Chapter 4

Technologies for Exploring the Exclusive Economic Zone

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Technologies for Exploring the Exclusive Economic Zone

INTRODUCTION

The Exclusive Economic Zone (EEZ) is the largest piece of "real estate" to come under the jurisdiction of the United States since acquisitions of the Louisiana Purchase in 1803 and the purchase of Alaska in 1867. The EEZ remains largely unexplored, both in the Lewis and Clark sense of gaining general knowledge of a vast new territory and in the more detailed sense of assessing the location, quantity, grade, or recoverability of resources. This chapter identifies and describes technologies for exploring this vast area, assesses current capabilities and limitations of these technologies, and identifies future technology needs.

The goal of mineral exploration is to locate, identify, and quantify mineral deposits, either for scientific purposes (e. g., better understanding their origin) or for potential commercial exploitation. Detailed sampling of promising sites is necessary to prove the commercial value of deposits. Obviously, it would be impractical and costly to sample the entire EEZ in the detail required to assess the commercial viability of a mineral deposit. Fortunately, this is not necessary as techniques other than direct sampling can provide many indirect clues that help researchers or mining prospectors narrow the search area to the most promising sites.

Clues to the location of potential offshore mineral accumulations can be found even before going to sea to search for them. The initial requirements of an exploration program for the EEZ are a thorough understanding of its geological framework and of the geology of adjacent coastal areas. In some instances, knowledge of onshore geology may lead directly to discoveries in adjacent offshore areas. For example, a great deal is currently known about the factors responsible for the formation of offshore heavy mineral deposits and gold placers. These factors include onshore sources of the minerals, transport paths, processes of concentration, and preservation of the resulting deposit.[1] In contrast, relatively little is known about the genesis of cobalt crusts or massive sulfides. Although a thorough understanding of known geology and current geological theory may not lead directly to a commercial discovery, some knowledge is indispensable for devising an appropriate offshore exploration strategy.

Rona and others have used the concept of 'closing range to a mineral deposit' to describe an exploration strategy for hydrothermal mineral deposits.[2] With some minor modifications this strategy may be applicable for exploration of many types of offshore mineral accumulations. It is analogous to the use of a zoom lens on a camera which first shows a large area with little detail but then is adjusted for a closeup view to reveal greater detail in a much smaller area. The strategy of closing range begins with regional reconnaissance. Reconnaissance technologies are used to gather information about the "big picture. While none of these techniques can provide direct confirmation of the existence, size, or nature of specific mineral deposits, they can be powerful tools for deducing likely places to focus more attention. As knowledge is acquired, exploration proceeds toward increasingly more focused efforts (see table 4-1), and the exploration technologies used have increasingly specific applications. Technologies that provide detailed information can be used more efficiently once reconnaissance techniques have identified the promising

[1] H.E. Clifton and G. Luepke, "Heavy Mineral Placer Deposits of the Continental Margin of Alaska and the Pacific Coast States, *Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins—Beaufort Sea to Baja California,* American Association of Petroleum Geologists, Memoir 43, in press, 1986, p. 2 (draft).

[2] P. A. Rona, ' 'Exploration for Hydrothermal Mineral Deposits at Seafloor Spreading Centers, *Marine Mining,* Vol. 4, No. 1, 1983, pp. 20-26.

Table 4-1.—Closing Range to a Mineral Deposit

Approximate range to deposit	Method
10 kilometers	Long-range side-looking sonar
	Regional sediment and water sampling
1 kilometer	Gravity techniques
	Magnetic techniques
	Bathymetry
	Midrange side-looking sonar
	Seismic techniques
100 meters.	Electrical techniques
	Nuclear techniques
	Short-range side-looking sonar
10 meters.	Near-bottom water sampling
	Bottom images
0 meter.	.Coring, drilling, dredging
	Submersible applications

SOURCE: Adapted from P.A. Rona, "Exploration for Hydrothermal Mineral Deposits at Seafloor Spreading Centers," *Marine Mining, vol. 4 No.* 1, 1963, pp. *20-26.*

areas. Systematic exploration does not necessarily mean comprehensive exploration of each acre of the EEZ.

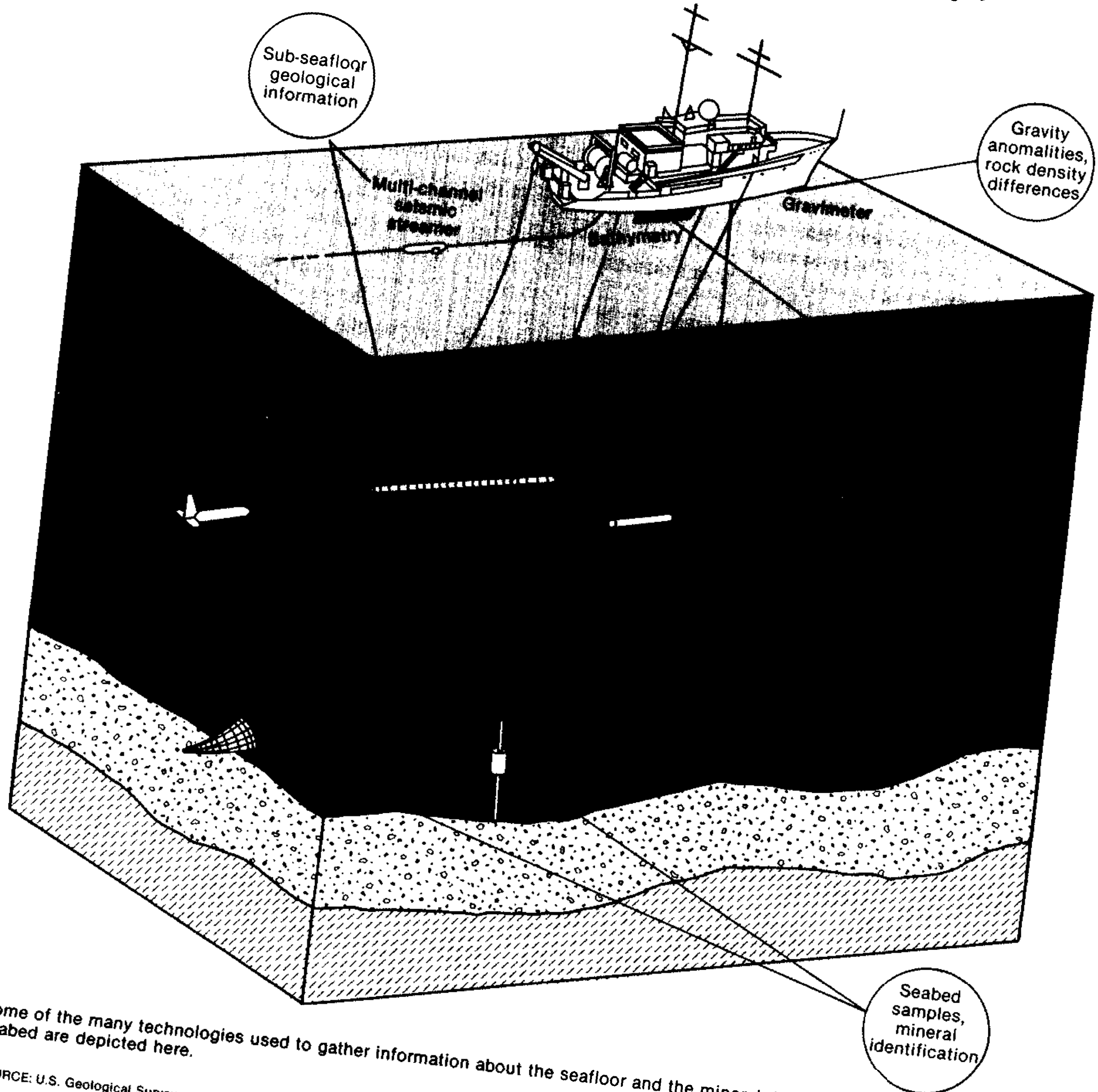
Accurate information about seafloor topography is a prerequisite for detailed exploration. Side-looking sonar imaging and bathymetric mapping provide indispensable reconnaissance information. Side-looking sonar provides an image of the seafloor similar to that provided by aerial radar imagery. Its use has already resulted in significant new discoveries of subsea geological features within the U.S. EEZ. By examining side-looking sonar images, scientists can decide where to focus more detailed efforts and plan a more detailed exploration strategy.

Long-range side-looking sonar (e. g., GLORIA or SeaMARC II, described below) may show patterns indicating large seabed structures. At somewhat closer range, a number of other reconnaissance technologies (figure 4-1) may provide more detailed textural and structural data about the seabed that can be used to narrow further the focus of a search to a specific mineral target.

Photo credit: U.S. Geological Survey

USGS *S.P. Lee*

Figure 4-1.—USGS Research Vessel *S.P. Lee* and EEZ Exploration Technologies



Some of the many technologies used to gather information about the seafloor and the mineral deposits found on or in the seabed are depicted here.

SOURCE: U.S. Geological Survey.

- Bathymetric profiling yields detailed information about water depth, and hence, of seabed morphology.
- Midrange side-looking sonars provide acoustic images similar to long-range sonars, but of higher resolution.
- Seismic reflection and refraction techniques acquire information about the subsurface structure of the seabed.
- Magnetic profiling is used to detect and characterize the magnetic field. Magnetic traverses may be used offshore to map sediments and rocks containing magnetite and other iron-rich minerals.
- Gravity surveys are used to detect differences in the density of rocks, leading to estimates of crustal rock types and thicknesses.
- Electrical techniques are used to study resistivity, conductivity, electrochemical activity, and other electrical properties of rocks.
- Nuclear techniques furnish information about the radioactive properties of some rocks.

Many of these reconnaissance technologies are also useful for more detailed studies of the seabed. Most are towed through the water at speeds of from 1 to 10 knots. Hence, much information may be gathered in relatively short periods of time. It is often possible to use more than one sensor at a time, thereby increasing exploration efficiency. Data sets can be integrated, such that the combined data are much more useful than information from any one sensor alone. Generally, the major cost of offshore reconnaissance is not the sensor itself, but the use of the ship on which it is mounted.

At still closer ranges, several other remote sensing techniques and technologies become useful. Short-range, higher frequency side-looking sonars provide very high resolution of seafloor features at a range of 100 meters (328 feet)[3] and less. At less than about 50 meters in clear water, visual imaging is often used. Photographs or videotapes may be taken with cameras mounted on towed or lowered platforms or on either unmanned or manned submersibles. Instruments for sampling the chemical properties and temperature of near-bottom water also may be carried aboard these platforms.

Indirect methods of detection give way to direct methods at the seabed. Only direct samples can provide information about the constituents of a deposit, their relative abundance, concentration, grain size, etc. Grab sampling, dredging, coring, and drilling techniques have been developed to sample seabed deposits, although technology for sampling consolidated deposits lags behind that for sampling unconsolidated sediments. If initial sampling of a deposit is promising, a more detailed sampling program may be carried out. In order to prove the commercial value of a mineral occurrence, it may be necessary to take thousands of samples.

While some technology has been specifically designed for minerals exploration, much technology useful for this purpose has been borrowed from technology originally designed for other purposes. Some of the most sophisticated methods available for exploration were developed initially for military purposes. For instance, development of multi-beam bathymetric systems by the U.S. Navy has proven useful for civilian charting, oceanographic research, and marine minerals exploration. Much technology developed for military purposes is not immediately available for civilian uses. Some technologies developed by the scientific community for oceanographic research are also useful for minerals exploration.

Advances in technology usually generate interest in finding applications to practical problems. It is often costly to adapt technology for marine use. When the military defines a need, the cost of development of new technology is commonly less constrained than may be the case for the civilian sector. Conversely, although certain exploration techniques (e. g., for sampling polymetallic sulfides) are not yet very advanced, it does not necessarily follow that the technical problems in research and development are overwhelming. Identification of the need for new technology may be recent, and/or the urgency to develop the technology, which might be high for military use, may be relatively low for civilian use.

[3]Many geophysical and geological measurements are commonly expressed in metric units. This convention will be retained in this chapter. For selected measures, units in both metric and English systems will be given.

RECONNAISSANCE TECHNOLOGIES

Side-Looking Sonars

Side-looking sonars are used for obtaining acoustic images of the ocean bottom. Most side-looking sonars use ship-towed transducers which transmit sound through the water column to the seafloor. The sound is reflected from the seabed and returned to the transducer. Modern side-looking sonars measure both echo-time and backscatter intensity. As the ship moves forward, successive sound pulses are transmitted, received, and digitally recorded. Side-looking sonars were originally designed for analog operation (i. e., for producing a physical trace of the returned echo), but most now use digital methods to facilitate image processing. The data are usually processed to correct for variations in the ship's speed, slant-range distance to the seafloor, and attenuation of sound in the water. The final product is a sonograph, or acoustic image, of the ocean floor. It is also possible to extract information about the texture of some seabed deposits from the sonar signal. Side-looking sonars useful for EEZ exploration are of three types:

1. long-range (capable of mapping swaths 10 to 60 kilometers wide),
2. mid range (1 to 10 kilometers swaths), and
3. short range (<1 kilometer swaths).[4]

Table 4-2 displays characteristics of several side-looking sonars.

Long-Range Side-Looking Sonar

One of the few technologies used to date to investigate large portions of the U.S. EEZ is a long-range side-looking sonar known as GLORIA (Geological LOng Range Inclined Asdic) (figure 4-2). GLORIA was designed by the Institute of Oceanographic Sciences (IOS) in the United Kingdom and is being used by the U.S. Geological Survey (USGS) for obtaining acoustic images of the U.S. EEZ beyond the continental shelf.[5] When processed, GLORIA images are similar to slant-range radar images. GLORIA's main contribution is that it gives geologists a valuable first look at expanses of the seafloor and enables them to gain insight about seabed structure and geology. For instance, the orientation and extent of large linear features such as ridges, bedforms, channels, and fracture zones can be determined.[6] Horizontal separations as little as 45 meters (148 feet) and vertical distances on the order of a few meters can be resolved.

USGS is using GLORIA to survey the EEZ relatively inexpensively and quickly. GLORIA can survey swaths of seabed as wide as 60 kilometers (although, in practice, a 45-kilometer swath width is used to improve resolution). When towed 50 meters beneath the sea surface at 8 to 10 knots and set to illuminate a 60-kilometer swath, GLORIA is capable of surveying as much as 27,000 square kilometers (about 8,300 square nautical miles) of the seafloor per day. It is less efficient in shallow water, since swath width is a function of water depth below the sonar, increasing as depth increases. GLORIA can survey to the outer edge of the EEZ in very deep water.

Processing and enhancement of digital GLORIA data are accomplished using the Mini-Image Processing System (MIPS) developed by USGS.[7] MIPS is able to geometrically and radiometrically correct the original data, as well as enhance, display, and combine the data with other data types. In addition, the system can produce derivative products, all on a relatively inexpensive minicomputer system.[8] It is also possible now to vary the scale and projection of the data without having to do much manual manipulation.

4P. R. Vogt and B. E. Tucholke (eds.) "Imaging the Ocean Floor—History and State of the Art, " in The Geology of *North* America, *Volume M, The Western North Atlantic Region* (Boulder, CO: Geological Society of America, 1986), p. 33.

5EEZ Scan 1984 Scientific Staff, *Adas of the Exclusive Economic Zone, Western Conterminous United States,* U.S. Geological Survey Miscellaneous Investigations Series 1-1792, Scale 1 :500,000, 1986.

6R. 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, *Geological Circular 912, 1983,* p. 16.

7P. S. Chavez, "Processing Techniques for Digital Sonar Images From GLORIA, *Photogrammetric Engineering and* Remote *Sensing*, vol. 52, No. 8, 1986, pp. 1133-1145.

8G. W. Hill, "U.S. Geological Survey Plans for Mapping the Exclusive Economic Zone Using 'GLORIA', *Proceedings: The Exclusive Economic Zone Symposium: Exploring the New Ocean Frontier*, M. Lockwood and G. Hill (eds.), conference sponsored by National Oceanic and Atmospheric Administration, L'. S. Department of the Interior, Smithsonian Institution, and Marine Technology Society, held at Smithsonian Institution, Oct. 2-3, 1985, p. 76.

Table 4.2.—Side-Looking Sonars

System	Frequency kilohertz	Max range km	Fish beamwidth degrees	Dimensions meters	Max weight pounds	Tow speed knots	Area coverage rate[c] km²/day	Resolution at max range meters	Tow depth meters	Equipment Cost[a] M = millions K=thousand	Cost/km²
Swath Map (SQS-26CX)	3.5	37	>2.5 x NA	hull mounted	—	20	66,000	>100	hull	—[b]	
GLORIA II	6.2/6.8	22.5	2.5 X 30	7.75 x .66 dia	4,000	10	20,000	100	50 typ	$1.3M	$2-$4
SeaMARC II	11/12	10	2.0 x 40	5.5 x 1.3 dia	3,800	8	3,000	10	200 typ	$1.2M	$5-$10
SeaMARC 1.	27/30	2.5	1.7 x 50	3 x 1.2x 1.1	1,300	5	1,100	5	6,000 max	$900K	$20-$40
SEAMOR	27/30	3	1.7 x 50	3.8 X 1.9x 2.3	6,400	2	500	3	6,000 max	$2M	
Deep Tow	110	1	.75x60	NA	2,000 (in water)	2	170	1	7,000	—	—
SAR	170/190	0.75	0.5x80	5 x 1.0 dia	4,800	2	130	0.75	6,100 max	—	—
EDO 4075	100	0.6	2.0 x 50	4.3 x 1.0 dia	2,000	2	104	0.5	6,000 max	$600K	$150-$400
SeaMARC CL.	150	0.5	1.5 x 50	2 x.4x.4	175	2	97	0.5	1,500 max	$250K	—
EG&G SMS 960	105	0.5	1.2 x 50	1.4 x.1 1 dia	55	15	670	0.5	600 max	$96K	$10-$60
SMS 260	105	0.5	1.2 x 50	1.4 x.1 1 dia	55	15	670	0.5	600 max	$42K	$10-$60
Klein	50	0.5	1.5 x 40	1.5 x .09 dia	62	16	710	0.5	2,300 max	$40-50K	$10-$60
	100	0.4	1.0 x 40	1.4 x .09 dia	52	16	570	0.4	2,300 max	$40-50K	$10-$60
	500	0.2	0.2 x 40	1.2 x .09 dia	48	16	280	0.2	2,300 max	$40-50K	$10-$60

[a] Costs are for complete systems including "fish" electronics (subsea and topside), analog or digital recording, and winch and cable Winch and cable costs are substantial ($250.000) for deep-water systems The ship positioning system is not Included, but fish positioning (relative to the ship) is included for deep. water systems (.$80,000) Costs probably tend to be underestimated because they are for more basic systems than would likely be used In general, costs range from $50,000 to $150,000 for shallow systems $600,000 to $900,000 for short-range, deep tow systems, and from $1 million to $3 million for long- range systems

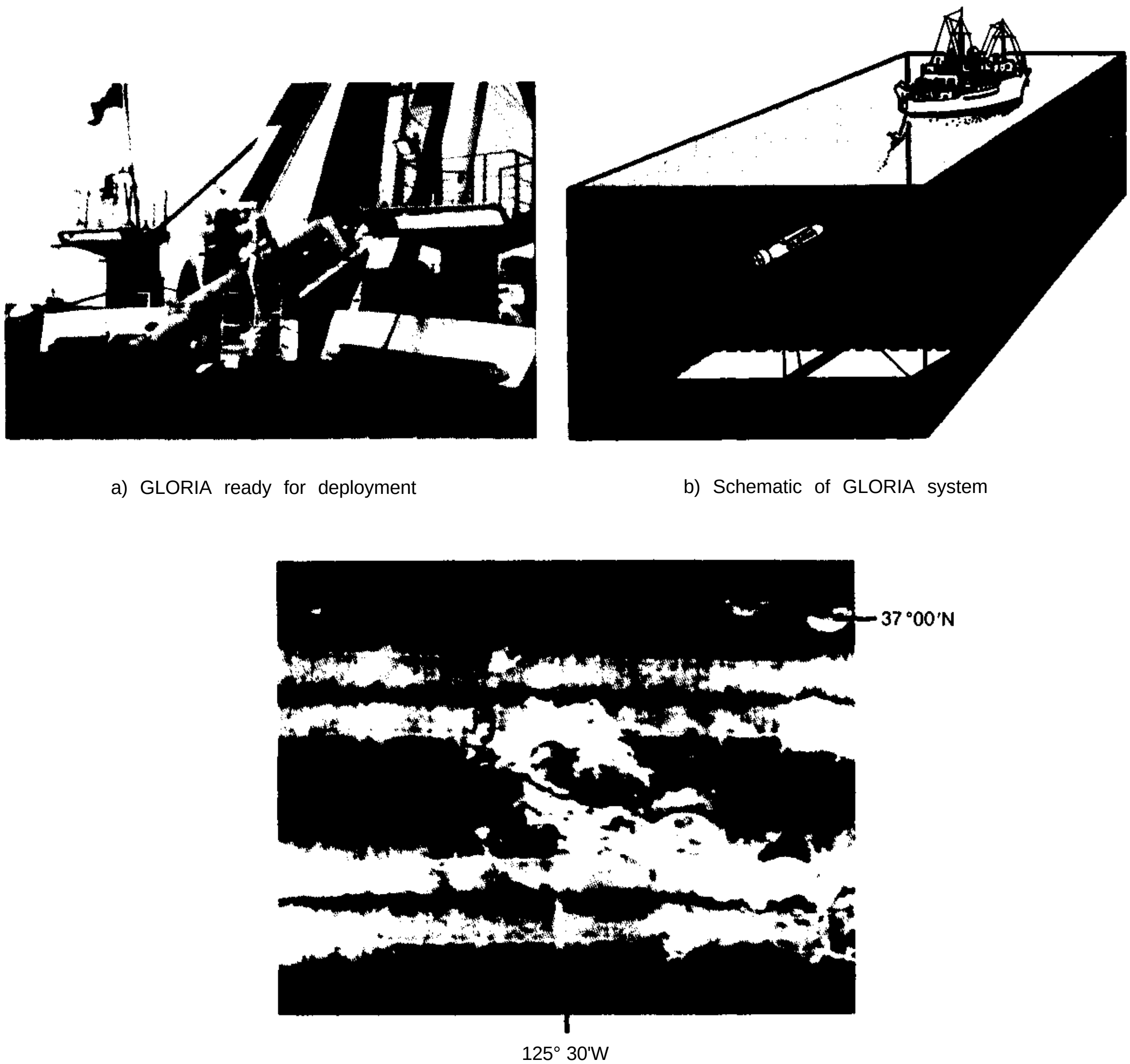
[b] No cost is estimated for SWATHMAP A graphic recorder is the only extra equipment needed if a frigate is equipped with an SQS-26CX sonar No cost estimate is given for Deep Tow because It has been a constantly evolving system incorporating many more capabilities than just the imaging system No cost is available for the French-developed SAR

[c] The figures given for area coverage rate assume operations at maximum speed and maximum range 24 hours per day In practice, transit time weather delays, crosslines, equipment failures, etc reduce the effective number of hours per day In shallow water the maximum useful range decreases because the image becomes distorted by refraction at shallow angles and its appearance deteriorates because of the changes in reflection characteristics if grazing angles are less than about 5

NA—not available

SOURCE National Oceanic and Atmospheric Administration

Figure 4-2.—GLORIA Long-Range Side. Looking Sonar



a) GLORIA ready for deployment

b) Schematic of GLORIA system

c) GLORIA image of Taney Seamounts

SOURCE: U S. Geological Survey.

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USGS **used GLORIA in 1984 to survey the EEZ adjacent to California, Oregon, and Washington. This entire area (250,000 square nautical miles) was** surveyed in 96 survey days (averaging about 2,600 square nautical miles per day). In 1985, USGS used GLORIA to complete the survey of the Gulf of Mexico started in 1982 and to survey offshore areas adjacent to Puerto Rico and the Virgin Islands. In 1986, GLORIA surveys were conducted in parts of the Bering Sea and in Hawaiian waters. The benefits of using GLORIA data to reconnoiter the EEZ have become apparent in that, among other things, several dozen previously unknown volcanoes (potential sites for hard mineral deposits) were discovered.[9] These and other features appear in USGS's recently published west coast GLORIA atlas, a collection of 36, 2- by 2-degree sheets at a scale of 1:500,000.[10] Digital GLORIA data will be even more useful in the future, as additional bathymetric, magnetic, gravity, and other types of data are collected and integrated in the database.

