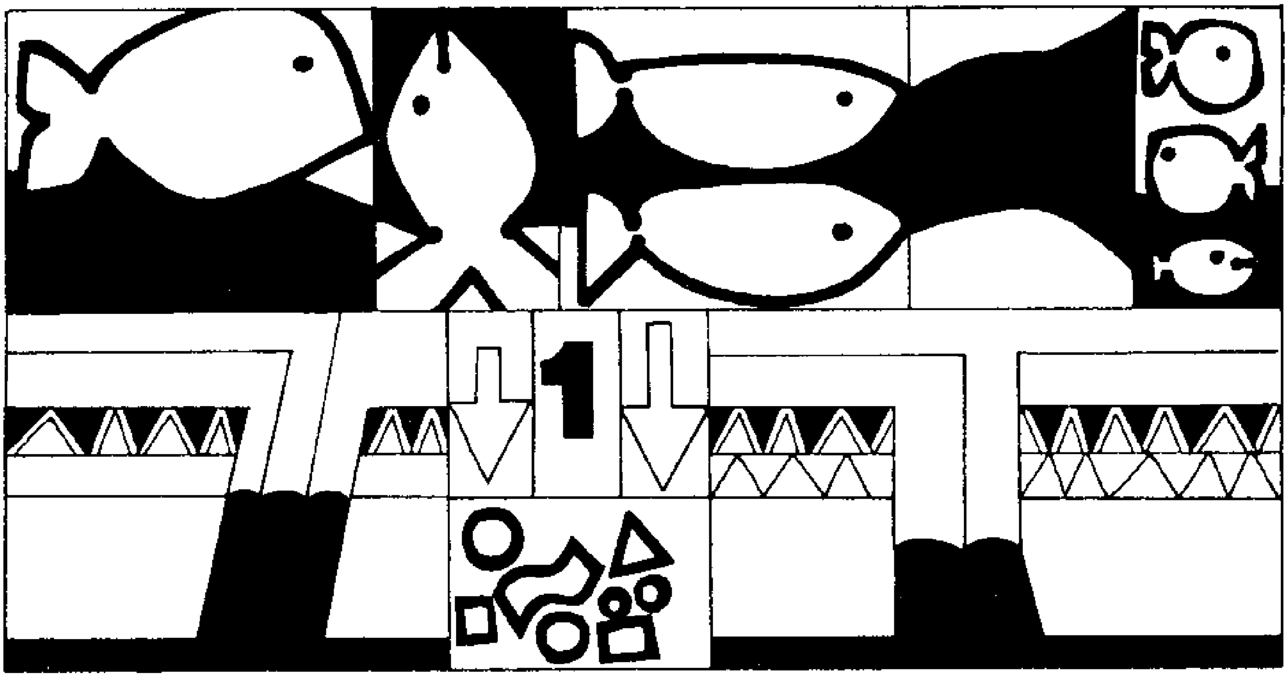
IDENTIFICATION OF TECHNOLOGIC GAPS IN EXPLORATION OF MARINE FERROMANGANESE DEPOSITS



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SEA GRANT ADVISORY REPORT NO. 4
UNIVERSITY OF WISCONSIN

The University of Wisconsin Sea Grant College Program is sponsored by the National Oceanic and Atmospheric Administration's Office of Sea Grant, U.S. Department of Commerce, and by the state of Wisconsin.

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MADISON, WISCONSIN 53706

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This article originally appeared in Inter-university Program of Research on Ferromanganese Deposits of the Ocean Floor, Phase 1 Report, April 1973. The report was sponsored by the Seabed Assessment Program, International Decade of Ocean Exploration, National Science Foundation, Washington, D.C.

SEA GRANT ADVISORY REPORT WIS-SG-73-404

OCTOBER, 1973

IDENTIFICATION OF TECHNOLOGIC GAPS IN EXPLORATION OF MARINE FERROMANGANESE DEPOSITS

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ABSTRACT

Requirements for knowledge and the means of obtaining it are examined with respect to exploration for marine ferromanganese deposits. Needs are shown to exist in the acquisition of data on:

Microtopography

Petrology

Mineralogy

Geochemistry and geodynamics of the deposits and the associated seafloor

Engineering properties including trafficability of the seafloor

Information on currents and water quality throughout the water column but particularly in a narrow seafloor and surface interface zone

Baseline data on the biota throughout the water column but particularly on bottom fauna and the effects of disturbance

Not all of these needs are due to lack of technology, but important gaps are shown to exist in:

Techniques for ecological measurements and prediction

High speed submersible platforms and bottom contact platforms

Permanent navigational and survey controls of the seafloor

Quantitative sampling of unconsolidated surface material for low-cost deposit evaluation

Geotechnical properties measurement and ecological assessment

Sampling of consolidated material on the bottom and in the subbottom

High speed television and camera survey

Acoustic scanning and indicator recognition

In-situ elemental analysis

Integrated data processing systems for shipboard use

Alternative solutions proposed include the delineation and characterization of a mining site, followed by continuous monitoring of an experimental mining operation. Proceeds from the sale of the ore from such a test would partially offset costs of the research program. The test would involve international cooperation, recognition of specific operational needs and encouragement to develop the resource.

INTRODUCTION AND BACKGROUND

A workshop on sea bed deposits of manganese nodules was convened at Columbia University in January, 1972, under the auspices of the United States International Decade of Ocean Exploration for the purpose of investigating the need for government funded research on marine ferromanganese deposits. The interest of participants from university, government and industrial organizations indicated a genuine need for a strong coordinated research program which would fall within the objectives of IDOE. Outline proposals were submitted by participants at the workshop for consideration at that time and following acceptance of the title proposal by the National Science Foundation, this research report has been prepared by J. Robert Moore of the University of Wisconsin, Marine Studies Center, and by Michael J. Cruickshank of the National Oceanic and Atmospheric Administration, Marine Minerals Technology Center.

The objective of the study was to identify and rank research needs in technology which are and will be required in support of IDOE goals with regard to sea bed deposits of metalliferous nodules.

It might be well here to review the six goals proposed by the Vice President (in 1969) in charging the National Science Foundation with responsibility for the United States Program for IDOE. Couched in specific terms relative to this particular project they were on an international basis to:

1. Observe the interaction of mining activities for manganese nodules, in order to establish a basis for (a) assessing and predicting man-induced and natural modifications of the character of the oceans; (b) identifying damaging or irreversible effects of mining at sea; and (c) comprehending the interaction of various levels of marine life to permit steps to prevent depletion or extinction of valuable species as a result of exploration and exploitation of manganese nodules;

2. Improve environmental forecasting to help reduce hazard to life and property and permit more efficient use of marine resources — by providing the basis for increased accuracy, timeliness, and geographic precision of environmental forecasts required during exploration and exploitation of manganese nodules;

3. Carry out activities that will promote better management — domestically and internationally — of manganese nodule exploration and exploitation by acquiring needed knowledge of seabed topography, structure, physical and dynamic properties, and resource potential, and to assist industry in planning more detailed investigations;

4. Develop an ocean monitoring system to facilitate prediction of oceanographic and atmospheric conditions in manganese nodule mining areas through design and deployment of oceanographic data buoys and other remote-sensing platforms;

5. Improve worldwide data exchange on manganese nodules through modernizing and standardizing national and international marine data collection, processing and distribution; and

6. Accelerate Decade planning to increase opportunities for international sharing of responsibilities and costs for ocean exploration for manganese nodules and to assure better use of limited exploration capabilities.

Each of these goals requires for its fulfillment a technological base. The identification of technological gaps, then, is the purpose of this study.

Our procedure is to answer first, what it is we are talking about; what are ferromanganese nodules and what is their environment; what does exploration involve in terms of technology?

It would be misleading, perhaps, to suggest that the nodules are the only potential mineral resource in the deepsea environment. Reference is made to other mineral resources and it will be obvious that much of the technology applicable to ferromanganese nodules will be applicable to other deepsea minerals. Technology requirements which are uniquely related to the nodules are apparent. These matters are dealt with in some detail, and then the needs for fulfillment of the IDOE goals in the future are examined. The disparity between future needs and present capabilities comprise the gaps. These are tabulated and then allocated priorities.

An extensive classified bibliography will be provided as a separate volume in this report series. The bibliography goes beyond the confining boundaries of manganese nodules and treats the subject of marine minerals as a whole. In this way, the subject of exploration for manganese nodules will be better placed in perspective, in relation to the whole spectrum of marine minerals exploration and exploitation. Without some knowledge of the exploitation phase, the requirements for exploration may not be fully understood.

The Universal Decimal Classification (UDC), an international system of subject classification is used in this study and in the bibliography.

THE ENVIRONMENT FOR MARINE FERROMANGANESE NODULES

Environment is an all-encompassing concept and can be applied to anything that is considered to have an effect. It may usefully be treated in two parts, the natural environment which is a product of natural forces, and the artificial environment produced by man. The natural environment may be influenced by man's works in positive and negative ways and certain facets of it may be reproduced on a minor scale. However, it is unlikely that man will ever control it and he must learn, therefore, to work within the restraints which it imposes. The artificial environment, being the product of man's whims, efforts and foibles, is more easily manipulated, but, nevertheless, it's restraints, many of them based on human nature, are equally formidable.

In the exploration for deepsea manganese nodules, many environmental factors must be considered and technology must be developed to overcome the imposed restraints. The following discussions are intended to illustrate the wide range of effects which may result from environment and which, therefore, must be considered in the development of any natural resource, including nodules.

The Natural Environment

The natural environment encompasses the land, the sea, the air and all living things. Only in the oceans are these mutually interfaced and the authigenic mineral deposits occurring on the deepsea floor are influenced by each of them. The following discussions, which refer in specific terms to the deepsea ferromanganese deposits, treat separately the geologic, oceanologic, meteorologic, ecologic, and physiologic environments, the last referring to man.

The Geologic Environment

Those elements of the submarine geologic environment, which must obviously be considered in the assessment of a marine minerals venture, such as geography, physiography and mineral distribution, are discussed in the following pages. But other geologic factors may affect operations just as directly. As on land, topography affects climate, and the nature of macro-geomorphology will have strong influences on the movement and dispersion of water masses and their attendant effects on sediment transport, turbidity and chemical activity. Micro-topography will have strong influences on the movement of equipment and machines on the seafloor, and the nature of the bottom will be of prime consideration in the design of structures and moving platforms, the methods of handling of earth materials and the requirement for ground and environmental control. Submarine geology, from the engineering standpoint, is a field somewhat in it's infancy, though the geological nature of the seafloor is one of prime importance to the design of engineering systems in contact with the bottom. Johnson and Heezen (1969) note with regard to submarine cable failures that chafing by bottom currents is found to be a potential danger to a depth of 300 fathoms in certain locales, and continental slopes, especially when seaward of a river, are especially hazardous due to turbidity currents. Inderbitzen (1970) points out that sediment properties of greatest interest are those that affect the bottom material's reaction to stress. Other studies on specific areas have been described (624.13). Few studies are known to have been made on in-place rock properties on the ocean floor, except where coastal engineering works have called for excavations in shallow water (Bruckshaw, 1961) and deep drilling for scientific purposes. Without question the geological environment of the seafloor is as varied as it's terrestrial counterpart, and it's effects on mineral exploration systems will be just as great.

Geographic Regions

The world surface is 30% land and 70% water. It is also a political aggregate of more than 300 countries of widely differing geography and ethnology subjoined by one common body of international waters.

In dealing with resource considerations, every effort should be made to place natural resources within natural boundaries. However, it is not possible to avoid the inclusion of restraints set by arbitrary and political boundaries.

In this study the continental blocks are subdivided into their respective plates according to the now widely accepted theories of plate tectonics, but, within the plates, the divisions are for the most part political (Figure 1). The oceans (Figure 2), with the exception of the area overlying continental shelf and slope, are divided into four major geographic regions. Within these regions, further subdivisions are largely apolitical.

