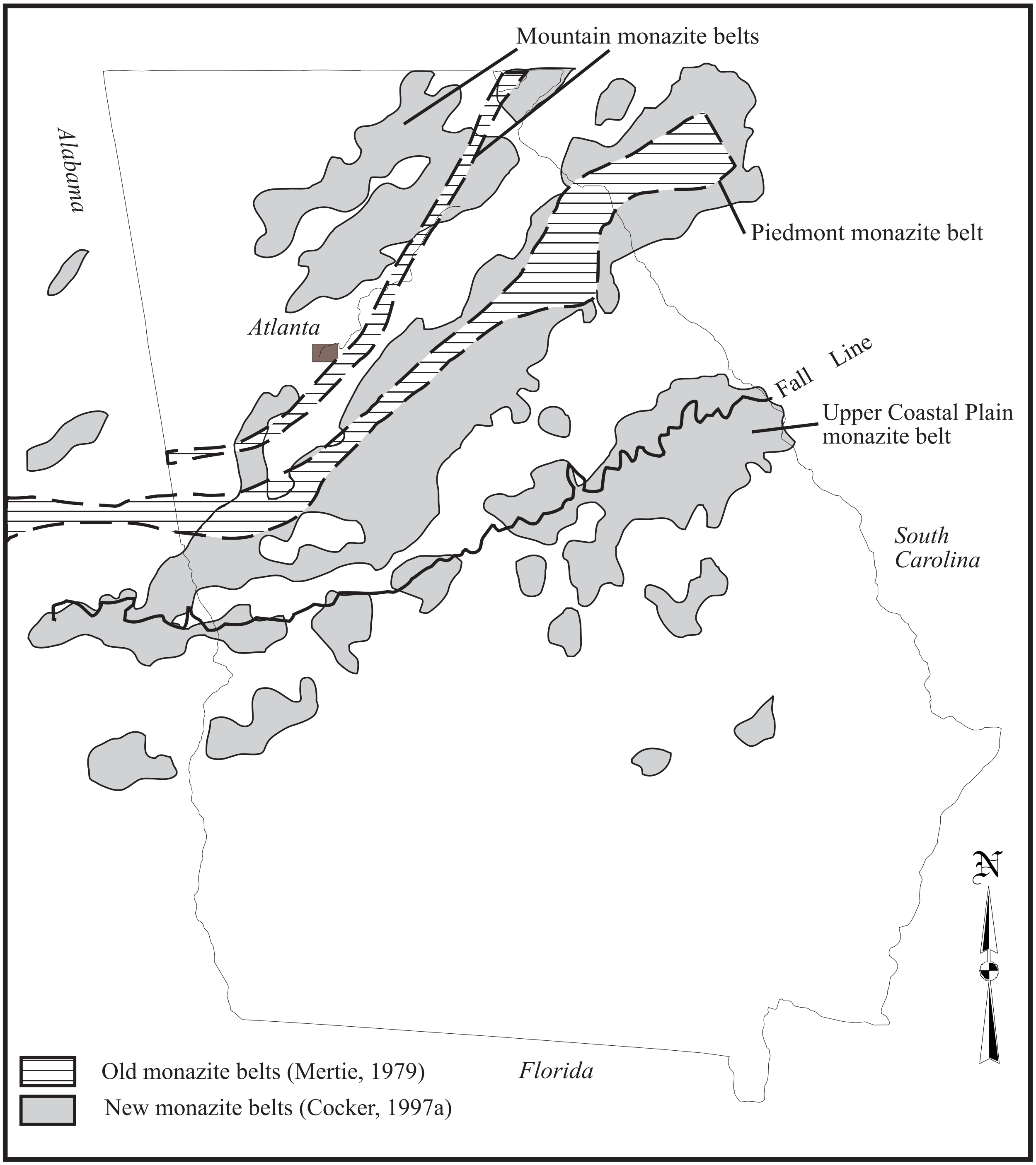


Figure 4. Monazite belts in the Piedmont and Upper Coastal Plain of Georgia as derived from NURE data and a GIS. Previous monazite belts as defined by Mertie (1979) are shown.

U.S. Department of Energy's National Uranium Resource Evaluation Program (NURE) and a number of additional smaller databases. Contoured stream sediment geochemical maps were developed for aluminum, arsenic, barium, beryllium, cerium, chromium, cobalt, copper, dysprosium, europium, hafnium, iron, lead, lanthanum, lithium, lutetium, magnesium, manganese, molybdenum, nickel, niobium, phosphorous, potassium, scandium, silver, sodium, strontium, thorium, tin, titanium, tungsten, uranium, vanadium, yttrium, ytterbium, and zinc. Contoured stream hydrogeochemical maps were developed for alkalinity, conductivity, pH, and water temperature. Correlation of stream sediment and stream water geochemistry with geologic rock units and regional tectonostratigraphy indicate that local rock composition and regional tectonostratigraphic packages (for example, metavolcanic, metasedimentary, and granitic terranes) are important influences on stream sediment and stream geochemistry. Techniques and information learned in these studies could be applicable to coastal areas as well.

Conclusions

Benefits arising from the CMP in Georgia are threefold: (1) data and interpretations that resulted directly from the program; (2) data and interpretations that resulted from studies that resulted from or complemented those funded by the CMP; and (3) development of a GIS system and GIS techniques learned during the CMP that prompted a wide variety of projects and that continues to develop. The CMP resulted in numerous benefits to understanding of coastal areas of Georgia, areas immediately offshore Georgia, and areas farther offshore to the Continental Slope. These benefits included stratigraphic framework studies of Tertiary strata, particularly strata of Miocene age, Miocene-age phosphate deposits, Pleistocene and Recent heavy minerals, and shallow aquifers in Miocene and younger sediments. Other benefits include the impetus for or the complement to investigations of heavy minerals in Pleistocene and Recent onshore deposits and deposits farther offshore on the Continental Shelf, and additional studies of Miocene-age phosphate-bearing strata. The CMP provided funding for computer hardware and software to establish a PC-based Coastal GIS. Techniques and training learned in using the GIS were critical to further investigations of heavy minerals in coastal areas, the Upper Coastal Plain, the Piedmont, and Blue Ridge of Georgia. These techniques and training were also critical to aiding development of river basin management plans for major river basins in the State of Georgia. Further use of the GIS is planned for additional environmental studies and perhaps for additional investigations in coastal Georgia.

References

Bonn, G. N., and Simonson, D. N., 1991, Evaluation of heavy mineral-bearing nearshore sand, Altamaha Sound, and the adjacent nearshore, Georgia: Georgia Geologic Survey, Open-File Report 90-3, 160 p.

Cocker, M. D., 1993a, Report on the Georgia Coastal Geographic Information System: Georgia Geologic Survey, Open-File Report 93-1, 19 p.

Cocker, M. D., 1993b, Relation of heavy mineral suites to Pleistocene to Holocene shoreline sequences in Georgia (abs.): Geological Society of America, Abstracts with Programs, v. 25, no. 4, p. 9.

Cocker, M. D., 1993c, A model for heavy mineral deposit formation within Pleistocene to Holocene shoreline sequences in Georgia (abs.): Geological Society of America, Abstracts with Programs, v. 25, no. 4, p. 9.

Cocker, M.D., 1995, Geochemistry and hydrochemistry of a major river basin in the Piedmont and Coastal Plain Provinces of Georgia: *in* Hatcher, K. J., ed., Proceedings of the 1995 Georgia Water Resources Conference, Carl Vinson Institute of Government, The University of Georgia, Athens, Georgia, p. 67–70.

Cocker, M. D., 1996a, Mapping terranes, structures and rock units in east Georgia with a GIS, stream sediment and stream geochemistry: Geological Society of America Abstracts with Programs, v. 28, no. 2, p. 7.

Cocker, M. D., 1996b, Background stream sediment geochemistry and hydrogeochemistry of a major river basin in Georgia: use in industrial mineral resource evaluation and environmental studies: *in* Austin, G. S. Hoffman, G. K., Barker, J., Zidek, J., and Gilson, N., eds., Proceedings of the 31st Forum on the Geology of the Industrial Minerals—The Borderland Forum: New Mexico Bureau of Mines and Mineral Resources Bulletin 154, p. 197–206.

Cocker, M. D., 1996c, Distribution of selected elements in stream sediments, stream hydrogeochemistry and geology of the Oconee River basin, Georgia: Georgia Geologic Survey Bulletin 121, 79 p.

Cocker, M. D., 1997a, Redefinition of monazite belts in Georgia and Alabama with the use of N.U.R.E. stream sediment data and GIS technology: Geological Society of America Abstracts with Programs, v. 29, no. 3, p. 9.

Cocker, M. D., 1997b, GIS mapping and analysis of stream sediment and stream geochemical data in relation to geological data for river basin management planning: examples from the Oconee, Chattahoochee and Flint River Basins: Geological Association of Canada–Mineralogical Association of Canada Joint Annual Meeting, Ottawa, Ontario.

Cocker, M. D., 1998a, Distribution of selected elements in stream sediments, stream hydrogeochemistry, lithogeochemistry and geology of the Chattahoochee River basin, Georgia and Alabama: Georgia Geologic Survey Bulletin 128, 147 p.

Cocker, M. D., 1998b, Distribution of selected elements in stream sediments, stream hydrogeochemistry, lithogeochemistry and geology of the Flint River

basin, Georgia: Georgia Geologic Survey Bulletin 129, 110 p.
Cocker, M. D., in press, Defining the heavy mineral potential in the upper coastal plain of Georgia with the use of NURE stream sediment geochemical data and a geographical information system, *in* Belanger, M., and Clark, T., eds., Proceedings of the 32nd Forum on the Geology of the Industrial Minerals for publication in Canadian Institute of Mining.
Cocker, M. D., and Dyer, T. R., 1993, Geochemistry and hydrogeochemistry of the Oconee River Basin, Georgia: the utility of a Geographic Information System (GIS): Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A350–351.
Cocker, M. D., and O'Connor, B. J., 1996, Advances in the understanding of mineral resources in Georgia: *in* Austin, G. S., Hoffman, G. K., Barker, J., Zidek, J., and Gilson, N., eds., Proceedings of the 31st Forum on the Geology of the Industrial Minerals—The Borderland Forum: New Mexico Bureau of Mines and Mineral Resources Bulletin 154, p. 197–206.
Cocker, M. D., and Shapiro, E. A., 1994, Distribution of heavy minerals on the Georgia Coastal Plain and Continental Shelf, *in* Dellagiarino, G., Masterson, A. R., and Miller, L. A., eds., Proceedings of the third symposium on studies related to continental margins—a summary of year-five and year-six activities: U.S. Department of the Interior, Minerals Management Service, and Association of American State Geologists, Continental Margins Committee, p. 55–61.
Grosz, A. E., 1993, Mineralogy and heavy-mineral resource potential of surficial sediments on the Atlantic Continental Shelf offshore of Georgia: Georgia Geologic Survey, Project Report 19, 31 p.
Henry, V. J., Jr., and Kellam, J. A., 1988, Seismic investigation of the phosphate-bearing, Miocene-age strata of the Continental Shelf of Georgia: Georgia Geologic Survey, Bulletin 109, 43 p.
Henry, V. J., and Faisal, M. I., 1992, Offshore minerals assessment studies on the Georgia Continental Shelf—Phase 2: Seismic stratigraphy of the TACTS area and evaluation of selected sites for economic hard minerals potential: Georgia Geologic Survey Project Report No. 18, 143 p.
Herring, J. R., Mannheim, F. T., Farrell, K. M., Huddlestun, P. F., and Bretz, B., 1992, Size analysis, visual estimation of phosphate and other minerals, and preliminary estimation of recoverable phosphate in size fraction of sediment samples from drill holes GAT-90, Tybee Island and GAS 90-2, Skidaway Island, Georgia: Georgia Geologic Survey, Project Report 16, 36 p.
Hughes, J. P., and Henry, V. J., 1995, Compilation and review of information on Neogene aquifers in Camden and Glynn Counties, Georgia: Georgia Geologic Survey Project Report 23, 56 p.
Kellam, M. F., ed., 1986, Geologic atlas of Coastal Georgia: Georgia Geologic Survey, Geologic Atlas 5, scale 1:249,285.
Kellam, J. A., Bonn, G. N., and Laney, M. L., 1992, Distribution of heavy mineral sands adjacent to the Altamaha Sound—a possible exploration model: Georgia Geologic Survey, Bulletin 110, 61 p.
Kellam, J. A., and Henry, V. J., 1986, Interpretation of the seismic stratigraphy of the phosphatic middle Miocene on the Georgia Continental Shelf: Georgia Geologic Survey, Geologic Atlas 4, 9 plates., scale 1:449,659.
Kellam, J. A., and Henry, V. J., 1987, Seismic investigation of the Tybee Trough area; Georgia/South Carolina: Southeastern Geology, v. 28, no. 2, p. 65–80.
Kellam, J. A., Shapiro, E. A., and Henry, V. J., 1988, Mineral resource assessments for the Continental Shelf of Georgia as a part of the Continental Margins Study Program, *in* Hunt, M. C., Ratcliff, D. C., Doenges, S., and Condon, C., eds., Proceedings of the first symposium on studies related to continental margins—a summary of year-one and year-two activities: U.S. Department of the Interior, Minerals Management Service, and Association of American State Geologists, Continental Margins Committee, p. 124–137.
Kellam, J. A., Mallary, M., and Laney, M. L., 1991, Heavy mineral-bearing sands from the Wicomico to the Princess Anne barrier complexes along the Georgia Coastal Plain: Georgia Geologic Survey, Bulletin 111, 50 p.
Mannheim, F. T., ed., 1992, Geology, stratigraphic relationships, and chemical composition of phosphatic drill cores (TACTS boreholes) from the Continental Shelf off Georgia: Georgia Geologic Survey, Project Report 17, 47 p.
McDowell, R. J., and Steele, W. M., in review, Hydrostratigraphic framework of the Miocene Brunswick aquifers: Georgia Geologic Survey Information Circular 20, 13 p. plus figures.
Mertie, J. B., Jr., 1979, Monazite in the granitic rocks of the southeastern Atlantic states—an example of the use of heavy minerals in geologic exploration: U.S. Geological Survey Professional Paper 1094, 79 p.
O'Connell, D. B., 1991, Report on the status of the Georgia Coastal Geographic Information System: Georgia Geologic Survey Open-File Report 91-1, 28 p.
Popenoe, P., 1992, Maps and cross sections depicting the shallow seismic stratigraphy of the Continental Shelf and slope off Georgia from interpretation of high-resolution seismic-reflection data: Georgia Geologic Survey, Project Report 15, 35 p.
Shapiro, E. A., 1986, Status report—Accelerated Economics Minerals Program: July 1985 through September 1986: Georgia Geologic Survey, Open-File Report 87-1, 55 p.
Shapiro, E. A., and Bonn, G. N., 1990, Heavy-mineral-bearing sands of coastal Georgia, *in* Hunt, M. C., Doenges, S.,

and Stubbs, G. S., eds., Proceedings of the second symposium on studies related to continental margins—a summary of year-three and year-four activities: U.S. Department of the Interior, Minerals Management Service, and Association of American State Geologists, Continental Margins Committee, p. 105–111.

Taylor, L., Harding, J., Henry, V. J., Kelly, J., and Tnilli, H., 1995, Assessment of environmental research and nonmineral resources offshore Georgia: Georgia Geologic Survey, Project Report 21, 368 p.

Watson, T. W., 1979, Aquifer potential of the shallow sediments of the coastal area of Georgia, *in* Investigations of alternative sources of ground water in the coastal area of Georgia: Georgia Geologic Survey Open-File Report 90-3, p. A-1–A-30.

Zellars-Williams, 1988, Offshore minerals assessment study: Georgia Geologic Survey, Project Report 14, 291 p.

Offshore Atlas Project: Methodology and Results

Lesley D. Nixon, Barbara J. Bascle, and David A. Marin

Minerals Management Service, 1201 Elmwood Park Boulevard, New Orleans, LA 70123

Abstract

The Offshore Atlas Project (OAP) grouped 4,325 Miocene and older and 5,622 Pliocene and Pleistocene productive sands in the Gulf of Mexico into 91 chronostratigraphic hydrocarbon plays to aid the oil and gas industry with regional hydrocarbon exploration and field development. OAP has produced a two-volume atlas series entitled *Atlas of Northern Gulf of Mexico Gas and Oil Reservoirs*. Volume 1 comprises Miocene and older reservoirs, while volume 2 comprises Pliocene and Pleistocene reservoirs.

Chronozones (Reed et al., 1987) were used to define geologic ages in the Gulf of Mexico. A chronozone is a time-stratigraphic unit defined by a particular benthic foraminifera biostratigraphic zone. The 26 chronozones identified by Reed et al. (1987) were further grouped into 14 Cenozoic and 2 Mesozoic chronozones for OAP. A composite type log (CTL), which shows the chronostratigraphic relationship of all productive sands in a field, was constructed for each of the 876 proved Federal fields in the Gulf of Mexico. Depositional facies (retrogradational, aggradational, progradational, and submarine fan) were next identified on each CTL. The four facies were primarily identified according to characteristic SP-curve shapes, paleoecozones, and sand content. The chronozones and depositional facies identified on each CTL were then correlated among fields across the Gulf of Mexico. All productive sands correlated to the same chronozone and depositional facies were then identified as a unique play.

Both Federal and State fields in the Gulf of Mexico contain original proved reserves (sum of cumulative production and remaining proved reserves) estimated at 12.481 Bbbl of oil and condensate and 156.466 Tcf of gas (40.322 Bboe [sum of liquids and energy equivalent gas]). Of this, 9.943 Bbbl of oil and condensate and 122.263 Tcf of gas (31.698 Bboe) have been produced. Miocene plays contain the most total original proved reserves with 41.9 percent, followed by Pleistocene plays (36.2%), Pliocene plays (18.6%), Mesozoic plays (2.9%), and Oligocene plays (0.4%). Miocene plays have produced the largest amount of total hydrocarbons, as well, at 43.5 percent, followed by Pleistocene plays (36.5%), Pliocene plays (19.1%), Oligocene plays (0.5%), and Mesozoic plays (0.4%). Just over two-thirds of the Gulf of Mexico's total original proved reserves are contained in progradational facies (67.4%), with the remainder comprising submarine-fan facies (18.5%), aggradational facies (9.9%), retrogradational facies (2.4%), combination facies (1.7%), and caprock and reef reservoirs (0.1%). Total cumulative production from the different facies closely mimics the distribution of original proved reserves. Of the 91 plays, the lower Pleistocene progradational play (LPL P.1) contains the most original proved gas reserves (10.5%) and has produced the most gas (11.4%). However, the upper upper Miocene eastern progradational play (UM3 P.1B) contains the most original proved oil and condensate reserves (18.9%) and has produced the most oil and condensate (21.4%).

Several technical studies resulting from OAP have been published. Hunt and Burgess (1995) described the distribution of OAP plays deposited by the ancestral Mississippi River delta system in the north-central Gulf of Mexico over the past ~24 million years. The lower Miocene plays are restricted to the western-most portion of the Louisiana shelf. In late middle Miocene, the depocenter migrated east of the present-day Mississippi River delta. During late upper Miocene, the depocenter began migrating back to the west and prograded basinward, and it continued to do so throughout the Pliocene and Pleistocene.

Lore and Batchelder (1995) discussed how OAP plays can be used to find exploration targets and assess undiscovered resources. As an exploration tool, OAP play maps can be used to identify conceptual submarine-fan plays downdip of established shallow water producing facies, and to identify wells where a known producing facies or chronozone has not yet been reached. As an assessment tool, the extensive data sets associated with each OAP play can be used to statistically infer the size of undiscovered resources in a play to determine if exploration in that play is economically justifiable.

Lore et al. (1995) estimated the amount of undiscovered conventionally recoverable resources in the Gulf of Mexico, basing their assessment on previous work performed for OAP. Mean level estimates show that, by far, submarine-fan plays have the greatest potential for additional oil and gas in the Gulf of Mexico, with 75.1 percent and 70.4 percent of the total oil and gas resources, respectively. Mean level estimates for the 13 OAP Miocene, Pliocene, and Pleistocene chronozones show that upper Pleistocene plays have the most oil resource potential (24.3%), while lower Pleistocene plays have the most gas resource potential (20.6%).

References

Hunt, J. L., Jr., and Burgess, G., 1995, Depositional styles from Miocene through Pleistocene in the north-central Gulf of Mexico: an historical perspective: Transactions of the Gulf Coast Association of Geological Societies, v. 45, p. 275–284.

Lore, G. L., and Batchelder, E. C., 1995, Using production-based plays in the northern Gulf of Mexico as a hydrocarbon exploration tool: Transactions of the Gulf Coast Association of Geological Societies, v. 45, p. 371–376.

Lore, G. L., Brooke, J. P., Cooke, D. W., Klazynski, R. J., Olson, D. L., Ross, K. M., 1995, Summary of the 1995 assessment of conventionally recoverable hydrocarbon resources of the Gulf of Mexico and Atlantic Outer Continental Shelf: U.S. Department of the Interior, Minerals Management Service OCS Report MMS 96-0047, 41 p.

Reed, C. R., Leyendecker, C. L., Khan, A. S., Kinler, C. J., Harrison, P. F., and Pickens, G. P., 1987, Correlation of Cenozoic sediments Gulf of Mexico Outer Continental Shelf, part 1: Galveston area, offshore Texas, through Vermilion area, offshore Louisiana: U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, OCS Report MMS 87-0026, 35 p.

Sequence Stratigraphy and Composition of Late Quaternary Shelf-Margin Deltas, Northern Gulf of Mexico

Robert A. Morton

Bureau of Economic Geology, The University of Texas at Austin,
University Station, Box X, Austin, TX, 78713-8924

John R. Suter

Conoco Inc., Houston, Texas

Abstract

High-resolution seismic profiles and foundation borings from the northwestern Gulf of Mexico record the physical attributes and depositional histories of several late Quaternary sequences that were deposited by wave-modified, river-dominated shelf-margin deltas during successive periods of lowered sea level. Each progressively younger deltaic sequence is thinner and exhibits a systematic decrease in the abundance and concentration of sand, which is attributed to a shift in the axis of trunk streams and greater structural influence through time.

Our study shows that (1) contemporaneous structural deformation controlled the thickness of each sequence, the oblique directions of delta progradation, the axes of major fluvial channels, and the geometries of delta lobes at the shelf margin, (2) sedimentation was rapid in response to rapid eustatic fluctuations and structural influence, (3) boundaries of these high-frequency sequences are the correlative conformities of updip fluvial incision, and coincide with downlap surfaces at the shelf margin, (4) the downlap surfaces are not true surfaces, but zones of parallel reflections that become progressively higher and younger in the direction of progradation, (5) the downlap zones are composed of marine muds that do not contain high concentrations of shell debris that would be expected in condensed sections, (6) possible paleosols capping the two oldest sequences are regressive surfaces of subaerial exposure that were preserved during transgressions, and (7) no incised valleys or submarine canyons breach the paleoshelf margin, even though incised drainages were present updip and sea-level curves indicate several periods of rapid fall. (Published in *AAPG Bulletin*, v. 80, p. 505–530)

Depositional and Diagenetic History and Petroleum Geology of the Jurassic Norphlet Formation of the Alabama Coastal Waters Area and Adjacent Federal Waters Area

Ralph L. Kugler

S.A. Holditch and Associates, College Station, TX

Robert M. Mink

Geological Survey of Alabama, 420 Hackberry Lane, Tuscaloosa, AL 35486

Abstract

The discovery of deep (>20,000 feet) gas reservoirs in eolian sandstone of the Upper Jurassic Norphlet Formation in Mobile Bay and offshore Alabama in the late 1970's represents one of the most significant hydrocarbon discoveries in the nation during the past several decades. Estimated original proved gas from Norphlet reservoirs in the Alabama coastal waters and adjacent Federal waters is 7.462 trillion cubic feet (Tcf) (75-percent recovery factor). Fifteen fields have been established in the offshore Alabama area.

Norphlet sediment was deposited in an arid environment in alluvial fans, alluvial plains, and wadis in updip areas. In downdip areas, the Norphlet was deposited in a broad desert plain, with erg development in some areas. Marine transgression, near the end of Norphlet deposition, resulted in reworking of the upper part of the Norphlet Formation.

Norphlet reservoir sandstone is arkose and subarkose, consisting of a simple assemblage of three minerals, quartz, albite, and K-feldspar. The present framework grain assemblage of the Norphlet is dominantly diagenetic owing to albitization and dissolution of feldspar. Despite the simple framework composition, the diagenetic character of the Norphlet is complex. Important authigenic minerals include carbonate phases (calcite, dolomite, Fe-dolomite, and breunnerite), feldspar (albite and K-feldspar), evaporite minerals (anhydrite and halite), clay minerals (illite and chlorite), quartz, and pyrobitumen. The abundance and distribution of these minerals varies significantly between onshore and offshore regions of Norphlet production. The lack of sufficient internal sources of components for authigenic minerals, combined with unusual chemical compositions of chlorite (Mg-rich), breunnerite, and some minor authigenic minerals, suggests Louann-derived fluids influenced Norphlet diagenesis.

In offshore Alabama reservoirs, porosity is dominantly modified primary porosity. Preservation of porosity in deep Norphlet reservoirs is due to a combination of factors, including a lack of sources of cement components and lack of pervasive early cement so that fluid-flow pathways remained open during burial.

Below the dominantly quartz-cemented tight zone near the top of the Norphlet, pyrobitumen is a major contributor to reduction in reservoir quality in offshore Alabama. The highest reservoir quality occurs in those wells where the present gas-water contact is below the paleo hydrocarbon water contact. This zone of highest reservoir quality is between the lowermost occurrence of pyrobitumen and the present gas-water contact.

Acknowledgments

We appreciate the assistance provided by Gary Lore and David Cooke (U.S. Department of the Interior Minerals Management Service, Gulf of Mexico OCS Region) and Steven J. Seni (Texas Railroad Commission) in compilation of data used to prepare this report. G. D. Irvin (Geological Survey of Alabama) assisted with capillary-pressure analysis. The U.S. Department of Interior Minerals Management Service provided financial support (Cooperative Agreement No. 14-35-0001-30731 through the Bureau of Economic Geology, The University of Texas at Austin).

Introduction

The discovery of deep (>20,000 feet) gas reservoirs in eolian sandstone of the Upper Jurassic Norphlet Formation in Mobile Bay and offshore Alabama in the late 1970's represents one of the most significant hydrocarbon discoveries in the nation during the past several decades (fig. 1). Fifteen Norphlet fields have been established in offshore Alabama and Mississippi with production from eolian dune, interdune, and marine reservoir facies. Estimated original proved gas reserves from Norphlet sandstone in the Alabama State coastal waters area are 7.462 trillion cubic feet (Tcf) of gas using a 75-percent recovery factor (Kugler and others, 1997). In addition to natural gas in offshore areas, the Norphlet also produces natural gas, carbon dioxide, condensate, and oil in panhandle Florida and onshore Alabama, and Mississippi. Recently, the Norphlet gas trend was extended significantly to the east in Federal waters off the Florida panhandle.

Although the depositional and diagenetic histories of Norphlet sandstone have been the focus of intense investigation, no regional synthesis of relationships among hydrocarbon producibility, depositional setting, and diagenetic character exists. At a regional scale, the producing area of the Norphlet encompasses a variety of predominantly nonmarine (alluvial fan, fluvial, and eolian) depositional facies whose distribution and reservoir character are controlled, in part, by location relative to regional fault systems, subbasins, structural highs, and salt movement. This, in turn, results in microscopic to megascopic variation in diagenetic character of Norphlet reservoir sandstone.

This paper documents the depositional and diagenetic character of Norphlet reservoirs in Alabama State coastal waters. Controls on reservoir quality of reservoirs in this area are compared with those for onshore fields in Alabama and Mississippi and for Federal OCS areas adjacent to Alabama.

An understanding of regional controls on producibility of Norphlet reservoirs relative to depositional and diagenetic history will aid delineation of hydrocarbon trends in frontier areas offshore, including the Mobile, Pensacola, and Destin Dome (MacRae and Watkins, 1992), and Desoto Canyon areas. An understanding of regional controls on Norphlet diagenesis will also contribute to understanding reservoir quality in overlying Smackover carbonate rocks.

Regional Framework

Mesozoic and Cenozoic strata of the eastern Gulf Coastal Plain form a seaward-dipping wedge of sediment that infilled differentially subsiding subbasins on the passive southern margin of North America as a result of the extensional opening of the Gulf of Mexico during the breakup of Pangea (Miller, 1982). Triassic and Jurassic strata in the study area unconformably overlie faulted and folded Paleozoic rocks and Precambrian and Paleozoic igneous and metamorphic rocks (fig. 2).

Major positive basement elements in the eastern Gulf include the Wiggins arch complex (Wiggins arch, Baldwin high, and associated paleohighs), the Choctaw ridge complex, the Conecuh ridge complex, the Pensacola ridge complex, and several unnamed basement features. These features were sources of sediment and significantly influenced pre-Jurassic and Jurassic depositional patterns.

Major basinal areas in the eastern Gulf include the Mississippi interior salt basin in onshore Alabama and Mississippi and the Apalachicola basin in offshore Florida. Halokinesis of widespread Middle Jurassic Louann Salt produced complex patterns of salt-related structures in these basins, including salt pillows, diapirs and massifs, salt-cored anticlines, and extensional fault and graben systems.

Depositional Setting

Post-Precambrian and Paleozoic, pre-Norphlet strata in the study area, including the Triassic Eagle Mills Formation, Jurassic Werner Formation, and Jurassic Louann Salt, are directly related to the initial rifting and opening of the Gulf of Mexico (fig. 3). The Norphlet Formation (Oxfordian) generally overlies the Louann Salt. Where the Louann is absent, the Norphlet

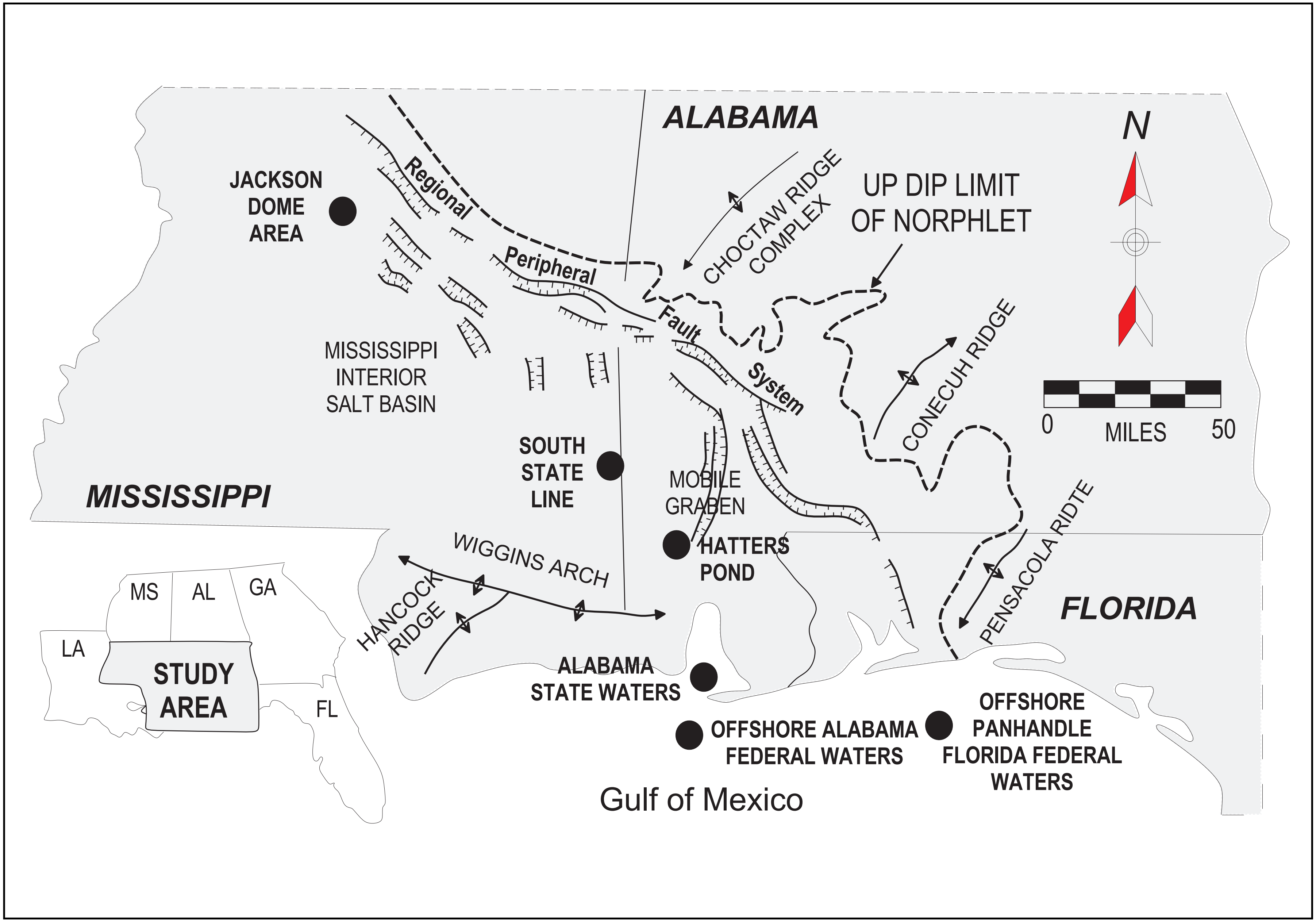


Figure 1. Location map showing areas of study and major structural features that affected deposition of Norphlet sandstone.

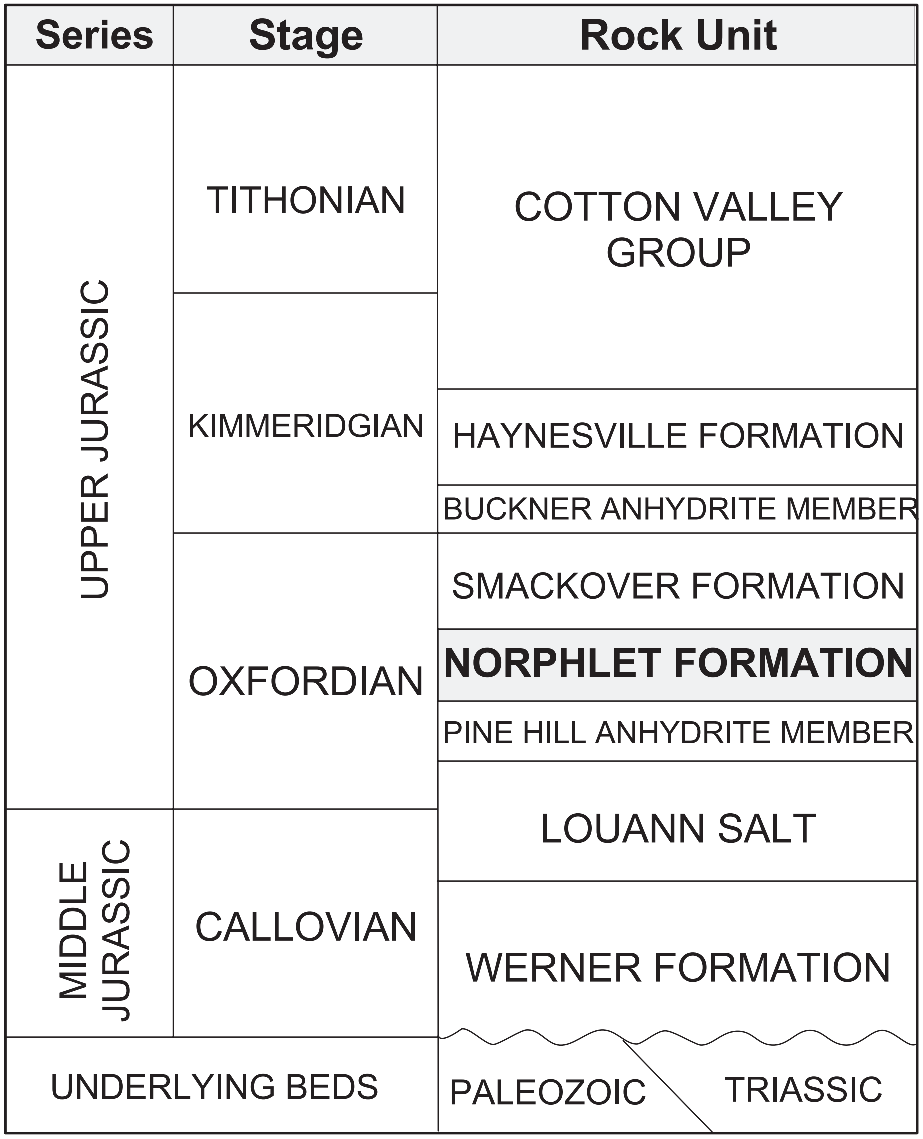


Figure 2. Generalized Middle and Upper Jurassic stratigraphic section for the study area.

disconformably overlies the Werner Formation, Eagle Mills Formation, or basement rocks (Tolson and others, 1983; Mink and others, 1985). The Norphlet is a regionally extensive, predominantly continental terrigenous clastic deposit, known only from the subsurface. Marine, reworked sandstone occurs at the top of the Norphlet in the study area. The thickness of the Norphlet varies from less than 1 foot to more than 1,000 feet in southwestern Alabama, panhandle Florida, and offshore areas (Levy, 1985; Kemmer, 1987; Hoar and others, 1990).