USGS has now acquired its own GLORIA (it previously leased one owned by 10 S). Known as GLORIA Mark III, this newest system is an improved version of earlier models, incorporating titanium transducers and a digitized beam-steering unit to correct for yaw.[11] During the next several years, GLORIA Mark III is scheduled to survey Alaskan, Hawaiian, and Atlantic EEZs. The USGS plan is to survey the entire U.S. EEZ by 1991, with the exception of the U.S. Trust Territories, the ice-covered areas of the Beaufort and Chukchi Seas, and continental shelf areas (i. e., areas shallower than 200 meters (656 feet)).

The potential market for GLORIA surveys has recently attracted a private sector entrepreneur, Marconi Underwater Systems of the United Kingdom. Marconi is convinced that other coastal states will wish to explore their EEZs and will look to commercial contractors for assistance. Eventually, USGS also may be in a position to use its GLORIA for mapping the EEZs of other countries. Once the U.S. EEZ is surveyed, GLORIA would be available for use to explore EEZs of countries that have cooperative science programs with the United States.

USGS is coordinating its GLORIA program with the detailed EEZ survey program of the National Oceanic and Atmospheric Administration (NOAA). NOAA is using Sea Beam and Bathymetric Swath Survey System (BS^3) technology (discussed below) to produce detailed bathymetric charts. NOAA uses GLORIA information provided by USGS for determining survey priorities. USGS geologists use NOAA's bathymetry in conjunction with GLORIA data to assist in interpreting the geologic features of the seafloor. The most accurate geological interpretations will result from use of many different types of data simultaneously: side-looking sonar, bathymetry, gravity, magnetic, seismic, electrical, etc.

Midrange Side-Looking Sonar

Like GLORIA, midrange systems record the acoustic reflection from the seafloor; however, they are capable of much higher resolution. In addition, whereas GLORIA is used to obtain a general picture of the seafloor, midrange and shortrange side-looking sonars are usually used for more detailed surveys. A seabed miner interested in looking for a specific resource would select and tune the side-looking sonar suitable for the job. For example, manganese nodule fields between the Clarion and Clipperton fracture zones in the Pacific Ocean were mapped in 1978 using an imaging system specially designed and built for that purpose.

The Sea Mapping And Remote Characterization systems—SeaMARC I and II—developed by International Submarine Technology, Ltd. (1ST), and, respectively, Lamont-Doherty Geological Observatory and the Hawaii Institute of Geophysics (HIG), are two of several such systems available. SeaMARC I recently has been used to survey the Gorda and Juan de Fuca ridges.[12] It can resolve tectonic and volcanic features with as little as 3 meters of relief. Higher resolution is obtained because midrange systems use wider bandwidths and generally operate at higher frequencies (10 to 80

[9]Ibid.
[10]EEZ Scan 1984 Scientific Staff, Atlas.
[11]D. Swinbanks, "New GLORIA in Record Time,' Nature, vol. 320, Apr. 17, 1986, p. 568.

[12]J.G Kosalos and D. Chayes, "A Portable System for Ocean Bottom Imaging and Charting, *Proceedings*, Oceans 83, sponsored by Marine Technology and IEEE Ocean Engineering Society, Aug. 29-Sept. 1, 1983, pp. 649-656.
[13]E.S. Kappel and W. B. F. Ryan, "Volcanic Episodicity and a Non-Steady State Rift Valley Along Northeast Pacific Spreading Centers: Evidence from Sea Marc I," Journal *of Geophysical* Research, 1986, in press

kilohertz) than long-range systems and because they are towed closer to the bottom.[14] However, higher resolution is obtained at the expense of swath width.

SeaMARC I data is relatively expensive to acquire, given the smaller area that can be surveyed in a given time; however, SeaMARC I coverage in specific areas is a logical follow-on to GLORIA regional coverage, as the information it provides is of much higher resolution. For example, little is known about the small-scale topography of seamounts and ridges where cobalt crusts are found. SeaMARC I surveys (or surveys by a similar deep-towed system) will be needed to determine this small-scale topography before appropriate mining equipment can be designed.[15]

Interferometric Systems

By measuring the angle of arrival of sound echoes from the seafloor in addition to measuring echo amplitude and acoustic travel time, interferometric systems are able to generate multi-beam-like bathymetric contours as well as side-scanning sonar imagery (table 4-3).[16] SeaMARC II developed jointly by 1ST and HIG, newer versions of SeaMARC I, and several other systems have this dual function capability.

SeaMARC II is a midrange to long-range side-looking sonar towed 100 meters below the surface (above SeaMARC I, below GLORIA). It is capable of surveying over 3,000 square kilometers (875 square nautical miles) per day when towed at 8 knots, mapping a swath 10 kilometers wide (20 kilometers or more when used for imaging only) in water depths greater than 1 kilometer. Some recent SeaMARC II bathymetry products have produced greater spatial resolution than Sea Beam or SASS bathymetry technologies (discussed below). Currently, SeaMARC II does not meet International Hydrographic Bureau accuracy standards for absolute depth, which call for sounding errors of no more than 1 percent in waters deeper than 100 meters, Although there are physical limits to improvements in SeaMARC accuracy, the substantial advantage in rate of coverage may outweigh needs for 1 percent accuracy, particularly in deep water.[17] SeaMARC **II's** swath width is roughly four times Sea Beam's in deep water, so at similar ship speeds the survey rate will be about four times greater.

Two other SeaMARC systems, both of which will have the capability to gather bathymetry data and backscatter imagery, are now being **developed at 1ST: SeaMARC TAMU and SeaMARC CL. SeaMARC TAMU is a joint project of the Naval Ocean Research and Development Activity, Texas A&M University, and John Chance Associates. The unit will be able to transmit and receive signals simultaneously at several frequencies, which may enable identification of texture and bottom roughness.**

Concurrently, developments are underway to use Sea Beam returns to measure backscattering strength; hence, technical developments are beginning to blur the distinction between SeaMARC and Sea Beam systems.[18] Additional advances in seabed mapping systems are being made in the design of tow vehicles and telemetry systems, in signal proc-

Table 4-3.—Swath Mapping Systems

Image only	Image and bathymetry	Bathymetry only
Side looking	*Interferometric*	*Sector scan*
Swath Map	SeaMARC II	Hydrosearch
GLORIA	SeaMARC/S	SNAP
SeaMARC I	SeaMARC TAMU	*Multibeam*
SeaMARC II	Bathyscan	Sea Beam
SeaMARC CL	TOPO-SSS	BSSS/Hydrochart
Deep Tow		SASS
SAR		BOTASS
EDO 4075		Krupp-Atlas
EG&G SMS960		Honeywell-Elac
EG&G 260		Simrad
Klein		Benetech

SOURCE: International Submarine Technology, Ltd.

[14] Rowland, Goud, McGregor, "The U.S. Exclusive Economic Zone—Summary," p. 18.

[15] J. R. Hein, L.A. Morgenson, D.A. Clague, et al, "Cobalt-Rich Ferromanganese Crusts From the Exclusive Economic Zone of the United States and Nodules From the Oceanic Pacific, Geology and *Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins—Beaufort Sea to Baja California,* D. Scholl, A. Grantz, and J. Vedder (eds.), American Association of Petroleum Geologists, Memoir 43, in press, 1986.

[16] J. G. Blackinton, D.M. Hussong, and J.G. Kosalos, "First Results From a Combination Side-Scan Sonar and Seafloor Mapping System (SeaMARC II)," *Proceedings,* Offshore Technology Conference, Houston, TX, May 2-5, 1983, OTC 4478, pp. 307-314.

[17] D. E. Pryor, National Oceanic and Atmospheric Administration. OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

[18] Vogt and Tucholke, "Imaging the Ocean Floors, p. 34.

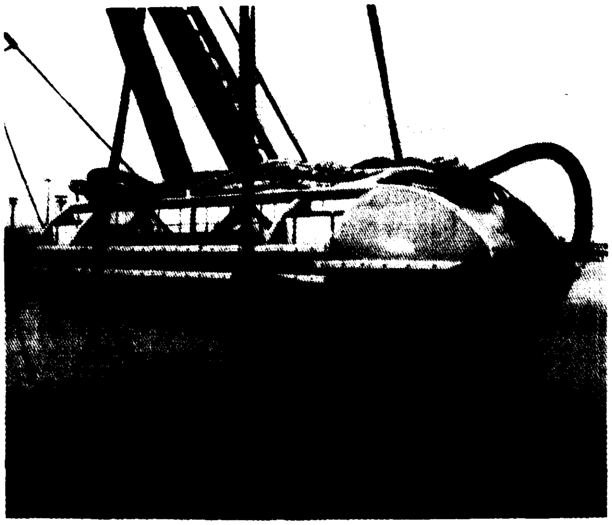


Photo credit: International Submarine Technology, Ltd.

Sea MARC II towfish

essing, in materials used in transducers, and in graphic recording techniques.[19]

Short-Range Side-Looking Sonar

Short-range side-looking sonar systems are used for acquiring acoustic images of small areas. They are not used for regional reconnaissance work, but they may be used for detailed imaging of seafloor features in areas previously surveyed with GLORIA or SeaMARC I or II. Operating frequencies of short-range sonars are commonly between 100 and 500 kilohertz, enabling very high resolution. Like midrange systems, they are towed close to the ocean bottom. Deep Tow, developed by Scripps Institution of Oceanography, has been used to study morphology of sediment bedforms and processes of crustal accretion at the Mid-Atlantic Ridge.[20] SAR (Systeme Acoustique Remorque) is a similar French system, reportedly capable of distinguishing objects as small as 30 by 76 centimeters (12 by 30 inches). It is towed about 60 meters off the seafloor and produces a swath of about 1,000 meters. Both of these deep-water systems have been used in the search for the *Titanic* .21

[19] M. Klein, "High-Resolution Seabed Mapping: New Developments, *Proceedings*, Offshore Technology Conference, Houston, TX, May 1984, p.75.

[20] Vogt and Tucholke, "Imaging the Ocean Floor, " p. 34.

[21] P.R. Ryan and A. Rabushka, "The Discovery of the *Titanic* by the U.S. and French Expedition, ' Ocean us, vol. 28, No. 4, winter 1985/86, p. 19.

SeaMARC CL is a short-range deep-towed interferometric system which is under development (figure 4-3). One model has been built for use in the Gulf' of Mexico; another has been configured by Sea Floor Surveys International for use by the private sector and is available for hire. Shallow water, high-resolution, side-looking sonar systems developed by EG&G and Klein are used for such activities as harbor clearance, mine sweeping, and detailed mapping of oil and gas lease blocks.

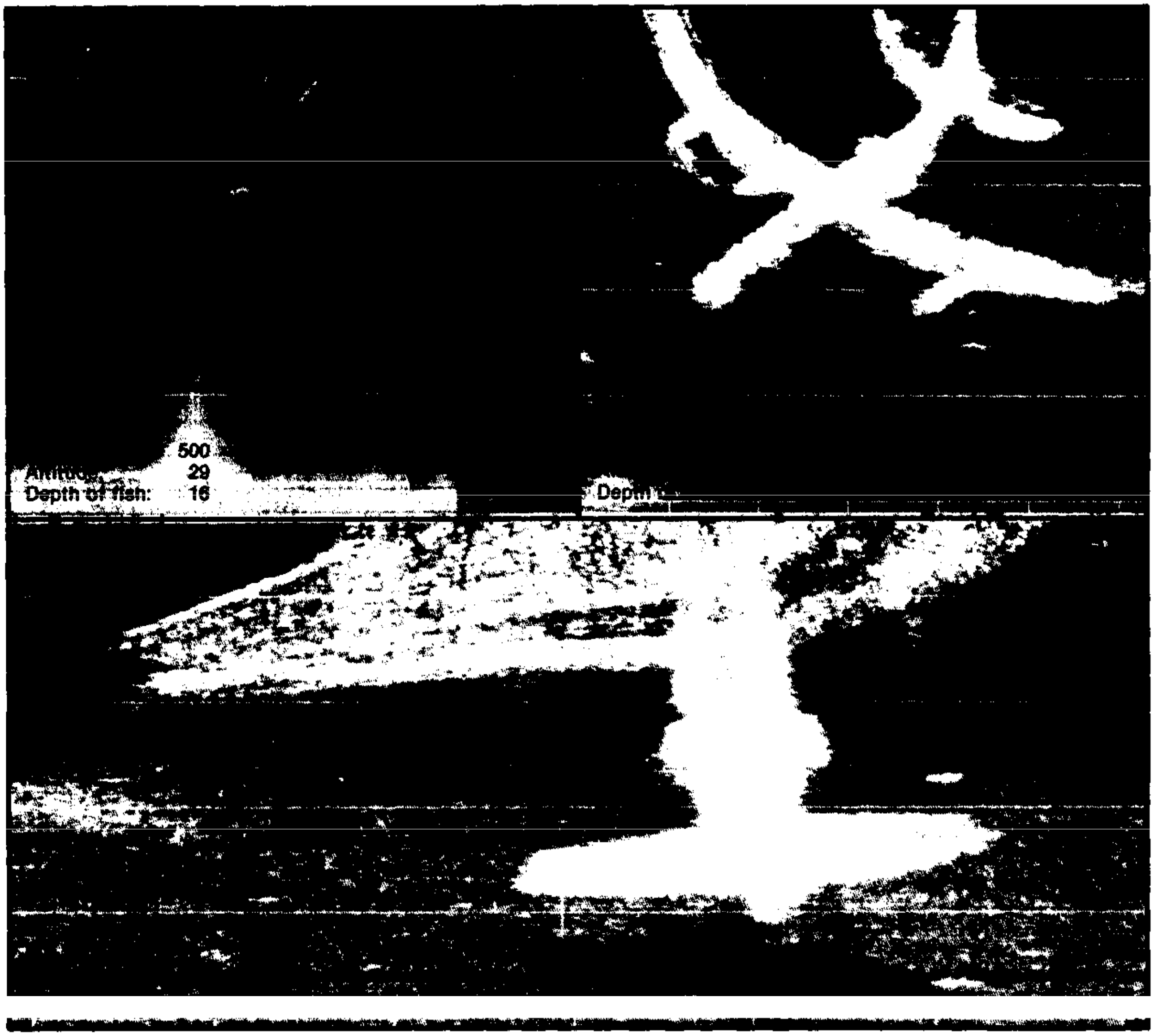
Bathymetric Systems

Bathymetry is the measurement of water depths. Modern bathymetric technologies are used to determine water depth simultaneously at many locations. Very accurate bathymetric charts showing the topography of the seafloor can be constructed if sufficient data are collected with precise navigational positioning (figure 4-4). These charts are important tools for geological and engineering investigations of the seafloor, as well as aids to navigation and fishing. If bathymetric and side- looking sonar data are integrated and used jointly, the product is even more valuable.

Most existing charts are based on data acquired using single beam echo-sounding technology. This technology has now been surpassed by narrow, multi-beam technology that enables the collection of larger amounts of more accurate data. The older data were obtained without the aid of precise positioning systems. Moreover, existing data in the offshore regions of the EEZ generally consist of soundings along lines 5 to 10 miles apart with positional uncertainties of several kilometers .22 Charts in the existing National Oceanic and Atmospheric Administration/National Ocean Service (NOAA/NOS) series are usually compiled from less than 10,000 data points. In contrast, similar charts using the newer multi-beam technology are compiled from about 400,000 data points, and this quantity constitutes a subset of only about 2 percent of the observed data. Hence, much more information is available for constructing very detailed charts.

[22] D. E. Pryor, "Overview of NOAA's Exclusive Economic Zone Survey Program, Ocean *Engineering and the Environment,* Oceans 85 Conference Record, sponsored by Marine Technology and IEEE Ocean Engineering Society, Nov. 12-14, 1985, San Diego, CA, pp. 1186-1189.

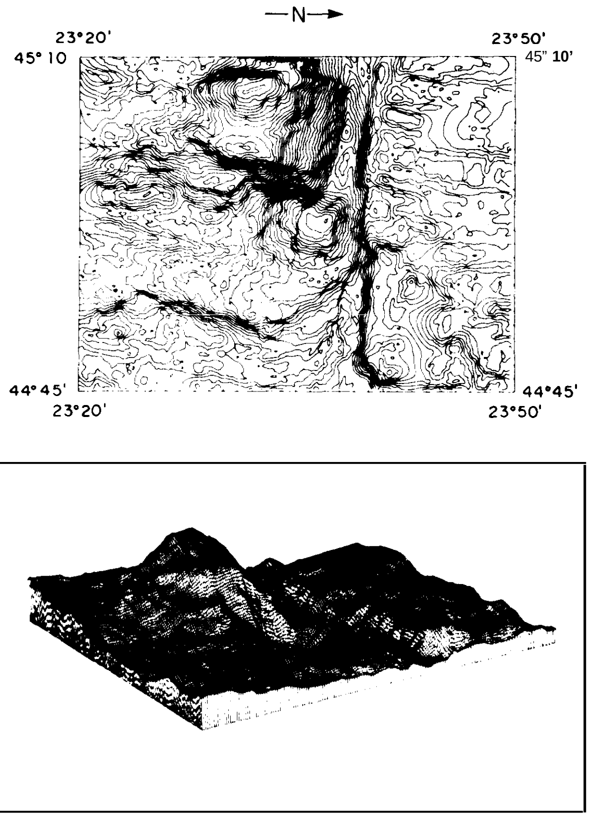
Figure 4-3.—SeaMARC CL images



Three images made of a PB4Y aircraft at the bottom of Lake Washington near Seattle. Swath width, altitude, and depth of towfish varies.

SOURCE: International Submarine Technology, Ltd.

Figure 4-4.—Multi-Beam Bathymetry Products



a) Contour map of part of the Kane Fracture Zone, Mid-Atlantic Ridge

b) Three-dimensional Mesh Surface Presentation of the same data. Charts and 3-D presentations such as these are important tools for geological and engineering investigations of the seafloor,

SOURCE: R. Tyce, Sea Beam Users Group.

Improvements in seafloor mapping have resulted from the development of multi-beam bathymetry systems (table 4-4), the application of heave-roll-pitch sensors to correct for ship motion, the improved accuracy of satellite positioning systems, and improved computer and plotter capability for processing map data.[23] These improvements make possible:

1. much higher resolution for detecting fine scale bottom features;
2. a significant decrease in time required for making area surveys;
3. nearly instantaneous automated contour charts, eliminating the need for conventional cartography;[24] and
4. the availability of data in digital format.

Deep-Water Systems

Swath bathymetric systems are of two types: those designed to operate in deep water and those designed primarily for shallow water. The principal deep-water multi-beam systems currently in use in the United States are Sea Beam and SASS. Sea Beam technology, installed on NOAA's NOS ships to survey EEZ waters deeper than 600 meters, first became available from General Instrument (GI) Corp. in 1977. GI's original multi-beam bathymetric sonar, the Sonar Array Sounding System (or SASS) was developed for the U.S. Navy and is not available for civilian use. Sea Beam is a spinoff from the original SASS technology.

Sea Beam is a hull-mounted system, which uses 16 adjacent beams, 8 port and 8 starboard, to survey a wide swath of the ocean bottom on both sides of the ship's track (figure 4-5). Each beam covers an angular area 2.670 square. The swath angle is the sum of the individual beam width angles, or 42.670, With the swath angle set, the swath width depends on the ocean depth. At the continental shelf edge, i.e., 200 meters, the swath width is about 150 meters at the bottom; in 5,000 meters (16,400 feet) of water, the swath width is approximately 4,000 meters. Therefore, Sea Beam's survey rate is greater in deeper waters. By carefully spacing ship tracks, complete (or overlapping) coverage of an area can be obtained. The contour interval of bathymetric charts produced from Sea Beam can be set as fine as 2 meters.

The Navy's older SASS model uses as many as 60 beams, providing higher resolution than Sea Beam in the direction perpendicular to the ship's track (Sea Beam resolution is better parallel to the ship's track). In current SASS models, the outer 10 or so beams are often unreliable and not used.[25]

[23] C. Andreasen, "National Oceanic and Atmospheric Administration Exclusive Economic Zone Mapping Project, in *Proceedings: The Exclusive Economic Zone Symposium: Exploring the New Ocean Frontier,* M. Lockwood and G. Hill (eds.), conference sponsored by National Oceanic and Atmospheric Administration, U.S. Department of the Interior, Smithsonian Institution, and Marine Society, held at Smithsonian Institution, Oct. 2-3, 1985, pp. 63-67.

[24] H. K. Farr, "Multibeam Bathymetric Sonar: Sea Beam and Hydrochart, *Marine Geodosy*, vol. 4, No. 2, pp. 88-89.

[25] Vogt and Tucholke, "Imaging the Ocean Floor, " p. 37.

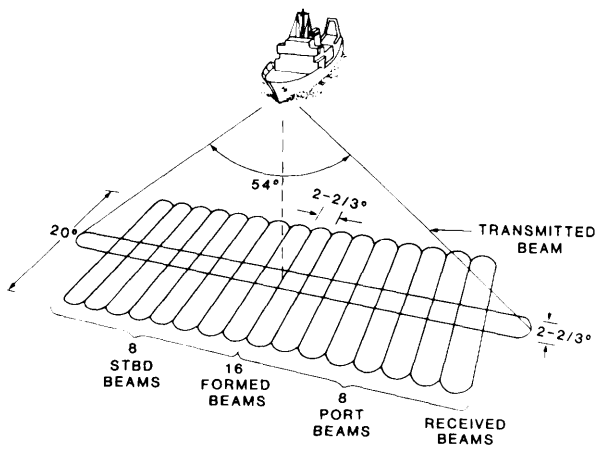
Table 4-4.--Bathymetry Systems[a]

System	Frequency kilohertz	Beams no.	Beamwidth degrees	Swath angle degrees	Max depth meters	System cost $10’
Sea Beam	12	16	2.7	42.7	11,000	1,800
Super Sea Beam (proposed)	12	48	2	96	11,000	—
Towed Sea Beam (proposed)	17	32	2	64	—	—
BS[3]/Hydrochart II	36	21/17	5	105	600/1,000	1,200
KRUPP Atlas Hydrosweep[b]	19.5	59	1.8	90	10,000	2,000
Honeywell ELAC Superchart[c]	12	45	2	90	7,000	3,000
	50	61	2	120	600	3,000
Minichart	50	40	3	120	1,000	—
SIMRAD EM 100	95	32	2/2.5	40/80/104	420	500
HOLLMING Echos 15/625	12	15	2	42		
Echos AD	15	15	2	42	600	
	45	60	2	90	6,000	
BENTECH Benigraph[d]	1,000	200	0.5	100	30	2,000
	740	200	0.75	100	50	2,000
	500	200	1	100	60	2,000

[a]Interferometric systems (e.g., SeaMARC II) are considered in table 4-2; however, they could be considered in the bathymetric table as well, as they have the potential of producing bathymetric data equivalent to that of multibeam systems. This system does not yet produce adequate bathymetric information, but improved versions are under development. Another system, the Bathyscan 300, has recently become commercially available. This system has demonstrated acceptable accuracy. It operates at 300 kilohertz, covers swaths of 200 meters width In waters less than 70 meters deep, weighs about 550 pounds, and costs about $400,000.
[b]Krupp-Atlas' Hydrosweep is installed on the Meteor II, but is not yet operational.
[c]The characteristics of Honeywell's ELAC are quoted from proposals. Honeywell claims no system was built other than an experimental one. The company did supply transducers to the Hollming Shipyard in Finland for three Soviet ships. Data from Hollming indicates that the systems that were built using these transducers were virtual clones of the Sea Beam system.
[d]Bentech's Benigraph is oriented toward use in pipeline construction. The unit has very high resolution and a short range and can easily be scaled to lower frequencies and used as a mapping system. Company management has stated that this approach is their intention.