Physiographic Regions and Their Mineral Potential

The marine waters of the world overlie a geological environment as complex and as varied as its terrestrial counterpart. Many workers have classified these regions (Kossina, 1921; Heezen and Menard, 1960; Menard and Smith, 1966; McKelvey et al., 1969; and McKelvey and Wang, 1969), and it appears generally agreed that the seafloor may be divided into at least eight significant provinces (Figure 3). As defined by Menard and Smith (1966), physiographic provinces are regions or groups of features having distinctive topography or bathymetric shape, usually characteristic structure and spatial relations to other provinces. They do not overlap, nor are they superimposed. Thus, the area of a volcano rising from an ocean basin is subtracted from the area of

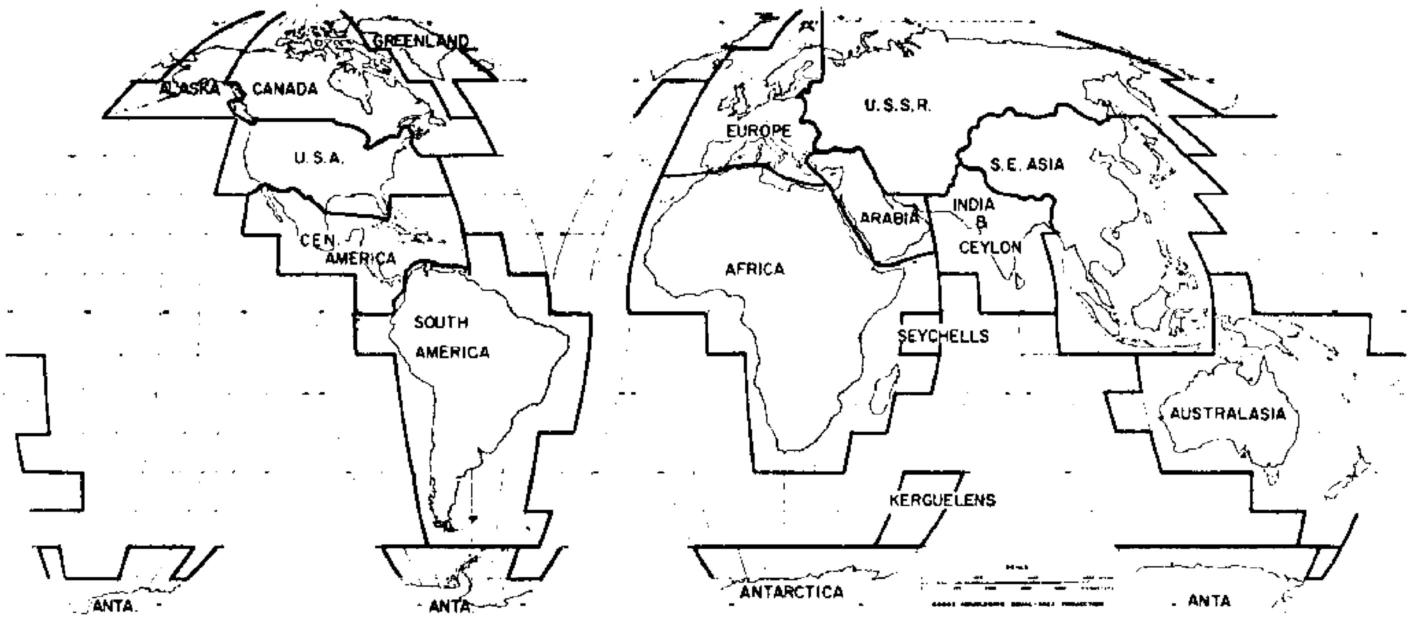


Figure 1. Geopolitical subdivisions of the continental land masses of the world

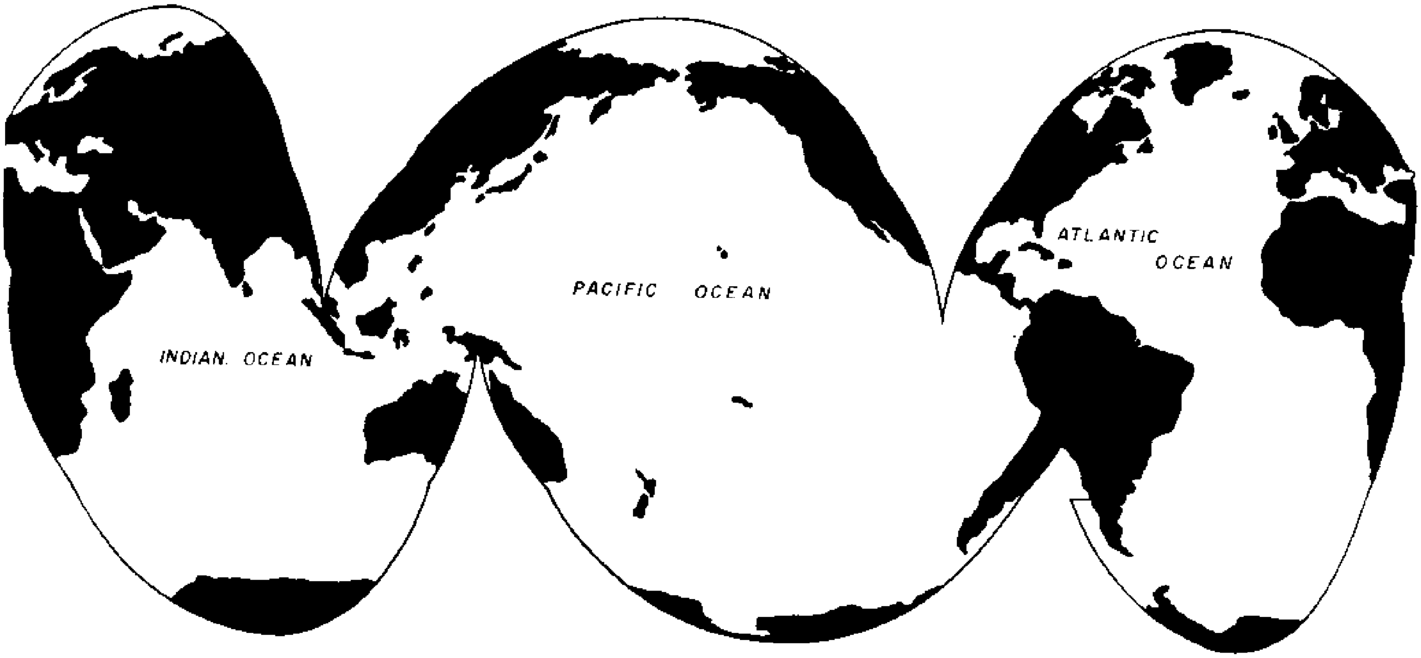


Figure 2. The world oceans

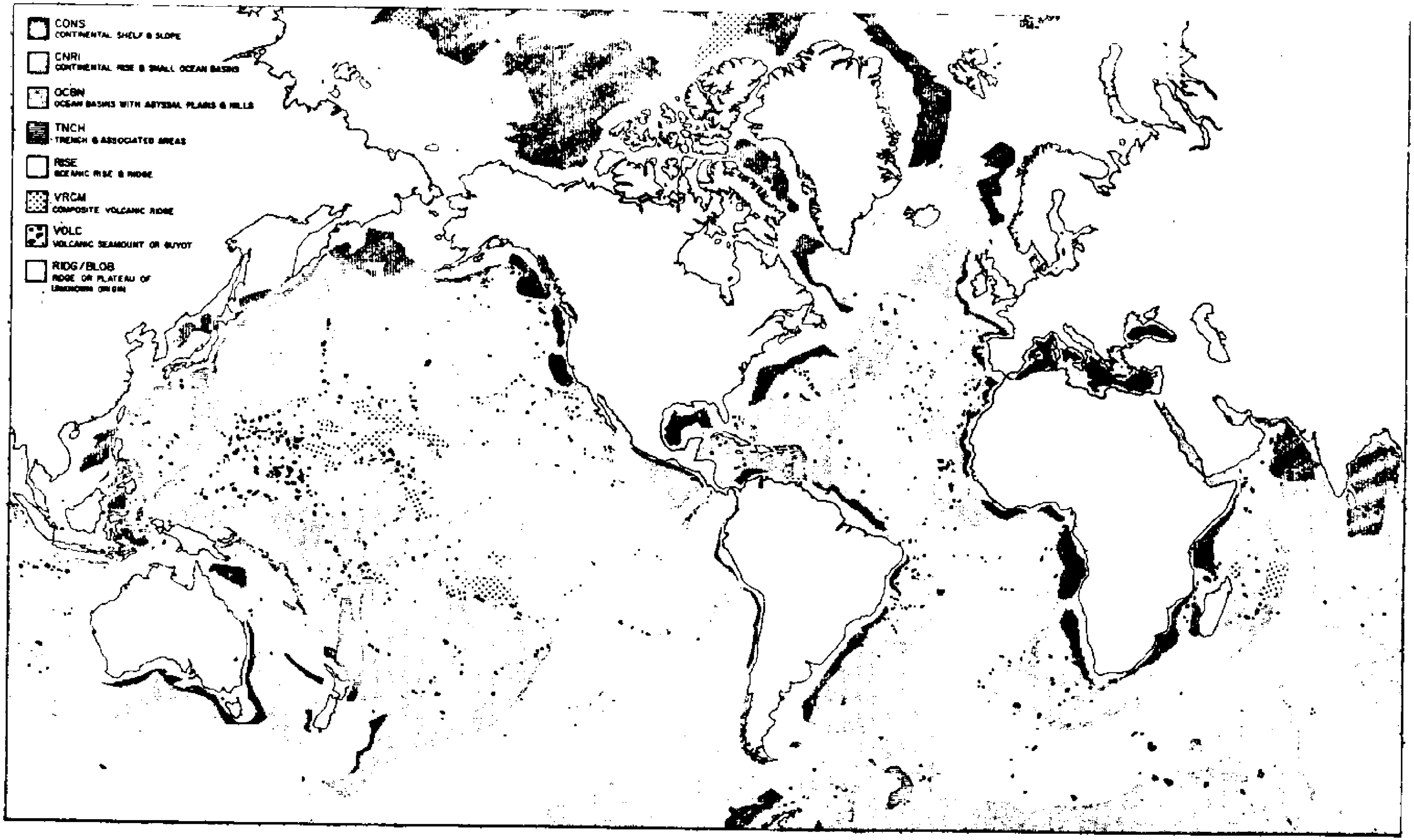
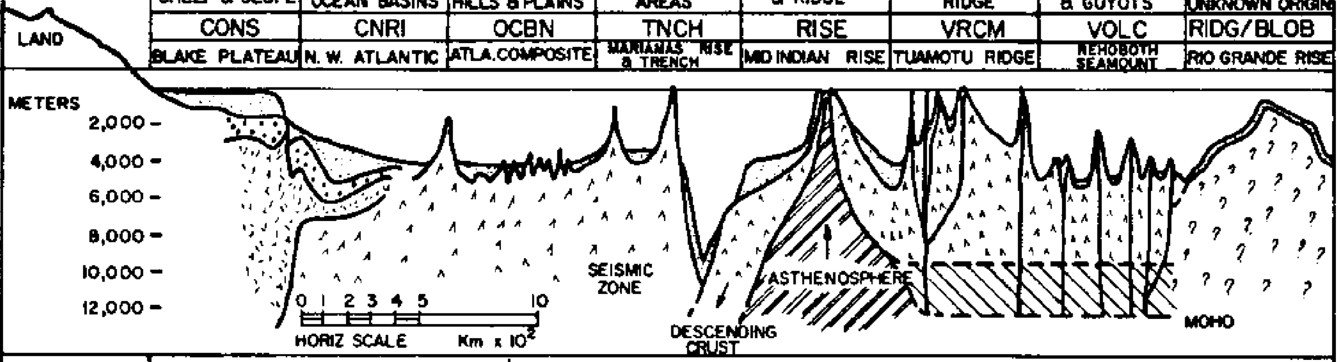


Figure 3. Physiographic provinces of the world's oceans and seas (after McKelvey and Wang, 1969)

PROVINCE		CONTINENTAL SHELF & SLOPE	CONTINENTAL RISE & SMALL OCEAN BASINS	OCEAN BASINS WITH ABYSSAL HILLS & PLAINS	TRENCHES & ASSOCIATED AREAS	OCEANIC RISE & RIDGE	COMPOSITE VOLCANIC RIDGE	VOLCANIC SEDIMENTS & GUYOTS	RIDGES OR PLATEAUX OF UNKNOWN ORIGIN	INDEX
CODE [2,3]		CONS	CNRI	OCBN	TNCH	RISE	VRCM	VOLC	RIDG/BLOB	
LOCATION		BLAKE PLATEAU	N. W. ATLANTIC	ATLA.COMPOSITE	MARIANAS RISE & TRENCH	MID INDIAN RISE	TUAMOTU RIDGE	REHOBOTH SEAMOUNT	RIO GRANDE RISE	░ UNCONSOLIDATED SEDIMENTS & SEDIMENTARY ROCKS ⁘ CONSOLIDATED SEDIMENTS & SEDIMENTARY ROCKS ▦ CONTINENTAL BASEMENT ▵ OCEAN CRUST ▧ PERIDOTITE ZONE ▨ ASTHENOSPHERE
BATHYMETRY [1,2] & STRUCTURAL SECTIONS										
DISTRIBUTION OF MAJOR SEDIMENT FACIES		←TERRIGENOUS SEDIMENTS	→	←PELAGIC SEDIMENTS					→	TOTALS
AREA Km² [2,3]	—	55,421	19,242	151.522	6.070	118.607	2.298	3.435	5.438	362.033
DEPTH RANGE Km	—	0-4.0	1.5-5.0	2.0-7.0	0-1.0	0-6.0	0-7.0	0-6.0	0.2-6.0	0-11.0
DISTRIBUTION % WORLD OCEANS	—	15.3	15.3	41.8	1.7	32.7		3.1		100
% PACIFIC	—	13.1	2.7	43.0	2.9	35.9		2.5		100
% ATLANTIC	—	17.7	8.0	39.3	0.7	32.3		2.0		100
% INDIAN	—	9.1	5.7	49.2	0.3	30.2		5.4		100
% ARCTIC	—	68.2	20.8	0	0	42		68		100

1. STRUCTURE AFTER HEEZEN et al, 1969
2. FROM HYDROGRAPHIC OFFICE, 1961
3. FROM MENARD & SMITH, 1966

Figure 4. Physiographic provinces of the world's oceans and seas showing areas, depth ranges and distributions

the basin. These features are presented in Figure 4. Areas for the continental shelf and slope were recomputed from the original data of Menard and Smith (1966) to represent the adjacent continents rather than the adjacent seas. It was felt that this was a more logical subdivision for the discussion of mineral resources of continental origin. Areas for the oceans and seas are used as presented. The potential for mineral enrichment in each province is dependent on its environmental characteristics. The present knowledge of these characteristics and of associated mineral deposits is in few places sufficient to allow more than gross deductions on the nature and extent of the mineralization, but, where such deductions are relevant to deepsea minerals, they are presented. The following descriptions of eight regions are based largely on work by McKelvey and Wang (1969), McKelvey et al., (1969), and Menard and Smith (1969).