The Norphlet was deposited on a broad desert plain, bordered on the north and east by highlands of Proterozoic and Paleozoic rock and on the south by the evolving Gulf of Mexico basin (fig. 4). The absence of Norphlet strata on the Wiggins arch complex indicates the presence of high regions within the area of deposition (Mancini and others, 1985). Sand and gravel, derived from the northern and eastern highlands, were deposited in proximal to distal alluvial fan, alluvial plain, and wadi environments. This sediment was reworked by eolian processes and deposited in dune and

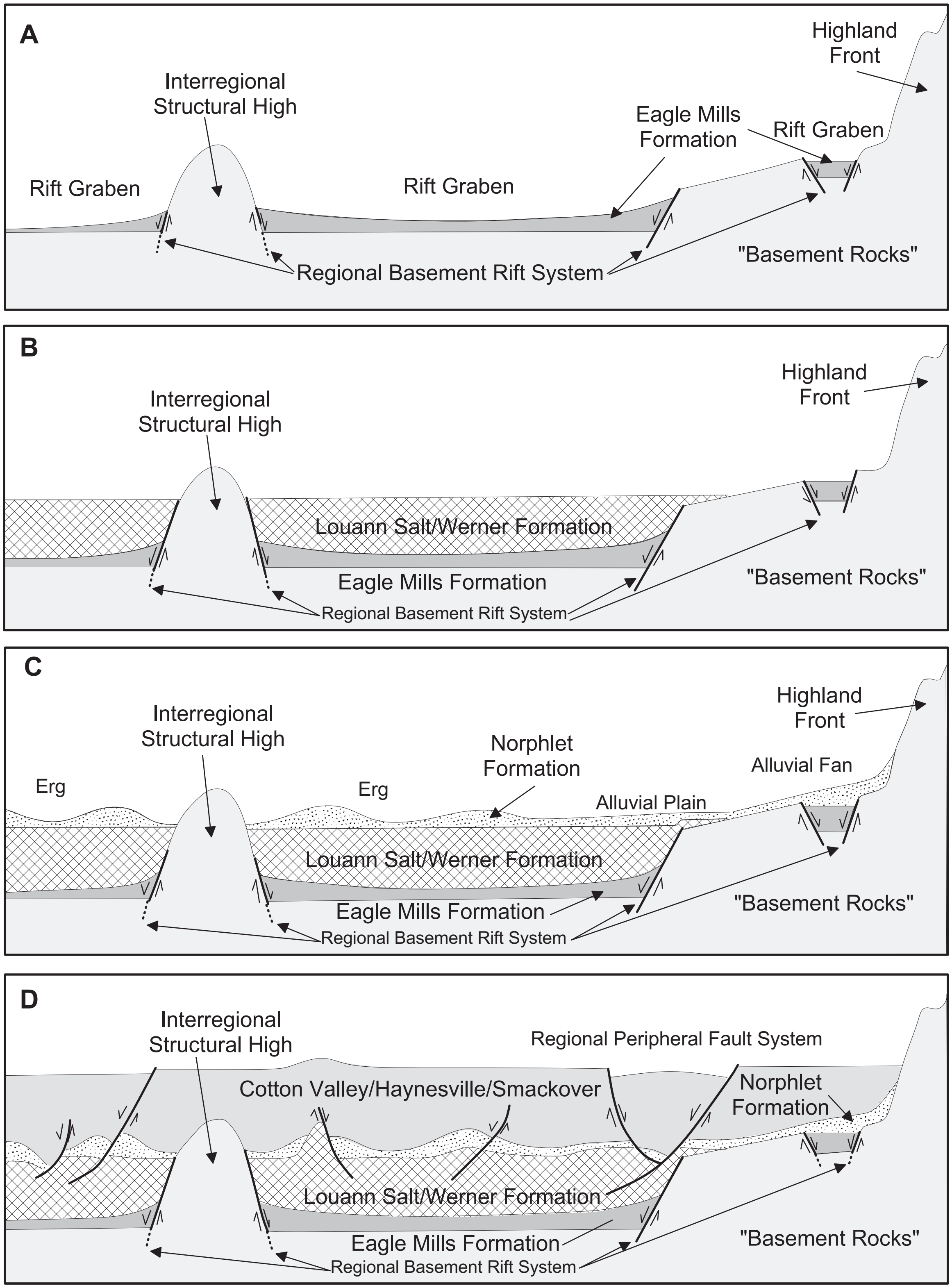


Figure 3. Generalized sequence of deposition and structural development of the Alabama, Florida, and Mississippi region (modified from Mink and others, 1990).

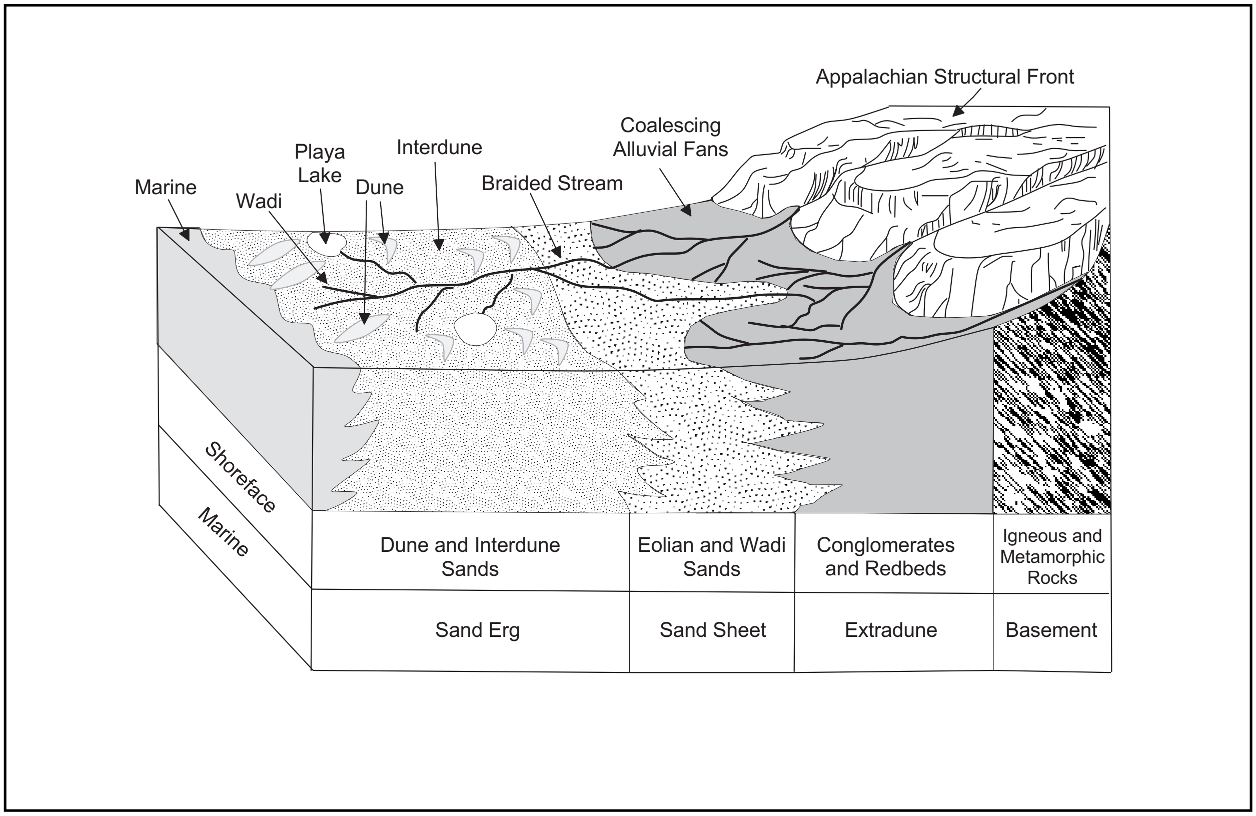


Figure 4. Block diagram showing Norphlet depositional systems and lateral facies associations (modified from Mancini and others, 1990).

interdune environments in the study area. Marine transgression near the end of Norphlet deposition reworked these eolian deposits. This transgression continued into early Smackover time. Carbonate mudstone and wackestone of the Smackover Formation, which conformably to disconformably overlie the Norphlet Formation, are the source rock for Norphlet reservoirs in the study area (Claypool and Mancini, 1989; Prather, 1992; Kopaska-Merkel and Hall, 1993).

Petrology

Knowledge of the detrital and authigenic mineral composition of sandstone is important to predicting producibility of hydrocarbons in clastic reservoirs. Understanding diagenetic patterns in Norphlet sandstone is particularly important because significant stratigraphic and aerial variation in diagenesis affects the quality of reservoir sandstone with similar detrital framework composition, deposited in similar depositional environments. In this paper, major emphasis is placed on wells in the Alabama coastal waters area because this is the area for which most data were available and these sandstone reservoirs are most similar to those in Federal OCS areas. Data from offshore Alabama State waters are compared with those from Mobil Blocks 822, 823, and 867 (offshore Alabama Federal OCS area), Hatter's Pond field (onshore Alabama), South State Line field (onshore Mississippi), and wells in the vicinity of Jackson Dome (onshore Mississippi) (McHugh, 1987; Kugler and McHugh, 1990). In combination, these data reveal that diagenetic heterogeneity exists in Norphlet sandstone at several scales, including (1) differences between adjacent laminae related to depositional facies and texture; (2) variation within single hydrocarbon-producing fields; (3) stratigraphic variation; and (4) regional variations that encompass several fields or offshore blocks (Kugler, 1989). Data used in this paper are tabulated in Kugler and Mink (1993).

Framework Composition

Norphlet sandstone is arkose and subarkose. Sandstones from offshore Alabama (State waters and Federal OCS areas) and onshore Alabama (Hatter's

Pond field) have similar present detrital framework composition. The present detrital framework mineralogy is simple, consisting of three minerals, quartz, albite, and K-feldspar (Kugler and McHugh, 1990). This framework composition is largely the result of diagenesis, through dissolution, albitization, and stabilization of feldspar.

Quartz is the most abundant detrital framework component, averaging approximately 75 percent of framework volume (Kugler and McHugh, 1990). Unvacuolized to slightly vacuolized monocrystalline quartz with straight to slightly undulose extinction accounts for 85 percent of total quartz. Some quartz contains inclusions of apatite, rutile, tourmaline, and, very rarely, vermicular chlorite (Kugler and Mink, 1993).

Feldspar accounts for 21 percent of total framework volume and consists of twinned and untwinned plagioclase, orthoclase, and microcline; perthite occurs in minor amounts. Plagioclase and K-feldspar occur in nearly equal amounts in offshore Alabama wells, but K-feldspar is slightly more abundant in onshore Alabama wells owing to greater alteration of plagioclase through dissolution and replacement by illite. Electron microprobe analysis reveals that plagioclase ranges in composition An_0 to An_{15}, although most is nearly pure albite; most K-feldspar ranges from Or_{90} to Or_{100} (Kugler and McHugh, 1990). Framework grain feldspar in Norphlet sandstone represents a diagenetic, rather than original detrital, assemblage. The large amount of albite is the result of albitization and of concentration of detrital albite through dissolution of calcic plagioclase. K-feldspar stabilized in deeply buried Norphlet sandstone because of the presence of K-rich fluids related to underlying Louann evaporites. Dissolution of more sodic K-feldspar also contributed to the near end-member K-feldspar assemblage in the Norphlet. Partially dissolved, skeletal K-feldspar and pristine-appearing grains may be present in the same sample; however, pristine grains are relatively more abundant in offshore wells.

Low-rank metamorphic, plutonic, felsic volcanic, and chert rock fragments compose four percent of framework volume. Rock fragment composition of Norphlet sandstone suggests a dominantly plutonic and metamorphic, southern Appalachian provenance for the study area, although the Wiggins arch complex may have served as a local source (Walls, 1985; Ryan and others, 1987). Although the provenance of Norphlet sandstone changes from Florida to Texas (Ryan and others, 1987), it does not appear to be of sufficient magnitude in the study area to account for the observed variation in diagenetic character of the sandstone.

Diagenesis

Even though the framework composition of Norphlet sandstone is simple, the diagenetic character is complex. The paragenetic sequence for onshore Alabama and Mississippi is more complex than that for offshore Alabama and Florida (fig. 5). Significant regional variation in the paragenetic sequence occurs in onshore Alabama and Mississippi (Kugler and McHugh, 1990). Volumetrically, the most important authigenic minerals are a variety of carbonate phases (calcite, dolomite, Fe-dolomite, and breunnerite), quartz, feldspar (albite and K-feldspar), pyrobitumen, and evaporite minerals (anhydrite and halite).

The clay minerals illite and chlorite, although volumetrically less abundant, significantly influence the quality of Norphlet reservoirs. Chlorite is more common in offshore sandstone, whereas illite is more abundant onshore. Norphlet sandstone containing authigenic chlorite typically has higher porosity and permeability than that containing authigenic illite (Kugler and McHugh, 1990). Chlorite in offshore Norphlet sandstone is Mg-rich in comparison to the Fe-rich composition common in other chlorite-bearing sandstones (Kugler and McHugh, 1990). This chlorite, combined with the presence of an unusual Fe-magnesite (breunnerite) cement in onshore Alabama, suggests that Louann evaporite-related fluids influenced Norphlet diagenesis.

Quartz precipitated at least two times during the diagenetic evolution of Norphlet sandstone. Early quartz cement is volumetrically minor. However, late quartz is volumetrically significant and is the dominant pore-occluding cement in the tight zone at the top of the Norphlet. This quartz typically occurs as syntaxial overgrowths. Scanning cathodoluminescence microscopy reveals well-developed growth banding in quartz overgrowths from the tight zone (Kugler, 1993). Below the tight zone, quartz replaces anhydrite in nodular masses that encompass several sand grains (Kugler and Mink, 1993). This quartz does not contain well-developed crystal growth banding when viewed by scanning cathodoluminescence microscopy (Kugler, 1993).

The composition of carbonate cement differs between onshore and offshore Alabama. Iron-rich carbonates, including Fe-dolomite and breunnerite

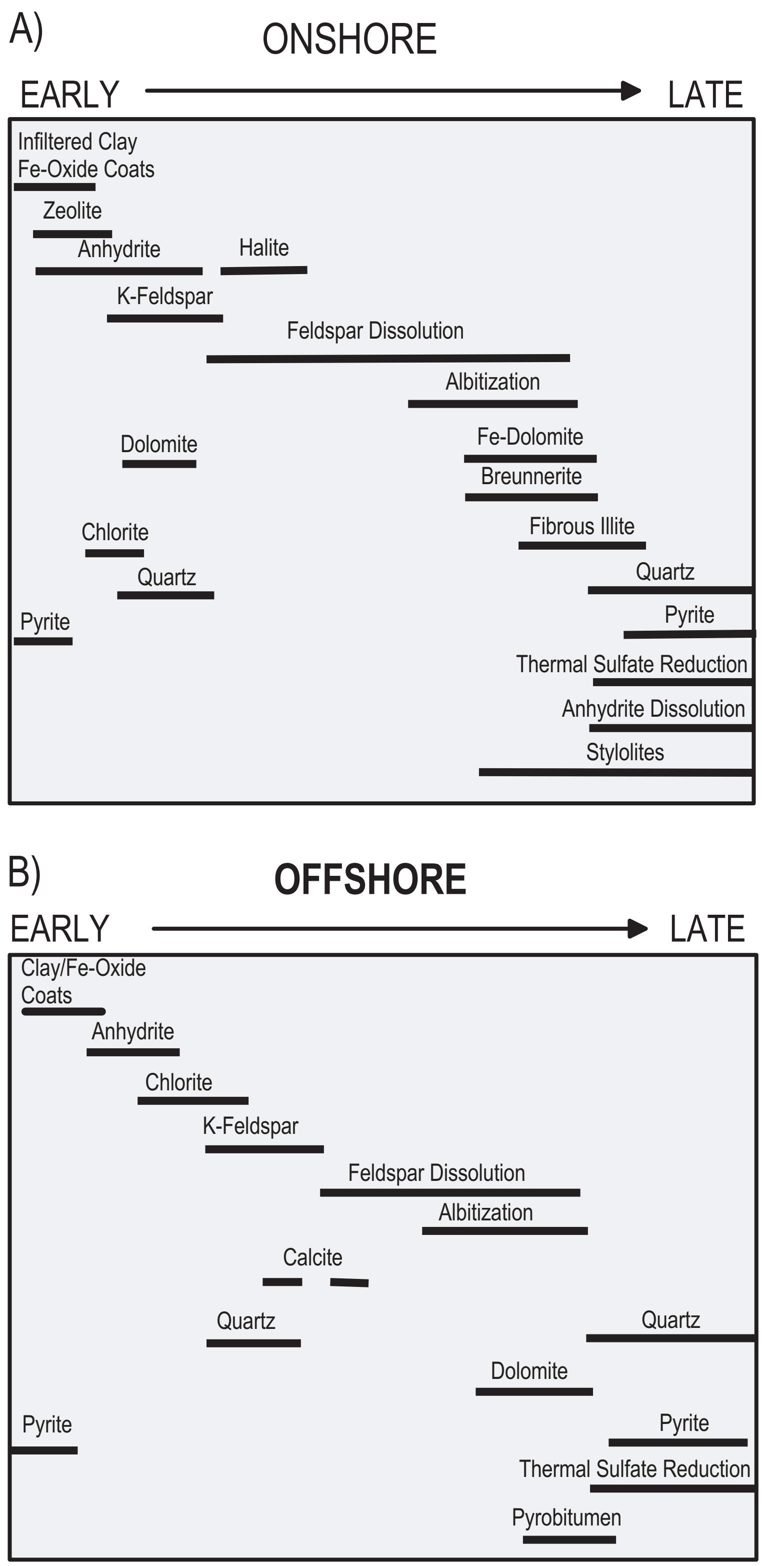


Figure 5. Generalized paragenetic sequences of major diagenetic events in Norphlet sandstone for (A) onshore fields and (B) offshore fields. Early and late are relative terms based on petrographic observation. Some minerals only occur locally. (Modified from Kugler and McHugh, 1990).

(an iron-rich magnesite) occur in onshore sandstone. The presence of the breunnerite again suggests that Louann-related fluids influenced Norphlet diagenesis (Kugler and McHugh, 1990). Carbonate cement is volumetrically less abundant in offshore Alabama and consists of nonferroan calcite and nonferroan dolomite.

Pyrite occurs in two forms in Norphlet sandstone. Early-formed pyrite occurs as framboids, most commonly at the Norphlet-Smackover contact. This pyrite causes a resistivity kick that is used to define the contact on well logs. Volumetrically minor, late pyrite occurs as masses that fill pores and replace detrital grains. Late pyrite masses formed as a result of thermal sulfate reduction of anhydrite (Siebert, 1985; Dunn and Surdam, 1991).

Norphlet sandstone apparently was affected by two stages of hydrocarbon generation and migration, one of which left a black pyrobitumen residue on detrital grain surfaces and another that accounts for present gas and condensate reserves. Many sandstones, particularly those from offshore areas, contain pyrobitumen coats that overlie chlorite grain coats but underlie quartz cement. Pyrobitumen imparts black or dark-gray color to sandstone in which it is present. Pyrobitumen is most abundant in the upper Norphlet. Sandstone lower in the section generally lacks pyrobitumen and is interpreted to be below present or paleo hydrocarbon-water contacts. Thus, the presence of pyrobitumen can be used to determine former positions of water contacts. Next to quartz, pyrobitumen is the primary cause of degradation of reservoir quality in the gas column in offshore areas.

Several authigenic minerals occur in trivial percentages or have limited geographic and/or stratigraphic distribution in Norphlet sandstone. These minerals include Ti-oxide (anatase), a zeolite (tentatively identified as mordenite), chalcopyrite, apatite, and tourmaline (Kugler and McHugh, 1990; Kugler and Mink, 1993). Although these minerals are not volumetrically abundant, their compositions give valuable clues to diagenetic pathways in Norphlet sandstone.

Evidence of chemical compaction of Norphlet sandstone is abundant, particularly in onshore areas. Long and sutured grain contacts and stylolites are most abundant in onshore sandstone where illite also is common. Stylolites occur as low-amplitude seams parallel to bedding or primary sedimentary structures. Stylolites are less common in offshore wells, where packing density of detrital grains also is lower, perhaps due to the presence of chlorite grain coats as an inhibitor of pressure solution. Grain contacts in offshore wells typically are point or long contacts. The amount of pressure solution in Norphlet sandstone appears to be inadequate to account for the volume of quartz cement (McBride and others, 1987). However, in some offshore areas significant volumes of quartz cement correlate with zones of pressure solution in the upper Norphlet (Thomas and others, 1993).

Porosity

The origin of porosity in Norphlet sandstone has been a matter of much speculation and controversy. Some investigators suggest that secondary porosity is a major, if not the most important, component of the pore system, whereas others suggest that most porosity is modified primary porosity. Both schools of thought have application in different areas of Norphlet production (Kugler and McHugh, 1990).

In offshore Alabama wells, there also is clear evidence of aluminosilicate framework grain dissolution; partially dissolved feldspar occurs in thin sections from all cores examined from these wells (Kugler and Mink, 1993). Thus, some porosity indisputably is secondary in the offshore area. However, pores between detrital framework grains account for a majority of pore volume in the Norphlet. The controversy regarding the origin of porosity centers around this intergranular volume. Those who argue that most porosity is secondary suggest that pervasive early carbonate- or evaporite-mineral cements provided support of the detrital framework during burial, resulting in an open pore system upon dissolution of the cements (for example, Marzano and others, 1988; Lock and Broussard, 1989; Schmoker and Schenk, 1994).

Alternatively, the Norphlet pore system may have remained relatively open during burial, being modified by grain rearrangement and dissolution of some cement. Proponents of relict primary porosity in the Norphlet suggested that pervasive early cements were not present. Dixon and others (1989) and Surdam and others (1989) argued that early carbonate cement could not have occurred as pervasive cements during burial because formation waters were acidic during residence time of the Norphlet in carbonate stability windows. Ajdukiewicz and others (1991) suggested that early decementation of early cements, chlorite rims, gas emplacement, and overpressuring did not contribute to high porosity in deeply buried Norphlet. Rather, they believed that neither adequate sources of cement nor geochemical conditions favoring cementation existed. On the basis of burial history modeling, including fluid-flow patterns, Ajdukiewicz and others (1991) concluded that conditions favorable to extensive quartz cementation never existed in most of the Norphlet because the unit was isolated from basinward sources of silica-saturated fluids.

Petrographic observations from wells in Alabama coastal waters areas (Kugler and Mink, 1993), as well as those of McHugh (1987), Kugler and others (1997), and Kugler and McHugh (1990) for wells in OCS blocks (822, 823, and 867) support the hypothesis that porosity in deep offshore Norphlet wells is mainly relict primary porosity. The presence of chlorite rims on detrital grains is important in preserving porosity because sandstones in both onshore and offshore wells with chlorite grain coats consistently have high porosity and permeability. However, we concur with Dixon and others (1989) and Ajdukiewicz and others (1991) that preservation of porosity of the offshore Norphlet is due to a combination of factors, including a lack of sources for cement and a lack of pervasive early cement so that fluid-flow pathways remained open during burial.

Controls on Norphlet Diagenesis

Because of the complexity of diagenetic mineral assemblages and the simplicity of the detrital assemblages, it is clear that chemical constituents must have been imported into Norphlet sandstone. In particular, authigenic albite, K-feldspar, and various magnesium-rich phases required more sodium, potassium, and magnesium than were available within the Norphlet (Kugler and McHugh, 1990). The most likely source for these components is the underlying Louann Salt. The presence of magnesium-rich, rather than iron-rich, chlorite (Kugler and McHugh, 1990) supports the importance of Louann evaporites in Norphlet diagenesis, as do authigenic tourmaline in the sandstone (Kugler and Mink, 1993) and unusual borosilicate minerals in lower Norphlet shale (Simmons, 1988). Models of dolomitization of Smackover carbonate rocks that call upon Louann-derived brines (Carpenter, 1978; Stoessell and Moore, 1983; Barrett, 1986; Worrall and Warren, 1986) further support the contention that these fluids were important in Norphlet diagenesis because they must have passed through the sandstone. Evaporite systems within the Norphlet also may have influenced diagenesis locally, as is indicated by the presence of an authigenic zeolite mineral in South State Line field, onshore Mississippi (Kugler and McHugh, 1990).

Some constituents, such as iron, most likely were derived from within the Norphlet. It is difficult to call upon Smackover carbonates or Louann evaporites as a source of iron, and the nature of downdip Norphlet marine equivalents is poorly known. The most likely source of iron is early clay/iron-oxide coats on detrital grains in Norphlet redbeds.

Diagenetic variation in Norphlet sandstone at a regional scale remains difficult to explain. The distribution of clay and carbonate mineral assemblages is not related to variation in provenance. Onshore and offshore fields are separated by the Wiggins arch and occur in different subbasins with different fluid-flow regimes. Variation in the composition of Louann evaporites or residual fluids may be partly responsible for variation in the diagenetic character of the Norphlet. The complex distribution of carbonate and clay mineral assemblages in Hatter’s Pond field (Kugler and McHugh, 1990; Kugler and Mink, 1993) suggests that variation in fluid-flow paths relative to fault systems, such as the Mobile graben, salt structures, and depositional texture are important controls on diagenetic character and reservoir quality of Norphlet sandstone at a more local scale.

In summary, diagenesis of Norphlet sandstone exhibits complex spatial variation at scales ranging from microscopic to regional. Some variation is due to depositional texture, but some also is related to other factors, including structure, position of fluid contacts, differences in fluid-flow paths and fluid composition in subbasins, and proximity to Louann evaporites. Thus, caution should be used in extrapolating knowledge of the diagenetic character of the sandstone from one area to other areas of Norphlet production.

Petrophysical Controls on Reservoir Quality in the Offshore Norphlet

Commercial core analyses for 13 wells and capillary pressure data from 3 wells in Alabama State waters were used to evaluate controls on petrophysical properties in offshore Norphlet reservoirs (Kugler and Mink, 1993). Core-analysis porosity correlates well with permeability to air for all wells examined from Alabama coastal waters areas. Coefficients of determination (R2) are generally higher than 0.80 and range from 0.63 to 0.91 (Kugler and Mink, 1993). This good correlation between porosity and permeability commonly does not exist, however, for onshore Norphlet wells because of the presence of authigenic illite (Kugler and McHugh, 1990). Porosity-permeability relationships in onshore wells are very complex, owing to position relative to fluid contacts (Hatters’s Pond field—Stoudt and others, 1992) and distribution of illite and chlorite (South State Line field—Thomson and Stancliffe, 1990). These variations in petrophysical properties make regression lines through porosity versus depth plots, such as those constructed from regional data by Dixon and others (1989), of questionable value as predictive tools for reservoir quality in individual areas of Norphlet production.

Pore-throat size distributions derived from capillary pressure analysis using high-pressure mercury porosimetry. Plots of incremental and cumulative mercury intrusion volume versus pore-throat radius reveal that pore-throat size distributions in Norphlet sandstone (fig. 6) are both unimodal and, more commonly, polymodal (Kugler and Mink, 1993). Pore-throat radius distributions in polymodal samples commonly have a dominant mode between 0.1 and 0.5 micrometers; however, there is significant variation in the range of pore-throat radius modes. These small pore-throat sizes represent pore throats between authigenic chlorite platelets that clog the larger throats between detrital framework grains. Similar small pore-throat sizes also may occur between secondary intragranular pores in detrital feldspar grains and between detrital grains in poorly sorted sandstone. Larger pore-throat size modes, between 2 and 7 micrometers, are representative of pore throats that are not significantly clogged by chlorite grain coats, pyrobitumen, or other small particle size authigenic or detrital material.

Crossplots of neutron porosity versus bulk density show that the highest porosity (>10 percent) in Alabama State waters wells typically occurs in the lower part of the Norphlet section (fig. 7; additional data in Kugler and Mink, 1993). This stratigraphic trend also is apparent from porosity versus depth plots constructed using commercial core analysis data (fig. 8). Because of the correlation between porosity and permeability in these wells, the permeability versus depth plot displays similar trends (fig. 8). The high-frequency, serrate pattern evident in lines connecting individual data points in figure 8 is due to variation in eolian stratification types, grain-size differences in laminae, and small-scale diagenetic variation. However, the larger scale trends, highlighted by the heavy lines in figure 8, are controlled mostly by factors other than stratification type or depositional facies.

Comparison of petrographic data to porosity and permeability versus depth plots (fig. 8) reveals that the base of the dominantly quartz-cemented tight zone at the top of the Norphlet in offshore areas does not coincide necessarily with increases in porosity and permeability lower in the section. Interestingly, mean and modal porosity, and therefore permeability, in the present gas zone is lower than mean and modal porosity in the water zone (fig. 8), a relationship that is opposite that observed in Hatter’s Pond field by Stoudt and others (1992). In some offshore Alabama wells, the present gas-water contact coincides with a change in porosity and permeability, but not in others (fig. 8). Petrographic data show that the lower limit of pyrobitumen grain coats approximately coincides with the changes in petrophysical properties shown on the porosity and permeability versus depth plots (fig. 8). Samples from the upper zone with lower porosity and permeability contain pyrobitumen, whereas those from the lower zone do not. Thus, the change in petrophysical properties records the former position of a hydrocarbon-water contact.

On the basis of the discussion of petrophysical properties and the distribution of pyrobitumen, it is apparent that changes in position of fluid contacts favorably influenced reservoir quality in several offshore Alabama wells (Kugler and Mink, 1993). Lowering of hydrocarbon-water contacts to present positions typically resulted in intervals between the quartz-cemented tight zone and the water contact with the highest permeability in the gas leg. More than one factor contributed to enhancement of reservoir properties in the lower part of the gas leg in these wells. First, pyrobitumen coats that reduce the size of pores and pore throats do not affect the lower part of the gas leg in wells in which the water contact shifted downward. Second, diagenetic reactions typically are inhibited by introduction of hydrocarbons but continue in water-saturated zones (cf. Saigal and others, 1992). Therefore, framework-grain dissolution reactions could continue to enhance porosity in water-saturated intervals after introduction of hydrocarbons into the reservoir. This factor degraded reservoir quality in Hatter’s Pond field through subsequent precipitation of illite but enhanced reservoir properties in offshore wells.

The volume of rock in Norphlet reservoirs affected by shifts in fluid contacts is dependent on the interplay of a large number of factors, including those that controlled the distribution of cements in the tight zone. Additionally, the direction of movement of the fluid contact, the stratigraphic position of the contact, and its location relative to reservoir structure influence the volume of rock affected by changes in position of the contact.

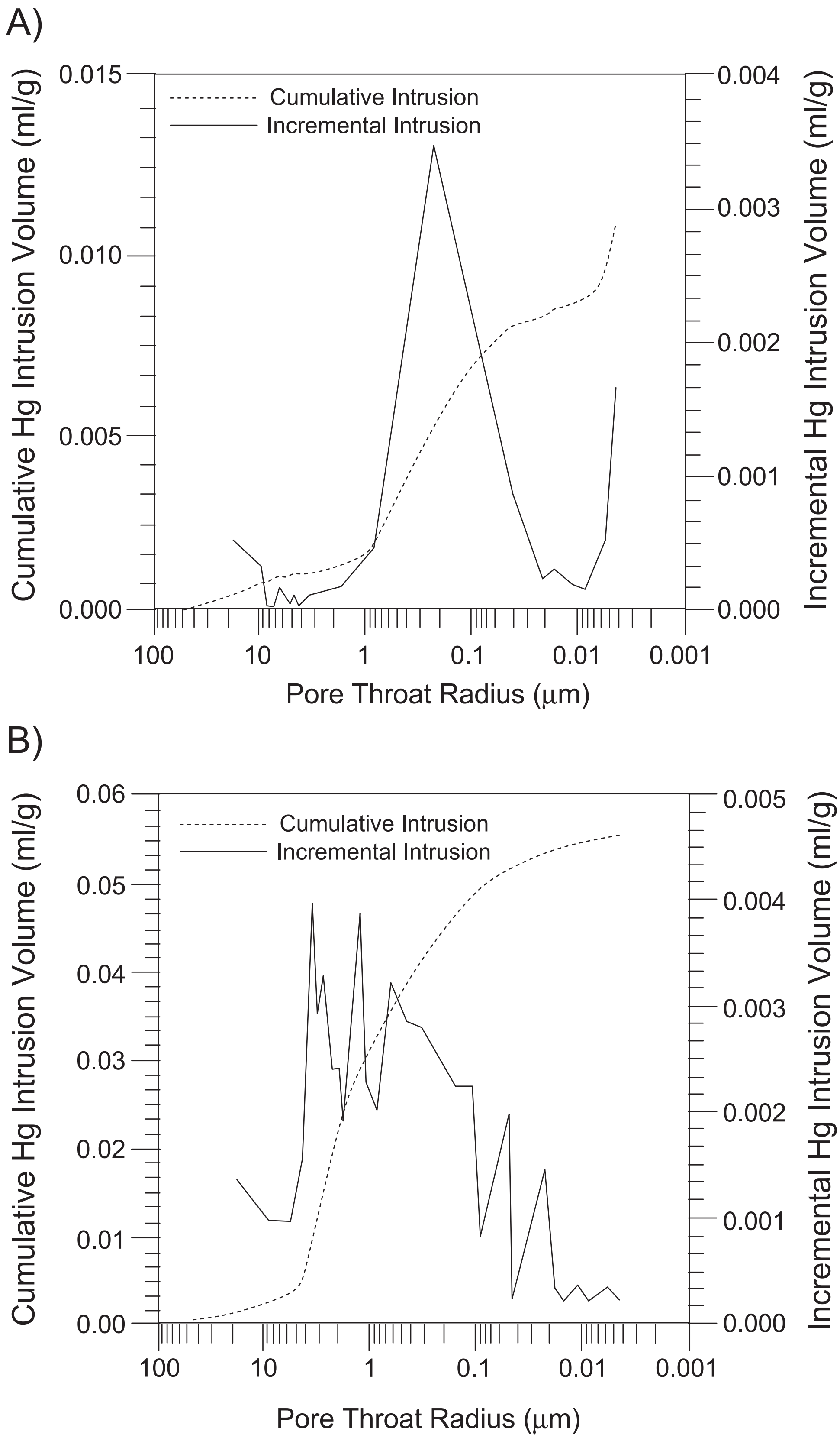


Figure 6. Plots of pore-throat radius versus cumulative and incremental mercury intrusion volume. (A) Norphlet sandstone with an unimodal pore-throat size distribution (Alabama State Oil and Gas Board permit number 3632 well, 20,709 feet). (B) Norphlet sandstone with a polymodal pore-throat size distribution (Alabama State Oil and Gas Board permit number 4266 well, 21,554 feet).

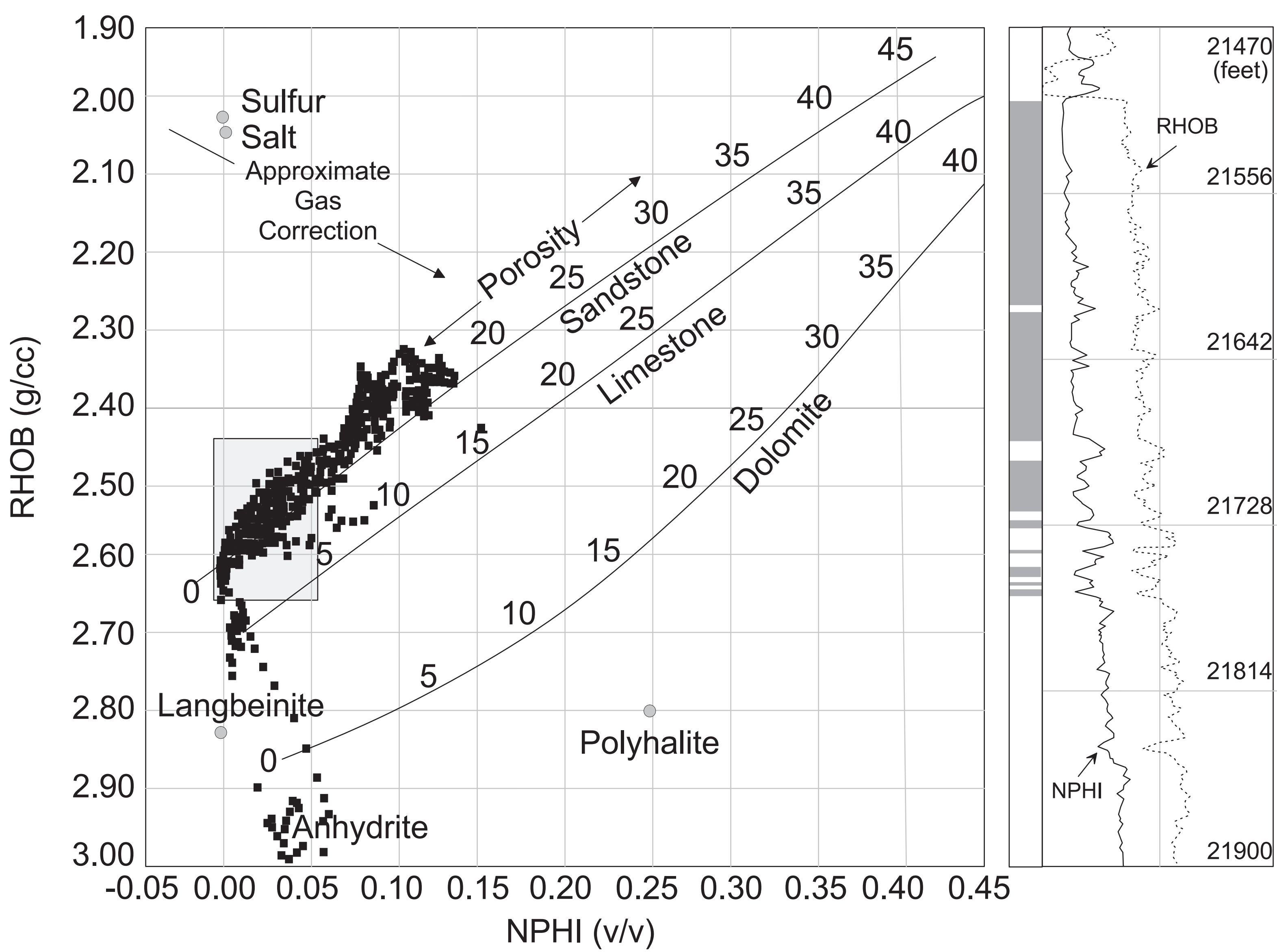


Figure 7. Neutron porosity (NPHI) versus bulk density (RHOB) for the Alabama State Oil and Gas Board permit number 4131 well showing the stratigraphic interval with porosity less than 10 percent (shaded area on crossplot).

