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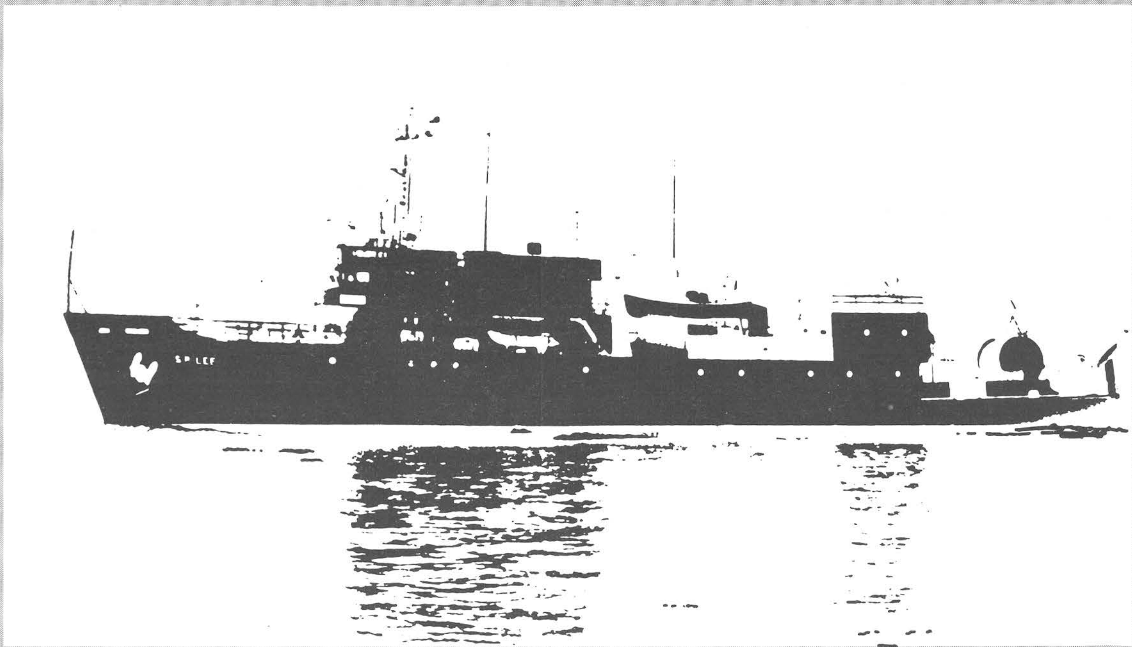
GEOLOGICAL SURVEY CIRCULAR 906

The Marine Geology Program of the U.S. Geological Survey



The Marine Geology Program of the U.S. Geological Survey

By N. Terence Edgar

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INTRODUCTION

On March 3, 1879, the U.S. Congress established the U.S. Geological Survey (USGS) and charged it with the responsibility for "the classification of public lands and examination of the geologic structure, mineral resources and products of the national domain." In 1879 much of the national domain was frontier. Today the Nation's geographic frontiers primarily lie beneath its surrounding waters. By Presidential proclamation in 1983, the national domain for seabed resources has been extended to 200 nautical miles offshore. This United States Exclusive Economic Zone (EEZ), a marine domain surrounding the continental U.S., Hawaii, and U.S.-related islands, constitutes an area about one and two-thirds larger than the size of the onshore area. In this vast domain lie resources of immense importance to the Nation: an estimated 35 percent of the economically recoverable oil and gas yet to be found in the United States; major resources of strategic metals like cobalt, manganese, and nickel in seafloor crusts, pavements, and nodules; massive-sulfide deposits actively forming today; and major concentrations of heavy minerals in nearshore sand bodies.

Along with the immense potential of these resources in this frontier area is the excitement of scientific frontiers. Most of the geologic framework of the Nation's continental margins (shelf, slope, and rise) is known from a relatively few and widely spaced deep seismic-reflection profiles, and only a handful of deep drillholes from which to study the rocks below the seafloor. The frontier character of the offshore domain is highlighted by considering that major sedimentary basins prospective for petroleum have been discovered in the last 8 years; sulfide deposits at seafloor spreading centers have been known only since 1978; cobalt-rich manganese crusts on Pacific seamounts (underwater extinct volcanoes) were recognized as important potential resources in 1982; new seafloor features like submarine canyons and seamounts are discovered virtually every year. It is through marine geologic surveys that key aspects of plate tectonics can be studied: the continual creation of new earth's crust at the midocean spreading centers; the formation of volcanic arcs and basins and of deep ocean trenches where ocean-crust plates collide; the migration of hotspots in the earth's mantle, creating a chain of volcanic islands, one after the other rising atop the overlying ocean crust. Through eons of plate tectonics and active crust-mantle processes, such features have been caught up in the accreting continents and may be studied in fragments on land. But they started in the oceans and the marine realm remains the laboratory where they and the fundamental tectonic and volcanic processes they reveal may be studied best.

ACKNOWLEDGMENTS

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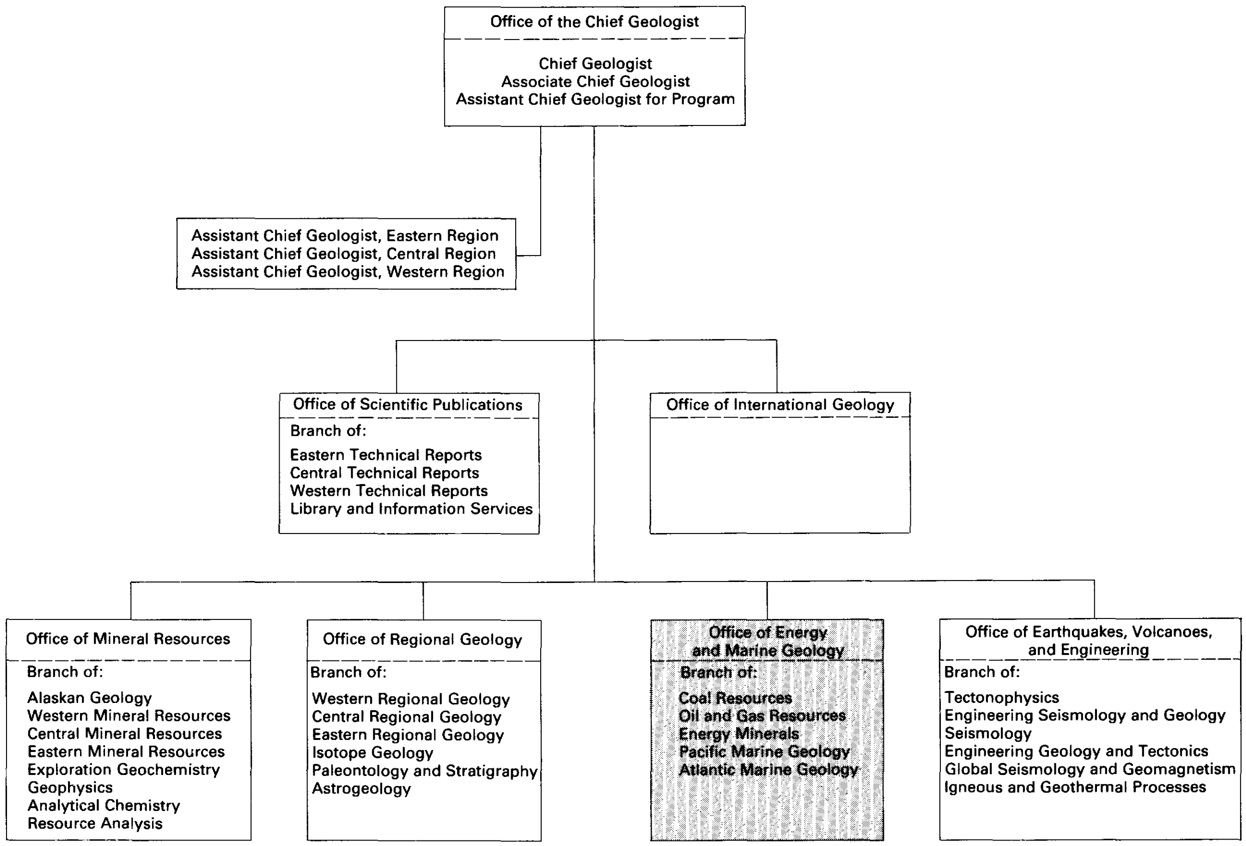
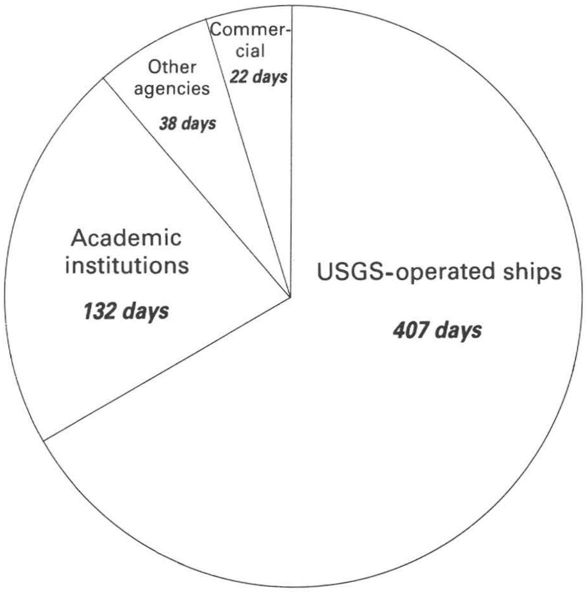


FIGURE 1.—Organizational chart of the Geologic Division, U.S. Geological Survey.

USGS CAPABILITY IN MARINE GEOLOGY

In the anatomy of a marine geology program, the backbone is its professional capability and the lifeblood is its marine operations. Although the researchers and the support staff involved in marine geology number only about 200, the capabilities of this program are strong, because a portion of this capability is derived from the interaction of marine studies with onshore research and its advances, because the program can and does draw on the specialized professional talent available in other units of the Survey, and because it uses Bureau-wide facilities such as the analytical laboratories of the USGS for analyses of samples of sediment and rock gathered from the continental shelves or deep ocean. These facilities serve to strengthen greatly the capability and competence of the marine research, particularly in the field of mineral genesis in the marine realm, a major new research direction. The association with the onshore arms of the USGS (fig. 1) provides great breadth and depth to the marine program and enables the USGS to respond effectively to a wide variety of user requirements and rally to meet urgent national needs. Associations with other Government agencies and academic institutions add still more capability to the program.

The Geological Survey's marine-operations, or seagoing, capability is based on a variety of USGS-operated vessels and charters from oceanographic institutions and commercial suppliers (fig. 2). In each case the task at hand determines the best and most cost-effective approach to the use of ships, with the understanding that any effective utilization of major sea-going facilities requires long-term planning and stability of programs. The USGS-operated vessels are used primarily for geologic and geophysical investigations, multidisciplinary in nature, in distant re-



Category	Number of vessels
USGS	5
Academic institutions	8
Other agencies	7
Commercial	4
	Total 24

Total operational days 599

FIGURE 2.—Pie diagram showing the relative use of USGS-operated vessels and ships owned by other Government agencies and the private sector.

gions where flexibility in scheduling and operations is essential, such as in areas where there is a narrow window of operations because of inclement weather or ice. This flexibility permitted the USGS to respond promptly to new initiatives of the Department of Interior or Congress and other Federal agencies, without lengthy procedures in contracting for and outfitting vessels with the specialized gear suited to the mission. Notwithstanding this need, the Survey has used very successfully many vessels chartered from the private and the academic sector, some for special tasks such as deep coring of the Atlantic Continental Shelf and routine geophysical surveys, and others for special mapping of the continental slope.

