Chapter 2
Resource Assessments and Expectations

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Resource Assessments and Expectations

WORLD OUTLOOK FOR SEABED MINERALS

Ever since the recovery of rock-like nodules from the deep ocean by the research vessel *H.M.S. Challenger* during its epic voyage in 1873, there has been persistent curiosity about seabed minerals. It was not until after World War II that the black, potato-sized nodules like those found by the *Challenger* became more than a scientific oddity. As metals prices climbed in response to increased demand during the post-war economic boom, commercial attention turned to the cobalt-, manganese-, nickel-, and copper-rich nodules that litter the seafloor of the Pacific Ocean and elsewhere. Also, as the Nation's interest in science peaked in the 1960s, oceanographers, profiting from technological achievements in ocean sensors and shipboard equipment developed for the military, expanded ocean research and exploration. The secrets of the seabed began to be unlocked.

Even before the *Challenger* discovery of manganese nodules, beach sands at the surf's edge were mined for gold and precious metals at some locations in the world (box 2-A). There are reports that lead and zinc were mined from nearshore subsea areas in ancient Greece at Laurium and that tin and copper were mined in Cornwall.[1] Coal and amber were mined in or under the sea in Europe as early as 1860. Since then, sand, gravel, shells, lime, precious coral, and marine placer minerals (e.g. titanium sands, tin sands, zirconium, monazite, staurolite, gold, platinum, gemstones, and magnetite) have been recovered commercially. Barite has been recovered by subsea quarrying. Ironically, deep-sea manganese nodules, the seabed resource that has drawn the most present-day commercial interest and considerable private research and development investment, have not yet been recovered commercially. Rich metalliferous muds in the Red Sea have been mined experimentally and are considered to be ripe for commercial development should favorable economic conditions develop.

Recent discoveries of massive polymetallic sulfides formed at seafloor spreading zones where superheated, mineral-rich saltwater escapes from the Earth's crust have attracted scientific interest and some speculation about their future commercial potential. These deposits contain copper, zinc, iron, lead, and trace amounts of numerous minerals. Similar deposits of ancient origin occur in Cyprus, Turkey, and Canada, suggesting that more knowledge about seabed mineralization processes could contribute to a better understanding of massive sulfide deposits onshore. Cobalt-rich ferromanganese crusts, found on the slopes of seamounts, have also begun to receive attention.

Beach placers and similar onshore deposits are important sources of several mineral commodities elsewhere in the world, Marine placer deposits of similar composition often lay immediately offshore. Among the most valuable marine placers, based on the value of material recovered thus far, are the cassiterite (source of tin) deposits off Burma, Thailand, Malaysia, and Indonesia. The so-called "light heavy minerals"—titanium minerals, monazite, and zircon—are found extensively along the coasts of Brazil, Mauritania, Senegal, Sierra Leone, Kenya, Mozambique, Madagascar, India, Sri Lanka, Bangladesh, China, and the southwestern and eastern coasts of Australia.

Although Australia has extensively mined "black" titaneous beach sands along its coasts, offshore mining of these sands has not proven economical.[2] Titaniferous magnetite, an iron-rich titanium mineral, has been mined off the southern coast of Japan's Kyushu Island.[3] Similar magnetite deposits exist off New Zealand and the Gulf of St. Lawrence. Chromite placers are extensive on beaches and in the near offshore of Indonesia, the Philippines, and New Caledonia. Chromite-

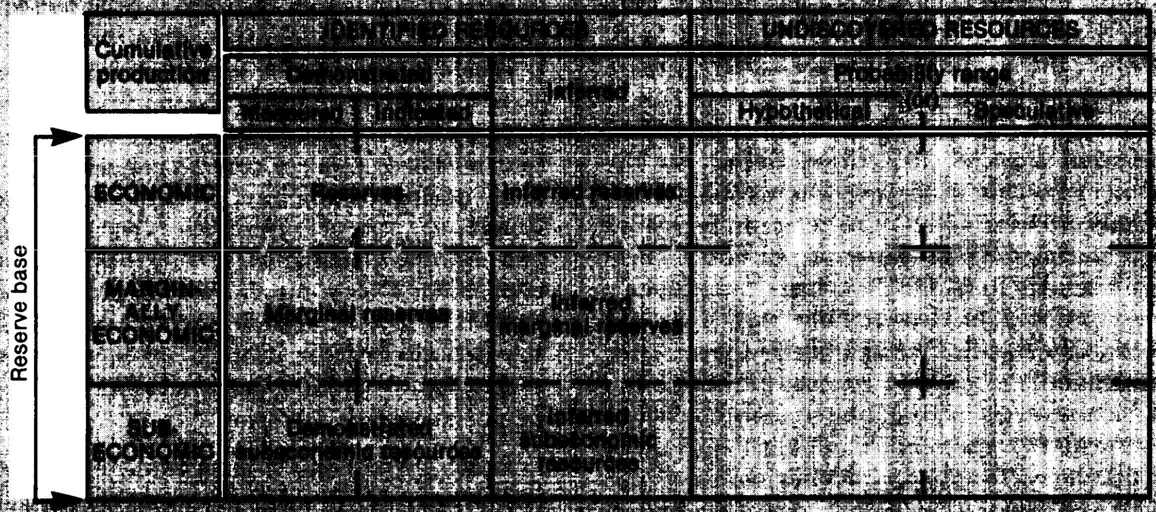
[1] M.J. Cruickshank and W. Siapno, "Marine Minerals—An Update and Introduction," *Marine Technology Society Journal*, vol. 19, 1985, pp. 3-5.

[2] I. Morley, *Black Sands: A History of the Mineral Sand Mining Industry in Eastern Australia* (St. Lucia: University of Queensland Press, 1981), p. 278.

[3] J. Mere, *The Mineral Resources of the Sea* (New York, NY: Elsevier Publishing Co., 1965), p. 16.

Box 2-A.—Mineral Resources and Reserves

A general classification for describing the status of mineral occurrences was developed by the U.S. Geological Survey and the U.S. Bureau of Mines in 1976. The so-called "McKelvey Box" named after the then-director of the USGS, Vincent McKelvey, further simplified the understanding of the economic relationships of the mineral-resource classification system.



The system is based on the judgmental determination of present or anticipated future value of the minerals in place according to the opinions of experts. Below are the economic definitions on which the resource-classification system is based:

- *Resource:* Naturally occurring material in a form and amount that economic extraction of a commodity is potentially feasible.
- *Identified Resources:* [illegible] characteristics are known or reliably estimated.
- *Demonstrated Resources:* Resources [illegible] and characteristics have been measured directly with [illegible] certainty (*indicated*).
- *Inferred Resources:* Resources estimated from assumptions and evidence that minerals may occur beyond [illegible].
- *Reserve Base:* Part of an identified resource that meets the economic, chemical and physical requirements that would allow it to be mined, including that which is estimated from geological knowledge (inferred reserve base).
- *Reserves:* Part of the reserve base that could be economically extracted at the time of determination.
- *Marginal Reserves:* Part of the reserve base that, at the time of determination borders on being economically producible.
- *Undiscovered Resources:* Resources whose existence is only postulated.

bearing beach sands were mined along the southern coast of Oregon during World War 11 with government support.

Gold has been mined from many beach placers along the west coast of the United States and elsewhere in the world. Marine placers of potentially minable gold are located in several nearshore Alaskan areas in the Bering Sea, Gulf of Alaska, and adjacent to southeastern Alaska. A commercial gold dredge mining operation was begun by Inspiration Resources near Nome in 1986, but a number of nearshore gold operations in the Nome area have been attempted and abandoned in the past. Diamonds have been recovered from nearshore areas in Namibia, Republic of South Africa, and Brazil.

The recovery of sand and gravel from offshore far exceeds the extent of mining of other marine minerals.[4] In the United States, offshore sand and gravel recovery is primarily limited to State waters, mostly in New Jersey, New York, Florida, Mississippi, and California. Japan and the European countries have depended more on marine sand and gravel than has the United States because of limited land resources. Special uses can be made of marine sand and gravel deposits in the Alaskan and Canadian Beaufort Sea—the offshore oil and gas industry uses such material for gravel islands and gravel pads for drilling.

[4] J. M. Broadus, "Seabed Materials," *Science*, vol. 235, Feb. 20, 1987, pp. 853-860. Also see M. Baram, D. Rice, and W. Lee, *Marine Mining of the Continental Shelf* (Cambridge, MA: Ballinger, 1978), p. 301

GENERAL GEOLOGIC FRAMEWORK

The potential for the formation of economic mineral deposits within the Exclusive Economic Zone (EEZ) of the United States is determined by the geologic history, geomorphology, and environment of its continental margins and insular areas. Continental margins are a relatively small portion of the Earth's total surface area, yet they are of great geological importance and of tremendous linear extent. In broad relief, the Earth's surface consists of two great topographic surfaces: one essentially at sea level—the continental masses of the world, including the submerged shelf areas—and the other at nearly 16,000 feet below sea level—representing the deep ocean basins. The boundaries between these two surfaces are the continental margins. Continental margins can be divided into separate provinces: the continental shelf, continental slope, and continental rise (see figure 2-1).

Continental margins represent active zones where geologic conditions change. These changes are driven by tectonic activity within the Earth's crust and by chemical and physical activity on the surface of the Earth. Tectonic processes such as volcanism and faulting dynamically alter the seafloor, geochemical processes occur as seawater interacts with the rocks and sediments on the seafloor, and sedimentary processes control the material deposited on or eroded from the seafloor. All of these processes contribute to the formation of offshore mineral deposits.

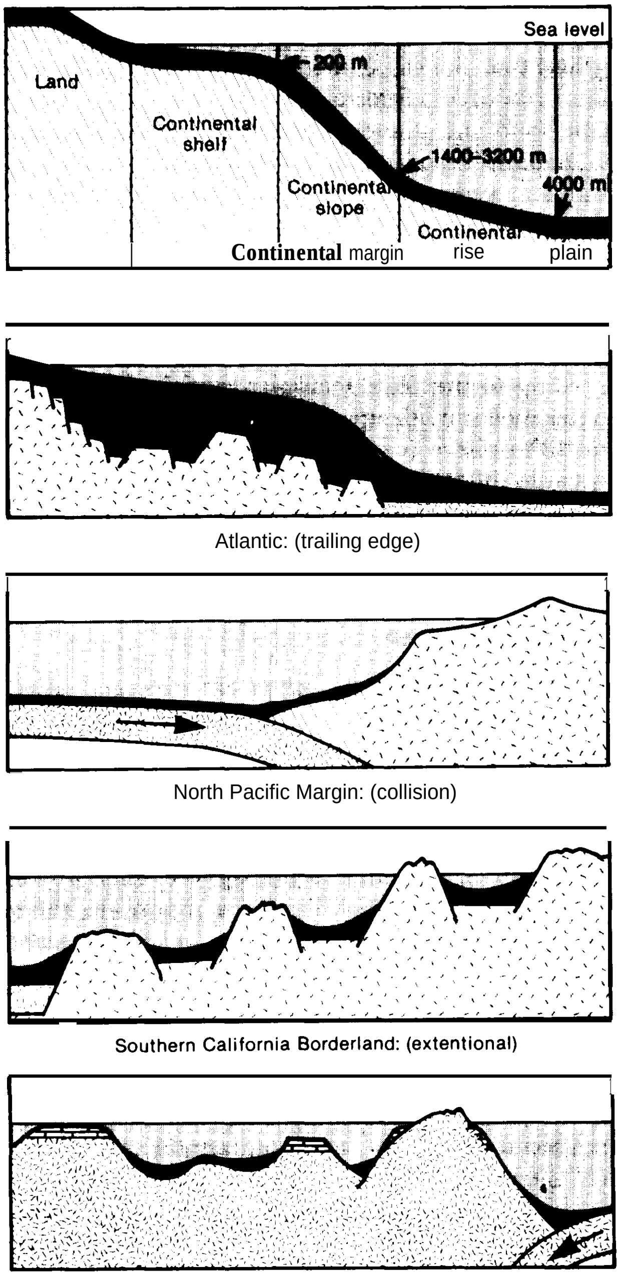
Advanced marine research technologies developed since World War II and the refinement and acceptance of the plate-tectonics theory have created a greater understanding of the dynamics of continental margins and mineral formation. According to the plate-tectonics model, the Earth's outer shell is made up of gigantic plates of continental lithosphere (crust and upper mantle) and/or oceanic lithosphere. These plates are in slow but constant motion relative to each other. Plates collide, override, slide past each other along transform faults, or pull apart along rift zones where new material from the Earth's mantle upwells and is added to the crust above.

Seafloor spreading centers are divergent plate boundaries where new oceanic crust is forming. As plates move apart, the leading edge moves against another plate forming either a convergent plate boundary or slipping along it in a transform plate boundary. Depending on whether the leading edge is oceanic or continental lithosphere, this process may result in the building of a mountain range (e.g., the Cascade Mountains) or an oceanic island arc (e. g., the Aleutian Islands) or, if the plates are slipping past one another, a transform fault zone (e.g., the San Andreas fault zone).

Four types of continental margins border the United States: active collision, trailing edge, extensional transform, and continental sea. Where collisions occur between oceanic plates and plates containing continental land masses, the thinner oceanic plate will be overridden by the thicker, less dense continental plate. The zone along which one plate overrides another is called a subduction zone and frequently is manifested by an oceanic trench.

Coastal volcanic mountain ranges, volcanic island arcs, and frequent earthquake activity are related to subduction zones. This type of active continental margin borders most of the Pacific Ocean and the U.S. EEZ adjacent to the Aleutian chain

Figure 2-1 .—Idealized Physiography of a Continental Margin and Some Common Margin Types



Atlantic: (trailing edge)

North Pacific Margin: (collision)

Southern California Borderland: (extentional)

South Pacific: (volcanic arcs, trenches, and carbonate reefs)

SOURCES: Office of Technology Assessment, 1987; R.W. Rowland, M.R. Goud, and B.A. McGregor, "The U.S. Exclusive Economic Zone—A Summary of its Geology, Exploration, and Resource Potential," U.S. Geological Survey Circular 912, 1983.

and the west coast (figure 2-1). These regions have relatively narrow continental shelves and their onshore geology is dominated by igneous intrusive and volcanic rocks. These rocks supply the thin veneer of sediment overlying the continental crust of the shelf. Further offshore, the Pacific coast EEZ extends beyond the shelf, slope, and rise to the depths underlain by oceanic crust. In the Pacific northwest, these depths encompass a region of seafloor spreading where new oceanic crust is forming. This region includes the Gorda Ridge and possibly part of the Juan de Fuca Ridge, which are located within the U.S. EEZ off California, Oregon, and Washington.

The trailing edge of a continent has a passive margin because it lacks significant volcanic and seismic activity. Passive margins are located within crustal plates at the transition between oceanic and continental crust. These margins formed at divergent plate boundaries in the past. Over millions of years, subsidence in these margin areas has allowed thick deposits of sediment to accumulate. The Atlantic coast of the United States is an example of a trailing edge passive margin. This type of coast is typified by broad continental shelves that extend into deep water without a bordering trench. Coastal plains are wide and low-lying with major drainage systems. The greatest potential for the formation of recoverable ore deposits on passive margins results from sedimentary processes rather than recent magmatic or hydrothermal activity.

The Gulf of Mexico represents another type of coast that develops along the shores of a continental sea. These passive margins also typically have a wide continental shelf and thick sedimentary deposits. Deltas commonly develop off major rivers because the sea is relatively shallow, is smaller than the major oceans, and has lower wave energy than the open oceans.

Plate edges are not the only regions of volcanic activity. Mid-plate volcanoes form in regions overlying "hot spots" or areas of high thermal activity. As plates move relative to mantle "hot spots, chains of volcanic islands and seamounts are formed

Table 2-1 .—Association of Potential Mineral Resources With Types of Plate Boundaries

Type of plate boundary/Potential mineral resources
Divergent:
• Oceanic ridges
—Metalliferous sediments (copper, iron, manganese, lead, zinc, barium, cobalt, silver, gold; e.g., Atlantis II Deep of Red Sea)
—Stratiform manganese and iron ixodes and hydroxides and iron silicates (e.g., sites on Mid-Atlantic Ridge and Galapagos Spreading Center)
—Polymetallic massive sulfides (copper, iron, zinc, silver, gold, e.g., sites on East-Pacific Rise and Galapagos Spreading Center)
—Polymetallic stockwork sulfides (copper, iron, zinc, silver, gold; e.g., sites on Mid-Atlantic Ridge, Carlsberg Ridge, Costa Rica Rift)
—Other polymetallic sulfides in disseminated or segregated form (copper, nickel, platinum group metals)
—Asbestos
—Chromite
Convergent:
• Offshore
—Upthrust sections of oceanic crust containing types of mineral resources formed at divergent plate boundaries (see above)
—Tin, uranium, porphyry copper and possible gold mineralization in granitic rocks
Convergent:
• Onshore
—Porphyry deposits (copper, iron, molybdenum, tin, zinc, silver, gold; e.g., deposits at sites in Andes mountains)
—Polymetallic massive sulfides (copper, iron, lead, zinc, silver, gold, barium; e.g., Kuroko deposits of Japan)
Transform:
. Offshore
—Mineral resources similar to those formed at divergent plate boundaries (oceanic ridges) may occur at offshore transform plate boundaries; e.g., sites on Mid-Atlantic Ridge and Carlsberg Ridge)

SOURCE: Peter A. Rona, "Potential Mineral and Energy Resources at Submerged Plate Boundaries," ***MTS Journal*****, vol. 19, No, 4, 19S5, pp. 18-25.**

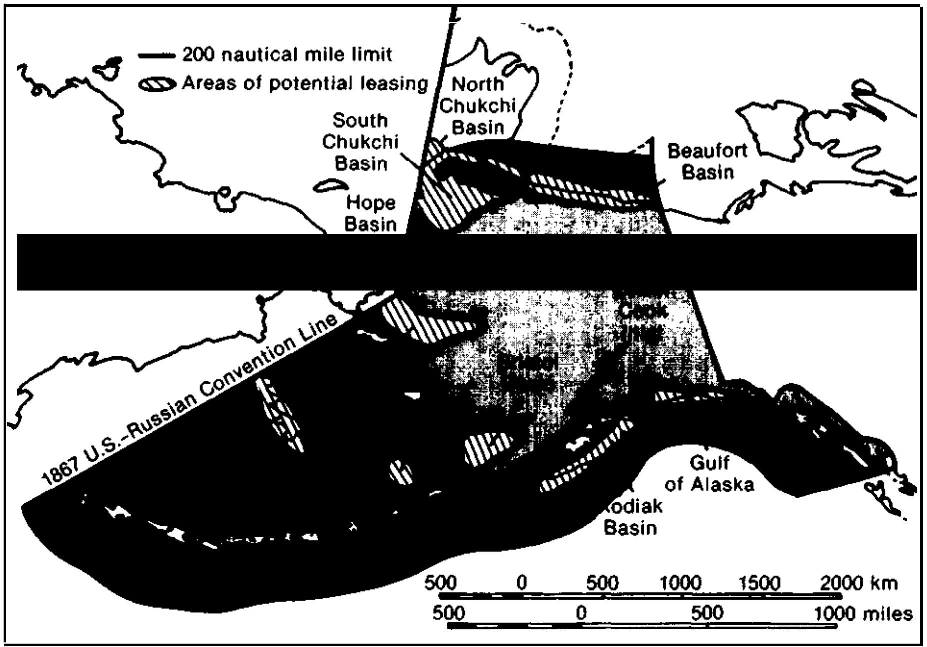
such as the Hawaiian Islands. These sites may also have significant potential for future recovery of mineral deposits.