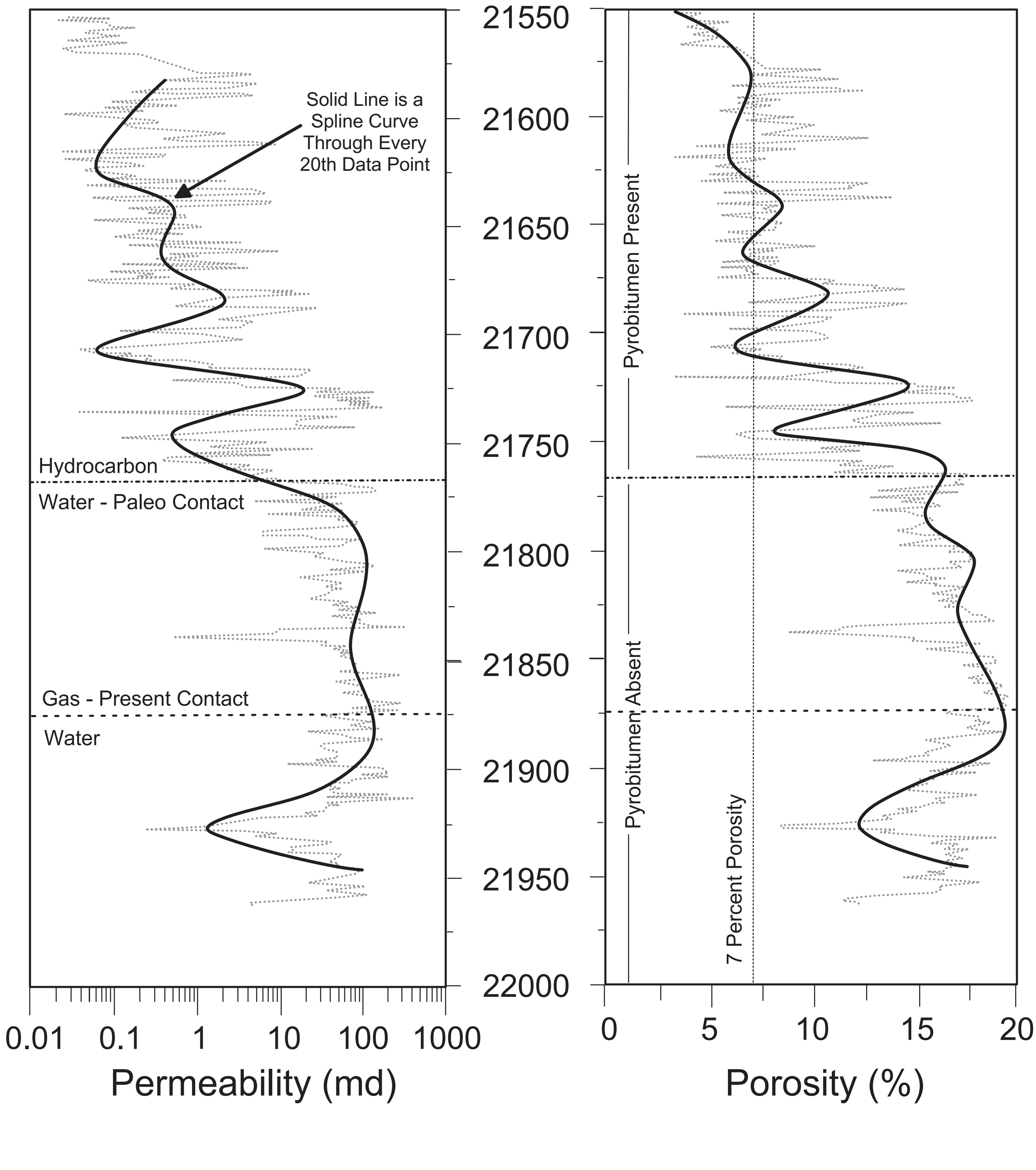


Figure 8. Plots of permeability and porosity versus depth from commercial core analysis data for the Alabama State Oil and Gas Board permit number 4131 well. The light-gray lines connect all data points. The heavy black lines are spline curves drawn through every twentieth data point to highlight major vertical trends. Note the positions of present and paleo fluid contacts relative to the extent of pyrobitumen grain coats.

Summary and Conclusions

Norphlet and pre-Norphlet strata comprise a seaward-dipping wedge of sedimentary rock that reflects the infilling of a differentially subsiding, depositional basin on the passive southern margin of the North American continent. Norphlet sediments were deposited in an arid environment as alluvial fans, distal alluvial fans, alluvial plains, and wadi environments in updip areas. In downdip areas, the Norphlet was deposited across a broad desert plain. Ergs developed in some areas. A marine transgression reworked the upper part of the Norphlet Formation. Deposition was affected by major positive basement elements, such as the Wiggins arch complex, the Choctaw ridge complex, the Conecuh ridge complex, and the Pensacola-Decatur ridge complex. Salt-related structures influencing the Norphlet include the regional peripheral fault trend, the Mobile graben, the Lower Mobile Bay fault system, the Destin anticline, and numerous salt diapirs, salt massifs, salt-cored anticlines, and extensional faults.

Estimated original proved gas reserves in Alabama State coastal waters are 7.462 Tcf, using a 75-percent recovery factor (Kugler and others, 1997), with production from eolian dune, interdune, wadi, and marine reservoir facies. Microbial carbonate mudstone in the lower Smackover Formation is the principal source rock for Norphlet reservoirs. Petroleum traps are structural, involving salt anticlines, faulted salt anticlines, and extensional fault traps associated with halokinesis of underlying Louann Salt.

Norphlet arkose and subarkose consist of a simple assemblage of quartz, albite, and K-feldspar. This simple assemblage is the product significant diagenetic alteration from albitization and dissolution of feldspar. Major diagenetic factors influencing reservoir quality vary significantly throughout the region of Norphlet hydrocarbon production. Major authigenic minerals affecting reservoir quality include clay miners (illite and chlorite), carbonate minerals (calcite, nonferroan and ferroan dolomite, and Fe-magnesite), and quartz. Ironically, hydrocarbons (pyrobitumen) degrade reservoir quality in offshore wells. Similarities in the original detrital composition of Norphlet sandstone in onshore and offshore Alabama suggest that provenance variations cannot be used to explain regional variation in diagenetic character. Because of the complexity of diagenetic mineral assemblages and the simplicity of detrital assemblages, chemical constituents must have been imported into the Norphlet from external sources, such as the Louann Salt.

The distribution of some diagenetic components in Norphlet reservoirs is controlled by depositional texture, including preferential cementation of coarser grained laminae, concentration of pyrobitumen in finer grained laminae, localization of pressure-solution seams, and concentrations of cements in specific eolian subenvironments, such as interdunes. Distribution of these diagenetic components, which create local to widespread barriers and baffles to fluid flow, can be determined by depositional modeling The distribution of other authigenic components, including quartz, clay minerals, and pyrobitumen, is independent of depositional texture and cannot be predicted by depositional modeling.

Factors controlling the distribution of texture-independent diagenetic components include availability of chemical constituents from external sources, past and present positions of hydrocarbon-water contacts, and the time available for diagenetic reactions to proceed. In onshore fields, such as Hatter's Pond field, the position of fluid contacts influences reservoir quality. For example, permeability is highest above the hydrocarbon-water contact, where authigenic illite is less abundant. The opposite relationship occurs in offshore fields in Alabama coastal waters and Federal Outer Continental Shelf areas where sandstone below ancient or modern hydrocarbon-water contacts has the highest reservoir quality.

As many as four diagenetic zones of differing reservoir quality occur stratigraphically in offshore wells. In descending order, they are (1) the dominantly quartz-cemented tight zone at the top of the Norphlet; (2) an interval above paleo or present fluid contacts in which pyrobitumen grain coats reduce pore volume and constrict pore throats; (3) an interval between paleo and present fluid contacts that lacks pyrobitumen and has the highest reservoir quality; and (4) an interval similar to interval 3 that lies below the present gas-water contact. Not all intervals are present in every well. However, the presence of these four zones indicates that Norphlet reservoir quality cannot readily be predicted through use of regional porosity-depth trends because the distribution of pyrobitumen is unrelated to these trends.

References

Ajdukiewicz, J.M., Paxton, S.T., and Szabo, J.O., 1991, Deep porosity preservation in the Norphlet Formation, Mobile Bay, Alabama (abs.): American Association of Petroleum Geologists Bulletin, v. 75, p. 533.

Barrett, M.L., 1986, Smackover (Jurassic) dolomite, Alabama: evidence for dolomitization by upward moving saline fluid (abs.): Abstracts, Society of Economic Paleontologists and Mineralogists Midyear Meeting, Raleigh, North Carolina, p. 6.

Carpenter, A.B., 1978, Origin and chemical evolution of brines in sedimentary basins: Oklahoma Geological Survey Circular 79, p. 60–77.

Claypool, G.E., and Mancini, E.A., 1989, Geochemical relations of petroleum in Mesozoic reservoirs and carbonate source rocks of Jurassic Smackover Formation, southwestern Alabama: American Association of Petroleum Geologists Bulletin, v. 73, p. 904–924.

Dixon, S.A., Summers, D.M., and Surdam, R.C., 1989, Diagenesis and preservation of porosity in Norphlet Formation (Upper Jurassic), southern Alabama: American Association of Petroleum Geologists Bulletin, v. 73, p. 707–728.

Dunn, T.L., and Surdam, R.C., 1991, Effects of thermal sulfate reduction on permeability distributions of the Norphlet Formation (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 707–708.

Hoar, Robert, Taylor, C.A., Story, K.R., Weise, E., Sharp, C.L., and Von Herneberg, W., 1990, Origin and exploration significance of lensing in the Norphlet Formation, Offshore Mafla: American Association of Petroleum Geologists Bulletin, v. 74, no. 5, p. 676.

Kemmer, D.A., 1987, Exploration in Jurassic of north MAFLA, eastern Gulf of Mexico (abs.): American Association of Petroleum Geologists Bulletin, v. 71, no. 5, p. 576.

Kopaska-Merkel, D.C., and Hall, D.R., 1993, Reservoir characterization of the Smackover Formation in southwest Alabama: Alabama Geological Survey Bulletin 153, 111 p.

Kugler, R.L., 1989, Small to large-scale diagenetic variation in Norphlet sandstone, onshore and offshore Mississippi, Alabama, and Florida (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 375–376.

Kugler, R.L., 1993**,** Low-intensity cathodoluminescence imaging of authigenic quartz in Norphlet sandstone: Abstracts, Southeastern Electron Microscopy Society Annual Meeting, Birmingham, Alabama, p. 20.

Kugler, R.L., and McHugh, A.E., 1990, Regional diagenetic variation in Norphlet sandstone: implications for reservoir quality and the origin of porosity: Gulf Coast Association of Geological Societies Transactions, v. 40, p. 411–423.

Kugler, R.L., and Mink, R.M., 1993, Depositional and diagenetic history and petroleum geology of the Jurassic Norphlet Formation of the Alabama coastal waters area and adjacent Federal waters area: U.S. Department of the Interior, Minerals Management Service Cooperative Agreement No. 14-35-0001-30643, Bureau of Economic Geology, University of Texas, 203 p.

Kugler, R.L., Mink, R.M., Burgess, G.L., Peterson, R.H., Bascle, B.J., and Nixon, L.D., 1997, Upper Jurassic aggradational sandstone, *in* Seni, S. J., and others, eds., Atlas of northern Gulf of Mexico gas and oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, p. 8–10.

Levy, J.B., 1985, Major discoveries in eolian sandstone: facies distribution and stratigraphy of Jurassic Norphlet sandstone (abs.): American Association of Petroleum Geologists Bulletin, v. 69, p. 278.

Lock, B.E., and Broussard, S.W., 1989, the Norphlet reservoir in Mobile Bay: origins of deep porosity: Gulf Coast Association of Geological Societies Transactions, v. 39, p. 187–194.

MacRae, Grant, and Watkins, J.S., 1992, Evolution of the Destin Dome, offshore Florida, north-eastern Gulf of Mexico: Marine and Petroleum Geology, v. 9, p. 501–509.

Mancini, E.A., Mink, R.M., Bearden, B.L., and Wilkerson, R.P., 1985, Norphlet Formation (Upper Jurassic) of southwestern and offshore Alabama: environments of depositions and petroleum geology: American Association of Petroleum Geologists Bulletin, v. 69, p. 881–898.

Marzano, M.S., Pense, G.M., and Andronaco, Peter, 1988, A comparison of the Jurassic Norphlet Formation in Mary Ann field, Mobile Bay Alabama to onshore regional Norphlet trends: Gulf Coast Association of Geological Societies Transactions, v. 38, p. 85–100.

McBride, E.F., Land, L.S., and Mack, L.E., 1987, Diagenesis of eolian and fluvial feldspathic sandstones, Norphlet Formation (Upper Jurassic), Rankin County, Mississippi and Mobile County, Alabama: American Association of Petroleum Geologists Bulletin, v. 75, p. 1563–1578.

McHugh, A.E., 1987, Styles of diagenesis in Norphlet sandstone (Upper Jurassic), onshore and offshore Alabama: University of New Orleans, unpublished Master's thesis, 164 p.

Miller, J.A., 1982, Structural control on Jurassic sedimentation in Alabama and Florida: American Association of Petroleum Geologists Bulletin, v. 66, no. 9, p. 1289–1301.

Mink, R.M., Bearden, B. L., and Mancini, E. A., 1985, Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area: State Oil and Gas Board of Alabama Oil and Gas Report 12, 58 p.

Mink, R.M., Tew, B.H., Mann, S.D., Bearded, B.L., and Mancini, E.A., 1990, Norphlet and pre-Norphlet geologic framework of Alabama and panhandle Florida coastal waters area and adjacent Federal waters area: Alabama Geological Survey Bulletin 99, 80 p.

Prather, B.E., 1992, Evolution of a Late Jurassic carbonate/evaporite platform, Conecuh embayment, northeastern Gulf Coast, U.S.A.: American Association of Petroleum Geologists Bulletin, v. 76, no. 2, p. 164–190.

Ryan, W.P., Ward, W.C., and Kugler, R.L., 1987, Provenance of Norphlet sandstone, northern Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 37, p. 457–468.

Saigal, G.C., Bjorlykke, Knute, and Larter, Steve, 1992, the effects of oil emplacement on diagenetic properties—examples from the Fulmar reservoir sandstones, central North Sea: American Association of Petroleum Geologists Bulletin, v. 76, p. 1034–1041.

Schmoker, J.W., and Schenk, C.J., 1994, Regional porosity trends of the Upper Jurassic Norphlet Formation in southwestern Alabama and vicinity, with comparisons to formations in other basins: American Association of Petroleum Geologists Bulletin. v. 78. p. 166–180.

Siebert, R.M., 1985, The origin of hydrogen sulfide, elemental sulfur, carbon dioxide, and nitrogen in reservoirs (abs.), *in* Timing of siliciclastic diagenesis: relationship to hydrocarbon migration: Program and Abstracts of the Sixth Annual Research Conference, Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, Austin, Texas, p. 30–31.

Simmons, W.B., 1988, Boron mineralization in the Louann Salt and Norphlet Shale, Clarke County, Alabama: Gulf Coast Association of Geological Societies Transactions, v. 38, p. 553–560.

Stoessell, R.K., and Moore, C.H., 1983, Chemical constraints and origins of four groups of Gulf Coast reservoir fluids: American Association of Petroleum Geologists Bulletin, v. 67, p. 896–906.

Stoudt, E.L., Thomas, A.R., Ginger, E.P., and Ninopal, R.J., 1992, Geologic reservoir characterization for reservoir simulation, Hatter's Pond field, Mobile County, Alabama: Society of Petroleum Engineers Paper 24713.

Surdam, R.C., Dunn, R.L., Heasler, H.P., and MacGowan, D.B., 1989, Porosity evolution in sandstone/shale systems, *in* Hutcheon, I. E., ed., Short course in burial diagenesis: Mineralogical Association of Canada, Short Course Handbook , v. 15, p. 61–134.

Thomas, A.R., Dahl, W.M., Hall, C.M., and York, Derek, 1993, Pressure solution, authigenic muscovite occurrence, and $^{40}Ar/^{39}Ar$ analyses as a method for dating stylolitization: Jurassic Norphlet Formation, offshore Alabama: Clays and Clay Minerals, v. 41, p. 269–279.

Thomson, Alan, and Stancliffe, R.J., 1990, Diagenetic controls on reservoir quality, eolian Norphlet Formation, South State Line field, Mississippi, *in* Barwis, J. H., McPherson, M. G., and Studlick, R. J., eds., Sandstone petroleum reservoirs: New York, Springer-Verlag, p. 181–204.

Tolson, J. S., Copeland, C. W., and Bearden, B. L., 1983, Stratigraphic profiles of Jurassic strata in the western part of the Alabama Coastal Plain: Alabama Geological Survey Bulletin 122, 425 p.

Walls, I. A., 1985, Provenance of the Jurassic Norphlet Formation in southwestern Alabama: University of Alabama, Tuscaloosa, Alabama, unpublished Master's thesis, 193 p.

Worrall, J.G., and Warren, J.K., 1986, Three stage dolomitization of Smackover Formation, southwest Alabama: evidence for near-surface and burial-derived fluids (abs.): Abstracts, Society of Economic Paleontologists and Mineralogists Midyear Meeting, Raleigh, North Carolina, p. 118–119.

The Petrophysical Characteristics of Jurassic Reservoirs of the Coastal Mississippi Counties and Adjacent State Waters

Stephen D. Champlin

Mississippi Office of Geology, P. O. Box 20307, Jackson, MS 39289-1307

Abstract

The purpose of this study is the determination of petrophysical characteristics observable for Jurassic reservoirs in the study area; these characteristics are important for hydrocarbon production from those reservoirs. The study area consists of the three Mississippi coastal counties, Hancock, Harrison, and Jackson, and Mississippi's State waters offshore. The section of importance to this study is the Upper Jurassic, which is made up of, from oldest to youngest, the Norphlet Formation, Smackover Formation, Haynesville Formation (including a Frisco City–equivalent granite wash and the Buckner Anhydrite), and Cotton Valley Group. Within the study area only one Upper Jurassic gas field has been discovered. The Catahoula Creek field is located onshore in Hancock County in the western portion of the study area and is productive of gas from Cotton Valley sands below 19,000 feet. Well log and core data from dry exploratory holes in the study area were used to supplement the limited reservoir data at Catahoula Creek. Nine wildcat wells have penetrated the Jurassic in the study area, so the Jurassic wildcat drilling density is approximately one wildcat well per 290 square miles. Because of this lack of data in the study area, published information on the following Upper Jurassic fields in southwestern Alabama, both onshore and offshore, is included: Chunchula field (Smackover), Hatter's Pond field (Smackover), Hatter's Pond field (Norphlet), and Lower Mobile Bay–Mary Ann field (Norphlet). Structurally, the three coastal counties and offshore State waters of Mississippi occupy the southern flank of the Wiggins Arch, an area of positive Paleozoic basement features, and the related Hancock Ridge. The Jurassic stratigraphic section in the study area consists of more than 5,000 feet of clastics, evaporites, and carbonates at depths below 17,000 feet to 24,000 plus feet.

Introduction

The purpose of this study is the determination of petrophysical characteristics observable for Jurassic reservoirs in the study area; these characteristics are important for hydrocarbon production from those reservoirs. The study area consists of the coastal Mississippi counties, Hancock, Harrison, and Jackson, and the State's adjacent offshore waters (fig. 1). The primary petrophysical characteristics of interest are porosity and permeability. By recognizing these factors and establishing petrophysical guidelines indicating the potential of commercial oil and gas production, future exploration in the Mississippi coastal counties and State waters will be greatly aided, possibly resulting in increased domestic oil and gas reserves.

By using existing geophysical well logs (density and neutron logs) and available core information for both productive and nonproductive wells on file with the Mississippi State Oil and Gas Board, the Mississippi Office of Geology, and private oil and gas industry sources, these objectives were determined to the extent possible using accepted interpretive methods. Collected or published core data and published oil and gas field data from Jurassic fields in adjacent areas of Mississippi, the Federal offshore waters, southwestern Alabama, and Alabama State waters (fig. 1) were used to supplement the information gathered in the study area. Few wells in the study area have penetrated the Jurassic, and only one Jurassic gas field is present in the study area.

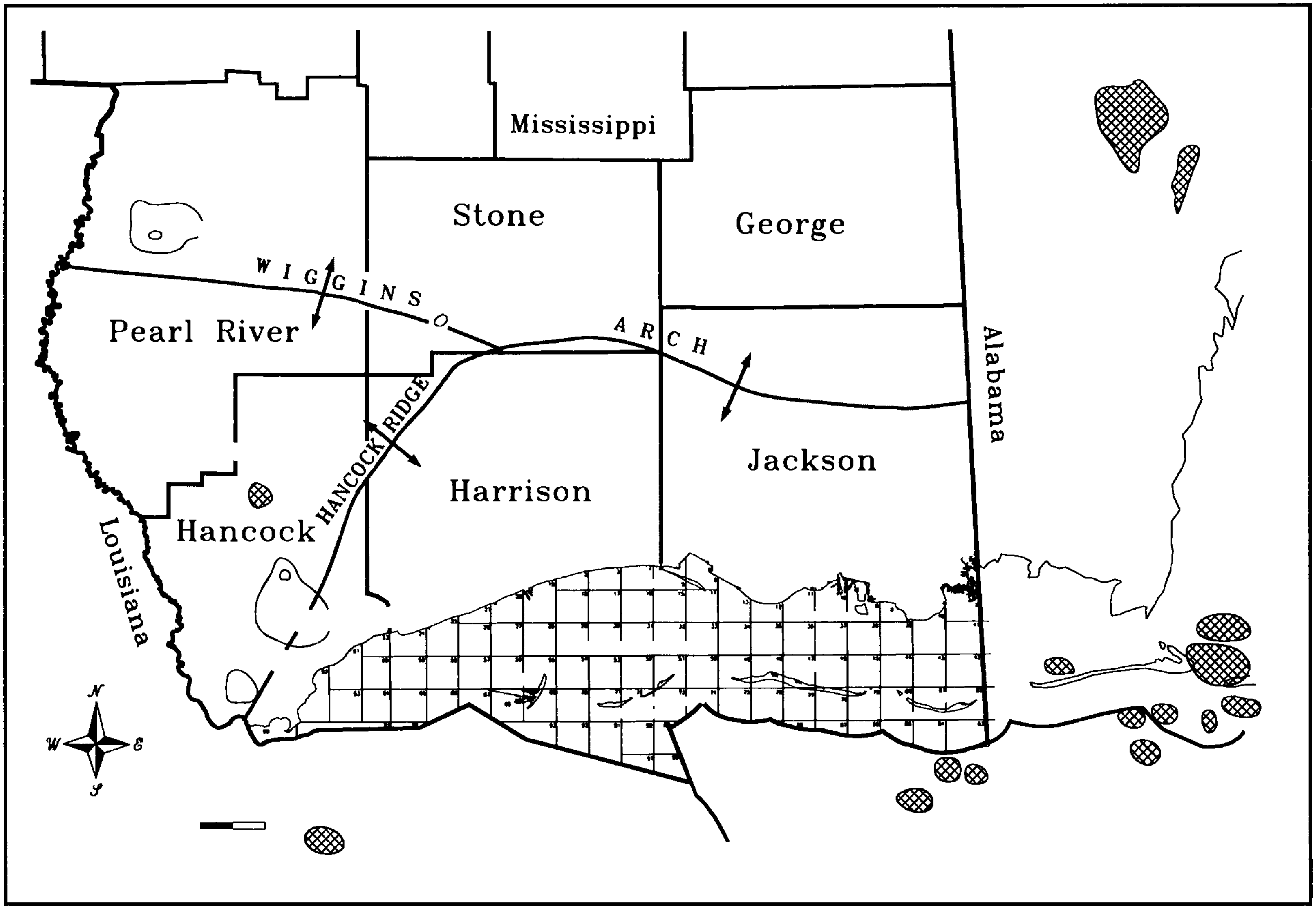


Figure 1. Index map showing structural features and location of Jurassic fields in and adjacent to the study area.

General Geology

Structurally, the three coastal counties and offshore State waters of Mississippi occupy the southern flank of the Wiggins Arch and the related Hancock Ridge (fig. 1). Rhodes and Maxwell (1993) provided an excellent analysis and interpretation of the Jurassic structure and stratigraphy over the study area. Rhodes and Maxwell had access to a significant amount of seismic and other data in the Wiggins Arch area acquired by Mobil Oil and Shell Oil between 1985 and 1991, including information from several wells the companies had drilled in the area.

For the purposes of this study the location of the Wiggins Arch is delineated using the same definition as Rhodes and Maxwell (1993), that being the region where the Louann Salt is absent over basement highs or too thin for halokinesis. Differential compaction and sedimentation across Paleozoic basement highs are the primary factors affecting Jurassic structure on the Wiggins Arch. These highs formed mountains at the edge of a Norphlet desert, and large islands throughout most of the Jurassic transgression. On the flanks of the Wiggins Arch, downdip in all directions, salt pillows and associated faulting form the primary structural features (Rhodes and Maxwell, 1993). Regional structural features bordering the Wiggins Arch are the Mississippi Interior Salt Basin to the north, the Mobile Graben and Pollard Fault System to the east, and the Mississippi/Alabama Shelf offshore to the southeast.

The Jurassic stratigraphic section in the study area consists of more than 5,000 feet of clastics, evaporites, and carbonates (Ericksen and Thieling, 1993). The Late Jurassic excluding the Cotton Valley was primarily a time of transgression. This was interrupted by two regressions that allowed the deposition of the Norphlet and what appears to be Frisco City time-equivalent clastic sections (Rhodes and Maxwell, 1993). Mississippi's coastal counties and State waters were part of a region where basinward shelf-edge migration was occurring (Petty and others, 1994). This shelf-edge migration combined with the presence of the Paleozoic highs of the Wiggins Arch area created a wide range of depositional environments. Well log correlations over any distance are difficult because of this. The section of importance to this study is the Upper Jurassic, which is made up of, from youngest to oldest, the Cotton Valley Group, the Haynesville Formation (including an apparent Frisco City Sand equivalent and the Buckner Anhydrite), the Smackover Formation, and the Norphlet Formation (fig. 2).

Reservoir Petrophysical Characteristics

The primary reservoir petrophysical characteristics of concern in this study are porosity. Within the three-county Mississippi coastal and offshore State waters study area only one Upper Jurassic gas field has been discovered. The field is Catahoula Creek, which is located onshore in Hancock County and is productive of gas from Cotton Valley sands below 19,000 feet. Because of the lack of oil or gas producing Upper Jurassic reservoirs in the study area, geophysical well log and core data from dry exploratory holes that have encountered porous Upper Jurassic sands and carbonates have been incorporated to supplement the field data from Catahoula Creek field. Nine Jurassic wildcat wells have been drilled in the study area (one offshore and eight onshore). This equates to one Jurassic wildcat well drilled per 225 square miles onshore and one Jurassic wildcat well per 800 square miles offshore. For the entire study area the Jurassic wildcat drilling density equals approximately one wildcat well per 290 square miles. In recent years several Upper Jurassic Norphlet gas fields have been discovered in the Federal offshore waters and Alabama's offshore State waters adjacent to Mississippi's offshore State waters.

Cotton Valley

The Cotton Valley Group, which ranges in thickness from 1,100 to 5,000 feet within the study area, is Upper Jurassic in age and generally conformably overlies the Haynesville Formation. In the study area the Cotton Valley consists of alternating sandstones, shales, carbonates, and minor amounts of anhydrite (Ericksen and Thieling, 1993). Various depositional systems are interpreted to have been present in Mississippi during Cotton Valley time. Across the central area of Mississippi two delta systems existed separated by an interdeltaic area and bounded to the south by a barrier-bar system. A strandplain system caused by the positive influence of the Wiggins Arch was present in southeastern Mississippi (Moore, 1983).

To date Catahoula Creek field is the only field productive of commercial quantities of natural gas from Upper Jurassic-age sediments in the three-county Mississippi coastal and offshore State waters area (fig. 1). Potentially, new Cotton Valley discoveries are possible on similar type features as the Catahoula Creek field structure and, additionally, in structural closures above Paleozoic basement highs where Cotton Valley

Era	System	Series	Unit		Lithology
MESOZOIC	CRETACEOUS	UPPER	SELMA GROUP		Chalk, massive chalk, shale
			EUTAW FORMATION		Sandstone, glauconitic sandstone, shale
			TUSCALOOSA GROUP	Upper	Sandstone with shale and claystone interbeds
				Marine	Shale with sandy streaks and thin sandstone beds
				Lower	Sandstone, thin to massive with shale interbeds
		LOWER	LOWER CRETACEOUS UNDIFFERENTIATED		Sandstone, fine to medium grained with traces of nodular limestone, thin anhydrite unit near middle
	?	?			
	JURASSIC	UPPER	COTTON VALLEY GROUP		Sandstone, fine to coarse grained, conglomeratic in part, with traces of metamorphic rock fragments, shale and sandy shale, thin limestones locally
			HAYNESVILLE FORMATION		Shale, thin anhydrite, dolomitic limestone, sandstone beds
			BUCKNER ANHYDRITE		Anhydrite, thin, silty, anhydritic and dolomitic shale beds
			SMACKOVER FORMATION		Limestone, microcrystalline to crystalline, oolitic in part, dolomitic in part, grades to dolomite; grades to shale and siltstone downdip
			NORPHLET FORMATION		Sandstone, fine grained, quartzose, calcareous in part; grades to shale and siltstone downdip
			PINE HILL ANHYDRITE		Anhydrite with salt interbeds where present
		MIDDLE	LOUANN SALT		Salt, massive with thin anhydrite and shale beds
			WERNER FORMATION		Anhydrite with sand and metamorphic rock fragments
	TRIASSIC		EAGLE MILLS FORMATION		Sandstone, arkosic with red shale

QAc3440c

Figure 2. Generalized Mesozoic stratigraphic column for southeastern Mississippi and southwestern Alabama (modified from Mink et al., 1987).

sands are draped across these features. The Mobil No. 1 Anderson well in Harrison County encountered six different mudlog gas shows in Cotton Valley sands between 16,600 and 17,700 feet. Cross-plotted porosities from the neutron/density log are in the 5-to-6-percent range.

Catahoula Creek Field

Catahoula Creek field was discovered by the Hunt Energy Corporation, No. 1 Rhoda Lee Brown well, which was completed on August 14, 1981, and is located in Section 28, T6S-R15W, Hancock County, Mississippi. The well was completed from perforations between 19,820 and 20,196 feet in Lower Cotton Valley sandstones. During the initial production test the well flowed 7,030 MCFGPD, 48 BWPD, on a 30/64-inch choke with a flowing tubing pressure of 6,549 psi. Bottom-hole pressure was 16,297 psi (Mississippi Geological Society, 1986). Stabilized flow rates of 10 to 13 MMCFGPD were measured with FTP of 9100-9250# through 28/64-inch choke (Sannes and Hancock, 1982). Structurally the field is a faulted anticline with normal faulting downthrown to the south-southwest and was probably created by deep salt movement. The reservoir sands at Catahoula Creek field have been interpreted as being part of an offshore barrier island complex (Ericksen and Thieling, 1993). A total of 114 net feet of gas sand was indicated in 11 different zones of porosity. Matrix porosity of 4 to 18 percent was measured, and matrix permeabilities of 0.1 to 0.3 millidarcys were indicated. Permeabilities are enhanced by vertical fracturing, which has measured permeabilities ranging from 1 to 4.3 millidarcys; this explains the high flow rates during testing (Sannes and Hancock, 1982).

Haynesville

Haynesville sediments in the study area range in thickness from 200 to 800 feet and have been described as a sequence of evaporites and associated sediments including shales, sands, and limestones. A conventional core cut in the Hunt No. 1 Crosby in Hancock County, Mississippi (western onshore portion of the study area), from 23,733 to 23,765 feet was described as predominantly gray shale and siltstone with some very fine grained sand (Ericksen and Thieling, 1993). Measured porosities in the sands ranged from 0.8 to 2.3 percent with all measured permeabilities being less than 0.01 millidarcys. Currently there is no known oil or gas production from the Haynesville in the study area; however, potential traps may be present in the Frisco City on the flanks of several Paleozoic highs on the Wiggins Arch.

Three wells in the study area encountered section that appears to be equivalent to the Frisco City Sand of southern Alabama. The Mobil No. 1 USA well in Harrison County penetrated 200 feet of granite wash, underlain by 70 feet of Buckner anhydrite. The Mobil No. 1 Anderson well also encountered 70 feet of granite wash overlying basement several miles to the northeast of the Mobil No. 1 USA well. The section is thought to have been deposited as alluvial fans off the flanks of several exposed Paleozoic highs on the Wiggins Arch. The granite-wash deposits are probably facies equivalent as well as time equivalent to the Alabama Frisco City Sand (Rhodes and Maxwell, 1993). Cross-plotted porosities from the two wells' neutron/density logs range from 3 to 6 percent. The third well, which is the Chevron Block 57, located in Mississippi's western offshore state waters, encountered a 230-foot-thick zone of clean white quartzose sand that Petty and others (1994) concluded was Frisco City equivalent, thus extending the Frisco City Sand 20 miles southwest of the Wiggins Arch. The environment of deposition would have to be dissimilar because of the distance from the crest of the Wiggins Arch and the difference in described lithology.

The Buckner Member of the Haynesville is present off the flanks of the exposed Paleozoic highs of the Wiggins Arch and is generally described as massive white anhydrite. Thicknesses range from zero to 80 feet. The Buckner is not thought to be a potential reservoir in the study area.

Smackover

The Smackover Formation, which ranges in thickness from 0 to 900 feet within the study area (Ericksen and Thieling, 1993), is Upper Jurassic in age and usually conformably overlies the Norphlet Formation. The upper Smackover is predominantly a moderate- to high-energy subtidal, intertidal, and supratidal dolomitized wackestone to grainstone. The lower Smackover, the "brown dense," is generally a low-energy mudstone deposited during a marine transgression following Norphlet deposition (Mancini and Benson, 1980). In the study area the Smackover is encountered at depths below 18,500 feet and deeper. No Smackover oil or gas fields are currently present in the study area.

In the study area three types of Smackover depositional environments are indicated to be present by Rhodes and Maxwell's work. They are as follows: a belt of grainstone shoals surrounding the Wiggins Arch, a lagoonal facies updip of the shoals, and the open-marine mudstones downdip of the shoals (Rhodes and Maxwell, 1993). With the onset of the regression that eventually led to deposition of the Frisco City granite wash off the exposed Paleozoic highs, the Smackover shoals moved downdip and built up, creating a belt of well-developed oolitic shoals surrounding the Wiggins Arch. This further restricted the updip lagoonal areas and allowed deposition of the Buckner anhydrite to begin.

The Buckner is thickest updip of the restricting Smackover shoals, thin or absent in the beltway of the restricting shoals, and absent downdip of the shoals (Rhodes and Maxwell, 1993). The above-described sequence of deposition sets up the potential for stratigraphic oil and gas traps in the upper Smackover shoal beltway, downdip of the thicker contemporaneously deposited Buckner anhydrite. In the study area no wells have actually penetrated the upper Smackover shoal beltway, but several wells in Stone County and George County, which are north of and adjacent to the study area, are shown to have penetrated this facies on the north flank of the Wiggins Arch by Rhodes and Maxwell's work. The Mobil No. 1 USA well encountered 300 feet of Smackover composed of primarily sucrosic dolomite. Total dolomitization has masked the original texture, but grainstones are the primary facies. Analysis of sidewall core samples from the well between 19,374 and 19,444 feet in the Smackover indicated porosities between 5.5 and 10.1 percent (Rhodes and Maxwell, 1993).

The two nearest Smackover fields in southwestern Alabama are Chunchula field and Hatter's Pond field, located in Mobile County to the east of and adjacent to the study area (fig. 1). The Smackover at both fields is described as dolostone with primary porosity being intercrystalline. A brief discussion of these two fields follows.