USGS-operated vessels provide the important basic component that permits program managers to plan, equip, and mobilize for sustained long-term annual use and to respond in a timely way to program and schedule modifications. The USGS operates two ocean-class vessels and four small boats for coastal and estuarine studies. The research vessels (R/V) are shown in figures 3–7. Capabilities are briefly described in the following table.

Vessels are also chartered regularly from other U.S. Government agencies, from academic institutions, and from companies for use in carrying out specific tasks that are suitable for charter operations. About 30 percent of the operations (in ship days) are conducted on such vessels (fig. 2). They are used commonly to place equipment onto or retrieve it from the seafloor, or to conduct surveys using portable equipment. About 20 vessels of various sizes, depending on the task, are used every year.

Major items of USGS equipment for marine surveys include a 24–channel seismic-reflection system for determining the structure and stratigraphy of the upper part of the Earth's crust in basins and other areas of the continental shelf, slope, and rise; a variety of high-resolution, shallow-penetration (100–1,000 m) seismic-reflection units; ocean-bottom seismometers; gravimeters and magnetometers; seafloor frames for mounting instruments for bottom-current and sediment mobility measurements; deep-tow side-scan sonar for imaging seafloor morphology; underwater camera arrays for photographing the seafloor; a variety of coring and sampling devices; and an array of sled-mounted instruments to measure sand and water movement in the surf zone. In addition, surveys may involve equipment from other sources, through lease, exchange, or cooperative-study agreements, such as a seafloor core drill, a deep submersible research vessel, an advanced underwater camera array, and a broad-swath side-scan imaging system.

PROGRAM ELEMENTS

The marine program has three major elements: (1) Regional Geologic Framework; (2) Marine Deposits and Sedimentary Dynamics; and (3) Formation of Marine Energy and Mineral Deposits. As described in the following section, scientific studies in these major elements provide answers to major offshore geologic questions that bear on the fundamental geologic makeup of the planet and concerns about the future availability of resources.

FIGURE 3.—R/V *Samuel P. Lee* departing Redwood City pier in California for extended cruise to the South Pacific and Bering Sea. Cooperating countries included Australia and New Zealand, with fiscal support in part from the U.S. Agency for International Development (AID). Areas with oil and gas potential were discovered along the island chain from the Kingdom of Tonga to the Republic of Vanuatu. The equipment on the fantail of the ship is part of the seismic system that is typically used in oil and gas exploration.

Summary of USGS-owned and -operated vessels

Vessel	Size	Owner	Capabilities
R/V *Samuel P. Lee*	208 ft	U.S. Navy	Open ocean capability; primary function multichannel seismic surveying for framework studies and oil and gas potential; piston-core and dredge sampling in deep ocean.
R/V *Polaris II*	160 ft	USGS	Open ocean capability; primary function sampling, can accommodate a small seafloor-mounted deep-sea drill; coring and dredging; gravity, magnetics, and high-resolution seismic surveys.
R/V *David Johnston*	43 ft	USGS	Coastal-estuarine (west coast); light geophysics and sonar; sampling.
R/V *Karluk*	42 ft	USGS	Coastal vessel; used exclusively in Arctic waters; light geophysics and side-scan sonar; shallow sampling.
R/V *Neecho*	38 ft	USGS	Coastal-estuarine (east coast); can be trailered to study area (rivers, lakes); geophysics and side-scan sonar; light sampling.

FIGURE 4.—R/V *Polaris* dockside in New Orleans, Louisiana, prior to departure for geophysical survey off the coast of Florida for the Defense Mapping Agency. The *Polaris* is outfitted primarily for sampling but can also conduct geophysical surveys.

REGIONAL GEOLOGIC FRAMEWORK

The Regional Geologic Framework element for the continental margins, marginal-sea basins, and deep-ocean basins includes investigations in regional stratigraphy, the paleoenvironmental conditions, and structural settings of selected areas, all of which influence the formation of petroleum and mineral deposits. Other studies include tectonism and seismicity, and magmatism and volcanism, as these processes relate to the settings of marine deposits, ocean-floor spreading, development of oceanic trenches, evolution of landmasses or islands, and geohazards that could impede future use of offshore lands. These activities lead to the analysis and interpretation of the evolution of continental margins, spreading centers, and island masses, in the context of geologic history and crustal framework.

Over the past 10 to 15 years our understanding of the major forces affecting the Earth's crust has been radically altered by a universal acceptance of the concept of moving or shifting crustal slabs or plates. These plates move and interact with one another and cause crustal depressions or basins to form, mountain building, earthquakes, and volcanoes. Most important, the plate-tectonic concept can account for the development of the basic crustal framework of the ocean, continent, and continental margin, and consequently provides an understanding of the dominant factor in controlling the geologic settings in which energy and mineral deposits develop in the oceans (fig. 8). Recent discoveries of hydrothermal sulfide deposits in the deep oceans resulted from application of geologists' rudimentary understanding of the process. Hence, to understand not only the basic structure or tectonic framework of the continental

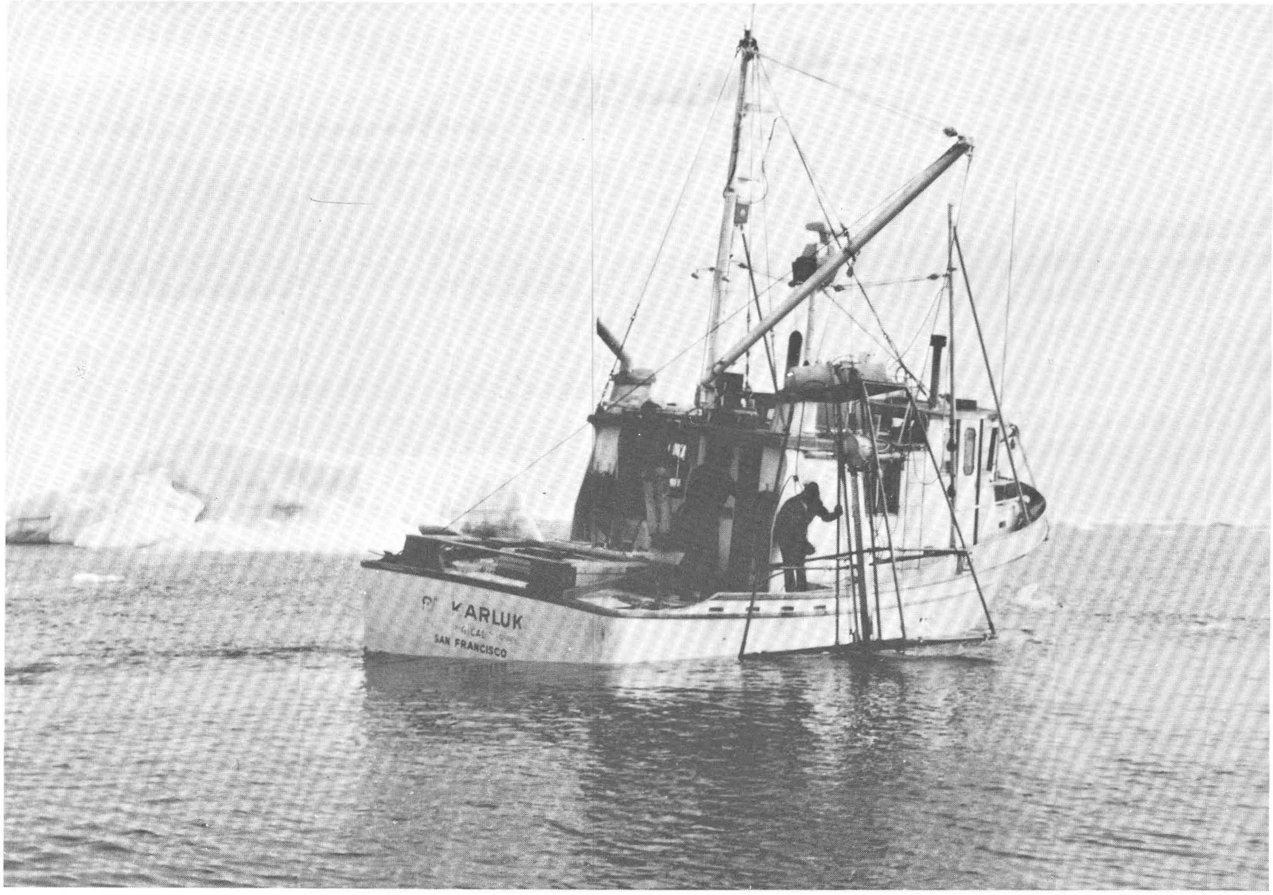


FIGURE 5.—R/V *Karluk* lowering sampling apparatus over the side in Beaufort Sea off the North Slope. *Karluk* operates exclusively in the Arctic, where studies have concentrated on the effect of ice and currents on the seafloor and gravel islands.

margins and deep oceans but also the processes which formed them is extremely important. Moreover, the processes active today on the ocean floor have in the geologic past influenced many of the Nation's land areas when these formed and as such are relevant to the understanding of the geologic evolution of all the continents. Modern marine geologic studies provide a basic geologic understanding that transcends the ocean-land boundaries and that will certainly be a guide to future discoveries of resources on the ocean floor and the continents.

Representative goals of this program element are to:

1. Map the framework geology of the U.S. continental margins, deep-ocean basins and adjacent areas to define crustal building blocks, structural and stratigraphic settings, and areas of potential geohazard risk.
2. Determine the geologic evolution of major segments of the margins to define and evaluate future resource targets.
3. Develop a fundamental understanding of processes and structural rates of movement at the interface of continental margins and ocean basins.
4. Explore and map the oceanic plateaus, seamounts and island chains, island arcs, marginal-sea basins, and mid-ocean ridges and determine their relationships to accreted continental terranes to evaluate their potential for containing resources.
5. Understand the geologic evolution of the deep-ocean basins and the processes that bear on mineral concentration, sediment accumulation, and crustal formation and modification.

Three basic steps are necessary to achieve the goals. The first is to map, by using geophysical in-

FIGURE 6.—R/V *Neecho* on trailer in preparation for transport to the next study area. The capability to transport the boat over highways greatly expands its value. Seismic surveys have been conducted at sea, in estuaries, on lakes, and on rivers.

struments, specific parts of the margins and ocean basins to determine their structural framework. The second is to correlate data from seafloor samples and cores with the geophysical data to interpret the geologic history of the region. The third is to develop and publish interpretive geologic models of the ocean basins and continental margins and, where appropriate, apply these models to the on-land areas.

The following are examples of activities appropriate to this element:

1. Mapping basement structures, sediment thicknesses, and zones of potential economic resources in, for example, the Arctic Ocean, the Bering Sea, and the deep-water portion of the Gulf of Mexico.
2. Studying the composition and structural framework of the Juan de Fuca Ridge, Blake Plateau, and the other rocks exposed on the ocean floor.
3. Sampling buried sediments and rocks on the seafloor by drilling and coring to determine their age, origin, and development.
4. Locating zones of seismic activity and studing the association of seismic events and faulting on the seafloor.