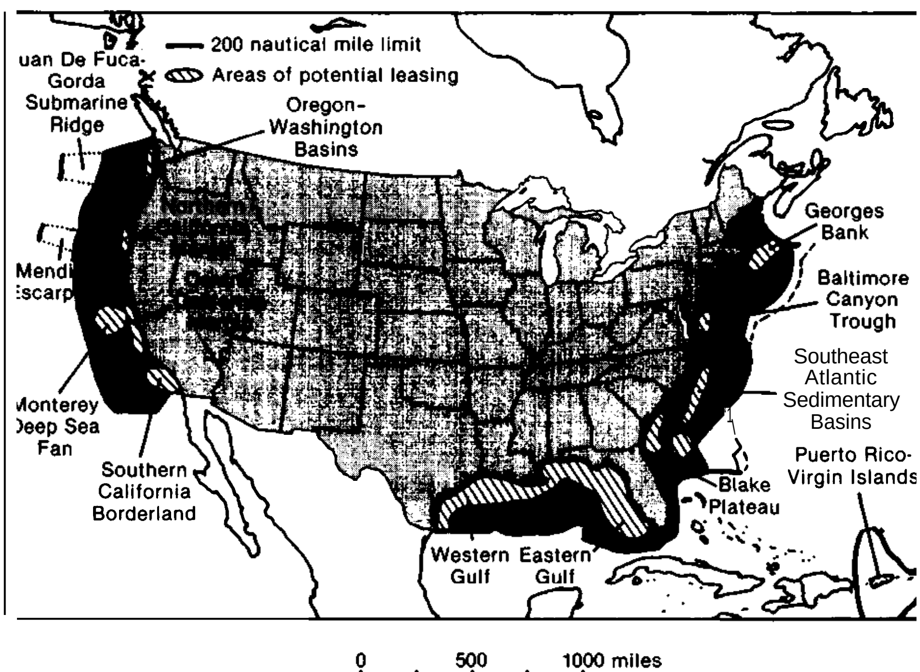
The theory of plate tectonics has led to the recognition that many economically important types of mineral deposits are associated with either present or former plate boundaries. Each type of plate boundary—divergent, convergent, or transform—is not only characterized by a distinct kind of interaction, but each is also associated with distinct types of mineral resources (table 2-1). Knowledge of the origin and evolution of a margin can serve as a general guide to evaluating the potential for locating certain types of mineral deposits.

ATLANTIC REGION

When the Atlantic Ocean began to form between Africa and North America around 200 million years ago, it was a narrow, shallow sea with much evaporation. The continental basement rock which formed the edge of the rift zone was block-faulted and the down-dropped blocks were covered with layers of salt and, as the ocean basin widened, with thick deposits of sediment. A number of sedimentary basins were formed in the Atlantic region along the U.S. east coast (figure 2-2). Very deep sediments are reported to have accumulated in the Baltimore Canyon Trough. In addition, a great wedge of sediment is found on the continental slope and rise. In places, due to the weight of the overlying sediment and density differential, salt has flowed upward to form diapirs or salt domes and is available as a mineral resource. In addition, sulfur is commonly associated with salt domes in the cap rock on the top and flanks of the domes. Both salt and sulfur are mined from salt domes (often by so-

Figure 2-2.–Sedimentary Basins in the EEZ





Several basins formed in the EEZ in which great amounts of sediment have accumulated. While of primary interest for their potential to contain hydrocarbons, salt and sulfur are also potentially recoverable from sedimentary basins in the Atlantic and Gulf regions.

SOURCES: Office of Technology Assessment, 1987; U.S. Department of the Interior, "Symposium Proceedings—A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 1983.

lution mining) and, thus, represent potentially recoverable mineral commodities from offshore deposits, although at present they would not be likely prospects in the Atlantic region.

While they have potential for oil and gas formation and entrapment, the bulk of these sedimentary rocks are not likely to be good prospects for hard minerals recovery because of their depth of burial. Exceptions could occur in very favorable circumstances where a sufficiently high-grade deposit might be found near the surface in less than 300 feet of water or where it could be dissolved and extracted through a borehole. Better prospects, particularly for locating potentially economic and mineable placer deposits, would be in the overlying Pleistocene and surficial sand and gravel.

The igneous and metamorphic basement rocks of the continental shelf, although possible sites of mineral deposits, would be extremely unlikely prospects for economic recovery because of their depth of burial. The oceanic crust that formed under what is now the slope and rise also probably contains accumulations of potential ore minerals, but these too would not be accessible. The best possibility for locating metallic minerals deposits in bedrock in the Atlantic EEZ probably would be in the continental shelf off the coast of Maine where the sediments are thinner or absent and the regional geology is favorable. There are metallic mineral deposits in the region and base-metal sulfide deposits are mined in Canada's New Brunswick.

One other area that may be of interest is the Blake Plateau located about 60 miles off the coasts of Florida and Georgia. It extends about 500 miles from north to south and is approximately 200 miles wide at its widest part, covering an area of about 100,000 square miles. The Blake Plateau is thought to be a mass of continental crust that was an extension of North America left behind during rifting. There is some expectation that microcontinents such as the Blake Plateau might be more mineralized than parent continents or the general oceanfloor, and, because they have received little sediment, their bedrock mineral deposits should be more accessible. s

'K .0. Emery and B. J. Skinner, "Mineral Deposits of the Deep-Ocean Floor, *Marine Mining,* vol. 1 (1977), No. 1/2, pp. 1-71.

Sand and Gravel

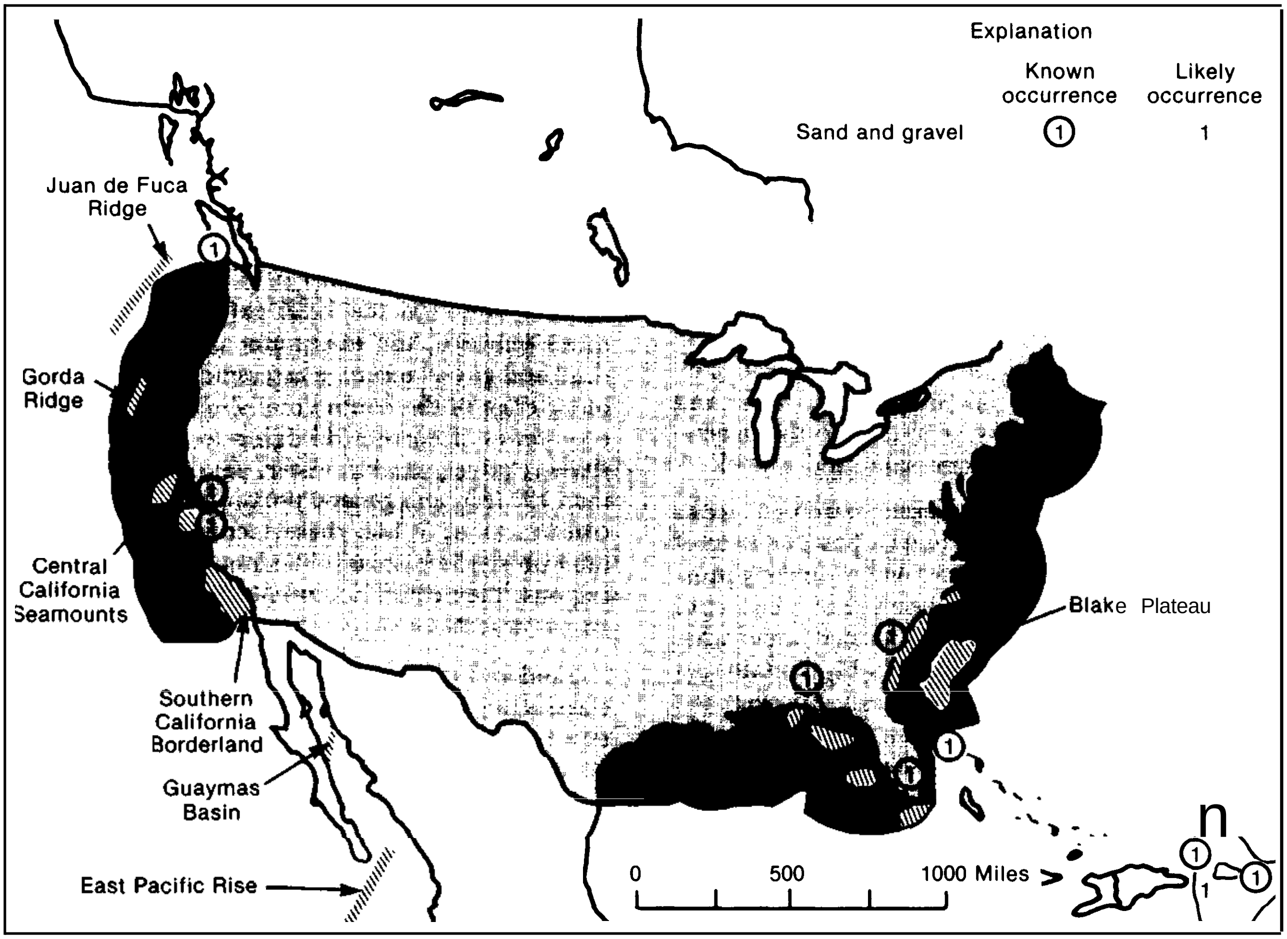
Sand and gravel are high-volume but relatively low-cost commodities, which are largely used as aggregate in the construction industry. Beach nourishment and erosion control is another common use of sand. Along the Atlantic coast most sand and gravel is mined from sources onshore except for a minor amount in the New York City area. For an offshore deposit to be economic, extraction and transportation costs must be kept to a minimum. Hence, although the EEZ extends 200 nautical miles seaward, the maximum practical limit for sand and gravel resource assessments would be the outer edge of the continental shelf. However, the economics of current dredging technology necessitate relatively shallow water, generally not greater than 130 feet, and general proximity to areas of high consumption. While these factors would further limit prospective areas to the inner continental shelf regions, they could potentially include almost the entire nearshore region from Miami to Boston.

Sand and gravel are terms used for different size classifications of unconsolidated sedimentary material composed of numerous rock types. The major constituent of sand is quartz, although other minerals and rock fragments are present. Gravel, because of its larger size, usually consists of multiple-grained rock fragments. Sand is generally defined as material that passes through a No. 4 mesh (O. 187-inch) U.S. Standard sieve and is retained on a No. 200 mesh (0.0029-inch) U.S. Standard sieve. Gravel is material in the range of O. 187 to 3 inches in diameter.

Because most uses for sand and gravel specify grain size, shape, type and uniformity of material, maximum clay content, and other characteristics, the attractiveness of a deposit can depend on how closely it matches particular needs in order to minimize additional processing. Thus the sorting and uniformity of an offshore deposit also will be determinants in its potential utilization.

The Atlantic continental shelf varies in width from over 125 miles in the north to less than 2 miles off southern Florida. The depth of water at the outer edge of the shelf varies from 65 feet off the Florida Keys to more than 525 feet on Georges Bank and the Scotian Shelf. A combination of glacial, outwash, subaerial, and marine processes have deter-

Figure 2-3.—Sand and Gravel Deposits Along the Atlantic, Gulf, and Pacific Coasts



Significant sand and gravel deposits lie on the continental shelf near urban coastal areas. As local onshore supplies of construction aggregate become exhausted, offshore deposits become more attractive. Sand is also needed for beach replenishment and erosion control.

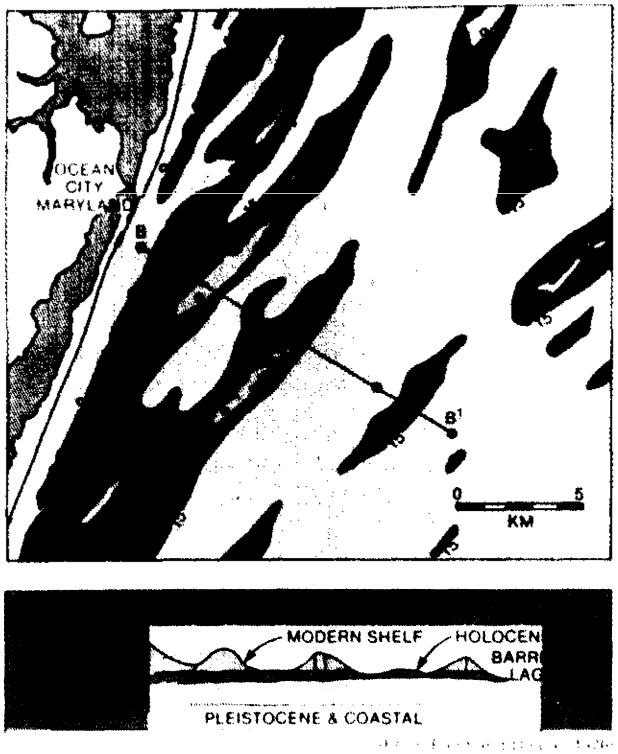
SOURCES: Office of Technology Assessment, 1987; S. Jeffress Williams, "Sand and Gravel–An Enormous Offshore Resource Within the U.S. Exclusive Economic Zone," manuscript prepared for U.S. Geological Survey Bulletin on commodity geology research, edited by John DeYoung, Jr.

mined the general characteristics and distribution of the sand and gravel resources on the shelf.

The northern part of the Atlantic shelf as far south as Long Island was covered by glaciers during the Pleistocene Ice Age. At least four major episodes of glaciation occurred. Glacial deposition and erosion have directly affected the location of sand and gravel deposits in this region. Glacial till and glaciofluvial outwash sand and gravel deposits cover much of the shelf ranging in thickness from over 300 feet to places where bedrock is exposed at the surface. The subsequent raising of sea level has allowed marine processes to rework and redistribute sediment on the shelf. Major concentrations of gravel in this region are located on hummocks and ridges in the vicinity of Jeffrey's Bank in the Gulf of Maine and off Massachusetts on Stellwagen Bank and in western Massachusetts Bay.

Concentrations of sand are found off Portland, Maine, in the northwestern Gulf of Maine and in Cape Cod Bay northward along the coast through western Massachusetts Bay to Cape Ann (figure 2-3). Large accumulations of sand also occur along the south coast of Long Island and in scattered areas of Long Island Sound. Large sand ridges on Georges Bank and Nantucket Shoals are also an impressive

Figure 2-4.—Plan and Section Views of Shoals Off Ocean City, Maryland



Several drowned barrier beach shoals off the Delmarva Peninsula are potential sources of sand and possibly heavy mineral placers.

SOURCE: S. Jeffress Williams, U S. Geological Survey

potential resource of medium to coarse sand. These ridges range in height from 40 to 65 feet and in width from 1 to 2 miles, with lengths up to 12 miles. The ridge tops are often at water depths of less than 30 feet, and a single ridge could contain on the order of 650 million cubic yards of sand.

South of Long Island through the mid-Atlantic **region,** the shelf area was not directly affected by glacial scouring and deposition, but the indirect effects are extensive. During the low stands of sea level, the shelf became an extension of the coastal plain through which the major rivers cut valleys and transported sediment. The alternating periods of glacial advance and marine transgression reworked the sediments on the shelf, yet a number of inherited features remain, including filled channels, relict beach ridges, and inner shelf shoals. Features such as these are particularly common off New Jersey and the Delmarva Peninsula and are potential sources of sand and possibly gravel (figure 2-4). Seismic profiles and cores indicate that the majority of these shoals consist of medium to coarse sand similar to onshore beaches. Geologic evidence suggests that most of the shoals probably formed in the nearshore zone by coastal hydraulic processes reworking existing sand bodies, such as relict deltas and ebb-tide shoals. [6] Some of the shoals may also represent old barrier islands and spits that were drowned and left offshore by the current marine transgression. Typical shoals in this region are on the order of 30 to 40 feet high, are hundreds of feet wide, and extend for tens of miles. South of Long Island, gravel is much less common and found only where ancestral river channels and deltas are exposed on the surface and reworked by moving processes.

The southern Atlantic shelf from North Carolina to the tip of Florida was even further removed from the effects of glaciation and also from large volumes of fluvial sediment. The shelf is more thinly covered with surficial sand, and outcrops of bedrock are common. Furthermore, unlike the middle Atlantic region, the southern shelf is not cut by river channels and submarine canyons, Sand resources in this region are described as discontinuous sheets or sandy shoals with the carbonate content (consisting of shell and coral fragments, limestone **grains, and oolites)** increasing to the south.

Although there is more information on the Atlantic EEZ than on other portions of the U.S. EEZ, estimates of sand and gravel resources on the Atlantic continental shelf are limited by a paucity of data. Resource estimates have been made using assumptions of uniform distribution and average thickness of sediment but these are rough approximations at best since the assumptions are known to be overly simplistic. A number of specific areas have been cored and studied in sufficient detail by the U.S. Army Corps of Engineers to make local resource estimates. [7] Resource assessments of specific sand deposits on the Atlantic shelf in water

[6] S.J. **Williams, "Sand and Gravel Deposits Within the U.S. Exclusive Economic Zone: Resource Assessment and Uses,** *Proceedings of the 18th Annual Offshore Technology Conference,* **Houston, TX, May 5-8, 1986, pp. 377-386.**

[7] D.B. **Duane and W. L.** Stubblefield, **"Sand and Gravel Resources, U.S. Continental Shelf, "** *Geology of North America: Atlantic Region, L'. S.,* **Ch. XI-C, Geological Society of America, Decade** *of North American Geology* **(in press).**

Table 2=2.—Areas Surveyed and Estimated Offshore Sand Resources of the United States

Geographic area	Seismic miles	Cores	Area surveyed (mile²)	Sand volume (x 10' cubic yards)
New England:				
Maine			10	123
Massachusetts (Boston)			175	57
Rhode Island			25	141
Connecticut (Long Island Sound)			50	130
Area totals	1,900	280	260	531
Southshore Long Island:				
Gardiners-Napeague Bays			100	162
Montauk to Moriches Inlet			160	1,912
Moriches to Fire Island Inlet			350	2,404
Fire island to East Rockaway Inlet			125	1,359
Rockaway			50	1,031
Area totals	955	122	785	6,868
New Jersey:				
Sandy Hook	255	10	50	1,000
Manasquan	86	11	25	60
Barnegat	200	32	75	448
Little Egg	389	38	120	180
Cape May	760	107	340	1,880
Area totals	1,660	198	610	3,568
Virginia:				
Norfolk	260	57	180	20
Delmarva	435	78	310	225
North Carolina	734	112	950	218
Florida:				
Northern:				
Fernandina—Cape Canaveral	1,328	197	1,650	295
Southern:				
Cape Canaveral	356	91	350	2,000
Cape Canaveral—Palm Beach	611	72	450	92
Palm Beach—Miami	176	31	141	581
Area totals	2,471	391	2,591	2,673
California:				
Newport-Pt. Dume	360	69	140	491
Pt. Dume—Santa Barbara	145	34	90	90
Area totals	505	103	230	599
Hawaii	Unknown	Unknown	Unknown	Unknown
Great Lakes:				
Erie	Unknown	Unknown	Unknown	Unknown
Grand totals	8.920	1.341	7,266	15,011

SOURCES: Published and unpublished reports of U.S. Army Corps of Engineers Coastal Engineering Research Center: David B. Duane, "Sedimentation and Ocean Engineering: Placer Mineral Resources," *Marine Sediment Transport* and *Environmental Management*, D.J. Stanley and D.J.P. Swift(eds) (New York, NY: John Wiley&Sons, 1976), p. 550.

depth of 130 feet or less are included in table 2-2. A total of over 15 billion cubic yards of commercial quality sand are identified in the table, and it is fair to say that the potential for additional amounts is large. Since the current annual U.S. consumption of sand and gravel is about 1,050 million cubic yards, these resources would clearly be ample to meet the needs of the east coast for the foreseeable future.

Placer Deposits

Offshore placer deposits are concentrations of heavy detrital minerals that are resistant to the chemical and physical processes of weathering. Placer deposits are usually associated with sand and gravel as they are concentrated by the same fluvial and marine processes that form gravel bars, sandbanks, and other surficial features. However, because they have different hydraulic behavior than less dense materials they can become concentrated into mineable deposits.

In addition to hydraulic behavior, a number of other factors influence the distribution and character of placer deposits on the continental shelf and coastal areas. These factors include sources of the minerals, mechanisms for their erosion and transport, and processes of concentration and preservation of the deposits.