Chunchula Field

The Smackover production at Chunchula field was discovered by the Union Oil Co. of California No. 1 International Paper Co. 22-13 well located in Section 22, T1S-R2W, Mobile County, Alabama. The discovery well was completed January 4, 1974, flowing 1,158 BCPD and 2,650 MCFGPD on a 16/64-inch choke with 2,475 psi from perforations at 18,421–18,438 feet in the Smackover. Initial reservoir pressure was 9,255 psi (Bolin and others, 1989). Structurally the field is a broad, low-relief anticline probably created by salt movement. Chunchula field is a combination trap with a loss of permeability to the north and northeast, and the gas-water contact varies considerably. Average net-pay thickness for the field is 34 feet (Kopaska-Merkel and others, 1993). The productive area for the Smackover is 22,113 acres (Bolin and others, 1989). The Smackover reservoir at Chunchula field is described as a dolostone with the primary porosity being dominated by intercrystalline pores. Interparticle, moldic, secondary intraparticle, and vuggy porosity are present and important, however. The average porosity and permeability for the reservoir rock are 12.9 percent porosity and 6.2 millidarcys of permeability (Kopaska-Merkel and others, 1993). Bolin and others (1989) reported the average porosity to be 12 percent and average permeability to be 2.0 millidarcys. The depositional environment is interpreted as subtidal and high energy (Bolin and others, 1989).

Hatter's Pond Field

The Smackover production at Hatter's Pond field was discovered by the Getty Oil Company No. 1 Peter Klein 3-14 well located in Section 3, T2S-R1W, Mobile County, Alabama. The discovery well was drilled to a total depth of 18,358 feet and completed December 2, 1974, flowing 2,166 BCPD and 6,198 MCFGPD on a 17/64-inch choke with 3,270 psi from perforations at 18,042–18,060 feet in the Smackover. Initial reservoir pressure was 9,108 psi (Bolin and others, 1989). The Norphlet was also determined to be productive. Structurally the field is a north-south-oriented, faulted anticline bounded to the east by a large down-to-the-east-southeast fault associated with the Mobile Graben Fault System. The structure has more than 700 feet of structural relief and resulted from salt movement along the western side of the fault system. The productive area for the Smackover is 6,418 acres (Bolin and others, 1989). Average net gas pay is 59 feet (Kopaska-Merkel and others, 1993). It was determined that the Smackover and Norphlet reservoirs were in communication and had the same gas-water contact of approximately -18,300 feet subsea. The Smackover reservoir at Hatter's Pond field is described as a dolostone (Bolin and others, 1989) with the primary porosity being dominated by intercrystalline pores (Kopaska-Merkel and others, 1993). Total Smackover porosity ranges from 1.2 to 24.4 percent and averages 9.4 percent. Total Smackover permeabilities range from 0.01 to 177 millidarcys. Actual reservoir porosity and permeabilities average 13.5 percent porosity and 10.6 millidarcys of permeability (Kopaska-Merkel and others, 1993). Bolin and others (1989) reported the average porosity as 12 percent and average permeability to be 2.0 millidarcys. The depositional environment is interpreted as subtidal and high energy (Bolin and others, 1989).

Norphlet

The Norphlet Formation, which ranges in thickness from 0 to 300 feet within the study area (Ericksen and Thieling, 1993), is Upper Jurassic in age and unconformably lies above the Louann Salt. The Norphlet is encountered at depths below 18,600 feet onshore and below 20,000 feet offshore. In the study area, Norphlet oil and gas production has not been established as of late 1995. However, with three Norphlet gas discoveries in the Federal Outer Continental Shelf (OCS) Mobile Area immediately south of Mississippi's eastern offshore State waters, the established deep Norphlet gas production to the east in Alabama's offshore State waters and recently published studies on the area, it is apparent that two areas for possible future successful exploration are present in the study area. One area is on the crest of the Wiggins Arch in Norphlet alluvial fans situated on the flanks of Paleozoic highs. The second area is in Mississippi's eastern offshore State waters in Norphlet eolian sands.

As a result of the work done by Rhodes and Maxwell (1993) and the drilling of several wells by Mobil and Shell, it has been shown that the Norphlet is present in the central and eastern onshore portion, as granite wash alluvial fan deposits off the flanks of several of the Paleozoic highs on the Wiggins Arch. These deposits do not extend significantly downdip, however. The Mobil No. 1 USA well in eastern Harrison County encountered what is described as 180 feet of a granite wash below the Smackover (Rhodes and Maxwell, 1993). Cross-plotted porosities from the well's neutron/density log ranged between 2 and 6 percent.

The Norphlet eolian facies is also interpreted as being present in the eastern onshore Jackson County area and Mississippi's eastern offshore State waters. Petty and others (1994) stated that Norphlet sand was also present in the Chevron Block 57 well located in Mississippi's western offshore State waters. An estimated 8- to 10-foot sand identified by paleontological and sample description is picked at 23,340 to 23,348 feet measured depth on the well's induction log (Petty and others, 1994). The depositional environment is not thought to be eolian but more probably marine (A. Petty, Minerals Management Service, personal communication, 1995). This would be the westernmost presence of Norphlet sand seen in the northeastern Gulf area.

Structurally, Mississippi's eastern offshore State waters area is located far enough downdip of the Wiggins Arch that the Louann Salt is thick enough for halokinesis. An east-west-trending system of faults, referred to as the Lower Mobile Bay fault trend, is present in the offshore of Alabama (Mink and Bearden, 1986) which, when combined with salt pillowing, plays an important part in the trapping of the deep Norphlet gas reserves there and in Federal OCS waters. A recent seismic interpretation of data covering the eastern area of Mississippi's State waters around Petit Bois Island (Ericksen and Thieling, 1993) reveals that at the near top of Norphlet level the Lower Mobile Bay fault trend probably extends into Mississippi waters and sets up several areas of possible production similar to those seen in Mobile area blocks 861, 862, and 904, which are gas productive from deep Norphlet sands just south of Mississippi's State waters, in Federal OCS waters. In 1992, Unocal reported testing of its Mobile Block 904 No. 1 well. Located approximately four and one half miles from Mississippi's three-mile State waters boundary, the well was drilled to a total depth of 22,400 feet and encountered a reported 185 feet of Norphlet gas pay. The well flowed at a rate of 97.6 MMCFGPD through a 42/62-inch choke from perforations between 22,130 and 22,290 feet measured depth. The well's flow rate is the highest reported in the Mobile OCS and also one of the highest reported in the entire Gulf of Mexico (Southeastern Oil Review, 1992). In December 1993, Chevron reported testing of the No. 8 well in Mobile Block 861. The well flowed 57 MMCFGPD from below 21,000 feet (Hart's Oil and Gas World, 1994). This well is located only about 2.5 miles south of Mississippi's 3-mile State waters boundary.

Reservoir characteristics (porosities and permeabilities in particular) should be similar in the eastern offshore Mississippi State waters as they are in the Norphlet fields of offshore Alabama and Federal OCS waters because of common depth of burial, depositional environments, and probable similar diagenetic histories. Secondary porosity created by decementation and dissolution is important in the deeper Norphlet reservoirs

(Marzano et al., 1988). Average porosities for the Norphlet reservoirs in the Alabama offshore State waters range from 10 to 15 percent (Schmoker and Schenk, 1994). Permeabilities can range up to 120 millidarcys. Information is presented next on two Alabama fields, one offshore and one onshore, and the Norphlet discoveries in Blocks 861 and 862 in the Federal OCS waters adjacent to Mississippi's offshore area (fig. 1).

Hatter's Pond Field

The Norphlet production at Hatter's Pond field was discovered by the Getty Oil Company No. 1 Peter Klein 3-14 well located in Section 3, T2S-R1W, Mobile County, Alabama. The discovery well was drilled to a total depth of 18,358 feet and completed December 2, 1974, flowing 1,416 BCPD and 4,389 MCFGPD on a 18/64-inch choke with 2,346 psi from perforations at 18,180–18,200 feet in the Norphlet. Initial reservoir pressure was 9,186 psi (Bolin and others, 1989). The Smackover was also determined to be productive in this well. Structurally the field is a north-south-oriented, faulted anticline bounded to the east by a large down-to-the-east-southeast fault associated with the Mobile Graben Fault System. The structure has more than 700 feet of structural relief and resulted from salt movement along the western side of the fault system. The Norphlet Sand reservoir at Hatter's Pond field is an eolian sandstone deposited in an arid environment. The top of the Norphlet sand was then reworked by a marine transgression (Mancini and others, 1985). Most of the pores in the Norphlet at Hatter's Pond field are formed by decementation of anhydrite or calcite and dissolution of grains (Honda and McBride, 1981). Average porosity in the Norphlet is 10 percent, and average permeabilities are 0.5 millidarcys (Bolin and others, 1989).

Lower Mobile Bay–Mary Ann Field

Lower Mobile Bay–Mary Ann field was discovered by the Mobil Oil Exploration & Producing Southeast, Inc., State Lease 347 No. 1 well located in Block 76 of Alabama's offshore State waters. The field area includes Alabama Blocks 76, 77, 94 and 95. The discovery well was drilled to a total depth of 21,113 feet and completed December 28, 1979, flowing 12,200 MCFGPD on a 28/64-inch choke with 2,996 psi from perforations at 20,634–20,873 feet. The well encountered 283 feet of gas pay in the Norphlet Sand (Marzano et al., 1988). Initial reservoir pressure was 11,330 psi, and temperature was 414°F (Bolin et al., 1989). Structurally the field is a broad, low-relief, east-west-oriented anticline bounded to the north by the large down-to-the-south Lower Mobile Bay fault and dissected by several smaller faults. The structure was created by the combination of salt movement and faulting. The primary reservoir for the Lower Mobile Bay–Mary Ann Field is an eolian sandstone deposited in an arid environment. The top of the Norphlet sand was then reworked by the marine transgression that eventually led to deposition of Smackover carbonates. This marine-reworked section has very low porosity and little permeability, and it is considered to form the seal for the reservoir in conjunction with the low-permeability carbonates of the Lower Smackover. The better reservoir rock is the eolian sand that has not been reworked by the marine transgression. Average porosity and permeabilities are 12 percent and 4 millidarcys (Marzano and others, 1988). Bolin and others (1989) reported the average porosity as 11 percent and average permeability to be 1.0 millidarcy. Porosity and permeabilities range up to 17 percent porosity and 120 millidarcys of permeability (Marzano and others, 1988). These high porosities are not normally seen at depths below 20,000 feet and are thought to be the result of a combination of preserved primary and secondary enhanced porosity. The Norphlet sand in the field area has undergone several episodes of cementation and decementation (Marzano and others, 1988).

OCS Blocks 861 and 862

In 1985, Chevron, U.S.A., Inc., began drilling its first test well in Mobile Block 861. The well was drilled to a total depth of 21,416 feet and encountered high pressure in the Norphlet. A reported underground blowout occurred, charging shallow zones that were unprotected by casing. A replacement well was drilled in 1991 on the block, and in December 1993 Chevron reported testing of the No. 8 well in Mobile Block 861. The well flowed 57 MMCFGPD from below 21,000 feet (Hart's Oil and Gas World, 1994). Additionally, a Norphlet test well has also been drilled and completed in Mobile Block 862, the block adjacent to Block 861 to the east. No information or test data have been released as yet by the operator for this well. Reservoir data for the two block discoveries are not available, but well logs indicate thick and porous Norphlet sand was encountered by both the Block 861, No. 8 well and the Block 862, No. 1 well. Approximately 460 feet of porous Norphlet sand was encountered by the Block 861, No. 8 well between 21,650 and 22,117 feet measured depth. Cross-plotted porosity values from the neutron/density log ranged from 8 to 19 percent. The logs for the Block 862 well indicated that the well had encountered at least 135 feet of Norphlet sand between 21,928 and 22,075 feet measured depth. Cross-plotted porosity values from the well's neutron/density logs ranged from 6 to 16 percent.

Conclusions

With only one Upper Jurassic–age discovery of deep natural gas production in the three coastal counties and offshore State waters of Mississippi, and a total wildcat drilling density of one well penetrating Jurassic rocks for every 290 square miles in an area that covers approximately 2,610 square miles, it can be said that much of Mississippi's coastal area and offshore waters is underexplored. The probable reasons for this are the initial drilling of mostly dry holes in the area, the lack of general data on the potential Jurassic reservoir rocks, the complicated stratigraphy and structure of the area, the rather poor cumulative gas production at the only gas field discovered in the area, depth of burial for most Jurassic sediments being below 16,000 to 20,000 plus feet, and low oil and gas prices.

Given the above-stated facts, recently published information on the area and the establishment of deep Norphlet gas production in Alabama's State offshore waters and the Federal OCS waters adjacent to Mississippi's eastern offshore State waters indicate excellent exploration potential is present in the eastern half of the study area. Seismic interpretations indicate the presence of several deep Norphlet structures in the State's offshore waters adjacent to gas-productive areas in the Federal OCS waters. The seismic stratigraphic interpretations presented in Rhodes and Maxwell's work (1993) indicate potential areas and models for exploration in the Smackover grainstone belt around the flanks of the Wiggins Arch, as well as potential exploration targets in the Haynesville Frisco City granite washes on the flanks of Paleozoic highs that are similar to the Frisco City trend of southern Alabama. Additionally, gas shows encountered by the Mobil No. 1 USA well in eastern Harrison County show that Cotton Valley sands may be gas productive in structural traps above the Paleozoic highs on the Wiggins Arch.

Even with these positive points, the great depth of most of the Upper Jurassic sediments in the study area will probably cause additional drilling in the study area to depend on generally higher prices for oil and gas. Still, Jurassic oil and gas production in Mississippi will continue to be an important economic resource to the State.

References

Bolin, D. E., Mann, S. D., Burroughs, D., Moore, H. E., Jr., and Powers, T. J., 1989, Petroleum atlas of southwestern Alabama: Geological Survey of Alabama, Atlas 23, 218 p.

Ericksen, R. L., and Thieling, S. C., 1993, Regional Jurassic geologic framework and petroleum geology, coastal Mississippi and adjacent offshore State and Federal waters: Mississippi Office of Geology, Open-File Report 22, 67 p.

Hart's Oil and Gas World, 1994, September, p. 30–32.

Honda, H., and McBride, E. F., 1981, Diagenesis and pore types of the Norphlet Sandstone (Upper Jurassic), Hatter's Pond area, Mobile County, Alabama: Gulf Coast Association of Geological Societies, Transactions, v. 31, p. 315–321.

Kopaska-Merkel, D. C., Hall, D. R., Mann, S. D., and Tew, H. T., 1993, Reservoir characterization of the Smackover Formation in Southwest Alabama: Final report prepared by Geological Survey of Alabama for the U.S. Department of Energy, DOE/BC/14425-7, 124 p.

Mancini, E. A., and Benson, D. J., 1980, Regional stratigraphy of Upper Jurassic Smackover carbonates of southwest Alabama: Gulf Coast Association of Geological Societies, Transactions, v. 30, p. 151–165.

Mancini, E. A., Mink, R. M., Bearden, B. L., and Wilkerson, R. P., 1985, Norphlet Formation (Upper Jurassic) of southwestern and Offshore Alabama: environments of deposition and petroleum geology: American Association of Petroleum Geologists Bulletin, v. 69, p. 881–898.

Marzano, M. S., Pense, G. M., and Andronaco, P., 1988, A comparison of the Jurassic Norphlet Formation in Mary Ann field, Mobile Bay, Alabama to onshore regional Norphlet trends: Gulf Coast Association of Geological Societies, Transactions, v. 38, p. 85–100.

Mink, R. M., and Bearden, B. L., 1986, Oil and gas exploration and development in Alabama State coastal waters and adjacent Federal OCS waters, October 1951–June 1985: State Oil and Gas Board of Alabama, Oil and Gas Report 7D, 44 p.

Mink, R. M., Hamilton, R. P., Bearden, B. L., and Mancini, E. A., 1987, Determination of recoverable natural gas reserves for the Alabama coastal waters area: Alabama State Oil and Gas Board, Oil and Gas Report 13, 74 p.

Mississippi Geological Society, 1986, Mesozoic-Paleozoic producing areas of Mississippi and Alabama, v. III.

Moore, T., 1983, Cotton Valley depositional systems of Mississippi: Gulf Coast Association of Geological Societies, Transactions, v. 33, p. 163–167.

Petty, A. J., Thieling, S., and Friedmann, T., 1994, Mesozoic stratigraphy of near shelf-edge deposits, southern Mississippi, adjacent State and Federal waters (abs.): Gulf Coast Association of Geological Societies, Transactions, v. 44, p. 583.

Rhodes, J. A., and Maxwell, G. B., 1993, Jurassic stratigraphy of the Wiggins Arch, Mississippi: Gulf Coast Association of Geological Societies, Transactions, v. 43, p. 333–344.

Sannes, T., and Hancock, D., 1982, Catahoula Creek field, a complex structural and stratigraphic trap in downdip Cotton Valley sands (abs.): Gulf Coast Association of Geological Societies, Transactions, v. 32, p. 89.

Schmoker, J. W., and Schenk, C. J., 1994, Regional porosity trends of the Upper Jurassic Norphlet Formation in southwestern Alabama and vicinity, with comparisons to formations of other basins: American Association of Petroleum Geologists Bulletin, v. 78, no. 2, p. 166–180.

Southeastern Oil Review, 1992, v. LIV, no. 46.

Undiscovered Oil and Gas Resources of the Pacific Outer Continental Shelf Region—An Overview of the 1995 National Assessment of Oil and Gas Resources[1]

Catherine A. Dunkel

U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, 770 Paseo Camarillo, Camarillo, CA 93010

Abstract

An assessment of the undiscovered oil and gas resources in the Federal offshore areas of Washington, Oregon, and California—performed by the Minerals Management Service (MMS) using data available as of January 1, 1995—estimates that 10.7 billion barrels (Bbbl) of undiscovered oil and 18.9 trillion cubic feet (Tcf) of undiscovered gas are recoverable with conventional techniques. Approximately one half of these resources (5.3 Bbbl of oil and 8.3 Tcf of gas) may be recovered profitably under economic conditions as of the assessment. Estimates of undiscovered oil and gas resources from this assessment are larger than estimates from previous MMS assessments because of the use of different methods and additional data.

Introduction

This paper summarizes an assessment of the undiscovered oil and gas resources of the Pacific Outer Continental Shelf (OCS) Region of the United States (that is, the Federal offshore areas of Washington, Oregon, and California). The assessment was performed as part of a national assessment of undiscovered oil and gas resources—in which the onshore and State offshore areas of the Nation were assessed by the U.S. Geological Survey and the Federal offshore areas of the Nation were assessed by the Minerals Management Service (MMS)—in order to develop an updated appraisal of the location and volume of undiscovered resources.

The commodities that have been assessed consist of *oil* (including crude oil and condensate) and *natural gas* (including associated and nonassociated gas). Two categories of undiscovered resources have been assessed: *undiscovered conventionally recoverable resources* are those that can be removed from the subsurface with conventional extraction techniques; *undiscovered economically recoverable resources* are those undiscovered conventionally recoverable resources that can be extracted profitably under specified economic and technological conditions.

The assessment of the Pacific OCS Region was performed by a team of MMS geoscientists in Camarillo, California, using a large volume and variety of proprietary and nonproprietary data (including geological, geochemical, geophysical, petroleum engineering, and economic data) available as of January 1, 1995. Data and interpretations from many of the nearly 1,100 wells and 200,000 miles of seismic-reflection profiles in the Region were used for the assessment.

For this assessment, the Region was subdivided into six assessment provinces: Pacific Northwest, Central California, Santa Barbara-Ventura Basin, Los Angeles Basin, Inner Borderland, and Outer Borderland (fig. 1). The provinces encompass 21 geologic basins and areas in which sediments accumulated and hydrocarbons may have formed. Fifty *petroleum geological plays* (groups of geologically related hydrocarbon accumulations) have been defined and described in 13 assessment areas, and 46 of these plays have been formally assessed.

[1]Excerpted from Dunkel, C. A., and Piper, K. A., eds., 1997, 1995 National Assessment of United States Oil and Gas Resources—Assessment of the Pacific Outer Continental Shelf Region: Minerals Management Service OCS Report MMS 97-0019, 265 p.

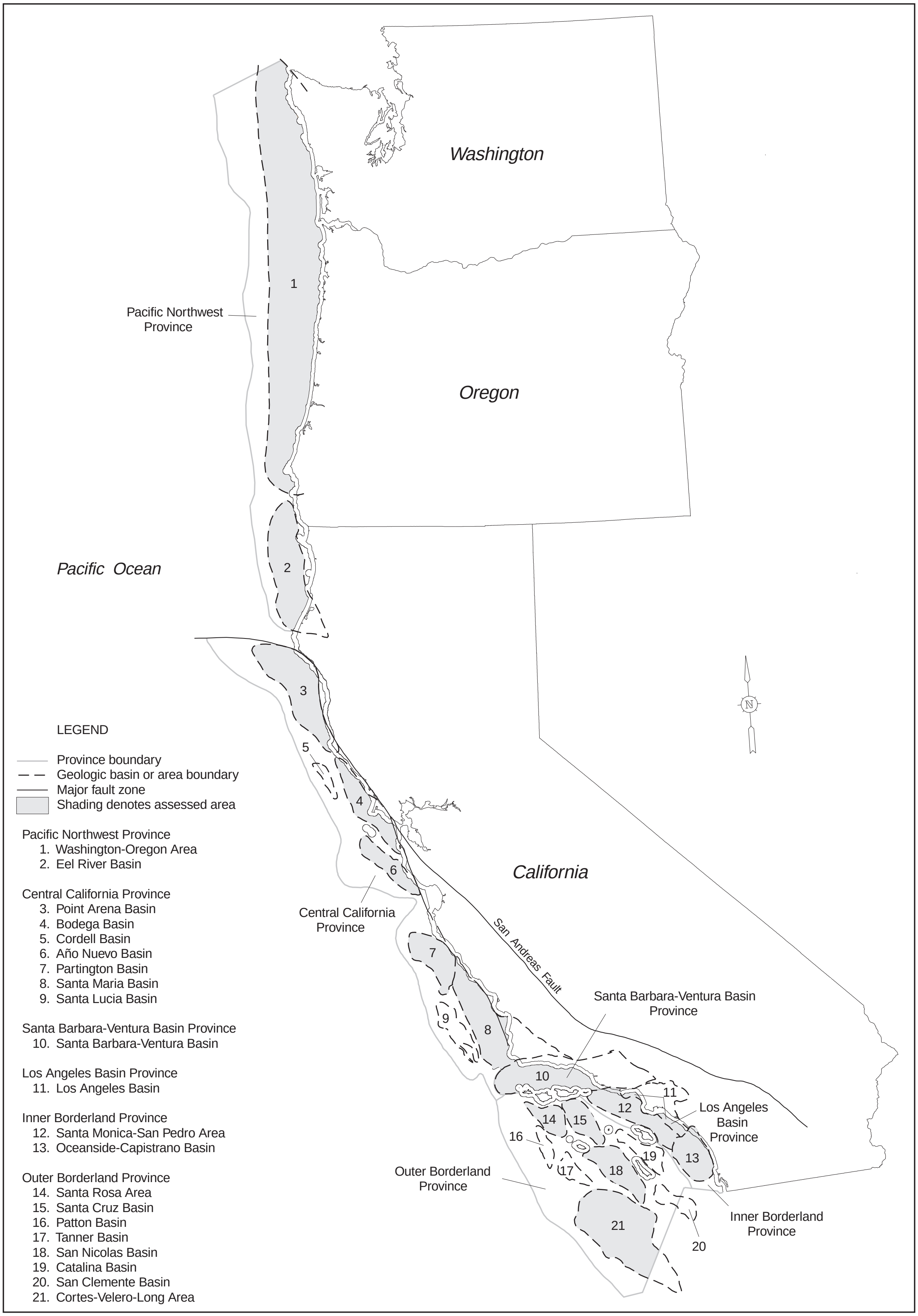


Figure 1. Map of the Pacific OCS Region showing assessment provinces, geologic basins and areas, and assessed areas.

Methodology

The principal procedural components of the assessment consisted of *petroleum geological analysis* to ascertain the areal and stratigraphic extent of potential petroleum source rocks, reservoir rocks, and traps; *play definition and analysis* to identify and describe the properties of plays; and *resource estimation* to develop estimates of the volume of undiscovered oil and gas resources. Estimation of the volume of undiscovered conventionally recoverable resources was performed for each play by developing a pool-size distribution (describing the number and size of discrete hydrocarbon accumulations) of the play and statistically aggregating the estimated volume of resources in the undiscovered pools; estimates of undiscovered conventionally recoverable resources are expressed as probability distributions to reflect their uncertainty. Estimation of the volume of undiscovered economically recoverable resources was performed for each assessment area by developing a field-size distribution (describing the number and size of fields, which may consist of multiple pools), and mathematically simulating the exploration and development of the area to determine the volume of undiscovered conventionally recoverable resources that can be extracted profitably; estimates of undiscovered economically recoverable resources are expressed as mean values for a range of economic scenarios.

Resource Estimates

Undiscovered Conventionally Recoverable Resources

The total volume of undiscovered conventionally recoverable oil resources (including crude oil and condensate) of the Region as of January 1, 1995, is estimated to range from 9.0 to 12.6 billion barrels (Bbbl) with a mean estimate of 10.7 Bbbl (table 1). Relatively large volumes of these oil resources (greater than 1 Bbbl) are estimated to exist in the Point Arena basin, Santa Barbara-Ventura basin, Bodega basin, and Oceanside-Capistrano basin (fig. 2). The total volume of undiscovered conventionally recoverable gas resources (including associated and nonassociated gas) in the Region is estimated to range from 15.2 to 23.2 trillion cubic feet (Tcf) with a mean estimate of 18.9 Tcf (table 1). Relatively large volumes of these gas resources (greater than 1 Tcf) are estimated to exist in the Santa Barbara-Ventura basin, Washington-Oregon area, Point Arena basin, Eel River basin, Bodega basin, Oceanside-Capistrano basin, and Cortes-Velero-Long area (fig. 3). Major contributors of undiscovered conventionally recoverable oil and gas resources are frontier and conceptual plays (in which hydrocarbon accumulations have not yet been discovered), oil plays (containing predominantly crude oil and associated gas), and plays having fractured siliceous reservoir rocks (for example, Monterey Formation).

Undiscovered Economically Recoverable Resources

The total volume of undiscovered conventionally recoverable resources of the Region that is estimated to be economically recoverable at economic and technological conditions as of January 1, 1995 (that is, at prices of $18 per barrel [bbl] of oil and $2.11 per thousand cubic feet [Mcf] of gas), is 5.3 Bbbl of oil and 8.3 Tcf of gas (mean estimates) (table 2). These resources include relatively large volumes of oil (greater than 1 Bbbl) and gas (greater than 1 Tcf) in the Santa Barbara-Ventura basin and Bodega basin (figs. 2 and 3). Larger volumes of resources are estimated to be economically recoverable at more favorable economic conditions (table 2).

Comparison of Resource Estimates with Previous Assessments

Estimates of the volume of undiscovered conventionally recoverable oil and gas resources in the Region from this assessment are larger than estimates from previous MMS assessments (table 3 and fig. 4), owing primarily to the use of significantly different methodology and some additional data for this assessment. The increased estimates of the volume of undiscovered economically recoverable oil and gas resources in the Region from this assessment (table 4 and fig. 5) are attributed to the increased estimated volume of undiscovered conventionally recoverable resources.

Table 1. Estimates of undiscovered conventionally recoverable oil and gas resources in the Pacific OCS Region as of January 1, 1995, by assessment area. All estimates are risked values. The low, mean, and high estimates correspond to the 95th-percentile, mean, and 5th-percentile values of a probability distribution, respectively. Percentile values are not additive; some total mean values may not equal the sum of the component values because of independent rounding.

Assessment Area	Oil (Bbbl)			Gas (Tcf)			BOE[1] (Bbbl)		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
Pacific Northwest Province									
Washington-Oregon Area	0.14	0.36	0.69	0.95	2.30	4.28	0.32	0.76	1.42
Eel River Basin	0.03	0.05	0.08	1.06	1.61	2.32	0.23	0.34	0.49
Total Province	*0.19*	*0.41*	*0.75*	*2.34*	*3.91*	*6.03*	*0.61*	*1.11*	*1.79*
Central California Province									
Point Arena Basin	1.50	2.03	2.66	1.45	2.14	3.01	1.77	2.41	3.18
Bodega Basin	0.97	1.42	1.98	1.00	1.57	2.30	1.16	1.70	2.37
Año Nuevo Basin	0.49	0.72	1.01	0.49	0.78	1.16	0.58	0.86	1.21
Santa Maria-Partington Basin	0.68	0.78	0.89	0.60	0.74	0.90	0.79	0.91	1.05
Total Province	*4.17*	*4.95*	*5.82*	*4.21*	*5.23*	*6.39*	*4.94*	*5.88*	*6.93*
Santa Barbara-Ventura Basin Province									
Santa Barbara-Ventura Basin	1.74	1.85	1.95	3.84	4.61	5.48	2.43	2.67	2.92
Total Province	*1.74*	*1.85*	*1.95*	*3.84*	*4.61*	*5.48*	*2.43*	*2.67*	*2.92*
Los Angeles Basin Province									
Los Angeles Basin	0.19	0.31	0.49	0.17	0.32	0.53	0.22	0.37	0.58
Total Province	*0.19*	*0.31*	*0.49*	*0.17*	*0.32*	*0.53*	*0.22*	*0.37*	*0.58*
Inner Borderland Province									
Santa Monica-San Pedro Area[2]	0.23	0.68	1.47	0.25	0.77	1.68	0.28	0.82	1.76
Oceanside-Capistrano Basin[2]	0	1.11	2.21	0	1.30	3.17	0	1.34	2.70
Total Province[2]	*0.87*	*1.79*	*3.18*	*0.79*	*2.07*	*4.19*	*1.04*	*2.16*	*3.85*
Outer Borderland Province									
Santa Cruz-Santa Rosa Area	0	0.44	0.93	0	0.78	1.85	0	0.58	1.24
San Nicolas Basin	0	0.55	1.18	0	0.91	2.42	0	0.71	1.58
Cortes-Velero-Long Area	0	0.41	1.20	0	1.10	3.49	0	0.61	1.80
Total Province	*0.63*	*1.40*	*2.56*	*0.98*	*2.79*	*5.89*	*0.82*	*1.89*	*3.56*
Total Pacific OCS Region[2]	*8.99*	*10.71*	*12.62*	*15.21*	*18.94*	*23.19*	*11.82*	*14.08*	*16.60*

[1] Barrels of oil-equivalent resources is the combined volume of oil and oil-equivalent gas, in which gas is expressed in terms of its energy equivalence to oil (5,620 cubic feet of gas per barrel of oil).
[2] Includes a small area and volume of resources in the State offshore and onshore area adjacent to the Federal offshore area.

Figure 2. Distribution of undiscovered conventionally recoverable and economically recoverable oil resources in the Pacific OCS Region, by assessment area based on risked mean estimates listed in tables 1 and 2. Bar chart (A) shows incremental volumes of undiscovered economically recoverable oil resources for three economic scenarios and additional undiscovered conventionally recoverable oil resources; the entire bar represents the estimated total volume of undiscovered conventionally recoverable oil resources. Pie charts show proportionate volumes of undiscovered conventionally recoverable oil resources (B) and undiscovered conventionally recoverable oil resources that are economically recoverable versus uneconomic at the $18-per-barrel scenario (C). The sum of the percentage values in some pie charts may not equal 100 percent because of independent rounding.

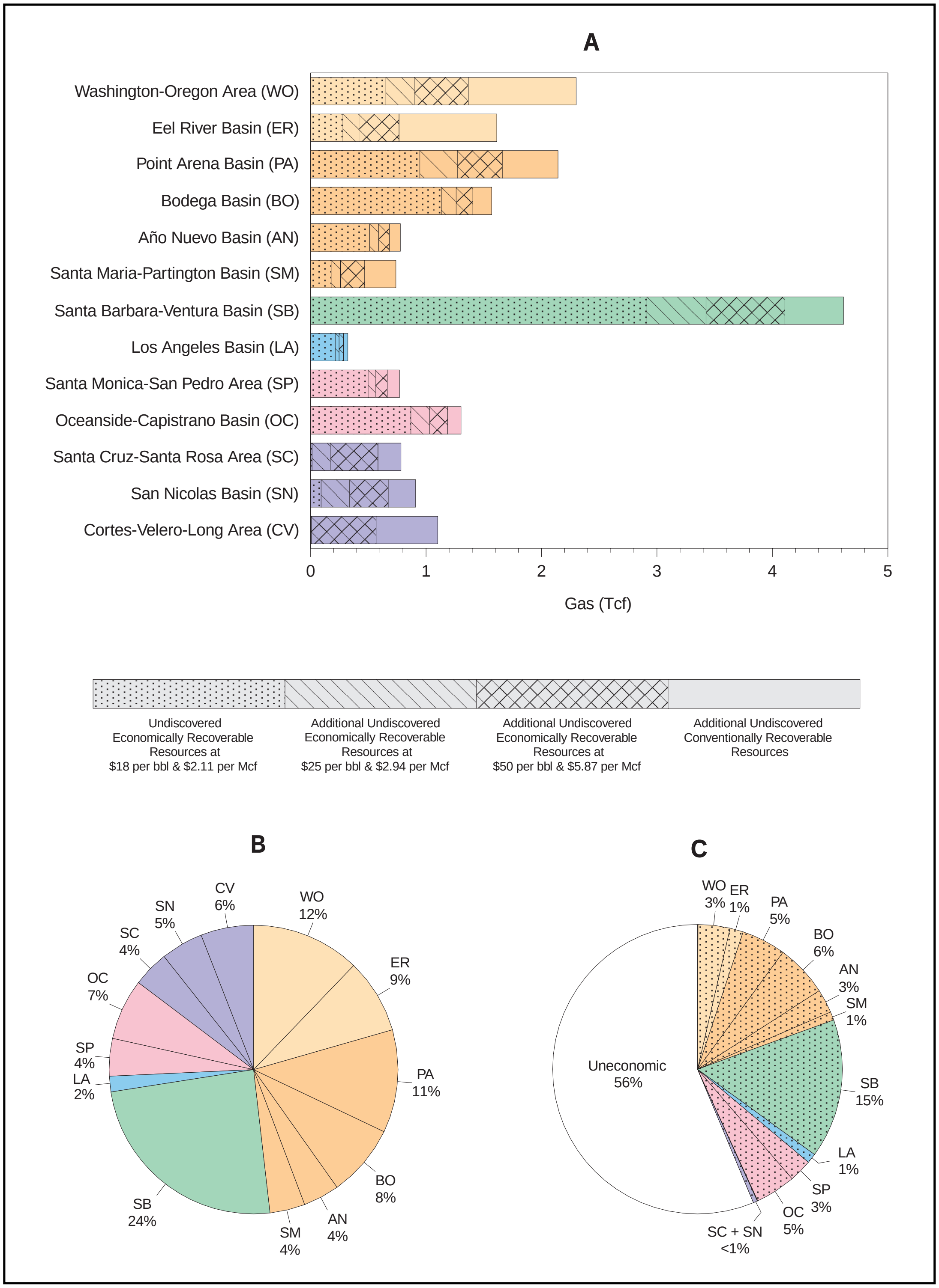


Figure 3. Distribution of undiscovered conventionally recoverable and economically recoverable gas resources in the Pacific OCS Region, by assessment area based on risked mean estimates listed in tables 1 and 2. Bar chart (A) shows incremental volumes of undiscovered economically recoverable gas resources for three economic scenarios and additional undiscovered conventionally recoverable gas resources; the entire bar represents the estimated total volume of undiscovered conventionally recoverable gas resources. Pie charts show proportionate volumes of undiscovered conventionally recoverable gas resources (B) and undiscovered conventionally recoverable gas resources that are economically recoverable versus uneconomic at the $18-per-barrel scenario (C). The sum of the percentage values in some pie charts may not equal 100 percent because of independent rounding.

Table 2. Estimates of undiscovered economically recoverable oil and gas resources in the Pacific OCS Region as of January 1, 1995, for three economic scenarios, by assessment area. All estimates are risked mean values. The $18-per-barrel scenario is based on prices of $18 per barrel of oil and $2.11 per thousand cubic feet of gas; the $25-per-barrel scenario is based on prices of $25 per barrel of oil and $2.94 per thousand cubic feet of gas; the $50-per-barrel scenario is based on prices of $50 per barrel of oil and $5.87 per thousand cubic feet of gas. Some total values may not equal the sum of the component values because of independent rounding.