MARINE DEPOSITS AND SEDIMENTARY DYNAMICS

Studies of marine deposits and sedimentary dynamics focus on presently active geologic processes modifying the seafloor and coastal zone, with awareness that similar processes acted to form sedimentary deposits throughout geologic time. Topics of concern are the shape and sedimen-

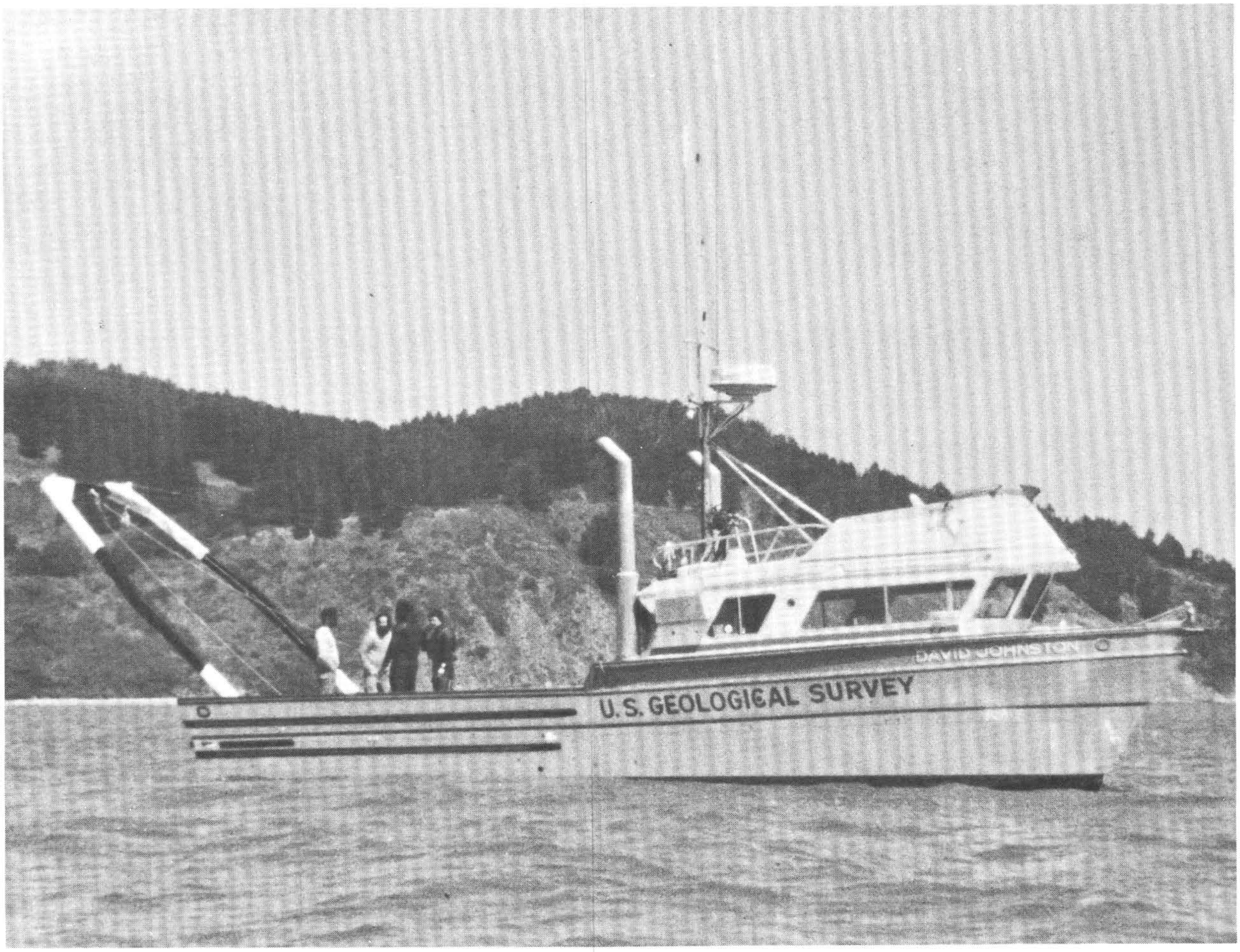


FIGURE 7.—R/V *David Johnston* is a coastal vessel used in San Francisco Bay and off the west coast for light geophysics and sampling.

tologic character of major marine sedimentary deposits and the mechanics of how they formed. In studies of sedimentary dynamics, work is focused on the geologic conditions conducive to, and the physics involved in, large-scale mass failures (subsea landslide hazards); on the dynamics of transport of sediments and pollutants on the seafloor; and on the geologic processes operating in and shaping estuaries, coastal zones, and submarine canyons. Because many basins on land today formed in marine environments, there is much transfer of information and insight from marine studies to land studies and vice versa.

In past years the accumulation of sediment in the oceans has been of dominating interest, but as we seek to understand the nature of the zone where the ocean and continental crusts meet and the dynamic processes that are involved, we are becoming increasingly aware of significant processes of erosion of the continental shelf and slope. The first evidence was seen in geophysical profiles that revealed buried ancient continental shelves as much as 70 km seaward of the present shelfbreak (fig. 8). More recently, high-resolution acoustic (sonar) imaging devices have revealed seafloor features never before seen. The discovery of many more canyons on the continental slope than were previously suspected suggests that submarine erosion is a geologic agent modifying the morphology of the slope at a higher rate than previously considered. In addition, fine striations mapped acoustically near the base of the slope (fig. 9) were examined with a manned deep-diving submersible and were found to be furrows of unknown origin (fig. 10). Deep submersible dives east of Florida have revealed that a near-vertical wall of limestone about 4 km high may have eroded back as much as 15 km in the past 37 million years. The

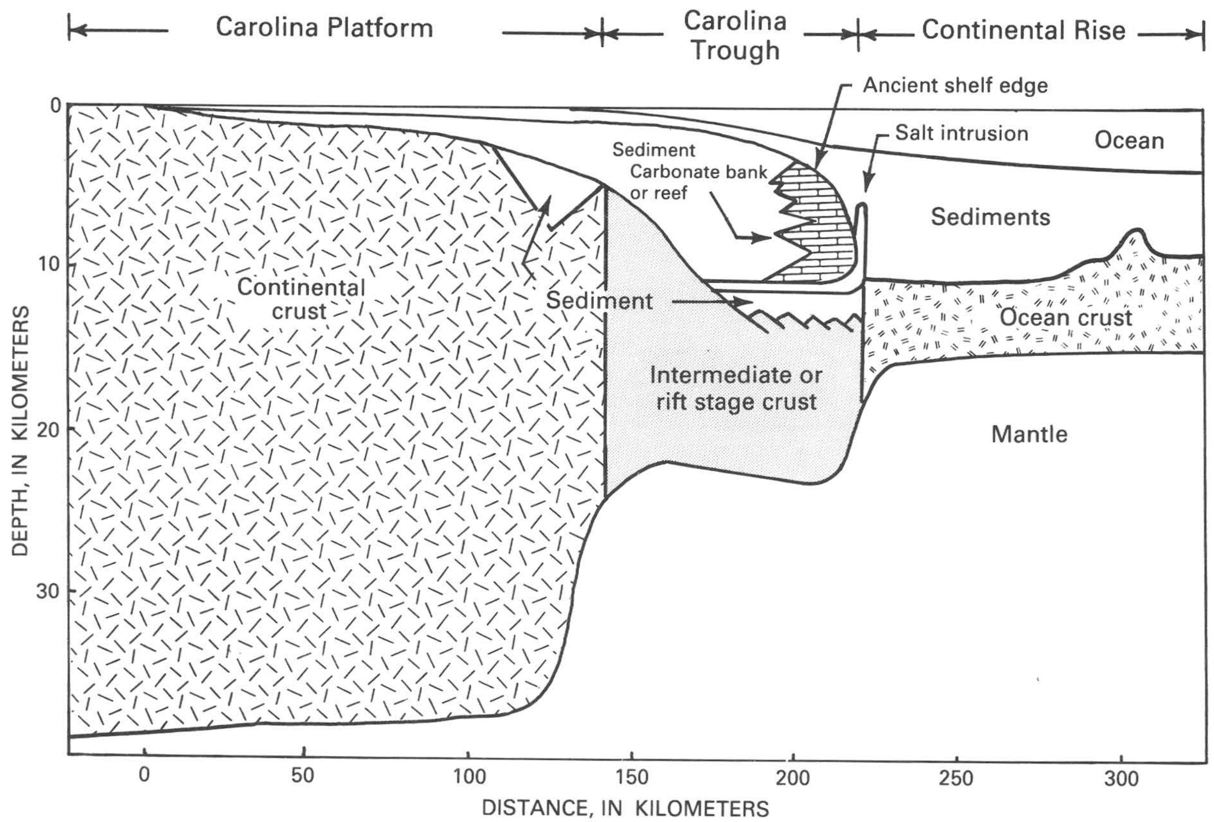


FIGURE 8.—A schematic crustal structure section across the U.S. Atlantic continental margin off North Carolina showing the geologic framework. The section is based on (1) interpretations of multichannel seismic data for the sediments and (2) compatible models of the magnetic and gravity fields for the upper and lower crusts, respectively.

evidence for erosion on such a scale in the past has significant implications for the preservation of oil and gas trapped within the continental margin and for resource exploration and development in deep water. The probing of the deeper parts of the continental slope is just beginning, but clearly there is much to be learned that will be of great value as oil and gas exploration and development continue into deeper waters.

The coastal zone is the principal point of contact between man and the marine realm. If the United States is to ensure that future generations will still be able to enjoy use of this area, by minimizing damage to this sensitive environment, there must be an understanding of the physical, chemical, geological, and biological aspects and of their interdependence in the coastal zone. In geology, the dynamics of sediment transport and knowledge of the characteristics of geologic materials on the shallow nearshore shelves and in the coastal zone (fig. 11) is of primary importance. This part of the shelf is of the most use to man in the transportation of goods, in recreation, in esthetics, and in fishery or mineral resources. This highly dynamic environment includes processes in estuaries, bays, lagoons, waterways, and river mouths.

Farther from shore the sedimentary aspects of greatest interest fall into three general categories: (1) the mechanics and rates of sediment erosion, transportation and deposition, and the associated pathways and residence times of potential pollutants (fig. 12); (2) geologic hazards resulting from the instability, undesirable engineering properties, or sudden failure of marine sediment that may constrain or endanger development of seafloor areas; and (3) the hydrodynamic and sedimentologic parameters that control the formation of large accumulations of marine sediment as a model for understanding similar, ancient, onshore sediment bodies, wherein the role of the organic fraction and hydrocarbon potential needs particular emphasis.