While placer minerals can be derived from previously formed, consolidated, or unconsolidated sedimentary deposits, their primary source is from igneous and metamorphic rocks, Of these rocks, those that had originally been enriched in heavy minerals and were present in sufficiently large volumes would provide a richer source of material for forming valuable placer deposits. For example, chromite and platinum-group metals occur in ultramafic rocks such as dunite and peridotite, and the proximity of such rocks to the coast would enhance the possibility of finding chromite or platinum placers. While small podiform peridotite deposits are found from northern Vermont to Georgia, ultramafic rocks are not overly common in the Atlantic coastal region. Consequently, the prospects for locating chromite or platinum placers in surficial sediments of the Atlantic shelf would be low. Other rock types, such as high-grade metamorphic rocks, would be a likely source of titanium minerals such as rutile, and high-grade metamorphic rocks are found throughout the Appalachians. Placer deposits are generally formed from minerals dispersed in rock units, when great amounts of rock have been reduced by weathering over very long periods of time.

Time is a factor in the formation of placer deposits in several respects. In addition to their chemistry, the resistance of minerals to weathering is time and climate dependent. In a geomorphologically mature environment where a broad shelf is adjacent to a wide coastal plain of low relief, such as the middle and southern Atlantic margin, the most resistant heavy minerals will be found to dominate placer deposit composition. These would include the chemically stable placer minerals such as the precious metals, rutile, zircon, monazite, and tourmaline. Less resistant heavy minerals, such as amphiboles, garnets, and pyroxenes, which are more abundant in igneous rock, dominate heavy mineral assemblages in more immature tectonically active areas such as the Pacific coast. These minerals are currently of less economic interest.

Placer deposits are frequently classified into three groups based on their physical and hydraulic characteristics. The first group is the heaviest minerals such as gold, platinum, and cassiterite (tin oxide). Because of their high specific gravities, which range from 6.8 to 21, these minerals are deposited fairly near their source rock and tend to concentrate in stream channels. For gold and platinum, the median distance of transport is probably on the order of 10 miles.[8] Heavy minerals with a lighter specific gravity, in the range of 4.2 to 5.3, form the second group and tend to concentrate in beach deposits; but they also can be found at considerable distances from shore in areas where sediments have been worked and reworked through several erosional and depositional cycles. Minerals of economic importance in this group include chromite, rutile, ilmenite, monazite, and zircon.[9] The third group is the gemstones of which diamonds are the major example. These are very resistant to weathering, but are of relatively low specific gravity in the range of 2.5 to 4.1.

As a first step in assessing placer minerals resources potential in the Canadian offshore, a set of criteria was developed and the criteria were listed according to their relative importance. A ranking scheme was then adopted to assess the implications of each criterion with regard to the likelihood of a placer occurring offshore (table 2-3). This approach can be applied to the U.S. EEZ.

[8]K. O. Emery and L.C. Noakes, "Economic Placer Deposits on the Continental Shelf, United Nations Economic Commission for Asia and the Far East, *Technical Bulletin, vol.* 1, 1968, pp. 95-111.

[9]Rutile and ilmenite are major titanium minerals (along with leucoxene), and monazite is a source of yttrium and rare earth elements which have many catalytic applications in addition to uses in metallurgy, ceramics, electronics, nuclear engineering, and other areas. Zircon is used for facings on foundry molds, in ceramics and other refractory applications, and in several chemical products. Zircon is also processed for zirconium and halfnium metal, which are used in nuclear components and other specialized applications in jet engines, reentry vehicles, cutting tools, chemical processing equipment, and superconducting magnets.

[10]P. B. Hale and P. McLaren, "A Preliminary Assessment of Unconsolidated Mineral Resources in the Canadian Offshore, *CIM Bulletin,* September 1984, p. 11.

Table 2-3.—Criteria Used in the Assessment of Placer Minerals

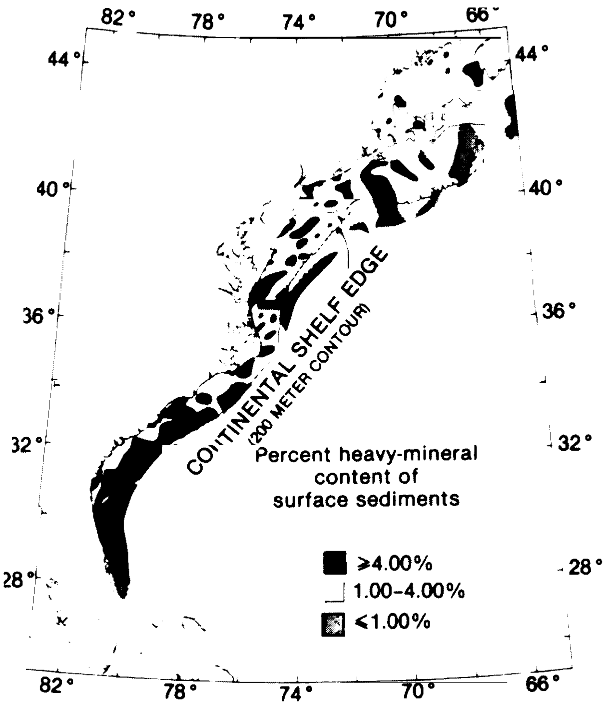
Criterion	Implication[a]		Information required: Types and sources
1. Presence in marine sediments of interest	+ + +	Direct evidence	Onsite bottom samples
2. Mineral presence in onland unconsolidated deposits close to the shoreline	+ + +	Alluvial sediments in seaward flowing watershed in glacial deposit	Historical placer mining records, geological reports
3. Presence of drowned river channels and strandlines offshore of coastal host rocks	++		High-resolution seismic surveys, detailed hydrographic surveys
4. Occurrence in source rock close to shore	++	With seaward flowing watershed	CANMINDEX geological reports, mining records, topographic maps, surficial geology maps
	+	No watershed but previously glaciated with offshore ice movement	
5. Presence of unconsolidated sediments seaward of onland host rocks	+		Offshore surficial geology maps, seismic records
6. Evidence of preglacial regoliths and mature weathering of bedrock	+	Liberation of resistant heavy minerals from bedrock for subsequent transportation and concentration	Reports of residual deposits and earlier formed regoliths
7. Sea-level fluctuations:			
(i) Transgression	+	For preservation of relict fluvial placers now submerged	Geological reports, air photos, tide records
(ii) Stable sea level	+	For formation of a contemporary beach placer	Geological reports, air photos, tide records
(iii) Regression	+	For formation of a contemporary river mouth placer	Geological reports, air photos, tide records
8. High-energy marine	+	For formation of a contemporary placer	Regional wave climates
	–	For preservation of a relict placer	
9. Previously glaciated		Glacial ice tends to scour out, disseminate or bury the heavy minerals	Geological reports, surficial geology maps
	+	In some circumstances glaciation liberates heavy minerals and transports them to considerable distance to the offshore	
10. Ice cover		Generally the longer the ice-free period the greater potential to generate a marine placer	Ice cover maps
11. Circulation patterns	+		Current maps
12. Climate	+	Important to the maturity of the mineral assemblage	Paleoclimatic maps

[a]A relative ranking scheme was adopted to assess the implications of each factor with regards to the likelihood of a placer occurring in the offshore. Favorable indications are as follows: + + + extremely favorable, + + + very favorable and, + favorable. Factors likely to detract from the possibility of an offshore placer utilize a similar approach with a negative sign.

SOURCE: Modified from Peter B. Hale and Patrick McLaren, "A Preliminary Assessment of Unconsolidated Mineral Resources in the Canadian Off shore," C/M *Bulletin*, September 19S4, p. 7.

Recent studies of heavy minerals in Atlantic continental shelf sediments have found mineral assemblages in the north Atlantic region dominated by less chemically stable minerals. The relatively immature mineral assemblages result from the direct glaciation that the northern shelf recently received. In general, glacial debris is less well sorted and often contains fresher mineral assemblages than sediment, which has been exposed to fluvial transport and weathering processes over a long period of time. While data for the north Atlantic region are too limited to be conclusive in terms of potential resources, greater concentrations of heavy minerals are found south of Long Island (figure 2-5). Total heavy mineral concentrations in the middle Atlantic region reach 5 percent or more in some areas, and the mineral assemblages show a greater degree of weathering. In comparison to the northern regions,

Figure 2-5.—Atlantic EEZ Heavy Minerals



Several areas of the Atlantic EEZ contain high concentrations of heavy minerals in the surficial sediments. Further research is needed to determine the extent of these deposits and possible economic potential.

SOURCES: Office of Technology Assessment, 1987; A.E. Grosz, J.C. Hathaway, and E.C. Escowitz, "Placer Deposits of Heavy Minerals in Atlantic Continental Shelf Sediments," Proceedings of the 18th Annual Offshore Technology Conference, Houston, Texas, OTC 5198, May 1988.

sediments of the southern Atlantic region contain lower concentrations of heavy minerals, but the assemblage becomes progressively more mature to the south and, hence, more concentrated in heavy minerals of more economic interest such as titanium.[11] This situation suggests that the mineral composition of the southern Atlantic shelf region holds the best prospects for economically attractive deposits.

Precious Metals

Although, in general, the north Atlantic region may have relatively poor prospects for economic placer deposits compared to the southern region, it might possibly be the most favorable area along the Atlantic EEZ for gold placers. Gold occurrences have been found in a variety of rocks along the Appalachians and in the maritime provinces of Canada, and both lode and placer gold deposits have been worked in areas that drain toward the coast. Because of its high specific gravity, placer gold is expected to be near its point of origin, which would be nearer to the coast in the New England area than in southern areas where broad coastal plains are developed. Further, glacial scouring and movement could have brought gold-bearing sediment offshore where it could be reworked and the gold concentrated by marine processes. While the prospects for gold placers are poor in the Atlantic EEZ, gold placers have been found on the coastal plain in the mid- and south Atlantic regions. To reach the EEZ in those regions, gold would have been transported by fluvial processes a considerable distance from its source and, if found, probably would be very fine-grained.

Heavy Minerals—Titanium Sands

The major area of interest for economic placer deposits, particularly titanium minerals, would be the middle and south Atlantic EEZ. Again the criteria in table 2-3 are useful. Concentrations of the commercially sought heavy minerals have been found in the sediments offshore (criterion 1) and titanium minerals mined onshore (criterion 2). In addition, several other criteria are also evident. These indicators would suggest a good potential for placer deposits offshore. An interesting aspect of this, however, is a reconnaissance study by the U.S. Geological Survey (USGS) that found significant concentrations of heavy minerals in surface grab-samples offshore of Virginia, where no economic deposits are found onshore.[12] However, rich rutile and ilmenite placer deposits have been mined in the drainage basin of the James River, a tributary of Chesapeake Bay. These deposits had their source in anorthosite and gneisses of the Virginia Blue Ridge.[13] An earlier study, which had found high

[11] A. E. Grosz, J. C. Hathaway, and E.C. Escowitz, "Placer Deposits of Heavy Minerals in Atlantic Continental Shelf Sediments, *Proceedings of the 18th Annual Offshore Technology Conference,* Houston, TX, May 5-8, 1986, pp. 387-394.

[12] A. E. Grosz and E. C. Escowitz, "Economic Heavy Minerals of the U.S. Atlantic Continental Shelf, W. F. Tanner (cd.), *Proceedings of the Sixth Symposium on Coastal Sedimentology,* Florida State University, Tallahassee, FL, 1983, pp. 231-242.

[13] J. P. Minard, E.R. Force, and G.W. Hayes, "Alluvial Ilmenite Placer Deposits, Central Virginia, " *U.S. Geological Survey Professional Paper 959-H, 1976.*

concentrations of heavy minerals parallel to the present shoreline off the Virginia coast in water depths between 30 and 60 feet, hypothesized sources from the Chesapeake Bay and the Delaware River.[14] The deposit was thought to be a possible ancient strandline where the heavy minerals were concentrated by hydraulic fractionation.

Bottom topography may be an important clue to surface concentrations of heavy minerals. One investigation off Smith Island near the mouth of Chesapeake Bay found high concentrations of heavy minerals on the surface of a layer of fine sand that was distributed along the flanks of topographic ridges.[15] However, coring data are needed to provide information on the vertical distribution of placer minerals and on whether or not similar buried topography is preserved and contains similar heavy mineral concentrations.

Overall, the south Atlantic EEZ would be a favorable prospective region for titanium placers, based on maturity of heavy mineral assemblages, although sediment cover is thinner and more patchy than farther north. However, individual features such as submerged sand ridges could contain concentrated deposits.

As with sand and gravel, regional resource estimates are probably not very useful since they are based on gross generalizations. This caveat notwithstanding, recent studies indicate that the average heavy mineral content of sediments on the Atlantic shelf is on the order of 2 percent, and that the total volume of sand and gravel may be larger than earlier estimates.[16 17] These studies suggest that whatever the total offshore resource base is estimated to be, the southern Atlantic EEZ may hold considerable promise for titanium placer deposits of future interest, particularly in areas of paleostream channels where there are major gaps in the Trail Ridge formation (a major onshore titanium sand deposit). In any event, only high-grade, accessible deposits would be potentially attractive, and the total heavy mineral assemblage would determine the economics of the deposit.

Phosphorite Deposits

Sedimentary deposits consisting primarily of phosphate minerals are called phosphorites. The principal component of marine phosphorites is carbonate fluorapatite. Marine phosphorites occur as muds, sands, nodules, plates, and crusts, generally in water depths of less than 3,300 feet. Phosphatic minerals are also found as cement bonding other detrital minerals. Marine phosphorite deposits are related to areas of upwelling and high bioproductivity on the continental shelves and upper slopes, particularly in lower latitudes.

Bedded phosphorite deposits of considerable areal extent are of major economic importance in the Southeastern United States. The bedded deposits in the Southeastern United States are related to multiple depositional sequences in response to transgressive and regressive sea level changes.[18] Major phosphate formation in this region began about 20 million years ago during the Miocene. Low-grade phosphate deposits are found in younger surficial sediments on the continental shelf, but these are largely reworked from underlying units. While these surface sediments are probably not of economic interest, they may be important tracers for Miocene deposits in the shallow subsurface.

On the Atlantic shelf, the northernmost area of interest for phosphate deposits is the Onslow Bay area off North Carolina. (Concentrations of up to 19 percent phosphate have been reported in relict sediments on Georges Bank, but these are unlikely to be of economic interest.) In the Onslow Bay area, the Pungo River Formation outcrops in an northeast-southwest belt about 95 miles long by 15 to 30 miles wide and extends into the subsurface to the east and southeast. The Pungo River Formation is a major sedimentary phosphorite unit under the north-central coastal plain of North Caro-

[14] B.K. Goodwin and J. B. Thomas, ' 'Inner Shelf Sediments Off of Chesapeake Bay III, Heavy Minerals, " *Special Scientific Report No. 68*, Virginia Institute of Marine Science, 1973, p. 34.

[15] C. R. Berquist and C. H. Hobbs, "Assessment of Economic Heavy Minerals of the Virginia Inner Continental Shelf, " Virginia Division of Mineral Resources Open-File Report 86-1, 1986, p. 17.

[16] U.S. Department of the Interior, *Program Feasibility Document.' OCS Hard Minerals Leasing*, prepared for the Assistant Secretaries of Energy and Minerals and Land and Water Resources by the OCS Mining Policy Phase II Task Force, August 1979, Executive Summary, p. 40.

[17] Grosz, Hathaway, and Esowitz, "Placer Deposits of Heavy Minerals in Atlantic Continental Shelf Sediments, " p. 387,

[18] S.R. Riggs, D.W. Lewis, A.K. Scarborough, et al., "Cyclic Deposition of Neogene Phosphorites in the Aurora Area, North Carolina, and Their Possible Relationship to Global Sea-Level Fluctuations, *Southeastern Geology, vol. 23, No. 4, 1982,* pp. *189-204.*

lina. Five beds containing high phosphate values have been cored in two areas of Onslow Bay. The northern area harboring three phosphate beds contains an estimated resource of 860 million short tons of phosphate concentrate with average phosphorus pentoxide (P_2O_5) values of 29.7 to 31 percent. The P_2O_5 content of the total sediment in these beds ranges from 3 to 6 percent. The Frying Pan area to the south contains two richer beds estimated to contain 4.13 billion tons of phosphate concentrate with an average content of 29.2 percent P_2O_5.[19] The P_2O_5 content of the total sediment in these beds ranges from 3 to 21 percent. Of the two areas, the Frying Pan district is given a better potential for economic development. The deposits are in shallow water relatively close to shore.

Further to the south, from North Carolina to Georgia, phosphates occur on the shelf in relict sands. Phosphate grain concentrations of 14 to 40 percent have been reported in water depths of 100 to 130 feet. On the Georgia shelf off, the mouth of the Savanna River, a deposit of phosphate sands over 23 feet thick has been drilled. Other deposits near Tyber Island, off the coast of Georgia, include a 90-foot-thick bed of phosphate in sandy clay averaging 32 percent phosphate overlying a 250-foot thick bed of phosphatic limestone averaging 23 percent phosphate. Concerns over saltwater intrusion into an underlying aquifer may constrain potential development in this area.

Further offshore, the Blake Plateau is an area of large surficial deposits of manganese oxides and phosphorites (figure 2-6). The Plateau is swept by the Gulf Stream and water depth ranges from 2,000 feet on the northern end to nearly 4,000 feet on the southeastern end. Phosphorite occurs in the shallower western and northern portions as sands, pellets, and concretions, The northern portion of the Blake Plateau is estimated to contain 2.2 billion tons of phosphorite.[20]

Off the Florida coast near Jacksonville, deep and extensive sequences of phosphate-rich sediments extend eastward onto the shelf. One bed, 20 feet thick beneath 260 feet of overburden, containing 70 to 80 percent phosphate grains, was slurry test-mined in this area. A core hole 30 miles east of Jacksonville contained a 11 5-foot section of cyclic phosphate-rich beds with the thickest unit up to 16 feet thick. The phosphate facies ran between 30 and 70 percent phosphate grains.

Deep drill data in the Osceola Basin have shown two phosphate zones extending eastward onto the continental shelf. The lower grade upper zone is 1,000 feet thick with 140 feet of overburden and phosphate grain concentrations of 10 to 50 percent of the total sediment. The higher grade deeper zone is 82 feet thick with 250 feet of overburden and phosphate grain concentrations ranging from 25 to 75 percent of total sediment.

The Miami and Pourtales Terraces off the southeast coast of Florida are also known to have phosphate occurrences. On the Pourtales Terrace, phosphorite occurs as conglomerates, phosphatic limestone, and phosphatized marine mammal bones. This deposit is thought to be related to the phosphatic Bone Valley Formation onshore.