Assessment Area	$18-per-barrel Scenario			$25-per-barrel Scenario			$50-per-barrel Scenario		
	Oil (Bbbl)	Gas (Tcf)	BOE[1] (Bbbl)	Oil (Bbbl)	Gas (Tcf)	BOE (Bbbl)	Oil (Bbbl)	Gas (Tcf)	BOE (Bbbl)
Pacific Northwest Province									
Washington-Oregon Area	0.09	0.65	0.21	0.13	0.90	0.29	0.20	1.37	0.44
Eel River Basin	<0.01	0.28	0.06	0.01	0.42	0.09	0.03	0.77	0.16
Total Province	*0.10*	*0.93*	*0.27*	*0.14*	*1.32*	*0.38*	*0.22*	*2.13*	*0.60*
Central California Province									
Point Arena Basin	0.90	0.95	1.06	1.21	1.27	1.43	1.58	1.66	1.87
Bodega Basin	1.03	1.13	1.23	1.14	1.26	1.37	1.27	1.41	1.52
Año Nuevo Basin	0.48	0.51	0.57	0.55	0.59	0.65	0.63	0.68	0.75
Santa Maria-Partington Basin	0.19	0.18	0.22	0.28	0.26	0.32	0.50	0.47	0.58
Total Province	*2.59*	*2.77*	*3.08*	*3.17*	*3.38*	*3.77*	*3.98*	*4.22*	*4.73*
Santa Barbara-Ventura Basin Province									
Santa Barbara-Ventura Basin	1.17	2.91	1.68	1.37	3.43	1.98	1.64	4.11	2.38
Total Province	*1.17*	*2.91*	*1.68*	*1.37*	*3.43*	*1.98*	*1.64*	*4.11*	*2.38*
Los Angeles Basin Province									
Los Angeles Basin	0.21	0.21	0.25	0.24	0.25	0.29	0.28	0.29	0.33
Total Province	*0.21*	*0.21*	*0.25*	*0.24*	*0.25*	*0.29*	*0.28*	*0.29*	*0.33*
Inner Borderland Province									
Santa Monica-San Pedro Area[2]	0.44	0.50	0.53	0.50	0.57	0.60	0.59	0.66	0.71
Oceanside-Capistrano Basin[2]	0.74	0.87	0.90	0.88	1.03	1.07	1.02	1.19	1.23
Total Province[2]	*1.19*	*1.37*	*1.43*	*1.39*	*1.60*	*1.67*	*1.61*	*1.85*	*1.94*
Outer Borderland Province									
Santa Cruz-Santa Rosa Area	<0.01	0.01	0.01	0.10	0.18	0.13	0.33	0.58	0.43
San Nicolas Basin	0.06	0.09	0.07	0.20	0.34	0.26	0.40	0.67	0.52
Cortes-Velero-Long Area	0	0	0	<0.01	<0.01	<0.01	0.21	0.57	0.31
Total Province	*0.06*	*0.10*	*0.08*	*0.30*	*0.52*	*0.40*	*0.94*	*1.83*	*1.27*
Total Pacific OCS Region[2]	*5.31*	*8.30*	*6.79*	*6.61*	*10.49*	*8.48*	*8.67*	*14.42*	*11.24*

[1] Barrels of oil-equivalent resources is the combined volume of oil and oil-equivalent gas, in which gas is expressed in terms of its energy equivalence to oil (5,620 cubic feet of gas per barrel of oil).
[2] Includes a small area and volume of resources in the State offshore and onshore area adjacent to the Federal offshore area.

Table 3. Comparable estimates of undiscovered conventionally recoverable oil and gas resources[1] in the Pacific OCS Region, by assessment. All estimates are risked values. The low, mean, and high estimates correspond to the 95th-percentile, mean, and 5th-percentile values of a probability distribution, respectively. N/R denotes an estimate not reported.

Assessment	Oil (Bbbl)			Gas (Tcf)			BOE[2] (Bbbl)		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
MMS 1987	0.81	3.51	8.92	3.50	8.01	15.07	N/R	4.94	N/R
MMS 1990	1.37	3.59	7.26	6.38	10.86	16.94	N/R	5.52	N/R
MMS 1995	8.99	10.71	12.62	15.21	18.94	23.19	11.82	14.08	16.60

[1] Estimates of undiscovered conventionally recoverable resources from the 1995 assessment are comparable to estimates of the undiscovered resource base from the 1987 and 1990 assessments.
[2] Barrels of oil-equivalent resources is the combined volume of oil and oil-equivalent gas, in which gas is expressed in terms of its energy equivalence to oil (5,620 cubic feet of gas per barrel of oil).

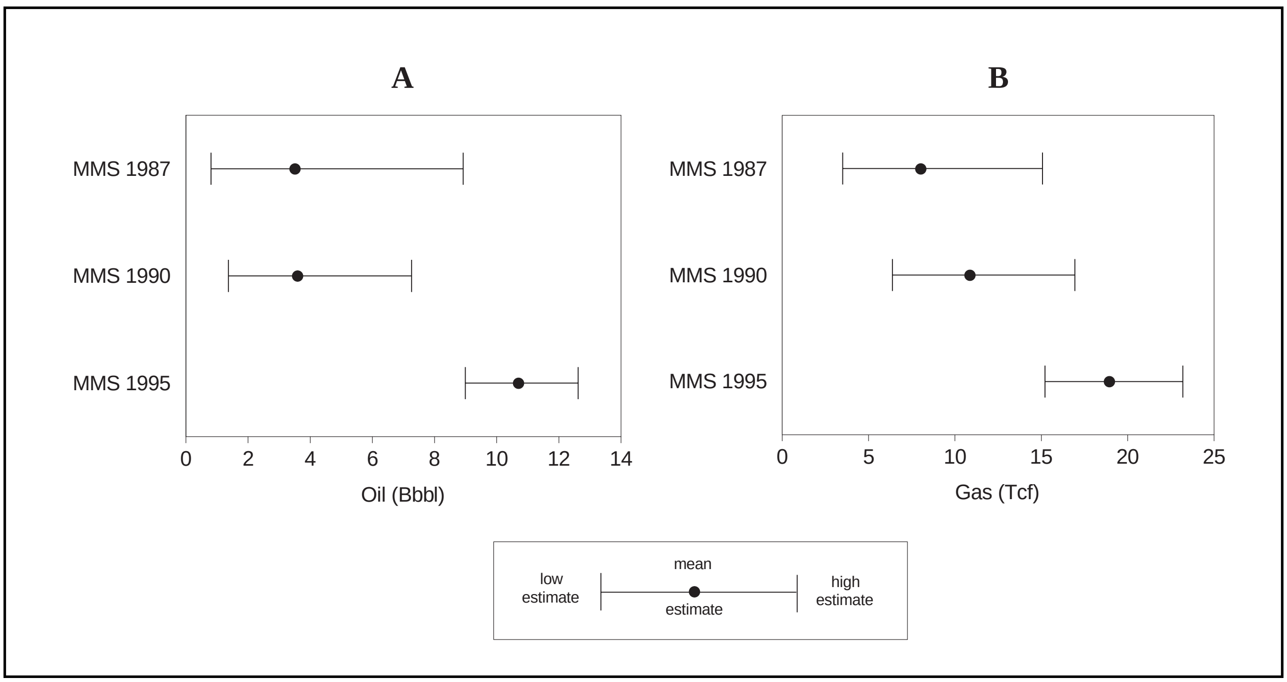


Figure 4. Comparison of estimates of undiscovered conventionally recoverable oil (A) and gas (B) resources in the Pacific OCS Region, by assessment. The estimates correspond to those listed in table 3.

Table 4. Comparable estimates of undiscovered economically recoverable oil and gas resources[1] in the Pacific OCS Region, by assessment. All estimates are risked values. The low, mean, and high estimates correspond to the 95th-percentile, mean, and 5th-percentile values of a probability distribution, respectively. N/R denotes an estimate not reported.

Assessment	Oil (Bbbl)			Gas (Tcf)			BOE[2] (Bbbl)		
	Low	Mean	High	Low	Mean	High	Low	Mean	High
MMS 1987	0.34	2.10	6.02	1.78	5.17	11.04	N/R	3.02	N/R
MMS 1990	0.63	2.49	6.12	2.46	6.15	12.14	N/R	3.58	N/R
MMS 1995	N/R	5.31	N/R	N/R	8.30	N/R	N/R	6.79	N/R

[1] Estimates of undiscovered economically recoverable resources from the 1987, 1990, and 1995 assessments are closely (but not completely) comparable, as follows:

Estimates from the 1987 and 1990 assessments are for the primary case economic scenario and are based on variable prices starting at $18.00 per bbl of oil and $1.80 per Mcf of gas.

Estimates from the 1995 assessment are for the $18-per-barrel economic scenario and are based on fixed prices of $18.00 per bbl of oil and $2.11 per Mcf of gas.

[2] Barrels of oil-equivalent resources is the combined volume of oil and oil-equivalent gas, in which gas is expressed in terms of its energy equivalence to oil (5,620 cubic feet of gas per barrel of oil).

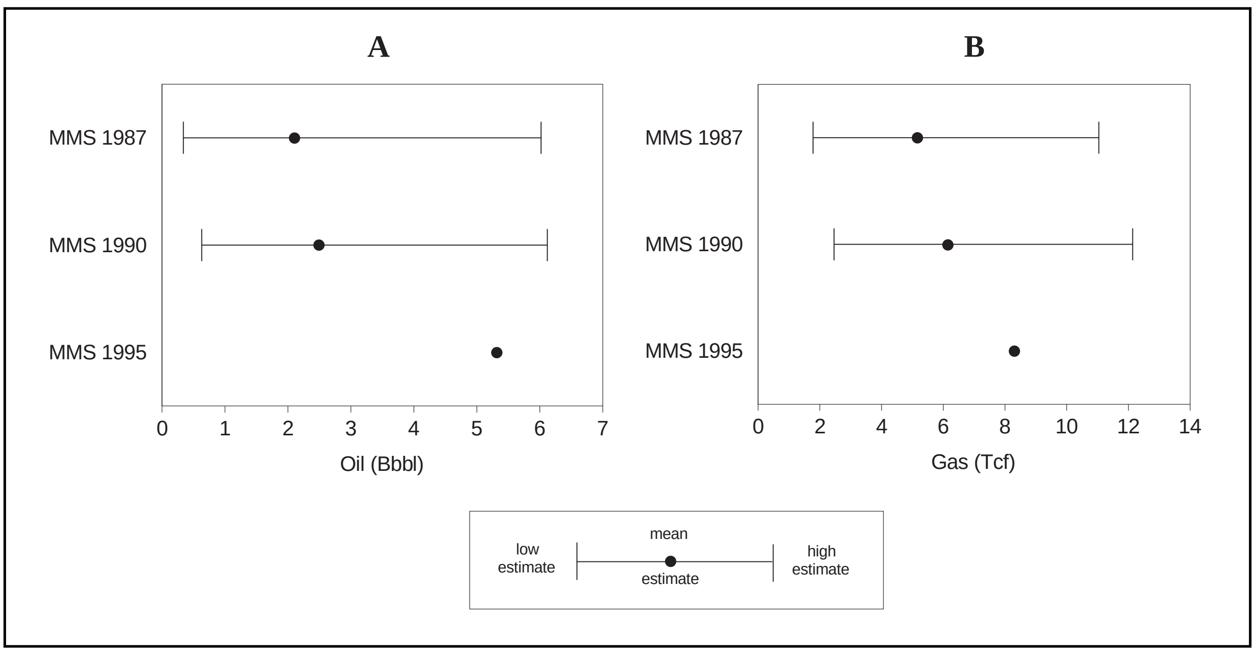


Figure 5. Comparison of estimates of undiscovered economically recoverable oil (A) and gas (B) resources in the Pacific OCS Region, by assessment. The estimates correspond to those listed in table 4.

The Geochemistry and Resource Potential of Manganese Crusts in the Johnston Island Exclusive Economic Zone

John C. Wiltshire

Ocean Resources Branch, Hawaii Department of Business, Economic Development and Tourism, Honolulu, Hawaii

Xi Yuan Wen

Department of Oceanography, University of Hawaii, Honolulu, Hawaii

De Yao

Institute of Marine Geology, Ministry of Geology and Mineral Resources, Qingdao, China

Abstract

The 200-mile exclusive economic zone (EEZ) around Johnston Island, 700 miles west of Hawaii, contains economically attractive concentrations of cobalt, nickel, platinum, and rare earth elements contained in manganese crusts on the surface of seafloor plateau areas. Detailed mineralogy and geochemistry reveal these deposits to be largely hydrogenous in origin although also containing elemental additions due to biological, weathering, hydrothermal, detrital, and diagenetic processes. The major mineralogical phase is vernadite (delta manganese dioxide) laid down in strataform crustal deposits. The most valuable metal, cobalt, shows concentrations highest in the upper layers of the crusts and decreasing with stratigraphic depth. Upcoming submersible dives will fully document the significance of this deposit.

Introduction

Three factors have significantly increased the likelihood that Pacific manganese nodule and crust resources will be mined at some point in the twenty-first century: (1) the legal clarification provided by the Law of the Sea Treaty now in full effect, (2) the rapid economic growth in East Asia, and (3) the sharp rise in world demand for cobalt for new high-tech uses such as batteries for electric cars and high-tensile-strength super alloys. There are also political and national policy considerations that are driving national programs in several Asian countries. The Chinese Ocean Minerals Research and Development Association (COMRA) has announced plans to begin mining marine manganese in the first part of the next century. COMRA has also recently signed a cooperative agreement with the State of Hawaii for the cooperative investigation of issues related to this industry (June 1997). Korean groups have also announced plans to continue their major mining development work with a view to mine around the year 2010. Other active programs are occurring in India and Japan. This activity will ultimately result in a deep-sea mining operation for manganese nodules or crusts.

Ferromanganese crusts on the top and sides of Pacific Seamounts are one of the richest sources of cobalt known. Detailed economic studies indicate that cobalt, nickel, platinum, manganese, and perhaps underlying phosphate may be extracted from these crusts. A major economic study has provided the necessary information to characterize a mine site (Loudat and others, 1993). A viable mine site would have a cobalt grade above 1 percent and preferably close to 1.25 percent. Platinum above 1.5 ppm would allow platinum to be extracted as the third most valuable metal after cobalt and nickel. A crust operation would need to extract 1.0 million tons of dry crust per year while taking only an additional 25 percent non-crust substrate material. In order to take so little substrate, an average crust thickness of 5 cm would be required in relatively flat terrain with total crust bottom coverage of more than 60 percent. Few Pacific seamounts meet these criteria; however, in the Johnston Island Exclusive Economic Zone (EEZ), 700 miles west of Honolulu, a number of plateau areas do meet these criteria because of their unique geology. For this reason, the Johnston Island EEZ has the potential to become a prime manganese crust exploitation site. Economic models indicate that an internal rate of return of 32 percent could potentially be realized from a crust mining operation around Johnston Island (Loudat and others, 1993). Given this information, a research program was structured to thoroughly investigate these crusts.

The work for this project involved a major ship expedition over a 17-day period to the Johnston Island EEZ. This November 12–28, 1993, expedition aboard the 225-foot University of Hawaii research vessel *Ka'imikai-o-Kanaloa* collected more than 2,500 lb of samples. Follow-up analytical work discussed in this article provides a very detailed description of the Johnston Island manganese crust deposit and its economic potential.

Mineralogy

Mineralogical and chemical determinations were conducted at China's Ministry of Geology and Mineral Resources Marine Geological Experiment and Testing Center in Qingdao. X-ray diffraction analyses of ferromanganese crusts were completed on D/Max-rA diffractometer with Cu K alpha radiation, a carbon curved-crystal monochrometer.

Sheetlike stratiform crusts are the most common facies in the Johnston Island area. The dominant manganese mineral in these ferromanganese crusts is vernadite (delta manganese dioxide) with contents varying from 34.8 to 99.3 percent. Spherical crusts, the other common morphological form, are found growing around loose debris. In a typical spherical crust, the lower section is characterized by a rough surface texture that is relatively poor in vernadite and rich in todorokite, similar to what might be anticipated in a manganese nodule but unlike the stratiform crusts (see table 1). By contrast, the upper surface of a typical spherical crust exhibits a smooth texture and is relatively rich in vernadite and poor in todorokite similar to the stratiform crusts.

The differences of composition of ferromanganese oxides here are directly controlled by the Eh value of the bottom water alone. But what are the geological factors accounting for the mineralogical differences? In the case of the loose spherical manganese-crust-covered debris, the water flow around the debris is restricted, especially in the area between the debris and underlying substrate. The Eh value of the water in this zone may be reduced through geochemical reaction between the water, and debris and substrate. This is a similar circumstance to manganese nodules on the deep sea floor. This may account for the higher concentration of todorokite on the lower crust-covered surfaces of loose debris.

One factor that has not been well studied in the mineralogical development of manganese crusts is the role of bacteria-mediated biofilms. It is well known that polysaccharide bacteria-formed layers grow very quickly on the crusts (within weeks). They are probably much more protected on the undersides of loose debris than on current swept flat surfaces. This may have a significant effect on the concentration of better ordered todorokite in these areas than vernadite.

Geochemistry

Analytical results were compiled for 36 elements in 68 samples and subsamples of ferromanganese crusts from two areas 100 miles east and 60 miles south of Johnston Island, the Karin Seamount Range and Keli Ridge, respectively. K, Fe, Pb, Zn and Cd were determined by flame atomic absorption spectrometer; Si and Mn were determined by chemical volumetry; all other elements were determined by inductively coupled plasma–atomic emission spectrometer (ICP-AES). The results are shown in table 2 as mean, maximum, and minimum values for each element. The mean contents of Mn and Fe are 25.43 and 12.56 percent, respectively, yielding an Mn/Fe ratio of 2.02. This Mn/Fe ratio is higher than the average for the entire central Pacific region, which has a ratio of 1.46 with Mn and Fe contents of 23.0 and 15.7 percent, respectively (Hein and others, 1990a). Most of the other metal contents are also higher than Pacific-wide averages (Baturin, 1988) and for the central Pacific specifically (Hein and others, 1990b). The mean contents of the economically important metals Co (0.88 percent) and Ni (0.71 percent) are significantly higher than the averages for the central Pacific.

The sum of all rare earth element concentrations (Total REE) ranges from 1,171 to 2,772 ppm with an average of 1,918 ppm (about 0.19 percent). The Johnston Island samples show a notable positive

Table 1. Major minerals in ferromanganese crusts (in percentage).

Sample no.	Vernadite	Todorokite	Birnesite	Aptite	Quartz	K-feldspar
sheetlike stratiform crusts						
RD1-1	99.3				0.7	
RD1-2a-2	94.5				1.8	
RD4-2-1	98.1				0.9	
RD4-2-2	90.9		6	0.7	1.5	1
Rd4-2-3	62.3			29	0.4	
RD11-3-1	75.6			24.4		
RD11-3-2	97.1				0.6	2.3
RD11-3-3	98				0.9	1.1
RD12-4-1	92.9			2.8	2.8	1.5
RD12-5-1	73.2			20.5	0.4	
spherical crusts						
RD6-4-1	58.4			40.4	1.2	
RD6-4-2	71.6			28.4		
RD6-4-3	92.1			2.5	0.7	0.9
RD6-4a-1	34.8	12.7	25.4	24.6	0.8	1.7
RD6-4a-2	46.5	3.1	7.4	42.6	0.4	
RD12-1-2	42.3	11.8	32	12.6	0.5	0.7
RD12-2-1	72.6	2.2	16.1	5.1	2.8	1.5
RD12-2-2	38.6	7.3	27.7	19.4	4.5	2.5

anomaly for the valuable rare earth Cerium. Total REE in 60 percent of the 68 samples and subsamples was higher than 0.18 percent. Total REE has no obvious relation with Co, but more than 85 percent of the 68 analytical results have Co content greater than 0.8 percent and/or Total REE greater than 0.18 percent.

From an economic point of view this is very significant. More than 80 percent of the world's currently documented rare earth element resources are in China. China's rare earth element resources are mainly associated with the Bayan Obo REE-Fe deposit in Inner-Mongolia. The rare earth element grade of the Bayan Obo REE-Fe deposit is 0.36 percent rare earth element oxide. For comparison, the grades of the other main types of rare earth element deposits in China expressed as oxides are as follows: 0.05–0.7 percent in REE-bearing granite; 0.1–0.5 percent in REE-Mn-Fe formation, and less than 0.9 percent in REE-P formation. It is clear that rare earth element contents in ferromanganese crusts from the Johnston Island EEZ are very close to the grades of major land-based rare earth element deposits and almost exactly the same as the grade of REE-Mn-Fe formation. This is an important economic result because the value of rare earth elements has not yet been factored into the economic calculation of the value of manganese crusts (Loudat and others, 1993). Almost 70 percent of the value of crusts is considered to be associated with their cobalt content. The economic enhancement from rare earth element recovery need only exceed the cost of extracting them from an already mined ore. At the grades discovered in this study, that would most certainly be the case.

Manganese crusts vary significantly in their chemical composition from one layer to the next. As this gives important economic and paleoceanographic information, we have performed selected detailed stratigraphic analysis of these layers. Several authors (Halbach and others, 1982) have noted that cobalt content generally decreases moving downward from the surface of crust toward the substrate. This relationship has also been documented in our analytical work. Generally, the thicker the crust, the higher the Co content in the surface layer of the crust. It appears that Co and Ni contents in each new ferromanganese oxide layer growing on the crust surface become more and more enriched as the crust grows and becomes thicker and thicker. The manganese-encrusted clastic

Table 2. Chemical composition of Johnston Island crusts (major elements, Mn to Na, in percentage; minor elements, Pb to TREE, in ppm).

Element	Minimum	Maximum	Average
Mn	14.05	31.87	25.43
Fe	5.74	19.89	12.56
Si	0.66	4.38	2.04
Al	0.11	1.97	0.49
Ca	2.41	17.89	6.59
Mg	0.83	2.20	1.48
Ti	0.56	1.82	1.07
P	0.46	8.71	2.53
Cu	0.04	0.31	0.10
Co	0.22	1.16	0.88
Ni	0.32	1.4	0.71
Ba	0.11	0.24	0.17
Sr	0.12	0.27	0.17
K	0.31	0.77	0.51
Na	1.07	1.93	1.50
Pb	687	1680	1312
V	424.5	892.5	685.1
Mo	294.6	946.1	622.3
Cd	1.7	10.8	5.04
Zn	467	1500	763
La	145	472	260
Ce	565	1890	1201
Pr	25.8	84.0	44.78
Nd	99.1	354.0	192.7
Sm	17.9	70.1	35.43
Eu	5.15	19.4	10.11
Gd	27.8	91.0	48.5
Tb	3.85	11.9	6.82
Dy	25.1	82.4	43.7
Ho	6.06	20.06	9.93
Er	18.0	59.7	28.9
Tm	2.85	7.63	4.34
Yb	17.8	48.7	27.9
Lu	2.30	6.56	3.60
Y	121	854	250
Sc	2.04	12.20	6.30
TREE	1171	2773	1918

debris shows a clear chemical variation between the upper part (characterized by a smooth surface), where Ca, P, Mn, Co, Ni, and some REE are richer, and the lower part (characterized by a rough surface), where these metals are less concentrated. Si and Al exhibit the reverse of this trend—that is, they are enriched in the lower layers. Although total REE content shows no obvious stratigraphic variation, REE partitions are significantly different. Of particular significance, the positive Ce anomaly in the upper zone is stronger than that in the lower zone. These compositional differences between the upper and lower zones demonstrate the influence of substrates, loose debris, and their submarine weathering on the composition of ferromanganese crusts.

Factor Analysis

Statistical treatment of the large data base collected for this project was performed by principal component, multivariate factor analysis with the STATISTICA program for Windows (version 4.5a). A correlation matrix was constructed, and the R-mode varimax rotated factor loadings were calculated. The purpose of this exercise was to sort out elemental assemblages that make sense from a geochemical viewpoint to try to get a handle on the processes of formation and change occurring with the manganese crusts. Four factors were uncovered that account for 80 percent of the variance in the data.

Factor 1 loads on trivalent REE and accounts for 36 percent of the sample variance. Because of their very similar chemical properties (Henderson, 1984), the trivalent REE show strong positive correlations with one another and a weak positive correlation with Fe, as noted in ferromanganese crusts from Line Islands (Aplin, 1984) and from the Hawaiian Archipelago (DeCarlo and McMurtry, 1992).

Factor 2 accounts for 22 percent of the sample variance with positive loadings on Mn, Fe, Co, Ti, K, Na, Pb, V, Mo, Cd and negative loadings on Ca and P. It is interpreted to represent hydrogenous Mn and Fe oxides and phosphatic material. Factor 1 and Factor 2 represent the dominant hydrogenous mineralization.

Factor 3 loads negatively on Ni, Mg, Cu, K, Cd, and Zn and accounts for 13 percent of sample variance. This suite of elements, which also includes weak negative loadings on Ba, Na, Mo, and Mn has been interpreted by the U.S. Geological Survey to represent a hydrothermal input in young manganese crusts dredged from the Haleakala Ridge off the Island of Maui in the Hawaiian chain. It is likely to also indicate a hydrothermal input in the Johnston EEZ, although this may be interpreted to represent a supply of hydrothermal elements to ferromanganese crusts through the submarine weathering of underlying volcanic substrates.

Factor 4 accounts for 7 percent of sample variance and shows high positive loadings on Si and Al. These are rock-forming elements. This elemental assemblage represents the mixing of detrital aluminosilicate sediment into the ferromanganese structure.

Fine-scale Stratigraphic Analysis

In order to elucidate the fine-scale elemental distribution in Johnston Island manganese crusts chemical variations were measured at 2-millimeter intervals using a variety of techniques. The results are presented in figures 1 through 4. This involved painstaking scraping of delicate crust layers for ICP and ICP-MS as well as in the case of platinum analysis using a laser ablation unit to vaporize millimeter shot holes (Wiltshire, 1990; Wen and others, 1997; Wiltshire and others, 1997).

Cobalt abundance is presented as a function of depth (fig. 1) in four of the Johnston Island crusts (RD11-3, RD11-4, RD5-3, RD5-4) collected during the 1993 expedition. Cobalt concentration ranges from 0.2 to 1.4 percent. Cobalt abundance is highest at the surface of the crusts, decreasing with stratigraphic depth. Platinum is also enriched in crusts. Platinum abundance also shows a relationship with depth in each of the crusts. Platinum concentration ranges from 0.2 to 1.3 ppm (fig. 2). Platinum abundance generally shows 1 to 3 narrow zones of higher concentration in each stratigraphic section. There is no correlation between Co and Pt in these crusts. These profiles indicate that Co and Pt are controlled by different geochemical factors. Cobalt and Pt abundance in Pacific ferromanganese crusts is generally 100 to 1,000 times higher than in pelagic clay (Wen and others, 1997). This is also true for Johnston Island crusts. The very slow growth rate of crusts and the surface scavenging properties of hydrous manganese dioxide are considered to be two important factors controlling Co and Pt distribution.

Interelemental Relationships

A previous study of interelemental relationships in ferromanganese crusts from the central Pacific Ocean partitioned the elements in crusts into four major groups (Wen and others, 1997). Elements were interpreted to represent hydrogenetic (Mn), biogenic (Ba), detrital (Al), and carbonate fluorapatite (P) groups. Reviews on the behavior of oceanic trace elements reveal that Ba and Pt are generally considered either nutrient-related or hydrothermal elements and that their distribution in seawater may be heavily influenced by biological activity. The elements Mn and Co, on the other hand, are considered scavenged-type elements whose distribution is mainly controlled by surface chemical interactions with particles.

A strong linear correlation is observed between Mn and Co within crusts (fig. 3). This relationship suggests that the distribution of Co in crusts, like manganese, is heavily controlled by seawater chemical conditions. In addition, this strong correlation between Co and Mn (fig. 3) also suggests that Co is strongly scavenged by the vernadite phase to incorporate into crusts. In contrast to manganese, there is no relationship between Co and detrital Al in most crusts. Nonetheless the direct source of Co in seawater is thought to be largely from weathering, a process contributing to the detrital fraction. The fact that there is no relationship observed in most crusts between the detrital Al and Co suggests a decoupling between the source of the Co and incorporation of this Co into the crusts; that is, the Co is from detrital sources in seawater but of hydrogenetic origin in the crusts. Cobalt also experiences dilution in the crusts from other elemental incorporations, most commonly with respect to phosphorus and calcium, which form carbonate fluorapatite particularly in lower layers of some crusts. For this reason, an inverse relationship is common between P and Co.

Platinum and Co are not related to each other. However, a positive correlation between Pt and Ba shows in figure 4. The strong linear correlation suggests that Pt enrichment may be influenced by the biogeochemical processes that cause incorporation of Ba into crusts.

In summary, our microanalysis indicates that seamount ferromanganese crusts are predominately of hydrogenetic origin, evidenced by concentrations of Mn and Co. There is detrital addition of silica and aluminum and diagenetic addition of calcium and phosphorus, which dilutes the hydrogenetically added material. Our results also suggest that Pt accumulation is mainly associated with barium and its biogeochemical processes. We speculate that this Pt distribution may mainly be mediated by biological activity. Several crusts show extremely high concentrations of platinum in one or two narrow bands. This undoubtedly indicates a different Pt source for these bands—perhaps a meteorite impact (Wiltshire, 1990).

Economics

With the presence of economically attractive amounts of cobalt, nickel, platinum, and rare earth elements, the Johnston Island manganese crusts merit serious resource consideration. In order to compare the Johnston Island deposit with other major developing mineral finds we did a detailed market analysis

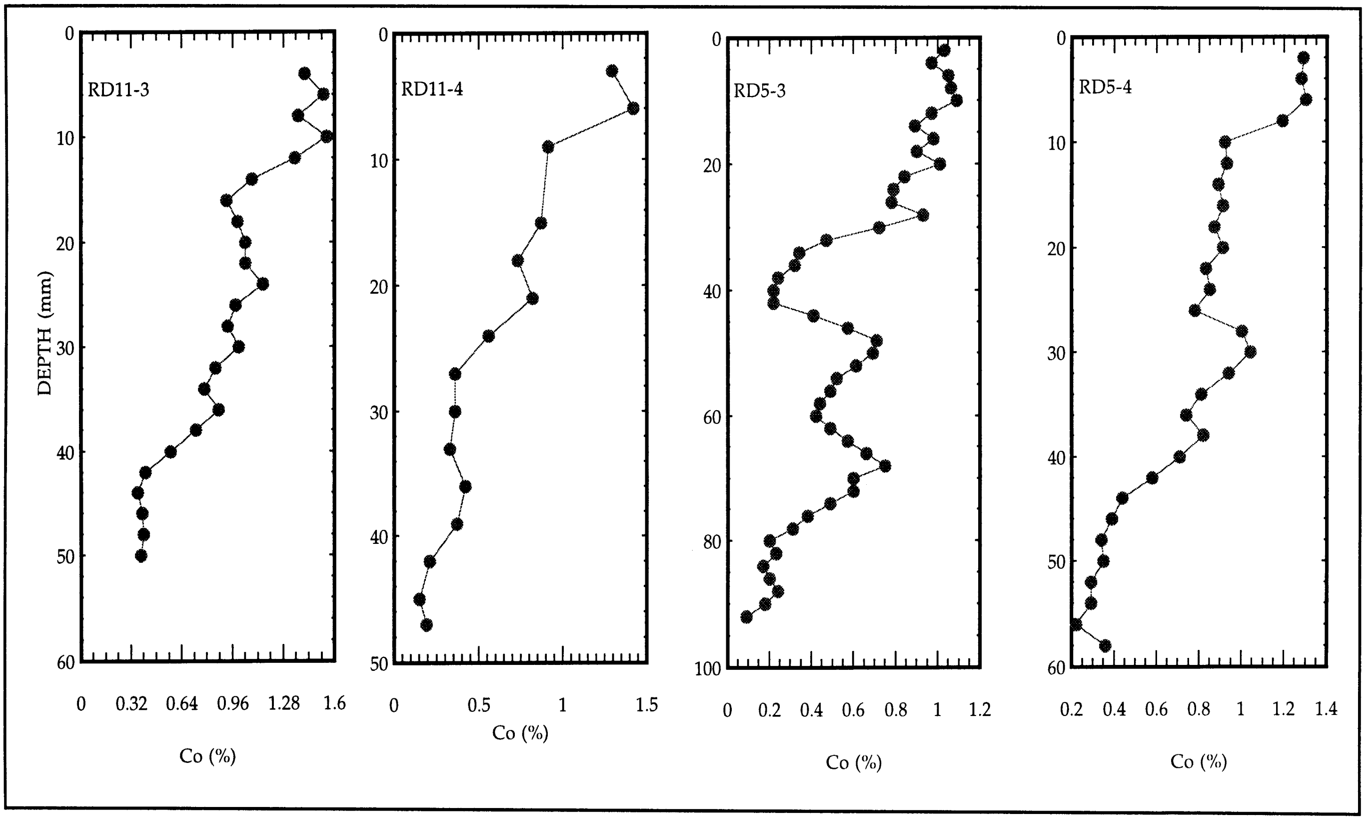


Figure 1. Stratigraphic profiles of cobalt concentration in marine Fe-Mn crusts from the Johnston Island EEZ.

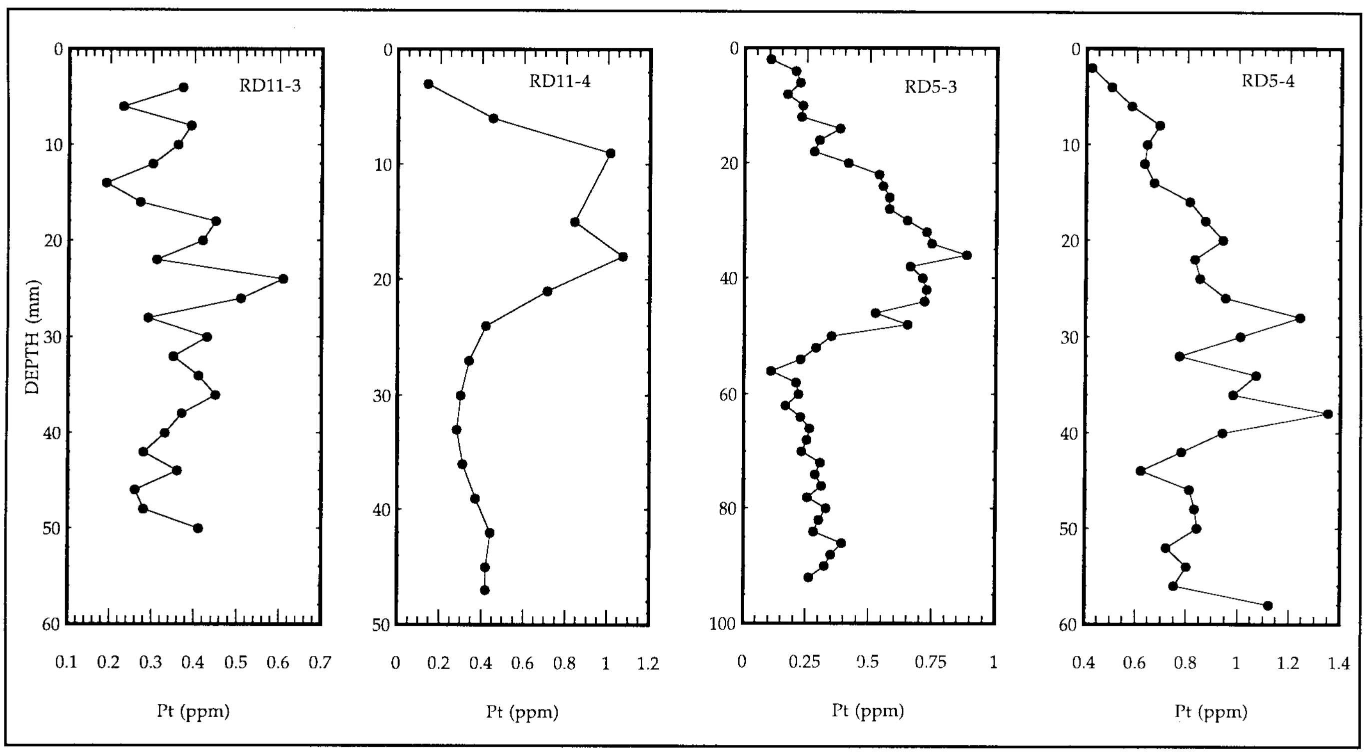


Figure 2. Stratigraphic profiles of platinum concentration in marine Fe-Mn crusts from the Johnston Island EEZ.