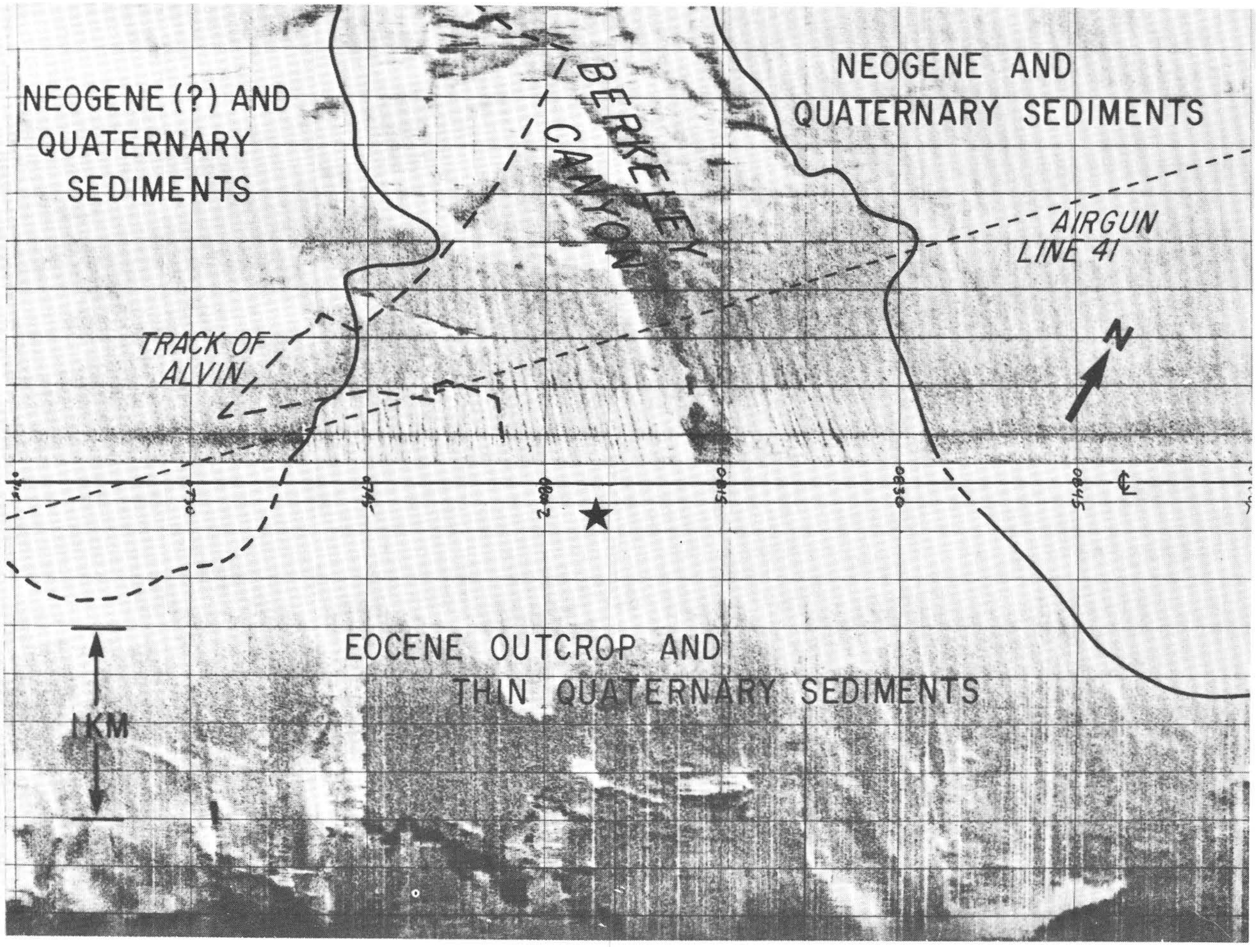


FIGURE 9.—Sea-MARC I side-scan sonograph of the lower continental slope off the Atlantic coast. The center line is the track made by the deeply towed instrument while it scanned acoustically to each side. Upslope direction is toward the top of the image. Striations in the center of the figure are of unknown origin. A close-up picture of one of them taken from the manned deep submersible *Alvin* is shown in fig. 10.

Studies of marine sediment deposits have a prominent role in the exploration for hydrocarbons and strategic metals such as titanium. The origin and concentration of these resources depend on the sedimentary environment in which the host rock was deposited, and models of the geometry and internal nature of such deposits provide a valuable exploration tool.

Representative goals of this program element are to:

1. Determine pathways and mechanisms of sediment transport by currents on the continental margin with particular regard to uptake, residence time, flushing and dispersal of contaminants.
2. Improve the understanding of sediment erosion and accumulation in coastal and nearshore areas.
3. Determine the regional extent and causes of submarine landslides and other forms of sediment instability that pose a risk to development on the continental margin.
4. Study the pertinent characteristics of large sediment bodies on the continental margin to provide critical information on modern and ancient environments of economic mineral and hydrocarbon deposits.

Accomplishment of these goals requires a multifaceted approach that combines new techniques for study of the seafloor, laboratory analysis, computer modeling, and comparison with ancient onshore examples and similar environments on other continental margins of the world. Techniques will also involve greater use of highly sophisticated acoustic techniques and a greater use of manned deep-diving submersibles. The latest acoustic systems are capable of mapping broad areas in a swath and geologists now can view the shape of seafloor features in two dimensions. On the other end of the scale, manned submersibles provide an opportunity to view the details of features close at hand, to photograph and sample what has been seen only by remote means. The combination of these two techniques opens new vistas for the study and subsequent understanding of geologic processes on the seafloor. Drillcores, where available, are of paramount importance in examining, and deciphering the history of, the sedimentary deposits. In all the program elements, but perhaps especially in this dynamic one, the complexity of the goals requires coordinated study by oceanographers, marine and on-land geologists, geophysicists, and geochemists within the USGS as well as specialists in industry and academia.

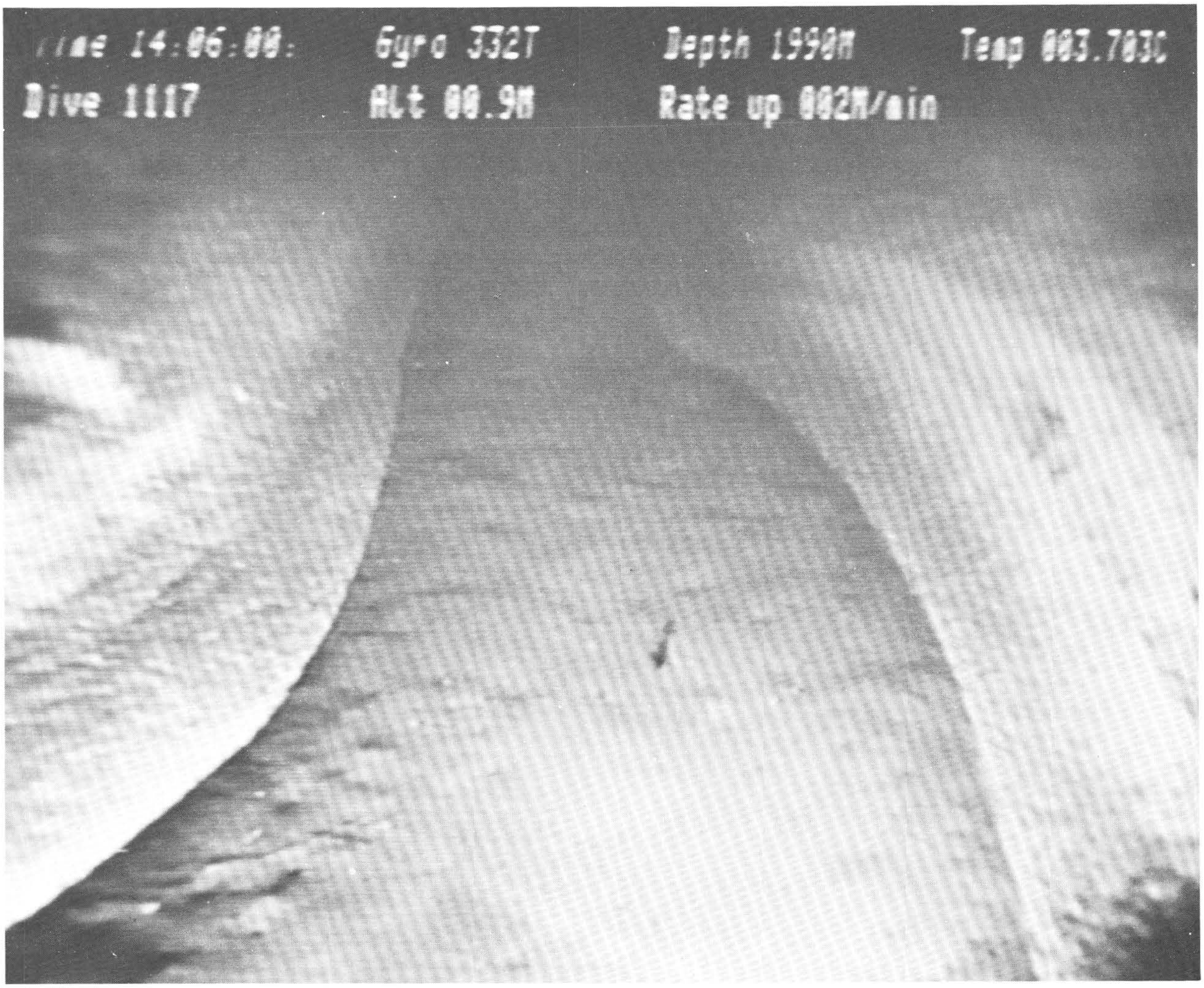


FIGURE 10.—Photograph of a video image taken from manned deep submersible *Alvin*. Photograph was taken looking upslope while tracing the 3–4-m-wide flat furrow. The origin of these almost straight furrows on the lower continental slope is unknown.

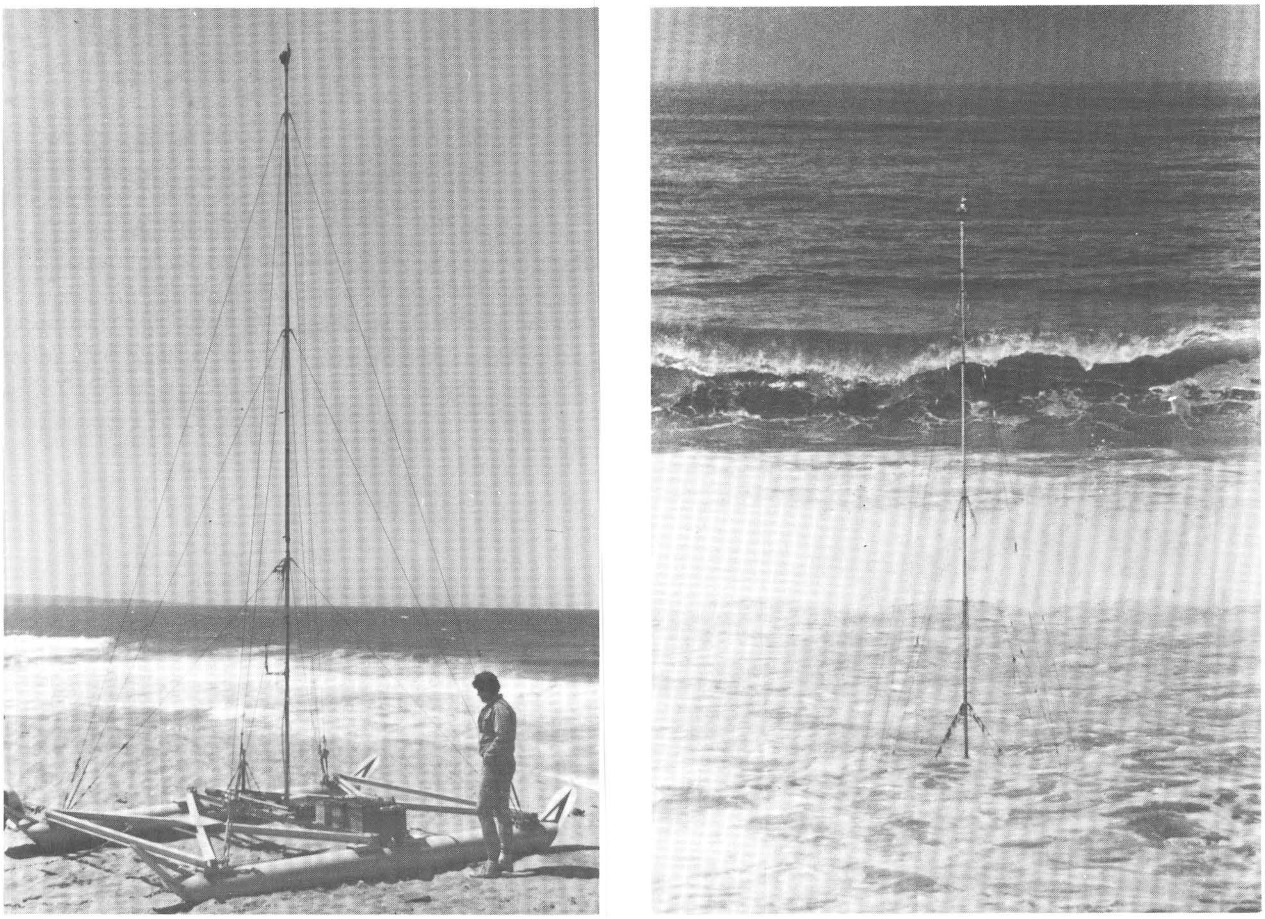


FIGURE 11.—In-situ measurements in the surf zone require a different technology. This instrumented sled was designed by USGS scientists to measure the water-sediment interaction in high-energy environments where conditions are difficult to study. It continues to take measurements and radio results directly to shore even under severe storm conditions.