Manganese Nodules and Pavements

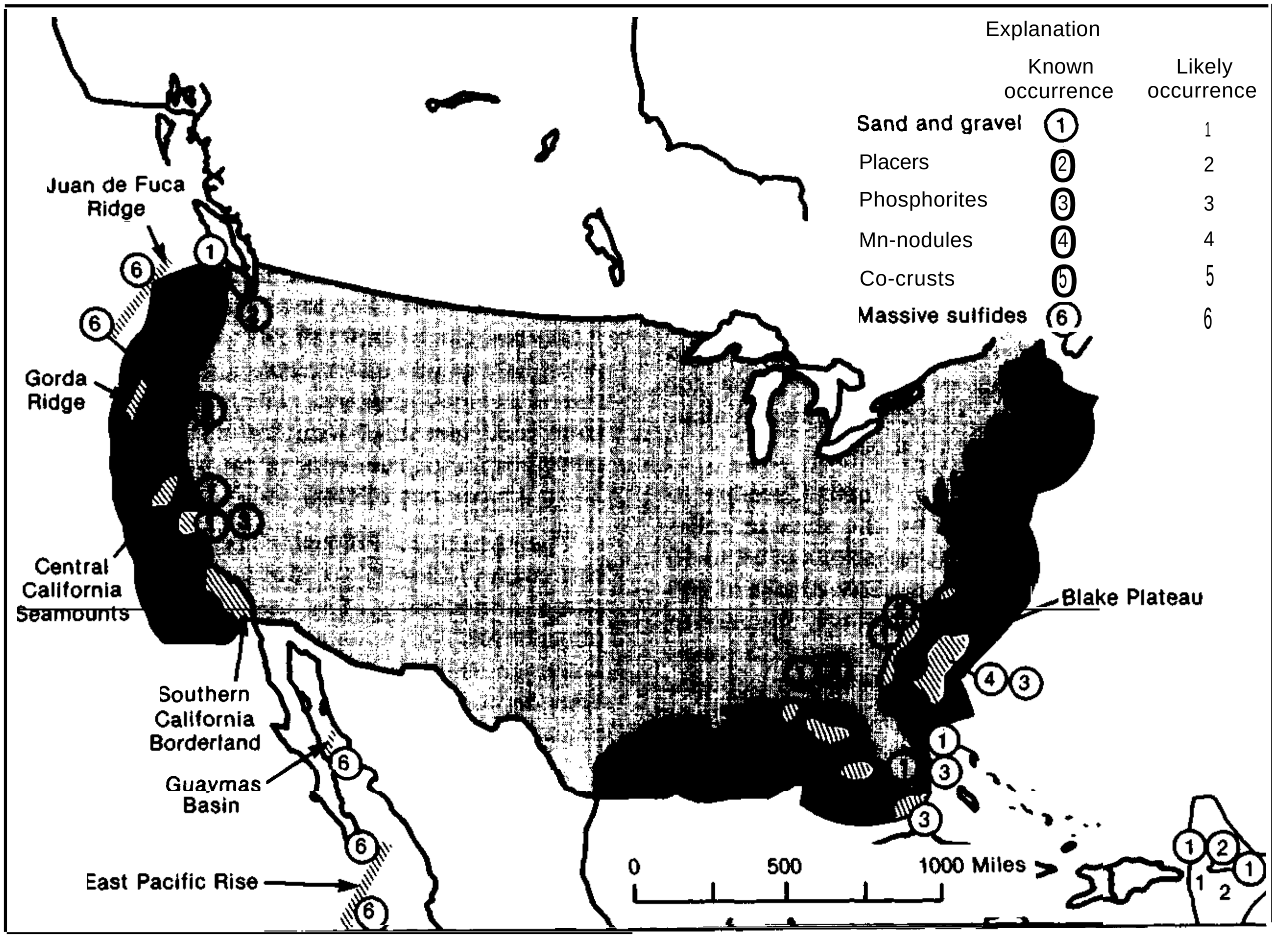
Ferromanganese nodules are concretions of iron and manganese oxides containing nickel, copper, cobalt, and other metals that are found in deep ocean basins and in some shallower areas such as the Blake Plateau off the Southeastern United States. On the Blake Plateau, nodule concretions are found at depths of 2,000 to 3,300 feet; and their centers commonly are phosphoritic. Ferromanganese crusts and pavements are more common at shallower depths of around 1,600 feet. The ferromanganese concretions of the Blake Plateau are well below the metal values found in the prime nodule sites in the Pacific Ocean, but the Blake Plateau offers the advantages of much shallower depths and proximity to the U.S. continent. Potential ferromanganese nodule resources on the Blake Plateau are estimated to be on the order of 250 billion tons averaging O. 1 percent copper, 0.4 percent nickel, 0.3 percent cobalt, and 15 percent manganese.[21]

f 9S.R.Riggs, S. W. P. Snyder, A.C. H ine, et al., "Geologic Framework of Phosphate Resources in Onslow Bay, North Carolina Continental Shelf, *Economic Geology,* vol. 80, 1985, pp. 716-738.

20F. T. Manheim, "Potential Hard Mineral and Associated Resources on the Atlantic and Gulf Continental Margins, *Program Feasibility Document—OCS Hard Minerals Leasing,* app. 12, U.S. Department of Interior, 1979, p. 42.

"I bid., p. 15.

Figure 2-6.–Potential Hard Mineral Resources of the Atlantic, Gulf, and Pacific EEZs



SOURCES: Office of Technology Assessment, 1987; U.S. Department of the Interior, "Symposium Proceedings—A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 1983.

PUERTO RICO AND THE U.S. VIRGIN ISLANDS

Puerto Rico and the U.S. Virgin Islands are part of an island arc complex with narrow insular shelves. The geologic environment of this type of active plate boundary suggests that sand and gravel deposits would not be extensive and that placer mineral assemblages would be relatively immature.

Sand and Gravel

Modern and relict nearshore delta deposits are the main source of offshore sediment for both Puerto Rico and the U.S. Virgin Islands. Further offshore the elastic sediments contain increasing amounts of carbonate material. In general, the islands lack large offshore sand deposits because wave action and coastal currents tend to rework and transport the sand across the narrow shelves into deep water. Submarine canyons also play a role in providing a conduit through which sand migrates off the shelf. The outer edge of the shelves is at a water depth of around 330 feet.

Three major sand bodies are located on the shelf of Puerto Rico in water depths of less than 65 feet. As one might expect in an area of westward moving winds and water currents, all three deposits are at the western ends of islands. Inferred resources have been calculated for two of these areas, the Cabo Rojo area off the west end of the south coast of Puerto Rico and the Escollo de Arenas area north of the west end of Vieques Island (near the east coast of Puerto Rico). The total volume of sand in these deposits is estimated at 220 million cubic yards, which could supply Puerto Rico's construction needs for over 20 years .22

In the U.S. Virgin Islands, several sand bodies contain an estimated total of 60 million cubic yards. Some of the more promising are located off the southwest coast of St, Thomas, near Buck Island, and on the southern shelf of St. Croix.

[22]R. W. Rodriguez, ' 'Submerged Sand Resources of Puerto Rico in USGS Highlights in Marine Research, USGS *Circular 938, 1984,* pp. 57-63.

Placer Deposits

Heavy mineral studies along the north coast of Puerto Rico found a strong seaward sorting with relatively heavy minerals such as monazite and magnetite enriched on the inner shelf relative to pyroxenes and amphiboles. The high degree of nearshore sorting may indicate a likelihood of the occurrence of placers, particularly in the inner shelf zone.[23] Gold has been mined in the drainage basin of the Rio de La Plata which discharges to the north coast of Puerto Rico, although no gold placers as yet have been found on the coast.

[23]O. H. Pilkey and R. Lincoln, "Insular Shelf Heavy Mineral Partitioning Northern Puerto Rico, " *Marine Mining, vol. 4, No. 4, 1984,* pp. 403-414.

GULF OF MEXICO REGION

The Gulf of Mexico is a small ocean basin whose continental margins are structurally complex and, in some cases, rather unique. The major structural feature of the U.S. EEZ in the northern Gulf of Mexico is the vast amount of sediment that accumulated while the region was subsiding. The structural complexity of the northern Gulf margin was enhanced by the mobility of underlying salt beds that were deposited when the region was a shallow sea. In general, the sedimentary beds dip and thicken southward and are greatly disrupted by diapiric structures and by flexures and faults of regional extent.

Sulfur and salt are both recovered from bedded evaporite deposits and salt domes in the Gulf region. Sulfur is generally extracted by the Frasch hot water process, which is easily adaptable to operation from an offshore platform. Sulfur has been recovered from offshore Louisiana and could be more widely recovered from offshore deposits if the market were favorable.

Sand and Gravel

The sand and gravel resources of the Gulf of Mexico are even more poorly characterized than the Atlantic EEZ. Most of the shallow sedimentary and geomorphological features of the Gulf were similarly developed as a result of the sea-level fluctuations during the Quaternary. The Mississippi River dominates the sediment discharge into the northern Gulf of Mexico. Over time, the Mississippi River has shifted its discharge point, leaving ancestral channels and a complex delta system. As channels shift, abandoned deltas and associated barrier islands are reworked and eroded, forming blanket-type sand deposits and linear shoals.[24] A number of these shoals having a relief of 15 to 30 feet are found off Louisiana. Relict channels and beaches are also good prospects for sand deposits. Relict channels and deltas have been identified off Galveston, containing over 78 million cubic yards of fine grained sand which may have uses for beach replenishment or glass sand. Sand and gravel resource estimates for the U.S. EEZ are given in table 2-4. Based on an average thickness of 16 feet, these are projected to be around 350 billion cubic yards of sand for the Gulf EEZ. No gravel resources are identified on the Gulf shelf although offshore shell deposits are common and have been mined as a source of lime. Until more surveys aimed at evaluating specific sand and gravel deposits are conducted, resource estimates are little more than an educated guess. In any event, the resource base is large, although meeting coarser size specifications may be a limiting factor in some areas.

[24]Williams, ' 'Sand and Gravel Deposits Within the United States Exclusive Economic Zone, p. 381._

Table 2-4.—Estimates of Sand and Gravel Resources Within the U.S. Exclusive Economic Zone

Province	Volumes (cubic meters)
Atlantic:	
Maine—Long Island	340 billion
New Jersey—South Carolina	190 billion
South Carolina—Florida	220 billion
Gulf of Mexico	269 billion
Caribbean:	
Virgin Islands	> 46 million
Puerto Rico	170 million
Pacific:	
Southern California	30 billion
Northern California—Washington	insufficient data
Alaska	> 160 billion
Hawaii	19 billion

SOURCE: Modified after S.J. Williams, "Sand and Gravel Deposits Within the United States Exclusive Economic Zone: Resource Assessment and Uses," 18th Annual Offshore Technology Conference, Houston, TX, 1986, pp. *377-386.*

Placer Deposits

Although reconnaissance surveys have not been conducted over much of the region, concentrations of heavy minerals have been found in a number of locations in the Gulf of Mexico. Several offshore sand bars or shoals are found off Dog Island, Saint George Island, and Cape San Bias in northwestern Florida that may contain concentrations of heavy minerals.[25] Some of these shoals are believed to be drowned barrier islands.

One recent survey of the shelf off northwest Florida found heavy mineral concentrations associated with shoal areas offshore of Saint George and Santa Rosa Islands. *G The heavy minerals of economic interest totaled about 39 percent of the heavy mineral fraction averaged over the study area. However, the percentages of heavy minerals and the composition of the heavy mineral sites reported are lower and of less economic interest, respectively, than those on the Atlantic shelf. Sediments derived from the Mississippi River off Louisiana contain heavy mineral fractions in which ilmenite and zircon are concentrated. In the western part of the Gulf, less economically interesting heavy minerals of the amphibole and pyroxene groups are dominant.[27]

An aggregate heavy-mineral sand resource estimate was not attempted for the gulf coast as part of the Department of the Interior's Program Feasibility Study for Outer Continental Shelf hard minerals leasing done in 1979. Too little data are available and aggregate numbers are not very meaningful in terms of potentially recoverable resources.

Phosphorite Deposits

Recent seismic studies indicate that the phosphate-bearing Bone Valley Formation extends at a relatively shallow depth at least 25 miles into the Gulf of Mexico and the west Florida continental shelf. An extensive Miocene sequence also extends across the shelf, and Miocene phosphorite has been dredged from outcrops on the mid-slope. This situation would suggest that the west Florida shelf may have considerable potential for future phosphate exploration.[28] Core data would be needed to assess this region more fully.

[25] W.F. Tanner, A. Mullins, and J. D. Bates, "Possible Masked Heavy Mineral Deposit: Florida Panhandle," *Economic Geology,* vol. 56, 1961, pp. 1079-1087.

[26] J.D. Arthur, S. Melkote, J. Applegate, et al., "Heavy Mineral Reconnaissance Off the Coast of the Apalachicola River Delta, Northwest Florida," Florida Bureau of Geology in Cooperation with U.S. Minerals Management Service, Contract No. 14-12-001-30115, Aug. 16, 1985 (unpublished).

[27] R.G. Beauchamp and M.J. Cruickshank, "Placer Minerals on the U.S. Continental Shelves—Opportunity for Development," *Proceedings OCEANS '83, vol.* II, 1983, pp. 698-702.

[28] W.C. Burnett, "Phosphorites in the U.S. Exclusive Economic Zone," *Proceedings, the Exclusive Economic Zone Symposium Exploring the New Ocean Frontier,* held at Smithsonian Institution, Washington, DC, October 1985 (Washington, DC: U.S. Department of Commerce, May 1986), pp. 135-140.

PACIFIC REGION

The continental margin along the Pacific coast and Alaska has several subregions. Southern California, from Mexico northward to Point Conception, is termed a "borderland, a geomorphic extensional complex of basins, islands, banks, ridges, and submarine canyons. Tectonically, this region is undergoing lateral or transform movement along the San Andreas fault system. The offshore basement (deep) rocks include metasediments, schist, andesites, and dacites. Thick sequences of Tertiary sediments were deposited in deep marine basins throughout the region. The shelf is fairly narrow (3 to 12 miles) and is transected by several submarine canyons extending to the edge of the shelf. From Point Conception north along the mountainous coast to Monterey Bay, the shelf is quite narrow in places, but north of San Francisco to Cape Mendocino it widens again to 6 to 25 miles. The coast in this area is generally rugged with a few lowland areas along river valleys. Wave energy is high along the entire coast and uplifted wave-cut terraces indicating former higher stands of sea level are common.

Northward along the coast of Oregon, the continental shelf is as narrow as 6 miles and averages less than 18 miles in width. Off Washington, the shelf gradually widens to over 30 miles and is underlain by a varied terrain of sedimentary rocks, mafic and ultramafic intrusive, and granite rocks. The Washington coast also has been influenced by glaciation, and glacial till and alluvium extend out onto the shelf. The Columbia River is a major source of sediment in the southern Washington and northern Oregon region. Beyond the shelf, but within the U.S. EEZ, the seafloor spreading centers of the Gorda and Juan de Fuca ridges and related subduction zones at the base of the continental slope contribute to the tectonic activity of the region.

Sand and Gravel

The narrow continental shelf and high wave energy along the Pacific coast limit the prospects for recovering a great abundance of sand and gravel from surficial deposits. In southern California, deposits of sand and gravel at water depths shallow enough to be economic are present on the San Pedro, San Diego, and Santa Monica shelves. Most coarse material suitable for construction aggregate is found in relict blanket, deltaic, and channel deposits off the mouth of major rivers. One deposit of coarse sand and gravel within 10 miles of San Diego Bay in less than 65 feet of water has been surveyed and estimated to contain 26 million cubic yards of aggregate. Total resource estimates for the southern California region indicate about 40 billion cubic yards of sand and gravel.[29] However, excessive amounts of overlying fine sand or mud, high wave energy, and unfavorable water depth may all reduce the economically recoverable material by as much as an order of magnitude. Individual deposits would need to be studied for their size, quality, and accessibility.

Sand and gravel resource estimates for northern California are based primarily on surface information with little or no data on depth and variability of the deposits. As is typical elsewhere, the sand and gravel deposits are both relict and recent. Much of the relict material appears to be too coarse to have been deposited by transport mechanisms operative at the present depth of the outer continental shelf.[30] These relict sands are thought to be nearshore bars and beach deposits formed during lower stands of sea level in the Pleistocene. Recent coarse material is nearer the coast and generally deposited parallel to the coastline by longshore currents. Sand and gravel estimates for the northern California shelf, assuming an average thickness of about 1 yard, are 84 million cubic yards of gravel, 542 million cubic yards of coarse sand, and 2.6 billion cubic yards of medium sand.[31] Most of this material would lie in State waters.

Off the coast of Oregon and Washington, sea level fluctuations and glaciation controlled the location of coarse sand and gravel deposits. Most of the gravel lies to the north off Washington, where it was deposited in broad outwash fans by glacial meltwater streams when the sea level was about 650 feet lower than present. Promising gravel resource areas convenient to both Portland and Seattle are off Gray's Harbor, Washington, and the southern Olympic Mountains. Smaller gravel deposits off Oregon lie in swales between submarine banks in relict reworked beach deposits. Little data on the thickness of individual deposits are available, but general information on the thickness of outwash and beach sediments in the area suggest that estimates of 3 to 15 feet average thickness are reasonable.[32]

[29] Williams, "Sand and Gravel Deposits Within the U.S. Exclusive Economic Zone," p. 382.

[30] S.G. Martindale and H.D. Hess, "Resource Assessment: Sand, Gravel, and Shell Deposits on the Continental Shelf of Northern and Central California," *Program Feasibility Document—OCS Hard Minerals Leasing*, app. 9, U.S. Department of the Interior, 1979, p. 5.

[31] Ibid., p. 7.

[32] G. W. Moore and M.D. Luken, "Offshore Sand and Gravel Resources of the Pacific Northwest, *Program Feasibility Document—OCS Hard Minerals Leasing*, app. 7, U.S. Department of the Interior, 1979, p. 8.

Precious Metals

Placer deposits containing precious metals have been found throughout the Pacific coastal region both offshore and along modern day beaches (figure 2-6). In the south, streams in the southern California borderland drain a coastal region of sandstone and mudstone marine sediments and granitic intrusive. These source rocks do not offer much hope of economically significant precious metal concentrations offshore, and fluvial placers have not been important in this area. North of Point Conception, gold placers have been worked and additional deposits might be found offshore.

The most promising region along the Pacific coast of the coterminous States is likely to be off northern California and southern Oregon where sediments from the Klamath Mountains are deposited. The Klamath Mountains are excellent source rocks containing, among other units, podiform ultramafic intrusive, which are thought to be the source of the platinum placers found in the region. Gold-bearing diorite intrusive are also present and provide economically interesting source rocks. Platinum and gold placers have both been mined from beaches in the region. In some areas, small flecks of gold appear in offshore surface sediments.

Several small gold and platinum beach placers have been mined on the coast of Washington from deposits which may have been supplied by glacially transported material from the north. The Olympic Mountains are not particularly noted for their ore mineralization, but gold and chromite-bearing rocks are found in the Cascades.

Two questions remain: do offshore deposits exist? and, if so, are they economic? For heavier minerals such as gold or platinum, only very fine-grained material is likely to be found offshore. Gold is not uncommon on Pacific beaches from northern California to Washington, but is often too fine-grained and too dispersed to be economically recovered at present. However, some experts also argue that in areas undergoing both uplift and cyclic glaciation and erosion, such as the shelf off southern Oregon, there may be several cycles of retrainment and progressive transport which could allow even the coarser grains of the precious metals to be transported some distance seaward on the shelf.[33]

Black Sand—Chromite Deposits

Chromite-rich black sands are found in relict beach deposits in uplifted marine terraces and in modern beach deposits along the coast of southern Oregon. The terrace deposits were actively mined for their chromium content during World War 11. Remaining onshore deposits are not of current economic interest. However, there are indications that offshore deposits may be of future economic interest. Geologic factors in the development of placer deposits in relatively high-energy coastal regimes offer clues to chromite resource expectations in the EEZ.

Geologic Considerations

The ultimate source of chromite in the black sands found along the Oregon coast of Coos and Curry counties is the more or less serpentinized ultramafic rock in the Klamath Mountains. However much of the chromite in the beach deposits appears to have been reworked from Tertiary sedimentary rocks.[34] Chromite eroded out of the peridotites and serpentine of the Klamath Mountains was deposited in Tertiary sediments. Changes in sea level eroded these deposits and the chromite was released again and concentrated into deposits by wind, wave, and current action. These deposits have been uplifted and preserved in the present terraces and beach deposits.

This reworking through deposition, erosion, and redeposition is an important consideration in the formation of offshore placer deposits. Not only does reworking allow for the accumulation of more minerals of economic value over time, but it also allows the less resistant (and generally less valuable) heavy minerals such as pyroxenes and amphiboles to break down and thus not dilute or lower the grade of the deposit.