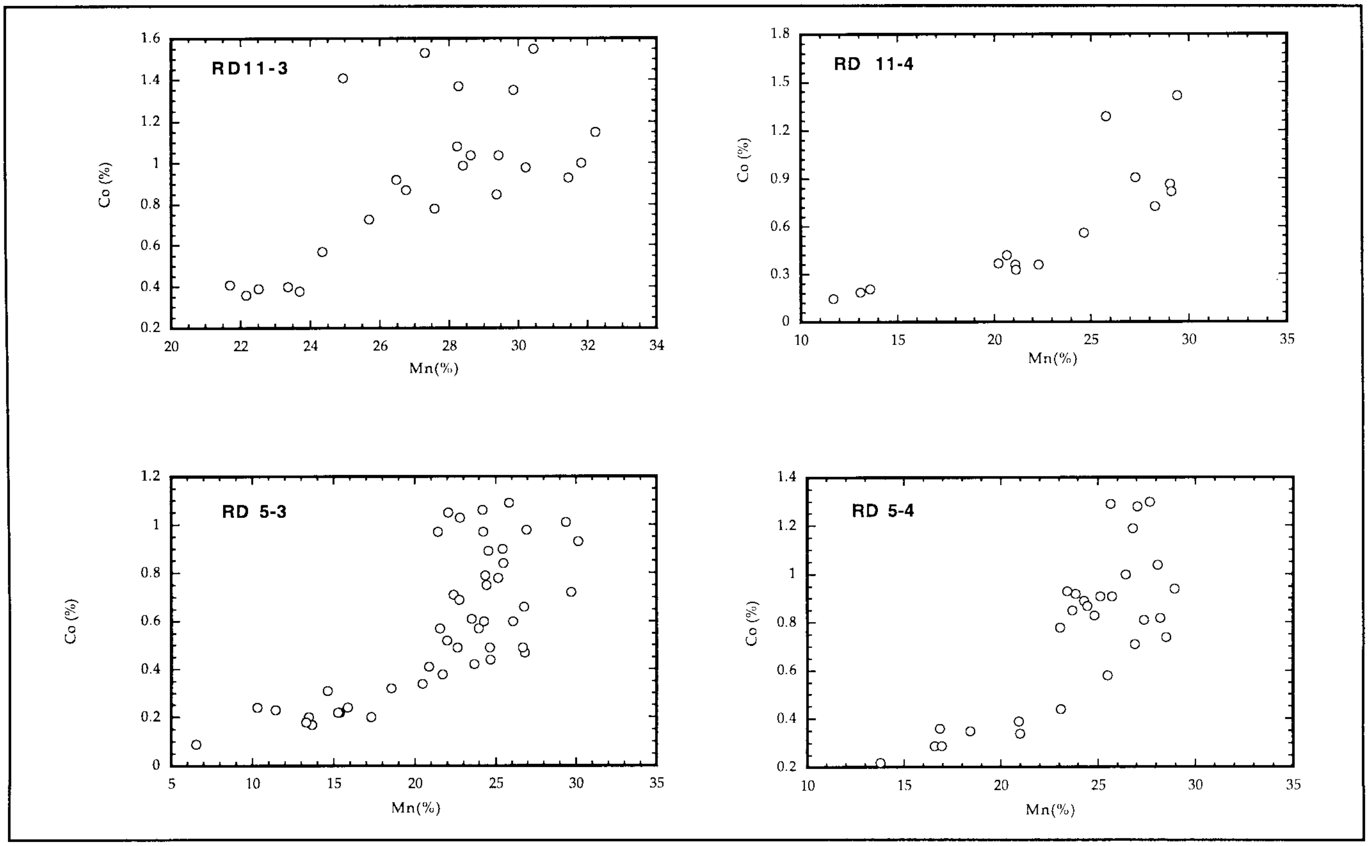


Figure 3. Relationship of cobalt to manganese in Fe-Mn crusts, showing a strong correlation.

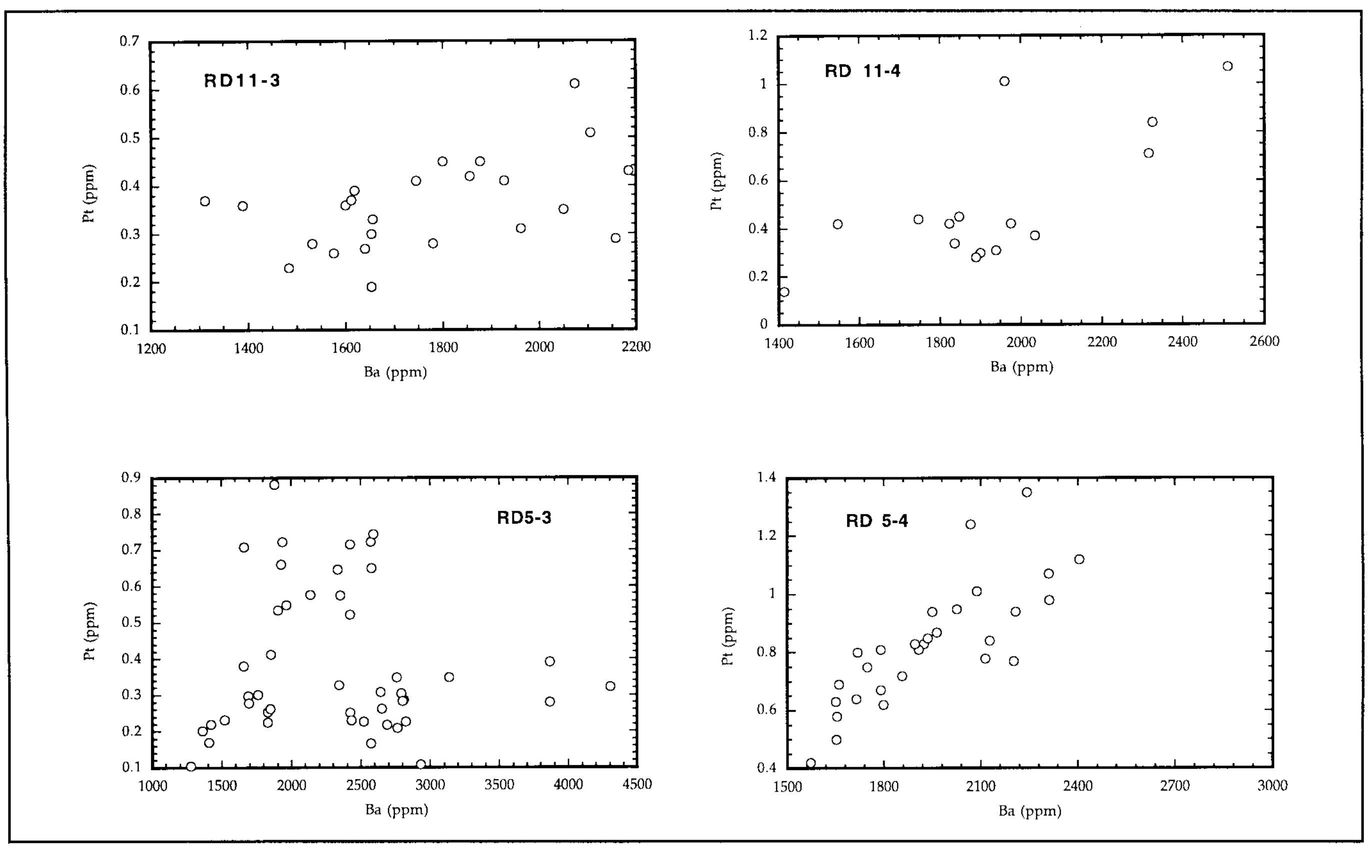


Figure 4. Relationship of platinum to barium in the Fe-Mn crusts, showing a strong direct correlation.

(Wiltshire, 1997). The results can be summarized as follows. To be profitable a marine manganese crust mining operation would largely depend on cobalt sales. However, compared with that of other metals markets, the cobalt market is smaller, more volatile, and inherently less predictable. The key factors shaping the cobalt market include its relative smallness, the wide variety of products that use cobalt, the relatively few numbers of large producers and consumers compared with other metals, the fact that most cobalt is mined as a byproduct of copper and nickel, and the highly politically unstable nature of some of the major cobalt producers. At the current growth rate of 4 percent, the annual cobalt demand will be 50,000 tons by the year 2015. At present, the world demand for cobalt and available supply are in equilibrium at today's high cobalt prices. This supply/demand balance on the world market is maintained by several factors. These are stockpile sales, metal substitution, and new sources of cobalt coming on line. Several new cobalt sources have been discovered and are anticipated to come on line after the turn of the century. At the current rate of development about 8,000 tons of new production should on line by the year 2005, adding to the current world production of about 25,000 tons/yr. This could give a world primary supply of more than 33,000 tons a year by 2005. If the current cobalt growth rate is maintained, demand in 2005 will be more than 37,000 tons, or a potential market shortfall of several thousand tons. A best mid-term guess on market size by several well-known market experts is 30,000 to 35,000 tons after the year 2000. Such a market could support one 3,000-ton-per-year manganese crust operation coming on line in the year 2000. This means that at least on paper the Johnston Island manganese crust deposits are a highly viable prospect.

Conclusions

(1) Ferromanganese crusts on the top and sides of Pacific seamounts are one of the richest sources of cobalt known. Detailed economic studies have indicated that cobalt, nickel, possibly platinum, manganese, the rare earth elements, and even perhaps the underlying phosphate may be extracted from these crusts.

(2) The dominant mineral in the ferromanganese crusts is vernadite. The crusts are rich in Co (0.88 percent) and rare earth elements (Total REE = 1,918 ppm) and poor in Cu (0.1%). They have a strong positive cerium anomaly (2.6) and an Mn/Fe ratio of 2.02. This is typical of hydrogenous ferromanganese crusts.

(3) Besides economically attractive Co and Ni, the contents of rare earth elements in the crusts are close to the grades of REE in major world-class land-based REE deposits. More attention should be given to the economic potential of rare earth elements in hydrogenous ferromanganese crusts.

(4) In spherical crusts, the upper part of the ferromanganese oxide layers is richer in vernadite, Mn, Co, Ni, Ca, and P than the lower part. Si and Al show the opposite trend. This compositional variation was probably initiated through a reaction between seawater and the seamount basement rocks. This reaction not only provides elemental materials but also changes the mineralization environment.

(5) The scope and extent of the reaction between seawater and the seamount rocks decreases with the growth of ferromanganese crusts on the seamount rocks. Therefore each new layer is progressively less influenced by submarine weathering of the upper areas of the seamount. This is probably the reason for the contents of Co and Ni increasing from substrate to crust surface in the stratiform crusts.

(6) R-mode factor analysis for 36 elements in the crusts suggests that there are at least four major processes controlling the ferromanganese crust formation. Mn, Fe, Co, Ni, and REE in crusts are controlled by hydrogenous processes, but hydrothermal input or submarine weathering of seamount rocks also provided some of the Ni. Ferromanganese oxides and associated metals in crusts have been diluted by mixing in aluminosilicates and phosphate.

(7) Among the Pacific seamount ferromanganese crusts, the Fe-Mn crusts from the Johnston Island EEZ merit further attention. There is very real economic potential in this deposit for the future ocean miner. The Johnston Island manganese crusts should be given considerably more detailed study including submersible dives.

Acknowledgments

This research has been supported by the Department of the Interior's Mineral Institute Program administered by the U.S. Bureau of Mines through the Generic Mineral Technology Center for Marine Minerals under grant number G1115128 and by the Minerals Management Service's Continental Margins Program. This work was also supported by China's Ministry of Geology and Mineral Resources, and China's National Natural Science Foundation. The authors thank the Hawaii Undersea Research Laboratory and the crew of *R/V Ka'imikai-o-Kanaloa* for their outstanding support. This work is State of Hawaii Ocean Resources Branch Contribution Number 136.

References

Aplin, A. C., 1984, Rare earth element geochemistry of Central Pacific ferromanganese encrustations: Earth and Planetary Science Letters, v. 71, p. 13–22.

Baturin, G. N., 1988, The geochemistry of manganese and manganese nodules in the Ocean: D. Reidel Publishing Co., 342 p.

DeCarlo, E. H. and McMurtry, G. M., 1992, Rare earth element geochemistry of ferromanganese crusts from the Hawaiian Archipelago, Central Pacific: Marine Geology, v. 95, p. 235–250.

Halbach, P., Manheim, F. T. and Otten, P., 1982, Co-rich ferromanganese deposits in the marginal seamount regions of the central Pacific basin—results of the Midpac'81: Erzmetall v. 35, p. 447–453.

Halbach, P., and Puteanus, D., 1984, The influence of the carbonate dissolution rate on the growth and composition of Co-rich ferromanganese crusts from Central Pacific seamount areas: *Earth and Planetary Science Letters*, v. 68, p. 73–87.

Hein, J. R., Schulz, M. S. and Gein, L. M., 1990, Central Pacific cobalt-rich ferromanganese crusts: historical perspective and regional variability: *in* Keating, B., and Bolton, B., eds., Geology and Offshore Mineral Resources of the Central Pacific Region, Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Houston, Texas.

Hein, J. R., Kirschenbaum, H. H., Schwab, W. C., Usui, A., Taggart, J. E., Stewart, K. C., Davis, A. S., Terashima, S., Quinterno, P. J., Olson, R. L., Pickthorn, L. G., Schulz, M. S., Morgan, C. L., 1990, Mineralogy and geochemistry of Co-rich ferromanganese crusts and substrate rocks from Karin Ridge and Johnston Island, Farnella Cruise F7-86-HW: U.S. Geological Open File Report 90-298, 80 p.

Hein, J. R., Manheim, F. T., Schwab, W. C., Davis, A. S., Daniel, C. L., Bouse, R. M., Morgenson, L. A., Sliney, R. E., Clague, D., Tate, G. B. and Cacchione, D. A., 1985, Geological and geochemical data for seamounts and associate ferromanganese crusts in and near the Hawaiian, Johnston Island and Palmyra Island Exclusive Economic Zones: U.S. Geological Survey Open-File Report 85-292, 129 p.

Henderson, P., ed., 1984, Rare earth element geochemistry: Elsevier, Amsterdam, Elsevier Developments in Geochemistry, 2, 510 p.

Loudat, T. A., Wiltshire, J. C., Allen, J. P. and Hirt, W. C., 1993, An investigation of the contribution of platinum and phosphorite to the economic viability of a manganese crust mining operation in the EEZ surrounding Hawaii and Johnston Island: State of Hawaii DBEDT Report, 66 p.

Morgan, C. L. and Wiltshire, J. C., 1994, Deep seabed rock dredging in areas with high relief: Marine Georesources and Geotechnology, v. 12, p. 227–236.

Wen, X, DeCarlo, E., and Li, Y., 1997, Inter element relationship in ferromanganese crusts from the Central Pacific Ocean: their implications for crust genesis: Marine Geology, v. 136, p. 277–297.

Wiltshire J. , 1997, The world cobalt market and its ability to support manganese crust mining, *in* Saxena, N., ed., Recent advances in marine science and technology '96: Honolulu, PACON International, p. 337–346.

Wiltshire, J., 1994, Manganese crust deposits in the Johnston Island EEZ as potential cobalt resources: Proceedings of Pacon China Symposium, Honolulu, PACON International, p. 159–168.

Wiltshire, J. C., 1990, Platinum accumulation in cobalt-rich ferromanganese crusts: Proceedings of the Fourth Pacific Congress on Marine Science and Technology, Honolulu, PACON International, v. 1 p. 405–412.

Wiltshire, J., Wen X., and DeCarlo, E., 1997, Fine-scale platinum-rich zones as stratigraphic markers in seamount ferromanganese crusts: Proceedings of PACON '97, August 6–8 1997, Hong Kong, Honolulu, PACON International, p. 36–47.

Low-Temperature Thermal History Using Fission Track Dating in Three Wells in Southern Alaska Offshore Basins: Lower Cook Inlet, Shelikof Strait, and Stevenson Trough

John M. Murphy

Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071

James G. Clough

Alaska Division of Geological and Geophysical Surveys (ADGGS), 794 University Avenue, Suite 200 Fairbanks, AK 99709-3645

Abstract

Three wells, all offshore, in southern Alaska studied using apatite fission track dating make a transect southward from Lower Cook Inlet to the Kodiak Shelf and include ARCO Lower Cook Inlet COST #1 well (LCI well), Chevron OCS-0248 #1A well (Shelikof Strait), and Kodiak COST KSSD #1 OCS 77-1 well (Stevenson Basin, Kodiak).

The ages of deep partially annealed samples from Lower Cook Inlet well suggest that the region cooled between ~100 and 75 Ma and/or sometime after. Two scenarios are presented: (1) maximum heating before cooling in Late Cretaceous times and (2) maximum heating before cooling during mid-Tertiary times. Which is better is uncertain from the thermal and age data alone, but mid-Tertiary or later uplift, erosion, and cooling is preferred because data from Shelikof well suggests that the mid-Cretaceous unconformity was minor relative to the mid-Tertiary unconformity. Finally, because of the ~12°C warmer past than present bottom-hole temperature, the base of the LCI well is now ~500 m shallower than during maximum burial (12°C/24°C/km geothermal gradient).

Single-grain apatite fission track ages (20–25 Ma) from deep in the Shelikof well approach the age of the overlying mid-Tertiary (Miocene; ~23 Ma) unconformity, suggesting significant and rapid exhumation. This suggests that strongly annealed, once deeply buried strata were uplifted and cooled quickly prior to onlap of the unconformity. The Miocene unconformity, therefore, is interpreted to be the major unconformity in the Shelikof well section. In this scenario the section was buried deepest, and was therefore hottest, until the onset of mid-Tertiary erosion. Approximately 665 m of late Tertiary and Quaternary strata have since been deposited in Shelikof Strait and have reburied the Shelikof section to within ~536 m of its original maximum burial depth. Including modern water depth, the Shelikof well section has experienced ~1 km of burial + submergence since ~25 Ma (832 m section + 166 m water = 998 m). It follows that the depth to the base of the well is now ~290 m shallower than it would have been during maximum burial.

Single-grain apatite fission track ages deep in the Kodiak KSSD1 well are as young as 20–25 Ma and approach the age of overlap of a mid-Miocene regional unconformity (<23 Ma). The deepest Eocene samples were exhumed to within 574 m of the Miocene unconformity surface during Miocene time and were reburied by ~1.7 km of late Tertiary strata. The total section before exhumation was ~5 km; this suggests that Oligocene-age deposits may have existed in the Stevenson Basin. Together with the known Eocene strata, such deposits were exhumed during ~4.4 km of uplift and erosion during a short interval culminating in early to middle Miocene times (>25–23 Ma). Unique and anomalous apatite compositions (high F^-, low Cl^-, moderate OH^-) from the Eocene section could provide a chemical tracer for determining their sediment source along the northeast Pacific rim prior to translation and accretion.

Introduction

This paper summarizes the results of the Thermal History of Tertiary Strata on the Outer Continental Shelf, Northcentral Gulf of Alaska, Using Apatite Fission Track Analysis project. Alaska Division of Geological and Geophysical Surveys Public Data File 95-23 (Murphy and Clough, 1995) provides sample details, data, summary plots, and detailed explanations of conclusions that can only be summarized here. The project was conducted by the Alaska Division of Geological and Geophysical Surveys (ADGG) in collaboration with the Department of Geology and Geophysics, University of Wyoming. It was funded by the U.S. Department of the Interior, Minerals Management Service and administered through The University of Texas at Austin, Bureau of Economic Geology in a cooperative agreement with ADGGS (Cooperative Agreement Number 14-35-0001-30731).

This paper is aimed at using apatite fission track data, vitrinite reflectance data, and past and present geothermal gradients to produce time-depth/temperature plots and burial/exhumation history plots that help answer when maximum burial/heating occurred, when inversion/cooling occurred, and what thickness of missing strata was present before uplift, erosion, and exhumation above unconformities in each of three wells. Details of fission track dating will not be discussed here. See, among others, Gleadow and Duddy (1981), Gleadow (1984), Naeser (1979), Green and others (1986, 1989), and Laslett and others (1987). Regional implications outside the basins are beyond the scope of this paper and are not presented here.

Regional Geologic Setting

The southern Alaska continental margin contains many tectonic elements of a convergent plate margin; however, it is complicated by the superposition of a young arc-trench system (Cenozoic-Aleutian arc and Prince William terrane; fig. 1) on older arc-trench system(s) (Mesozoic-Peninsular and Chugach terranes). The younger Aleutian volcanic arc, since about 55 Ma, has resulted from partial melting of northward-subducting oceanic lithosphere of the Pacific Plate beneath, within, and on top of (A) “trapped” oceanic lithosphere west of the Alaska Peninsula, and (B) amalgamated Mesozoic arc rocks and accreted terranes of the North American Plate east of, and including, the Alaska Peninsula (Plafker and Berg, 1994, and references therein).

This study concerns the thermal history of sedimentary basins in the eastern part of the system from Lower Cook Inlet to the continental shelf offshore of Kodiak Island (fig. 1). The area consists of Cenozoic trench-slope basins underlying Kodiak Shelf and a Mesozoic-Cenozoic forearc basin beneath Shelikof Strait that extends northeastward beneath Cook Inlet (Cook Inlet Basin; Fisher and Magoon, 1978).

The strata underlying Lower Cook Inlet and Shelikof Strait are laterally persistent and are part of greater Cook Inlet Basin; on the basis of seismic data all pre-Pleistocene unconformities are present (figs. 2–7; Magoon, 1986a). Pleistocene sequences are also separated by unconformities (for example, Horizons A and A′—Turner, 1987, and references therein). Accretionary basement on the Kodiak Shelf, at >1.8-km depth, is Eocene in age (Plafker and others, 1994), whereas strata of this age in the forearc basin form only a thin veneer (<400 m; Magoon, 1986a).

Fission Track Dating of Stratigraphic Test Wells

None of the stratigraphic test wells drilled in southern Alaska have penetrated strata that has been deep enough or hot enough for generating petroleum *in situ* or reducing apatite fission track ages (~105°C). Both the maximum estimated paleotemperatures (from vitrinite reflectance [VR] data) and modern bottom-hole temperatures indicate that the temperature in any well has never exceeded ~105°C. Since fission tracks are only partially annealed in the temperature range of ~50–120°C (the partial annealing zone of apatite, or PAZ), *none of the calculated mean or pooled fission track ages reported here directly represent actual times of geologic heating or cooling events in the wells studied.* The apatite fission track data summarized here reflect sediment source area ages (provenance age; shallow samples <50°C) or are partially reset and therefore younger than source area ages (deeper samples >50°C; figs. 2–4).

The southern continental margin of Alaska was largely explored for petroleum during the 1970’s and early 1980’s, and only the LCI well had been previously studied using fission track dating (ADGGS-GMC, 1992, Geotrack, 9 Ap). Onshore fission track thermal history studies have yielded 27 apatite (Ap) ages and 29 zircon (Zr) ages (for example, Clendenen, 1991, 17 Ap, 13 Zr; Kveton, 1989, 3 Ap, 16 Zr; Little and Naeser, 1989, 2 Ap; Hawley and others, 1984, 2 Ap; ADGGS-GMC Report, 1994, 3 Ap, 3 Zr).

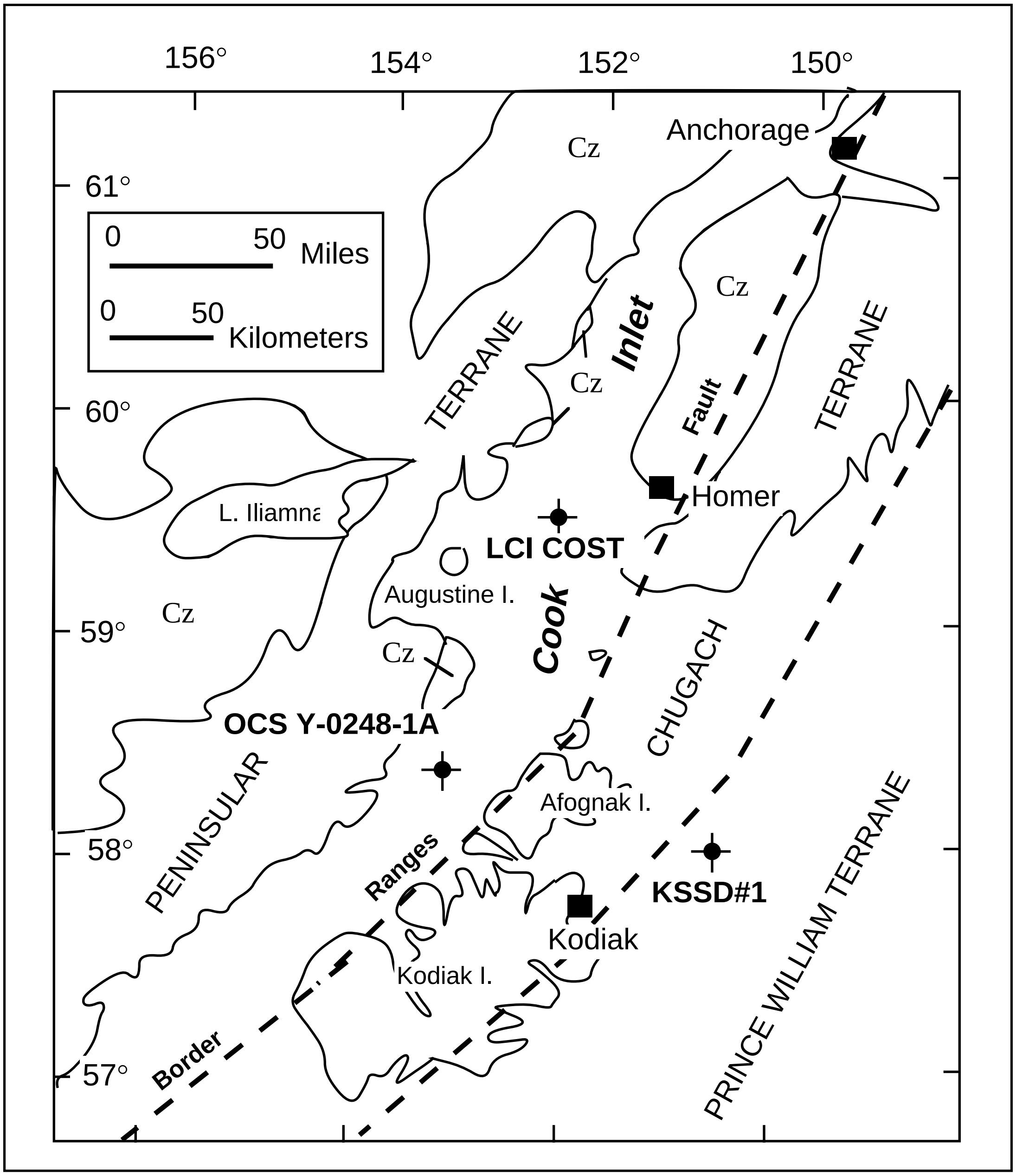


Figure 1. Regional map of southern Alaska showing locations of three wells.

Atlantic Richfield Company Lower Cook Inlet COST #1 (LCI COST)

The Atlantic Richfield Company (ARCO) Lower Cook Inlet COST #1 well (LCI well) was drilled in 65.2 m (214 ft.) of water in the southern part of Cook Inlet to a total depth of 3,775.6 m (12,387 ft). The Mesozoic and Tertiary stratigraphy is described in Magoon (1986a) and references therein (figs. 2 and 3). Four rock units are separated by unconformities: (1) Upper Jurassic deep marine siltstone and sandstone turbidites (2112.3 to T.D.@ 3775.6 m; >1663.3 m thick; Naknek Fm., Oxfordian-Tithonian), (2) Lower Cretaceous deep marine shale and sandstone turbidites with *Inoceramus* sp. fragments (1540.8 to 2112.3 m; 571.5 m thick; Herendeen Limestone, Valanginian(?)/ Hauterivian-Barremian), (3) Upper Cretaceous deep-to-shallow marine shale, silt, sandstone and minor coal (832.1 to 1540.8 m; 708.7 m thick; Kaguyak Fm., Maestrichtian), and (4) Lower Tertiary shallow marine

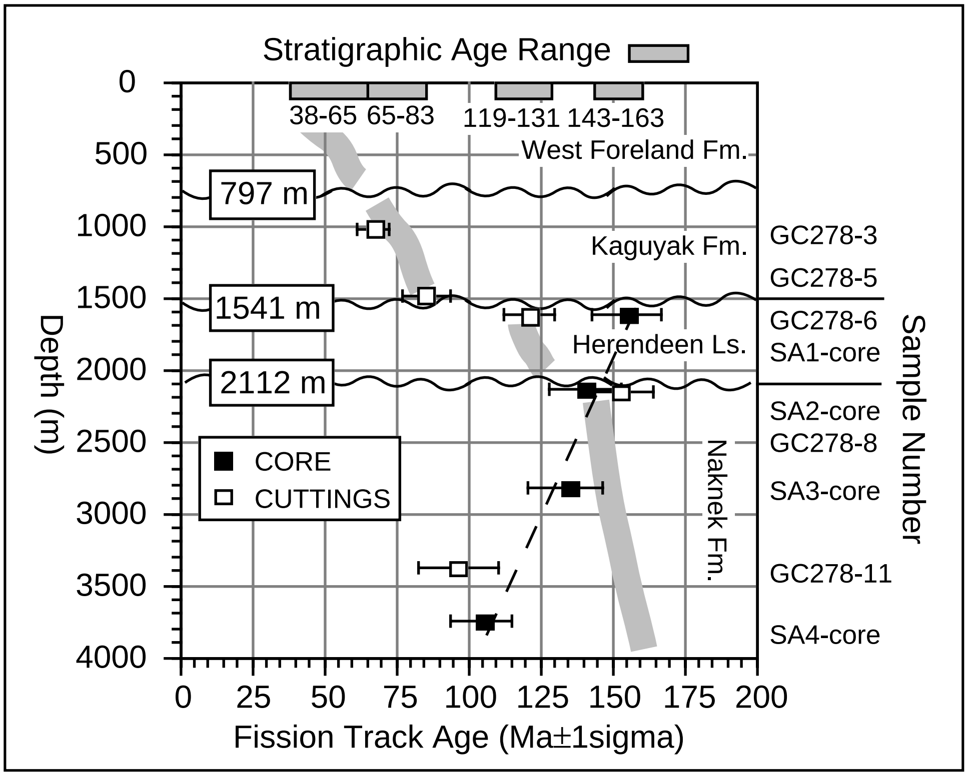


Figure 2. Plot of depth versus apatite fission track age of samples from the Lower Cook Inlet COST #1 well. Five samples are from unwashed cuttings composited from 30-ft intervals over ~500 ft (152 m) of section above and below the sample point plotted. Four samples are from sandstone cores 1 through 4.

to continental sandstone, conglomerate and minor coal (<413.3 to 797.1 m; 383 m thick; West Foreland Fm., Paleocene-Eocene).

The modern geothermal gradient in LCI well is ~22.8 C/km (Magoon, 1986b), so rocks deeper than ~4 km are now near the top of the oil window (>100°C). The formation temperature at the bottom of the well is 92.4°C (at 3775 m). The maximum vitrinite values of ~0.65 R_o near the base of the well yield a maximum predicted paleotemperature of ~105°C for a 10-m.y. heating duration (equation 2 of Burnham and Sweeney, 1989). It follows that the base may have been 12.5°C hotter in the past; either the section was once more deeply buried or the geothermal gradient in the area has diminished over time.

Two scenarios are presented in figures 3A and 3B to infer the post-Late Jurassic burial/thermal history of the LCI well. The ages of partially annealed outcrop samples from Lower Cook Inlet suggest that the region cooled either between ~100 and 75 Ma (fig. 4A) or sometime thereafter (fig. 3B). Figure 3A shows a scenario for maximum heating followed by cooling in Late Cretaceous times, and figure 3B shows one possibility for cooling during mid-Tertiary times. Which scenario is better on the basis of thermal data from this well alone is uncertain, but mid-Tertiary or later cooling is preferred (fig. 3B) because data from the Shelikof well suggest that erosion at the mid-Cretaceous unconformity, although perhaps longer duration, was minor relative to erosion at the mid-Tertiary unconformity. Finally, the estimated difference of ~12°C in past and present temperatures suggests that the base of the well may be ~500 m shallower now than at maximum burial (12°C/24°C/km).

Chevron OCS-Y-0248 #1A (Shelikof well)

The Chevron OCS-Y-0248-1A well (Shelikof well), in Shelikof Strait between the Alaska Peninsula and Kodiak Island, was completed in 166 m (546 ft) of water to a total depth of 3,088 m (10,130 ft; Feb. 1985). The depth to seafloor is 636 ft, and the section penetrated was 2894 m (9,494 ft; K.B. = 90 ft). The stratigraphy in the Shelikof well (figs. 4 and 5) consists mainly of Late Cretaceous shelfal to deep marine strata

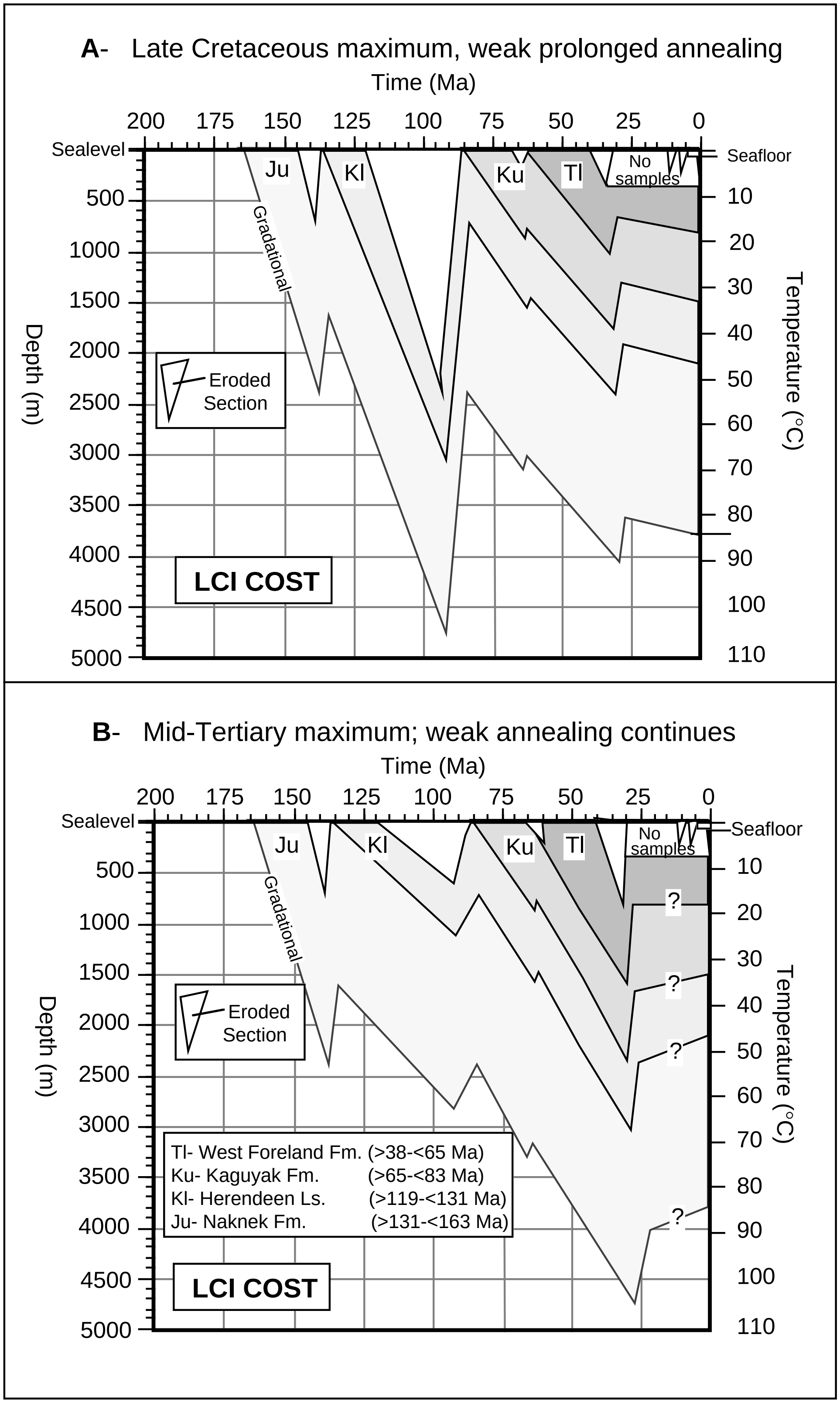


Figure 3. Schematic time-temperature/depth plots for Lower Cook Inlet COST #1 well. (A) Late Cretaceous maximum heating (~105°C) then complex, prolonged low-temperature annealing. (B) Mid-Tertiary maximum heating followed by weak, continuous annealing. There are no stratigraphic constraints after early Tertiary times. All contacts are unconformities.

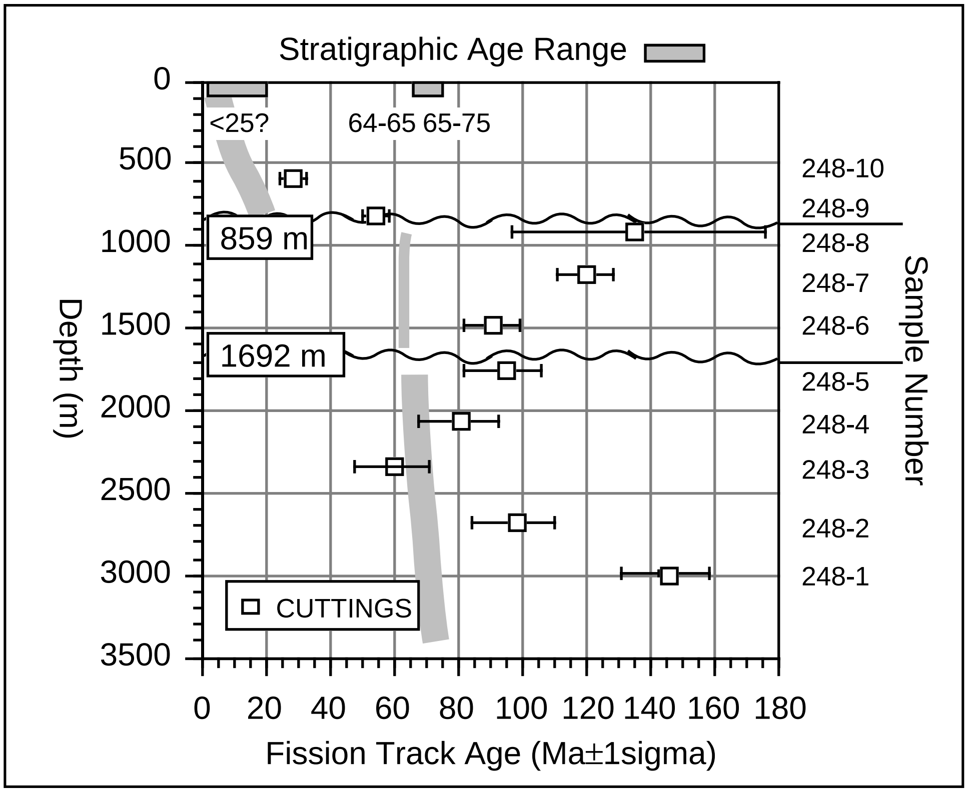


Figure 4. Plot of depth versus apatite fission track age of samples from the Shelikof well (Chevron OCS-Y-0248-#1A). All samples are from unwashed cuttings composited from 30-ft intervals over ~500 ft (152 m) of section above and below the sample point plotted.