Continental Shelf and Slope

This province represents that part of the continental borderland from the shoreline to the base of the steep continental slope, which is sometimes termed the continental terrace. The major part of the submerged edge of the continental blocks is thus included. Depths of the bottom edge of the slope, as recorded, vary considerably between 1.5 and 5.5 km, depending on the adjacent seaward physiography. Isolated areas of continental blocks such as the Kerguelen Islands and the Seychelles are included with the neighbouring continent. Mineral deposits will, for the most part, approximate those found in equivalent or adjacent terrestrial areas and will include unconsolidated deposits of heavy minerals mostly close inshore or in estuarine or drowned river valleys; sands, gravels, shells and similar nonmetallic deposits laid down under shallow water or subsareal conditions and in local areas; authigenic deposits of phosphorite, and ferromanganese oxides with associated minerals. Consolidated deposits within the bedrock should occur on the average in equal proportion to those underlying terrestrial areas and will be as varied in size and mineral content.

Continental Rise and Small Ocean Basins

Gently sloping, thick layers of sediments eroded from the adjacent continent and overlying the typical oceanic crust appear to constitute the major earth material of this province. Where the edge of the continent forms a closed or partially closed marine basin such as in the Gulf of Mexico or the western Mediterranean, sediment accumulation may be many kilometers thick. The province is possibly favorable for sulfur and potash, in areas underlain by saline deposits, but it is not thought to be favorable for other minerals.

Ocean Basins with Abyssal Plains and Hills

The ocean basins constitute the greatest area of any of the provinces, amounting to 41.8 percent of the ocean floor. The major features of relief are the abyssal plains — very flat and gentle of slope, on the landward side of the basin — and abyssal hills found seaward of the plains, usually in parallel belts. The hills vary in width from 0.1 to 100 km and in elevation up to 1,500 m. The plains are thought to be formed largely by infilling and covering over the hills by terrigenous sediments transported by turbidity currents activated by slumping of the unstable continental slopes. Pelagic sediments which overlie most of the ocean basins are characterized by a rate of deposition (5×10^{-5} to 5×10^{-4} cm/yr for the terrigenous component) which is several orders of magnitude less than that of sediments transported by bottom currents and slow enough to allow an even layer to form over the underlying bottom. Localised areas of pelagic sediments may be found near the coast under favorable conditions (Kuenen, 1950; Emery, 1960; Shepard, 1963; and Menard, 1964) where continental sediments are not deposited. Basement rocks underlying the ocean basins appear to be, for the most part, typical oceanic basalts. Manganese nodules and manganese pavement may be present over large areas. Along bedrock fracture zones and in surficial sediments, the province is considered favorable for metalliferous deposits containing copper, nickel, chromium, cobalt and platinum; where sediment thickness exceeds 1,000 m, sulfur and potash may be found (McKelvey and Wang, 1969).

Trenches and Associated Arcs and Ridges

Deep ocean trenches and any noncontinental systems of adjacent island arcs and ridges are included in this province. Bedrock is mainly basalt and related rocks overlain in places by sediments of variable thickness up to several kilometers, some of which may be consolidated. The bottoms of some trenches are flat plains due to the influx of sediment from the steep slopes. The sediments are conceivably favorable, locally, for metalliferous deposits (McKelvey and Want, 1969), but no exploration has been conducted to establish metal values.

Ocean Rises and Ridges

The oceanic ridge system extends some 40,000 km through the world oceans and supposedly constitutes the upwelling oceanic crust which forms the spreading seafloors. The features have highly variable relief up to 5,000 m, with widths of 300 to 5,000 km. The bedrock is largely basalt and related rock types, which are exposed on the seafloor in many areas and covered only by a thin veneer of sediment elsewhere. Ferromanganese deposits may be present locally as nodules or crust. Although unfavorable for sulfur and potash, the province is conceivably favorable, locally, for metalliferous deposits in bedrock, particularly in fracture zones, and possibly in surficial sediments, particularly where a rift zone lies in a small ocean basin or contains closed depressions (McKelvey and Wang, 1969).

Composite Volcanic Ridges

Volcanic ridges may be formed by overlapping volcanoes, and this type of structure is exemplified in the Hawaiian and Tuamotu Island groups. Bedrock is basalt, generally unfavorable for extensive mineralization, but selective pelagic deposition may form mineral concentrations.

Volcanic Seamounts or Guyots

Seamounts are, by definition, any submerged peaks over 500 m high (Heezen and Menard, 1963). They occur in every physiographic province, either randomly scattered or in linear rows and often in abundance. Heezen and Menard (1963) report 10,000 in the Pacific alone. They are subject to the characteristic mineralization of deepsea sediments, within a wide range of environments, and their potential is only now being recognized by mining companies and international agencies.

Ridges or Plateaux of Unknown Origin

Some elevated areas have not yet been examined sufficiently well to specify their origin; they may be either oceanic or continental. Associated deepsea sediments may contain mineral concentrates, and local areas may be favorable for metalliferous deposits in bedrock.

Mineral Deposits and Their Distribution

There are several ways of classifying the minerals of the sea and its environs, e.g., by mineral composition, elemental content, origin, location, method of concentration, environmental association, or by method of exploitation. Each one may be suited to a particular purpose, but, for natural resource assessment, a combination of methods is both logical and useful.

The first simplistic breakdown assumes three classes of deposit: (1) dissolved minerals concentrated in the sea water and in the biomass, (2) unconsolidated mineral deposits above the bedrock and (3) consolidated deposits within the bedrock. In this study, the deepsea minerals of the latter two classes only are examined. Within any <u>mineral</u> classification there is overlap, with some minerals occurring in more than one type of deposit. Ferromanganese concretions, for example, occur both as unconsolidated nodular deposits and as consolidated crusts.

TABLE 1

CLASSIFICATION OF POTENTIAL MINERAL RESOURCES OF THE DEEPSEAS

	DEEPSEA MINERALS			
	Bathyal 200-2,000 meters		Abyssal 2,000-6,000 meters	
UNCONSOLIDATED (Placer)	Surficial	Substratal	Surficial	Substratal
Terrigenous		Hemipelagics Blue mud Volcanic mud Yellow mud Glacial sediment		Red Clays Kaolinite Quartz
Biogenic		Organic muds Calcareous muds Coral muds		Calcareous ooze Globigerina Pteroped Coccolith Silicious ooze Radiolarian Diatom Phosphorite clay Fish bone debris
Authigenic	Phosphorite Barium sulphate concretions Glauconite K(MgFe)Al Silicate	Metalliferous mud Au/Ag/Cu/Pb/Zn	Fe/Mn Nodules Mn/Co/Cu/Ni	Fe oxides Fe
Diagenic	Phosphorite Dolomite			
Volcanogenic				Zeolite Feldspars
Cosmic				Ni/Fe spherules
CONSOLIDATED (Hard Rock)				
Surficial	Phosphorite Fe/Mn oxides		Fe/MN oxides Dolomite	
Underground	Not classified but potential		Not classified but potential	
Fluid (contained)	Hydrothermal fluids		Hydrothermal fluids	

A number of the deepsea deposits are peculiar to the marine environment and there are indications that totally new forms of mineralization may het be discovered (Blissenbach, 1972).

Known or projected world wide distribution of marine mineral deposits of saline minerals, sulfur, phosphorite, metalliferous muds and ferromanganese nodules are shown in Figure 5.

It is suspected that the deposits are intimately associated both physically and chemically with the underlying seafloor as well as with the superjacent waters.

<u>Unconsolidated Deposits</u>

Unconsolidated deposits are defined as naturally occurring concentrations of mineral grains in the marine environment which are not indurated and which may be a potential mineral resource. They are amenable to dredging.

The classification of unconsolidated mineral-bearing sediments has been admirably accomplished by many authorities from the point of view of the sedimentologist (Twenhofel, 1932), the economic geologist (Lindgren, 1933) or the oceanographer (Sverdrup <u>et al.</u>, 1942; Kuenen, 1960; Arrhenius, 1961; Lisitzin, 1972); and many alternative approaches are available.

The classifications cited are based upon mode of occurrence, origin, physical appearance or chemical composition. Two major divisions are commonly made which cause confusion because of common usage of the same terminology, namely Terrigenous/Hemipelagic/Pelagic or Terrigenous/Authigenic/Biotic. Terrigenous in the first example usually refers to either the location or the source of the sediment, whereas in the second it refers strictly to the source. Red clay is probably the greatest enigma in classification terminology. Named by John Murray from H.M.S. CHALLENGER samples as "red clay," this sediment, nevertheless, may be brick red, brown, or even blue (Sverdrup <u>et al.</u>, 1942). It is a pelagic sediment and yet it is made up of greater than 70% terrigenous material. Using source as the basis for classification, red clay would be a terrigenous sediment in the Terrigenous/Pelagic grouping. Using location, there would be no terrigenous deepsea sediments. The influence of transport on the ultimate sediment type is significant, illustrated by Figure 6 and Table 2. Many other contradictions and confusions occur due to the casual use of terminology and lack of definition.

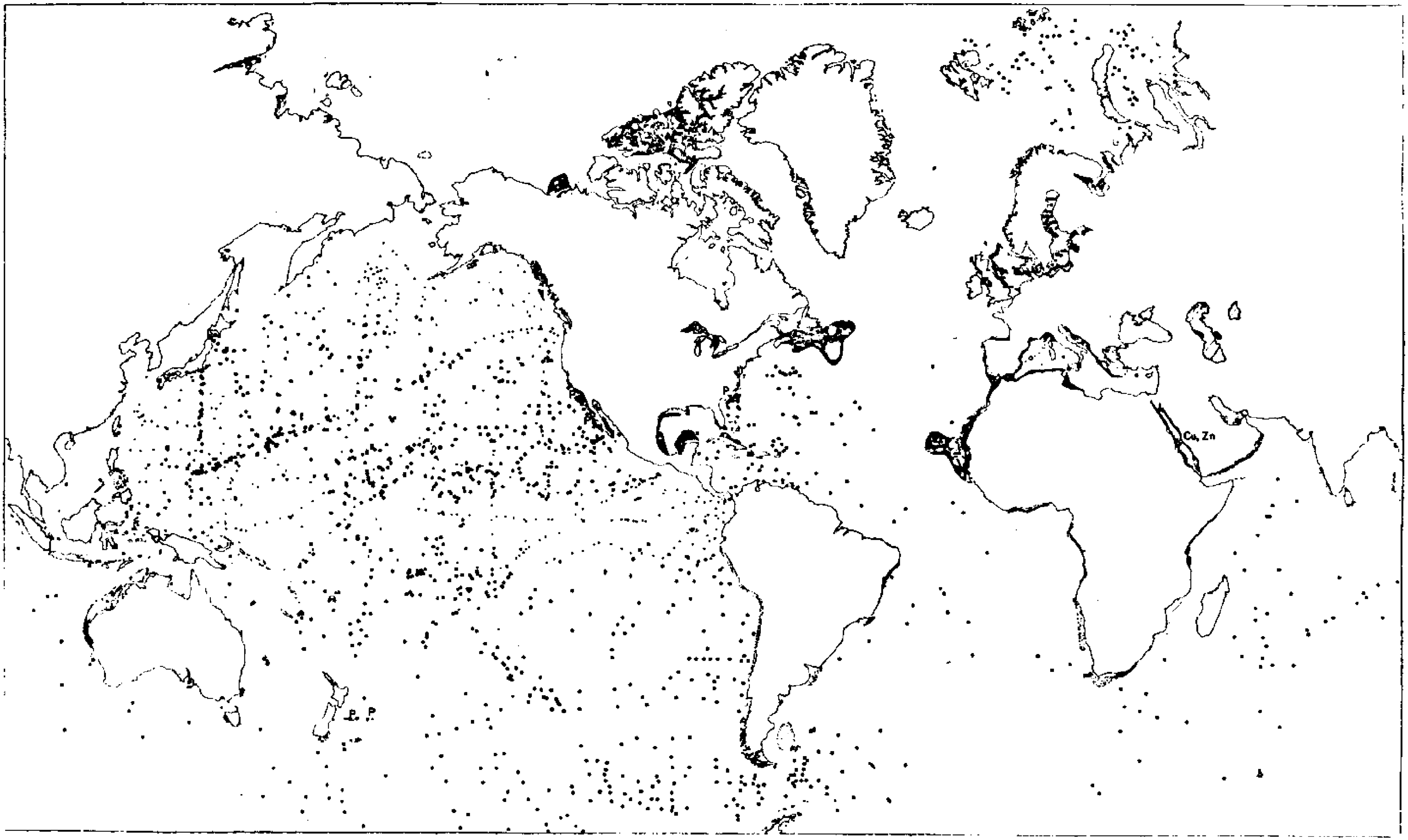


Figure 5. Distribution of known marine deposits of saline minerals, sulphur, phosphate, metalliferous nodules and metalliferous muds (after McKelvey and Wang, 1969). KEY follows this figure.