SOURCE: National Oceanic and Atmospheric Administration.

Figure 4-5.—Sea Beam Beam Patterns



The Sea Beam swath width at the seafloor depends on water depth. In 200 meters of water the swath width is about 150 meters; in 5,000 meters of water, the swath width is approximately 4,000 meters.

SOURCE: R Tyce, Sea Beam Users Group

Hence, an upgraded SASS is now being designed that will be more reliable and will feature improved beam-forming and signal-processing capabilities. These should improve performance of the outer beams in deep water.

Improvements in Sea Beam, which has performed very well but which is now considered to be old technology, have also been proposed. One proposed modification is to develop a capability to quantify the strength of the signal returning from the bottom.[26] With such information, it would be possible to predict certain bottom characteristics. Nodule fields, for example, already have been quantified using acoustic backscatter information, Another proposed modification is to build a towed Sea Beam system. Such a system could be moved from ship to ship as required.[27]

All bathymetric systems have resolution and range limits imposed by wave front spreading, absorption, and platform noise. However, by reducing Sea Beam's current beam width, its resolution can be improved. There are limitations to using the immense amounts of data that would be collected by a higher resolution system. Only a small fraction (2 percent) of existing Sea Beam data are

[26]C. de Moustier, ‘ ‘Inference of Managese Nodule Coverage From Sea Beam Acoustic Backscattering Data, ” *Geophysics* 50, 1985, pp. 989-1001.
[27]D. White, Vice President, General Instruments, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

used in making bathymetric charts (except for charts of very small areas), and generating charts with a 1- meter contour interval is impractical. Sea Beam, unlike SASS, may be installed on small ships. In order to build a Sea Beam with a 10 beam width, an acoustic array 2.5 times longer than current models would be required. To accommodate such an array, one must either tow it or use a larger ship. The Navy has found that the current Sea Beam system is capable of producing contour charts of sufficient quality for most of its needs and is currently considering deploying Sea Beam systems for several of its smaller ships.

It is important to match resolution requirements with the purpose of the survey. Use of additional exploration technologies in conjunction with Sea Beam data may provide better geological interpretations than improving the resolution of the Sea Beam system alone. For instance, combined bathymetry and side-looking sonar data may reveal more features on the seafloor.

Improving swath coverage is probably more important than improving resolution for reconnaissance surveys. Wider swath coverage, for example, could increase the survey rate and reduce the time and cost of reconnaissance surveys. Sea Beam's swath angle is narrow compared to that of GLORIA or SeaMARC (figure 4-6); thus the area that can be surveyed is smaller in the same time period. It may be possible to extend Sea Beam capability from the current 0.8 times water depth to as much as 4 times water depth without losing hydrographic quality.[28] The current limit is imposed by the original design; hence, a small amount of development may produce a large gain in survey coverage without giving up data quality.

Another factor that affects the survey rate is the availability of the Global Positioning System (GPS) for navigation and vessel speed. Currently, NOAA uses GPS when it can; however, it is not yet fully operational. When GPS is inaccessible, NOAA survey vessels periodically must approach land to maintain navigational fixes accurate enough for charting purposes. This reduces the time available for surveying. Ship speed is also a factor, but increases in speed would not result in as great improvements in the survey rate as increases in swath width. Operating costs for some typical bathymetric systems are shown in figure 4-7.

Shallow-Water Systems

Several shallow-water bathymetric systems are available from manufacturers in the United States, Norway, West Germany, and Japan. NOAA uses Hydrochart, commonly known as the Bathymetric Swath Survey System (BS^3), for charting in coastal waters less than 600 meters (1 ,970 feet) deep. One of the principle advantages BS^3 has over Sea Beam is the wider angular coverage available, 1050 versus 42.70, enabling a wider swath to be charted. This angular coverage converts to about 260 percent of water depth, in contrast to 80 percent of depth for Sea Beam. Data acquisition is more rapid for BS^3 because the swath width is wider and transmission time in shallow water is reduced.[29] Hence, signal processing and plotting requirements for BS^3 are different than those for Sea Beam. GI has recently introduced Hydrochart H, an improved version of Hydrochart. The principal difference is a maximum depth capability of 1,000 meters. With its 17 beams, Hydrochart II offers much greater resolution and accuracy than older single-beam sonars.

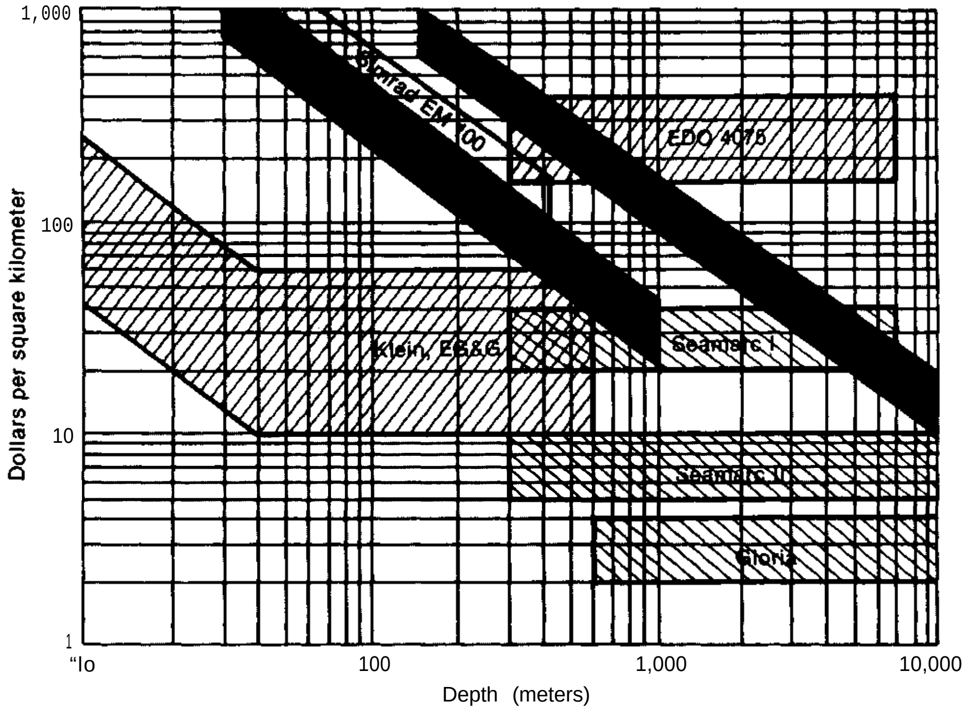
Along the narrow continental shelf bordering the Pacific Coast, bathymetry in very shallow water is fairly well known. Thus, NOAA has set an inshore limit of 150 meters for its BS^3 surveys (except for special applications), even though BS^3 is designed to be used in water as shallow as 3 meters. In regions where there are broad expanses of relatively shallow water and where the bathymetry is less well known, as off Alaska and along the Atlantic Coast, BS^3 maybe used in water less than 150 meters deep.

Various bathymetric charting systems are currently under development which may enable systematic surveying of very shallow waters, limited only by the draft of the vessel. One such system, for use in waters less than 30 meters deep, is the airborne laser. Laser systems are under development by the U.S. Navy, the Canadians, Australians, and others. NOAA's work in this field

[28] R. Tyce, Director, Sea Beam Users Group, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

[29] Farr, "Multibeam Bathymetric Sonar," p. 91.

Figure 4-6.–Operating Costs for Some Bathymetry and Side. Looking Sonar Systems



NOTES: 1. Operating costs are not really system characteristics but are primarily determined by platform (ships, etc.) costs (including Positioning system operation). platform costs are highly variable. Variability is influenced more by economic conditions, ship operating costs, etc. than by survey system requirements.

2. For shallow water imaging systems, work generally takes place in relatively protected areas not far from a port. Shallow water surveys can be performed using small (30-60 ft long) vessels at costs of from $500-$1200 per day, but operations would likely be limited to daylight hours. Considering daily transits, it would be difficult to survey more than 8 hours per day in an area or, given downtimes caused by inclement weather, to average more than 4 hours daily

3. Acquisition of deep water acoustic data commonly requires use of a larger, oceangoing vessel that can operate 24 hours a day. At this time, operational costs range from $5K-$15K a day for such vessels. With a system capable of withstanding 10 knot towing speeds, it should be possible to survey, on the average, 100 nautical track miles a day. Production goals for the *Surveyor* and the *Davidson* are 65 linear nautical miles per day.

4. Several imaging systems can be operated in different modes to give higher resolution data, but this will be at a penalty to the cost of coverage.

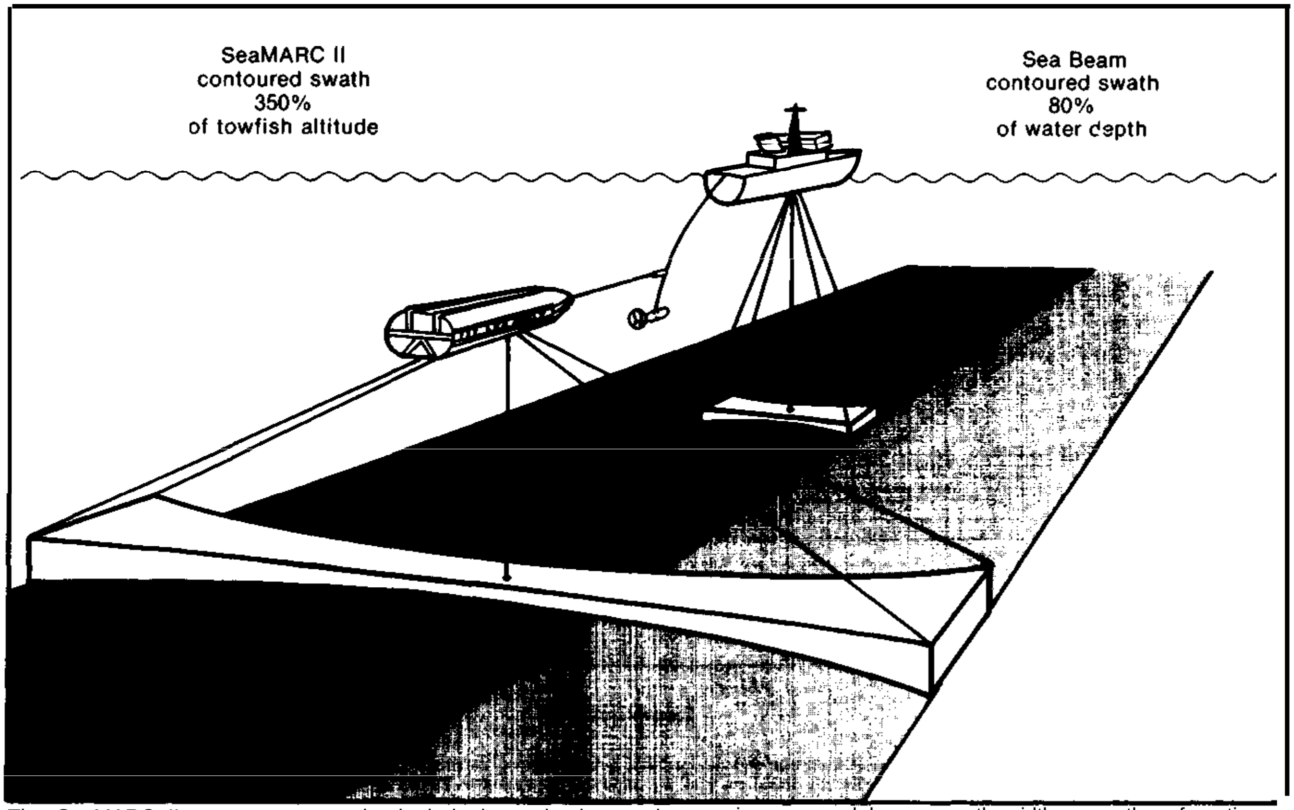
5. Experience with only three bathymetric systems is adequate enough (and not classified) to estimate operating costs. These are Sea Beam, BSSS/Hydrochart 11, and the Simrad EM100.

6. Bathymetric system operating costs are based on the assumption that 100 nautical miles of seafloor a day can be surveyed using a vessel costing $5K-$15K per day.

7. Costs of processing data (whether side-looking or bathymetric) are not included.

SOURCE: D. Pryor, National Oceanic and Atmospheric Administration.

Figure 4-7.—Comparing SeaMARC and Sea Beam Swath Widths



The SeaMARC II system can acquire both bathymetric data and sonar imagery and has a swath width more than four times that of the Sea Beam system. The Sea Beam system, however, produces more accurate bathymetry.

SOURCE: International Submarine Technology, Ltd., Redmond, WA.

stopped in 1982, due to limited funds. The Canadian system, the Larsen 500, is now being used by the Canadian Hydrographic Service. The Australian laser depth sounding system, WRELADS, has been used experimentally to map a swath 200 meters wide.[30] Water must be clear (i. e., without suspended sediments) for the airborne lasers to work. Towed underwater lasers have not yet been developed.

Another method currently under development for use in very shallow water is airborne electromagnetic (AEM) bathymetry. This technique has recently been tested at sea by the Naval Ocean Research and Development Activity (NORDA).[31] NORDA reports that with additional research and development, the AEM method maybe able to produce accurate bathymetric charts for areas as deep as 100 meters. Passive multispectral scanners also have been applied to measuring bathymetry.[32] A combination of laser, AEM, and multispectral techniques may be useful to overcome the weather and turbidity limits of lasers alone. Satellite altimeters and synthetic aperture radar images of surface expressions can also indicate bathymetry, but much

[30] R. K. Bullard, "Land Into Sea Does Not Go, " *Remote Sensing Applications in Marine Science and Technology,* A.P. Cracknell (cd.) (Hingham, MA: D. Reidel Publishing Co., 1983), p. 366.

[31] I.J. Won and K. Smits, "Airborne Electromagnetic Bathymetry, " Norda Report 94, U.S. Navy, Naval Ocean Research and Development Activity, April 1985.

[32] D. R. Lyzenga, "Passive Remote Sensing Techniques for Mapping Water Depth and Bottom Features, *Applied Optics,* vol. 17, *No. 3,* February 1978, pp. 29-33.

less accurately.[33] If airborne bathymetric survey techniques for shallow water can be further refined, they would have the distinct advantage over ship-based systems of being able to cover much more territory in much less time and at reduced cost. Technology for airborne surveys in deep water has not yet been developed.

Systematic Bathymetric Mapping of the EEZ

NOAA has recently begun a long-range project to survey and produce maps of the entire U.S. EEZ. The NOAA ship *Surveyor is equipped* with Sea Beam and has been mapping the EEZ since May 1984. Initial Sea Beam surveys were made of the Outer Continental Shelf, slope, and upper rise off the coasts of California and Oregon. 34 A second Sea Beam was installed aboard *Discoverer* in 1986. The *Davidson* has been equipped with BS^3 since 1978, NOAA plans to acquire two additional swath mapping systems with 1987 and 1988 fiscal year funds.

NOAA is currently able to map between 1,500 and 2,500 square nautical miles per month (with two ships, *Surveyor* and *Davidson,* working on the west coast continental slope). This is significantly below the expected coverage rate for the Sea Beam. Transit time, weather, crosslines, equipment failure, and decreased efficiency in shallower water are factors that have limited production to about 50 square nautical miles per ship per day. Moreover, NOAA has not yet surveyed any areas beyond 120 miles from the coast. With the GPS available only part-time, too much time would be wasted in maintaining accurate navigation control on the outer half of the EEZ. Delays in launching satellites, the Challenger accident, and several recent failures of GPS satellites already in orbit are further eroding the near-term usefulness of GPS and, therefore, limiting the efficiency of NOAA surveys.

The agency would like to map all 2.3 million square nautical miles of the U.S. EEZ. With current technology, funding, and manpower, this project could take more than 100 years. In order to ensure that the most important areas are surveyed first, NOAA consults with USGS and uses USGS's GLORIA side-looking sonar imagery to select survey targets. USGS has provided funds to NOAA for data processing; in return, NOAA accepts the survey priorities set by USGS.

By mid-1986, less than 1 percent of the U.S. EEZ had been systematically surveyed with NOAA's Sea Beam and BS^3 systems. To date, few of the charts or raw data have been publicly released because the U.S. Navy has determined that public dissemination of high-resolution bathymetric data could endanger national security. NOAA and the Navy are currently exploring ways to reduce the security risks while producing bathymetric charts useful for marine geologists, potential seabed miners, fishermen, and other legitimate users (see ch. 7).

NOAA's Survey Program is the only systematic effort to obtain bathymetry for the entire EEZ; however, several academic institutions have mapped small portions of the EEZ. For instance, Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory, and Scripps Institution of Oceanography have their own Sea Beam systems. Much of the mapping these institutions have done has been outside the U.S. EEZ. Moreover, additional bathymetric data (how much of it useful is unknown) are gathered by the offshore petroleum industry during seismic surveys. As much as 10 million miles of seismic profiles (or about 15 percent of the EEZ) have been shot by commercial geophysical service companies in the last decade, and almost all of these surveys are believed to contain echo soundings in some form (probably mostly 3.5 kilohertz data) .35 Some of these data are on file at the National Geophysical Data Center (NGDC) in Boulder, Colorado; however, most remain proprietary. Moreover, maps made from these data might

[33] W. Alpers and 1. Hennings, "A Theory of the Imaging Mechanism of Underwater Bottom Topography by Real and Synthetic Aperture Radar, ' '*Journal of Geophysical Research, vol. 89,* No. *C6,* Nov. 20, 1984, pp. 10,529-10,546.

[34] D. E. Pryor, "NOAA Exclusive Economic Zone Survey Program, " in *PA CON 86,* proceedings of the Pacific Congress on Marine Technology, sponsored by Marine Technology Society, Hawaii Section, Honolulu, HA, Mar. 24-28, 1986, pp. OST5/9,10.

[35] R. B. Perry, ' 'Mapping the Exclusive Economic Zone, *Ocean Engineering and the Environment*, Oceans 85 Conference Record, Sponsored by Marine Technology Society and IEEE Ocean Engineering Society, Nov. 12-14, 1985, San Diego, CA, p. 1193. The seismic profiles themselves generally include ocean bottom reflections when water depths are more than about 150 meters. These profiles are accurate, continuous bathymetric records along the line of survey.

also be considered classified under current Department of Defense policy. The grid lines are often only one-quarter mile apart, indicating that these maps would be very accurate (although a standard 3.5 kilohertz echo sounding does not have the resolution of Sea Beam) .36

NOAA is currently exploring ways to utilize data acquired by academic and private institutions to upgrade existing bathymetric maps to avoid duplication. In some areas, it may be possible to accumulate enough data from these supplemental sources to improve the density and accuracy of coverage. However, because these data usually were not gathered for the purpose of making high-quality bathymetric maps, these data may not be as accurate as needed. NOAA is adhering to International Hydrographic Bureau standards because these standards are: widely accepted by national surveying agencies, result in a product with a high degree of acceptance, and are feasible to meet. NOAA could relax its standards if this meant that an acceptable job could be done more efficiently. For example, if depth accuracy of the SeaMarc 11 system (which has a much wider swath width than Sea Beam) could be improved from the present 3 percent of depth to 1.5 percent or better, NOAA might consider using SeaMarc II in its bathymetric surveys.

Public data sets rarely have the density of coverage that would provide resolution approaching that of a multi-beam survey. Commercial survey data are not contiguous over large areas because they cover only selected areas or geologic structures. Data may be from a wide beam or deep seismic system, possibly uncorrected for velocity or unedited for quality. Data sets would also be difficult to merge. Unless the lines are sufficiently dense, computer programs cannot grid and produce contours from the data at the scale and resolution of multi-beam data.[37]

SASS data acquired by the U.S. Navy is classified. NOAA neither knows what the bathymetry is in areas surveyed by SASS nor what areas have been surveyed. More optimistically, once the Global Positioning System becomes available around the clock, thereby enabling precise navigational control at all times, it may be possible for NOAA to utilize multi-beam surveys conducted by others, e.g., by University National Oceanographic Laboratory System (UNOLS) ships. If the three university ships currently equipped with Sea Beam could be used as ' 'ships of opportunity' when otherwise unemployed or underemployed, both NOAA and the academic institutions would benefit. NOAA has already discussed the possibility of funding Sea Beam surveys with the Scripps Institution of Oceanography.

Reflection and Refraction Seismology

Seismic techniques are the primary geophysical methods for acquiring information about the geological structure and stratigraphy of continental margins and deep ocean areas. Seismic techniques are acoustic, much like echo sounding and sonar, but lower frequency sound sources are used (figure 4-8). Sound from low-frequency sources, rather than bouncing off the bottom, penetrates the bottom and is reflected or refracted back to one or more surface receivers (channels) from the boundaries of sedimentary or rock layers or bodies of different density (figure 4-9). Hence, in addition to sedimentary thicknesses and stratification, structural characteristics such as folds, faults, rift zones, diapirs, and other features and the characteristic seismic velocities in different strata may be determined (figure 4-10).

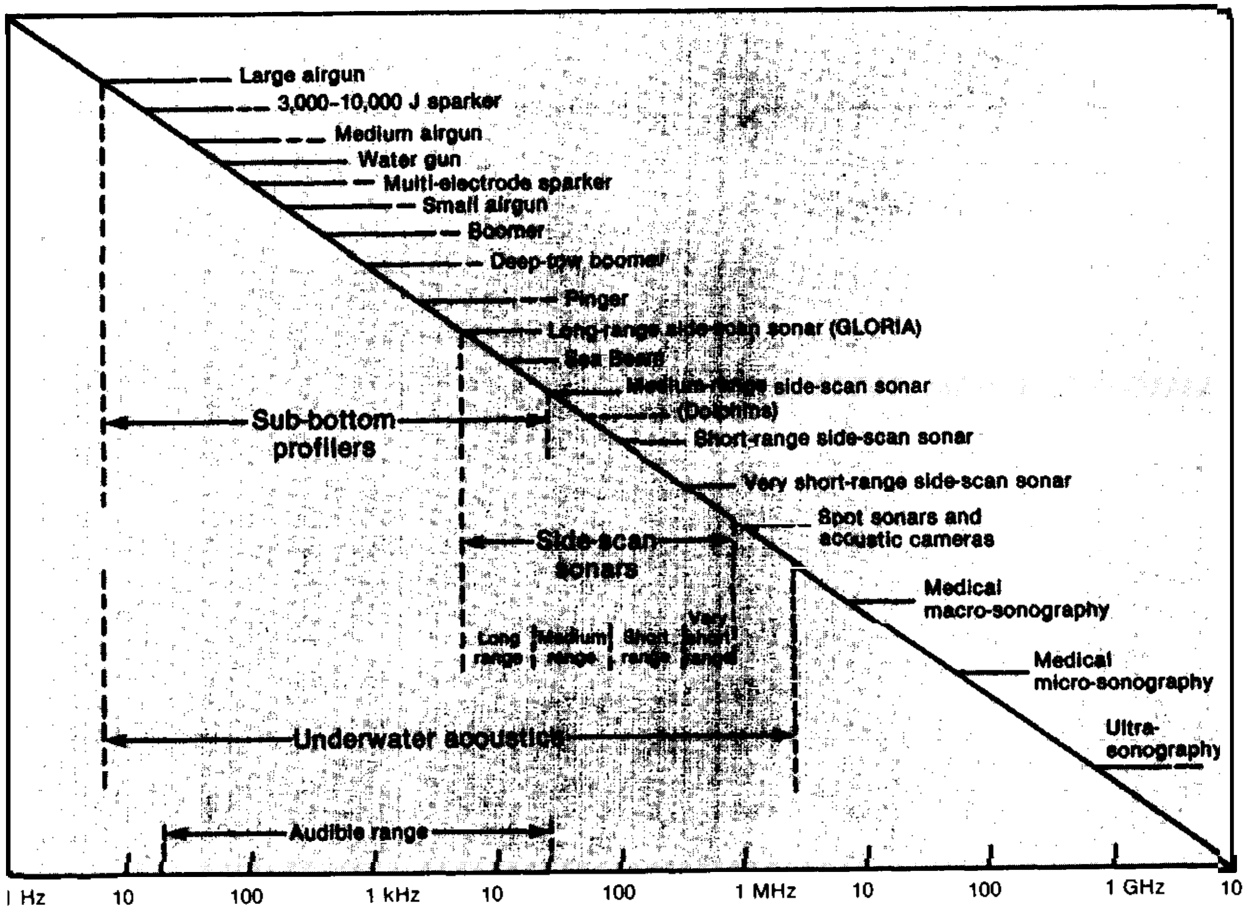
Seismic reflection techniques are used extensively to search for oil, but they are also used in mineral exploration. Reflection techniques have been and continue to be refined primarily by the oil industry. Seismic refraction, in contrast to seismic reflection, is used less often by the oil industry than it once was; however, the technique is still used for academic research. Ninety-eight percent of all seismic work supports petroleum exploration; less than 2 percent is mineral oriented.