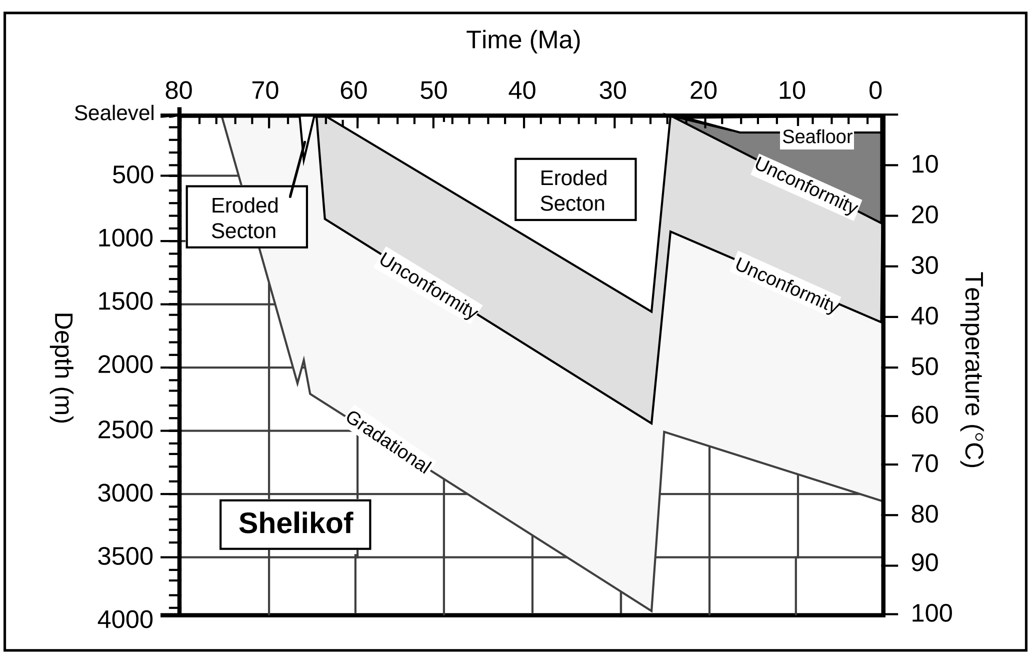


Figure 5. Schematic time-temperature/depth plots for Shelikof well (Chevron OCS-Y-0248-#1A) showing mid-Tertiary maximum heating (~100°C), rapid cooling, then poorly constrained weak annealing. All contacts are unconformities.

including (1) Middle Campanian marine claystone (average 80 percent) with minor siltstone, sandstone, and tuff (2734 to T.D.@ 3088 m; 353 m thick), (2) Late Campanian claystone (60–90 percent) with interbedded sandstone and siltstone (1,692 to 2,679 m; 987 m thick), (3) Early Maestrichtian to Late Campanian claystone (853 to 1,692 m; 839 m thick), unconformably overlain by (4) inner neritic to nonmarine, Tertiary sandstone and conglomerate (Eocene[?] and younger; <549–853 m; ~832 m thick) (R. Turner, 1990, personal communication cited in Clendenen, 1991).

The geothermal gradient in the Shelikof well, although not well known, is estimated from a measured 108°F (42.2°C) formation temperature at a depth of 1,367 m (4,484 ft), which, after subtracting a ~5°C water temperature, yields a geothermal gradient of ~27°C/km (37.2°C/1.37 km = 27.1°C/km). Using this number yields a modern bottom-hole temperature of ~79°C (27°C/km * 2.89 km = 78.6°C). A regional estimate of the geothermal gradient of 24±2°C/km for all of Lower Cook Inlet (Bergman, 1995, personal communication to J. Murphy) yields a lower bottom-hole temperature of ~69±6°C, which is used to produce time-temperature and burial history plots.

Vitrinite reflectance values in the Shelikof well decrease upward from 0.59 (100°C) near the base to 0.48 (85°C) at about 1,000 m, then increase sporadically to more than 0.69 above a mid-Tertiary unconformity at about 860 m (Chevron unpublished data). The sporadic values in the Tertiary section must be from recycling of metasedimentary clasts and organics. In the deeper Cretaceous section then, maximum converted paleotemperatures range from 100 to 85°C from base to top. Comparison of modern with maximum paleotemperatures results in a difference of perhaps 31°C (past>present), corresponding to about 1,290 m of erosion (~24°C/km gradient). The maximum burial depth of the base of the well, therefore, was ~4.2 km (2.89 + 1.29 = 4.18). Because there are two unconformities in the section the question is which, or if both, were accompanied by rapid and large amounts of erosion.

The inferred post-Campanian burial/thermal history of the Shelikof well is summarized in figure 5. Because single-grain ages deep in the well approach the age of the mid-Tertiary unconformity (Miocene; ~23 Ma overlap), it is interpreted to be the major unconformity in the Shelikof well section. In this scenario the Shelikof section was buried deepest, and was therefore hottest, until the onset of mid-Tertiary erosion. The Late Cretaceous unconformity is minor in comparison (stratigraphy supports this). The ~665 m of late Tertiary and Quaternary strata deposited in Shelikof Strait has reburied the section to within ~536 m of its original maximum depth. It has also been submerged beneath 166 m of water; therefore, the Shelikof well section has experienced a total of ~1 km of submergence since ~25 Ma (832 m section + 166 m water = 998 m). It follows that the base of the well is only ~290 m shallower now than it was during maximum burial.

Kodiak COST KSSD #1 OCS 77-1 (Kodiak Shelf)

The Kodiak COST KSSD #1 OCS 77-1 well (KSSD1 well), completed in July 1977 at a total depth of 2,596 m (8,517 ft; 2,436 m subseafloor), was completed in 160 m (526 ft) of water into the western flank of the Stevenson Basin on the southern Alaska offshore continental shelf (~100 km east of Kodiak, Alaska; fig. 1).

The KSSD section consists of two marine sequences separated by a Miocene angular unconformity (figs. 6 and 7) and a third sequence of glacial deposits (not shown) that mark the seaward limit of Pleistocene glacial ice advance (Turner, 1987). The older two sequences are of concern: (1) deformed Eocene(?) marine clastic sediments comprising basement (>2,596 to 1,872 m; >724 m thick), and (2) unconformably overlying Miocene(?) to Quaternary turbiditic marine mudstone, siltstone, sandstone, and minor conglomerate (1,872 to 610 m; ~1,262 m thick). The Miocene angular unconformity at 1,872 m extends regionally and has been variously named the Miocene unconformity (von Huenne and others, 1980) and the Horizon C unconformity (Hoose, 1987). We use the term Miocene unconformity.

The modern geothermal gradient in the KSSD1 well is 18.8°C/km (1.03°F/100 ft), and the bottom-hole temperature is calculated as ~46 °C (Flett, 1987b). Vitrinite reflectance values at the base of the well (Ro = 0.56) convert to paleotemperatures of ~95°C, suggesting that the base was possibly 49°C warmer during maximum heating relative to now. If the geothermal gradient has not changed, which we will assume because too few vitrinite values are available for regression (n = 4; Johnsson and others, 1992) and there is strong potential for reworked high-temperature material in the vitrinite samples (Flett, 1987a), then the Eocene section, prior to cooling, was buried ~2.6 km deeper than now (49°C/18.8°C/km = 2.60 km). The Miocene unconformity is the only major unconformity in the section, so cooling accompanied erosion during the hiatus of ~35–23 Ma.

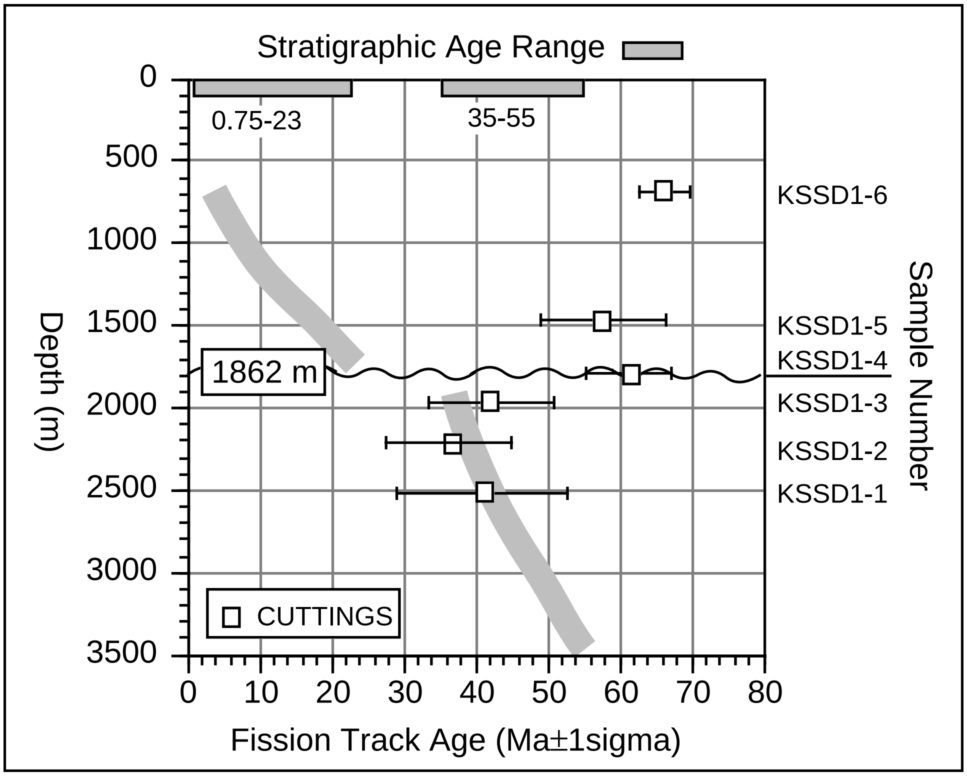


Figure 6. Plot of depth versus apatite fission track age of samples from the KSSD1 well (Stevenson Basin). All samples are from unwashed cuttings composited from 30-ft intervals over ~500 ft (152 m) of section above and below the sample point plotted.

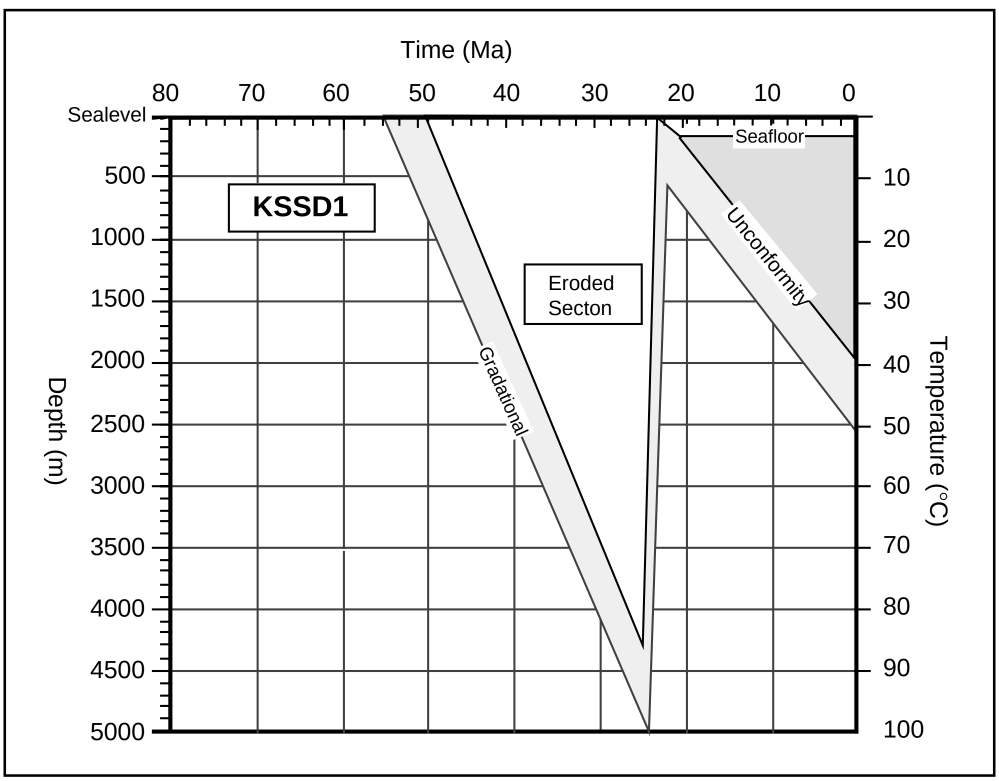


Figure 7. Schematic time-temperature/depth plots for KSSD1 well (Stevenson Basin) showing mid-Tertiary maximum heating (~100°C), rapid cooling, then poorly constrained weak annealing. All contacts are unconformities.

The inferred post-Eocene burial/thermal history of the KSSD1 well is summarized in figure 7. The deepest Eocene deposits sampled in the well were exhumed to within 574 m of the Miocene unconformity "surface" and have since been reburied by ~1.7 km of late Tertiary strata. The fission track evidence suggests that the total section prior to exhumation was ~5 km. This suggests that Oligocene-age deposits may once have been deposited in the Stevenson Basin and, along with known Eocene deposits, where exhumed during ~4.4 km of uplift and erosion during a short interval in early to middle Miocene times (>25–23 Ma).

Unique and anomalous apatite compositions from the Eocene section could provide a chemical tracer for determining the source of sediments along the northeast Pacific rim (Murphy and Clough, 1995). These grains have exceptionally low chlorine values (0–0.4 weight percent Cl^-), relatively high hydroxyl values (0–1.39 weight percent OH^-), and very high fluorine values (1.08–3.83 weight percent F^-). The theoretical maximum amount of Cl^- in a pure chlorapatite is 6.9 weight percent, 2.5 weight percent OH^- in pure hydroxyapatite, and 3.75 weight percent F^- in pure fluorapatite.

Acknowledgments

We thank Mark S. Robinson (ADGGS-retired) for originally pursuing the project; Steven Bergman (ARCO) for mounts of LCI well core samples, KSSD1 microprobe analyses, and regional insight; John Reeder (ADGGS-GMC) for KSSD1 well cuttings and original grain mounts of Geotrack International—who also provided irradiation details; Holly Fuller, Ed Donovan, and Rick Chamberlain (Chevron U.S.A. Inc.) for Chevron OCS Y-0248 #1A well cuttings and unpublished data; Mark Myers and Tim Ryherd (ADGGS-Oil and Gas) for valuable public data and insight. Chris Rickard, Roger Wilmot, and James R. Steidtmann (University of Wyoming) and Paula Kauth (ADGGS) helped the research to proceed. Rocky Reifenstuhl reviewed the original manuscript.

References

ADGGS-GMC, 1994, Data resulting from U.S. Minerals Management Service 1993 geologic field program in Lower Cook Inlet, Alaska: Alaska Division of Geol. and Geophys. Surveys Geologic Material Center Data Report No. 233, 182 p.

ADGGS-GMC, 1992, Basic data for apatite fission track analysis of cuttings (413-12,375 ft.) from the Atlantic Richfield Lower Cook Inlet COST Well No. 1: Alaska Division of Geol. and Geophys. Surveys Geologic Material Center Data Report No. 180, 12 p.

Burnham, A. K., and Sweeney, J. J., 1989, A chemical kinetic model of vitrinite maturation and reflectance: Geochimica et Cosmochimica Acta, v. 53, p. 2649–2657.

Clendenen, W. S., 1991, Thermal history and vertical tectonics of the southern Alaska convergent margin: Brown University, Ph.D. dissertation, 177 p.

Fisher, M. A., and Magoon, L. B., 1978, Geologic framework of Lower Cook Inlet, Alaska: Amer. Assoc. of Petrol. Geol. Bull. v. 62, p. 373–402.

Flett, T. O., 1987a, Organic geochemistry (of KSSD1 well), *in* Turner, R. F., ed., Geological and operational summary, Kodiak Shelf Stratigraphic Test Wells, Alaska: Minerals Management Service OCS Report MMS 87-0109, p. 193–224.

Flett, T. O., 1987b, Geothermal gradient (of KSSD1 well), *in* Turner, R. F., ed., Geological and operational summary, Kodiak Shelf Stratigraphic Test Wells, Alaska: Minerals Management Service OCS Report MMS 87-0109, p. 225–228.

Gleadow, A. J. W., 1984, Fission track dating methods II—a manual of principles and techniques: Workshop on fission track analysis: principles and applications: James Cook University, Townsville, Australia 4-6 September, 35 p.

Gleadow, A. J. W. and Duddy, I. R., 1981, A natural long-term annealing experiment for apatite: Nuclear Tracks and Radiation Measurements, v. 5, p. 169–174.

Green, P. F., Duddy, I. R., Gleadow, A. J. W., and Lovering, J. F., 1989, Apatite fission track analysis as a palaeo-temperature indicator for hydrocarbon exploration: *in* Naeser, N.D., and McCulloh, T.H., (eds.), Thermal histories of sedimentary basins: Methods and case histories: Springer-Verlag, New York, p. 181–195.

Green, P. F., Duddy, I. R., Gleadow, A. J. W., Tingate, P. R. and Laslett, G. M., 1986, Thermal annealing of fission tracks in apatite—1: a qualitative description: Chemical Geology (Isotope Geoscience Section), v. 59, p. 237–253.

Hawley, B. W., Bruhn, R. L., and Evans, E. H., 1984, Vertical tectonics in a fore arc region: southern Alaska, using fission track dating of apatite grains and flexural beam modeling: Geol. Soc. Amer. Abstracts with Programs, v. 16, p. 533.

Hoose, P. J., 1987, Seismic stratigraphy and tectonic evolution of the Kodiak shelf, *in* Turner, R. F., ed., Geological and operational summary, Kodiak Shelf Stratigraphic Test Wells, Alaska: Minerals Management Service OCS Report MMS 87-0109, p. 71–102.

Johnsson, M. J., Pawlewicz, M. J., Harris, A. G., and Valin, Z. C., 1992, Vitrinite reflectance and conodont color alteration index data from Alaska: data to accompany the thermal maturity map of Alaska: U.S. Geol. Surv. Open-File Report 92-409, 3 discs.

Kveton, K. J., 1989, Structure, thermochronology, provenance and tectonic history of the Orca Group in southwestern Prince William Sound, Alaska: University of Washington, Ph.D. dissertation, 173 p.

Laslett, G. M., Green, P. F., Duddy, I. R. and Gleadow, A. J. W., 1987: Thermal annealing of fission tracks in apatite—2: a quantitative analysis: Chemical Geology (Isotope Geoscience Section), v. 65, p. 1–13.

Little, T. A., and Naeser, C. W., 1989, Tertiary tectonic history of the Border Ranges Fault system, Chugach Mountains, Alaska: deformation and uplift in a forearc setting: Jour. Geoph. Res., v. 94, p. 4333–4359.

Magoon L. B., 1986a, Stratigraphic units of the COST No. 1 well, *in* Magoon, L. B., ed., Geologic studies of the Lower Cook Inlet COST no. 1 well, Alaska outer continental shelf: U.S. Geol. Surv. Bull. 1956, p. 17–22.

Magoon L. B., 1986b, Present-day geothermal gradient (of COST No. 1 well), *in* Magoon, L. B., ed., Geologic studies of the Lower Cook Inlet COST no. 1 well, Alaska outer continental shelf: U.S. Geol. Surv. Bull. 1956, p. 41–49.

Murphy, J. M., and Clough, J. G., 1995, Low-temperature thermal history of three wells in southern Alaska offshore basins: Lower Cook Inlet, Shelikof Strait and Sevenson Trough: Alaska Division of Geological and Geophysical Surveys Public-Data File 95-23, 77 p.

Naeser, C. W., 1979, Fission track dating and geologic annealing of fission tracks. *in* Jager, E., and Hunziker, J. C., eds., Lectures in isotope geology: New York, Springer Verlag, p. 154–169.

Plafker, G., and Berg, H., 1994, Overview of the geology and tectonic evolution of Alaska. *in* Plafker, G., and Berg, H. C., eds., The geology of Alaska: Geological Society of America Decade of North American Geology Volume G-1, p. 989–1022.

Plafker, G., Moore, J. C., and Winkler, G. R., 1994, Geology of the southern Alaska margin, *in* Plafker, G., and Berg, H. C., eds., The geology of Alaska: Geological Society of America Decade of North American Geology Volume G-1, p. 389–450.

Turner, R. F., 1987, Geological and operational summary, Kodiak Shelf stratigraphic test wells, Western Gulf of Alaska, *in* Turner, R. F., ed., Geological and operational summary, Kodiak Shelf Stratigraphic Test Wells, Alaska: Minerals Management Service OCS Report MMS 87-0109, 7 pls., 341 p.

von Huenne, R., Hampton, M. A., Fisher, M. A., Varchol, D.J., and Cochrane, G. R., 1980, Map showing near-surface geologic structures of Kodiak Shelf, Alaska: U.S. Geol. Surv. Misc. Field Map MF-1200, 1 sheet, scale 1:500,000.

Appendix: Publications Resulting from the Continental Margins Program

Title	Type of work	Date	State
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	Interim Report	1984	Alabama
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	Final Report	1985	Alabama
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	Abstract in Program and Abstracts, First Symposium on Studies Related to Continental Margins	1987	Alabama
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Alabama
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	State Oil and Gas Board of Alabama Oil and Gas Report	1985	Alabama
Upper Jurassic Norphlet petroleum potential on and off Mississippi, Alabama, and Florida	Oil and Gas Journal paper	1986	Alabama
Jurassic petroleum trends in the Eastern Gulf Coastal Plain and Central and Eastern Gulf of Mexico	AAPG Bulletin abstract	1986	Alabama
Integrated geological, geophysical, and geochemical interpretation of Upper Jurassic petroleum trends in the eastern Gulf of Mexico	Gulf Coast Association of Geological Societies Transactions paper	1986	Alabama
Regional geologic framework of the Norphlet Formation of the onshore and offshore Mississippi, Alabama and Florida area	Proceedings, Oceans	1988	Alabama
Regional Jurassic geologic framework of Alabama coastal waters area and adjacent Federal waters area	Marine Geology paper	1989	Alabama
Upper Jurassic Norphlet eolian dune, wadi, and marine petroleum reservoirs	Presentation, American Association of Petroleum Geologists Annual Convention	1985	Alabama
Upper Jurassic Norphlet Formation—New Frontier for hydrocarbon prospecting in the central and eastern Gulf of Mexico regions	Presentation, American Association of Petroleum Geologists Annual Convention	1984	Alabama
Jurassic petroleum trends in the eastern Gulf of Mexico Coastal Plain and central and eastern Gulf of Mexico	Presentation, American Association of Petroleum Geologists Annual Convention	1986	Alabama
Integrated geological, geophysical, and geochemical interpretation of Upper Jurassic petroleum trends in the eastern Gulf of Mexico	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1986	Alabama
Regional geologic framework and petroleum geology of Miocene strata of Alabama coastal waters area and adjacent Federal waters area	Interim Report	1986	Alabama

Appendix (cont.)

Title	Type of work	Date	State
Regional geologic framework and petroleum geology of Miocene strata of Alabama coastal waters area and adjacent Federal waters area	Final Report	1988	Alabama
Regional geologic framework and petroleum geology of Miocene strata of Alabama coastal waters area and adjacent Federal waters area	Abstract in Programs and Abstracts, Second Symposium Studies Related to Continental Margins	1989	Alabama
Regional geologic framework and petroleum geology of Miocene strata of Alabama coastal waters area and adjacent Federal waters area	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Alabama
Regional geological framework and petroleum geology of Miocene sandstones in coastal and offshore Alabama	AAPG Bulletin abstract	1987	Alabama
Middle and upper Miocene natural gas sands in onshore and offshore Alabama	AAPG Bulletin abstract	1988	Alabama
Middle and upper Miocene natural gas sands in onshore and offshore Alabama	Gulf Coast Association of Geological Societies Transactions paper	1988	Alabama
Regional geologic framework and petroleum geology of Miocene strata of Alabama coastal waters area and adjacent Federal waters area	State Oil and Gas Board of Alabama Oil and Gas Report	1988	Alabama
Miocene marine shelf bar and deltaic petroleum reservoirs of coastal Alabama and the Mississippi/Alabama shelf	AAPG Bulletin abstract	1989	Alabama
Regional biostratigraphy and paleoenvironmental history of the Miocene of onshore and offshore Alabama	Gulf Coast Association of Geological Societies Transactions paper	1989	Alabama
Upper Miocene Dauphin natural gas sands in offshore Alabama	Gulf Coast Association of Geological Societies Transactions paper	1997	Alabama
Regional geological framework and petroleum geology of Miocene sandstones in coastal and offshore Alabama	Presentation, American Association of Petroleum Geologists Annual Convention	1987	Alabama
Middle and upper Miocene natural gas sands in onshore and offshore Alabama	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1988	Alabama
Foraminiferal biostratigraphy, paleoenvironmental history and rates of sedimentation within subsurface Miocene of southern Alabama and adjoining State and Federal waters areas	Presentation, American Association of Petroleum Geologists Annual Convention	1989	Alabama
Miocene marine shelf-bar and deltaic petroleum reservoirs of coastal Alabama and the Mississippi/Alabama shelf	Presentation, American Association of Petroleum Geologists Annual Convention	1989	Alabama

Appendix (cont.)

Title	Type of work	Date	State
Regional biostratigraphy and paleoenvironmental history of the Miocene of onshore and offshore Alabama	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1989	Alabama
Upper Miocene Dauphin natural gas sands in offshore Alabama	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1997	Alabama
Norphlet and pre-Norphlet geologic framework of Alabama and Panhandle Florida coastal waters area and adjacent Federal waters area	Final Report	1990	Alabama
Geologic framework of Norphlet and pre-Norphlet strata of the onshore and offshore eastern Gulf of Mexico area	A Summary of Year-Five and Year-Six Activities	1991	Alabama
Norphlet and pre-Norphlet geologic framework of Alabama and Panhandle Florida coastal waters area and adjacent Federal waters area	Geological Survey of Alabama Bulletin	1990	Alabama
Geologic framework of Norphlet and pre-Norphlet strata of the onshore and offshore eastern Gulf of Mexico area	Gulf Coast Association of Geological Societies Transactions paper	1991	Alabama
Salt and basement faulting in the eastern Gulf Coastal Plain: structural development and hydrocarbon accumulation	GSA abstract	1990	Alabama
Geologic framework of Norphlet and pre-Norphlet strata of the onshore and offshore eastern Gulf of Mexico area	AAPG Bulletin abstract	1991	Alabama
Geologic framework of Norphlet and pre-Norphlet strata of the onshore and offshore eastern Gulf of Mexico area	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1991	Alabama
Regional geologic framework and petroleum geology of the Smackover Formation, Alabama coastal waters area and adjacent Federal waters area	Annual Report	1991	Alabama
Regional geologic framework and petroleum geology of the Smackover Formation, Alabama coastal waters area and adjacent Federal waters area	Annual Report	1992	Alabama
Regional geologic framework and petroleum geology of the Smackover Formation of Alabama and Panhandle Florida coastal waters area and adjacent Federal waters area	Final Report	1993	Alabama
Hydrocarbon productivity characteristics of Upper Jurassic Smackover carbonates, eastern Gulf Coastal Plain	AAPG Bulletin abstract	1992	Alabama
Hydrocarbon productivity characteristics of Upper Jurassic Smackover carbonates, eastern Gulf Coastal Plain	Gulf Coast Association of Geological Societies Transactions paper	1992	Alabama
Regional geologic framework and petroleum geology of the Smackover Formation of Alabama and Panhandle Florida coastal waters area and adjacent Federal waters area	Geological Survey of Alabama Bulletin	1993	Alabama

Appendix (cont.)

Title	Type of work	Date	State
Geologic framework of the Jurassic (Oxfordian) Smackover Formation in the Alabama coastal waters area	Gulf Coast Association of Geological Societies Transactions paper	1993	Alabama
Characterization and geologic framework of the Jurassic (Oxfordian) Smackover Formation in the Alabama State coastal waters area	Presentation, American Association of Petroleum Geologists Annual Convention	1993	Alabama
Geologic framework of the Jurassic (Oxfordian) Smackover Formation in the Alabama coastal waters area	Presentation, Gulf Coast Association of Geological Societies Annual Convention	1993	Alabama
Depositional and diagenetic history and petroleum geology of the Jurassic Norphlet Formation of the Alabama coastal waters area and adjacent Federal waters area	Annual Report	1993	Alabama
Depositional and diagenetic history and petroleum geology of the Jurassic Norphlet Formation of the Alabama coastal waters area and adjacent Federal waters area	Final Report	1996	Alabama
Depositional and diagenetic history and petroleum geology of the Jurassic Norphlet Formation of the Alabama coastal waters area and adjacent Federal waters area	A Summary of Year-9 and Year-10 Activities	in progress	Alabama
Depositional and diagenetic history and petroleum geology of the Jurassic Norphlet Formation of the Alabama coastal waters area and adjacent Federal waters area	Geological Survey of Alabama Bulletin	in progress	Alabama
Age revisions of the Nanook Limestone and Katakturuk Dolomite, northeastern Brooks Range, Alaska	Paper in USGS Circular 978	1986	Alaska
Age revision of the Katakturuk Dolomite and Nanook Limestone, northeastern Brooks Range, Alaska	GSA abstract	1986	Alaska
Peritidal sedimentary facies and stromatolites of the Katakturuk Dolomite (Proterozoic), northeastern Alaska	Abstract, 12th International Sedimentological Congress	1986	Alaska
General stratigraphy of the Katakturuk Dolomite in the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1989	Alaska
Timing of uplift/erosion events in the North Slope-Beaufort Sea petroleum basin, Alaska	Abstract in Program and Abstracts, Third Symposium on Studies Related to Continental Margins	1992	Alaska
Bedrock geology of the Sadlerochit and Shublik Mountains and apatite fission track thermal history of Permian to Tertiary sedimentary rocks in the Arctic National Wildlife Refuge, northeastern Alaska	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Alaska
Geology and petroleum potential of Hope and Selawik Basins	Public-Data File	1988	Alaska
Geology and petroleum potential of Hope and Selawik Basins, offshore northwestern Alaska	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Alaska

Appendix (cont.)

Title	Type of work	Date	State
Geology and petroleum potential of Hope and Selawik Basins, offshore northwestern Alaska	Marine Geology paper	1989	Alaska
Low-temperature thermal history of three wells in southern Alaska offshore basins: Lower Cook Inlet, Shelikof Strait, and Stevenson trough	Public-Data File	1995	Alaska
Timing of tectonic events on the North Slope of Alaska by apatite fission track analysis, and a comparison between these tectonic events and the offshore sedimentary record	Public-Data File	1991	Alaska
Preliminary results of 14 apatite fission-track analyses of samples from the Umiat and Colville River region, North Slope, Alaska	Public-Data File	1989	Alaska
Timing of Tertiary tectonic events affecting the North Slope foreland basin, Alaska	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Alaska
Kemik Sandstone—petrology, physical properties, and facies of 40 outcrop and subsurface samples, Canning River to Sagavanirktok River, northeast North Slope, Alaska	Map	1994	Alaska
Kemik Sandstone: an environmental of deposition interpretation from a Canning River section, North Slope, Alaska	Abstract, International Conference on Arctic Margins	1992	Alaska
Bedrock geology of part of the Mt. Michelson B-4 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Bedrock geology of part of the Mt. Michelson B-3 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Bedrock geology of the Mt. Michelson C-2 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Bedrock geology of the Mt. Michelson C-1 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Bedrock geology of part of the Mt. Michelson B-2 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Bedrock geology of the Mt. Michelson C-3 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Geology of the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, northeastern Alaska	Professional Report	1989	Alaska
Bedrock geology of the Mt. Michelson C-4 Quadrangle, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1987	Alaska
Geology of the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1991	Alaska
Arctic National Wildlife Refuge, northeastern Alaska, preliminary bedrock geologic map of part of the Mt. Michelson C-3 Quadrangle, Sadlerochit Mountains, northeastern Alaska	Public-Data File	1986	Alaska

Appendix (cont.)

Title	Type of work	Date	State
Colville River geologic transect: vitrinite reflectance, palynology, TAI, and fission track data, central North Slope, Alaska	Public-Data File	1990	Alaska
Preliminary bedrock geologic map of part of the Mt. Michelson C-4 quadrangle, Sadlerochit Mountains, northeastern Alaska	Public-Data File	1986	Alaska
Arctic National Wildlife Refuge, northeastern Alaska, preliminary bedrock geologic map of part of the Mt. Michelson C-2 Quadrangle, Sadlerochit Mountains, northeastern Alaska	Public-Data File	1986	Alaska
Chronologic variations along the contact between the Echooka Formation and the Lisburne Group in the northeastern Brooks Range, Alaska	Public-Data File	1992	Alaska
Microfossil compilation of Mesozoic and Cenozoic units, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1986	Alaska
Arctic National Wildlife Refuge, northeastern Alaska: volume magnetic susceptibility data from the Arctic National Wildlife Refuge (ANWR), Alaska	Public-Data File	1987	Alaska
The Mt. Copleston Limestone, a new Lower Devonian formation in the Shublik Mountains, northeastern Brooks Range, Alaska	Paper in USGS Bulletin 1999	1992	Alaska
Late Ordovician brachiopod and gastropod paleobiogeography of Arctic Alaska and Chukotka	Abstract, International Conference on Arctic Margins	1992	Alaska
Arctic National Wildlife Refuge, northeastern Alaska: stratigraphy of the Lisburne Group, eastern Sadlerochit Mountains, northeastern Alaska	Public-Data File	1986	Alaska
Selected examples of Proterozoic to Devonian carbonates of ANWR, Holitna Basin and Kandik Basin, Alaska	Paper in Short Course	1988	Alaska
XBED, a spreadsheet template for the rotation of paleocurrent measurements using Quattro Pro	Public-Data File	1991	Alaska
Porosity, permeability and grain density analyses of twenty Katakturuk Dolomite outcrop samples, northeastern Brooks Range, Alaska	Public-Data File	1995	Alaska
Measured stratigraphic section of the Lisburne Group Limestone (85LSB), western Sadlerochit Mountains, Mt. Michelson C-3 Quadrangle, Alaska	Public-Data File	1986	Alaska
Depositional environments of the Katakturuk Dolomite (Proterozoic) and the Nanook Limestone (Proterozoic to Devonian), Arctic National Wildlife Refuge, Alaska	AAPG Bulletin abstract	1988	Alaska
Third-order vertical variations in parasequence character of the lower gray craggy member, Katakturuk Dolomite (Proterozoic), northeastern Brooks Range, Alaska	AAPG abstract	1992	Alaska
Deposition on a late Proterozoic carbonate ramp, Katakturuk Dolomite, northeast Brooks Range, Alaska	GSA abstract	1995	Alaska

Appendix (cont.)

Title	Type of work	Date	State
Precambrian carbonate platform sedimentation of the Katakturuk Dolomite (Proterozoic), Sadlerochit and Shublik Mountains, northeastern Brooks Range, Alaska	GSA abstract	1987	Alaska
Paleokarst-dominated stratigraphy of the Katakturuk Dolomite (Proterozoic), northeastern Brooks Range, Alaska	Abstract, International Conference on Arctic Margins	1992	Alaska
Paleokarst in the Katakturuk Dolomite (Proterozoic), northeastern Brooks Range, Alaska	Paper in Proceedings, 1992 International Conference	1994	Alaska
Geology and age of Franklinian and older rocks in the Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge, Alaska	Abstract, Geological Association of Canada and Mineralogical Association of Canada	1990	Alaska
Surficial geology of the Mt. Michelson C-1 Quadrangle, northeastern Alaska	Report of Investigations	1988	Alaska
Preliminary detailed stratigraphic sections of the carboniferous Lisburne Group, central Shublik to the northern Franklin Mountains, northeastern Alaska	Public-Data File	1988	Alaska
Twenty measured sections of Permian Echooka Formation, northeastern Brooks Range, Alaska	Public-Data File	1986	Alaska
Eighteen measured sections of the lower Triassic Ivishak Formation in the Sadlerochit Mountains, northeastern Alaska	Public-Data File	1987	Alaska
Arctic National Wildlife Refuge, northeastern Alaska: preliminary detailed stratigraphic sections and bedrock maps of the Lisburne Group, Mt. Michelson C-3 and C-4 Quadrangles, western Sadlerochit Mountains and northwest Shublik Mountains, NW AK	Public-Data File	1986	Alaska
Generalized geologic map of the Arctic National Wildlife Refuge, northeastern Brooks Range, Alaska	Special Report	1994	Alaska
Compilation of megafossils of Mesozoic and Cenozoic units, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1986	Alaska
Thirty-seven measured sections of lower Cretaceous Kemik sandstone, northeastern Alaska	Public-Data File	1986	Alaska
Arctic National Wildlife Refuge, northeastern Alaska: structural evolution of the eastern Sadlerochit Mountains, northeastern Brooks Range, Alaska	Public-Data File	1986	Alaska
Geometry and deformation of a duplex and its roof layer: observations from the Echooka Anticlinorium, northeastern Brooks Range, Alaska	Paper in Professional Report	1995	Alaska
Kemik Sandstone, Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1986	Alaska
Organic-rich shale and bentonite in the Arctic Creek unit, Arctic National Wildlife Refuge: implications for stratigraphic and structural interpretations	Paper in Professional Report	1993	Alaska

Appendix (cont.)