▨

Offshore

Beds of anhydrite (ruled), in many areas with beds (tinted) and domes or plugs (small circles) of salt within sedimentary basins of marine origin. Locally favorable for potash and magnesium deposits associated with salt and for sulphur (Frasch type) deposits associated with anhydrite in beds and salt-dome caprock. Evaporite basins of marine origin are broadly favorable for accumulation of petroleum, and salt domes provide favorable structures for its entrapment.

■

Offshore
Known potash deposit

●

Offshore
Known sulphur deposit

Frasch type only. Sour natural gas (hydrogen-sulfide rich) and asphalt-base crude oil may be an important source of sulphur in some areas.

☐

Phosphorite

Offshore areas in which deposits are known or which are favorable for their occurrence.

● ○ ◐ ·

Manganese-oxide pavements, crusts or
nodules on the seafloor

Location of nodules recovered by sampling shown by circle with cross; photograph showing more than 25% of bottom covered by nodules indicated by plain circle; photograph showing 25% or less of bottom covered by nodules indicated by half-circle; photograph showing no nodules indicated by dot.

▼ P

Area where offshore exploration is in progress. Principal mineral indicated by letter: P, phosphorite; Cu, copper; Zn, zinc.

♦

Metal-bearing mud

Reported thus far only from the Red Sea, a submarine volcano off Indonesia and, in less concentrated deposits, on the crest of the East Pacific Rise. Possibly present also in other rift or fracture zones, in parts of the deep trenches, in volcanic craters or in other environments in which rising hydrothermal solutions may have been trapped.

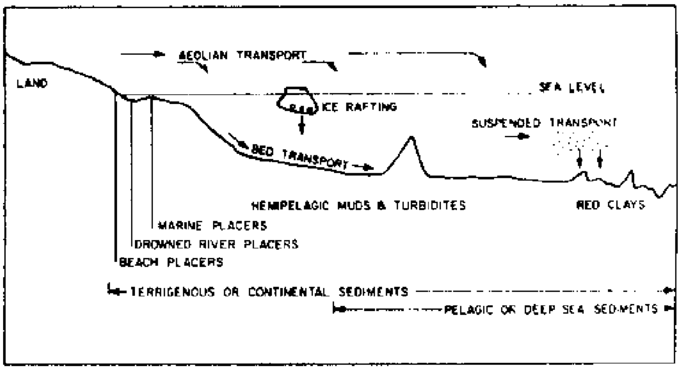


Figure 6. The role of transport mechanisms in the differentiation of terrigenous recent marine sediments

TABLE 2

TRANSPORT TIME FOR COMMON MARINE SEDIMENTS

TYPE	NATURE OF SEDIMENT	TRANSPORT TIME
Placers	An alluvial deposit containing a valuable constituent.	Several seasons
Hemipelagic Muds	A pelagic sediment in bathyal depths in which the terrigenous content is greater than 3% and may be related by analysis to adjacent land mass (after Kuenen 1960).	Fast, may be single event
Turbidites	Outer shelf coarse sediment transported to continental slope or abyssal plain by turbidity current.	Very fast, single event
Red Clays	Deep sea pelagic sediments with maximum deposition rates for the terrigenous component in the range of 5x105x 10^{-4} cm/yr (Arrhenius 1960), contains less than 30% biotic material.	Very slow, 10^2 years

In an earlier study by Cruickshank et al. (1968), it was pointed out that the major change in systems components affecting the technology of mineral exploitation by dredging were increasing water depth and increasing distance from land. For this reason, a classification based on water depth is considered to be most relevant. In this discussion, the deposits are classified initially on the basis of their depositional region and, secondly, on the basis of the origin of their principal mineral constituents. Common names for deposit types or mineral species are used, and, where multiple terminology occurs in the literature, this will be clarified. Table 3 defines the environmental classification used in this study and the genetic subdivisions are presented in Table 4.

TABLE 3
ENVIRONMENTAL CLASSIFICATION OF UNCONSOLIDATED MARINE MINERAL DEPOSITS

CLASSIFICATION	DEFINITION*
Littoral	Occuring in the continental shelf and slope in a depth in range of approximately 0-300 meters (Hedpeth 1957, p. 18). Included are Non Metallics of specific gravity 2-4 and mineral content 15-100%. Heavy minerals of specific gravity 4-8 and mineral content 0.1-15% and Native Elements and Gems of specific gravity 8-20 (except gems, specific gravity 3-3.5) and mineral content less than 1 ppm (Cruickshank 1972).
Bathyal	Occurring largely on the continental shelf and slope or in small ocean basins at depths of between 300-2,000 meters. Included are surficial deposits occurring at the sea water/sea floor interface, and substratal deposits occurring at depth below the sea floor. Synonymous with hemipelagic.
Abyssal	Occurring in water deeper than 2,000 meters and generally from 5,000-6,000 meters. The surficial and substratal distinction also applies. Synonymous with pelagic.

*As with most natural phenomenan, the definition is an approximation.

TABLE 4
GENETIC CLASSIFICATION OF UNCONSOLIDATED MARINE MINERAL DEPOSITS

TYPE	DEFINITION
Terrigenous	Products of mechanical breakdown of continental rock
Biogenic	Products of living organisms
Authigenic	Products of chemical deposition in place
Diagenic	Products of chemical replacement
Volcanogenic	Detrital products from volcanic activity
Cosmic	Meteoritic and other material from outer space

TABLE 5
AREAS OF SEAFLOOR COVERED BY SPECIFIC MARINE SEDIMENTS (AFTER KUENEN, 1960)

SEDIMENT TYPE	AVE. DEPTH (M)	AREA ($KM^2 \times 10^6$)	SEAFLOOR (%)
Littoral	0-200	30	8
Bathyal	200-2,000	73	18
Blue Mud	2,560	5	13
Red & Yellow Mud	1,130	0.5	0.2
Coral Mud	1,350	10	2
Coral Sand	320	10	2
Green Mud	935	4	1
Volcanic Mud	1,880	2	0.5
Abyssal	2,000-12,000	268	74
Red Clay	4,990	102	28
Globigerina Ooze	3,630	126	35
Pteropod Ooze	1,900	2	1
Diatom Ooze	2,690	31	8
Radiolarian Ooze	5,250	7	2

*Depths of individual types (from Clark,1926).

The areas of the seafloor covered by specific marine sediments for each of the three depth environments are listed in Table 5, and their gross distribution throughout the world oceans is illustrated in Figure 7.

Abyssal Deposits

Commonly referred to as pelagic or deepsea deposits, these can also be distinguished as surficial or substratal. Deposits of ferromanganese oxide concretions are by far the best known mineral resource, but, because of the extent and thickness of most of the abyssal sediments, very little is yet known about possible concentrations of other minerals beneath the surface.

Surficial Deposits

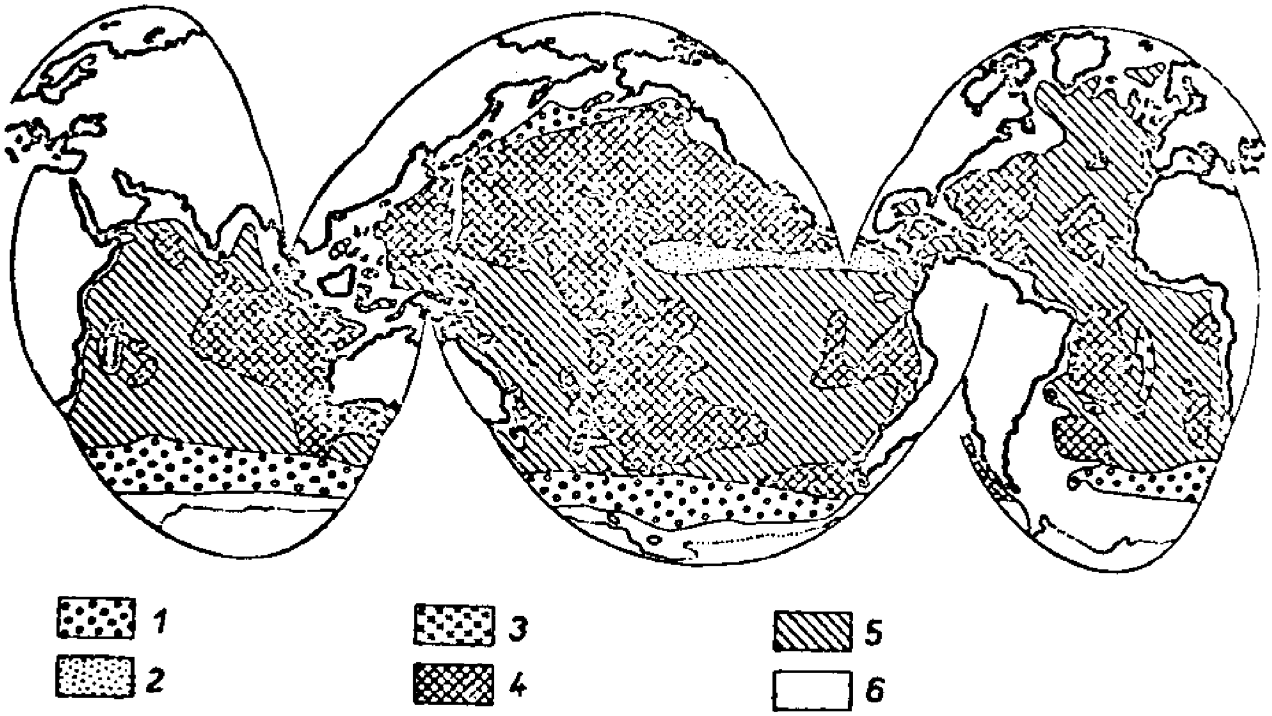
The importance of the deepsea deposits of hydrous ferromanganese oxides or manganese nodules [622*70(26)] with their associated minor element content of cobalt, nickel, copper and other elements has been well established over the past decade. The deposits occur ubiquitously on the seafloor as grains grains, nodules or concretions, slabs, encrustations, replacement of coral and organic debris or as impregnations of porous material. The origin of the nodules is still open to question. Bonatti (1972) cites several theories, including introduction of manganese from land drainage and subsequent precipitation on the seafloor (Pratt and McFarlin, 1966); introduction from submarine volcanism with subsequent precipitation in an oxidizing environment; and dissolution from hemipelagic sediments under reducing conditions and re-precipitation near the oxidizing sediment/water interface. It is quite likely that any one of these mechanisms may predominate, depending on the local environment. A somewhat more controversial theory is that nodule growth and dissolution is controlled by bacterial action and both theoretical and experimental evidence for this has been presented by Ehrlich (1970).

The nodules are widespread, if uneven. In large areas, they may cover 100 percent of the seafloor and, in other areas, be entirely absent. The range of concentration reported varies from 0.05 gm/cm^2 to 3.8 gm/cm^2 in the Pacific (Mero, 1965) and 0.001 gm/cm^2 to 4.3 gm/cm^2 in the Indian Ocean (Bezrukov, 1962). A concentration ratio of 1 gm/cm^2 is equivalent to 10,000 MT/km^2. Ratios of accumulation and age of the nodules have been reported by a number of workers (Goldberg, 1954; Arrhenius, 1964), and a growth rate of 0.1 mm per 1,000 yr has been widely quoted (Mero, 1965) and often disputed (Goodier, 1972).

The mineralogy of the nodules is known to be represented by three major manganese phases, birnessite, 10 Å manganite and 7 Å manganite, and minor Mn; and Fe phases including todorokite $(Mn^{2+}, Mg^{2+}, Ba^{2+}, Ca^{2+}, K^{+}, Na^{+})_2 Mn_5^{4+}O_{12}3H_3O$, ramsdelite, psilomelane and goethite (Bender, 1970).

Analysis of the nodules and their minor constituents differ over a wide range (Table 6), although there appear to be correlations between minor element content and other nodule parameters and environmental factors.