Following are examples of activities appropriate to this element:

1. Mapping the shape, geometry, and environmental setting of modern shallow marine sand bodies to provide guidelines for exploration for strategic minerals and hydrocarbons in similar ancient deposits on land.
2. Examining the shape, geometry, and history of large deep-sea sediment bodies (submarine fans) to provide guidelines for exploration on land and for future exploration in the deep sea.
3. Conducting a shallow drilling program on the inner continental margin to examine long-term sedimentation history and engineering properties.
4. Establishing methods of modeling the erosional rates and causes on the various continental margins.
5. Conducting a broad-swath mapping sonar program on the Pacific and Alaskan margins to identify the morphology of the slope and rise, to map submarine canyons that can be conduits of sediment transport, and to map features indicative of seafloor instability.
6. Analyzing the physical and geochemical properties of unconsolidated marine sediment masses to determine the critical parameters that make them unstable.
7. Determining the cycles of erosion and deposition in the nearshore zone and relating these cycles quantitatively to the complex interaction of waves and currents, including their extreme conditions in storms.
8. Monitoring the long-term (greater than a year) variations in sediment concentration in near-bottom waters and the role of storms and regional currents in causing these changes.

9. Mapping the regional distribution of submarine landslides and establishing their relation to triggering mechanisms such as waves, currents, and earthquakes; to gravitational forces induced by slope gradients, rapid sedimentation, and excess pore pressures; and to geotechnical parameters such as consolidation rates.
10. Studying the combined influence of ice and waves on the erosion of coastlines, the redeposition of materials and the uptake of sediments by ice in polar regions to identify and understand those processes and their effects.

FORMATION OF MARINE ENERGY AND MINERAL DEPOSITS

Finds of new mineral deposits in the oceans during the past few years are high on the list of exciting geologic discoveries of the past decade. For several years, geologists had speculated that seawater and rock might react in areas of volcanic heating to form mineral deposits, and in 1979, massive sulfide deposits were discovered accumulating, just as expected, around a hydrothermal vent on the crest of the mid-ocean ridge in the Pacific Ocean. The mid-ocean ridge is a world-encircling mountain range, the crest of which represents the site of new crust forming in the ocean. Where the new crust generation is rapid the ridge is characterized by a shallow magma chamber that provides heat to the surface. Seawater reacts with hot rock in the walls of seafloor cracks and is convected vigorously to the surface where it discharges as hot water (350° C) laden with sulfides of zinc, copper, and silver (fig. 13), some of which precipitates to form deposits. Since the initial discovery, such sulfide deposits have been found at five other locations along the ridge (fig. 14). For the first time, geologists can witness a massive-sulfide type of deposit being formed. The value of research into this process has worldwide implications in onshore exploration for future deposits. Even though some of these deposits contain as much as 55 percent zinc, what their mineralogy, extent, and grade are, and whether they may some day constitute economic deposits under 2,000 to 2,500 m of water are as yet unanswered questions.

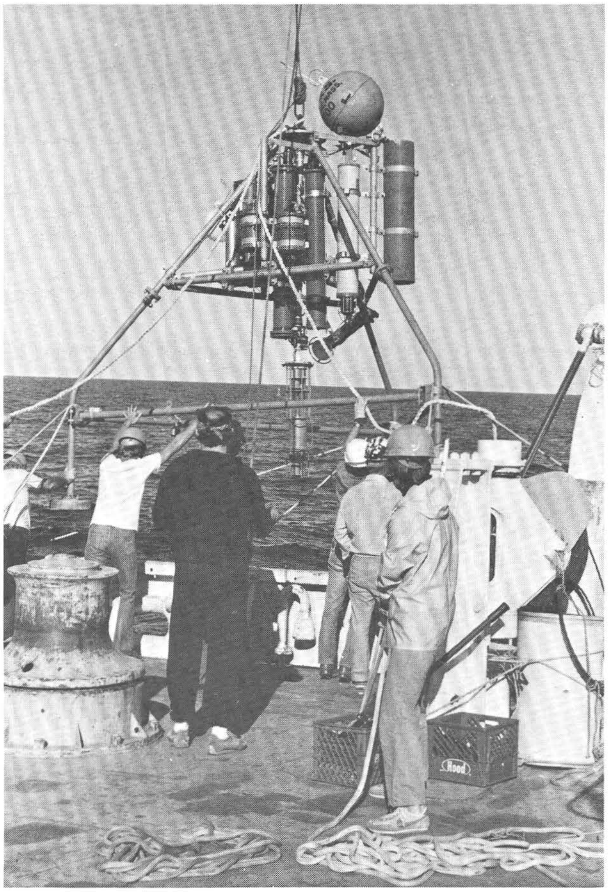


FIGURE 12.—Measurements of water dynamics and their effects on sediment mobilization are made by long-term measurements on the seafloor. The frame shown here holds sophisticated instruments that measure a suite of parameters during calm and stormy conditions. Anomalous readings by one instrument will activate others that lie dormant under "normal" conditions.

In addition to these rapidly forming sulfide deposits, manganese crusts recovered from seamounts in the Pacific Ocean were found to contain cobalt, the concentration of which increased as water depth decreased. The most favorable depth range, where the cobalt content exceeds that of commercial deposits onshore, is from 1,000 to 2,600 m. These deposits lie on the flanks of islands and seamounts within 200 nautical miles of U.S. territory.

The program element Marine Energy and Mineral Deposits is concerned with developing an understanding that will lead to geologic concepts from which we can define settings and conditions of the origin and concentration of marine minerals and hydrocarbons. The U.S. is dependent on foreign sources for a large percentage of its petro-

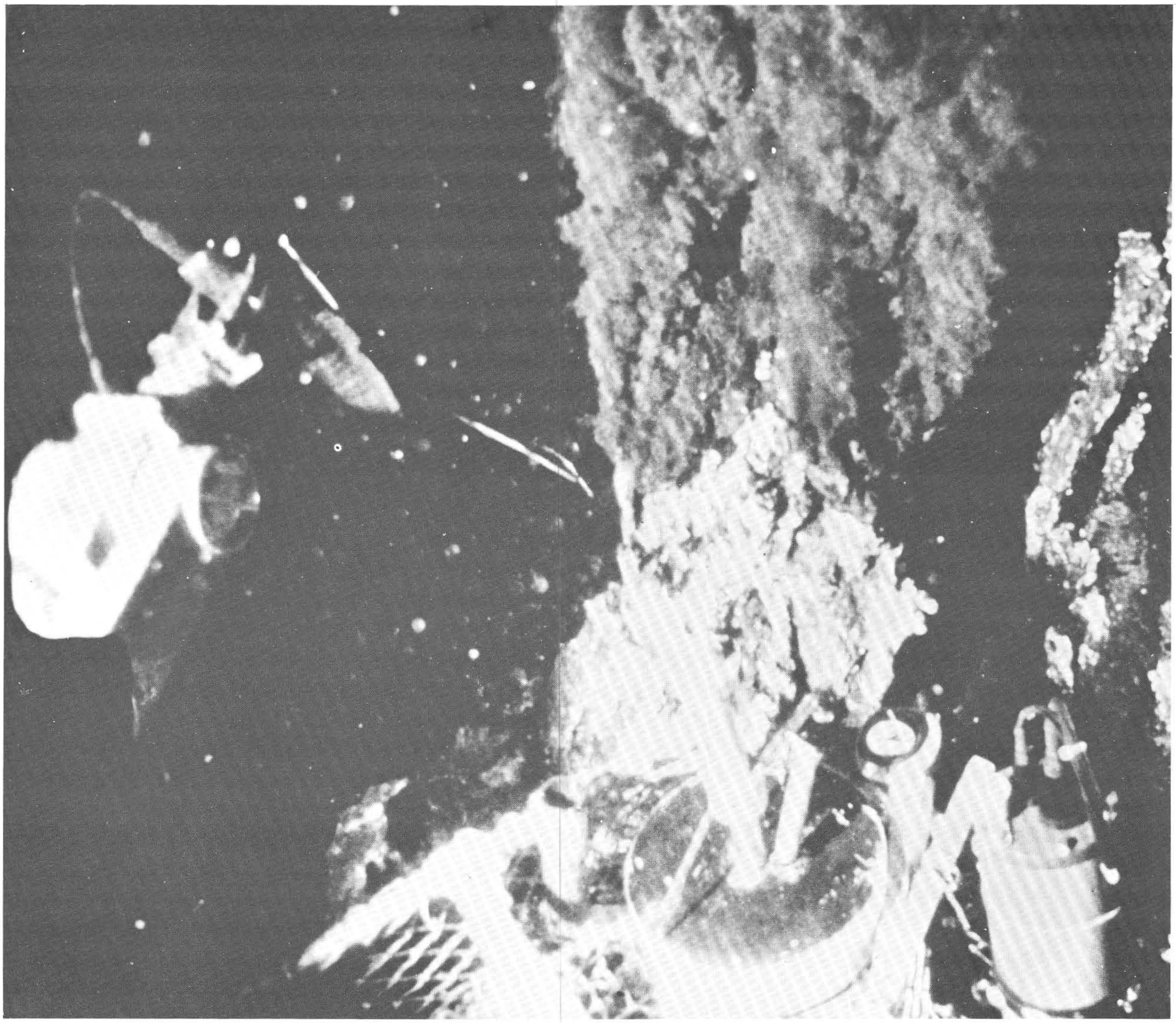


FIGURE 13.—Hydrothermal vent with sulfide-laden hot water pouring out into cold sea water on the ocean floor. Picture was taken from the manned deep submersible *Alvin*. On the left *Alvin*'s claw holds a temperature probe. The basket is for samples.

leum and for several strategic minerals, such as cobalt. This dependence underscores the need to perform research on the distribution and origins of these and other resources in the marine realm.

All three program elements come together in studying marine basins and sediment fans or wedges for hydrocarbons. It is necessary to understand the setting and character of the sediment accumulation, the source of the sediments, and the possibility of organic material being present and of thermal maturity sufficient to generate hydrocarbons that might migrate and become trapped. During the past few years, research by the USGS has revealed previously unknown arctic offshore basins of suspected petroleum resource potential. In addition, program scientists identified the possible occurrence of gas in the deep Aleutian Basin of the Bering Sea, through inferences from seismic records, and confirmed the presence of gas hydrates (gas and water in the solid state) in sediments lying in deep water off the Atlantic coast (fig. 15). Gas hydrates also may form an impermeable seal under which recoverable gas and oil may collect. With developing technologies, the gas hydrate itself may become an exploitable resource.