The river systems in the region were largely responsible for eroding and transporting the heavy minerals from the Klamath Mountains. Once in the marine environment, reworking of minerals was enhanced during periods of continental glaciation when the sea level fluctuated and the shoreline

[33] K. C. Bowman, "Evaluation of Heavy Mineral Concentrations on the Southern Oregon Continental Shelf," *Proceedings, Eighth Annual Conference, Marine Technology Society, 1972,* pp. 237-253.

[34] A. B. Griggs, "Chromite-Bearing Sands of the Southern Part of the Coast of Oregon, *U.S. Geological Survey Bulletin, 945-E,* pp. 113-150.

retreated and advanced across the shelf at least four times. During these glacial periods, high rainfall, probable alpine glaciation in the higher Klamath peaks, and increased stream gradients from lowered base levels **all** contributed to accelerated erosion of the source area. Concentrations of heavy opaque minerals along the outer edge of the continental shelf off southern Oregon demonstrate **the** transport capacity of the pluvial-glacial streams during low stands of the sea.[35] High discharge and **low** stands of sea also allow for the formation of channel deposits on the shelf. During high interglacial stands of the sea, estuarine entrapment of sediments is a larger factor in the distribution of heavy minerals in the coastal environment. Each transgression and regression of the sea has the opportunity to rework relict or previously formed deposits. Preservation of these deposits is related to changes in the energy intensity of their environment.

While most geologists agree that uplifted beach terrace deposits and submerged offshore deposits are secondary sources of resistant heavy minerals in the formation of placer deposits, questions remain about which secondary source is more important. Differing views on the progressive enrichment of placer deposits have implications for locating concentrations of heavy minerals of economic value. One view is that each sea-level transgression reworks and concentrates on the shelf **the heavy** minerals laid down earlier, and any deposits produced during the more recent transgression are likely to be richer or more extensive than the raised terrace deposits that served as secondary sources since their emergence. This concentration effect would especially include those deposits now offshore which could be enriched by a winnowing process that removes the finer, lighter material, thereby concentrating **the heavy** minerals.[36] The other view is that offshore deposits are likely to be reworked as the sea level rises and heavy mineral concentrations in former beaches tend to move shoreward with the transgressing shore zone so that then the modern beaches would be richest in potentially economic heavy minerals. In this view, offshore deposits would be important secondary sources to the modern beaches, and raised terraces would be the next richest in heavy minerals. 37

Prospects for Future Development

The black sand deposits that were mined for chromite in the past offer a clue as to the nature of the deposits that might be found offshore. During World War II, approximately 450,000 tons of crude sand averaging about **10** percent chromite **or** 5 percent chromic oxide (Cr_2O_3) were produced. This yielded about 52,000 tons of concentrate at 37 to 39 percent Cr_2O_3. The chromium to iron ratio of the concentrate was 1.6:1. A number of investigators have examined other onshore deposits. The upraised terraces near Bandon, Oregon, have been assessed for their chromite content with the aid of a drilling program. Over 2, **1** million tons of sand averaging 3 to 7 percent Cr_2O_3 is estimated for this **15-mile** area.[38] Deposit thicknesses range from **1 to** 20 feet, and associated minerals include magnetite, ilmenite, garnet, and zircon.

In a minerals availability appraisal of **chromium, the U.S. Bureau** of Mines assessed the southwest Oregon beach sands as having demonstrated resources (reserve base) of **11,935,000 short tons of mineralized material with a contained Cr_2O_3 content of 666,000** tons.[39] In the broader category of identified resources, the Oregon beach sands contain 50,454,000 tons of mineralized material with a Cr_2O_3 content of 2,815,000 tons. None of the beach sand material is ranked as reserves because it is not economically recoverable at current prices. If recovered, the demonstrated resources would amount to a little over one year's current domestic chromium consumption.

Another indication of the nature of potential Oregon offshore deposits comes from studies of coastal terrace placers, modern beach deposits, and offshore current patterns. In general, longshore currents tend to concentrate heavy minerals along the southern side of headlands. This concentration is

[35] 1 bid., p. 241.
[36] Bowman, Evaluation of Heavy Mineral Concentrations on the Southern Oregon Continental Shelf, p. 243.
[37] Emery and Noakes, "Economic Placer Deposits on the Continental Shelf, " p. 107.
[38] Bowman, "Evaluation of Heavy Mineral Concentrations on the Southern Oregon Continental Shelf, " pp. 242-243.
[39] J.F. Lemons, Jr, , E. H. Boyle, Jr. , and CC. Kilgore, ' 'Chromium Availability—Domestic, A Minerals Availability System Appraisal, " *U.S. Bureau of Mines Information Circular,* IC *8895, 1982,* p. 4.

thought to be the result of differential seasonal longshore transport and shoreline orientation with regard to storm swell approach and zones of decelerating longshore currents. In addition, platform gradient also influences the distribution of placer sands, with steeper gradients increasing placer thickness. Similarly, the formation of offshore placer deposits would be determined by paleoshoreline position and geometry, platform gradient, and paleo-current orientation .[40]

Bathymetric data indicate several wave-cut benches left from former still stands of sea level. Concentrations of heavy minerals that may be related to submerged beach deposits have been found in water depths ranging from 60 to 490 feet. Surface samples of these deposits have black sand concentrations of 10 to 30 percent or more, and some are associated with magnetic anomalies indicating a likelihood of black sand placers within sediment thicknesses ranging from 3 to 115 feet. In addition, gold is found in surface sediments in some of these areas. These submerged features would be likely prospects for high concentrations of chromite and possibly for associated gold or platinum.

Several Oregon offshore areas containing concentrations of chromite-bearing black sands in the surface sediment have been mapped. These areas range from less than 1 square mile to over 80 square miles in areal extent, and they are found from Cape Ferrelo north to the Coquille River, with the largest area nearly 25 miles long, centered along the coast off the Rogue River. If metal tenor (content) increases with depth, as some investigators expect, there may be considerable potential for economically interesting deposits offshore. Also depending on the value of any associated heavy minerals, chromite might be recovered either as the primary product or as the byproduct of other minerals extraction.

Other Heavy Minerals

North of Point Conception in California, a few small ultramafic bodies are found within coastal drainage basins. Heavy mineral fractions in beach and stream sediments are relatively high in titanium minerals associated with monazite and zircon, and small quantities of chromite have been found. Titanium minerals have been mined from beach sands in this area in the past.

The Klamath Mountains of southwestern Oregon and northwestern California contain a complex of sedimentary, metasedimentary, metavolcanic, granitoid, and serpentinized ultramafic rocks that are the source of most, if not all, of the heavy minerals and free metals found on the continental shelf in that region. In addition to metallic gold, platinum metals, and chromite discussed previously, these minerals include ilmenite, magnetite, garnet, and zircon. Abrasion during erosion and transport of these minerals is minimal, and they are generally resistant to chemical weathering.

Another area of interest for heavy mineral placer deposits is off the mouth of the Columbia River. The Columbia River drains a large and geologically diverse region and its sediments dominate the coastal areas of northern Oregon and southern Washington. A large concentration of titanium-rich black sand has been reported on the shelf south of the Columbia River.[41] Sand from this deposit has been found to average about 5 percent ilmenite and 10 to 15 percent magnetite. Several other smaller areas on the Oregon shelf containing high heavy mineral concentrations lie seaward of or adjacent to river systems. Estimates of heavy mineral content on the Oregon shelf suggest a potential of several million tons each of ilmenite, rutile, and zircon.[42]

Chromite, ilmenite, and magnetite are also found in heavy mineral placers on the Washington coast. Five areas on the Washington shelf contain anomalously high concentrations of heavy minerals. Three areas south of the Hoh River and off Gray's Harbor are at depths of 60 to 170 feet and probably represent beach deposits formed during low stands of the sea. Two more areas are near the mouth of the Columbia River.

[40] C. D. peterson, G. W, Gleeson, and N. Wetzel, "Stratigr-aphic Development, Mineral Sources, and Preservation of Marine Placers from Pleistocene Terraces in Southern Oregon, USA, " *Sedimentary Geology,* in press.

[41] R. L.. Phillips, "Heavy Minerals and Bedrock Minerals on the Continental Shelf off Washington, Oregon, and California, " *Program Feasibility Document—OCS Hard Minerals Leasing,* app. B, U.S. Department of the Interior, 1979, pp. 14-17.

[42] Beauchamp and Cruickshank, "Placer Minerals on the U.S. Continental Shelves—Opportunity for Development, p. 700.

Phosphorite Deposits

The southern portion of the California borderland is well known for marine phosphorite deposits. The deposits are located on the tops of the numerous banks in areas relatively free of sediment. The phosphorites are Miocene in age and are generally found in water depths between 100 and 1,300 feet. The deposits consist of sand, pebbles, biological remains, and phosphorite nodules. Relatively rich surficial nodule deposits averaging 27 percent P_2O_5 are found on the Coronado, Thirty Mile and Forty Mile banks, and west of San Diego. Estimates based on available data on grade and extent of the major deposits known in the region indicate a resource base of approximately 72 million tons of phosphate nodules and 57 million tons of phosphatic sands.[43] However, because assumptions were necessary to derive these tonnages, these estimates should be regarded as being within only an order of magnitude of the actual resource potential of the area. Further sampling and related investigations are necessary to define the resource base more accurately.

Phosphorite deposits are also found further north off central California at water depths of 3,300 to 4,600 feet. These deposits, located off Pescadero Point, on Sur Knoll and Twin Knolls, range in P_2O_5 content from 11.5 to 31 percent, with an average content of 24 percent.[44] However, their patchy distribution and occurrence at relatively great water depths make them economically less attractive than the deposits off the southern California shore.

Polymetallic Sulfide Deposits

"*Polymetallic* sulfide" is a popular term used to describe the suites of intimately associated sulfide minerals that have been found in geologically active areas of the oceanfloor. The relatively recent discovery of the seabed sulfide deposits was not an accident. The discovery confirmed years of research and suggestions regarding geological and geochemical processes at the ocean ridges. Research related to: 1) separation of oceanic plates, 2) magma upwelling at the ocean ridges, 3) chemical evolution of seawater, and 4) land-based ore deposits that were once submarine, has contributed to and culminated in hypotheses of seawater circulation and mineral deposition at ocean spreading centers that closely fit recent observations. Much of the current interest in the marine polymetallic sulfides stems from the dynamic nature of the processes of formation and their role in hypotheses of the evolution of the Earth's crust. An understanding of the conditions resulting in the formation of these marine sulfides allows geologists to better predict the occurrence of other marine deposits and to better understand the processes that formed similar terrestrial deposits.

Geologic Considerations

The Gorda Ridge and possibly part of the Juan de Fuca Ridge (pending unsettled boundary claims) are within the EEZ of the United States. They are part of the seafloor spreading ridge system that extends over 40,000 miles through the world's oceans. These spreading centers are areas where molten rock (less dense than the solid, cold ocean crust) rises to the seafloor from depth, as the plates move apart. Plates move apart from one another at different rates, ranging from 1 to 6 inches per year. Limited evidence suggests that the relative rate of spreading has an influence on the type, distribution, and nature of the hydrothermal deposits formed, and that significant differences can be expected between slow-spreading centers and intermediate- to fast-spreading centers.[45]

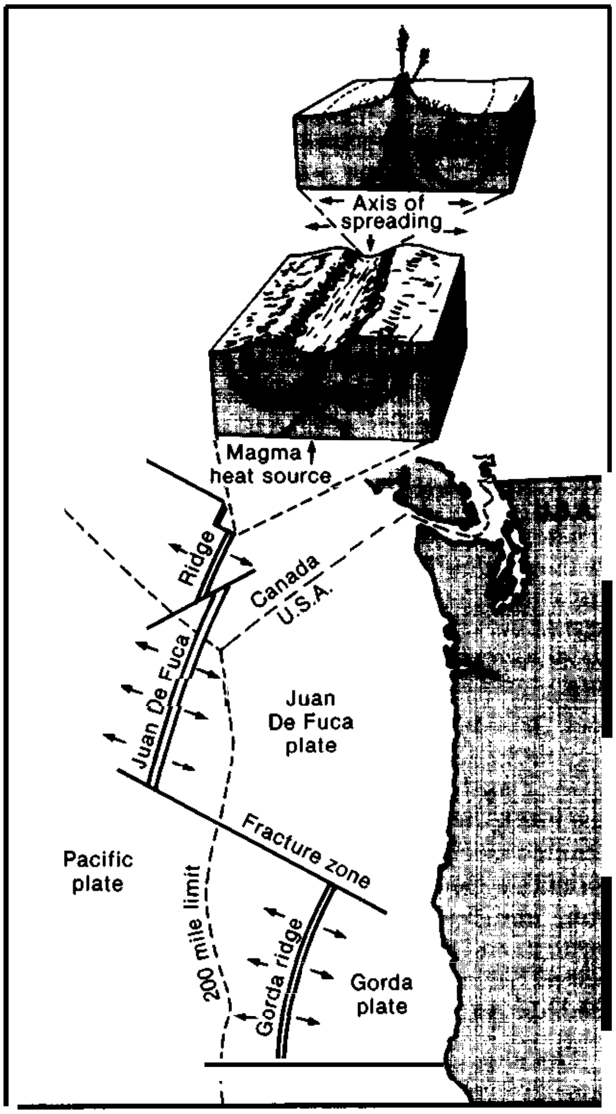
The mineralization process involves the interaction of ocean water with hot oceanic crust. Simply stated, ocean water percolates downward through fractures in the solid ocean crust. Heated at depth, the water interacts with the rock, leaching metals. Key to the creation of an ore deposit, the metals become more concentrated in the percolating water than they are in the surrounding rocks. The hot (300 to 400° centigrade) metal-laden brine moves upward and mixes with the cold ocean water, causing the metals to precipitate, forming sulfide min-

[43] H. D. Hess, "Preliminary Resource Assessment—Phosphorites of the Southern California Borderland," *Program Feasibility Document—OCS Hard Minerals Leasing*, app. 11, U.S. Department of the Interior, 1978, p. 21.

[44] H. T. Mullins and R. F. Rasch, "Sea-Floor Phosphorites along the Central California Continental Margin," *Economic Geology*, vol. 80, 1985, pp. 696-715.

[45] P. A. Rona, "Hydrothermal Mineralization at Slow-Spreading Centers: Red Sea, Atlantic Ocean, and Indian Ocean," *Marine Mining*, vol. 5, No. 2, 1985, pp. 117-145.

Figure 2-7.—Formation of Marine Polymetallic Sulfide Deposits



The Juan de Fuca and Gorda Ridges are active spreading centers off the coasts of Washington, Oregon, and California. Polymetallic sulfides are formed at spreading centers, where seawater heated by magma circulates through the rocks of the seafloor dissolving many minerals and depositing massive sulfide bodies containing zinc, copper, iron, lead, cadmium, and silver. Such sulfide deposits have been found on the Juan de Fuca Ridge within the EEZ of Canada and on the Gorda Ridge within the U.S. EEZ.

SOURCES: Office of Technology Assessment, 19S7; M.A. Champ, W.P Dillon, end D.G. Howell, "Non-Living EEZ Resources: Minerals, Oil, and Gas," Oceanus, volume 27, number 4, winter 19S4/S5.

erals along cracks, crusts on the oceanfloor, or chimneys or stacks (figure 2-7). High temperatures suggest little or no mixing with cold seawater before the solutions exit through the vents.

The degree to which the ore solution is diluted in the subsurface depends on the porosity or fracturing of the near surface rock and also determines the final exit temperature and composition of the hydrothermal fluids. The fluid ranges from manganese-rich in extreme dilution to iron-dominated at intermediate dilution levels to sulfide deposition when little dilution occurs. In support of these observations, investigators have found sulfide deposition at the vents with manganese oxide deposits farther away from the seawater-hydrothermal fluid interface.[46] Iron oxides are often found in association with, but at a distance from, the active vent and sulfide mineralization.

An important control on the location of hydrothermal mineralization, either beneath or on the seafloor at a spreading center, is whether the subseafloor hydrothermal convection system is leaky or tight. In leaky high-intensity hydrothermal systems, seawater penetrates downward through fractures in the crust and mixes with upwelling primary hydrothermal solutions, causing precipitation of disseminated, stockwork, and possibly massive copper-iron-zinc sulfides beneath the seafloor. Dilute, low-temperature solutions depleted in metals discharge through vents to precipitate stratiform iron and manganese oxides, hydroxide, and silicate deposits on the seafloor and suspended particulate matter enriched in iron and manganese in the water column.[47] In tight, high-intensity hydrothermal systems, primary hydrothermal solutions undergo negligible mixing with normal seawater beneath the seafloor and discharge through vents to precipitate massive copper-iron-zinc sulfide deposits on the seafloor and suspended particulate matter enriched in various metals in the water column.

[46] East Pacific Rise Study Group, "Crustal Processes of the Mid-Ocean Ridge," *Science*, vol. 213, July 3, 1981, pp. 31-40.
[47] Rena, "Hydrothermal Mineralization at Slow-Spreading Centers: Red Sea, Atlantic Ocean, and Indian Ocean," p. 123.

Table 2-5.—Estimates of Typical Grades of Contained Metals for Seafloor Massive Sulfide Deposits, Compared With Typical Ore From Ophiolite Massive Sulfide Deposits and Deep-Sea Manganese Nodules

	Sulfides, lat 21° N. & Juan de Fuca Ridge	Sulfides Galapagos rift	Sulfide ore, Cyprus	Deep-sea manganese nodules
Element	Typical grade, in percent	Typical grade, in percent	Typical grade, in percent	Typical grade, in percent
Zinc	30	0.2	0.2	0.13
Copper	0.5	5.0	2.5	0.99
Nickel	—	—	—	1.22
Cobalt	—	0.02	—	0.23
Molybdenum	—	0.017	—	0.018
Silver	0.02	—	—	—
Lead	0.30	—	—	—
Manganese. .	—	—	—	28.8
Germanium. .	0.01	—	—	.

SOURCE: Adapted from V. E. McKelvey, "Subsea Mineral Resources," U.S. Geological Survey, Bulletin, 1669-A, 1966, p. 62

Prospects for Future Development

At the present time, too little is known about marine polymetallic sulfide deposits to project their economic significance. Analysis of grab samples of sulfides collected from several other spreading zones indicate variable metal values, particularly from one zone to another. In general, all of the deposits sampled, except those on the Galapagos rift, have zinc as their main metal in the form of sphalerite and wurtzite. The Galapagos deposits differ in that they contain less than 1 percent zinc but have copper contents of 5 to 10 percent, mainly in the form of chalcopyrite. Weight percentage ranges of some metals found in the sulfide deposits are given in table 2-5. Some of the higher analyses are from individual grab samples composed almost entirely of one or two metal sulfide minerals and analyze much higher in those metal values (e. g., a Juan de Fuca Ridge sample which is 50 percent zinc is primarily zinc sulfide). While this is impressive, it says nothing about the extent of the deposit or its uniformity. In any event, it is certain that any future mining of hydrothermal deposits would recover a number of metal coproducts.

Highly speculative figures assigning tonnages and dollar values to ocean polymetallic sulfide occurrences have begun to appear. Observers should be extremely cautious in evaluating data related to these deposits. The deposits have only been examined from a scientific perspective related primarily to the process of hydrothermal circulation and its chemical and biological influence on the ocean. No detailed economic evaluations of these deposits or of potential recovery techniques have been made. Thus, estimates of the extent and volume of the deposits are based on geologic hypotheses and limited observational information. Even estimates of the frequency of occurrence of submarine sulfide deposits would be difficult to make at present. Less than 1 percent of the oceanic ridge system has been explored in any detail.

A further note of caution is also in order. In describing the potential for polymetallic sulfide deposits, several investigators have drawn parallels or made comparisons to the costs of recovery and environmental impacts of ferromanganese nodule mining. There is also a parallel with regard to economic speculation. Early speculative estimates of the tonnages of ferromanganese nodules in the Pacific Ocean were given by John Mero in 1965 as 1.5 trillion tons.[48] Even though this estimate was subsequently expressed with caveats as to what might be potentially mineable (10 to 500 billion tons),[49] the estimate of 1.5 trillion tons was widely quoted and popularized, thus engendering a common belief at the time that the deep seabed nodules were a virtually limitless untapped resource—a wealth that could be developed to preferential benefit of less developed nations. The unlimited abun-

[48]Mero, *The Mineral Resources of the Sea*, p. 175.