In a review of work by others, Ehrlich (1968) notes that depth correlates directly with cobalt and copper content in the Pacific, lead and titanium in the Atlantic and inversely for lead and strontium in the Pacific, copper and strontium in the Atlantic. Ehrlich, in his review, also notes direct relationships for nickel and copper with manganese concentrations; nickel and copper with each other, both being low in iron poor nodules; titanium and cobalt concentration, and chromium with manganese. Titanium is contained in insoluble silicates, he reviews, cobalt enriched in δ -MnO_2 phases; titanium and calcium substituted for iron in todorokite, and nickel cop-



Regional distribution of individual types of pelagic sediments. 1. Diatom ooze, 2. Radiolarian ooze, 3. Pteropod ooze, 4. Brown (red) clay, 5. Globigerina ooze, 6. Terrigenous deposits and continent. After H. U. Sverdrup *et al.* (1942).

Figure 7. Gross distribution of major sediments in the marine environment (after Kuenen, 1960)

TABLE 6
ANALYSES OF MANGANESE NODULES FROM THE MAJOR OCEANS (FROM BENDER, 1970)

	PACIFIC OCEAN			INDIAN OCEAN			ATLANTIC OCEAN		
	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average
Al_2O_3	138,000	10,000	58,000 (54)	106,000	4,000	68,000	98,000	26,000	54,000 (17)
SiO_2	402,000	13,000	94,000 (54)	371,000	184,000	58,000 (6)	338,000	23,000	140,000 (20)
P	4,300	200	1,400 (44)	---	---	2,600 (1)	280	280	1,690 (5)
Ti	17,000	1,100	6,700 (54)	6,500	2,500	4,200 (6)	9,100	530	44,000 (19)
Mn	530,000	17,000	193,000 (216)	210,000	95,000	140,000 (5)	189,000	101,000	138,000 (16)
Fe	212,000	900	117,000 (216)	209,000	97,000	140,000 (6)	259,000	15,400	164,000 (2)
Co	15,000	10	3,200 (210)	2,900	900	1,900 (6)	9,100	900	3,300 (19)
Ni	24,600	360	6,600 (210)	11,500	1,300	6,300 (6)	5,900	1,600	4,200 (19)
Cu	15,000	300	3,890 (194)	18,100	1,100	5,400 (6)	3,000	300	1,300 (19)
Zn	800	400	470 (54)	650	470	570 (4)	710	350	560 (15)
Mg	24,000	10,000	17,000 (54)	---	---	---	24,000	14,000	17,000 (4)
Ca	44,000	8,000	19,000 (54)	18,000	10,400	14,000 (4)	111,000	4,000	33,000 (16)
Sr	1,600	240	810 (54)	960	640	860 (4)	1,900	580	1,100 (15)
Ba	6,400	800	1,800 (54)	5,000	2,600	3,700 (4)	8,000	1,400	4,900 (15)
Pb	3,600	200	900 (54)	1,500	1,000	1,300 (4)	2,300	930	1,800 (16)
Na	47,000	15,000	26,000 (54)	---	---	---	35,000	14,000	23,000 (4)
K	31,000	3,000	8,000 (54)	---	---	---	9,500	4,900	40,000 (8)

Note: Numbers in parentheses indicate number of analyses.

per, zinc, magnesium, barium, sodium and potassium substituted for divalent manganese in the same phase. Cobalt and lead are preferred in nodules containing only birnessite, and nickel and copper in those containing both birnessite and todorokite. Cerium and lanthanum ratios are independent of mineralogy. The mineralogy shows some dependence on depth (Figure 8), birnessite being almost absent below 3,000 m.

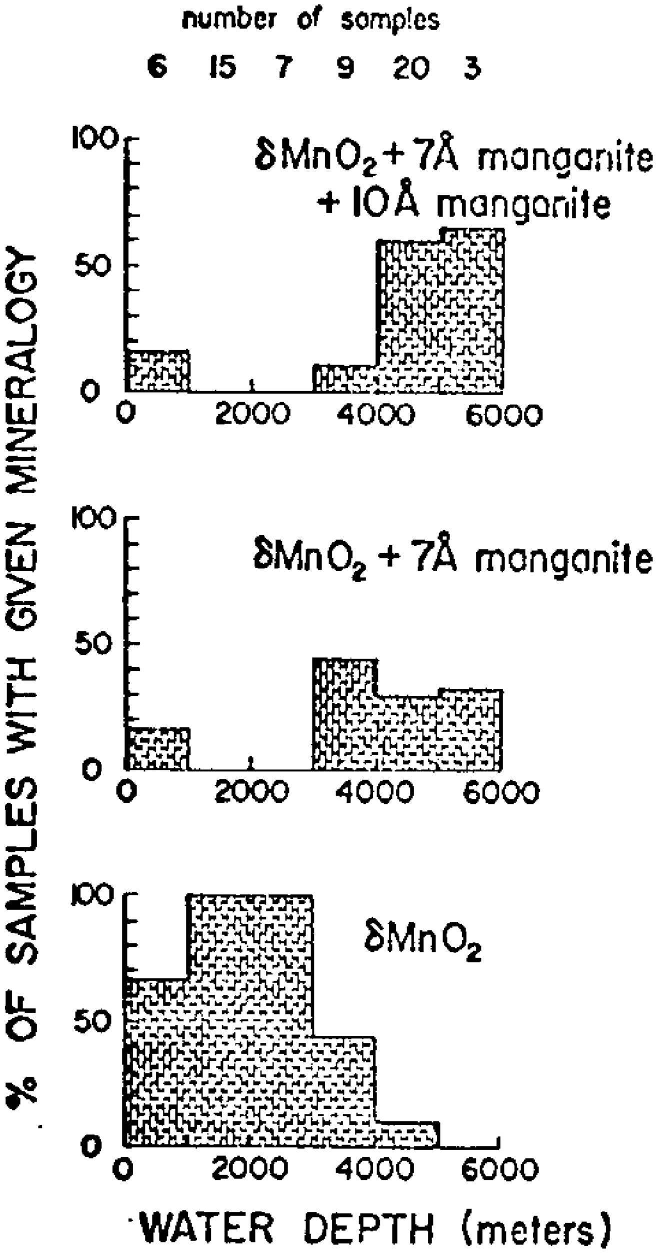


Figure 8. Depth dependence of the mineralogy of manganese nodules (from Bender, 1970, after Barnes)

From a resource standpoint, the depth zones between 3,000 and 6,000 m are indicated to have the most potential (Kauffman, 1972). Mero (1965) presents significant compositional regions for the Pacific (Figure 9), and Horn et al. (1972) indicate strong correlation between minor element content and sediment type.

Few other minerals are found on the surface of the deepseafloor. Occasional volcanic debris, cosmic spherules and rafted material may be obtained, but none apparently of any particular economic interest.

TABLE 7
ANALYSES OF ABYSSAL DEPOSITS (FROM CLARK, 1926)

	A	B	C	D	E	F
Ignition	4.50	7.41	5.30	7.90	1.40	2.00
SiO_2	62.10	56.02	67.92	31.71	1.36	3.05
Al_2O_3	16.06	10.52	.55	11.10	.65	.80
Fe_2O_3	11.83	14.99	.39	7.03	.60	3.06
MnO_2	.55	3.23	----	trace	----	----
CaO	.28	.39	----	.41	----	----
MgO	.50	.25	----	.12	----	----
$CaCO_3$	.92	3.89	19.29	37.51	92.54	82.66
$Ca_3P_2O_6$	.19	1.39	.41	2.80	.90	2.44
$CaSO_4$	.37	.41	.29	.29	.19	.73
$MgCO_3$	2.70	1.50	1.13	1.13	.87	.76
Insoluble*	----	----	4.72	----	1.49	3.90
	100.00	100.00	100.00	100.00	100.00	100.00

A. Red Clay

B. Radiolarian Oooze

C. Diatom Ooze

D. Globigerina Oooze

E. Globigerina Oooze

F. Pteropod Ooze

*Contains silica, alumina, and ferric oxide, not separated.

Substratal Deposits

Basically the deepsea sediments are of three kinds: red clays, calcareous oozes and siliceous oozes (Table 7).

Probably the best known of the deepsea sediments by name are the so-called red clays: Although the composition and color of red clays seem to be somewhat undefined, it is agreed that they are pelagic or deepsea sediments of which the major fraction is terrigenous or continental detritus, and the color ranges generally from reddish through brown to blue (Sverdrup et al., 1942). They are formed in the deep ocean by the settling of suspended particulate matter, mainly hydrated aluminum silicate, from continental erosion. Although the inorganic mineral constituent appears in all deep water sediments, it is masked in oozes by a much larger biogenic fraction. The depositional rate of red clays is extremely slow and associated with them, besides a small organic fraction, are other materials (Table 8) such as magnetite, manganese micronodules, horneblende , palagonite, quartz, plagioclase, mica, zeolites, cosmic spherules, rock fragments, zircon and tourmaline. Lisitzin (1972) classifies them, for this reason, as polygenic.

The composition of red clays is quite variable both in major and minor constituents (Table 9). The major constituent, silica, ranges from 46 to 67 percent and alumina from 11 to 24 percent. The ranges of the trace elements are similar, but Sverdrup et al (1942) postulate a single type of composition rather than a number of varieties. Red clays, as previously noted, are widely distributed over 102.2 x 10^6 km^2 of ocean floor (Table 5).

Biogenic sediments on the deep ocean floor are generally classed as oozes, a term which defines a content of less than 30 percent terrigenous material, usually red clay. Predominant are the calcareous oozes, of which a major constituent organism is the foraminifera Globigerina bulloides and which cover 48

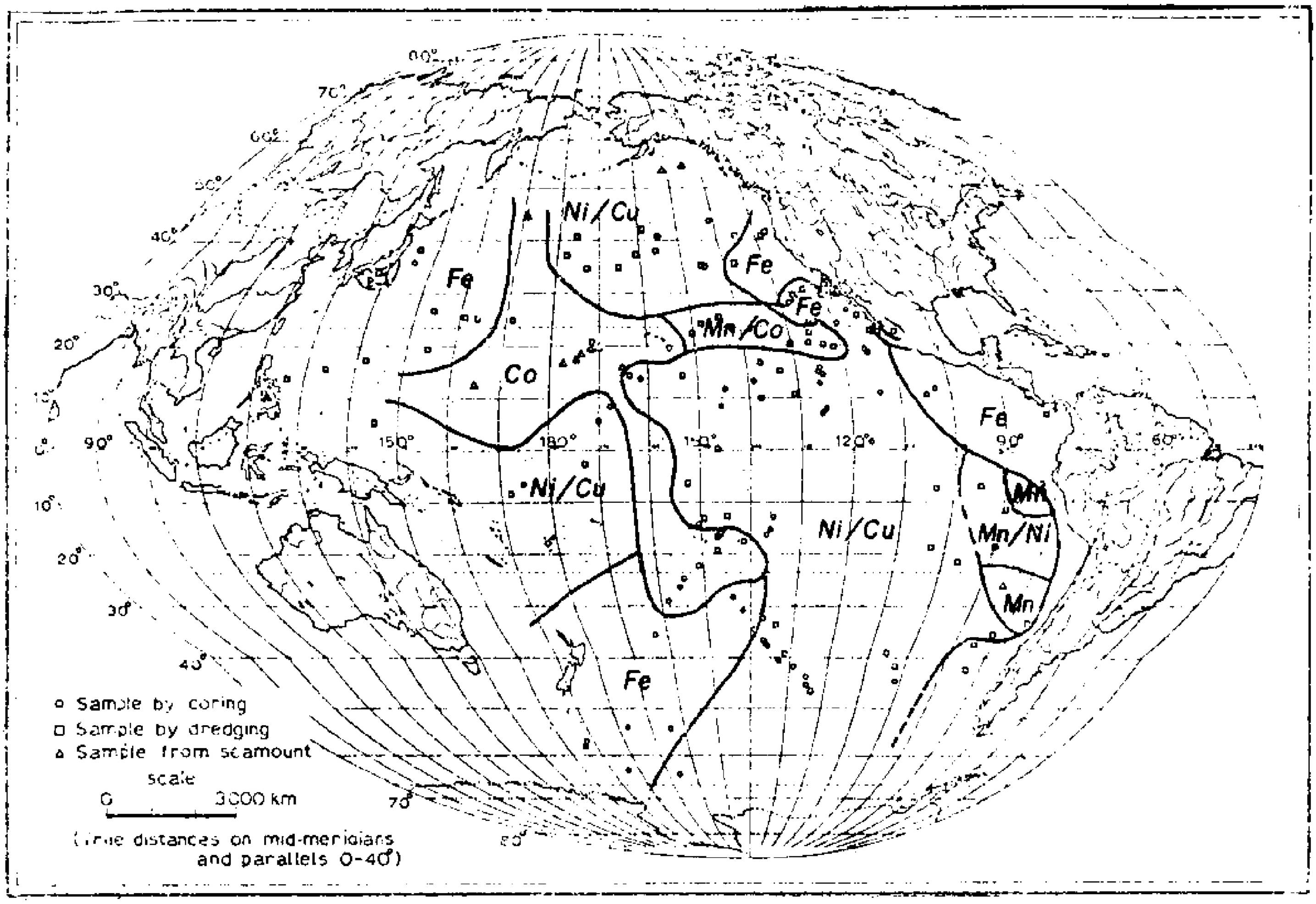


Figure 9. Compositional regions in the Pacific Ocean showing areas of significant elemental concentrations in manganese nodules (after Mero, 1964).