The depth of wave penetration varies with the frequency and power of the sound source. Low-frequency sounds penetrate deeper than high-frequency sounds; however, the higher the frequency of the sound source, the better the resolution possible. Seismic systems used for deep penetration

[36]C. Savit, Senior Vice President, Western Geophysical, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

"Perry, "Mapping the Exclusive Economic Zone, " p. 1193.

Figure 4-8.—Frequency Spectra of Various Acoustic Imaging Methods



SOURCE: B.W. Flemming, "A Historical Introduction to Underwater Acoustics, With Special Reference to Echo Sounding, Sub-bottom Profiling, and Side Scan Sonar," in W.G A. Russell-Cargill (cd.), *Recent Developments in SidesCan Sonar Techniques* (Capetown, South Africa: ABC Press, Ltd., 1982).

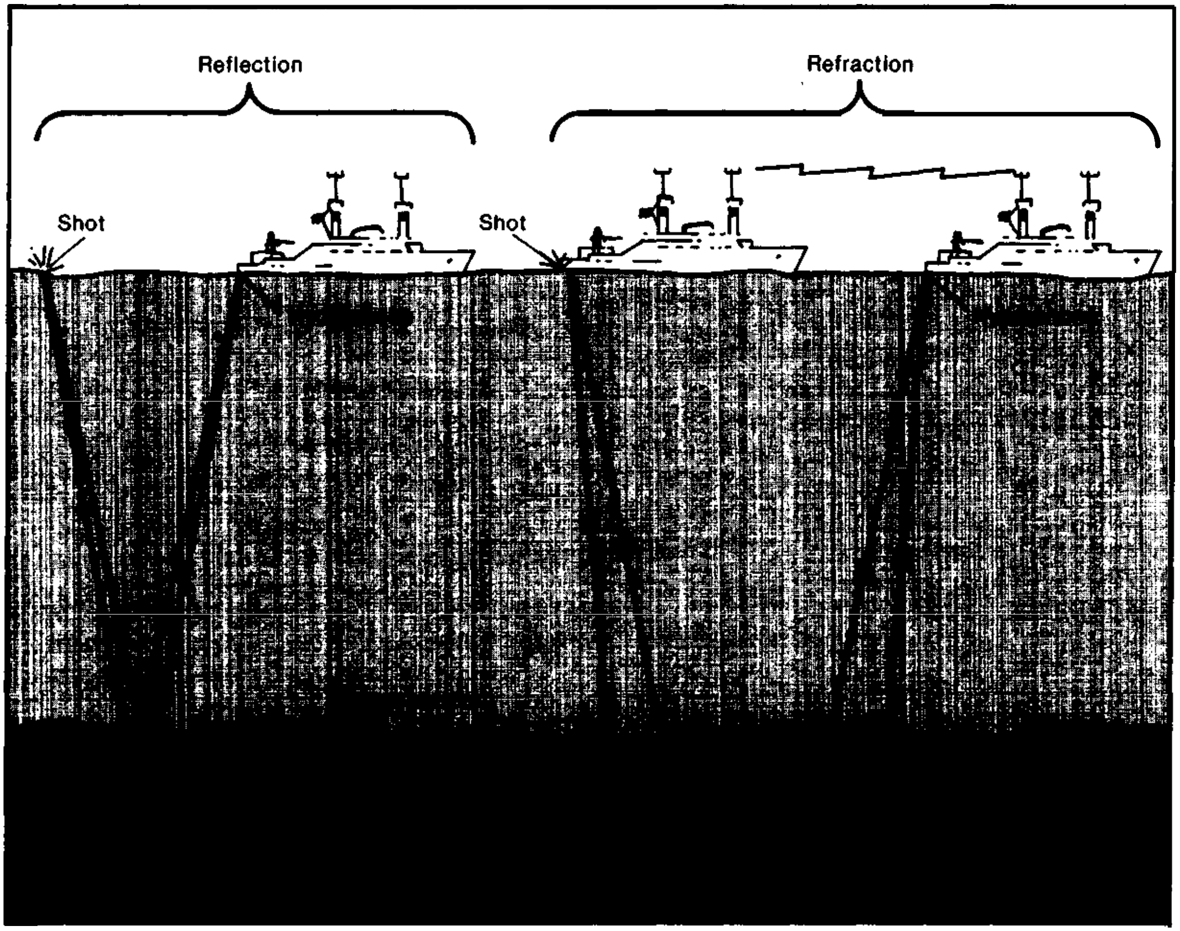
range in frequency from about 5 hertz to 1 kilohertz. The systems with sound frequencies in this range are very useful to the oil and gas industry. Most often these are expensive multi-channel systems. Since most mineral deposits of potential economic interest are on or near the surface of the seabed, deep penetration systems have limited usefulness for mineral exploration. Seismic systems most often used for offshore mineral exploration are those that operate at acoustic frequencies between 1 and 14 kilohertz (typically 3.5 kilohertz). These systems, known as sub-bottom profilers, provide continuous high-resolution seismic profile recordings of the uppermost 30 meters of strata.[38] Typically, they are single-channel systems. They can be operated at the same ship speeds as bathymetric and sonar systems. A few towed vehicles are equipped with both side-looking sonar and sub-bottom profiling capability using the same coaxial tow cable.[39]

One drawback with single-channel systems is that they suffer from various kinds of multi-path and pulse reverberation problems, problems best handled by multi-channel systems. A 100 or 500 hertz multi-channel system is able to provide shallow penetration data while avoiding the problems of

[38] P. K. Trabant, *Applied High-Resolution Geophysical Methods: Offshore Geoengineering Hazards* (Boston, MA: International Human Resources Development Corp., 1984), p. 81.

[39] C.J. Ingram, "High-Resolution Side-Scan Sonar/Subbottom Profiling to 6000M Water Depth," unpublished, presented at the Pacific Congress on Marine Technology, sponsored by Marine Technology Society, Hawaii Section, Honolulu, HA, Mar. 24-28, 1986.

Figure 4.9.—Seismic Reflection and Refraction Principles



In the seismic reflection technique, sound waves from a source at a ship bounce directly back to the ship from sediment and rock layers. In the seismic refraction technique, the sound waves from a "shooting" ship travel along the sediment and rock layers before propagating back to a "receiving" ship.

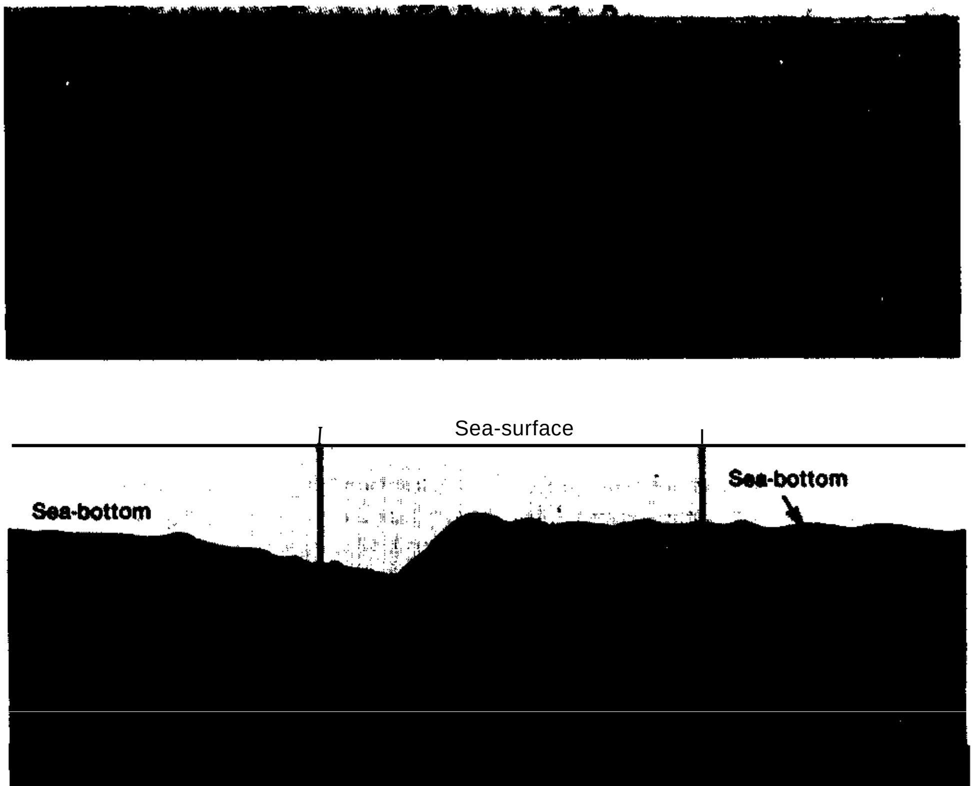
SOURCE: P.A. Rena, *Exploration Methods for the Continental Shelf: Geology, Geophysics, Geochemistry*, NOAA Technical Report ERL 238-AOML 8 (Boulder, CO: National Oceanic and Atmospheric Administration, 1972), p. 15.

single-channel systems. Because of cost, however, a multi-channel system is usually not used for reconnaissance work.

High-resolution seismic reflection techniques are able to detect the presence of sediment layers or sand lenses as little as 1 meter thick. In addition, information about the specific type of material detected sometimes may be obtained by evaluating the acoustic velocity and frequency characteristics of the material. Seismic techniques may provide clues for locating thin, surficial deposits of manganese nodules or cobalt crusts, but side-looking sonar is a better tool to use for this purpose. Ryan reports that a 1 to 5-kilohertz sub-bottom profiler was very effective in reconnaissance of sediment-hosted sulfides of the Juan de Fuca Ridge.[40] While seismic methods provide a cross-sectional view of stratigraphic and structural geologic framework, geologists prefer to supplement these methods with coring, sampling, and drilling (i. e., direct methods), with photography and submersible observa-

[40] W.B.F. Ryan, Lamont-Doherty Geological Observatory, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

Figure 4-10.—Seismic Record With Interpretation



Academic and industry researchers interpret seismic records to help them determine geological structure and stratigraphy below the seabed.

SOURCE: U.S. Geological Survey.

tions, and with geochemical sampling of bottom sediments and of the water column, etc., for the highest quality interpretations.

Advances in reflection seismology have been made more or less continuously during the approximately 60 years since its invention.[41] Recent technological innovations have been the development of three-dimensional (3-D) seismic surveying and interactive computer software for assisting interpretation of the mountains of 3-D data generated. To acquire enough data for 3-D work, survey lines are set very close together, about 25 to 100 meters apart. Data for the gaps between lines then can be interpolated. The efficiency of data acquisition can be increased by towing two separate streamers (and technical advances will soon enable two lines of profile to be acquired from each of two separate cables).[42]

Interactive programs allow the viewer to look at consecutive cross-sections of a 3-D seismic profile or at any part of it in horizontal display. Thus, if desired, the computer can strip away everything but the layer under study and look at this layer at any angle. Moreover, the surveyed block can be cut along a fault line, and one side can be slid along the other until a match is made. Interpretation of data can be accomplished much faster than on paper. Such systems are expensive. While the cost of acquiring and processing 20 kilometers of two-dimensional seismic data may be from $500 to $2,000 per kilometer, a 3-D high-density survey

[41] C. H. Savit, "The Accelerating Pace of Geophysical Technology," Oceans *84 Conference Record,* Sponsored by Marine Technology Society and IEEEE Ocean Engineering Society, Sept. 10-12, 1984, (Washington, D. C.: Marine Technology Society, 1984), pp. 87-89.

[42] Savit, OTA Workshop, June 10, 1986.

of a 10-by 20-kilometer area could cost on the order of $3 million.

Resolution also continues to improve, assisted by better navigation, positioning, and control methods. An innovation which promises to further improve resolution is the use of chirp signals rather than sound pulses. Chirp signals are oscillating signals in which frequency is continuously varying. Using computer-generated chirp signals, it is possible to tailor and control emitted frequencies. In contrast, pulse sources produce essentially uncontrolled frequencies, generating both useful and unneeded frequencies at the same time.

About 10 million miles of seismic profiles have been run in the U.S. EEZ. Most of these data are deep penetration profiles produced by companies searching for oil and are therefore proprietary. The Minerals Management Service within the U.S. Department of the Interior (MMS) purchases about 15 percent of the data produced by industry, most of the data are held for 10 years and then turned over to the National Geophysical Data Center. NGDC archives about 4 million miles of public (mostly academic) seismic data. Much of this data is for regions outside the EEZ. NGDC also archives USGS data, most of which are from the EEZ (see ch. 7).

It is possible to acquire shallow-penetration seismic information (as well as magnetic and gravity data) at the same time as bathymetric data, so that surface features can be related to vertical structure and other characteristics of a deposit. NOAA acknowledges that simultaneous collection of different types of data could be accomplished easily aboard its survey ships. Additional costs would not be significant relative to the cost of operating the ships, but would be significant relative to currently available funds. The agency would like to collect this data simultaneously if funds were available. NOAA hopes to interest academia and the private sector, perhaps with USGS help, to form a consortium to coordinate and manage the gathering of seismic and other data, using ships of opportunity.[43] The offshore seismic firms serving the oil and gas industry are opposed to any publicly funded data acquisition that could deprive them of business opportunities. All but very shallow penetration data generally are of interest to the petroleum industry and therefore could be considered competitive with private sector service companies.

Magnetic Methods

Some marine sediments and rocks (as well as sunken ships, pipelines, oil platforms, etc.) contain iron-rich minerals with magnetic properties. Magnetic methods can detect and characterize these magnetic materials and other features by measuring differences (or anomalies) in the geomagnetic field. Magnetic (and gravity) techniques are inherently reconnaissance tools, since the data produced must be compiled over fairly broad areas to detect trends in the composition and structure of rock. However, spatial resolution, or the ability to detect increasingly fine detail, varies depending on the design of the sensor, the spacing of survey lines, and the distance of the sensor from the source of anomaly.

Satellite surveys are able to detect magnetic anomalies on a global or near-global scale. Satellite data are important for detecting global or continental structural trends of limited value to resource exploration. At such broad scale, mineral deposits would not be detected. Airplane and ship surveys record finer scale data for smaller regions than satellites, enabling specific structures to be detected. The closer the sensor to the structure being sensed, the better the resolution, but the time required to collect the data, as well as the cost to do so, increases proportionately.

Regional magnetic surveys, usually done by airplane, can detect the regional geologic pattern, the magnetic character of different rock groups, and major structural features which would not be noted if the survey covered only a limited area.[44] For example, oceanic rifts, the transition between continental and oceanic crusts, volcanic structures, and major faults have been examined at this scale. Regional magnetic surveys also have been used extensively in exploring for hydrocarbons. Accurate measurement of magnetic anomalies can help ge-

[43] C. Andreasen, NOAA EEZ project manager, interview by W. Westermeyer at NOAA, Rockville, MD, Apr. 22, 1986.

[44] P.V. Sharma, *Geophysical Methods in Geology (New York,* NY: Elsevier Science Publishing Co., 1976), p, 228.

ophysicists delineate geologic structures associated with petroleum and measure the thickness of sediments above magnetic basement rocks .45

Surveys also may be conducted to locate concentrations of ferromagnetic minerals on or beneath the seafloor. The detection of magnetite may be particularly important in mineral prospecting because it is often found in association with ilmenite and other heavy minerals. Ilmenite also contains iron, but it is much less strongly magnetized than the magnetite with which it is associated (it also may have weathered during low stands of sea level and may have lost magnetic susceptibility).

The precise location of a mineral deposit or other object may require a more detailed survey than is possible by satellite or airplane. Use of ship-towed magnetometers has met with varying measures of success in identifying placer deposits. Improvements in sensitivity are needed. If enough data are gathered to determine the shape and amplitude of a local anomaly, the size of an iron-bearing body and its trend can be estimated, a common practice on land. When magnetic information can be correlated with other types of information (e. g., bathymetric, seismic, and gravity) interpretation is enhanced.

Magnetic anomalies also can be used to locate and study zones of alteration of the oceanic crust. The initial magnetization of the oceanic crust is acquired as it cools from a magma to solid rock. For the next 5 to 10 million years, hydrothermal circulation promotes the alteration of this igneous rock and the generation of new secondary minerals. Initially, the heat of hydrothermal circulation destroys the thermal remanent magnetization. Rona suggests that this reduction in magnetization will produce a magnetic anomaly and signal the proximity of active or inactive smokers or hydrothermal vents.[46] The Deep Sea Drilling project and Ocean Drilling Program drilling results suggest that as the secondary minerals grow, they acquire the magnetization of the ambient magnetic field. This aggregate magnetization produces a signature which is detectable on a regional scale and might be used to determine the degree and rate of regional alteration. 47

Variations in the intensity of magnetization (total field variations) are detected using a magnetometer. Magnetometers deployed from ships or airplanes are either towed behind or mounted at an extreme point to minimize the effect of the vessel's magnetic field. Among the several types of magnetometers, proton precession and flux-gate types are most often used. These magnetometers are relatively simple to operate, have no moving parts, and provide relatively high-resolution measurements in the field. The technology for sensing magnetic anomalies is considered mature. A new helium-pumped magnetometer with significantly improved sensitivity has been developed by Texas Instruments and is being adapted to oceanographic work.

Most magnetic measurements are total field measurements. A modification of this technique is to use a second sensor to measure the difference in the total field between two points rather than the total field at any given point. Use of this gradiometry technique helps eliminate some of the external noise associated with platform motion or external field variation (e. g., the daily variation in the magnetic field). This is possible because sensors (if in close enough proximity) measure the same errors in the total field, which are then eliminated in determining the total field difference between the two points. Gradiometry improves sensitivity to closer magnetic sources .[48]

The most important problem in acquiring high-quality data at sea is not technology but accurate navigation. The Global Positioning System, when available, is considered more than adequate fme navigation and positioning needs. Future data, to be most useful for mineral exploration purposes, will necessarily need to be collected as densely as possible. It is also important that magnetic (and gravity) data be recorded in a manner that minimizes the effects of external sources, such as of the towing platform, and that whatever data are meas-

[45] P. A. Rona, "Exploration Methods for the Continental Shelf: Geology, Geophysics, Geochemistry, *NOAA Technical Report,* F. RI. 238-AOML 8 (Boulder, CO: NOAA, 1972), p. 22.

[46] Rona, " Exploration for Hydrothermal Mineral Deposits at Seafloor Spreading Centers, " p. 25.

[47] J. L, LaBrecque, Lament-Dohe~, Geological Observatory, OTA, May 1, 1987,

[48] J. Brozena, Naval Research Laboratory, and J. LaBreque, Lament-Doherty Geological Observatory, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

ured be incorporated into larger data sets, so that data at different scales are simultaneously available to investigators.

Gravity Methods

Like magnetic methods, the aim of gravity methods is to locate anomalies caused by changes in physical properties of rocks.[49] The anomalies sought are variations in the Earth's gravitational field resulting from differences in density of rocks in the crust—the difference between the normal or expected gravity at a given point and the measured gravity. The instrument used for conducting total field gravity surveys is a gravimeter, which is a well-tested and proven instrument. Techniques for conducting gradiometric surveys are being developed by the Department of Defense, although these will be used for classified defense projects and will not be available for public use.[50]

The end product of a gravity survey is usually a contoured anomaly map, showing a plane view or cross-section. The form in which gravity, as well as magnetic, data is presented differs from that for seismic data in that the fields observed are integrations of contributions from all depths rather than a distinct record of information at various depths. Geophysicists use such anomaly characteristics as amplitude, shape, and gradient to deduce the location and form of the structure that produces the gravity disturbance.[51] For example, low-density features such as salt domes, sedimentary infill in basins, and granite appear as gravity "lows" because they are not as dense as basalt and ore bodies, which appear as gravity "highs. Interpretation of gravity data, however, is generally not straightforward, as there are usually many possible explanations for any given anomaly. Usually, gravity data are acquired and analyzed together with seismic, magnetic, and other data, each contributing different information about the sub-bottom geological framework.

Since variations in terrain fleet the force of gravity, terrain corrections must be applied to gravity data to produce an accurate picture of the structure and physical properties of rocks. Bathymetric data are used for this purpose; however, terrain corrections using existing bathymetry data are relatively crude. Terrain corrections using data produced by swath mapping techniques provide a much improved adjustment.

Like magnetic data, the acquisition of gravity data may be from satellite, aircraft, or ship. The way to measure the broadest scale of gravity is from a satellite. SEASAT, for instance, has provided very broad-scale measurements of the geoid (surface of constant gravitational potential) for all the world's oceans. To date, almost all gravity coverage of the EEZ has been acquired by ship-borne gravimeters. Gravimetry technology and interpretation techniques are now considered mature for ship-borne systems. However, the quality of ship-based gravity data more than 10 years old is poor. Airborne gravimetry is relatively new, and technology for airborne gravity surveys (both total field and gravity gradient types) is still being refined. As airborne gravity technology is further developed, it can be expected that this much faster and more economical method of gathering data will be used.

Of all the techniques useful for hard mineral reconnaissance, however, gravity techniques are probably the least useful. This is because it is very difficult to determine variations in structure for shallow features (e. g., 200 meters or less). Shallow material is all about the same density, and excess noise reduces resolution. Gravity techniques are used primarily for investigating intermediate-to-deep structures—the structure of the basement and the transition between continental and oceanic crust. Many of these structures are of interest to the oil industry. Although large faults, basins, or seamounts may be detected with air- or ship-borne gravimeters, it is unlikely that shallow placer deposits also could be located using this technique.

USGS has published gravity maps of the Atlantic coast, the Gulf of Mexico, central and southern offshore California, the Gulf of Alaska, and the Bering Sea. However, little of the EEZ has been mapped in detail, and coverage is very spotty. For example, port areas appear to be well-surveyed, but density of track lines decreases quickly with distance from port. Oil companies have done the most grav-

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[49] Sharma, *Geophysical Methods in Geology,* p. 88.

[50] J. Brozena, Naval Research Laboratory, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, Washington, DC, June 10, 1986.

[51] Sharma, *Geophysical Methods in Geology,* p. 131.

ity surveying, but the information they hold is proprietary. Little surveying has been done in very shallow waters (i. e., less than 10 meters), as the larger survey ships cannot operate in these waters.

The availability of high-density gravity data (and possibly also magnetic data) for extensive areas of the EEZ may pose a security problem similar to that posed by high-resolution bathymetry. Gravitational variations affect inertial guidance systems and flight trajectories. The Department of Defense has concerns about proposals to undertake systematic EEZ gravity surveys, particularly if done in conjunction with the systematic collection of bathymetry data, since characteristic subsea features might be used for positioning missile-bearing submarines for strikes on the United States.

SITE-SPECIFIC TECHNOLOGIES

Site-specific exploration technologies generally are those that obtain data from small areas relative to information provided by reconnaissance techniques. Some of these technologies are deployed from a stationary ship or other stationary platform and are used to acquire detailed information at a specific site. Often, in fact, such techniques as coring, drilling, and grab sampling are used to verify data obtained from reconnaissance methods. Other site-specific technologies are used aboard ships moving at slow speeds. Electrical and nuclear techniques are in this category.