[49]J. L, Mere, "Potential Economic Value of Ocean-Floor Manganese Nodule Deposits,' *Ferromanganese Deposits on the Ocean Floor*, D.R. Horn (cd.), National Science Foundation, International Decade of Ocean Exploration, Washington, DC, 1972, p. 202.

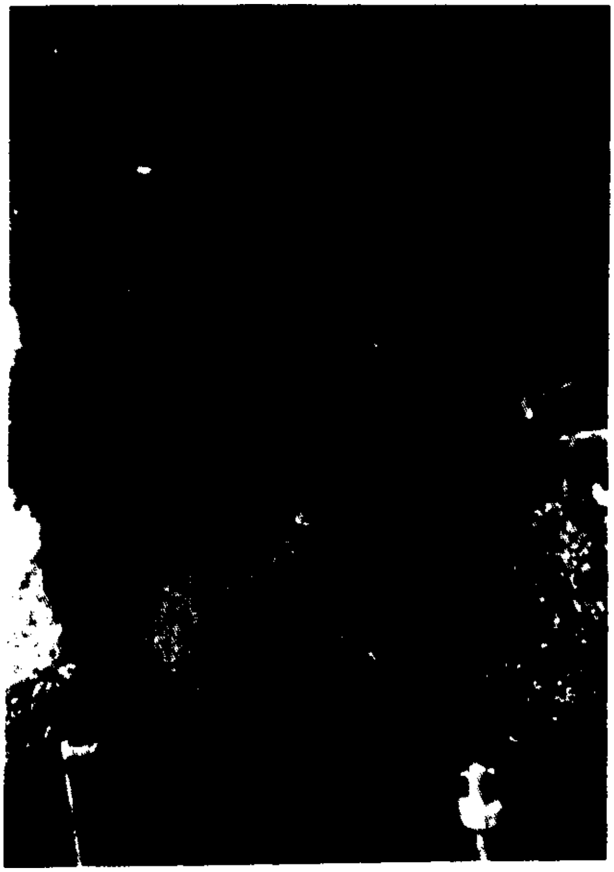


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Photo credit: U.S. Geological Survey

Hand sample of sulfide minerals recovered from Juan de Fuca Ridge.

dance of seabed nodules was a basic premise on which the Third United Nations Conference on the Law of the Sea was founded. Economic change and subsequent research indicate both a more limited mineable resource base and much lower projected rates of return from nodule mining. However, as often happens, positions that become established on the basis of one set of assumptions are difficult to amend when the assumptions change.

Creating expectations on the basis of highly speculative estimates of recoverable tonnages and values for hypothetical metal deposits serves little purpose. Avoiding the present temptation to extrapolate into enormous dollar values could avoid what may, upon further research, prove to be less than a spectacular economic resource in terms of recovery. This is not to say that the resource may not be found, but simply that it is premature to define its extent and estimate its economic value.

What then can be said about expectations for the U.S. EEZ? The Gorda Ridge is a relatively slow spreading active ridge crest. Until recently, most sulfide deposits were found on the intermediate- to fast-spreading centers (greater than 2 inches per year). This trend led some investigators to consider the potential for sulfide mineralization at slow-spreading centers to be lower than at faster spreading centers. On the other hand, the convective heat transfer by hydrothermal circulation is on the same order of magnitude for both types of ridges. This suggests that, if crustal material remains close to hydrothermal heat sources for a longer period of time, it might become even more greatly enriched through hydrothermal mineralization.[50] In any event, a complete series of hydrothermal phases can be expected at slow-spreading centers, ranging from high-temperature sulfides to low-temperature oxides. The hydrothermal mineral phases include massive, disseminated and stockwork sulfide deposits and stratiform oxides, hydroxides, and silicates,

To account further for their differences, the deeper seated heat sources at slow-spreading centers can be inferred to favor development of leaky hydrothermal systems leading to precipitation of the sulfides beneath the seafloor. This inference, however, cannot be verified until the deposits are drilled extensively.

Another view regarding the differences in potential for mineralization between fast- versus slow-spreading ridge systems suggests that the extent of hydrothermal activity and polymetallic sulfide deposition along oceanic ridge systems is more a function of that particular segment's episodic magmatic phase than the spreading rate of the ridge as a whole.[51] According to this view, at any given time a ridge segment with a medium or slow average spreading rate may show active hydrothermal venting as extensive as that found along segments with fast spreading rates. Thus, massive polymetallic sulfide deposits may be present along slow-spreading ridge segments, but they probably would be separated by greater time and distance intervals.

Another factor, particularly on the Gorda Ridge, is the amount of sediment cover. The 90-mile-long, sediment-filled Escanaba Trough at the southern part of the Gorda Ridge is similar to the Guaymas Basin in the Gulf of California, where hydrothermal sulfide mineralization has been found. The amount of sediment entering an active spreading center is critical to the formation and preservation of the sulfide deposits. Too much material delivered during mineralization will dilute the sulfide and reduce the economic value of the deposit. On the other hand, an insufficient sediment flux can result in eventual oxidation and degradation of the unprotected deposit.

Sulfide deposits and active hydrothermal discharge zones have been found on the southern Juan de Fuca Ridge beyond the 200-nautical-mile limit of the EEZ. The Juan de Fuca Ridge is a medium-rate spreading axis separating at the rate of 3 inches per year. Zinc and silver-rich sulfides have been dredged from two vent sites that lie less than a mile apart. Photographic information combined with geologic inference suggests a crude first-order estimate of 500,000 tons of zinc and silver sulfides in a 4-mile-long segment of the axial valley.[52]

Although marine polymetallic sulfide deposits may someday prove to be a potential resource in their own right, the current value of oceanfloor sulfides lies in the scientific understanding of their formation processes as well as their assistance in the possible discovery of analogous deposits on land (figure 2-8). Cyprus; Kidd Creek, Canada; and the Kuroko District in Japan are all mining sites for polymetallic sulfides, and all of these areas show the presence of underlying oceanic crust. The key to the past by studying the present is unraveling the mechanisms by which this very important class of minerals and ores were formed.

[50] Rena, "Hydrothermal Mineralization at Slow-Spreading Centers: Red Sea, Atlantic Ocean and Indian Ocean," p. 140.

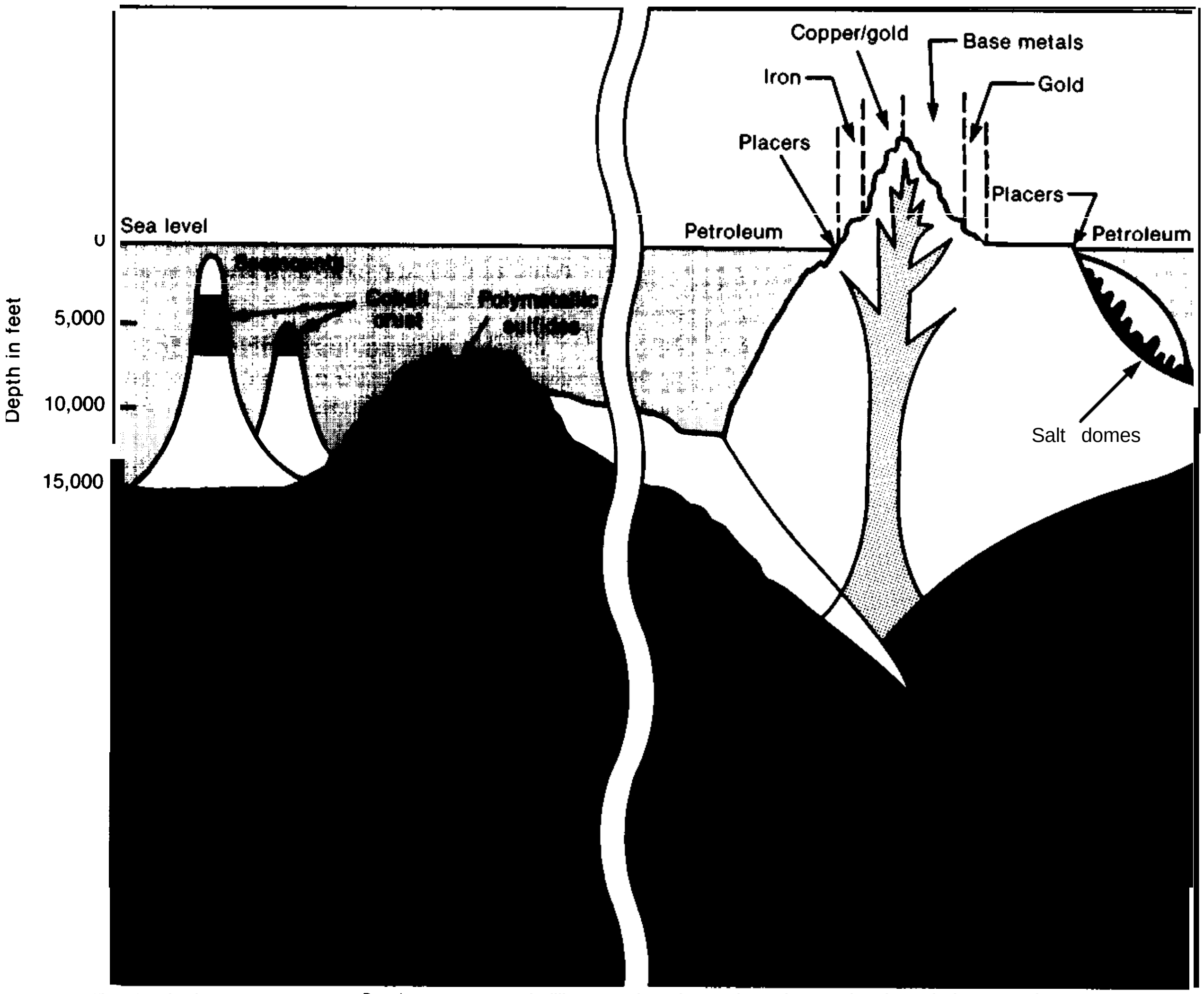
[51] A. Malahoff, "Polymetallic Sulfides-A Renewable Marine Resource, *Marine Mining: A New Beginning, Conference Proceedings,* July 18-21, 1982, Hilo, HI, State of Hawaii, sponsored by Department of Planning and Economic Development, 1985, pp. 31-60.

[52] R.A. Koski, W.R. Normark, and J. L. Morton, "Massive Sulfide Deposits on the Southern Juan de Fuca Ridge: Results of Investigations in the USGS Study Area, 1980-83, *Marine Mining,* vol. 4, No. 2, 1985, pp. 147-164.

ALASKA REGION

In southeastern Alaska, the coast is mountainous and heavily glaciated. Glacial sediments cover much of the shelf, which averages about 30 miles in width. The Gulf of Alaska has a wide shelf that was mostly covered by glaciers during the Pleistocene. The eastern coast of the Gulf is less mountainous and lower than the steep western coast. The source rocks in the region include a wide range of

Figure 2-8.—Locations of Mineral Deposits Relative to Physiographic Features (vertical scale exaggerated)



SOURCES: Office of Technology Assessment, 1987; Bonnie A. McGregor and Millington Lockwood, "Mapping and Research In the Exclusive Economic Zone," Department of the Interior, U.S. Geological Survey and Department of Commerce, National Oceanic and Atmospheric Administration.

sedimentary, metamorphic, volcanic, and intrusive bodies.

The Alaska Peninsula and Aleutian Islands consist of intrusive and volcanic rocks related to the subduction zone along the Pacific side. The shelf narrows westward from a width of nearly 125 miles to places where it is nearly nonexistent between the Aleutian Islands. The Aleutians are primarily andesitic volcanics while granitic intrusive are found on the peninsula.

The Bering Sea shelf is very broad and generally featureless except for a few islands, banks, and depressions. A variety of sedimentary, igneous, and metamorphic rocks are found in the region. In the south, of particular mineralogical interest, are the Kuskokwim Mountains containing Precambrian schist and gneiss, younger intrusive rocks, and dunite. The Yukon River is the dominant drainage system entering the Bering shelf, although several major rivers contribute sediments including streams on the Asian side, The region also has been significantly affected by glaciation and major sea level changes. Glacial sediment was derived from Siberia as well as Alaska. Barrier islands are found along the northern side of the Seward Peninsula.

The major physiographic feature of the north coast of Alaska is the gently sloping arctic coastal plain, which extends seaward to form a broad shelf under the Chukchi and Beaufort Seas. This area was not glaciated during the Pleistocene, and only one major river, the Colville, drains most of the region into the Beaufort Sea. The drainage area includes the Paleozoic sedimentary rocks of the Brooks Range and their associated local granitic intrusive and metamorphosed rocks.

Sand and Gravel

Approximately 74 percent of the continental shelf area of the United States is off the coast of Alaska. Consequently, Alaskan offshore sand and gravel resources are very large. However, since these materials are not generally located near centers of consumption, mining may not always be economically viable.

While glaciation has deposited large amounts of sand and gravel on Alaska's continental shelf, the recovery of economic amounts for construction aggregate is complicated by two factors:

1. much of the glacial debris is not well sorted, and
2. it is often buried under finer silt and mud washed out after deglaciation.

Optimal areas for commercial sand and gravel deposits would include outwash plains or submerged moraines that have not been covered with recent sediment, or where waves and currents have winnowed out finer material.

In general, much of the shelf of southeastern Alaska has a medium or coarse sand cover and is not presently receiving depositional cover of fine material. The Gulf of Alaska is currently receiving glacial outwash of fine sediment in the eastern part and, in addition, contains extensive relict deposits of sand and gravel. Economic deposits of sand have been identified parallel to the shoreline west of Yakutat and west of Kayak Island. An extensive area of sand has been mapped in the lower Cook Inlet, and gravel deposits are also present there (figure 2-9). Large quantities of sand and gravel are also found on the shelf of Kodiak Island. The Aleutian Islands are an unfavorable area for extensive sand and gravel deposits. Relict glacial sediments should be present on the narrow shelf, but the area is currently receiving little sediment.

Large amounts of fine sand lie in the southern Bering Sea and off the Yukon River, but the northern areas may offer the greatest resource potential for construction aggregate. Extensive well-sorted sands and gravels are found at Cape Prince of Wales and northwest of the Seward Peninsula. However, distances to Alaskan market areas are considerable. Sand, silt, and mud are common on the shelf in the Chukchi Sea and Beaufort Sea. Small, thin patches of gravel are also present, but available data are sparse. The best prospect of gravel in the Beaufort Sea is a thick layer of Pleistocene gravel buried beneath 10 to 30 feet of overburden east of the Colville River.

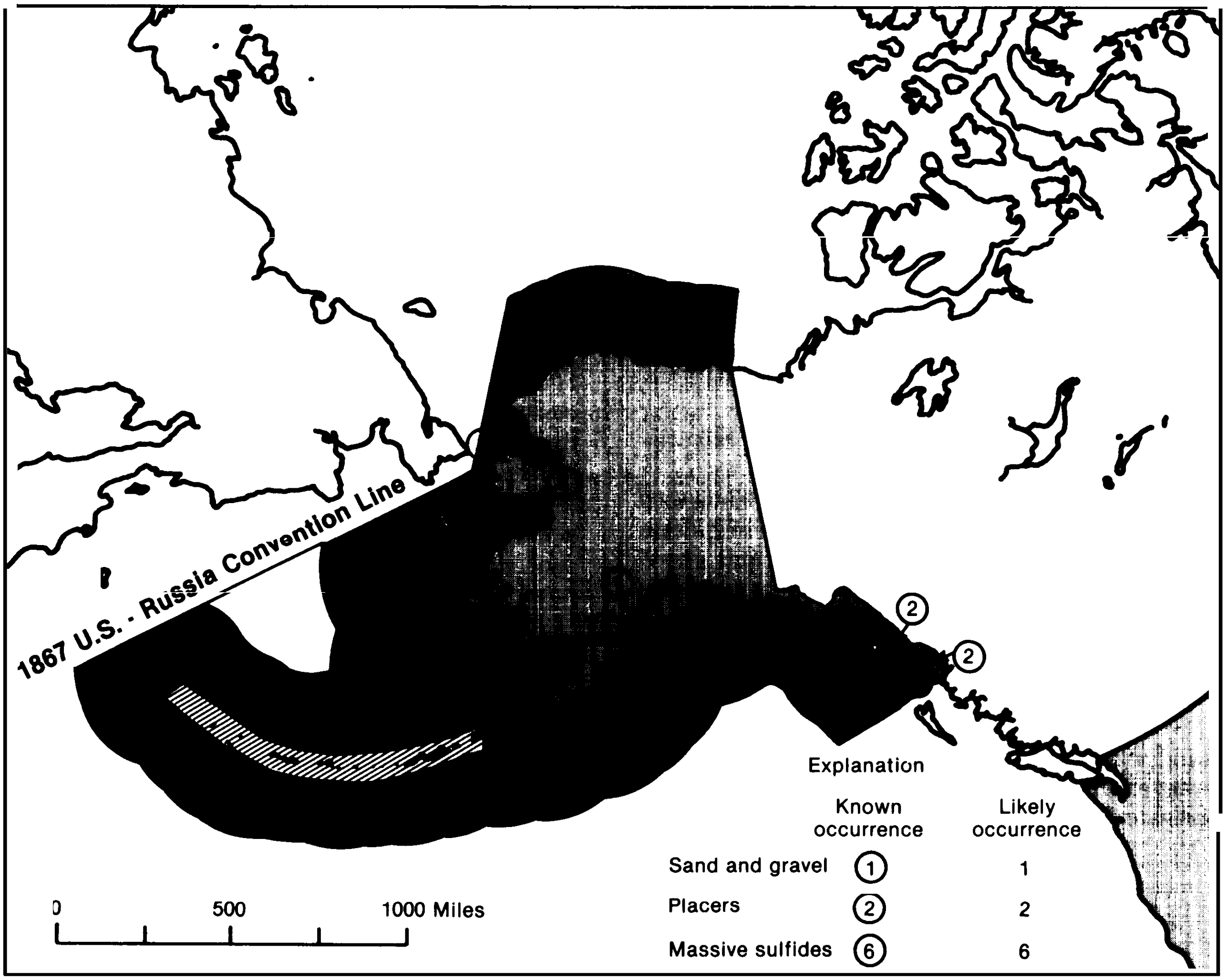
Overall sand and gravel resource estimates of greater than 200 billion cubic yards are projected for Alaska (table 2-4). In many areas, environmental concerns in addition to economic considerations would significantly influence development.

Precious Metals

Source rocks for sediments in southeastern Alaska are varied. Gold is found in the region and has been mined from placer deposits. Platinum has been mined from lode deposits on Prince of Wales Island. Although few beach or marine placer deposits are found in the area, the potential exists since favorable source rocks are present. However, glaciation has redistributed much of the sediment, and the shelf is receiving relatively little modern sediment.

Some gold has been recovered from beach placers in the eastern Gulf of Alaska; but, in general, the prospects for locating economic placers offshore would not be great because of the large amount of glacially derived fine-grained material entering the area. In the western Gulf, the glaciation has removed much of the sediment from the coastal area and deposited it offshore where subsequent reworking may have formed economically interesting

Figure 2-9.– Potential Hard Mineral Resources of the Alaskan EEZ



Gold and gravel have been mined from Alaskan waters and the potential exists for locating other offshore placer deposits.

SOURCES: Off Ice of Technology Assessment, 1987; U.S. Department of the Interior, "Symposium Proceedings-A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 1983.

placer deposits.[53] Gold is found in the region and has been mined from beaches on Kodiak Island and Cook Inlet. Placer deposits may have formed on the outer shelf but recovery may be difficult. Lower Cook Inlet might be the best area of the Gulf to prospect.