TABLE 8
CONSTITUENTS OF PELAGIC RED CLAY
(AFTER MURRAY AND RENARD, 1891)

CONSTITUENT	WEIGHT PERCENTAGE
Pelagic Foraminifera	4.8
Bottom-living Foraminifera	0.6
Other organisms	1.3
Siliceous organisms	2.4
Minerals	5.6
Fine washings*	85.4
TOTAL	100.1

*Mainly hydrated aluminum-silicates but also containing particles of all other constituents.

percent of the ocean floor. Other planktonic species are coccoliths and pteropods whose organic shell structures contain aragonite providing a possible site for the concentration of heavy metal ions of lead, copper, barium, strontium, titanium and iron from sea water (Arrhenius, 1963). The noncarbonate fraction may contain similar material to the red clay. The carbonate content of deep pelagic sediment is largely controlled by bathymetry. Carbonates are rarely found below the critical depth at which dissolution sharply increases — generally around 6,000 m — although variations in tropical areas do exist. Using a thickness estimated by Revelle of 400 m overlying 128 x 10^6 km^2, Mero (1965) has estimated a body of 10^{16} T of carbonate sediments for all oceans.

Of lesser extent and covering only 14 percent of the ocean floor are the siliceous oozes composed of skeletal structures of opaline silicate secreted by a number of marine organisms including the planktonic diatoms, radiolarians, silicoflagellates and even some benthic sponges. Although much of the opal is dissolved after the death of the organism, the remaining, relatively rich fraction, often forms a significant proportion of the sediment, particularly below areas of high productivity such as divergences or convergences of water masses. Wind is also an important transport medium for quartz in deepsea sediments. Eolian quartz sometimes constitutes 30 percent of equatorial Atlantic sediments

(Arrhenius, 1963). Also, frequently constituent are plagioclase feldspars, probably windblown, and authigenic orthoclase.

Consolidated Deposits

In the deepsea, consolidated deposits of ferromanganese oxides have been reported as encrustations on bedrock. Other potential deposits of iron oxides, phosphates and dolomite have been noted in surface outcroppings and in the reports of the Deep Sea Drilling Program. Deposits of minerals occurring in bedrock and workable by underground methods are likely in association with certain physiographic regions (McKelvey and Wang, 1969), although few examples have yet been reported for the deepsea. Similarly, fluid inclusions of ore-bearing fluids could present a potential source of metals.

Oceanologic Environment

For the purposes of minerals exploration and exploitation at sea, it is logical to subdivide the ocean environment (551.46) into the air/water interface, the water mass and the water/sediment interface.

The Air/Water Interface

All surface effects are considered here, including motion due to waves, evaporative effects and interchange of energy between ocean and atmosphere. The considerations of motion (551.466) would appear to be most important where surface craft are involved, and evaporative effects, of course, are decisive in the consideration of solar-assisted minerals concentration.

The Water Mass

Consideration of the water mass includes all physical (551.463) and chemical(551.464) properties of the water as they relate to any specific mining situation. The depth of water, the magnitude and direction of currents (551.465), temperature, light transmission and acoustic properties will all be of importance in underwater mining operations. Moreover, chemistry of the water involving its composition, salinity, pH, Eh and other factors such as chemical species present are critically important.

The Water/Seafloor Interface

The seafloor is the site for a number of significant interchange processes between the geological environment and the water. Such may take the form of chemical interchange which is most significant in the formation of authigenic minerals, energy interchange through heat flow, as well as water movement exemplified by sediment transport processes both in deep water and along the shore. Many of the problems associated with seafloor interactions with technology are discussed elsewhere in the sections on characterization and the geological environment.

The Meteorological Environment

The weather is critically important in regard to ocean operations. At sea, not only the effect of storms and waves must be taken into account, but, also, the effects of ice, electrical storms, high humidity and the temperature of the living and working environment.

TABLE 9
CHEMICAL COMPOSITION OF RED CLAYS FROM VARIOUS PACIFIC LOCATIONS IN WEIGHT PERCENTAGES (AFTER GOLDBERG AND ARRHENIUS, 1958)

(Latitude) (Longtitude) (Depth m)	S 16°36' W 162°43' 5,125	S 12°46' W 143°33' 4,380	N 9°17' W 124°9' 4,410	N 19°1' W 177°19' 4,774	N 27°38' W 124°26' 4,400	N 35°9' W 157°17' 5,600	N 53°1' W 176°13' 3,660	Composite of 51 samples[1]	Antlantic Ocean Sample[2]
SiO	45.8	47.0	56.0	61.3	57.5	52.8	67.0	54.5	53.3
Al O	20.5	14.7	15.9	19.5	17.8	14.8	11.4	15.9	23.7
Fe	6.2	6.2	4.6	3.5	4.6	5.7	4.0	6.7	5.1
Ti	0.78	0.36	0.38	0.43	0.49	0.44	0.33	0.6	0.6
Mg	1.8	1.9	1.7	2.4	2.4	2.2	2.3	2.0	2.1
Ca	3.3	5.9	2.0	5.8	1.2	2.1	2.9	1.4	3.6
Na	4.5	4.4	3.9	4.1	2.8	2.6	2.5	1.5	2.8
K	2.6	2.2	2.5	3.1	2.2	2.9	1.1	2.4	2.6
Sr	0.005	0.041	0.035	0.061	0.040	0.030	0.036	0.047	0.019
Ba	0.069	0.26	1.2	0.16	0.60	0.11	0.10	0.18	0.45
Mn	1.5	3.0	0.87	1.6	0.46	1.6	0.14	0.7	0.09
Ni	0.028	0.039	0.031	0.083	0.011	0.026	0.003	0.02	0.012
Cu	0.077	0.14	0.20	0.0093	0.066	0.038	0.010	0.019	0.012
Co	0.031	0.024	0.011	0.031	0.009	0.009	0.001	0.01	0.008
Cr	0.006	0.014	0.004	0.005	0.010	0.008	0.006	0.008	0.037
V	0.043	0.020	0.012	0.025	0.031	0.021	0.014	0.024	0.018
Pb	0.017	0.021	0.012	0.008	---	0.010	0.012	0.007	0.008
Mo	0.0065	0.0008	0.0017	0.011	0.037	---	---	---	---
Zr	0.21	0.013	0.012	0.017	0.018	0.023	0.010	---	0.03
Y	0.016	0.039	0.013	0.0038	0.005	0.017	0.002	---	---
Sc	0.0018	0.0044	0.0037	0.0040	0.0022	0.0028	0.0020	---	---

1. Sverdrup *et al.*,1942
2. Correns,1939

TABLE 10
CLIMATOLOGICAL AND OCEANOGRAPHIC DATA FOR AREA
0°-25°N 110°-155°W SUMMARIZED IN TERMS OF ANNUAL
RANGES

CLIMATOLOGY	AVERAGE ANNUAL RANGE
Precipitation	7-52 days/yr.
Surface winds	0-30 KN
Storm Tracks (month)	7, 8, 9, 10
Tropical storms and tyhpoons	None recorded
Visibility	1-5 miles
Total cloud amount .8 clouds	10-60%
Air temperature	68-82°F
Dew point	60-70°F
Air-sea temperature difference	1-4°
OCEANOGRAPHY	
Surface Currents velocity	.2-2 KN
Seas (5 feet)	5-40%
Seas (8 feet)	2-10%
Seas (12 feet)	0-2%
Ice concentrations and extremes	-0-
Sea temperature	70-85°F
Density	1.0210-1.0245
Immersion hypothermia[2]	3 hrs.+

1. Data from Department of Commerce,1961. Climatological and Oceanographic Atlas for Mariners. V. II, North Pacific Ocean: USDC Washington 25 DC.
2. Depending on physical condition of victim.

A typical range of environmental parameters for an area subject to exploration for manganese nodules in the North West Pacific is given in Table 10. Weather and sea state are closely interrelated, and, in consideration of exploratory operations, both must be examined.

In the region under consideration, a mild climate generally prevails. The major environmental characteristics which will influence the operation of a surface vessel are those related to vessel movement, i.e., surface winds, surface currents and seas. These range from 0 to 30 kn, 0.2 to 2 kn and less than 8 ft for 90 percent of the time, respectively. None of these seem likely to present major constraints in sea keeping. As far as safety at sea, rain occurs from 7 to 52 days per year, and visibility is generally from 1 to 5 miles. Again, no major problems seem to prevail. In the equatorial regional (0 to 5°N), however, alternating surface and subsurface currents may present major problems in operations control with a deep submerged dredge string.

The Ecologic Environment

The non-human ecosystem involves all living creatures apart from man (577.4), and disturbance of the environment in any way will have some effect on the associated biomass. One of the greatest concerns which has become centered in the concept of environmental impact is that of pollution. Most simply defined as too much of anything, this term is unfortunately very widely applied to any form of environmental disturbance or impact, particularly if visible, without regard to its true effect on the surrounding biota. The effect may be detrimental, enhancing or insignificant, and, although the literature is not extensive on effects due to minerals operations [628,628(26) Batelle, 1971], some good work has been done on providing guidelines for baseline studies (Ebersole, 1971) and for the preparation of environmental impact statements involving such operations (Sorenson, 1971; Leopold et al., 1971).

The Deepsea Environment (after Madsen, F. J., 1966, Abyssal Zone)

In the deepsea, life conditions are reasonably uniform, except for food sources. The temperature generally is between 0 and 2°C, constant within the geographical areas and with no seasonal variation. Enclosed deepsea basins have higher bottom temperatures and do not possess a true abyssal fauna.

The salinity is 34.8 ± 0.2 percent. The concentrations of phosphate, carbon dioxide and silicate and the alkalinity also vary only slightly. The oxygen content is entirely dependent on the continuous supply of oxygenated water masses, as oxygen can only be added in the upper water layers through the photosyntheses of the pelagic plants and by absorption of air at the surface. Generally, however, the bottom water contains sufficient oxygen for the support of animal life, i.e., on an average 5 to 6 cc/l in the Atlantic and 3.5 to 4 cc/l in the Pacific. Close to the bottom, in some areas, there may be a decrease in oxygen content which is evidently connected with the biological processes, and oxygen is low, of course, in the oxygen minimum layer.

The abyssal zone is normally a calm milieu. The change from primarily terrigenous to pelagic deposits takes place at an approximate depth of 2,000 m which frequently coincides with the upper limit of the abyssal fauna. Down to depths around 4,000 m (in mid and low latitudes), the sediment is primarily ooze. In depths exceeding 4,000 m, most of the calcareous deposits have been dissolved, and the sediment is largely red clay. In other areas, e.g., higher latitudes, siliceous ooze predominates. Slow currents occur along the bottom, varying in velocity up to about 5 cm/sec, and deepsea photographs showing ripple marks indicate that, at least to depths about 3,000 m and around sea mounts, the currents may occasionally increase to 16 cm/sec, occasionally higher.

Ultimately, the food supply for deepsea life is dependent upon the supply of organic matter from land and from the upper water layers where it is basically produced by the photoautotrophic phytoplankton, the first link in the oceanic food chain. When the epipelagic organisms sink, they are utilized by the bathypelagic fauna. However, the remains of plants, animals and excrements which sink below a depth of 2,000 m will reach the bottom having been little influenced by the depths as the abyssopelagic life is very poor. The common assertion that the greater the depth, the less the supply of food is, therefore, true only in connection with distance from land or from areas with a high productivity at the surface. Abyssal heterotrophic bacteria assimilate the organic matter and are considered to constitute the main source of food, either directly or as the second link in a new food chain. Terrigenous deposits which support a much richer animal life than the eupelagic deposits may be transported into the deep ocean by turbidity currents. Plant debris is very abundant on the abyssal bottom in certain tropical areas. The sunken dead bodies of large animals, e.g., whales, form temporary local food supplies and are mentioned as being one explanation for the patchy distribution of some abyssal species.

Animal Life

The environmental conditions are, apart from the pressure, no different from any that can be found in shallower regions, and the abyssal fauna possess few fundamental differences in life processes from the fauna of shallow regions. Characteristics shown by the abyssal animals are correlated with their life in a dark, calm, soft-bottomed environment. The mobile animals have long, slender legs, and the sessile ones are often stalked (which may in part be an adaptation for raising them above the oxygen-poor water layer close to the bottom). Many fishes and crustaceans are blind, and, in some fishes, the pelvic fins are developed as tactile organs.

Life in the abyssal region is concentrated on or close to the bottom. All the major groups of marine invertebrates are represented, in addition to several benthic kinds of fish, porifera, coelenterata, polychaeta, crustacea, echinoderma, mollusca, tunicate and vertebrata.