Electrical Techniques

Electrical prospecting methods have been used extensively on land to search for metals and minerals, but their use offshore, particularly as applied to the shallow targets of interest to marine miners, is only just beginning. Recent experiments by researchers in the United States and Canada suggest that some electrical techniques used successfully on land may be adaptable for use in marine mineral exploration.[57] Like other indirect exploration techniques, the results of electrical methods usually can be interpreted in various ways, so the more independent lines of evidence that can be marshaled in making an interpretation, the better.

The aim of electrical techniques is to deduce information about the nature of materials in the earth based on electrical properties such as conductivity, electrochemical activity, and the capacity of rock to store an electric charge. Electrical techniques are similar to gravity and magnetic techniques in that they are used to detect anomalies—in this case, anomalies in resistivity, conductivity, etc. , which allow inferences to be made about the nature of the material being studied.

The use of electrical methods in the ocean is very different from their use on land. One reason is that seawater is generally much more conductive than the underlying rock, the opposite of the situation on land where the underlying rock is more conductive than the atmosphere. Hence, working at sea using a controlled-source electromagnetic method is somewhat analogous to working on land and trying to determine the electrical characteristics of the atmosphere. In both cases, one would be looking at the resistive medium in a conductive environment. The fact that seawater is more conductive than rock appeared to preclude the use of electrical techniques at sea, Improvements in instrumentation and different approaches, however, have overcome this difficulty to a degree, A difference which benefits the use of electrical techniques at sea is that the marine environment is considerably quieter electrically than the terrestrial environment. Thus, working **in a low-noise environment, it is possible to use much higher gain amplifiers, and it is usually not necessary to provide the noise shielding that would be needed on land. Also, coupling to the seafloor environment for both source and receiver electrodes is excellent. Thus, electrode resistances on the seafloor are typically less than 1 ohm, whereas on land the resistance would be on the order of 1,000 ohms.**

Electrical techniques that may be useful for marine mineral prospecting include electromagnetic

[52] A.D. Chave, S.C. Coustable, and R.N. Edwards, "Electrical Exploration Methods for the Seafloor," in press, 1987. See also S. Cheesman, R.N. Edwards, and A.D. Chave, "On the Theory of Seafloor Conductivity Mapping Using Transient EM Systems, *Geophysics*, February 1987; and J.C. Wynn, ' 'Titanium Geophysics—A Marine Application of Induced Polarization, unpublished draft, 1987.

methods, direct current (DC) resistivity, self potential, and induced polarization.

Electromagnetic Methods

Electromagnetic (EM) methods detect variations in the conductive properties of rock. A current is induced in the conducting earth using electric or magnetic dipole sources. The electric or magnetic signature of the current is detected and yields a measure of the electrical conductivity of the underlying rock. The Horizontal Electric Dipole and the Vertical Electric Dipole method are two controlled-source EM systems that have been used in academic studies of deep structure. Both systems are undergoing further development. Recent work suggests that these techniques may enable researchers to determine the thickness of hydrothermal sulfide deposits, of which little is currently known. Changes in porosity with depth are also detectable.[53] To date, little work has been done regarding the potential applicability of these techniques for identifying marine placers.

Researchers at Scripps Institution of Oceanography are currently developing the towed, frequency domain Horizontal Electric Dipole method for exploration of the upper 100 meters of the seabed. A previous version of this system consists of a towed silver/silver-chloride transmitting antenna and a series of horizontal electric field receivers placed on the seafloor at ranges of 1 to 70 kilometers from the transmitter. Since this arrangement is not very practical for exploratory purposes, the Scripps researchers are now developing a system in which the transmitter and receiver can be towed in tandem along the bottom. Since the system must be towed on the seabed, an armored, insulated cable is used. The need for contact with the ocean floor limits the speed at which the system can be towed to 1 to 2 knots and the type of topography in which it can be used; hence, this method, like other electrical techniques, would be most efficiently employed after reconnaissance methods have been used to locate areas of special interest.

The Vertical Electric Dipole method is being developed by researchers at Canada's Pacific Geoscience Center and the University of Toronto. The Canadian system is known as MOSES, short for magnetometric offshore electrical sounding. It consists of a vertical electric dipole which extends from the sea surface to the seafloor and a magnetometer receiver which measures the azimuthal magnetic field generated by the source.[54] The receiver is fixed to the seafloor and remains in place while a ship moves the transmitter to different locations. A MOSES survey was conducted in 1984 at two sites in the sediment-filled Middle Valley along the northern Juan de Fuca Ridge. Using MOSES, researchers estimated sediment and underlying basalt resistivity, thickness, and porosity.

Another electromagnetic method with some promise is the Transient EM Method. Unlike controlled source methods in which a sinusoidal signal is generated, a source transmitter is turned on or off so that the response to this "transient' can be studied. An advantage of the Transient EM method is that the effects of shallow and deep structure tend to appear at discrete times, so it is possible to separate their effects. Also, the effects of topography, which are difficult to interpret, can be removed, allowing researchers to study the underlying structure. The Transient EM method also may be particularly useful for locating sulfides, since they have a high conductivity relative to surrounding rock and are located in ragged areas of the seafloor. A prototype Transient EM system is currently being designed for survey purposes. It will use a horizontal magnetic dipole source and receiver and will be towed along the seafloor.[55]

Direct Current Resistivity

Resistivity is a measure of the amount of current that passes through a substance when a specified potential difference is applied. The direct current resistivity method is one of the simplest electrical techniques available and has been used extensively on land to map boundaries between

[53] P.A. Wolfgram, R.N. Edwards, L. K. Law, and M. N. Bone, "Polymetallic Sulfide Exploration on the Deep Seafloor: The Mini-Moses Experiment," *Geophysics* 51, 1986, pp. 1808-1818.

[54] D.C. Nobes, L.K. Law, and R.N. Edwards, "The Determination of Resistivity and Porosity of the Sediment and Fractured Basalt Layers Near the Juan de Fuca Ridge," *Geophysical Journal of the Royal Astronomical Society 86, 1986*, pp. 289-318.

[55] Cheesman, Edwards, and Chave, "On the Theory of Seafloor Conductivity Mapping."

layers having different conductivities.[56] Recent marine DC resistivity experiments suggest that the DC resistivity method may have applications for locating and delineating sulfide ore bodies. For example, during one experiment at the East Pacific Rise in 1984, substantial resistivity anomalies were detected around known hydrothermal fields, and seafloor conductivities were observed that were twice that of seawater.[57] In this experiment the source and receiver electrodes were towed from a research submersible. Conversely, resistivity techniques would not be expected to detect placer deposits, except under the most unusual circumstances. This is because seawater dominates the resistivity response of marine sediments (as they are saturated near the surface), and, in this case, only the relative compaction (porosity) of the sediments could be measured.[58]

Self Potential

The self potential (or spontaneous polarization) (SP) method is used to detect electrochemical effects caused by the presence of an ore body. The origin of SP fields is uncertain, but it is believed that they result from the electric currents that are produced when a conducting body connects regions of different electrochemical potential, 59 On land, SP has been used primarily in the search for sulfide mineral deposits. It is a simple technique in that it does not involve the application of external electric fields. However, its use offshore has been limited. Results of some experiments have been inconclusive, but the offshore extension of known land sulfide deposits was successfully detected in a 1977 experiment.[60] More recently, researchers at the University of Washington have proposed building a towed SP system for exploring the Juan de Fuca Ridge. SP may prove effective for detecting the presence of sulfide deposits; however, it is unlikely to be of help in assessing the size of deposits.

Induced Polarization

The induced polarization (1P) method has been used for years to locate disseminated sulfide minerals on land. Recent work by USGS to adapt the technique for use as a reconnaissance tool to search for offshore titanium placers (figure 4-11) has produced some promising preliminary results. The 1P effect can be measured in several ways, but, in all cases, two electrodes are used to introduce current into the ground, setting up an electric potential field. Two additional electrodes are used, usually spaced some distance away, to detect the 1P effect. This effect is caused by ions under the influence of the potential field moving from the surrounding electrolyte (groundwater onshore, seawater in the seabed sediments) onto local mineral-grain interfaces and being adsorbed there. When the potential field is suddenly shut off, there is a finite decay time when these ions bleed back into the electrolyte, similar to a capacitor in an electric circuit.

If perfected for offshore use, the reconnaissance mode of 1P may enable investigators to determine if polarizable minerals are present, although not precisely what kind they are (although ilmenite and some base metal sulfides, especially pyrite and chalcopyrite, have a significant 1P effect, so do certain clays and sometimes graphite). In the reconnaissance mode, the 1P streamer can be towed from a ship; as seawater is highly conductive, it is not necessary to implant the 1P electrodes on the seafloor. Consequently, it is "theoretically possible to cover more terrain with 1P measurements in a week offshore than has been done onshore by geophysicists worldwide in the last 30 years."[61] Best results are produced when the electrodes are towed 1 to 2 meters off the bottom (although before 1P exploration becomes routine, a better cable depressor and more abrasion-resistant cables will have to be developed). Electrodes spaced 10 meters apart enable penetration of sediments to a depth of about 7 meters. The current USGS system is designed to work in maximum water depths of 100 meters.

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[56] M. B. Dobrin, *Introduction to Geophysical prospecting* (New York, NY: McGraw-Hill Book Co., 1976), p. 6.

[57] T.J.G. Francis, ''Resistivity Measurements of an Ocean Floor Sulfide Mineral Deposit From the Submersible *Cyana*,'' *Marine Geophysical Research 7, 1985,* pp. 419-438.

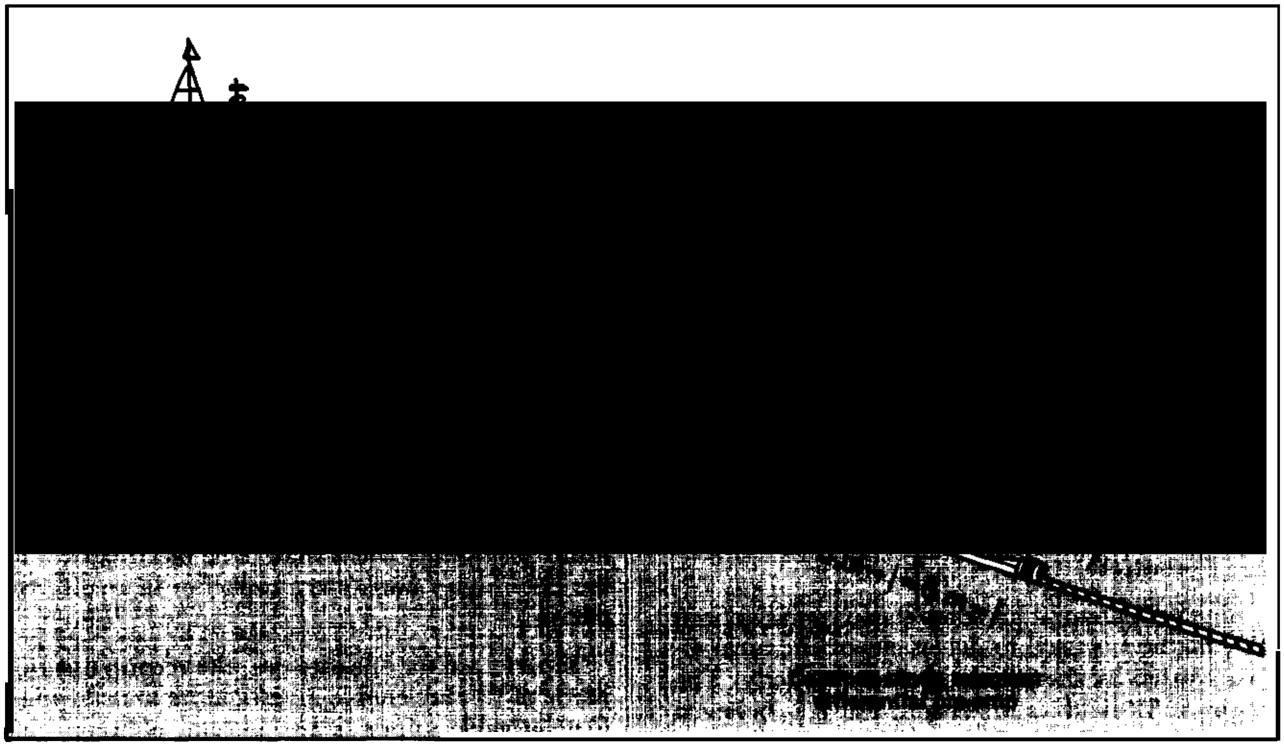
"J. Wynn, U.S. Geological Survey, letter to W, Westermeyer, OTA, May 1986.

[59] Chave, Coustable, and Edwards, "Electrical Exploration Methods for the Seafloor.

[60] Ibid.

"J. C. Wynn and A.E. Grosz, ''Application of the Induced Polarization Method to Offshore Placer Resource Exploration, *Proceedings,* Offshore Technology Conference 86, May 5-8, 1986, Houston, TX, OTC 5199, pp. 395-401.

Figure 4-11 .—Conceptual Design of the Towed-Cable-Array Induced Polarization System



Induced polarization, used for many years onshore, is currently being adapted for use at sea to search for titanium placers.

SOURCE: J.C. Wynn and A.E. Grosz, "'Application of the Induced Polarization Method to Offshore Placer Resource Exploration," *Proceedings*, Offshore Technology Conference S6, May 5-8, 1986, Houston, TX (OTC 5199), p. 399.

When polarizable minerals are located, there is some hope that a related method, spectral induced polarization (which requires a stationary ship), may be able to discriminate between the various sources of the 1P effect, It has been demonstrated that certain onshore titanium minerals (e. g., ilmenite and altered ilmenite) have strong and distinctive 1P signatures, and that these signatures can be used in the field for estimating volumes and percentages of these minerals.[62] One factor complicating interpretation of the spectral 1P signature for ilmenite could be the degree of weathering. More work is required to determine if spectral 1P works as well offshore as it does onshore. If so, it may be possible to survey large areas of the EEZ using reconnaissance and spectral 1P. Sampling then could be guided in a much more efficient manner.[63]

The applicability of 1P to placers other than titanium-bearing sands has not been demonstrated, but USGS researchers also believe that it may be possible, by recalibrating 1P equipment, to identify and quantify other mineral sands. Experiments are now being designed to determine if 1P methods can be used to identify gold and platinum sands.[64] The applicability of 1P techniques to marine sulfide deposits and to manganese-cobalt crusts, too, has yet to be demonstrated. USGS researchers hope to acquire samples of both types of deposits to perform the necessary laboratory measurements.

[62] J.C. Wynn, A. E. Grosz, and V. M. Foscz, "Induced Polarization Response of Titanium-Bearing Placer Deposits in the Southeastern United States, " Open-File Report 85-756 (Washington, DC: U.S. Geological Survey, 1985).

[63] Wynn and Grosz, "Applications of the Induced Polarization Method, " p. 397.

[64] A. Grosz Eastern Mineral Resources, USGS, telephone conversation with W. Westermeyer, OTA, Apr. 8, 1986.

Induced Polarization for Core Analysis

Another interesting possibility now being investigated is to use 1P at sea to assay full-length vibracore samples. Many techniques can assist geologists and mineral prospectors in identifying promising areas for mineral accumulations. Nevertheless, to determine precisely what minerals are present and in what quantities, it is still necessary to do laborious, expensive site-specific coring. Moreover, once a core is obtained, it often takes many hours to analyze its constituents, and much of this work must be done in shore-based laboratories.

To explore a prospective offshore mine site thoroughly, hundreds or even thousands of core samples would be needed. Geologists need analytical methods that would enable them to quickly identify and characterize deposits. USGS researchers have begun to insert 1P electrodes into unopened vibracores to determine the identity and proportion of polarizable minerals present. Such a procedure can be done in about *20* minutes and can therefore save considerable time and expense. If the analysis showed interesting results, the ship could immediately proceed with more detailed coring (shore-based analysis of cores precludes revisiting promising sites on the same voyage).

Geochemical Techniques

Water Sampling

Measurement of geochemical properties of the water column is a useful exploration method for detecting sulfide-bearing hydrothermal discharges at active ridge crests.[65] Some techniques have been developed for detecting geochemical anomalies in the water column 500 kilometers (310 miles) or more from active vent sites. Used in combination with geophysical and geological methods, these techniques help researchers "zero in' on hydrothermal discharges. Other geochemical methods are used to sense water column properties in the immediate vicinity of active vent sites.

Reconnaissance techniques include water sampling for particulate metals, elevated values of dissolved manganese, and the helium-3 isotope. Iron and manganese adsorbed on weak acid-soluble particulate matter have been detected 750 kilometers (465 miles) from the vent from which they were issued. Total dissolvable manganese is detectable several tens of kilometers from active hydrothermal sources. Methane, which is discharged as a dissolved gas from active vent systems, can be detected on the order of several kilometers from a vent site.[66] Analysis of water samples for methane has the advantage that it can be done aboard ship in less than an hour. Analysis for total dissolvable manganese requires about 10 hours of shipboard time.

At a distance of 1 kilometer or less from an active vent, the radon-222 isotope and dissolved metals also may be detected. The radon isotope produced by uranium series decay in basalt, reaches the seafloor through hydrothermal circulation and can be sampled close to an active vent. Helium-3 derived from degassing of the mantle beneath oceanic crust and entrained in subseafloor hydrothermal convection systems may be detectable in the vicinity of active vents. Other near-field water column measurements which may provide evidence of the proximity of active vents include measurements of light scattering due to suspended particulate matter, temperature, thermal conductivity, and salinity. Light scattering and temperature observations proved to be very useful in identifying hydrothermal plumes along the southern Juan de Fuca Ridge.[67]

Geochemical properties of the water column are measured using both deep-towed instrument packages and "on-station' sampling techniques. For example, NOAA's deep-towed instrumented sled, SLEUTH has been used to systematically survey portions of the Juan de Fuca Ridge. Measurements made by SLEUTH sensors over the ridge crest were supplemented by on-station measurements up to 100 kilometers off the ridge axis.[68] Similar surveys have been made over the Mid-Atlantic Ridge[69] and elsewhere. The sensitivity and precision of instruments used to acquire geochemical information continues to improve. Perhaps as importantly,

[65] Rona, " Exploration for Hydrothermal Mineral Deposits, pp. 7-37.

[66] Ibid.

[67] E.T. Baker, J.W. Lavelle, and G.J. Massoth, "Hydrothermal Particle Plumes Over the Southern Juan de Fuca Ridge, *Nature,* vol. *316,* July 25, 1985, p, 342.

[68] Ibid.

[69] P. A. Ron,, G. Klinkhammer, T.A. Nelsen, J. H. Trefey, and H. Elderfield, ''Black Smokers, Massive Sulfides, and Vent Biota at the Mid-Atlantic Ridge, " *Nature, vol. 321,* May 1, 1986, p. 33.

towed instrument packages like SLEUTH are enabling systematic surveys of large ocean areas to be undertaken.

Nuclear Methods

Nuclear methods consist of physical techniques for studying the nuclear or radioactive reactions and properties of substances. Several systems have been developed to detect the radiation given off by such minerals as phosphorite, monazite, and zircon. One such device was developed by the Center for Applied Isotope Studies (CAIS) at the University of Georgia. In the mid-1970s, the Center developed an underwater sled equipped with a radiation detector that is pulled at about 3 knots over relatively flat seabed terrain. The towed device consists of a four-channel analyzer that detects potassium-40, bismuth-214, thallium-208, and total radiation. The sled has been used to locate phosphorite off the coast of Georgia by detecting bismuth-214, one of the radioactive daughters of uranium, often a constituent of phosphorite. In another area offshore Georgia, the Center's towed sled detected thallium-208, an indicator of certain heavy minerals. Subsequent acquisition of surficial samples (grab samples) of the area confirmed the presence of heavy mineral sands.[70]

A similar system for detecting minerals associated with radioactive elements has been developed by Harwell Laboratory in the United Kingdom. The Harwell system identifies and measures three principal elements: uranium, thorium, and potassium. The seabed probe resembles a snake and is towed at about 4 knots in water depths up to 400 meters (1, 300 feet). The Harwell system is now commercially available and is being offered by British Oceanics, Ltd., as part of its worldwide survey services.[71]

A second type of nuclear technique with promise for widespread application in marine mineral exploration uses X-ray fluorescence to rapidly analyze surface sediments aboard a moving ship. The method was developed by CAIS and uses X-ray fluorescence as the final step. X-ray fluorescence is a routine method used in chemical analyses of solids and liquids. A specimen to be analyzed using this technique is irradiated by an intense X-ray beam which causes the elements in the specimen to emit (i. e., fluoresce) their characteristic X-ray line spectra. The elements in the specimen maybe identified by the wavelengths of their spectral lines.[72]

The CAIS Continuous Seafloor Sediment Sampler was originally developed for NOAA's use in rapid sampling of heavy metal pollutants in nearshore marine sediments. A sled is pulled along the seafloor at about three knots. The sled disturbs the surficial sediments, creating a small sediment plume. The plume is sucked into a pump system within the sled and pulled to the surface as a slurry. The slurry is further processed, after which small portions are collected on a continuous filter paper. After the water is removed, a small cookie-like wafer remains on the paper (hence, the system is known as the "cookie maker' '). ' 'Cookies' are coded for time, location, and sample number and can be made about every 30 seconds, which, at a ship speed of 3 knots, is about every 150 feet. An X-ray fluorescence unit is then used to analyze the samples. It is possible to analyze three or four elements aboard ship and approximately 40 elements in a shore-based laboratory. The system has been designed to operate in water 150 feet deep but could be redesigned to operate in deeper water.[73]

The cookie maker can increase the speed of marine surveys. Not only are samples quickly obtained but preliminary analysis of the samples is available while the survey is still underway. Availability of real-time data that could be used for making shipboard decisions could significantly improve the efficiency of marine surveys. One current limitation is that samples are only obtainable from the top 3 or 4 centimeters of sediment. Researchers believe that some indication of underlying deposits may be obtained by sampling the surfacial sediments, but further tests are needed to determine if the technique also can be used for evaluating the composition of deeper sediments.

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[70] J. Noakes, Center for Applied Isotope Studies, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, Washington, DC, July 16, 1986.

[71] "Radiometric Techniques for Marine Mineral Survey s," *World Dredging and Marine Construction*, Apr. 1, 1983, p. 208.

[72] *Encyclopedia of Science and Technology*, 5th ed. , (New York, NY: McGraw-Hill, 1982), p. 741.

[73] J. Noakes, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, Washington, DC, July 16, 1986.

A third type of nuclear technique, neutron activation analysis, has been used with some success to evaluate the components of manganese nodules from the deep seafloor.[74] The technique consists of irradiating a sample with neutrons, using californium-252 as a source. Gamma rays that are emitted as a result of neutron interactions then can be analyzed. Ideally, the identification and quantification of elements can be inferred from the spectral intensities of gamma ray energies that are emitted by naturally occurring and neutron-activated radioisotopes.[75] Although the neutron activation technique can be used at sea to obtain chemical analyses of many substances, its use is limited by the difficulty of taking precise analytical weights at sea. The X-ray fluorescence method has proven both easier to use at sea and less expensive.

Manned Submersibles and Remotely Operated Vehicles

Both manned and remotely operated vehicles (ROVs) have been working in the EEZ for many years. One characteristic that all undersea vehicles share is the ability to provide the explorer with a direct visual or optical view of objects in real-time. Another common characteristic is that undersea vehicles operate at very slow speeds relative to surface-oriented techniques. Indeed, a great deal of the work for which undersea vehicles are designed is accomplished while remaining stationary to examine or sample an object with the vehicles manipulators. As a consequence, neither manned nor unmanned vehicles are cost-effective if they are employed in large area exploration. Their best application is in performing very detailed exploration of small areas or in investigating specific characteristics of an area.

All manned submersibles carry a crew of at least 1 and as many as 12, one of which is a pilot. Most of the many types of manned submersibles are battery-powered and free-swimming; others are tethered to a surface support craft from which they receive power and/or life support (tables 4-5 and 4-6). A typical untethered, battery-powered manned submersible is *Alvin* which carries a crew of three (one pilot; two observers); its maximum operating depth is 4,000 meters (13,000 feet).