[53] H. E. Clifton and G. Luepke, *Heavy-Mineral Placer Deposits of the Continence Margin of Alaska* and the Pacific Coast States, in *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basin-Beaufort Sea to Baja, California*, American Association of Petroleum Geologists Memoir, ed., D.W. Scholl, (in press).

The shelf along the Aleutian Islands is a relatively unfavorable prospective locale for finding economic placer deposits. Sediment supply is limited, and ore mineralization in the volcanic source rocks is rare. Lode and placer gold deposits have been found on the Alaska Peninsula, and gold placers may be found off the south shore near former mining areas.

Platinum has been mined from alluvial placers near Goodnews Bay on the Bering Sea. Anomalous concentrations of platinum are also found on the coast south of the Salmon River and in sediments in Chagvan Bay.[54] The possibility exists that platinum placers may be found on the shelf if glacially transported material has been concentrated by marine processes. Source rocks are thought to be dunites in the coastal Kuskokwim Mountains, but lode deposits have not been found. Gold placers are also found along the coast of the Bering Sea and are especially important to the north near Nome. Lode gold and alluvial placers are common along the southern side of the Seward Peninsula, and tin placers have also been worked in the area. Gold has been found offshore in gravel on submerged beach ridges and dispersed in marine sands and muds. Economic deposits may be found in the submerged beach ridges or in buried channels offshore. The region around Nome has yielded about 5 million ounces of gold, mainly from beach deposits, and it is suggested that even larger amounts may lie offshore.[55] How much of this, if any, may be discovered in economically accessible deposits is uncertain, but the prospects are probably pretty good in the Nome area.

[54] R. M. Owen, ' 'Geochemistry of Platinum-Enriched Sediments: Applications to Mineral Exploration, *Marine Mining,* vol. 1, No. 4, 1978, pp. 259-282.

[55] Beauchamp and Cruickshank, "Placer Minerals on the U.S. Continental Shelves—Opportunity for Development, p. 700.

Other Heavy Minerals

The eastern Gulf of Alaska is strongly influenced by the modern glaciers in the area. Fresh, glacially derived sediments, including large amounts of fine-grained material, are entering the area and being sorted by marine processes. Heavy mineral suites are likely to be fairly immature and burial is rapid. In general, the prospects for locating economically interesting heavy mineral placers offshore in this area would not be great.

About 2,000 tons of tin have been produced from placers on the western part of the Seward Peninsula. Tin in association with gold and other heavy minerals may occur in a prominent shoal which extends over 22 miles north-northeast from Cape Prince of Wales along the northwest portion of the Seward Peninsula. While seafloor deposits off the Seward Peninsula might be expected to contain gold, cassiterite, and possibly tungsten minerals, data are lacking to evaluate the resource potential.

In general, the Chukchi and Beaufort seas may not contain many economic placers. Source rocks are distant, and ice gouging tends to keep bottom sediments mixed.

HAWAII REGION AND U.S. TRUST TERRITORIES

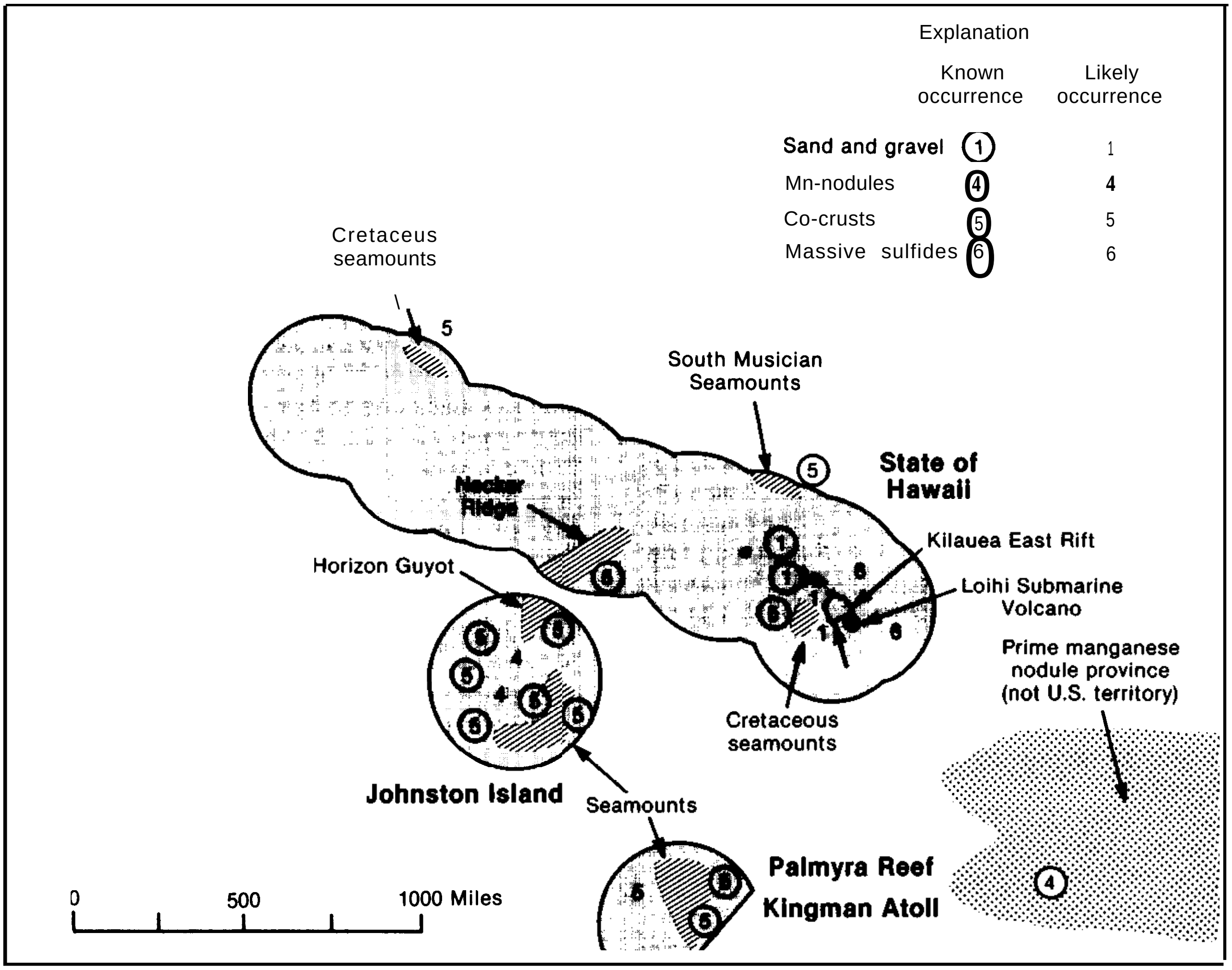
Hawaii is a tectonically active, mid-ocean volcanic chain with typically narrow and limited shelf areas. Sand and gravel resources are in short supply. The narrow shelf areas in general do not promote large accumulations of sand and gravel offshore. One area of interest is the Penguin Bank, which is a drowned shore terrace about 30 miles southeast of Honolulu (figure 2-10). The bank's resource potential is conservatively estimated at over 350 million cubic yards of calcareous sands in about 180 to 2,000 feet of water.[56] This resource could supply Hawaii's long-term needs for beach restoration and, to a lesser extent for construction. However, high winds and strong currents are common on the Penguin Bank. Total sand and gravel resource estimates for Hawaii may be as high as 25 billion cubic yards (table 2-4).

[56] W.B. Murdaugh, ' 'Preliminary Feasibility Assessment: Offshore Sand Mining, Penguin Bank, Hawaii, " *Program Feasibility Document—OCS Hard Minerals Leasing,* app. 19, U.S. Department of the Interior, 1979, p. 14.

No metalliferous deposits are mined onshore in Hawaii. Thus the prospects are somewhat poor for locating economically attractive placer deposits on the Hawaiian outer continental shelf. Minor phosphorite deposits have been found in the Hawaii area, although phosphorite is found on seamounts elsewhere in the Pacific.

The geology of the U.S. Trust Territories is generally similar to Hawaii with the islands being of volcanic origin, often supporting reefs or limestone deposits. Clastic debris of the same material is present and concentrated locally, but very little information is available as to the nature and extent of any sand or gravel deposits. Other areas are rela-

Figure 2-10.–Potential Hard Mineral Resources of the Hawaiian EEZ



SOURCES: Office of Technology Assessment, 1987; U.S. Department of the Interior, "Symposium Proceedings—A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 1983.

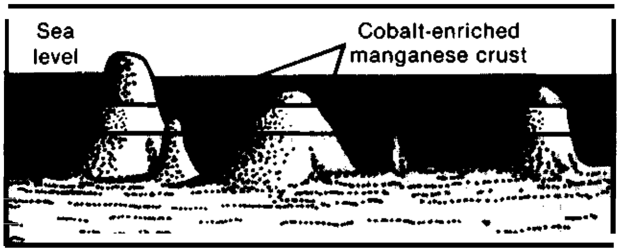
tively free of sediment or are covered with fine sediment consisting of red clay and/or calcareous ooze. The extent to which the United States has jurisdiction over the EEZs of the various Trust Territories (figure 2-1 1) is examined in appendix B.

Cobalt-Ferromanganese Crusts

Recently, high concentrations of cobalt have been found in ferromanganese crusts, nodules, and slabs on the sides of several seamounts, ridges, and other raised areas of ocean floor in the EEZ of the central Pacific region. The current interest in cobalt-enriched crusts follows an earlier period of considerable activity during the 1960s and 1970s to determine the feasibility of mining manganese nodules from the deep ocean floor, While commercial prospects for deep seabed nodule mining have receded because of unfavorable economics compounded by political uncertainties resulting from the Law of the Sea Convention, commercial interest in cobalt-ferromanganese crusts is emerging. A number of factors are contributing to this shift of interest, including seamount crusts that:

1. appear to be richer in metal content and more widely distributed than previously recognized,
2. are at half the depth or less than their abyssal counterparts,

Figure 2-11 .—Cobalt-Rich Ferromanganese Crusts on the Flanks of Seamounts and Volcanic Islands



Iron-manganese crusts enriched in cobalt occur on the flanks of volcanic islands and seamounts in geochemically favorable areas of the Pacific. Samples have been recovered for scientific purposes, but equipment for potential commercial evaluation and recovery has not been developed.

SOURCES: Office of Technology Assessment, 1987; Bonnie A. McGregor and Terry W. Of field, "The Exclusive Economic Zone: An Exciting New Frontier, " U.S. Department of the Interior, Geological Survey.

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3. can be found within the U.S. EEZ which could provide a more stable investment climate, and
4. may provide alternative sources of strategic metals.

Geologic Considerations

Ferromanganese crusts range from thin coatings to thick pavements (up to 4 inches) on rock surfaces that have remained free of sediment for millions of years. The deposits are believed to form by precipitation of hydrated metal oxides from near-bottom seawater. The crusts form on submarine volcanic and phosphorite rock surfaces or as nodules around nucleii of rock or crust fragments. They differ from deep ocean nodules, which form on the sediment surface and derive much of their metals from the interstitial water of the underlying sediment. Several factors appear to influence the composition, distribution, thickness, and growth rate of the crusts. These factors include metal concentration in the seawater, age and type of the substrate, bottom currents, depth of formation, latitude, presence of coral atolls, development of an oxygen-minimum zone, proximity to continents, and geologic setting.

The cobalt content varies with depth, with maximum concentrations occurring between 3,300 and 8,200 feet in the Pacific Ocean. Cobalt concentrations greater than 1 percent are generally restricted to these depths. Platinum (up to 1.3 parts per million) and nickel (to 1 percent) are also found associated with cobalt in significant concentrations in many ferromanganese crust areas. Other metals found in lesser but significant amounts include lead, cerium, molybdenum, titanium, rhodium, zinc, and vanadium (table 2-6).

At least two periods of crust formation occur in some crusts. Radiometric dating and other analyses indicate that crusts have been forming for the last 20 million years, with one major interruption in ferromanganese oxide accretion during the late Miocene, from 8 to 9 million years ago, as detected in some samples. During this period of interruption, phosphorite was deposited, separating the older and younger crust materials. In some areas, there is evidence of even older periods of crust formation. Crust thickness is related to age; consequently, within limits, the age of the seafloor is an important consideration in assessing the resource potential of an area. However, crust thickness does not ensure high cobalt and nickel concentrations.

The U.S. Geological Survey found thick crusts with moderate cobalt, manganese, and nickel concentrations on Necker Ridge, which links the Mid-

Table 2-6.–Average Chemical Composition for Various Elements of Crusts From <8,200 Feet Water Depth From the EEZ of the United States and Other Pacific Nations (all data are in weight percent)

Areas	n	Mn	Fe	Co	Ni	Cu	Pb	Ti	SiO_2	P_2O_5	Fe/Mn
Hawaii and Midway (on axis)	2-38	24	16.0	0.91	0.45	0.05		1.1	7.9	—	0.73
Hawaii and Midway (off axis)	4-15	21	18.0	0.60	0.37	0.10	0.18	1.3	16.0	1.0	0.88
Johnston Island	12-40	22	17.0	0.70	0.43	0.11	0.17	1.3	12.0	1.2	0.81
Palmyra Atoll-Kingman Reef	7-8	27	16.0	1.1	0.51	0.06	0.17	1.1	5.5	1.9	0,61
Howland-Baker Islands	3	29	18.0	0.99	0.63	0.08	0.14	1.2	6.2	1.7	0.64
Marshall Islands	5-13	26	14.0	0.94	0.56	0.13	0.25	1.1	5.6	0.90	0.56
Average central Pacific crusts	34-117	23	17.0	0.81	0.45	0.09	0.18	1.2	9.1	1.3	0.75
Northern Marianna Islands (and Guam)	6-7	12	16.0	0.09	0.13	0.05	0.07	–	–	—	1.41
Western U.S. borderland	2-5	19	16.0	0.30	0,30	0.04	0.15	0.31	17.0	—	0.95
Gulf of Alaska Seamounts	3-6	26	18.0	0.47	0.44	0.15	0.17	0.57	–	0.87	0.72
Lau Basin (hydrothermal)	2	46	0.60	0.007	0.005	0.02	0.006	0.005	–	0.05	0.01
Tonga Ridge and Lau Basin (hydrogenous)	6-9	16	20.0	0.33	0.22	0.05	0.16	1.0	–	1.0	1.26
South China Sea	14	13	13.0	0.13	0.34	0.04	0.08	–	14.0	—	1.07
Benin Island area (Japan)	1-1o	21	13.0	0.41	0.55	0.06	0.12	0.67	4.9	0.82	0.70
French Polynesia	2-9	23	12.0	1.2	0.60	0.11	0.26	1.0	6.5	0.34	0.56
Average for Pacific hydrogenous crusts (all data from figures 2-8)	55-319	22	15.0	0.63	0.44	0.08	0.16	0,98	11.0	1.1	0.81

n = Number of analyses for various elements.
— = No data.

SOURCE: J.R. Hein, L.A. Morgenson, D.A. Clague, and R.A. Koski, "Cobalt-Rich Ferromanganese Crusts From the Exclusive Economic Zone of the United States and Nodules From the Oceanic Pacific," D. Scholl, A. Grantz, and J. Vedder (eds.), Geology *and Resource Potential* of *the Continental Margins of Western North American and Adjacent Ocean Basins: American Association of Petroleum Geologists, Memoir,* in press.

Pacific Mountains and the Hawaiian Archipelago.[57] Further, high cobalt values of 2.5 percent were found in the top inch or so of crusts from the S.P. Lee Seamount at 8° N. latitude. These deposits occur at depths coincident with a water mass that contains minimum concentrations of oxygen, leading most investigators to attribute part of this cobalt enrichment to low oxygen content in the seawater environment. However, high cobalt values (greater than 1 percent) have also been found in the Marshall Islands, the western part of the Hawaiian Ridge province, and in French Polynesia, all of which are outside the well-developed regional equatorial oxygen-minimum zone but which appear to be associated with locally developed oxygen-minimum zones. Oxygen-minimum zones are also associated with low iron/manganese ratios. Figure 2-12 illustrates the zone of cobalt enrichment in ferromanganese crusts on seamounts and volcanic islands. In general, while progress is being made to understand more fully the physical and geochemical mechanisms of cobalt-manganese crust formation, the cobalt enrichment process is still uncertain. investigations to gain insight in this area will be of considerable benefit in identifying future resources.

[57] J. R. Heine, et al., "Geological and Geochemical Data for Seamounts and Associated Ferromanganese Crusts In and Near the Hawaiian, Johnston Island, and Palmyra Island Exclusive Economic Zones," U.S. Geological Survey, *Open File Report 85-292, 1985,* p. *129.*

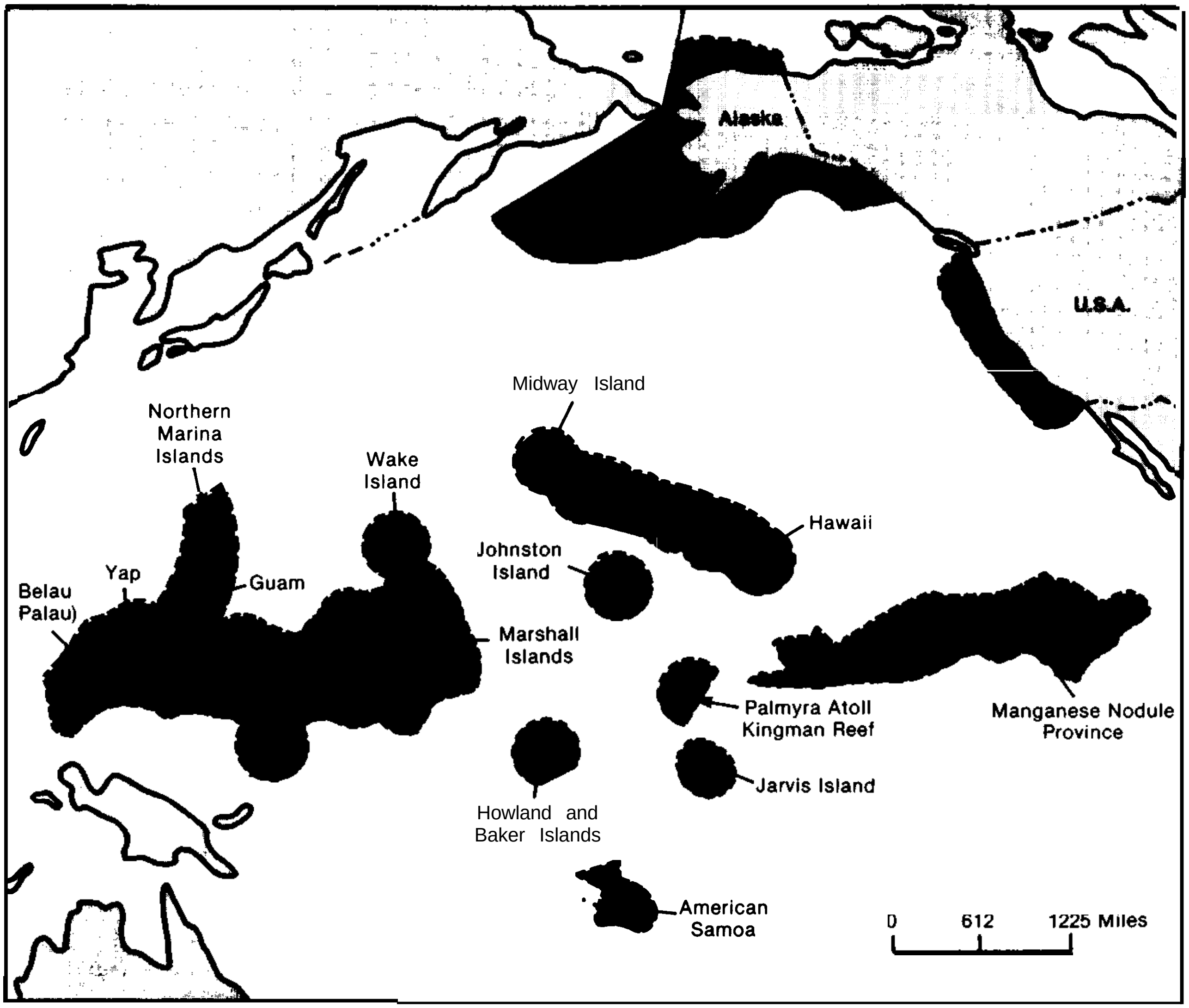
Surface texture, slope, and sediment cover also may influence crust growth rates. For example, sediment-free, current-swept regions appear to be favorable sites for crust formation.