The abyssal fauna, like the cold water faunas and infaunas of the shallower depths, is composed, to a large extent, of comparatively few widespread species with a relative abundance of individuals. In addition, there are many species, especially the epifauna, which show patchy distributions. The epifauna will also be concentrated on and around the sea mounts where increased currents may expose a firm surface or a coarser grade of bottom.

With increasing depth, the number of suspension feeders (feeding from the suspended detritus) and deposit feeders (feeding on the deposited organic matter) increase in relation to that of carnivores and scavengers. The Porcelanasteridae, a family of mud eaters within the otherwise carnivorous sea stars, are unknown from depths less than 1,000 m. They constitute a fourth of the species of sea stars recorded from 4,000 m and half of those from 6,000 m. The mud-eating holothurians, the Elasipoda, are the all-dominant animals in the abyss, and some of the abyssal fishes are also deposit feeders.

The density of life is very low compared to that of the moderate depths. Expressed in biomass, i.e., quantity of substance in live organisms in g/m^2, life density, even in the richer abyssal regions (the Antarctic and northern Boreal), is no more than 1 percent of that in the richer sublittoral, and some eupelagic deposits may be almost barren (Table 11). Further, productivity may be extremely poor.

TABLE 11
FIGURES FOR BIOMASS IN NORTHWESTERN PACIFIC
(FROM MADSEN, 1966)

	GM/M^2
Coastal zone	1,000-5,000
50-200 m	200
ca. 4,000 m	ca .5
Kuril-Kamchatka Trench	
ca. 6,000 m	1.2
ca. 8,000 m	0.3
Central part of the ocean floor	0.01
Tonga Trench 10,500 m	0.001

Life Cycles

The rate of reproduction seems slow, and a considerable longevity is also postulated for abyssal animals in general. It is yet unknown whether they show seasonal life rhythms, but there are indications that, for the true abyssal species, this is not the case and that reproduction may take place at any time of the year, with only a small number of eggs ripening simultaneously. A nonpelagic development seems to be usual for the true abyssal benthic species and for the majority of those extending into the zone, though some may be expected to have free-swimming larval stages of some duration. Some species possess pelagic larvae, and some of the benthic-abyssopelagic fishes have larvae living in the upper pelagial. How mining might interfere with life cycles, if at all, is unknown.

Deepsea Zonation

The deepsea bathyal and abyssal regions have quite extensive variations of environment (Figure 10). The abyssal zone may be divided into an upper and a lower zone at a depth of about 4,500 m where a change in the composition of the species occurs. A number of the species distributed worldwide belong exclusively to the lower abyss.

Uniform life conditions and the absence of definite topographical barriers account for the wide distribution of many of the endemic forms in the abyss. An almost cosmopolitan distribution seems to be a general rule for species of benthic fishes, anthozoa, echinoderms and tunicates, whereas crustaceans and mollusks show restricted distributions. With respect to the echinoderms, another barrier for the distribution would seem to be the sparse food resources of the mid-Pacific deepsea. The extremely cold water (0°C) of the Antarctic deepsea probably accounts for the special composition of the abyssal fauna there. Three main zoogeographical subdivisions of the abyssal regions may be distinguished: (1) the Atlantic and Indian Oceans, inclusive of the Southwestern Pacific, (2) the East Pacific and (3) the Antarctic deepsea. A more detailed zoogeographical subdivision will, for the greater part, reflect only the zoogeography of the bathyal region.

Numerous species extend from the bathyal into the neighboring abyss and constitute a very considerable part of the actual abyssal fauna. Such species have been called secondary abyssal species or guests since, though able to live in the abyssal habitat, they may be unable to produce a constant series of generations there. It is probable also that many species may be prevented from spreading into the distant oceanic deepsea because of the decreasing food supply. It is believed (Madsen, 1966) the low temperature in the deepsea is a recently acquired condition, and, prior to the late tertiary, temperatures of around 10°C may have been typical.

Interactions in the Ecosystem

There are a great many aspects of ecosystems disturbance that are poorly studied, and it is of prime importance that our knowledge of these matters be increased so that sensible ecological forecasting can be carried out.

Along with the present industrial activity in preparing for dredging of manganese nodules from the deep ocean [622*70(26)], a number of studies have been carried out on the possibilities of environmental degradation (Welling, 1972; Garland and Hagerty, 1972; Turekian, 1972; Rools et al., 1972). Garland lists some typical characteristics of the nodule environment (Table 12). So far, none of the studies suggest that much effect can be anticipated. Other studies, however, have been carried out in coastal (Roby, 1972) and estuarine areas (FWPCA, 1969) with quite different conclusions.

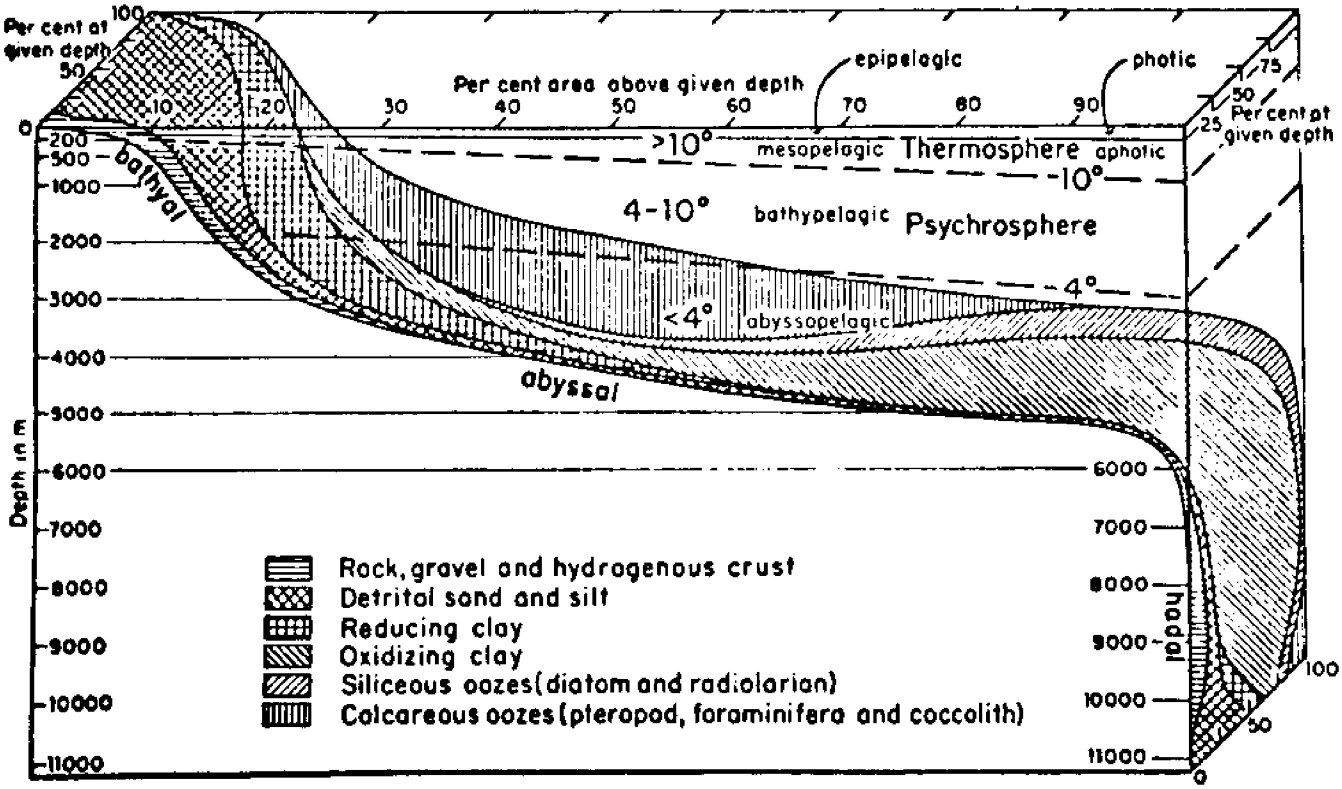


Figure 10. Ecological zonation of the deepsea (from GALATHEA report, 1959)

TABLE 12
TYPICAL CHARACTERISTICS OF DEEP OCEAN NODULE MINING ENVIRONMENT (GARLAND & HAGERTY, 1972)

VARIABLE	VALUE OR CONDITION	
Geographic location	North Central Pacific Ocean	
Distance from land	Greater than 1000 nm (1800 km)	
Water depths	10,000-18,000 ft (3-6,000 m)	
Location of ore	Exposed at sediment/water interface & extending only 1-2 inches below	
	SEA SURFACE	SEA FLOOR
Depth thermocline	50-100 m	---
Temperature	Yearly mean 23-26°C; Aug. 20-28°C; Feb. 18-26°C	0.6-1.4°C constant
Salinity	34-35.5^{o}/oo	34.6^{o}/oo
Oxygen (Eh)	4.5±0.5 ml/l (+430 mv)	Water: 3.5-4.5 ml/l (+430 mv) Sediment: highly oxidized (+400-500 mv)
pH	8.0±0.2	Water: 7.6±0.2 Sediment: 7-8
Sediment type	---	Pelagic "red" caly, low BOD
Primary product'y	Low; 50 $gC/m^2/yr$ compared to 200-600 in productive waters	10-100 mg/m^2
Biomass	Zooplankton only;	10-100 mg/m^2 compared to 1000 in coastal areas
Commercial fisheries	Very low activity (10% of world's catch from all deep ocean areas)	None at present & none foreseen
Nutrient level	Low	Medium to high

In determining interactions in the ecosystems, some critical points should be noted. The balance between trace elements and organisms is delicate. The full involvement of bacterial action with many mineral concentration processes is not known but is thought to be significant for a number of cases such as ferromanganese oxides [622*70(26):567.8], sulphides of copper and other elements [622.775:567.8]. Some environments have a greater significance in the ecosystem than others. Primary productivity, for example, in salt marshes and coral reefs is reported in Table 13 as 2,200 $gm/m^2/yr$, as opposed to deepsea areas where it is only 50 $gm/m^2/yr$. The catastrophic mass mortalities resulting from periodic red tides are thought to be responsible for some mineral concentrations.

The Physiologic Environment

Human restraints are due to the limitations of the human body to adapt to all natural conditions and are mostly concerned with safety and health. To those inexperienced in working in the marine environment, the unforgiving nature of the weather, the water and the waves may not be realized. The ocean is a harsh and hazardous environment for man. It can be adapted to only with care.

During operations at sea, winds, seas and tides become important factors. In heavy weather, safe working loads often cannot be trusted; unexpected strains in rigging occur; operational time is shortened because everything takes a little longer, and work falls behind. Motion sickness is a prevalent and displeasing problem. When conditions are good, there is often a tendency to try and catch up by hurrying and taking short cuts. Safety precautions that would otherwise be observed may be bypassed with resultant risk of accidents.

Commercial ships and offshore structures are required to meet certain construction, manning, navigation, health and safety standards set by international treaty, U.S. laws and regulations and marine insurance underwriters.

Characteristics such as hull form, the mode of operation, styles, propulsion, manning, travel routes and national jurisdiction will dictate what design and safety requirements should be imposed. This will result in considerable variation, and specific re-

TABLE 13

ESTUARINE HABITAT REMOVED BY DREDGING AND FILLING OPERATIONS (FWPCA, 1969)

BIOPHYSICAL REGION	AVAILABLE HABITAT IN 1955 (ACRES)		HABITAT LOST, 1947-1967	
	AREA OF TOTAL MARSH AND WETLAND	AREA OF IMPORTANT WILDLIFE HABITAT	AREA DREDGED AND/OR FILLED	PERCENT OF HABITAT LOST
NORTH ATLANTIC	168,000	167,000	4,000	7.0
MIDDLE ATLANTIC	424,000	424,000	89,000	8.6
CHESAPEAKE BAY	441,000	428,000	3,000	0.5
SOUTH ATLANTIC	1,551,000	797,000	25,000	2.3
CARIBBEAN (FLORIDA ONLY)	469,000	99,000	15,000	7.5
GULF OF MEXICO	6,000,000	3,426,000	167,000	4.8
PACIFIC SOUTHWEST	165,000	162,000	256,000	67.0
PACIFIC NORTHWEST	174,000	98,000	5,000	4.0
ALASKA	INSUFFICIENT DATA		1,100	0.2
PACIFIC ISLANDS	10			
TOTAL	9,392,000	6,175,000	565,100	7.0

References: U.S.D.I., Fish & Wildlife Circular 39, Wetlands of the United States, 1956.
U.S.D.I., Fish & Wildlife Service Data presented in Congressional Hearings, 'Estuarine Areas', House Serial # 90-3.

quirements can only be specified for particular cases; however, the following general areas should be considered:

Structural strength, structural fire protection and access means of escape

Stability and subdivision

Fire protection equipment (portable, semi-portable and fixed)

Lifesaving equipment

Emergency lighting and power systems

Removal of ignition sources and emergency control stations

Internal communications systems

Navigation lights and markings

Emergency shutdown equipment, closure and tightness

The Artificial Environment

Restraints take many forms, and those imposed on resource development by man's own needs are no less real than those imposed by nature.