ROVs are unmanned vehicle systems operated from a remote station, generally on the sea surface. There are five main categories of ROVs:

[74] Ibid.

[75] *A Borehole Probe for In Situ Neutron Activation Analysis*, Open File Report 132-85 (Washington, DC: U.S. Bureau of Mines, June 1984), p. 8.

Table 4-5.—U.S. Non-Government Submersibles (Manned)

Vehicle	Date built	Length (ft)	Operating depth (ft)	Power supply	Crew/observers	Manipulators/viewports	Operators
Arms I,II,III and IV	1976-1978	8.5	3,000	Battery	1/1	3/Bow dome	Oceaneering International, Santa Barbara, CA
Auguste Piccard	1978	93.5	2,000	Battery	6/3	0/1	Chicago, Inc., Barrington, IL
Beaver	1968	24.0	2,700	Battery	1/4	I/Bow dome	International Underwater Contractors, City Island, NY, NY
Deep Quest	1967	39.9	8,000	Battery	2/2	2/2	Lockheed Missiles & Space, San Diego, CA
Delta	1982	15.0	1,000	Battery	1/1	1/19	Marfab, Torrence, CA
Diaphus	1974	19.8	1,200	Battery	1/1	I/Bow dome	Texas A & M University, College Station, TX
Jim (14 ea)	1974	–	1,500	Human	1/0	2/1	Oceaneering International, Houston, TX
Johnson-Sea-Link I & II	1971 1975	22.8	3,000	Battery	1/3	1/Panoramic	Harbor Branch Foundation, Ft. Pierce, FL
Mermaid II	1972	17.9	1,000	Battery	1/1	I/Bow dome	International Underwater Contractors, City Island, NY
Nekon B&C	1968 1970 1972	15.0	1,000	Battery	1/1	I/Bow dome	Oceanworks, Long Beach, CA
Pioneer	1978	17.0	1,200	Battery	1/2	2/3	Martech International, Houston, TX
Pisces VI	1976	20.0	6,600	Battery	1/2	2/3	International Underwater Contractors, City Island, NY
Snooper	1969	14.5	1,000	Battery	1/1	1/10	Undersea Graphics, Inc., Torrance, CA
Makalii	1966	17.7	1,200	Battery	1/1	1/6	University of Hawaii, Honolulu, HI
Wasp	1977	–	2,000	Surface	1/10	2/Bow dome	Oceaneering International, Houston, TX

SOURCE: Busby Associates, Inc. Arlington, VA

Table 4-6.—Federally Owned and Operated Submersibles

Vessel	Date built	Length (ft)	Operating depth	Power supply	Crew/ observers	Manipulators/ view ports	Speed (kts) cruise/max	Endurance (hrs) cruise/max
UNOLS								
Alvin	*1964*	*25*	12,000	Battery	1/2	1/4	1/2	—
NOAA								
Pisces V	*1973*	**20**	4,900	Battery	1/2	2/3	0.5/2	6/2
NAVY								
Sea Cliff	*1968*	*26*	20,000	Battery	2/1	2/5	0.5/2.5	8/2
Turtle	1968	26	10,000	Battery	2/1	2/5	0.5/2.5	8/2
NR-1	1969	136	—	Nuclear	7/—	—	—	—

SOURCE: Busby Associates, Inc., Arlington, VA.

1. tethered, free-swimming vehicles (the most common);
2. towed vehicles;
3. bottom crawling vehicles;
4. structurally-reliant vehicles; and
5. autonomous or untethered vehicles.

For exploring the EEZ, two types of ROVs appear most appropriate: tethered, free-swimming vehicles and towed vehicles (table 4-7). A typical tethered, free-swimming ROV system is shown in figure 4-12. Typically, vehicles of this type carry one or more closed-circuit television cameras, lights, and, depending on their size, a variety of tools and monitoring/measuring instrumentation. Almost all of them receive electrical power from a surface support vessel and can maneuver in all directions using onboard thrusters.

Towed vehicles are connected by a cable to a surface ship. Most often these vehicles carry television cameras and still cameras. Lateral movement is generally attained by maneuvering the towing vessel, and depth is controlled by reeling in or reeling out cable from the surface. These vehicles are designed to operate within the water column and not on the bottom, but some have been designed and equipped to periodically scoop sediment samples from the bottom.

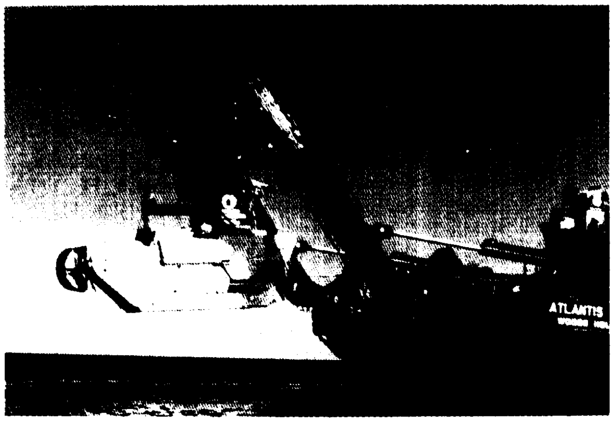


Photo credit: Office of Undersea Research, NOAA

The Submersible *Alvin* and the *At/antis //. Alvin* is an untethered, battery-powered manned submersible capable of operating in 13,000 feet of water.

Table 4-7.—U.S. Government Supported ROVs

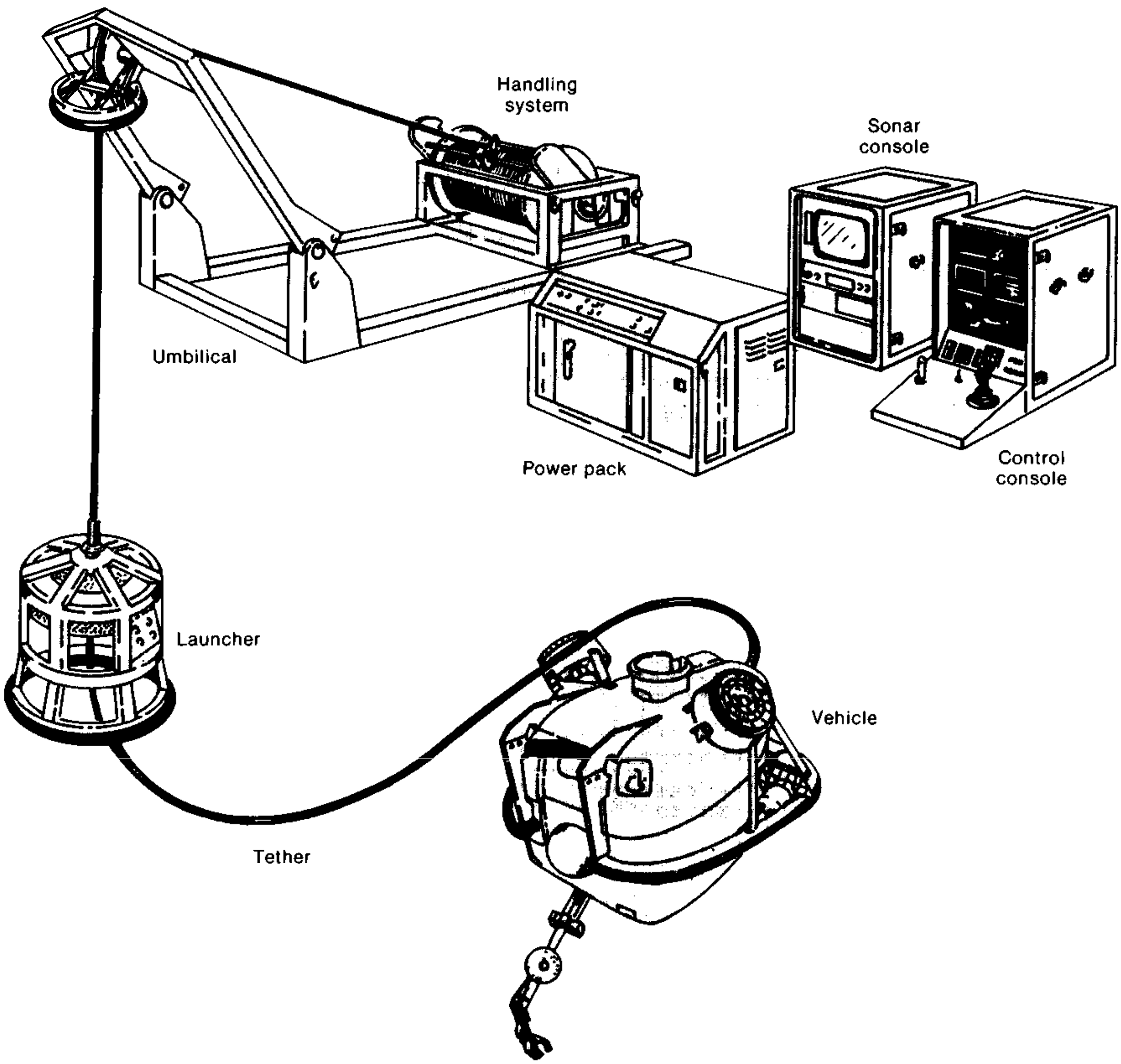
Type	Depth (ft)	Operator
Tethered fnw-swimming:		
Mini Rover.	*328*	U.S. Navy
ADROV	1,000	U.S. Navy
Mini Rover MK II, ...	1,200	NOAA
Pluto, ...	1,300	U.S. Navy
Snoopy (2). .. .,., ...	1,500	U.S. Navy
Recon IV (4)	1,500	U.S. Navy
Curv II (2)	***2,500***	U.S. Navy
URS-1	***3,000***	U.S. Navy
Super Scorpio (2)	***4,900***	U.S. Navy
Deep Drone ., ...	***5,400***	U.S. Navy
Curv III	10,000	U.S. Navy
Towed:		
Manta, ., .,	***2,100***	NOAA, NMFS
Teleprobe, ., ...	***20,000***	U.S. Navy
Deep Tow, ...	***20,000***	Scripps
Argo/Jason	***20,000***	Woods Hole
ANGUS . .	***20,000***	Woods Hole
Katz Fish	***2,500***	Lamont-Doherty
STSS ., ...	***20,000***	U.S. Navy
Untethered:		
Eave East .	***150***	University of New Hampshire
Eave West	***200***	U.S. Navy
SPURV 1.	***12,000***	University of Washington
SPURV II	***5,000***	University of Washington
UFSS	1,500	U.S. Navy

SOURCE Busby Associates, Inc , Arlington, Virginia

Advantages and Limitations

Manned submersibles, particularly in the industrial arena, have gradually given way to ROVs. The relatively few manned vehicles that have remained in service have done so because they offer a unique capability which ROVs have yet to dupli-

Figure 4-12.—A Tethered, Free-Swimming Remotely Operated Vehicle System



Vehicles of this type usually carry one or more closed-circuit television cameras, lights, grabbers, and instruments for monitoring and measuring.

SOURCE: Busby Associates, Inc.

cate. Comparisons of the relative advantages and disadvantages of manned submersibles and ROVs are difficult to make unless a particular task has been specified and the environment in which it has to operate is known. The first major advantage of a manned vehicle is that the observer has a direct, three-dimensional view of the target to be investigated or worked on. Second, the manipulative capability of certain types of manned vehicles is superior to ROVs. Third, the absence of a drag-producing cable connecting the manned submersible to its support ship permits the submersible to operate within stronger currents and at greater depths than most ROVs can presently operate.

Nonetheless, manned submersibles have several drawbacks. Most industrial applications require working around and within a structure where the possibility of entanglement/entrapment is often present and, consequently, human safety is potentially in jeopardy. Manned vehicles that operate independently of a surface-connecting umbilical cord can operate for a duration of 6 to 8 hours before exhausting batteries. Even with more electrical power, there is a limit to how long human occupants can work effectively within the confines of a small diameter sphere—6 to 8 hours is about the limit of effectiveness. Relative to ROVs, a manned submersible operation will always be more complex, since there is the added factor of providing for the human crew inside.

The two major advantages of ROVs are that they will operate for longer durations than manned vehicles (limited only by the electrical producing capability of the support ship) and that there is a lower safety risk for humans. Towed ROVs, for example, can and do operate for days and even weeks before they need to be retrieved and serviced. The many varieties of ROVs (at least 99 different models produced by about 40 different manufacturers) permit greater latitude in selecting a support craft than do manned submersibles (which usually have dedicated support vessels). Many ROVs, because of their small size, can access areas that manned vehicles cannot. Because ROV data and television signals can be relayed continuously to the surface in real-time, the number of topside observers participating in a dive is limited only by the number of individuals or specialists that can crowd around one or several television monitors. Depending on the depth of deployment and the type of work conducted, an ROV may incur only a fraction of the cost of operating a manned submersible.

Probably the most debated aspect of manned v. unmanned vehicles is the quality of viewing the subsea target. There is no question that a television camera cannot convey the information that a human can see directly. Even with the high quality and resolution of present underwater color television cameras and the potential for three-dimensional television viewing, the image will probably never equal human observation and the comprehension it provides. To the scientific observer, direct viewing is often mandatory. For the industrial user, this is not necessarily the case. Some segments of industry may be satisfied with what can be seen by television, and, while they would probably like to see more, they can see well enough with television to get the job done. The distinction between scientific and industrial needs is important because in large part, it allowed the wide-scale application of the ROV, which contributed to the slump in manned vehicle use.

costs

The cost of undersea vehicles varies as widely as their designs and capabilities. One of the few generalizations that can be made regarding costs is that they increase in direct proportion to the vehicle's maximum operating depth.

Manned submersibles can cost from as little as $15,000 for a one-person vehicle capable of diving to 45 meters (150 feet) to as much as $5 million for an *Alvin* replacement. A replacement for the Johnson-Sea-Link, which is capable of diving to over 900 meters (3,000 feet), would cost from $1.5 million to $2 million. These figures do not include the support ships necessary to transport and deploy the deeper diving vehicles. Such vessels, if bought used, would range from $2 million to $3 million; if bought new, they could cost from $8 million to $10 million.

ROVs also range widely in costs. There are tethered, free-swimming models currently available that cost from $12,000 to $15,000 per system, reach depths of 150 and more meters, and provide video only. At the other end are vehicles that reach depths in excess of 2,400 meters, are equipped with a wide array of tools and instrumentation, and cost from $1.5 million to $2 million per system. Intermediate depth (900 meters/3,000 feet) systems equipped with manipulators, sonars and sensors range from $400,000 to $500,000. Most of the towed vehicles presently available are deep diving (20,000 feet) systems requiring a dedicated support ship and extensive surface support equipment. Such systems start at about *$2* million and can, in the case of the towed hybrid systems, reach over $5 million.

The foregoing prices are quoted for new vehicles only. However, in today's depressed offshore service market, there are numerous opportunities for obtaining used manned and remotely operated vehicle systems for a fraction of the prices quoted above. Likewise, support ships can be purchased at similar savings. This generalization does not apply to the towed or the hybrid systems, since they were built by their operators and are not commercial vehicles.

Capabilities

The environmental limits within which a vehicle can work are determined by such design features as operating depth, speed, diving duration, and payload. These factors are also an indication of a vehicle's potential to carry equipment, The actual working or exploration capabilities of a manned or unmanned vehicle are measured by the tools, instruments, and/or sensors that it can carry and deploy. These capabilities are, in large part, determined by the vehicle's carrying capacity (payload), electrical supply, and overall configuration. For example, *Deep Tow* represents one of the most sophisticated towed vehicles in operation. Its equipment suite includes virtually every data-gathering capability available for EEZ exploration that can be used with this type of vehicle. On the other hand, there are towed vehicles with the same depth capability and endurance as *Deep Tow* **but which cannot begin to accommodate the vast array of instrumentation this vehicle carries, due to their design. Table 4-8 is a current worldwide listing of towed vehicles and the instrumentation they are de**signed to accommodate. Towing speed of these vehicles ranges from 2 to 6 knots.

Tethered, free-swimming ROVs offer another example of the wide range in exploration capabilities available in today's market. Vehicles with the most basic equipment in this category have at least a television camera and adequate lighting for the camera (although lighting may sometimes be optional). However, there is an extensive variety of additional equipment that can be carried, The ROV Solo, for example, is capable of providing real-time observations via its television camera, photographic documentation with its still camera, short-range object detection and location by its scanning sonar, and samples with its three-function grabber (i. e., manipulator). The vehicle is also equipped for conducting bathymetric surveys. Assuming it is supported by an appropriate subsea navigation system, it can provide:

- a high-resolution topographic profile map on which the space between sounding lanes is swept and recorded by side-looking sonar,
- a sub-bottom profile of reflective horizons beneath the vehicle,
- a chart of magnetic anomalies along the tracks covered,
- television documentation of the entire track,
- selective stereographic photographs of objects or features of interest, and
- the capability to stop and sample at the surveyor's discretion.

With adequate equipment on the vehicle and support ship and the proper computer programs, the entire mapping program, once underway, can be performed automatically with little or no human involvement. At least a dozen more competitive models exist that can be similarity equipped.

In addition to ROVs of the *Deep Tow* and Solo class, several vehicles have been designed to conduct a single task rather than multiple tasks. One such vehicle is the University of Georgia's Continuous Seafloor Sediment Sampler, discussed earlier in the section on nuclear methods.

Untethered, manned vehicles are, for the most part, equipped with at least one television camera, still camera, side-looking sonar, and manipulator, and with pingers or transponders compatible with whatever positioning system is being used. The absence of an umbilical cable has an advantage that received little attention until the *Challenger* space shuttle tragedy in 1986. *Challenger's* debris was scattered under the Atlantic Ocean's Gulf Stream, which flows at maximum speed on the surface but decreases to less than 0.25 knot at or near the bottom. Once the manned submersibles used in the search descended below the swift flowing surface waters (upwards of 3 knots), they worked and maneuvered without concern for the current. The ROVs used, on the other hand, **were all tethered, and, even though the vehicle itself might be operating within little or no discernible current, the umbilical had to contend with the current at all times. This caused considerable difficulty at times during the search operation.**

Table 4-8.—Worldwide Towed Vehicles

Vehicle	Depth (ft.)	Instrumentation	Operator
ANGUS	20,000	Still camera w/strobe, echo sounder, temperature sensor	Woods Hole Oceanographic Institution, Woods Hole, MA, USA
Brut /V	*900*	TV camera w/light, still camera w/strobe, automatic altitude control	Biological Station, St. Andrews, New Brunswick, NS, Canada
CSA/STCS	1,000	TV w/light	Continental Shelf Associates, Jupiter, USA
CSA/UTTS	1,150	TV w/lights, still camera w/strobe, altimeter	Continental Shelf Associates, Jupiter, USA
Deep Challenger	*20,000*	TV w/lights, still camera w/strobe, side-looking sonar, sub-bottom profiler, depth/altitude sensor, C/T/D sensors	Japan Marine Science & Technology Center, Yokosuka, Japan
Deep Tow	*20,000*	Slow-scan TV w/ strobe illumination, echo sounder, side-looking sonar, scanning sonar, magnetometer, stereo camera system, C/T/D sensors, transponder	Marine Physical Laboratory, Scripps Institution of Oceanography, La Jolla, CA, USA
Deep Tow Survey System	*20,000*	TV w/ light, still camera w/ strobe, side-looking sonar, magnetometer sub-bottom profiler, current meter, altitude/depth sensor	Lockheed Ocean Laboratory, San Diego, CA, USA
DSS-125 (4 each)	20,000	TV w/ light, still camera w/ strobe, magnetic compass	Japanese and West German industrial firms.
Manta	2,132	TV w/ lights, still camera w/ strobe, side-looking sonar, C/T/D sensors	National Marine Fisheries Service, Pascagoula, MS, USA
Nodule Collection Vehicle	NA	Cutting and pumping devices to collect nodules for transport to surface	National Research Institution for Resources & Pollution, Japan
Ocean Rover	1,000	TV on pan/tilt w/ light, still camera w/ strobe, depth and speed sensor	Seametrix Ltd., Aberdeen, Scotland
OFOS	*20,000*	Color TV and three still cameras w/ appropriate lighting	Preussag Meerestechnik, Hannover, West Germany
Raie //	20,000	Still cameras w/ strobe echo sounder, pressure/depth sensor, transponder	IFREMER, Brest, France
Sea *Bed 2.*	*6,500*	Side-looking sonar (6km swath), sub-bottom profiler	Huntec, Ltd. Scarborough, Ontario, Canada
Sea Kite	1,000	TV, still camera, pipe, tracker, scanning sonar, side-looking sonar, sub-bottom profiler, magnetometer	Blue Deep Sari, Valmondois, France
Sound (b each)...	13,000	TV w/ light, still camera w/ strobe, side-looking sonar, magnetometer, seismic profiler	Institute of Oceanology, Moscow, USSR
STSS	20,000	TV w/ light, still camera w/ strobe, scanning sonar, side-looking sonar, altitude/depth sonar, transponder	Submarine Development Group One, U.S. Navy, San Diego, CA, USA
Teleprobe	*20,000*	TV w/ light, stereocameras w/ strobes, magnetometer, side-looking, altitude/depth sonar	U.S. Naval Oceanographic Office, Bay St. Louis, MS, USA
Turn s	*20,000*	TV w/ light, stereocameras w/ strobe, scanning sonar, side-looking sonar, magnetometer, manipulator	Royal British Navy

SOURCE: Busby Associates, Inc., Arlington, Virginia.

Very little work using manned or ROVs has been done solely for exploration purposes. In the industrial arena, the work has been in support of offshore oil and/or gas operations, including pipeline and cable route mapping and inspection, bottom site surveying, structural inspection and maintenance, and a wide variety of other tasks. Scientific application of undersea vehicles has been almost always directed at studying a particular phenomenon or aspect of an ecosystem. In only a few instances have undersea vehicles been used to verify the data collected by surface-oriented techniques.

Hard mineral exploration, however, is a task well-suited for manned vehicles and tethered, free-swimming ROVs. A wide array of manipulator-held sampling equipment for these vehicles has been developed over the past two decades. This sampling capability ranges from simple scoops to gather unconsolidated sediment to drills for taking hard-rock cores. Present undersea vehicles cannot, however, collect soft sediment cores much beyond 3 feet in length or hard-rock cores more than a few inches in length,

The Continuous Seafloor Sediment Sampler is an example of a specially designed vehicle. Vehicles of this type might find extensive application in the EEZ by providing relatively rapid mineral assays of the bottom within areas of high interest. If supported with appropriate navigation equipment, a surficial mineral constituent chart could be developed fairly rapidly. Due to the vehicle's present design, such a map could only be made over bottoms composed of unconsolidated, fine-grained sediments.

A recent example of a vehicle application was the search for and subsequent examination of the RMS *Titanic,* which sank in the Atlantic in 1912. The vessel was thought to be somewhere within a 120-square-nautical-mile area. A visual search with an undersea vehicle could literally take years to complete at the 4,000-meter (13,000-foot) depths in which she lay. Instead, the area was searched using a side-looking sonar which detected a target of likely proportions after about 40 days of looking. To verify that the target was the *Titanic,* the towed vehicle *ANGUS* was dispatched with its television and still cameras. The next step, to closely examine the vessel, was done with the manned vehicle *Alvin* and the tethered, free-swimming ROV *Jason Junior (JJ). Alvin* provided the means to ' 'home on' and board the vessel, while JJ provided the means to explore the close confines of the vessel's interior.

The search for the space shuttle *Challenger* debris is another example of the division of labor between undersea vehicles and over-the-side techniques. Since the debris was scattered over many square miles and intermixed with debris from other sources, it would have taken months, perhaps years, to search the area with undersea vehicles. Instead, as with the *Titanic,* side-looking sonar was used to sweep the area of interest and likely targets were plotted to be later identified by manned and unmanned vehicles. The same vehicles were subsequently used to help in the retrieval of debris. Once again, the large area was searched with the more rapid over-the-side techniques while precision work was accomplished with the slower moving undersea vehicles.