Nodules are also found associated with cobalt-rich manganese crusts in some areas. These nodules are similar in composition to the crusts and, consequently, differ from their deep ocean counterparts. Another difference between crust-associated nodules and deep ocean nodules is the greater predominance of nucleus material in the crust-associated nodules. The cobalt-rich nodules generally occur as extensive fields on the tops of seamounts or within small valleys and depressions. While of much lesser extent overall than crust occurrences, these nodules may prove more easily recoverable and, hence, possibly of nearer term economic interest.

Prospects for Future Development

The geologic considerations mentioned previously are important determinants in assessing the

Figure 2-12.—EEZs of U.S. Insular and Trust Territories in the Pacific



In addition to the waters off the fifty states, the Exclusive Economic Zone includes the waters contiguous to the insular territories and possessions of the United States. The United States has the authority to manage these economic zones to the extent consistent with the legal relationships between the United States and these islands.

SOURCES: Office of Technology Assessment, 19S7; J.R. Hein, L.A. Morgenson, D.A. Clague, and R.A. Koski, "Cobalt-Rich Ferromanganese Crusts From the Exclusive Economic Zone of the United States and Nodules From the Oceanic Pacific," in D. Scholl, A. Grantz, and J. Vedder, eds., "Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins," American Association of Petroleum Geologists Memoir 43, in press.

resource potential of cobalt-rich ferromanganese crusts. Using three primary assumptions based on these factors, the East West Center in Hawaii produced a cobalt-rich ferromanganese crust resource assessment for the Minerals Management Service .58 The first assumption was that commercial concentrations of cobalt-rich crusts would be confined to the slopes and plateau areas of seamounts in water depths between 2,600 and 7,900 feet. The second assumption was that commercial concentrations would be most common in areas older than 25 million years, where both generations of crust would be found, and less common in areas younger than 10 million years, where only thinner younger crust generation occurs. The third primary assumption was that commercial concen-

[58] A. L. Clark, P. Humphrey, C. J. Johnson, et al., *Cobalt-Rich Manganese Crust Potential,* OCS Study, MMS 85-0006, U.S. Department of the Interior, Minerals Management Service, 1985, 35 pp.

Table 2-7.—Resource Potential of Cobalt, Nickel, Manganese, and Platinum in Crusts of U.S. Trust and Affiliated Territories

	Resource Potential			
Territory	Cobalt	Nickel (t x 10⁶)	Manganese	Platinum (oz x 10⁶)
Belau/Palau	0.55	0.31	15.5	0.68
Guam	0.55	0.31	15.5	0.68
Howland-Baker	0.19	0.11	5.5	0.48
Jarvis	0.06	0.03	1.6	0.15
Johnston Island	1.38	0.69	41.6	3.50
Kingman—Palmyra	3.38	1.52	76.1	5.70
Marshall Islands	10.55	5.49	281.3	21.50
Micronesia	17.76	9.96	496.0	34.70
Northern Mariana Islands	3.60	1.97	100.2	7.70
Samoa	0.03	0.01	0.8	0.04
Wake	0.98	0.51	26.8	2.00

NOTE: The above are estimates of in-place resources and as such do not indicate either potential recoverability or mineable quantities.

SOURCE: Allen L. Clark, Peter Humphrey, Charles J. Johnson, and Dorothy K. Pak, *Cobalt-Rich Manganese Crust Potential*, OCS Study MMS 65-0006, 1985, p. 20.

trations would be most common in areas of low sediment cover that have been within the geographically favorable equatorial zone for the majority of their geologic history.

The East-West Center's procedure was to use detailed bathymetric maps to determine permissive areas for each EEZ of the U.S. Trust and Affiliated Territories in the Pacific. The permissive areas included all the seafloor between the depths of 2,600 and 7,900 feet, making corrections for areas of significant slopes. Then, based on published data, the metal content and thickness of crust occurrences for each area were averaged. Crust thicknesses were also assigned on the basis of ages of the seamounts, guyots, and island areas. Seamounts older than 40 million years were assigned a thickness of 1 inch. Seamounts younger than 10 million years were assigned a thickness of one-half inch, and seamounts younger than 2 to 5 million years were not included in the resource calculations. These data are summarized in table 2-7.

According to table 2-7, the five territories of highest resource potential would be the Federated States of Micronesia, Marshall Islands, Commonwealth of the Northern Mariana Islands, Kingman-Palmyra Islands, and Johnston Island. Further geologic inference suggests that the resource potential of the Federated States of Micronesia and the Commonwealth of the Northern Mariana Islands could be reduced because of uncertainties in age and degree of sediment cover. Thus, according to their more qualitative assessment, the largest resource potential for cobalt crusts would likely be in the Marshall Islands, followed by the Kingman-Palmyra, Johnston, and Wake Islands (figure 2-13). The territories of lesser resource potential would include, in decreasing order, the Federated States of Micronesia, Commonwealth of the Northern Mariana Islands (figure 2-14), Belau-Palau, Guam, Howland-Baker, Jarvis, and Samoa.[59]

Another assessment of crust resource potential using grade and permissive area calculations with geologic and oceanographic criteria factored in is given in table 2-8.[60] This assessment is also a qualitative ranking without attempting to quantify tonnages. In this regard, other factors that would have to be considered to assess the economic potential of any particular area include: nearness to port facilities and processing plants, and the cost of transportation. In addition, factors highly critical to the economics of a potential crust mining operation would be the degree to which the crust can be separated from its substrate and the percentage of the

[59] Ibid., p. 21.

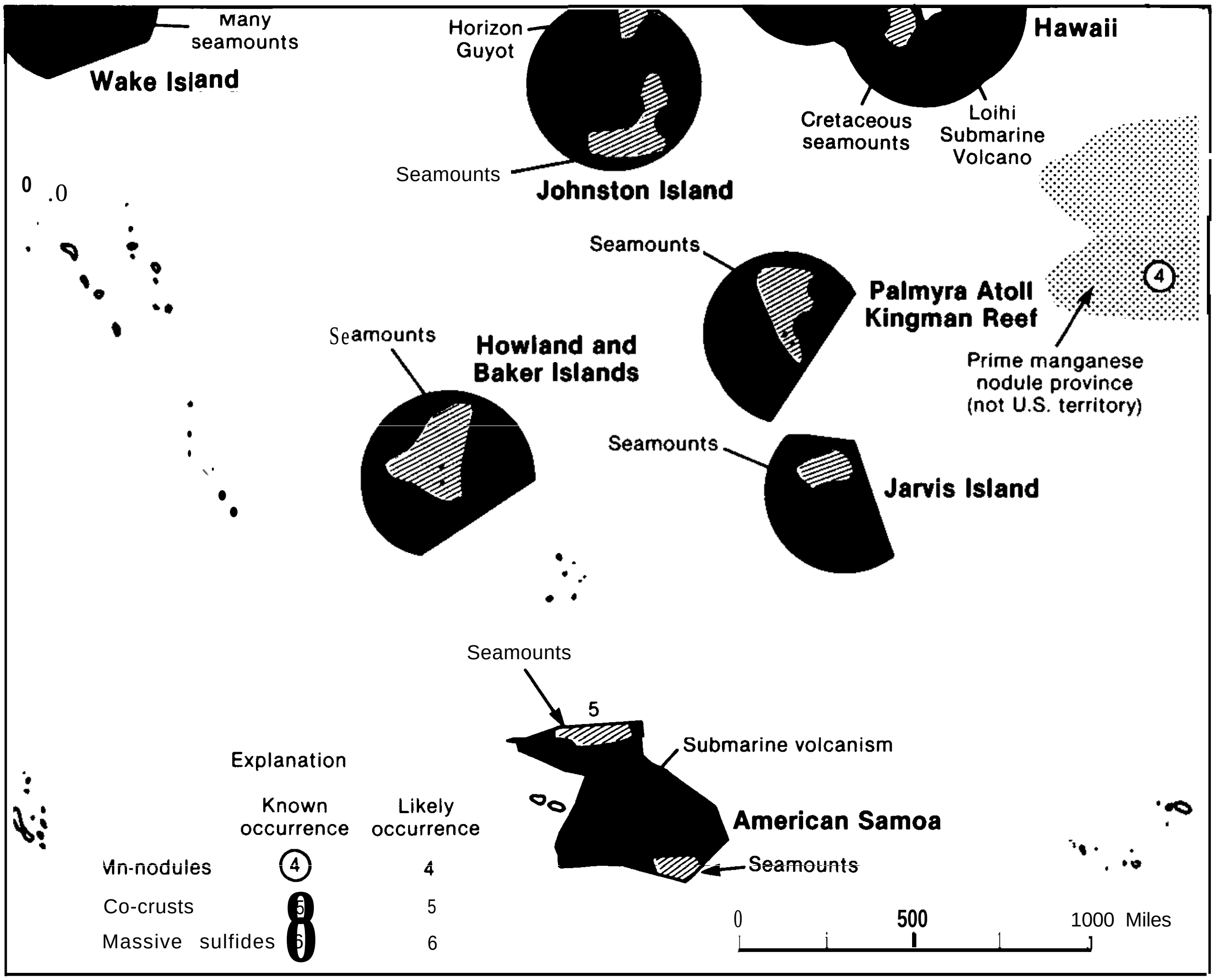
[60] J. R. Hein, L.A. Morgenson, D.A. Glague, and R.A. Koski, "Cobalt-Rich Ferromanganese Crusts From the Exclusive Economic Zone of the United States and Nodules From the Oceanic Pacific, D. Scholl, A. Grantz, and J. Vedder (eds.), Geology *and Resource Potential of the Continental Margins of Western North America and Adjacent Ocean Basins,* American Association of Petroleum Geologists, Memoir (in press), 1986.

Table 2-8.—Estimated Resource Potential of Crusts Within the EEZ of Hawaii and U.S. Trust and Affiliated Territories

Pacific area	Relative banking	Potential
Marshall Islands	1	High
Micronesia	2	High
Johnston Island	3	High
Kingman-Palmyra	4	High
Hawaii-Midway	5	Medium
Wake	6	Medium
Howland-Baker	7	Medium
Northern Mariana Islands	8	Low
Jarvis	9	Low
Samoa	10	Low
Belau/Palau	11	Low
Guam	12	Low

SOURCE: Modified from J.R. Hein, F.T. Manheim, and W.C. Schwab, *Cobalt-Rich Ferromanganese Crusts from the Central Pacific*, OTC 5234, Offshore Technology Conference, May 1966, pp. 119126,

Figure 2-13.–Potential Hard Mineral Resources of U.S. Insular Territories South of Hawaii



SOURCES: Office of Technology Assessment, 1987; U.S. Department of the Interior, "Symposium Proceedings—A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 1983.

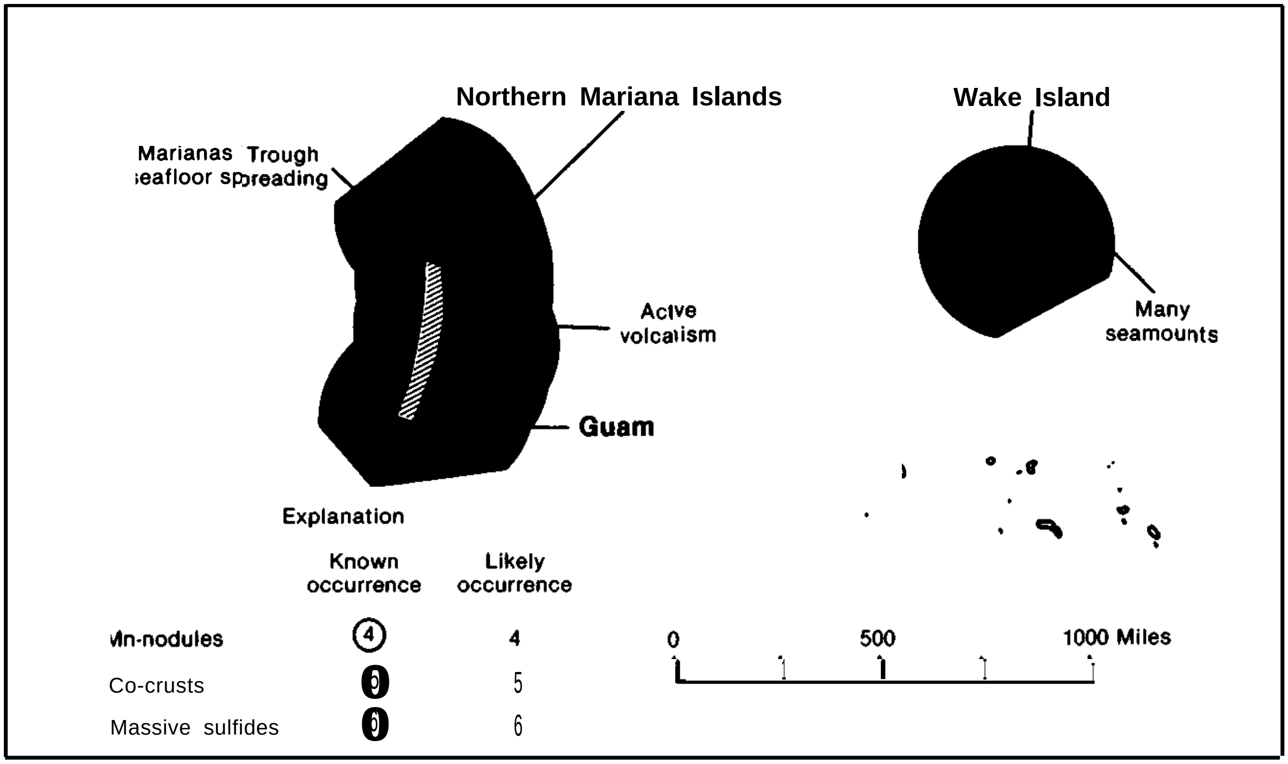
area that could not be mined because of roughness of small-scale topography. When asked to place the stage of knowledge of the economic potential of cobalt crusts on the time-scale experienced in the investigations of manganese nodules, one leading researcher chose 1963.[61]

[61] J. M. Broadus, *Seabed Mining,* report to the Office of Technology Assessment, U.S. Congress, Feb. 14, 1984, p. 24,

Manganese Nodules

Ferromanganese nodules are found at most water depths from the continental shelf to the abyssal plain. Since the formation of nodules is limited to areas of low sedimentation, they are most common on the abyssal plain. Nodules on the abyssal plain are enriched in copper and nickel and, until recently, have been regarded as candidates for commercial recovery. Nodules found on topographic highs in the Pacific are enriched in cobalt and were mentioned in the previous section.

Figure 2-14.–Potential Hard Mineral Resources of U.S. Insular Territories West of Hawaii



SOURCES: Office of Technology Assessment, 19S7; U.S. Department of the Interior, "Symposium Proceedings-A National Program for the Assessment and Development of the Mineral Resources of the United States Exclusive Economic Zone," U.S. Geological Survey Circular 929, 19S3.

The prime area considered for commercial recovery of nodules in the Pacific lies in international waters between the Clarion and Clipperton fracture zones in the mid-Pacific ocean. However, several other smaller areas may contain suitable mine sites, for example, southwest of Hawaii. A mine site should have an average grade of about 2.25 percent copper plus nickel with 20 pounds of nodules per square yard to be commercially interesting. Because of uncertainties brought about by the United Nations Law of the Sea Convention in regard to mining in international waters, and because of the low price of copper on the world market, the recovery of nodules from the Clarion-Clipperton region is not attractive at this time.

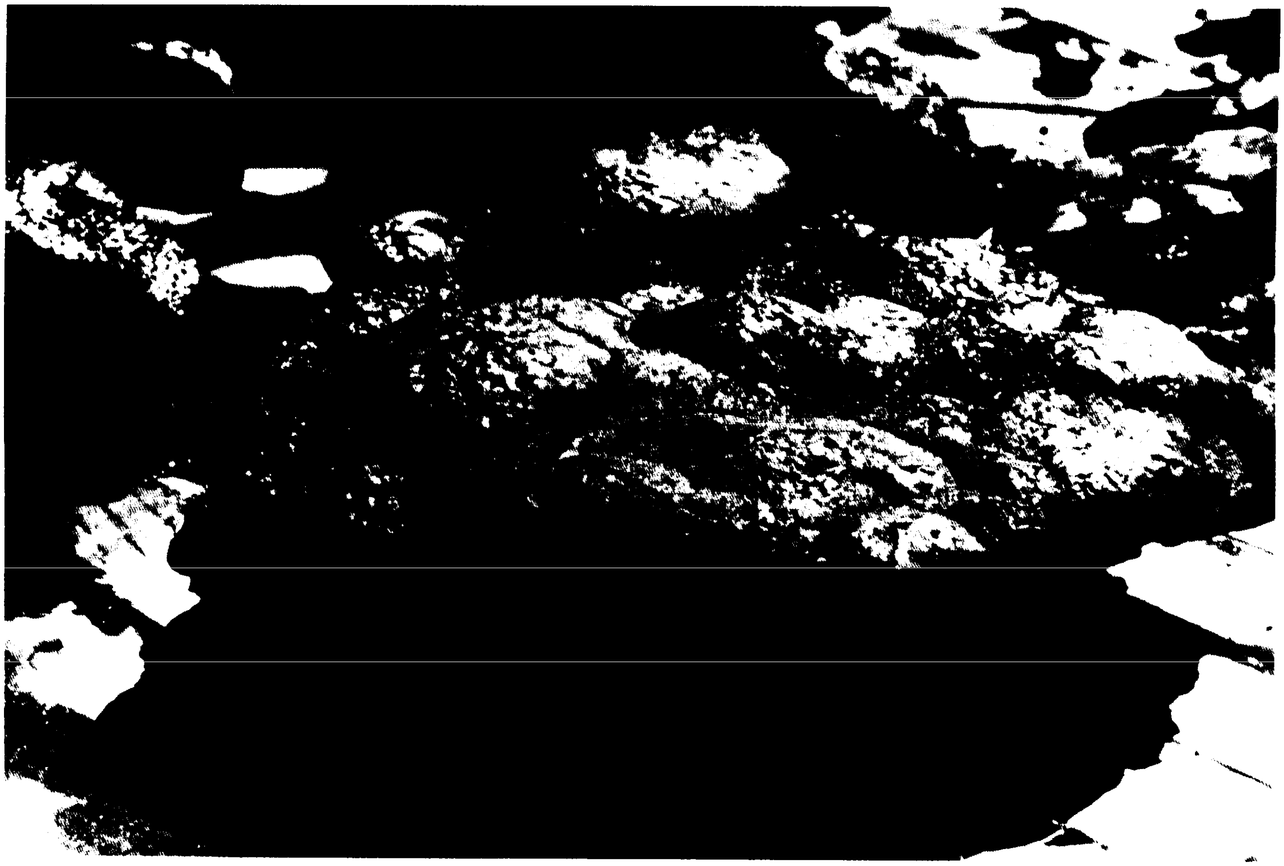


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Photo credit: National Oceanic and Atmospheric Administration

Manganese nodules on the seafloor. Ferromanganese nodules have been studied extensively as a potential source of copper, nickel, cobalt, and manganese. Prototype mining systems have successfully recovered several tons of nodules from sites such as this, but full-scale mining systems have not been built and tested. Current market conditions do not encourage further commercial development.