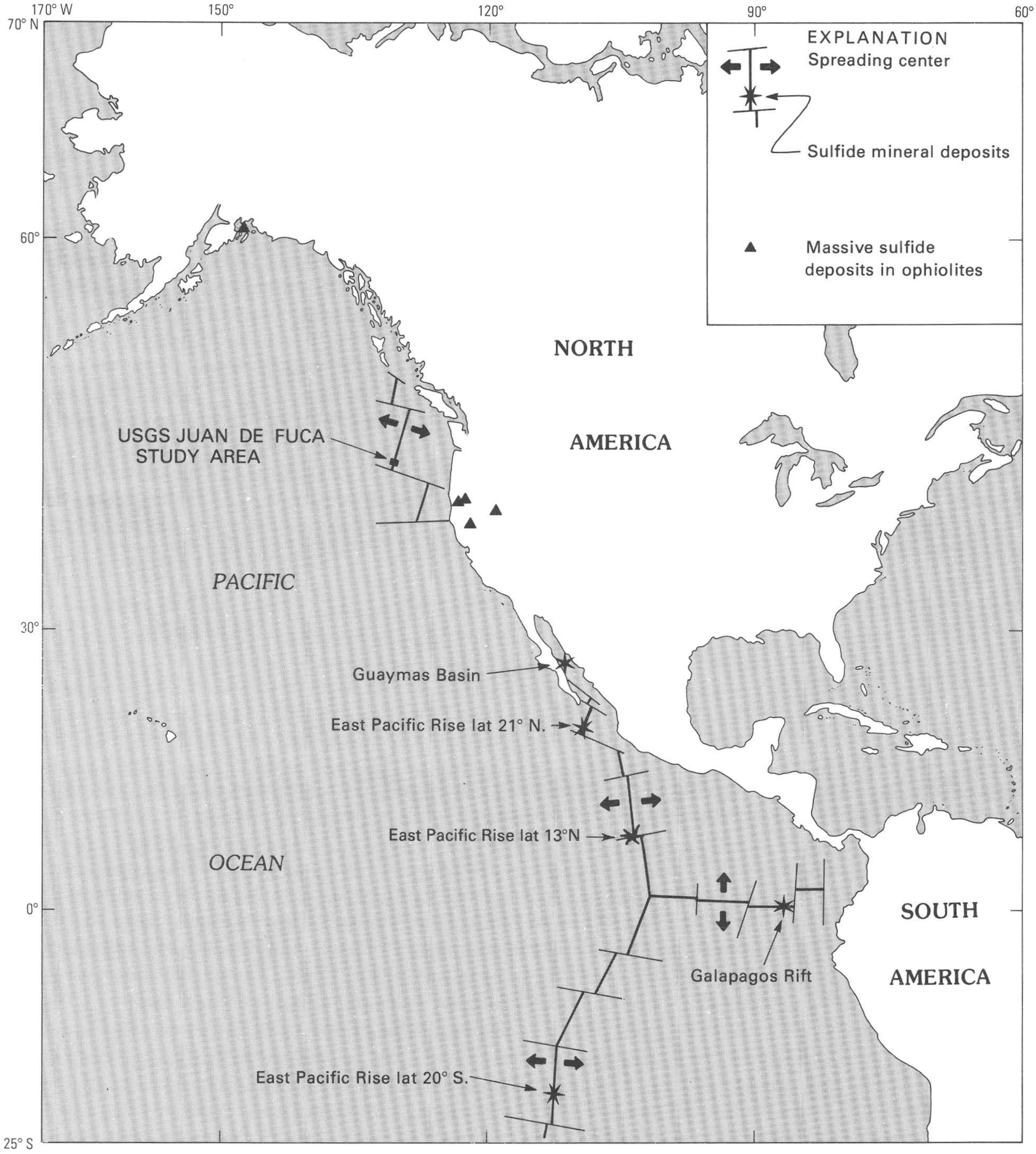


FIGURE 14.—Location of sulfide deposits on the crest of the mid-ocean ridge. The USGS discovered the deposits on the Juan de Fuca Ridge, 270 nautical miles off the Oregon coast.

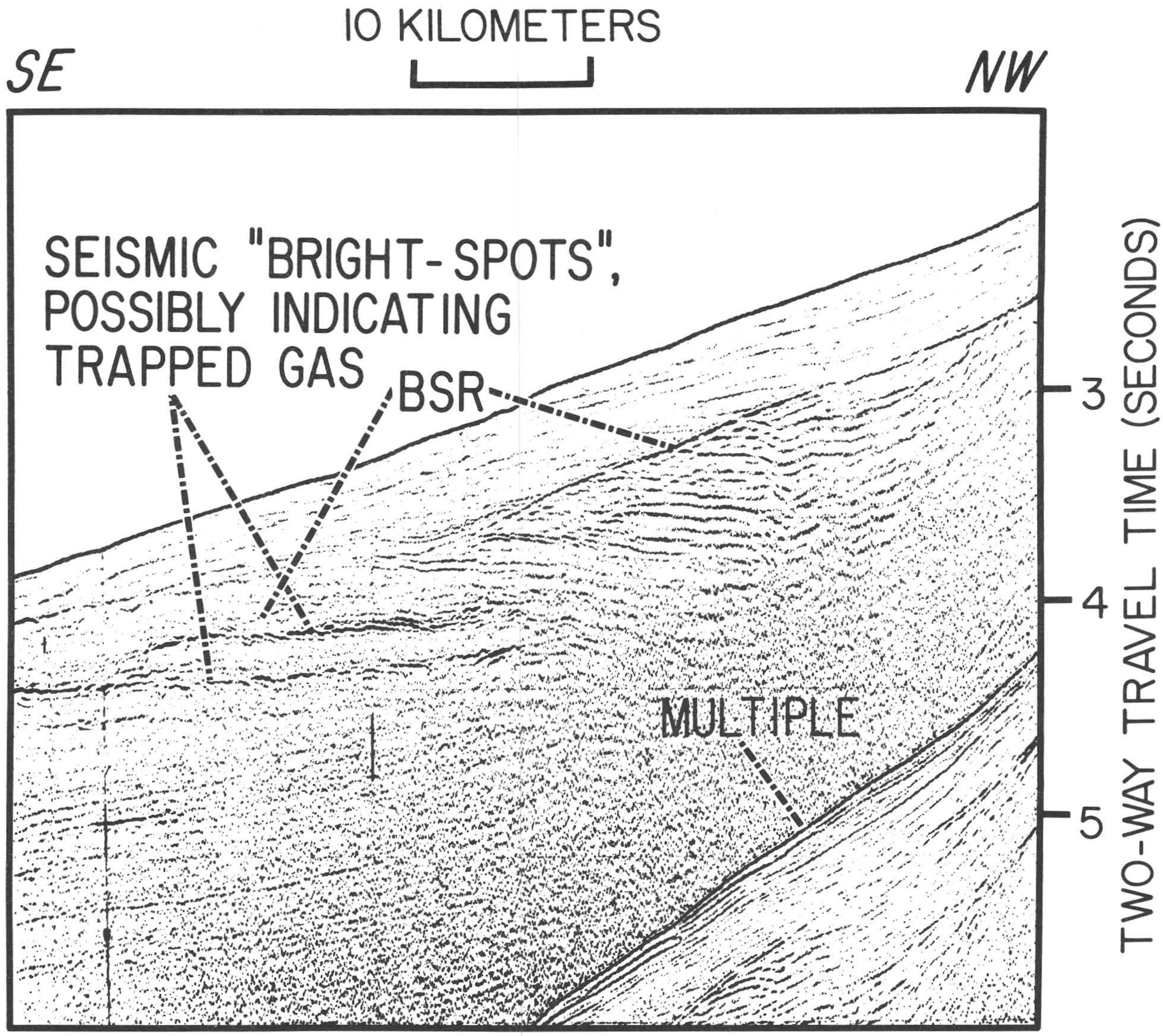


FIGURE 15.—Seismic record showing a "BSR", or Bottom Simulating Reflector, interpreted to be a gas hydrate (gas combined with water, forming an "ice"). The hydrate may have sealed the rock, forming an impermeable layer that has trapped gas by cutting across near-horizontal sedimentary layers.

Representative goals of the program element are to:

1. Map and determine the origins of cobalt-rich manganese encrustations on seamounts, oceanic plateaus, and the submarine slopes of islands and evaluate their resource potential.
2. Develop a fundamental understanding of the origin of sulfide-rich hot springs on the seafloor, the physical and chemical processes that form these massive sulfides, the sizes and distributions of the deposits (area resource assessment), and the relationships between seafloor mineralization and areas on land where similar geologic conditions in the past may have made ore deposition possible.
3. Determine whether gas hydrates present in marine sediments may be a hydrocarbon resource of the future.
4. Determine the origin and economic potential of hydrocarbons in frontier regions such as deep-water marginal basins or fans of the

continental slope and rise, ridge-top basins of island arcs, and subduction complexes.
5. Map the placer and sand and gravel deposits on the continental-shelf regions of the U.S.

To achieve these goals, sampling and mapping techniques will be used to evaluate mineral deposits and potential occurrences of hydrocarbons in geologic settings where oil and gas are not commonly found. In the future, verification of geologic interpretations based on remote means will be accomplished by the use of submersible vehicles and by deep drilling.

Following are examples of specific activities appropriate to this program element:

1. Dredging, drilling, bottom photography, and vent-water sampling of sulfide deposit vents identified at the south end of Juan de Fuca Ridge, off the coast of Oregon and Washington.
2. Dredging and coring of cobalt-manganese seafloor encrustations on Pacific seamounts to determine presence and extent of deposits.
3. Mineralogic/geochemical study of sulfide and cobalt-manganese samples to determine character, genesis, and possible resource potential.
4. Study of gas hydrates in the laboratory to define physical characteristics, together with detailed study of seismic records, to discover possible occurrence of gas hydrates in basin sediments.
5. High-resolution seismic-reflection surveys and coring to define sites for possible nearshore channel accumulations of sand and gravel, or placer minerals.

DOMESTIC AND INTERNATIONAL COOPERATION

Associated with the marine program is a large community of users, beneficiaries, and cooperating organizations including Federal agencies, State and local agencies, international agencies, academic institutions and researchers, and the public. The last category includes corporations, interest groups, and individual citizens. From numerous examples, a few that are highlighted follow.

The Office of Energy and Marine Geology has conducted cooperative programs with the Departments of State, Commerce, Defense, Energy, and Transportation, as well as other units in the Department of Interior. As one example of the need for geologic data by other Federal agencies, the Department of State has repeatedly requested interpretation and appraisals of geologic resources in offshore boundary areas. We have supplied negotiators with advice and evaluations for sectors adjacent to the Bahamas, Canada, Mexico, and the Soviet Union. With this resource information negotiators will be informed of long-term economic tradeoffs associated with boundary decisions still to be made. Currently, the USGS is adding a variety of information to its offshore geologic maps by conducting marine gravity and related surveys for the other Federal agencies.

Cooperative marine programs are in place with coastal States such as California, Texas, Connecticut, and Massachusetts. These continuing programs are designed to provide a series of geologic maps that facilitate the evaluation of potential resources (such as sand and gravel), the siting of coastal facilities, the identification of geologic hazards, and the assessments of the impact of pollutants introduced into the coastal environment. The USGS has maintained an active office in Puerto Rico that is engaged in continental shelf studies with a focus on sand and gravel resources that are almost nonexistent on land.

The USGS has recently completed a resource evaluation cruise to the South Pacific. Under the joint auspices of Australia, New Zealand, and the United States and supported by funding from Australia and the United States Agency for International Development, the USGS R/V *Samuel P. Lee* conducted 60 days of exploration in the Kingdom of Tonga, the Republic of Vanuatu (formerly the New Hebrides) and the Solomon Islands. Preliminary results of the spring 1982 cruise are already available, and the USGS geologists and geophysicists involved in the study are responding to enquiries from oil exploration companies interested in concessions or leases from the island nations. This type of foreign-aid investigation provides data and direction in regions where even a small oil or gas discovery would make a substantial improvement in the economics of these newly independent nations. The USGS has also conducted jointly sponsored geophysical and sonar-mapping surveys with the United Kingdom, France, West Germany, and Spain.