Title	Type of work	Date	State
Preliminary results of 42 apatite fission-track analyses of rock samples from Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1988	Alaska
Apatite fission-track study of the thermal history of Permian to Tertiary sedimentary rocks in the Arctic National Wildlife Refuge, northeastern Alaska	Public-Data File	1988	Alaska
Thermal history of Mississippian to Tertiary sedimentary rocks on the North Slope, Alaska: using fission-track analysis	Public-Data File	1989	Alaska
Results of nine apatite fission track analyses of samples from outcrop localities in Ignek Valley and along the Sadlerochit River, Arctic National Wildlife Refuge, Alaska	Public-Data File	1990	Alaska
Preliminary results of 25 apatite fission track analyses of samples from five wells on the North Slope of Alaska	Public-Data File	1990	Alaska
Biostratigraphic report of 12 Cretaceous to Jurassic age outcrop samples from the Sagavanirktok, Mt. Michelson, and Chandler Lake Quadrangles, North Slope, Alaska	Public-Data File	1991	Alaska
Lithofacies, petrology, and petrophysics of the Kemik Sandstone (lower Cretaceous), eastern Arctic Slope, Alaska	Paper in Professional Report	1995	Alaska
Micropaleontology of 38 outcrop samples from the Chandler Lake, Demarcation Point, Mt. Michelson, Philip Smith Mountains, and Sagavanirktok Quadrangles, northeast Alaska	Public-Data File	1993	Alaska
Kerogen microscopy of coal and shales from the North Slope of Alaska	Public-Data File	1989	Alaska
Stratigraphic and structural framework of Ellesmerian and older sequences in Sadlerochit and Shublik Mountains, Arctic National Wildlife Refuge (ANWR), northeastern Alaska	AAPG Bulletin abstract	1988	Alaska
Detailed bedrock geologic mapping of the Sadlerochit and part of the Shublik Mountains, Arctic National Wildlife Refuge, northeastern Brooks Range, Alaska	GSA abstract	1987	Alaska
Preliminary bedrock geologic map of the northern central Shublik Mountains and Ignek Valley, northeastern Alaska	Public-Data File	1986	Alaska
Structural evolution of the central Shublik Mountains and Ignek Valley, Arctic National Wildlife Refuge, northeastern Brooks Range, Alaska	Public-Data File	1989	Alaska
Preliminary bedrock geologic map of the western Shublik Mountains, Arctic National Wildlife Refuge, northeastern Brooks Range, Alaska	Public-Data File	1988	Alaska
Turbidite depositional environments of the upper Cretaceous to Tertiary Canning Formation, Arctic National Wildlife Refuge (ANWR), Alaska	Public-Data File	1986	Alaska
Carboniferous Lisburne Group of the Arctic National Wildlife Refuge, Brooks Range, northeastern Alaska	Public-Data File	1989	Alaska
Structure contour map of pre-Mesozoic basement, landward margin of Baltimore Canyon trough	Miscellaneous Map Series	1984	Delaware

Appendix (cont.)

Title	Type of work	Date	State
Geologic framework for the development of the U.S. mid-Atlantic continental margin	GSA Abstract	1984	Delaware
Inner margin of Baltimore Canyon trough: future exploration play	AAPG Bulletin abstract	1984	Delaware
Seismic stratigraphy along three multichannel seismic reflection profiles off Delaware's coast	Miscellaneous Map Series	1986	Delaware
Early Mesozoic rift basins and the development of the United States middle Atlantic continental margin, *in* Triassic-Jurassic rifting	Paper	1988	Delaware
Seismic reflection profile across southern Delaware and eastern shore Maryland: basement thrusts, synrift rocks, postrift faults	GSA abstract	1988	Delaware
Geologic framework of the offshore region adjacent to Delaware	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Delaware
Geologic framework of the offshore region adjacent to Delaware	Marine Geology paper	1989	Delaware
Oligocene rocks in the subsurface of Delaware	GSA abstract	1989	Delaware
Geologic structures of the Appalachian orogen, Mesozoic rift basins, and faulted coastal plain rocks revealed by new Vibroseis and drill-hole data, southern Delaware and adjacent Maryland	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Delaware
Geologic and hydrologic studies of the Oligocene-Pleistocene section near Lewes, Delaware	Report of Investigations	1990	Delaware
Buried Mesozoic rift basins of the U.S. middle Atlantic continental margin	AAPG Bulletin abstract	1991	Delaware
Exploration for oil and gas in a frontier area: the United States middle Atlantic continental margin	Paper in Augustana College Library Publication	1992	Delaware
Map of exposed and buried early Mesozoic rift basins/synrift rocks of the U.S. middle Atlantic continental margin	Miscellaneous Map Series	1992	Delaware
Mesozoic rift basins of the U.S. middle Atlantic continental margin	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Delaware
Mid-Oligocene unconformity and faulting in the Atlantic Coastal Plain of Delaware correlated with uplift history of the Appalachian-Labrador and Bermuda rises	GSA abstract	1994	Delaware
Palynological, foraminiferal, and aminostratigraphic studies of Quaternary sediments from the U.S. middle Atlantic upper continental slope, continental shelf, and coastal plain	Quaternary Science Reviews paper	1995	Delaware
Centennial Continent/Ocean Transect #19, E-3 Southwestern Pennsylvania to Baltimore Canyon Trough	GSA pamphlet	1995	Delaware
Chronology of early Mesozoic rift basins, continental flood basalts, seaward-dipping reflectors, and postrift sedimentary rocks of the North American Atlantic continental margin	GSA abstract	1997	Delaware

Appendix (cont.)

Title	Type of work	Date	State
Cross section of the Quaternary deposits along the Atlantic coast of Delaware	Miscellaneous Map Series		Delaware
Heavy mineral reconnaissance off the coast of the Apalachicola River Delta	Report	1986	Florida
Sand gravel and heavy mineral resources potential of surficial sediments offshore of Cape Canaveral, Florida	Report	1990	Florida
Sand gravel and heavy-mineral resource potential of Holocene sediments offshore of Florida, Cape Canaveral to the Georgia border	Report	1991	Florida
Metal analysis in sediments of the Steinhatchee River Estuary, North-Central Florida	GSA abstract	1995	Florida
Cation exchange capacity and normalization of trace metal concentrations in sediments of the Steinhatchee River Estuary, North Florida	GSA abstract	1997	Florida
Baseline investigation of estuarine sediment metals for the Steinhatchee River area of the Florida Big Bend	Environmental Geoscience	1997	Florida
Baseline sediment trace-metals investigation: Steinhatchee River Estuary, Florida Northeast Gulf of Mexico	Paper	1997	Florida
Interpretation of the seismic stratigraphy of the phosphatic middle Miocene on the Georgia Continental Shelf	Geologic Atlas	1986	Georgia
Seismic investigation of the Tybee Trough area; Georgia/South Carolina	Southeastern Geology paper	1987	Georgia
Seismic investigation of the phosphate-bearing, Miocene-age strata of the Continental Shelf of Georgia	Georgia Geologic Survey Bulletin	1987	Georgia
Mineral resource assessments for the Continental Shelf of Georgia as a part of the Continental Margins Study Program	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Georgia
Mineral resource assessments for the Continental Shelf of Georgia as part of the Continental Margins Studies Program: seismic interpretation of the phosphatic Miocene-age Hawthorne Group	Marine Geology paper	1989	Georgia
Heavy-mineral-bearing sands of coastal Georgia	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Georgia
Evaluation of heavy mineral-bearing nearshore sand, Altamaha Sound, and the adjacent nearshore, Georgia	Open-File Report	1991	Georgia
Report on the status of the Georgia Coastal Geographic Information System	Open-File Report	1991	Georgia
Distribution of heavy mineral sands adjacent to the Altamaha Sound—a possible exploration model	Georgia Geologic Survey Bulletin	1992	Georgia
Report on the Georgia Coastal Geographic Information System	Open-File Report	1993	Georgia

Appendix (cont.)

Title	Type of work	Date	State
Distribution of heavy minerals on the Georgia Coastal Plain and Continental Shelf	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Georgia
Compilation and review of information on Neogene aquifers in Camden and Glynn Counties, Georgia	Project Report	1995	Georgia
The Continental Margins Program in Georgia	Abstract in Program and Abstracts, Fourth Symposium on Studies Related to Continental Margins	1997	Georgia
Precious metal accumulation in manganese crusts from the Hawaiian and Johnston Island Exclusive Economic Zones	Abstract in Program and Abstracts, Second Symposium on Studies Related to the Continental Margins	1989	Hawaii
Platinum accumulation in cobalt-rich ferromanganese crusts	Paper in Proceedings, Fourth Congress on Marine Science and Technology	1990	Hawaii
Precious metal accumulation in manganese crusts from the Hawaiian and Johnston Island Exclusive Economic Zones	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Hawaii
The application of laser ablation ICP-MS to the investigation of platinum accumulation in ferromanganese crusts	Abstract, Toronto ’91 Abstracts	1991	Hawaii
An assessment of substrate phosphorite resources in the Hawaiian EEZ	Paper in Proceedings, Oceans ’91	1991	Hawaii
Application of ferromanganese marine mineral tailings in concrete and ceramics	Proceedings, 22d Underwater Mining Institute Conference	1991	Hawaii
Beneficial uses of ferromanganese marine mineral tailings	Abstract, Pacific Congress on Marine Science and Technology	1992	Hawaii
Applications of manganese nodule tailings in the manufacture of innovative building materials	Abstract, Symposium on Ocean Technology	1992	Hawaii
Seafloor cobalt deposits: a major untapped resource	Paper in Cobalt at the Crossroads Conference Volume	1992	Hawaii
The economics of mining manganese crust with recovery of platinum and phosphorus	Paper in Recent Advances in Marine Science and Technology	1993	Hawaii
Beneficial uses of ferromanganese marine mineral tailings in N. Saxena	Paper in Recent Advances in Marine Science and Technology	1993	Hawaii

Appendix (cont.)

Title	Type of work	Date	State
Potential ferromanganese crust mine sites in the Johnston Island EEZ	Abstract, Pacific Congress on Marine Science and Technology	1993	Hawaii
Manganese crust deposits in the Johnston Island EEZ as potential cobalt resources	Paper in Proceedings, Pacific Congress on Marine Science and Technology	1993	Hawaii
The identification of potential manganese crust mine sites	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Hawaii
Deep seabed rock dredging in areas with high relief	Marine Georesources and Geotechnology paper	1994	Hawaii
An economic analysis of the feasibility of manganese crust mining and processing	Technical Report	1994	Hawaii
Mineralogy and geochemistry of ferromanganese crusts from Johnston Island EEZ	Abstract, Third International Conference on Asian Marine Geology	1995	Hawaii
Geochemical constraints on platinum accumulation in seamount ferromanganese crusts	AGU abstract	1995	Hawaii
Solution mining of Johnston Island manganese crusts: an economic evaluation	Paper in Proceedings, Oceans ’95 Conference	1995	Hawaii
The use of marine tailings in the formulation of specialty glasses, ceramic-glasses and glazes	Paper in Proceedings, Oceans ’96 Conference	1996	Hawaii
Mineralogy and geochemistry of ferromanganese crusts from Johnston Island EEZ	Paper in Proceedings, Oceans ’96 Conference	1996	Hawaii
Use of marine mineral tailings for aggregate and agricultural applications	Paper in Proceedings, International Offshore and Polar Engineering Conference	1997	Hawaii
Formulation of specialty glasses and glazes employing marine mineral tailings	Paper in Recent Advances in Marine Science and Technology	1997	Hawaii
Manganese tailings utilization in rust and biofouling and termite coatings	Abstract, Pacific Congress on Science and Technology	1997	Hawaii
Platinum-rich zones as stratigraphic markers for manganese crust correlation in the Johnston Island Exclusive Economic Zone	Abstract, Pacific Congress on Science and Technology	1997	Hawaii
An investigation of the contribution of platinum and phosphorite to the economic viability of a manganese crust mining operation in the EEZ surrounding Hawaii and Johnston Island	Report	1993	Hawaii
Deep seabed rock dredging in areas with high relief	Marine Georesources and Geotechnology paper	1994	Hawaii
Inter element relationship in ferromanganese crusts from the Central Pacific Ocean: their implications for crust genesis	Marine Geology paper	1997	Hawaii

Appendix (cont.)

Title	Type of work	Date	State
Fine-scale platinum-rich zones as stratigraphic markers in seamount ferromanganese crusts	Paper in Proceedings, Pacific Congress on Science and Technology	1997	Hawaii
Sand & shell aggregate resource inventory for Louisiana Continental Shelf	Final Report to MMS	1984	Louisiana
Sand resources in Shell Island region, Louisiana	Final Report to MMS	1988	Louisiana
Sand resources in the Trinity shoal region, Louisiana	Final Report to MMS	1989	Louisiana
Stratigraphic assessment of the mineral resources in the St. Bernard Shoals: offshore Louisiana	Final Report to MMS	1990	Louisiana
Stratigraphic assessment of the sand resources offshore of the Holly and Peveto Beaches in Louisiana	Final Report to MMS	1991	Louisiana
Shell resource inventory of offshore Louisiana: Marsh Island to Point Au Fer	Coastal Geology Technical Report	1992	Louisiana
Mapping sand resources in the Barataria Bight: offshore Grand Terre	Final Report to MMS	1993	Louisiana
Offshore sand resources for coastal erosion control in Louisiana	Gulf Coast Association of Geological Societies Transactions paper	1990	Louisiana
Offshore and onshore sediment resource delineation and usage for coastal erosion control in Louisiana; the Isles Dernieres and Plaquemines barrier systems	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Louisiana
Preliminary assessments of the occurrence and effects of utilization of sand and aggregate resources of the Louisiana inner shelf	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Louisiana
Preliminary assessments of the occurrence and effects of utilization of sand and aggregate resources of the Louisiana inner shelf	Marine Geology paper	1989	Louisiana
Nearshore sand resources of the Mississippi River delta plain: Marsh Island to Sandy Point	Coastal Geology Technical Report	1991	Louisiana
Reconnaissance investigation of shoreface and inner shelf sand resources in Terebonne Parish: Point Au Fer to Timbalier Island	Open-Files Series	1988	Louisiana
Nearshore sand resources in the eastern Isles Dernieres barrier island arc	Open-Files Series	1988	Louisiana
Transgressive evolution of the Chandeleur Islands, Louisiana	Gulf Coastal Association of Geological Societies Transactions paper	1988	Louisiana
Geomorphology and sedimentary framework of the inner continental shelf of southwestern Maine	Open-File Report	1986	Maine
Geomorphology and sedimentary framework of the inner continental shelf of southcentral Maine	Open-File Report	1986	Maine
Variability in the evolution of adjacent bedrock framed estuaries in Maine	Academic Press paper	1986	Maine

Appendix (cont.)

Title	Type of work	Date	State
Sedimentary framework of southern Maine's inner shelf	Report	1987	Maine
Geomorphology and sedimentary framework of the inner continental shelf of Central Maine	Open-File Report	1988	Maine
Seismic-stratigraphic and geomorphic evidence for a post-glacial sea-level lowstand in the northern Gulf of Maine	Journal of Coastal Research paper	1991	Maine
Physiography, surficial sediments and Quaternary stratigraphy of the inner continental shelf and nearshore region of central Maine, United States of America	Continental Shelf Research paper	1991	Maine
Sedimentary framework of the Penobscot Bay and adjacent shelf, Maine	Open-File Report	1989	Maine
Sedimentary framework of the southern and Central Maine inner continental shelf	Abstract in Program and Abstracts, Second Symposium on Studies Related to Continental Margins	1989	Maine
A submerged shoreline on the inner continental shelf of the western Gulf of Maine	Paper in Studies in Marine Geology	1989	Maine
Depositional sequence modeling of late Quaternary geologic history, west central Maine Coast	Paper in Studies in Marine Geology	1989	Maine
Geomorphology and late Quaternary evolution of the Saco Bay region, Maine Coast	Paper in Studies in Marine Geology	1989	Maine
Sedimentary framework of the southern Maine inner continental shelf: influence of glaciation and sea-level change	Paper in Studies in Marine Geology	1989	Maine
Giant sea-bed pockmarks: evidence for gas escape from Belfast Bay, Maine	Geology paper	1994	Maine
Sedimentary framework of the southern Maine inner continental shelf: preliminary results from vibracores	Open-File Report	1990	Maine
Geomorphology and sedimentary framework of Blue Hill and Frenchmans Bays, Maine	Open-File Report	1991	Maine
Carbonate accumulation on the inner continental shelf of Maine—a modern consequence of late Quaternary glaciation and sea-level change	Journal of Sedimentary Research paper	1995	Maine
Sea-level change and the introduction of late Quaternary sediment to the southern Maine inner continental shelf	SEPM Special Paper	1992	Maine
Geomorphology and sedimentary framework of the inner continental shelf of downeast Maine	Open-File Report	1994	Maine
Volume and quality of sand and gravel aggregate in the submerged paleodelta, shorelines and modern shoreface of Saco Bay, Maine	Open-File Report	1995	Maine
Volume and quality of sand and gravel aggregate in the submerged paleodeltas of the Kennebec and Penobscot River mouth areas, Maine	Open-File Report	1995	Maine
Late Quaternary relative sea-level change in the Western Gulf of Maine: evidence for a migrating glacial forebulge	Geology paper	1995	Maine

Appendix (cont.)

Title	Type of work	Date	State
Sequence stratigraphy of submerged river-mouth deposits in the northwestern Gulf of Maine: responses to relative sea-level changes	GSA Bulletin paper	1997	Maine
Mapping the Gulf of Maine with side-scan sonar—a new bottom-type classification for complex seafloors	Journal of Coastal Research paper	1998	Maine
Sedimentary framework of the inner continental shelf of Maine, with special emphasis on commercial quality sand and gravel deposits and potentially economic heavy mineral placers	Open-File Report	1996	Maine
The seafloor revealed—the geology of Maine's inner continental shelf	Open-File Report	1997	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Piscataqua River to Biddeford Pool	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Ogunquit to the Kennebec River	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Cape Elizabeth to Pemaquid Point	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Boothbay Harbor to North Haven	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Rockland to Bar Harbor	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Mt. Desert Island to Jonesport	Geologic Map	1996	Maine
Surficial geology of the inner continental shelf of the northwestern Gulf of Maine—Petit Manan Point to West Quoddy Head	Geologic Map	1996	Maine
Physiography of the inner continental shelf of the northwestern Gulf of Maine	Open-File Report	1998	Maine
Sedimentary framework of the inner continental shelf of Maine, with special emphasis on commercial quality sand and gravel deposits and potentially economic heavy mineral placers	Open-File Report	1997	Maine
Non-energy mineral and surficial geology of the continental margin of Maryland	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Maryland
Surficial sediments and later Quaternary sedimentary framework of the Maryland continental shelf	Paper in Proceedings, Coastal Sediments '87	1987	Maryland
Late Quaternary stratigraphy of the inner continental shelf of Maryland	Open-File Report	1988	Maryland
Subbottom structure and stratigraphy of the inner continental shelf of Maryland	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Maryland

Title	Type of work	Date	State
Comments on "Late Pleistocene barrier island sequence along the southern Delmarva Peninsula: implications for middle Wisconsin sea level"	Geology	1989	Maryland
Non-energy minerals and surficial geology of the continental margin of Maryland	Marine Geology paper	1989	Maryland
Quaternary stratigraphy of the inner continental shelf of Maryland: Maryland Geological Survey	Report of Investigations	1989	Maryland
Quaternary stratigraphy and sea-level history of the U.S. middle Atlantic Coastal Plain	Quaternary Science Reviews paper	1992	Maryland
Record of oxygen isotope stage 5 on the Maryland inner shelf and Atlantic Coastal Plain—A post transgressive-highstand regime Quaternary Coasts of the United States	Paper in SEPM Special Publication	1992	Maryland
Sieve analyses and heavy mineral concentrations of the sand taken from the inner continental shelf of Maryland	Open-File Report	1990	Maryland
Heavy mineral abundances on the continental shelf of Maryland	Open-File Report	1990	Maryland
Heavy mineral abundances on the continental shelf of Maryland	Open-File Report	1991	Maryland
Non-energy resources and shallow geological framework of the inner continental margin off Ocean City, Maryland	Open-File Report	1994	Maryland
Geochemistry and geophysical framework of the shallow sediment of Assawoman Bay and Isle of Wight in Maryland	Open-File Report	1994	Maryland
The surficial sediments of Assawoman Bay and Isle of Wight in Maryland: physical and chemical characteristics	File Report	1994	Maryland
Physical inventory and repository of vibracores collected on Maryland's continental shelf	File Report	1996	Maryland
Jurassic framework studies	MMS Final Report	1909	Mississippi
Jurassic framework studies	Open-File Report	1993	Mississippi
Jurassic framework studies	Abstract, Mississippi Academy of Science	1994	Mississippi
Jurassic framework studies	Presentation, Society of Independent Earth Scientists	1994	Mississippi
Spin-off studies: Mesozoic stratigraphy of near shelf-edge deposits...southern MS adjacent State and Federal waters	Abstracts	1994	Mississippi
Spin-off studies: stratigraphic analysis of Block 57 well	Presentation, Gulf Coast Association of Geological Societies	1995	Mississippi
Cretaceous framework studies	MMS Final Report	1993	Mississippi
Cretaceous framework studies	Open-File Report	1993	Mississippi
Cretaceous framework studies	Abstract/poster, Gulf Coast Association of Geological Societies Transactions	1992	Mississippi
Miocene framework studies	MMS Final Report	1994	Mississippi
Miocene framework studies	Open-File Report	1994	Mississippi

Appendix (cont.)

Title	Type of work	Date	State
Miocene framework studies	SIPES Presentation	1994	Mississippi
Miocene framework studies	Academy of Science abstract/presentation	1994	Mississippi
Miocene framework studies	Mississippi Geological Society presentation	1994	Mississippi
Jurassic reservoirs studies	MMS Final Report	1996	Mississippi
Jurassic reservoirs studies	Mississippi Office of Geology Open-File Report	1996	Mississippi
Jurassic reservoirs studies	Mississippi Academy of Science presentation	1997	Mississippi
Cretaceous reservoirs studies	MMS Final Report	1995	Mississippi
Cretaceous reservoirs studies	Mississippi Office of Geology Open-File Report	1995	Mississippi
Cretaceous reservoirs studies	Mississippi Academy of Science abstract/presentation	1995	Mississippi
Geologic framework offshore southern New Jersey	MMS Report	1986	New Jersey
Geologic framework and hydrocarbon potential offshore southern New Jersey	MMS Report	1987	New Jersey
Seismic reflection and gravity study of proposed Taconic suture under New Jersey Coastal Plain: implications for continental growth	GSA Bulletin paper	1991	New Jersey
Basement crustal and seismic stratigraphic interpretation of the Buena 557 Vibroseis line in the New Jersey Coastal Plain	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	New Jersey
Textural, physiographic, bathymetric, and geologic factors controlling economic heavy minerals distribution in surficial sediments on the Atlantic continental shelf offshore of New Jersey	USGS Open-File Report	1989	New Jersey
Physiographic, bathymetric and textural controls on heavy-mineral enrichment in surficial sediments of the New Jersey shelf	NEGSA abstract	1991	New Jersey
Preliminary textural and mineralogical analysis of vibracore samples collected between Absecon and Barnegat Inlets, New Jersey	Open-File Report	1990	New Jersey
Distribution of heavy minerals and gravel in vibracores collected between Absecon and Barnegat Inlets, New Jersey	MMS Report	1993	New Jersey
Distribution of heavy minerals and gravel in offshore sediments as determined from vibracore samples from Barnegat to Absecon Inlets, New Jersey	NEGSA abstract	1992	New Jersey
Distribution of heavy minerals and gravel in sediments of the New Jersey shelf as determined from grab and vibracore samples	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	New Jersey

Appendix (cont.)

Title	Type of work	Date	State
Preliminary textural and mineralogical analyses of Cretaceous and Holocene sediments from the northern New Jersey Coastal Plain	MMS Report	1994	New Jersey
High-resolution marine seismic reflection data acquisition using an engineering seismograph	MMS Report	1994	New Jersey
High-resolution marine seismic reflection data acquisition using an engineering seismograph	Presentation, Symposium on the Application of Geophysics to Engineering and Environmental Problems	1994	New Jersey
Digital continuous seismic reflection profiles of New Jersey inner shelf sand ridges	NEGSA abstract	1993	New Jersey
Heavy-mineral analysis of 32 vibracore samples collected between Hereford and Absecon Inlets, New Jersey	MMS Report	1996	New Jersey
An investigation of the possible extension of the Connecticut River Triassic graben into New York State offshore—concentration in central Long Island	Report	1985	New York
An investigation of the possible extension of the Connecticut River Triassic graben into New York State offshore-concentration in eastern Long Island	Report	1986	New York
Prospecting for sand and gravel in the New York State offshore, Phase I: synthesis of existing information	Report	1988	New York
Prospecting for sand, gravel and heavy minerals in the New York State offshore	Abstract	1988	New York
Recent developments: U.S. Atlantic shelf marine mineral surveys	Paper	1988	New York
Prospecting for sand, gravel and heavy minerals in the New York State offshore: Phase II, reconnaissance of drill core and seismic data	Report	1989	New York
Prospecting for sand, gravel and heavy minerals in the New York State offshore	Abstract	1989	New York
Preliminary mineralogic analysis of vibracore samples from offshore of the north shore of Long Island, New York	Report	1989	New York
Garnet in offshore deposits—estimating the potential of "by-product" resources	Abstract	1990	New York
Assessment of aggregate and heavy mineral resource potential in New York coastal waters	Report	1990	New York
Prospecting for sand, gravel and heavy minerals in the New York State offshore: reconnaissance and analysis of drill core	Report	1991	New York
Titanium-zirconium-rare-earth placer resources potential of surficial sediments on the Atlantic continental shelf offshore of New York, Rhode Island, and southern Massachusetts	Report	1991	New York
Potential sand, gravel and heavy-mineral resources on the continental shelf south of Long, Island, New York	Report	1992	New York

Appendix (cont.)

Title	Type of work	Date	State
Aggregate and heavy-mineral resources of the continental shelf in the eastern New York bight	Abstract	1993	New York
Foraminifera populations as indicators of sedimentary environments in the New York bight	Abstract	1994	New York
Prospects for sand, gravel and heavy minerals on the continental shelf south and east of Long Island, New York	Report	1994	New York
Chemical analysis of heavy minerals from the continental shelf south of Long Island, New York	Report	1997	New York
Sedimentological analysis of vibrocores from the near-shore shelf south of Rockaway Beach, Queens County, New York	Report	1997	New York
Seismic reflection profiles and the nature of sand ridges on the continental shelf south of Fire Island, Suffolk County, New York	Report	1997	New York
Analysis of vibrocores recovered south of Rockaway Beach, Queens County, New York, clues to modern sediment dynamics and Holocene stratigraphic development	Report	1997	New York
Elements of the subsurface geologic framework of a segment of the North Carolina outer coastal plain and adjacent continental shelf	Unpublished Contract Report	1985	North Carolina
Seismic stratigraphic studies of the Pamlico-Albemarle-Croatan Sound area, coastal North Carolina	SEPM abstract/talk	1986	North Carolina
Lithostratigraphic-seismic evaluation of hydrocarbon potential: North Carolina coastal and continental margins	Abstract in Program and Abstracts, First Symposium on Studies Related to Continental Margins	1987	North Carolina
Lithostratigraphic-seismic evaluation of hydrocarbon potential: North Carolina coastal and continental margins	Open-File Report	1987	North Carolina
Lithostratigraphic-seismic evaluation of hydrocarbon potential: North Carolina coastal and continental margins	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	North Carolina
Subsurface stratigraphic framework studies of the Pamlico-Albemarle Sound, North Carolina: MMS/AASG phase four	Abstract in Program and Abstracts, Second Symposium on Studies Related to Continental Margins	1989	North Carolina
Sequence stratigraphy and foraminiferal biostratigraphy for selected wells in the Albemarle embayment	Open-File Report	1989	North Carolina
Sequence stratigraphy and foraminiferal biostratigraphy for selected wells in the Albemarle embayment, NC	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	North Carolina
Review of seismic reflection data from the N.C. coastal plain and adjacent continental shelf	Open-File Report	1990	North Carolina

Appendix (cont.)

Title	Type of work	Date	State
Heavy-mineral resource potential of surficial sediments on the Atlantic continental shelf offshore of North Carolina: a reconnaissance	Open-File Report	1990	North Carolina
Heavy-mineral resource potential of surficial sediments on the Atlantic continental shelf offshore of North Carolina: a reconnaissance	Open-File Report	1990	North Carolina
Stratigraphic framework and heavy-mineral resource potential of the inner continental shelf, Cape Fear area, North Carolina: first interim progress report	Open-File Report	1991	North Carolina
Heavy-mineral resource studies within the EEZ of the Cape Fear cuspate foreland area, NC: stratigraphic framework	GSA abstract	1992	North Carolina
Prospective target area for placer resources exploration on the North Carolina continental shelf	Abstract in Program and Abstracts, Third Symposium on Studies Related to Continental Margins	1992	North Carolina
Prospective target area for placer resources exploration on the North Carolina continental shelf	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	North Carolina
Heavy-mineral data for selected vibracores from the southern inner continental shelf of North Carolina	Open-File Report	1993	North Carolina
Seismic stratigraphic framework of the inner continental shelf: Mason Inlet to New Inlet	NCGS Bulletin	1994	North Carolina
Mineralogy of vibracore heavy-mineral concentrates and preliminary stratigraphic framework of the southern inner continental shelf of North Carolina	Open-File Report	1994	North Carolina
Archiving and electronic publishing of vibracore data from the North Carolina continental shelf	GSA abstract	1997	North Carolina
Stratigraphic and heavy-mineral data from continental shelf vibracores: Cape Fear cuspate foreland region, North Carolina	Open-File Report	1997	North Carolina
Stratigraphic and heavy-mineral studies, Atlantic continental shelf of Onslow and Long Bays, North Carolina	Abstract in Program and Abstracts, Fourth Symposium on Studies Related to Continental Margins	1997	North Carolina
Elemental content of heavy-metal concentrations on the continental shelf off Oregon and northernmost California	Open-File Report	1988	Oregon
Onshore-offshore geologic cross section from the Mist gas field, northern Oregon coast range to the northwest Oregon continental shelf and slope	Oil and Gas Investigation	1990	Oregon
Onshore-offshore geologic cross section, northern Oregon coast range to continental slope	Special Paper	1992	Oregon
Offshore-onshore geologic cross section from the PanAmerican Corporation well (continental shelf) to the Umpqua River (southern Oregon coastal range)	Unpublished Report		Oregon

Appendix (cont.)

Title	Type of work	Date	State
Oil and gas potential of the southern Tyee Basin, southern Oregon coast range	Oil and Gas Investigation	1996	Oregon
Geologic map of the Coos Bay Quadrangle, Coos Bay, Oregon	Geologic Map Series	1995	Oregon
Assessment of aggregate resources offshore Puerto Rico and recommendations to evaluate the potential environmental implications of resource development	Preliminary Draft	1997	Puerto Rico
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1984	1986	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Paper in Proceedings, First Symposium on Studies Related to Continental Margins	1988	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1985	1987	Rhode Island and Connecticut
A seaward extension of the Lordship deposit	Presentation	1988	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1986	1988	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Marine Geology paper	1989	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1987	1989	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Paper in Proceedings, Second Symposium on Studies Related to Continental Margins	1990	Rhode Island and Connecticut
Detailed seismic-reflection analysis of an ice-marginal lacustrine fan in Long Island Sound	Presentation	1990	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1988	1991	Rhode Island and Connecticut
Late Quaternary stratigraphy and depositional history of the Long Island Sound Basin	Paper	1991	Rhode Island and Connecticut
Geologic history of Long Island Sound	Paper	1992	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1989	1994	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1990	1993	Rhode Island and Connecticut
Use of side-scan sonar for landscape approaches to habitat mapping	Presentation	1994	Rhode Island and Connecticut

The Commonwealth of Puerto Rico participated in the Continental Margins Program only during year 2.

Appendix (cont.)

Title	Type of work	Date	State
Stratigraphical and depositional history of Long Island Sound	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1991	1994	Rhode Island and Connecticut
Protocol development for seafloor mapping in Long Island Sound	Presentation	1995	Rhode Island and Connecticut
Benthoscape structure and infaunal community responses in central and western U.S.	Presentation	1996	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters	Final Report, FY 1992	1996	Rhode Island and Connecticut
Non-energy resources Connecticut and Rhode Island coastal waters, year nine and year ten activities	Presentation	1997	Rhode Island and Connecticut
Habitat mapping in Long Island Sound	Presentation	1997	Rhode Island and Connecticut
Non-energy resources, Rhode Island coastal waters	Abstract and Poster Presentation, Rhode Island Natural History Survey Annual Meeting	1996	Rhode Island and Connecticut
Sequence stratigraphy and composition of Late Quaternary shelf margin deltas, northern Gulf of Mexico	AAPG Bulletin paper	1996	Texas
Contrasting styles of late Neogene deep-water sandstone deposition, offshore Texas	Paper in Proceedings, Third Symposium on Studies Related to Continental Margins	1994	Texas
Sequence stratigraphic implications of Quaternary shelf-margin deltas, High Island Area northwestern Gulf of Mexico	AAPG abstract	1994	Texas
Failed shelf-margin embayments: An alternate depositional system to transfer sand from the shelf into deep water	AAPG abstract	1993	Texas
Attributes and origins of ancient submarine slides and filled embayments: examples from the Gulf Coast Basin	AAPG Bulletin paper	1993	Texas
Contrasting styles of late Neogene deep-water sandstone deposition, offshore Texas	Abstract in Program and Abstracts, Third Symposium on Studies Related to Continental Margins	1992	Texas
Response of Holocene depositional systems tracts to sediment influx, northern Gulf of Mexico	Paper, GCSSEPM 12th Annual Research Conference	1991	Texas
Contrasting styles of late Neogene deep-water sandstone deposition, offshore Texas	Paper in SEPM Concepts in Sedimentology and Paleontology	1991	Texas

Appendix (cont.)

Title	Type of work	Date	State
Preliminary assessment of nonfuel minerals on the Texas continental shelf	Paper, MMS Proceedings, Ninth Annual Information Transfer Meeting	1989	Texas
Reservoir characterization of selected distal Frio Formation fields, offshore Texas	Abstract in Program and Abstracts, Second Symposium on Studies Related to Continental Margins	1989	Texas
Geometry, genesis, and reservoir characteristics of shelf sandstone facies, Frio Formation (Oligocene) Texas coastal plain	Paper in Proceedings, GCSSEPM Seventh Annual Research Conference	1989	Texas
Origin, depositional pattern, and reservoir characteristics of middle Miocene shallow-marine sandstones, offshore south Texas	Paper in Proceedings, GCSSEPM Seventh Annual Research Conference	1989	Texas
Preliminary assessment of non-fuel mineral resources of the Texas continental shelf	Paper, MMS Proceedings, Eighth Annual Gulf of Mexico Information Transfer Meeting	1988	Texas
Assessment of economic heavy minerals of the Virginia inner continental shelf	Studies	1986	Virginia
Reconnaissance of economic heavy minerals of the Virginia inner continental shelf	Studies	1988	Virginia
Study of economic heavy minerals of the Virginia inner continental shelf	Studies	1988	Virginia
Evaluation of sediment dynamics and the mobility of heavy minerals on the Virginia inner continental shelf	Studies	1989	Virginia
Acoustic geology of a portion of Virginia's innermost continental shelf	Heavy-Mineral Studies: Publication 103	1990	Virginia
Chemical analyses of offshore heavy-mineral samples, Virginia inner continental shelf	Heavy-Mineral Studies: Publication 103	1990	Virginia
Heavy-mineral concentration in sediments of the Virginia inner continental shelf	Heavy-Mineral Studies: Publication 103	1990	Virginia
Heavy-mineral-studies—Virginia inner continental shelf	Studies	1990	Virginia
Investigation of isolated sand shoals on the inner shelf of southern Virginia	Studies	1991	Virginia
Preliminary geologic section across the buried part of the Taylorsville basin, Essex and Caroline Counties, Virginia	Studies	1991	Virginia
Structural section across the Atlantic Coastal Plain, Virginia and southeasternmost Maryland	Studies	1995	Virginia
Investigations of offshore beach sands: Virginia Beach and Sandbridge, Virginia	Studies	1995	Virginia
Investigations of isolated sand shoals and associated deposits, Virginia inner shelf	Studies	1996	Virginia

Appendix (cont.)

Title	Type of work	Date	State
Preliminary observations on marine stratigraphic sequences, central and western Olympic Peninsula	Washington Geology paper	1995	Washington
Distribution of some Paleogene sedimentary rocks and implications for oblique-slip faulting in western Washington	Abstract, University of Washington Quaternary Research Center	1993	Washington
Miocene to Recent development of the Juan de Fuca accretionary prism, northwest Washington	Abstract in Program and Abstracts, Third Symposium on Studies Related to Continental Margins	1992	Washington
Petroleum geochemistry of Washington—a summary	Washington Geology paper	1991	Washington
Structure and kinematics of the Olympic subduction complex, NW Washington, and implications for mechanical models of accretionary prisms	GSA abstract	1991	Washington
A compilation of reflection and refraction seismic data for western Washington and adjacent offshore areas	Open-File Report	1991	Washington