These two examples suggest that the main role of undersea vehicles in the EEZ is and will be to provide the fine details of the bottom. A typical exploration scenario might begin with bottom coverage with a wide-swath side-looking sonar, like GLORIA, progress to one of the midrange side-looking sonars or a Sea Beam-type system, and end with deployment of a towed vehicle system or a tethered, free-swimming ROV or manned submersible to collect detailed information.

Needed Technical Developments

Thanks to technological advances in offshore oil exploration, the tools, vehicles, and support systems available to the EEZ minerals explorer have increased dramatically in numbers and types since the 1960s. It would appear that adequate technology now exists to explore selected areas within the EEZ using undersea vehicles. But, as with offshore oil, some of these assets will probably prove to be inadequate when they are used for hard mineral exploration instead of the tasks for which they were designed, Identification of these shortcomings is probably best accomplished by on-the-job evaluation.

More than likely, whatever technological improvements are made will not be so much to the vehicles themselves but to the tools and instrumentation aboard the vehicles that collect the data. Hence, it is important to identify precisely the data-collecting requirements for hard mineral exploration and mining. Potential discovery of new underwater features, processes, and conditions must also be anticipated. For example, prior to 1981, nothing was known of the existence of deepwater vents or of the existence of the animals that inhabit these areas. Once the vents and their associated fauna were discovered, tools and techniques for their investigation were developed as necessary.

Certain aspects of undersea vehicles and their equipment are perennial candidates for improve-

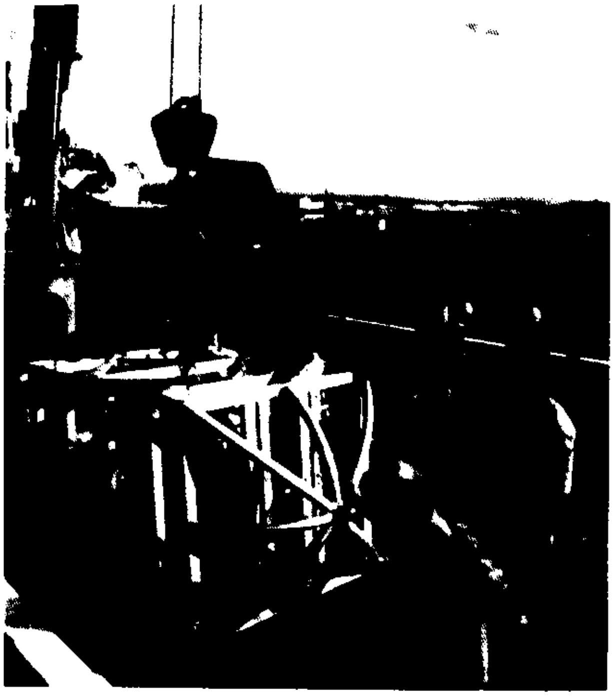


Photo credit: U.S. Geological Survey

Underwater camera system, ready for deployment

ment. These include, but are not limited to, broader bandwidths for television signals, greater manipulative dexterity and sensory perception, and more precise station-keeping and control of the vehicle itself. The advent of the microprocessor has introduced other candidates: artificial intelligence, pattern recognition, teach/learn programs, greater memory, all of which can serve to improve the capability of the vehicles and their accompanying sensors and tools. There is no question that these aspects of vehicle technology are worthy of consideration and that they will undoubtedly improve our underwater exploration capability. But before additional development or improvement of undersea vehicle technology for EEZ hard minerals exploration begins, it may be more important to assess fully the applicability of the currently available technology.

Optical Imaging

Optical images produced by underwater cameras and video systems are complementary to the images and bathymetry provided by side-looking sonars and bathymetry systems. Once interesting features have been identified using long-range reconnaissance techniques, still cameras and video systems can be used for closeup views. Such systems can be used to resolve seafloor features on the order of 10 centimeter to 1 meter. The swath width of imaging systems depends on such factors as the number of cameras used, the water characteristics, and the height of the imaging system above the seafloor. Swaths as wide as 200 meters are currently mappable.

ANGUS (Acoustically Navigated Underwater Survey) is typical of many deep-sea photographic systems. Basically, *ANGUS* consists of three 35-millimeter cameras and strobe lights mounted on a rugged sled. The system is towed approximately 10 meters off the bottom in water depths up to 6,000 meters (19,700 feet), and is capable of taking 3,000 frames per sortie. It has been used in conjunction with dives of the submersible *Alvin.*

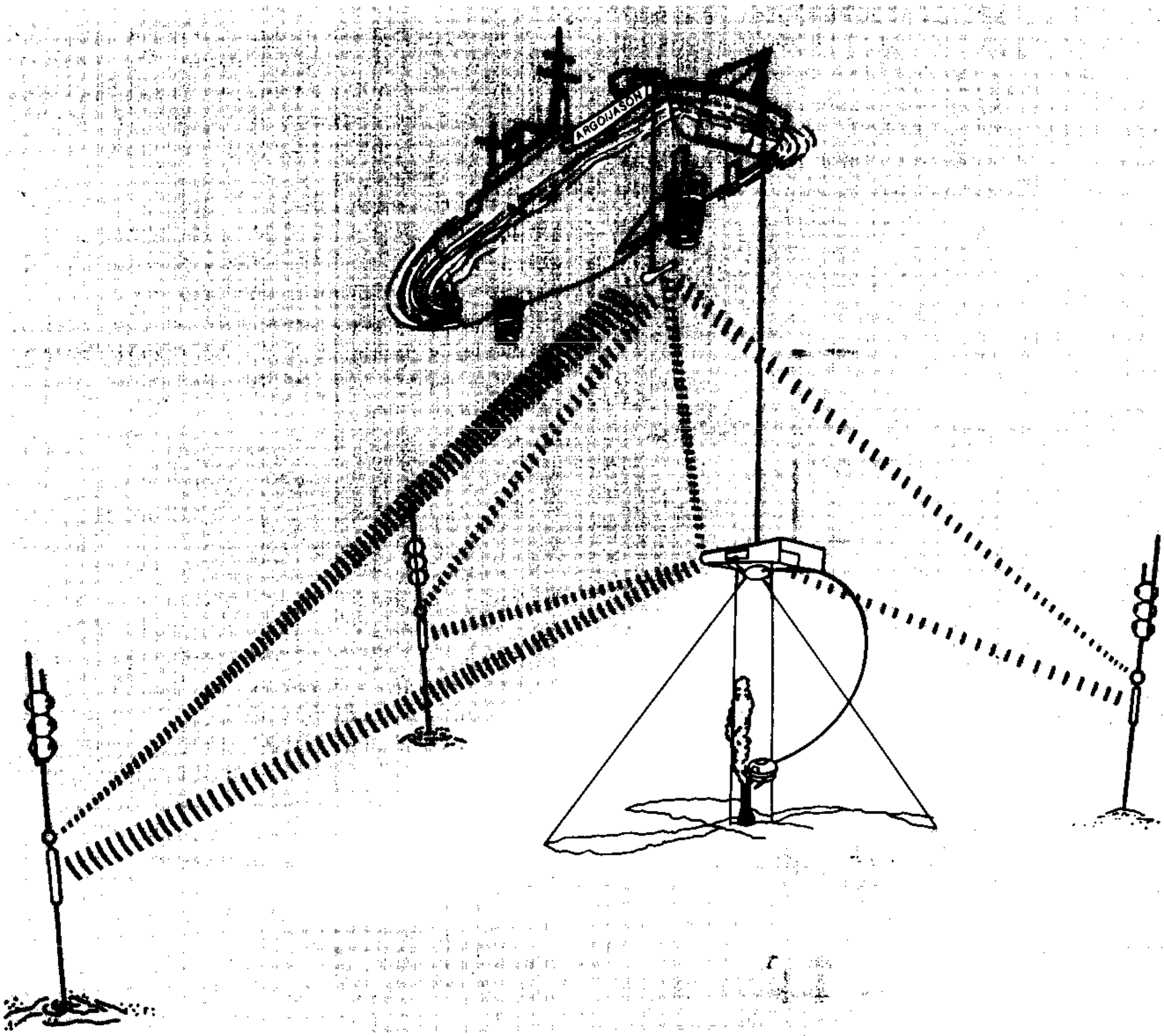
A newer system, currently under development at the Deep Submergence Laboratory (DSL) at Woods Hole Oceanographic Institution, is *Argo.* On her maiden voyage in September 1985 *Argo* assisted in locating the *Titanic.* Like *ANGUS, Argo is* capable of operating in water depths of 6,000 meters. *Argo,* however, is equipped with a wide-area television imaging system integrated with side-looking sonar.[76] It currently uses three low-light-level, silicon-intensified target cameras (one forward-looking, one down-looking, and one down-looking telephoto), extending the width of the imaged swath to 56 meters (184 feet) when towed at an altitude of 35 meters.

Argo is being designed to accommodate a second ROVs, to be known as *Jason. Jason* will be a tethered robot capable of being lowered from *Argo* to the seafloor for detailed camera (and sampling) work (figure 4-13). Its designers plan to equip *Jason* with stereo color television "eyes."[77] One current limitation is the lack of availability of an adequate transmission cable for the color television pictures. Color television transmissions exceed 6 million bits per second, and large bandwidth cables capable of carrying this amount of information have not yet been developed for marine use. Fiber-optic cables are now being designed for this

[76] S.E. Harris and K. Albers, "Argo: Capabilities for Deep Ocean Exploration, *Oceanus*, *vol. 28, No. 4, 1985/86,* p. 100.

[77] R. D. Ballard, ' 'Argo-Jason, *Oceans,* March 1983, p. 19.

Figure 4-13.—Schematic of the *Argo-Jason* Deep-Sea Photographic System



The *Argo-Jason* system is currently under development at Woods Hole's Deep Submergence Laboratory. *Argo* has already assisted in locating the *Titanic. Jason is* being designed to be launched from *Argo* and will handle detailed camera work.

SOURCE: Woods Hole Oceanographic Institution.

and related marine data transmission needs. However, before fiber-optic cables can be employed, problems of handling tensional stress and repeated flexing of the cable must be overcome. Personnel at DSL believe that when the *Argo-Jason* system is fully developed, the need for manned submersibles will be much reduced.

The current subject-to-lens range limit for optical imaging is 30 to 50 meters in clear water. Several improvements are expected in the future that may enable subjects to be imaged as far as 200 meters from the lens under optimal viewing conditions. For instance, work is underway to increase the sensitivity of film to low light levels. A 200,000

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ASA equivalent speed film was used to take pictures of the *Titanic* under more than 2 miles of water. Higher film speed ratings, perhaps as high as 2 million ASA equivalent, will enable pictures to be taken with even less light. Improved lighting will also help. The optimal separation between camera and light in the ocean is about 40 meters, which suggests that towed light sources could provide an advantage. Use of polarization filters can also help increase viewing potential. Gated light sources, which emit short pulses of light, will be more expensive to develop. Development of a technique to open the camera shutter at the precise time the gated light illuminates the subject will help reduce scattering of the reflected light. 78

Direct Sampling by Coring, Drilling, and Dredging

Once a prospective site is located using geophysical and/or other reconnaissance methods, direct sampling by coring, drilling, or dredging (as appropriate) is required to obtain detailed geological information. Direct sampling provides "ground truth' correlation with indirect exploration methods of the presence (and concentration) or absence of a mineral deposit. The specific composition of a deposit cannot be determined without taking samples and subjecting them to geochemical analyses. Representative sampling provides potential miners with information about the grade of deposit, which is necessary to decide whether or not to proceed with developing a mine site.

Placer Deposits

The state-of-the-art of sampling marine placers and other unconsolidated marine sediments is more advanced than that of sampling marine hard-rock mineral deposits such as cobalt crusts and massive sulfides. There are various methods for sampling unconsolidated sediments in shallow water, whereas technology for sampling crusts and sulfides in deep water is only now beginning to be developed. Two significant differences exist between sampling placer deposits and marine hard-rock deposits. One is the greater depth of water in which crusts and sulfides occur. The other is the relative ease of penetrating placers.

Grab samplers obtain samples in the upper few centimeters of surfacial sediments. For obtaining a sample over a thicker section of sediments and preserving the sequence of sedimentary layers, vibracore, gravity, piston, and other coring devices are used. These corers are used to retrieve relatively undisturbed samples that may indicate the concentration of minerals by layer and the thickness of the deposit. On the other hand, to determine the average grade of ore at a particular site and for use in processing studies, large bulk samples obtained by dredging (including any waste material or overburden), rather than undisturbed cores, may be sufficient.

The characteristics of a sampling device appropriate for a scientific sampling program are not necessarily appropriate for proving a mine site. In order to establish tonnage and grade to prove a mine site, thousands of samples may be required. It is essential that the sampling device provide consistently representative samples at a reasonable cost. The ability to carry out commercial-scale sampling, required to define an ore body, in water deeper than about 60 feet is still very limited. Scientific sampling can be done in deeper water, but as table 4-9 indicates, sampling costs rapidly escalate with water depth. The costs of sampling in deeper water probably will have to be reduced significantly before commercial development in these areas can take place.

Only a few areas within the U.S. Exclusive Economic Zone have been systematically sampled in three dimensions. Much of the data collected to date have been from surface samples and hence are not reliable for use in quantitative assessments. 79 Adequate knowledge of the mineral resource potential of the EEZ will require extensive three-dimensional sampling in the most promising areas.

Several factors, as suggested above, are important in evaluating the performance of a placer sampling system[80] (in general, these factors are equally

[78] R. Ballard, Deep Submergence Laboratory, Woods Hole Oceanographic Institution, OTA Workshop on Technologies for Surveying and Exploring the Exclusive Economic Zone, June 10, 1986.

[79] See, for example, Clifton and Luepke, "Heavy Mineral Placer Deposits.

[80] B. Dimock, "An Assessment of Alluvial Sampling Systems for Offshore Placer Operations, Report, Ocean Mining Division, Resource Evaluation Branch, Energy, Mines, and Resources Canada, January 1986.

Table 4-9.—Vibracore Sampling Costs[a]

	Shallow water	Deep water
Water depth	30-60 feet	200 to 300 feet
Type of coring equipment	Vibracorer	Vibracorer (equipped for deep water operation)
Number of cores in program	50	50
Depth of penetration	20 feet	20 feet
Type of vessel	100- to 150-foot open deck work boat, twin screw equipped with A-frame and double point mooring gear	150- to 200-foot open deck work boat, twin screw, equipped with A-frame and double point mooring gear
Mobilization/demobilization cost	$25,000	$50,000
Vessel cost	$50,000 (10 days at $5,000 per day; assumes 6 cores per day; 30°/0 downtime for weather)	$160,000 (20 days at $8,000 per day; assumes 3 cores per day; 30% down time for weather)
Coring equipment and operating crew	$30,000 (10 days at $3,000 per day)	$100,000 (20 days at $5,000 per day)
Contingency funds	$25,000	$25,000
Total cost	$130,000	$335,000
Cost per core	$2.600	$6,700

[a]Costs do not include core analysis and program management.

SOURCE: Office of Technology Assessment, 1987.

applicable to technologies for sampling massive sulfides and cobalt crusts). The representativeness of the sample is very important. A sample is representative if what it contains can be repeatedly obtained at the same site. In this regard, the size of the sample is important. For example, for minerals that occur in low concentrations (e. g., precious metals), a representative sample must be relatively large. A representative sample for concentrated heavy minerals may be much smaller. The depth of sediment that a sampling tool is capable of penetrating also affects the representativeness of the sample.

Undisturbed samples are particularly important for studying the engineering properties and depositional history of a deposit. They are less important for determining the constituents of a deposit.

Other relevant factors affecting sampling performance include: the time required to obtain a sample; the ease of deploying, operating, and retrieving the sampling device in rough seas; the support vessel requirements; and the core storage capability. Sampling tools that can sample quickly, can continue to operate under adverse conditions, and can be deployed from small ships are preferred when the cost of sampling is a significant factor. More often, the solution is a compromise among these factors.

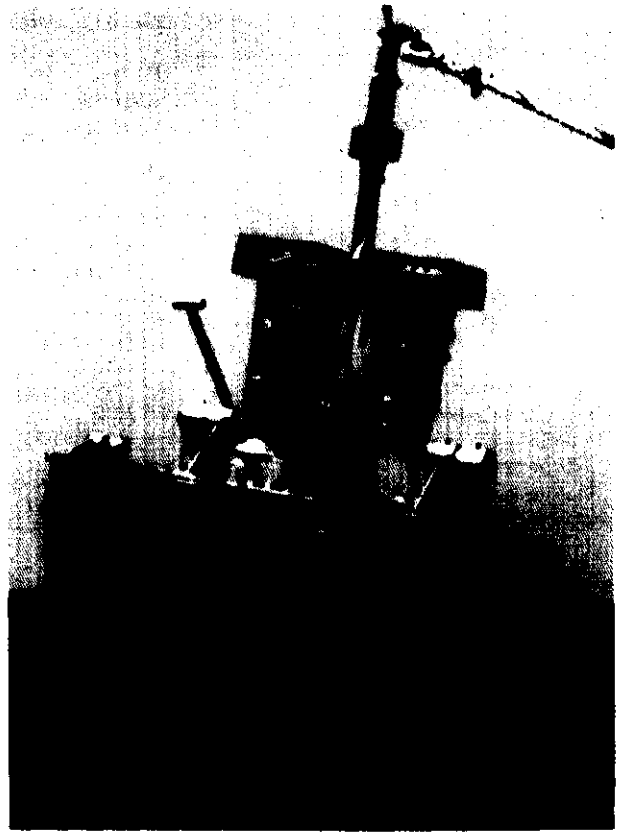
Grab and Drag Sampling.—Grab sampling is a simple and relatively inexpensive way of obtaining a sample of the top few inches of the seafloor. With its mechanical jaws, a grab sampler can take a bite of surficial sediment. However, a sample of surficial sediment is not likely to be representative of the deposit as a whole. Buried minerals may be different from surface minerals, or, even if the same, their abundance may be different. Moreover, the sediments retrieved in a grab sample are disturbed. Some of the finer particles may even escape as the sample is being raised, particularly if stones or debris prohibit the jaws from closing properly.

Notwithstanding their shortcomings, grab samples have helped geologists gain some knowledge of possible heavy mineral concentrations along the Eastern U.S. seaboard. However, grab samples provide limited information and are not appropriate for detailed, quantitative sampling of a mineral occurrence. Drag sampling is similar to grab sampling in that it is designed to retrieve only samples from the surface. An additional limitation of this type of sampling is that sample material is retrieved all along the drag track and, therefore, sampling is not representative of a specific site.

Coring and Drilling Devices.—For more quantitative sampling, numerous types of coring or drilling technologies have been developed. Impact corers use gravity or some type of explosive mechanism to drive a core barrel a short distance into sediment. Percussion drilling devices penetrate sediment by repeated pile driving action. Vibratory

Photo credits: US. Bureau of Mines, U.S. Geological Survey

Chain bag dredge



Grab dredge

Dredges Used for Sampling the Seafloor

corers use acoustical or mechanical vibrations to penetrate material .81

An example of an impact coring device is the box core. An advantage of this type of sampling system is that it retrieves relatively undisturbed cores. A disadvantage is that a box corer is capable of sampling only the top few feet of an unconsolidated deposit. It is rarely used in sand because penetration requires additional vibratory or percussive action.

Well-known percussion drilling devices include the Becker Hammer Drill and the Amdril series of drills. The Becker drill penetrates sediment using a diesel-powered hammer that strikes a drill pipe 91 times per minute. It also uses reverse circulation, meaning that air and/or water is pumped down the annulus between the inner and outer drill pipes, continuously flushing sample cuttings to the surface through the inner pipe.[82] Among the advantages of the Becker drill are: its capability to recover all types of deposits, including gravel, sand, boulders, and clay; its ability to drill in a combined depth of water and sediments up to about 150 feet; and its capacity to recover representative samples. However, open water use of the Becker drill is slow and relatively expensive.

The Becker drill is rated by some[83] as one the best existing systems for offshore quantitative sam-

[81] M.S. Barre and W. Lee, *Marine Mining of the Continental Shelf: Legal, Technical and Environmental Considerations* (Cambridge, MA: Ballinger Publishing Co., 1978), p. 70.

[82] Dimock, "An Assessment of Alluvial Sampling Systems, p. 10.
[83] 1 bid., p. 55,

Photo credit: *Bonnie McGregor, U.S. Geological Survey*

The box core retrieves relatively undisturbed cores but only of the first few feet of sediment.

pling of marine placers. It has been widely and reliably used in offshore programs around the world. Other systems may work well but the Becker drill has gained the confidence of investment bankers, who must know the extent and tenor of a deposit with a high degree of accuracy before investing money in development. For developing commercial deposits, it is particularly important that the method used be one with a proven record.

The Amdril, available in several different sizes, is another type of percussion drilling device. Unlike the Becker Hammer Drill, Amdrils are submersible and virtually independent of the support ship's movements. As a result, this drill can operate in much deeper water than the Becker drill. Rather than using the reverse circulation method, an independent pipe supplies air to the casing to raise the drill cuttings. Although the Amdril cannot sample boulders or bedrock, it is capable of sampling gravel (unlike vibratory corers) using an airlift system. One type of Amdril has successfully sampled marine sands and gravels off Great Britain.[84]

A somewhat similar system, the Vibralift, developed by the Mississippi Mineral Resources Institute, has proved successful in sampling a variety of mineral deposits, including heavy minerals in dense and semi-hard material. The Vibralift is basically a counterflush system. It utilizes a dual wall drill pipe driven into the sediment by means of a pneumatic vibrator. Water under pressure is introduced to the annular space of the dual pipe via a hose from a shipboard pump and is jetted into the inner pipe just above the cutting bit. In this way, the core rising in the inner pipe during the sample drive is broken up by the water jets and transported up the pipe through a connecting hose and finally to a shipboard sample processor. Additional lift is obtained by routing exhaust air from the vibrator into the inner pipe. Samples are collected in a dewatering box to minimize the loss of fine material.[85]

Several types of vibratory corers have been developed over the years. Designs vary by length of core obtained (6 to 12 meters), by core diameter (5 to 15 centimeters), by water depth limits of operation (25 to 1,000 meters), by method of penetration (electric, hydraulic, and pneumatic), by portability, etc. Vibratory corers have been widely used for scientific and reconnaissance sampling. This method is probably the best low-cost method for coring sand and gravel deposits. Relatively undisturbed and representative cores can be retrieved in unconsolidated sediments such as most sands, clay, and gravel. However, the effectiveness of vibratory corers decreases in dense, fine, relatively consolidated sands and in stiff clays. Some progress has been reported in sampling dense, fine-grained, heavy mineral placers with a jet bit that does not disturb the core.[86] Vibratory corers will not penetrate boulders or shale. This type of sampling device is less expensive and more portable than the Becker Hammer Drill and is, therefore, probably

** Ibid., p. 31.
[85] R. Woolsey demonstrated at Underwater Mining Institute Conference, Biloxi, MS, November 1986.
[86] Ibid.

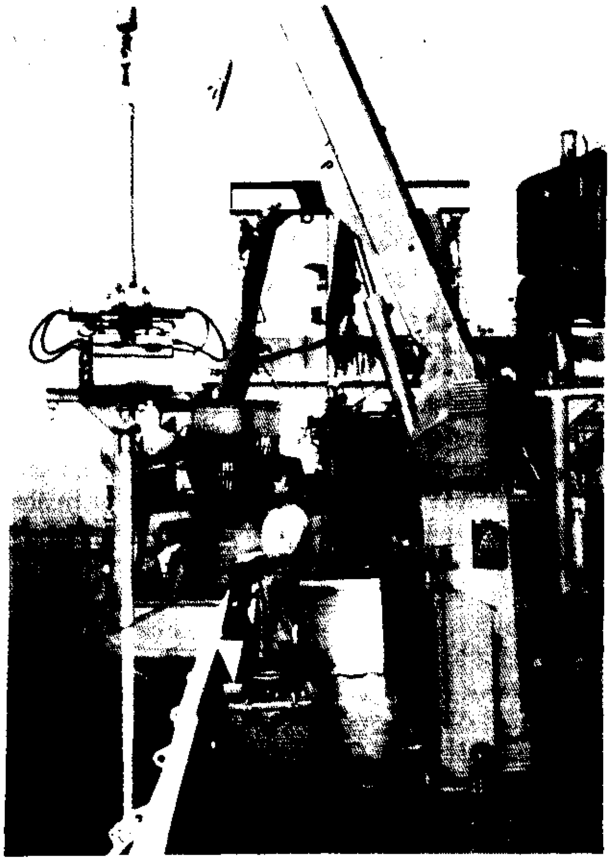


Photo source: P. Johnson, Office of Technology Assessment

Vibracore ready for deployment from side of ship. Vibracores can retrieve relatively undisturbed samples in many types of unconsolidated sediment.

more suitable for reconnaissance work than the Becker drill; however, given limitations in the type of deposit that can be sampled, vibratory corers would be less appropriate for proving certain mine sites.