Cooperation with the Nation's academic institutions is primarily through institutions that have marine capabilities and programs. The USGS researchers working the Atlantic and Gulf of Mexico coasts have, for the last 5 years, used oceanographic ships and submersibles from Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory of Columbia University, the University of Rhode Island, the University of Miami, Duke University, the University of Texas, and Texas A & M. On the Pacific coast, USGS studies have involved ships, scientists, and equipment from Scripps Institute of Oceanography, the University of Southern California, Oregon State University, and the University of Washington. Recent research in the Juan de Fuca Ridge sulfide zone has been a cooperative effort between scientists from the USGS and the University of Washington. Major programs sponsored by the National Science Foundation and the former Bureau of Land Management to examine the mechanisms of sediment transport and landslides on the continental shelf have relied heavily on the successful cooperation between scientists in the USGS and academia.

Other interactions range from those with multinational corporations to those with individual citizens. For the American continental margins the USGS marine group has more publicly available data than any other group. In addition, by means of publishing in journals, issuing reports, and making presentations at professional and public meetings these data are released for public use. In return, this produces exchange of information of considerable benefit to the USGS.

Before the Minerals Management Service (MMS) was established the USGS marine program was an integral part of the offshore leasing process. Because the agencies were separated and USGS had no formal input into the system, valuable research information could be overlooked unless a formal mechanism of information transfer were to be established. Consequently, the two agencies have recently formally arranged USGS support for the MMS in summarizing the latest publicly available geologic and geoenvironmental studies on prospective lease areas.

The USGS has conducted many offshore studies for the Bureau of Land Management's (BLM) Environmental Studies Program. The studies focused on features of the seafloor that could present a hazard to development and on paths and rates of current-transported sediment that would define the dispersal route of pollutants. Some of these studies are continuing through the same BLM group that is now housed in the Mineral Management Service.

The USGS and the National Oceanic and Atmospheric Administration (NOAA) have engaged in cooperative studies on the Outer Continental Shelf (OCS) and in the deep water mineral regime. On the OCS, responsibility for various energy-related studies was defined by Memorandum of Understanding (MOU) in which investigations of the water column and marine biology were accepted as the responsibility of NOAA and investigations of nonliving resources of the sea were to be conducted by the USGS. In the absence of a MOU for research responsibility in the deep ocean, the USGS and NOAA worked cooperatively on manganese nodule studies in preparation for anticipated deep-ocean mining.

IMPORTANT RESEARCH DIRECTIONS

COMPREHENSIVE ANALYSIS OF MARINE BASINS ON CONTINENTAL MARGINS

Depositional basins are major geologic features that essentially compose the sedimentary geologic record and reflect the tectonic history of any area. Marine depositional basins, which typically form on the margins of continents, are particularly important as the Nation's primary source of oil and gas. Similarly, other large-scale depositional features, such as the wedge of sedimentary rock which forms the coastal plain and continental margin, often contain important water, mineral, and hydrocarbon resources. Successful prediction of these resources requires understanding of basin history including its tectonic framework and depositional, thermal, and diagenetic processes.

The broad outlines of most of the depositional basins on the continental margins of the United States have been defined and their relation to components of present-day crustal plates established. However, the precise character of the sediments that fill the basins on the continental margin, and their depositional histories, are generally unknown and, in the absence of drill-hole data, can be inferred only from interpretation of seismic stratigraphy, gravity, or other geophysical evidence. Geophysical interpretations depend on the physical properties of the rock and sediment within the basin, and, in the absence of samples, can be based only on expert opinion and analogy with similar, better known areas. Active thermal processes can be measured in a modern basin, but without data pertaining to the composition of the basin sediment and fluids it is difficult to define the processes of diagenesis and hydrocarbon maturation active within the basin.

Some of the basins have been drilled and available well samples can be used to improve and evaluate geophysical interpretations. As the Department of Interior's Outer Continental Shelf Leasing Program progresses, more well data will become available and more definitive basin analyses can be made.

Antarctica

In less than a decade the Antarctic Treaty will be due for consideration by nations interested in that continent and its potential resources. Recent events (1982 Consultative Meeting, Antarctic Treaty Nations) indicate that the Antarctic Treaty Nations will work towards establishing a regime for assessing Antarctic mineral resources. The potential for finding mineral resources offshore is believed to be substantial, and this evaluation has motivated Russia, Norway, Germany, and Japan to conduct marine geophysical surveys to collect data necessary for basic research and for the assessment of oil and gas resources as well. The United States has no such data. The USGS has a multipurpose ice-strengthened geophysical research vessel with proven ability from extensive high-arctic experience. Surveys conducted with this ship will provide mineral and energy resources data for the assessment of Antarctic minerals by Treaty Nations. The Survey's Antarctic program plans are being developed with approval of the Antarctic Policy Group and in cooperation with the National Science Foundation, which manages the U.S. Antarctic Research Program.

Antarctica is one of the most challenging areas for marine research. The separation of Antarctica and Australia began about 55 million years ago and for the following 20 million years an extensive rift basin existed, in which organic carbon-rich silts and clays were deposited. These sediments are the source rocks from which were generated the rich oil and gas deposits of the Tasman Straits. Thus the Antarctic margin conjugate to the Tasman area (Cape Adare, Bellemy Basin, and Ross Sea Shelf) may hold promise for the generation of oil and gas.

At about 38 million years ago there was a drastic climate deterioration initiating major continental glaciation that continued to the present. In its present polar position, Antarctica has been the primary source of the cold saline bottom waters that have circulated throughout the world's oceans influencing the distribution of seafloor sediment for millions of years.

The primary scientific objective of our Antarctic marine program would be the understanding of the basic geological framework of the Antarctic continental margin. The location, geometry, and orientation of the major sedimentary basins and the sedimentary units contained within them should be surveyed, studied, and mapped (fig.16). Major structural trends and characteristics should be examined to further our understanding of the nature of the separation at the continental margin and the development of structural trends that may have been imprinted at a later time. Seismic surveys of the young continental margin in this passive plate-tectonic setting also will provide stratigraphic information that bears on the effects of rifting and subsequent thermal subsidence. These studies are fundamental to the appraisal of oil and gas resources and have considerable analogy with the older, but similar, eastern margin of the North American plate.

Morphological studies on the Antarctic continental margin are of particular interest because the continental shelf is much deeper (about 350 m) than the average of about 130 m over most of the world ocean. A major unanswered question is whether the depth of the shelf results from crustal depression caused by the weight of the glaciers or whether the sediment accumulation has not kept pace with crustal subsidence. In addition, parts of the continental shelf are characterized by inner-shelf troughs that are about 200 to 300 m in depth below the seafloor and lie parallel to the coast. The origin of these features is unknown, but it is believed that they are related in some way to the ice.

Caribbean Basin Studies

The Caribbean Basin is geologically one of the most complex assemblages of island arc, continent, and ocean crust in the world. Studies in this

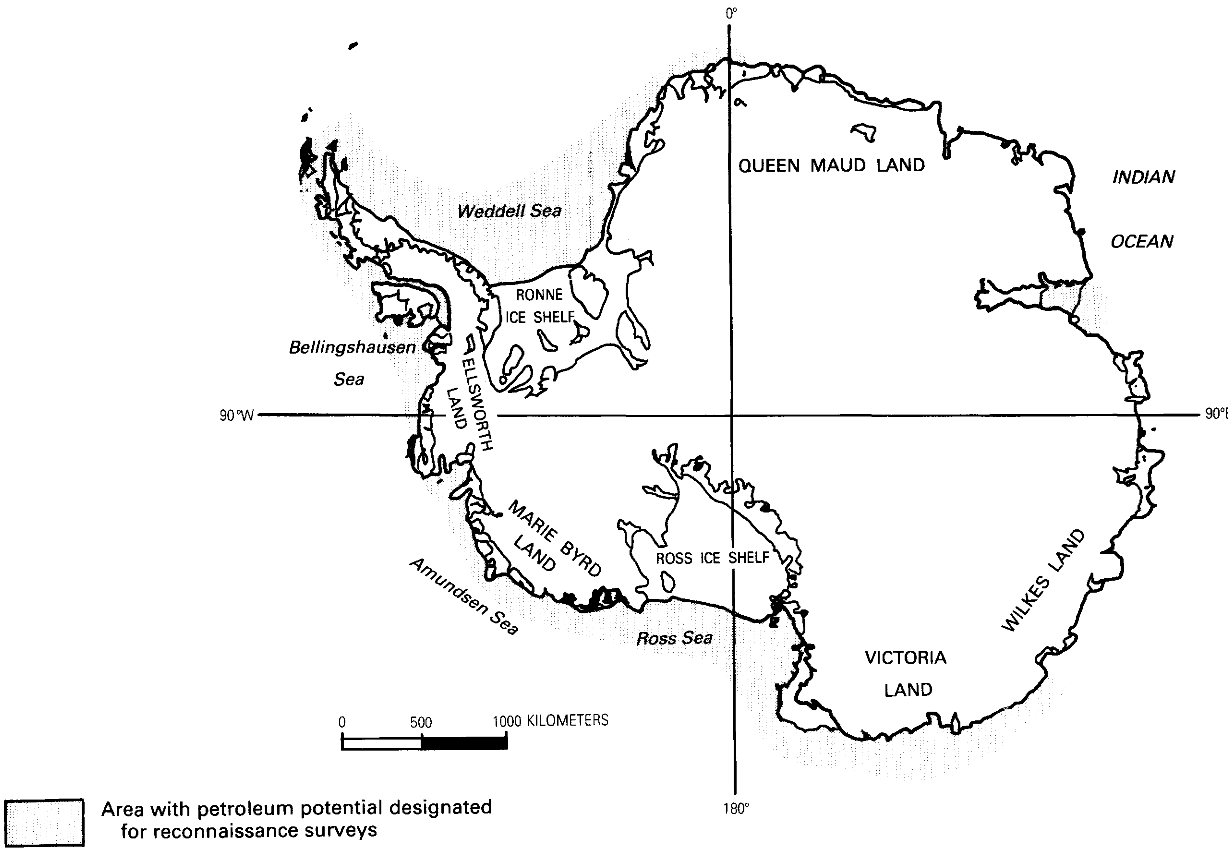


FIGURE 16.—Map of Antarctica showing the offshore areas that may have petroleum potential. Plans call for surveys seaward of the ice in these areas.

area can provide much needed insight into the nature of the interaction among the various crustal components. The Caribbean Sea once may have been a piece of the Pacific Ocean that became trapped like a wedge between North and South America as the two continents separated during their westward drift away from Africa and Europe. What then was the origin and geologic history of the Greater and Lesser Antilles during this major crustal interaction and how did the east-west movement affect the development of the northern margin of South America? The answers to these fundamental questions provide the framework for developing the geologic understanding needed for energy and mineral resource appraisal of the Caribbean Basin. The southwestern end of the Caribbean is also of great interest for it is there that the Pacific and Caribbean crusts decoupled, and plate-tectonic interactions resulted in a land barrier between the two oceans.

A major research objective would be to evaluate the overall potential for energy and mineral resources in the offshore areas of the Caribbean Basin. For many of the countries, geophysical studies are inadequate to evalute the regional structure, so additional data will be gathered where needed. It is particularly important that the study be conducted on a regional basis, rather than country-by-country, because geologic provinces need to be studied and evaluated in total to understand the framework and to make a responsible assessment. For example, the Greater Antilles are a part of one continuous geologic structure. Hence, the mineral and energy appraisal for each country must be done in the context of the entire Antilles structure.

Resource Appraisal of the National Marine Domain

The United States recently established an Exclusive Economic Zone that will increase the area of national domain by about one and two-thirds. Almost all the deep water and continental margin areas (fig. 17) that may be of interest around the United States are frontier regions where geologic data are sparse. Our familiarity with the subsea geologic provinces and our knowledge of the seafloor mineral resource potential are but rudimentary.

The type, size, and location of potential resources in these extensive subsea areas are prerequisite for the formulation of a sound national energy and strategic minerals policy. Knowledge obtained through research in this area will almost certainly lead to the recognition of new geological factors that could aid in the discovery of new mineral-bearing and (or) petroliferous provinces, both beneath the oceans and on land.

Geophysical, geological, and geochemical techniques will be used to collect data needed for appraisal of the resource potential of selected important areas and geologic settings such as: (1) deep sea fans (examples—Astoria, Monterey, and Mississippi); (2) sediments of the lower continental slope, particularly along deformation fronts (examples—Oregon and Washington margin); (3) continental rises (examples—Arctic Basin and Atlantic rise); and (4) modern and ancient plate-tectonic collision complexes (examples—Aleutian Trench, Washington and Oregon outer continental shelves).

Offshore Geologic Mapping

Over the years, as individual marine surveys have been completed, the USGS has released immense amounts of reconnaissance or detailed survey data in maps and other formats. Work is now beginning to pull these data, of widely varying kinds and scales, and of nonuniform distribution, into a formal series to be called "Marine Geologic Atlas." Intended coverage is the entire United States continental margin. Map scale will depend in places on abundance of data but generally will be at 1:1,000,000. Data displayed will include, as available, bathymetry framework geology, cross sections, geohazards, sediment thickness, structure contours, surface sediment distribution, physiographic provinces, gravity, magnetics, seismicity, resources, and special features such as diapirs and sediment-transport directions. Image bases will be produced, with interpretation maps, where seafloor sonar images have been taken.

APPENDIX OF SELECTED ACCOMPLISHMENTS

The Survey's marine geologists and geophysicists undertook a monumental task of surveying the Nation's continental shelf to evaluate the offshore oil and gas potential and provide the government with an understanding of where the best prospects may be found. USGS scientists discovered large sedimentary basins such as the Navarin, Hope, North Chukchi, and Amlia Basins off Alaska and the Carolina Trough off the Atlantic margin. These investigations greatly improved our understanding of the structure and history of development of our continental margin—an understanding that has been instrumental in providing responsible assessments of the energy and mineral potential of the area.

Following the Santa Barbara oil-well blowout the USGS undertook a major program of evaluating the continental shelf in terms of geologic features that could be hazardous to exploration and development. Potential hazards include active faulting, earthquakes, shallow gas, sediment mass-movement, sediment instability, and ice effects. Regional maps were prepared showing where various potential hazards exist and where special care should be exercised in evaluating individual tracts for stipulations or deletions.

USGS scientists were part of the team that first discovered the sulfide-rich hydrothermal vents in the Pacific, first recognized rocks recovered from the area as possible metal-rich sulfides, discovered vents on the Juan de Fuca Ridge off Oregon, and made pioneering studies into the geochemical mechanism of sulfide enrichment in the hot vent waters. Survey scientists discovered that the cobalt content of manganese crusts coating the sides of seamounts and islands in the central Pacific Ocean increases with decreasing water depth to about 1,000 m and may be a significant resource. The cobalt content, which exceeds 1 percent, is of possible economic interest particularly in the shallow-water regions around U.S.-related islands in the Pacific Ocean.

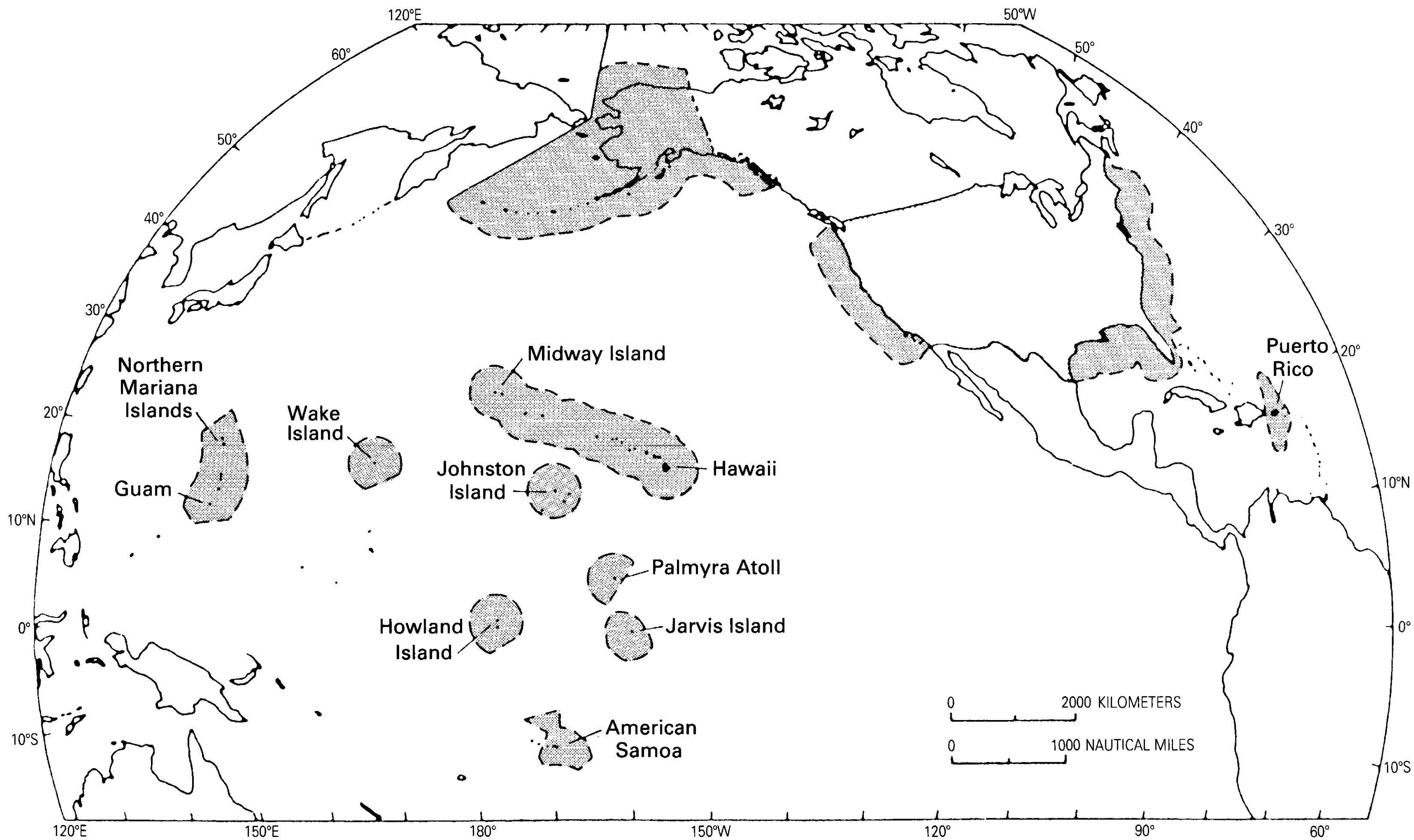


FIGURE 17.—Map showing offshore area covered by a 200-nautical-mile Exclusive Economic Zone (EEZ) of the United States, Commonwealth of Puerto Rico, Commonwealth of the Northern Mariana Islands, and overseas possessions (outlines of map are approximate). The area is about two-thirds larger than the size of the conterminous U.S. and Alaska. Geologic studies of these areas will be needed to evaluate their mineral potential. Square kilometers now deemed within the U.S. EEZ include U.S. proper—11.2 million; Commonwealth of Northern Mariana Islands—1.2 million; and Territories, possessions, etc.—3.3 million (U.S. Department of the Interior/Geological Survey).

Researchers studying the seafloor seaward of the continental shelf documented large-scale mass wasting of the continental slope as indicated by careful mapping of canyons, cliff faces, sediment slumps, cirquelike features and large blocks of sediment that have slid and rolled down the slope. Slide scars have been documented on the slope seaward of Georges Bank but the slope off Baltimore Canyon appears to be relatively stable. Off the east coast of Florida, divers with a manned deep submersible indicate erosion or mass wasting of enormous sea cliffs in the order of kilometers.

Gas hydrates have been mapped by seismic techniques on the Atlantic margin and along the continental margin north of Alaska. These hydrates may form impermeable seals capable of trapping underlying gas in the free state. Indications of trapped free gas have been found on the Atlantic margin. Not all seismic reflections have the characteristics of hydrates; USGS scientists discovered that similar reflection may be caused by the conversion of siliceous fossils (diatoms) to a different form of silica.

The USGS has mapped the regional extent of VAMPS—deep water bright spots of seismic anomalies—that signal the potential of gas in the deepest (3,000 m) part of the Bering Sea.

The Office of Energy and Marine Geology entered into a tripartite agreement with Australia and New Zealand to apply our resource investigations for the benefit of South Pacific nations. These studies were conducted by the Office of the Coordinating Countries for Offshore Prospecting (CCOP) of the United Nations Development Program (UNDP). In support of these resource investigations, the Survey's R/V *Samuel P. Lee* operated off Tonga, Vanuatu, and the Solomon Islands in April, May, and June 1982. Multichannel, geophysical, and bathymetric data, and samples of submerged outcrops were collected and demonstrated that there is oil and gas potential within the study area.

Marine studies also have played a major role in understanding coastal-zone processes and conditions. An accomplishment of great public importance was the determination that throughout large areas of the San Francisco Bay, critical biological conditions were inextricably linked to the passage of Sacramento River through the bay. These studies have influenced scientific, public, and political decisions regarding development in this region.

USGS scientists developed techniques for mounting an array of instruments on a frame that is lowered to the seafloor and monitors for months at a time bottom currents, waves, and sediment transport. These measurements and photographs demonstrated that storms violently disturbed the seafloor at depths much greater than previously believed. The information has provided important insight regarding the significance of brief storm events and mobility of large sand-wave fields, all of which point to the pathways that would be followed by pollutants.

Investigations in the Beaufort and Chukchi Seas off northern Alaska have demonstrated that ice keels (downward projections of floating ice) have gouged deeply (several meters) into the seafloor. These gouges are extremely numerous and extend into water depths greater than 50 m. On the basis of these discoveries, it is apparent that oil pipelines and other seafloor mounted systems must be buried to prevent damage and possible rupture.

While engaged in geologic studies, USGS scientists discovered that Pacific Gray whales feed on organisms in sand and gravel deposits on the seafloor offshore Alaska. The removal of sand and gravel from these areas for construction of offshore exploration drilling islands, roads, causeways, etc., could have a significant effect on the whale population.

At the request of the Government of the U.S. Virgin Islands, a U.S. Trust Territory, the Survey mounted a search for offshore sand that could be used in construction. The Virgin Islands, like many Caribbean islands, have little or no onshore sand except for the tourist-populated beaches which are illegally mined to the detriment of the tourist business. The Survey found large accumulations of offshore sand deposits, capable of supplying the Virgin Islands for about 300 years at the current rate of consumption. Similar studies in shallow waters around Puerto Rico also resulted in discovery of huge deposits of sand of great economic importance.