Vibracore systems, properly designed and operated, have successfully evaluated thin (i.e., less than 12 meters), surficial, unconsolidated deposits of fine-to-coarse-grain material, such as sand and gravel, shell, heavy minerals, and phosphorite. Vibratory corers are inadequate for the more disseminated precious mineral placers such as gold, platinum, and diamonds, due to system limitations in sampling host gravels typically containing cobbles and boulders. Vibratory corers are also useless for any deposit where the thickness of overburden and/or zones of interest exceed the penetration limits of the system.

The costs of offshore sampling vary widely, depending on such factors as water depth, mobilization costs, weather, navigation requirements, and vessel size and availability. One of the most important factors in terms of unit costs per core is the scope of the program. Costs per hole for a small-scale program will be higher than costs per hole for a large-scale program. Table 4-9 shows typical costs of offshore vibracore programs in shallow and deep water. Costs per core are seen to vary between about $2,500 and $7,000.

An alternative or supplementary strategy to taking the large numbers of samples that would be needed to prove a mine site is to employ a small, easily transportable dredge in a pilot mining project. Each situation is unique, but for some cases the dredge may be less expensive and may be better at reducing uncertainty than coring or drilling. Such a program was recently completed with a pilot airlift dredge off the coast of west Africa. Four tons of phosphorite concentrate were recovered for an economic evaluation.[87] Dredging would cause significantly more environmental disruption and may, unlike other sampling methods, require an environmental impact statement.

Crusts

Cobalt-rich ferromanganese crusts were discovered during the 1872-76 expedition of the HMS *Challenger*, but detailed studies have only recently begun, In general, existing coring and other devices developed to sample shallow-water placers are not appropriate for sampling crusts in deep water; therefore, new sampling technologies must be developed. An important consideration in developing new technology is that crusts and underlying substrate are usually consolidated and hard and therefore not as easily penetrated by either dredges or coring devices. Moreover, crusts are found at much greater depths than most unconsolidated deposits. The most desirable crusts are believed to occur between 800 and 2,500 meters water depth; thus, sampling equipment must at least be able to operate as deep as 2,500 meters. Crusts known to date rarely exceed 12 centimeters (5 inches) in thickness; therefore, there is no requirement for long samples.

[87] A. Woolsey and D. Bargeron, "Exploration for Phosphorite in the Offshore Area of the Congo," *Marine Mining, vol. 5, No. 3, 1986, pp. 217-237.*

A few small samples of crust have been retrieved using standard deep-sea dredges. As these dredges are pulled along the bottom, they are able to dislodge chunks of the outcrop or gather already dislodged material; however, techniques and technology for precise, controlled sampling have yet to be developed .88 USGS has identified several needs in quantitative crust sampling and, through its Small Business Innovative Research program, has begun several feasibility studies to develop sampling tools.

As an aid **in selecting sampling sites and in quantifying the volume of crust in a given area, a device that can measure crust thickness is an important** need. Deepsea Ventures, Inc., has completed a conceptual study for such a device for USGS.[89] The goal is to develop a tool to measure crust thickness continuously and in real-time. Conceptually, a very-high-frequency acoustic-reflection profiler able to detect the crust surface and the interface between crust and host rock would be mounted aboard a sled and, with a video camera, towed 20 to 25 centimeters off the seafloor. A continuous signal would be sent to the surface ship via the tow cable. An important design consideration is the very rough terrain in which some cobalt crusts are found. Current design criteria call for the device to operate over relatively smooth areas with less than a 20° slope. Although it will not be able to operate on slopes steeper than 200, it is assumed that, at least initially, any crust mining that does occur will be done in relatively flat areas.

For quantitative sampling, two types of coring devices have been proposed and currently are being designed. Deepsea Ventures has developed concepts for a special sampling tool for taking an undisturbed sample suitable for studying the engineering properties of crust and underlying rock. [90] This corer would be capable of cutting a disc-shaped core 56 centimeters (22 inches) in diameter by 23 centimeters (9 inches) thick. The corer and a video camera would be mounted on a tripod anchored to the sea bottom while the core is being cut. This type of corer would not be useful for detailed mapping of a deposit because the tripod must be lowered, positioned, and raised for each core cut, a process that would take more than 2 hours in 1,500 meters of water.

A second coring device more appropriate for reconnaissance sampling (and perhaps also for proving a mine site) has been designed and built by Analytical Services, Inc. (figure 4-14).[91] The device is a percussion coring sampler that is designed

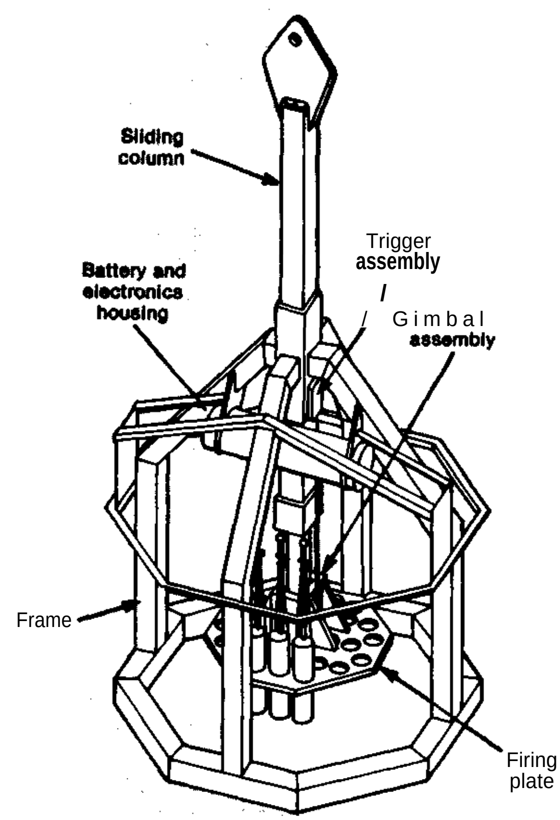
88D S Cronan, H. Kunzendorf, et al. , "Report of the Working Group on Manganese Nodules and Crusts, *Marine Minerals: Advances in Research and Resource Assessment,* P.G. Teleki, et at. (eds.) (Dordrecht, *Holland: 11,* Reidel Publishing Co,, 1987), NATO ASI Series, p. 24,

89W. Siapno, Consultant, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, Wash ington, DC, July 16, 1986.

"'Ibid.

91J. Toth, Analytical Services, Inc., OTA Workshop on Site-Specific Technologies for "Exploring the Exclusive Economic-Zone, Washington, DC, July 16, 1986.

Figure 4-14.—Prototype Crust Sampler



Coring devices such as this, designed to be quick and inexpensive, will be needed for quantitative sampling of crusts

SOURCE: Analytical Services, Inc., Cardiff, CA

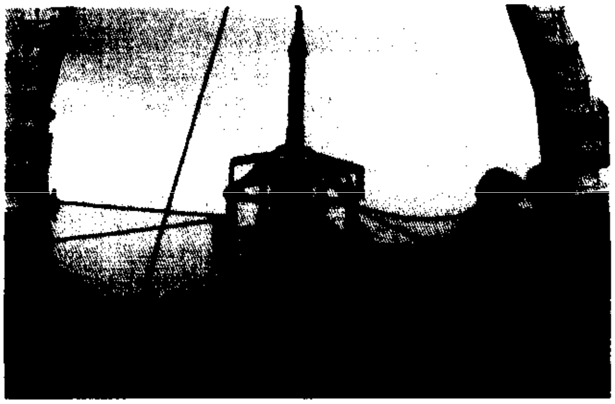


Photo credit: Analytical Services, Inc., Cardiff, CA

Prototype crust sampler about to be deployed from stern of ship.

to collect as many as 30 short cores during each deployment. The speed at which samples can be taken and the cost per sample are important design features—especially for corers that are used in proving a mine site— and this coring operation is designed to be both relatively quick and inexpensive. Sampling is initiated by a bottom-sensing trigger that starts a firing sequence. To fire the "gun," an electric spark ignites the powder. As many as four samples may be taken at any one site, after which the system can be lifted from the seabed, moved to another spot, and lowered again. Cores are expected to be 10 to 12 centimeters long (long enough to sample crust and some substrate in most cases) and 2 centimeters (1 inch) in diameter. The system is designed to operate in water depths of 5000 meters. Eventually, a video system, scanning sonar, and thruster will be incorporated into the system, enabling the sampler to be steered. A second-generation prototype sampler has been built and was tested in 1987.

Large, bulk samples are required for processing and tonnage/grade studies. To meet these needs, the Bureau of Mines is developing a dredge capable of cutting into crust that maybe similar in principle to a commercial mining dredge of the future.[92] Current dredges are not designed to cut into crust and substrate. The experimental dredge would theoretically collect 500 pounds of in situ material in each pass. Problems were encountered in initial testing of the dredge in rough terrain, but the dredge may be redesigned to better cope with rough seafloor features. The continuous bucket line dredge, used in sampling manganese nodules, is also proposed to be adapted for bulk sampling of crusts.

Polymetallic Sulfides

Massive sulfides have a third dimension that must be considered in sampling. At the moment, very little is known about the vertical extent of sulfide deposits, as drilling them has not been very successful. The problem lies in the absence of suitable drills .93 Without a sediment overburden of 100 meters (328 feet) or so it is difficult to confine the drill bit at the start of drilling. The state-of-the-art of massive sulfide sampling is demonstrated by the fact that one of the largest samples collected to date was obtained by ramming a research submersible into a sulfide chimney, knocking the chimney over, and picking up the pieces with the submersible's manipulator arm.[94] Clearly, current bulk and core sampling methods leave something to be desired,

Recent advances have been made in bare-rock drilling. For example, one of the main purposes of Leg 106 of the Ocean Drilling Program (ODP) in December 1985 was to test and evaluate new bare-rock drilling techniques. Drilling from the ODP's 143 meter (470 foot) drill ship *JOIDES Resolution* took place in the Mid-Atlantic Ridge Rift Valley some 2,200 kilometers (1 ,200 nautical miles) southeast of Bermuda. The scientists and engineers of Leg 106 were partly successful in drilling several holes using such innovative techniques as a hard-rock guide base to confine the drill bit during initial ' 'spud-in, a low-light television camera for imaging the seafloor and for monitoring drilling operations, and new downhole drilling and coring motors. The first hole took 25 days to penetrate 33.3 meters (1 10 feet) of rock below the seafloor, while recovering about 23 percent of the core material .[95]

[92] R Willard, Bureau of Mines, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, Washington, DC, July 16, 1986.

[93] J. M. Edmond, F.P. Agterberg, et al., "Report of the Working Group on Marine Sulfides," *Marine Minerals: Advances in Research and Resource Assessment*, P.G. Teleki, et al. (eds.) (Dordrecht, Holland: D. Reidel Publishing Co., 1987), NATO ASI Series, p. 36.

[94] P. Hale, Offshore Minerals Section, Energy, Mines, and Resources Canada, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, Washington, DC, July 16, 1986.

[95] R. S. Detrick, "Mid-Atlantic Bare-Rock Drilling and Hydrothermal Vents, Nature, vol. 321, May 1986, pp. 14-15.

Although improvements in drilling rates and core recovery are needed, the techniques demonstrated during Leg 106 open up new possibilities for drilling into massive sulfides.

In 1989, the *JOIDES Resolution* is tentatively scheduled to visit the Juan de Fuca Ridge, thus providing an opportunity to obtain a few cores from massive sulfide deposits. However, the *JOIDES Resolution* is a large, specially designed drill ship. Its size is governed, in part, by requirements for handling and storing drilling pipe. Because operating the *JOIDES Resolution is* expensive, it is **not** economically advantageous for inexpensive exploration sampling of massive sulfides in extensive areas.

An alternative and relatively less expensive approach to using a large and expensive drill ship for hard-rock sampling is to use a remotely operated submersible drill which is lowered by cable from a surface vessel to the seafloor.[96] In addition to lower cost, the advantages to using this type of drill are the isolation of the coring operation from sea-state-induced ship motions and reduced station-keeping requirements. Maintaining contact with a remotely operated drill while it is drilling remains difficult; if the umbilical is jerked during the drilling operation, the drill can easily jam. Several remotely operated drills have been conceived and/or built, as described below.

The drill developed by the Bedford Institution of Oceanography in Canada has probably had the most experience coring sulfides, although the performance of the drill to date has not met its design specifications. The Bedford drill is electrically powered from the surface and is designed to operate in over 3,500 meters of water. The drill can be deployed in winds of 25 to 30 knots and in currents up to 3 knots. It is designed to cut a core 6 meters long (extendable another 2.5 meters) with a diameter of 2.5 centimeters. A commercial version of this drill, made by NORDCO of St. John's, Newfoundland, is now available and has been sold to Australia, India, and Norway.[97]

Nine cores drilled through basalt were obtained with the Bedford drill in 1983 on the Juan de Fuca Ridge, but the total core length retrieved was only 0.7 meter.[98] Obtaining long cores has been difficult. Drillers have found that competent, unfractured rocks, such as metamorphic or intrusive types, yielded the longest cores, while young, glassy, highly fractured basalts were difficult to sample.[99] The massive sulfides themselves are easier to drill than fractured basalts.

Since 1983, the performance of the Bedford drill has improved. Recently, two cores, each about 1 meter long, were retrieved in gabbro. Drilling took place at the Kane Fracture Zone. Several foot-long cores containing sulfides also were taken from the Endeavor Segment of the Juan de Fuca Ridge. Mechanically, the drill has not been changed much, but electronics and control systems are better. The experience gained thus far suggests that it is essential to do preliminary reconnaissance work before emplacing the drill. During emplacement, a video camera attached to the drill frame also has proved helpful, as it lets drillers locate a stable position for the drill.

Several other remotely controlled drills have been designed and/or built. In the early 1970s, Woods Hole Oceanographic Institution built a rock drill designed to recover a 1 meter long, 2 centimeter diameter rock core from water depths as much as 4,000 meters. The drill was originally designed to be deployed from the research submersible *Alvin* but was later reconfigured to be deployed from a surface ship. It has not been used extensively.[100] A Japanese firm, Koken Boring & Machine Co., has built a remote battery-powered drill and used it successfully in 500 meters of water. NORDCO has recently developed a sampling system, that, depending on its configuration, can be used to sample either sediment or rock. This system was used in October 1985 to recover eight cores in 800 meters of water off Baffin Island.[101] Finally, design of a

[96] R. petters and M. Williamson, "Design for a Deep-Ocean Rock Core Drill," *Marine Mining, vol.* 5, *No. 3, 1986,* p. 322.

[97] P.J.C. Ryall, "Remote Drilling Technology, *Journal of Marine Mining,* in press, 1986.

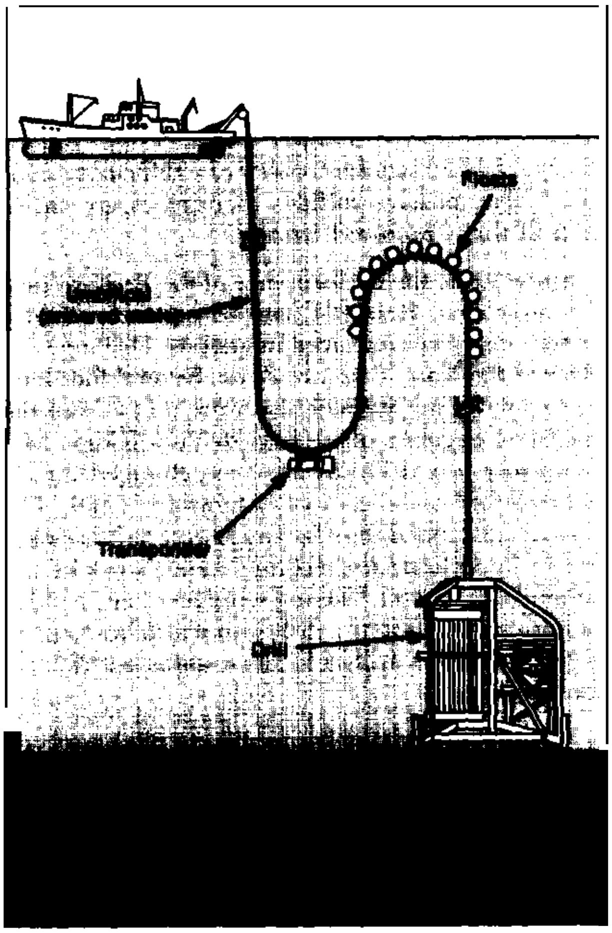
[98] Hale Offshore Miner& Section, Energy, Mines, and Resources Canada, OTA Workshop on Site-Specific Technologies for Exploring the Exclusive Economic Zone, July 1986.

[99] Ryall, "Remote Drilling Technology."

[100] R E Davis D, L. Williams, and R. P. Von Herzen, "ARPA Rock Drill Report," Woods Hole Oceanographic Institution, Technical Report 75-28, June 1975.

[101] Ryan, "Remote Drilling Technology."

Figure 4=15.-Conceptual Design for Deep Ocean Rock Coring Drill



An alternative and less expensive approach to using a large and expensive drill ship for hard rock sampling is to use-a remotely operated submersible drill which is lowered by cable from a surface vessel to the seafloor. (Not to scale).

SOURCES: Williamson & Associates, Inc., and Sound Ocean Systems, Inc.

rock corer was recently started by Sound Ocean Systems & Williamson and Associates (figure 4-15).[102] This corer has not been built, but in concept it is similar to the Bedford drill. A major difference is that it is designed to core continuously to a depth of 53 meters (175 feet) (by adding core barrels from a storage magazine). Alternatively, it can be configured to recover 40 1.5-meter cores in a single deployment. A workable system for obtaining cores longer than 1 meter would be a significant advancement. Both ODP and Bedford drillers have experienced jamming beyond the first few meters and have not been able to obtain longer cores.

Very little sampling of sediment-hosted sulfides (e.g., in the Escanaba Trough off the coast of northern California) has been attempted yet. Today's percussion and vibratory devices rated for deep water use probably will be suitable for shallow sampling of sediment hosted sulfides but not for deeper drilling. Additional problems may occur if the water temperature is above 250 'C. Hot water could cause a good core to turn to homogenized muck as a sample is retrieved. Current technology also is not capable of doing downhole sampling (e. g., using a temperature probe) if the temperature is above 250 ºC. If the water temperature is above 350 °C, embrittlement of the drill string could occur.

[102]Petters and Williamson, "Design for Deep-Ocean Rock Core Drill. "

NAVIGATION CONCERNS

Technology for navigation and positioning is essential in all marine charting and exploration work. The accuracy required varies somewhat depending on the purpose, but, for most purposes, present technology for navigating and for positioning a ship on the surface is considered adequate. Most seafloor exploration can be done quite well with local systems with internal uncertainties on the order of 10 meters and uncertainties relative to global coordinates of a kilometer or so. Use of a navigation system that can position a ship within 1 kilometer of a target would enable a ship to return to the immediate vicinity of a survey area or mine site, for example. Use of a system that could reliably position one within 10 meters relative to local coordinates (established, for example, by transponders placed on the seafloor) would enable one to return to within visual range to photograph or take samples.[103]

Gravity surveys and seismic reflection surveys do present demanding navigational requirements. For detailed gravity surveys, the velocity of the measuring instrument must be known with uncertainties less than 0.05 meter/second. For seismic work, the quality of the data is directly related to the positioning accuracy of the sequence of shots and the streamer hydrophores. Three-dimensional seismic surveys for exploration geophysics require positioning precision on the order of 10 centimeters over a survey area of about 100 square kilometers.[104] In some instances (e. g,, determining relative motion of oceanic plates) accuracy on the order of 1 centimeter is important, but exploration technologies generally do not require this high degree of precision.

Precise positioning and tracking of remote systems, such as towed "fish' or ROVs, is also considered challenging. Positioning is usually done by acoustic rather than electromagnetic systems. Long baseline systems employ three or more fixed-bottom or structure-mounted reference points (e. g., acoustic transponders), while short baseline systems employ three or more ship-mounted transducers that receive an acoustic pulse from a subsea acoustic source.[105]

Accurate marine charting requires precise navigational control relative to global coordinates. Although requirements are stringent, the state-of-the-art is sufficient for producing high-quality bathymetric charts. The National Ocean Survey (NOS) has established a ' 'circular error of position" standard of 50 meters (164 feet) or better (in compliance with international standards for charting). This is about the average for survey ships operating beyond the range at which navigation technologies can be frequently calibrated. Accuracies of 5 to 10 meters are typical with calibrated equipment.[106]

NOS, for example, uses ARGO and Raydist systems for charting work within about 120 miles of the coast, where these systems may achieve horizontal position accuracies of 5 to 10 meters. They are cumbersome to use, however, because they require special onshore stations to be set up and must be calibrated by a more precise system, such as a line-of-sight system like Mini-Ranger.[107] Beyond about 120 miles of the coast, these systems are unable to reliably meet NOAA's 50-meter standard. Far offshore, only the Global Positioning System (GPS) is capable of meeting the desired accuracy for charting.

LORAN-C is a commonly used ground-based navigation system. LORAN-C coverage is available within most of the U.S. EEZ, and it is accurate relative to global coordinates to within 460 meters. Users who want to return to a site whose coordinates have been measured with LORAN-C can expect to return to within 18 to 90 meters (60 to 295 feet) of the site using LORAN-C navigation; 18 to 90 meters is thus the system's repeatable accuracy. LORAN-C is expected to be phased out once the GPS is fully operational. However, this is not expected to occur before 2000. Once GPS is fully operational, plans call for a 15-year transition period during which both LORAN-C and GPS will be available. A satellite system available for civilian use is TRANSIT. This system is often used to correct for certain types errors generated by LORAN-C .

GPS is a satellite navigation system intended for worldwide, continuous coverage. When fully deployed, the system will consist of 18 satellites and three orbiting spares. Only six R&D satellites are operating now, and, due to the interruption in the space shuttle launch schedule, deployment of the operational satellites has been delayed about 2 years. The system is now scheduled to be fully deployed by 1991. Some of the current R&D satellites may also be used in the operational system. Costs to use the GPS are expected to be less than costs to use current systems.

GPS is designed for two levels of accuracy. The Precise Positioning Service, limited to the military and to users with special permits (NOS, for in-

101 National Research Council, *Seafloor Referenced Positioning: Needs and Opportunities* (Washington, DC: National Academy Press, 1983), p. 6.

104 Ibid. , pp 8-10.

105 Frank Busby, *Undersea Vehicles Directory—1985* (Arlington, VA: Busby Associates, Inc., 1985), pp. 426-430

106 Perry, " Mapping the Exclusive Economic Zone."

107 Ibid., p. 1192

stance), is accurate to 16 meters or better. GPS accuracy to within 10 meters is considered routine. The less precise Standard Positioning Service is primarily for civilian use and is accurate to within about 100 meters. (Use of GPS, as well as LORAN-C and other systems in the differential mode—in which a ground receiver at a known location is used to check signals and measure range errors, allows higher accuracies to be achieved but takes much longer). NOS uses GPS when it can to calibrate the other systems it uses (Raydist and ARGO). GPS is currently available about 4 hours a day; however, it is impractical to go to sea for just the short period in which the ' 'window' is open. Consequently, in the near term, NOS is focusing its survey work on the inner half of the EEZ where Raydist and ARGO can be used.