In the exploration and exploitation of natural resources, including deepsea ferromanganese nodules, the artificial environment may be considered to include economic, political, social, legal and technical restraints. These are each discussed in the following pages on terms of environment relative to deepsea minerals.

Economic Restraints

Money is a tangible quantitative medium of value. Our technologic advancement is based on it, and the economic environment for which money is the standard is built on natural resources. The impact of resource disturbance will be measurable on the economy.

Many recent studies have examined the impact of the contained metals on manganese nodules on the world market [622*70(26):622.013]. As Sorensen and Mead (1969) noted in referring to an offshore phosphorite venture, considering the risk involved from the point of view of both costs and eventual markets, it is not unreasonable to predict that expected net rates of return on investment in marine mining of from 30 to 40 percent will be required to bring the necessary capital on line. This may also be true of manganese nodules. In many cases where the externalities of a marine mining venture are very substantial, it may well be that some different economic approaches must be made. Value or cost is no longer strictly a function of money.

With regard to the world pictures for minerals, some significant trends are becoming apparent as indicated by the following quotations:

> The unmistakable conclusion reflected in the data and commodity summaries is that, as the Nation's needs continue to grow and as per capita consumption of materials in other countries increases at an even faster rate than ours, it becomes increasingly difficult for the United States to fill its ever-growing deficit by imports, even at increasing prices. (National Commission on Materials Policy, 1972)

> In Section 3.8, the supply of natural resources was assumed sufficient to last for 250 years at the 1970 rate of usage. But in Figure 4-1, the rate of usage (not plotted) rises another 50 percent between 1970 and 2000 because of the rising population and the increasing capital investment. Well before natural resources disappear, their shortage depresses the world system because of the natural-resource-extraction multiplier described in Section 3.6 that introduces the more difficult extraction task resulting from depleted and more diffuse stocks of resources. The effect of rising demand and falling supply is to create the dynamic consequences of shortage, not 250 years in the future, but only 30 to 50 years hence. (Forrester, J. W., 1971)

These remarks originate from two quite different but equally informed sources, and it is becoming increasingly obvious that there is little cause for complacency in reviewing our accessible supplies of mineral raw materials on land. Not only are there trends towards actual national and world shortages, but there are tremendous socio-economic pressures against environmental disturbances particularly in developed countries and socio-political pressures against economic exploitation, and we use the word this time in its derogatory sense, in the underdeveloped countries. No longer can we complacently define conservation as the use of someone else's resources rather than our own. In the United States, out of 88 mineral commodities considered (Table 14), the resources of 31 of them are indicated to be inadequate to meet the projected cumulative demand through the year 2000, now less than 30 years away. We presently import over 50 percent of our needs for eleven of these commodities. The world picture is not much better. Twenty mineral commodities are indicated to have resources inadequate to supply the demand through the year 2000, even without the constraint referred to previously. If we consider 30 years to be a long time, there may not be an emergency. But how often have we heard that the consumption of minerals in the past 30 years has been equal to or greater than the prior consumption by man since the beginnings of recorded time — and it is increasing every year. Many informed persons and many uninformed persons have written and talked about the problems of environment, ecosystems and man (301), and, no matter how it is analyzed, the ultimate problem becomes the high rate of world population growth. As the beginning quotations indicate, the earth is a closed system with finite mineral resources and finite capacities to accommodate the impact of man. Nevertheless, even if this basic problem is resolved, mineral demands will continue. The ultimate solution to mineral shortage may be recycling, but, until that equilibrium state is attained, alternative sources of supply must be sought. Examination of the potential world mineral resources of the marine environment (Table 14) indicates that large amounts of nearly all known mineral commodities are to be found. Not all of them will serve within our lifetime as sources of supply, but some of them may very well become (and are even now) our sole source of supply. There is no question that these figures indicate a potential importance of the role of marine minerals which can no longer be dismissed as futuristic or exaggerated. There is no question but that the problems of exploration and exploitation will be many and costly to solve. It may be that the needs of the public sector can no longer be fulfilled entirely on the efforts of private enterprise.

A strong relationship between government and industry and between nation and nation will be essential to the development of this new resource base. A sense of urgency should prevail in the development of new engineering technology; and wise management practices, suited to the exploration of minerals from this new and somewhat hostile marine environment, should be rapidly agreed upon. Deepsea ferromanganese deposits present a known and suitable place to start.

Marine Mineral Resource Estimates

The economics of mineral resources are largely tied to the needs of consumers. Shortages can increase the value of a mineral commodity to the extent that the resource moves to the category of reserves. Surpluses can reduce commodities from the reserve category to that of resources. McKelvey (1968) (Figure 11) has classified the mineral resources to differentiate between the situations prevailing at the time of categorization. He states:

> Although subsea resources of petroleum and several other minerals are potentially large and widely distributed, only a small part are likely to be economically recoverable within the next few decades, and an unpredictable part may never be recoverable. In order to give economic and geologic perspective to estimates of resources, it is desirable to view them in a framework that takes account of the degree of certainty of knowledge about their existence and character, and the feasibility of their recovery and sale. In the classification below, the degree of certainty of knowledge of the dimensions and quality of mineral deposits is shown on the abscissa, and the feasibility of recovery and marketing is shown on the ordinate. The classification of individual deposits shifts with progress in exploration, advance in technology, or changes in economic conditions. Recoverable reserves are marketable materials that are producible under locally prevailing economic and technologic conditions. Paramarginal resources are prospectively marketable materials that are recoverable at prices as much as 1.5 times those prevailing now or with a comparable advance in technology. Submarginal resources are materials recoverable at prices higher than 1.5 times those prevailing now but that have some forseeable use and prospective value.

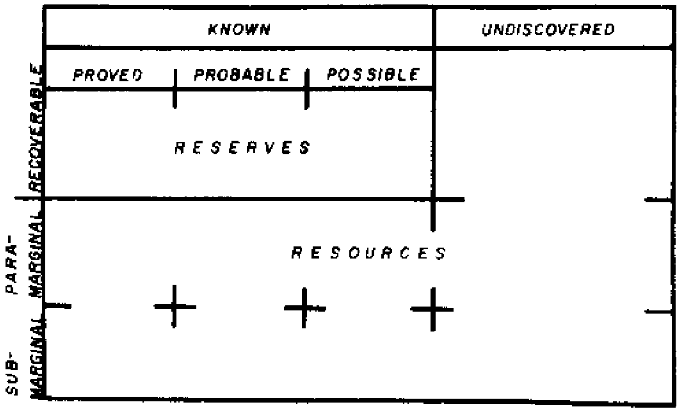


Figure 11. Classification of reserves and resources (according to McKelvey, 1968)

Seen in this framework, the presently recoverable proved reserves of most minerals are relatively small compared to the resources that may eventually be found by exploration or become recoverable as a result of technologic advances or changes in economic conditions. This is particularly true of the seabed resources because only a small part of the seabed has been explored and most of the resources it contains are not yet economically recoverable.

In this study, estimates of resources include all classes of reserves and resources without differentiation as to class. These are termed Apparent Resources.

Three major classes of marine mineral resources are known: (1) the dissolved minerals in sea water, (2) the minerals in unconsolidated deposits which occur in a variety of locations from coastal beaches to the deepseafloor and (3) the minerals in consolidated deposits in the underlying bedrock. Manganese nodules occur in the second class, and, in order to fully assess their potential, it is necessary to understand as much as we can about their environment and the many factors influencing their origin and distribution. Our present knowledge of these matters in the ocean compared to our knowledge for other minerals on land is sadly lacking, but sufficient statistical data are available to make, within orders of magnitude at least, an assessment of what our potential deepsea mineral resource might be. Marine mineral resources are examined in the light of present day knowledge and with the assumption that the present techno-economic base lines are changing at least as fast as they have in the past quarter century.

TABLE 14
RESOURCE COMPARISONS FOR 88 MINERAL COMMODITIES TO THE YEAR 2000

	PRESENT DEMAND		CUMULATIVE DEMAND TO 2000 AD		APPARENT RESOURCES (LAND)		ADEQUACY (LAND)		APPARENT RESOURCES (MARINE)		
	US	World	US	World	US	World	US	World	Diss.	Unc.	Con.
Anthracite	8.862	10.173	10.200	11.549	11.580	13.297	+	+	NA[5]		13.11
Bituminous coal and lignite	10.233	11.103	12.196	12.556	13.182	14.234	+	+	NK[7]		13.87
Carbon	9.550	10.3[illegible]	11.286	12.161			+	+	13.367		NA
Geothermal	ND	ND	ND	ND	14.196[1]	14.305	+	+	ND[6]		14.11
Helium	8.253	8.268	10.267	10.311	11.281	11.281	+	+	ND		ND
Hydrogen	9.515	10.186	12.148	12.319	--	--	+	+			ND
Natural Gas	10.311	10.486	12.380	12.850	11.471	12.188	-	-	NA		ND
Peat	8.106	10.268	9.584	12.114	12.161	13.336	+	+	NA		NA
Petroleum	11.137	11.316	12.878	13.243	13.102	13.173	+	-	NA	INC[3]	NA
Shale Oil	--	8.900	11.600	11.822	13.909	15.951	+	+	NA		15.36
Thorium	7.150	7.270	9.266	9.859	10.818	11.239	+	+	NA		11.11
Uranium	8.509	8.924	11.450	11.833	11.309	11.384	-	-	12.578		11.16
Chromium	8.241	9.105	10.147	10.639	9.106	11.412	-	+	8.813	INC	10.44
Cobalt	8.262	8.817	10.124	10.369	9.603	10.890	-	+	11.227	INC	11.35
Columbium	7.590	8.119	9.483	10.110	9.435	11.276	-	+	ND	INC	11.90
Iron	11.129	10.659	11.689	12.342	12.277	13.174	+	+	10.236	INC	12.32
Manganese	8.637	9.457	10.288	11.250	10.376	13.104	+	+	10.169	INC	11.23
Molybdenum	8.904	9.224	10.596	11.159	11.102	11.175	+	+	12.557	INC	10.13
Nickel	9.300	9.878	11.210	11.618	10.978	12.138	-	+	11.576	INC	11.62
Rhenium	6.400	7.100	8.367	8.840	9.232	12.609	+	+	ND		9.48
Silicon	9.148	9.488	10.839	11.322	12.144	13.144	+	+	15.132	NVA	14.33
Tantalum	8.114	8.197	8.935	10.175	8.704	10.678	-	+	ND		11.18
Tungsten	8.427	9.197	10.490	11.141	10.165	10.879	-	-	ND	INC	10.22
Vanadium	8.196	8.578	10.229	10.537	11.123	11.425	+	+	11.156	INC	12.15
Aluminum	10.198	10.525	12.295	12.832	10.678	11.678	-	-	13.390	NVA[4]	11.77
Antimony	8.193	8.632	10.122	10.339	9.268	10.393	-	+	11.280		8.76
Arsenic	7.380	7.840	[illegible].182	9.412	9.304	9.672	+	+	11.490		9.13
Beryllium	8.407	8.593	10.307	10.492	11.134	12.190	+	+	ND	NVA	12.10
Bismuth	7.920	8.304	9.495	10.158	9.164	9.870	-	-	11.245	INC	9.66
Cadium	8.353	8.830	10.316	10.832	9.554	10.381	-	-	10.806		9.40
Cesium	--	--	6.400	6.200	0.000	9.132	-	+	10.919		11.23
Copper	10.130	10.774	12.168	12.597	11.684	12.287	-	-	10.747	INC	11.16
Gallium	6.400	7.310	8.236	8.705	10.324	11.300	+	+	13.834		13.67
Germanium	7.200	7.920	9.131	9.630	8.123	9.240	-	-	ND	NVA	12.13
Gold	9.259	10.116	11.214	11.773	11.117	11.470	-	-	12.275	INC	10.20
Hafnium	7.310	7.740	9.204	9.493	11.213	11.527	+	+	ND	NVA	12.35
Indium	7.150	7.530	8.739	9.273	8.318	9.196	-	-	ND		10.32
Lead	9.243	9.831	11.133	11.445	10.837	11.278	-	-	11.413	INC	10.17
Magnesium	9.144	9.511	11.346	11.589	11.106	13.182	-	+	16.141		13.61
Mercury	8.332	9.138	10.342	11.153	9.500	10.803	-	-	10.634		10.27
Platinum-group metals	9.202	9.643	11.141	11.496	9.583	11.824	-	+	ND	INC	10.96
Radium	--	--	--	--	10.117	11.117	+	+	ND	NVA	11.13
Rare-earth elements	8.204	8.354	10.150	10.308	11.171	11.306	+	+	11.138	INC	12.25
Rubidium	--	--	6.100	6.200	6.900	8.288	+	+	13.166	NVA	6.37
Scandium	--	--	7.230	7.260	9.351	10.351	+	+	ND	NVA	13.81
Selenium	7.550	8.134	9.245	9.659	9.255	9.964	+	+	12.625	NVA	9.38
Silver	9.193	9.728	11.132	11.496	11.105	11.231	-	+	12.304	INC	10.26
Tellurium	7.130	7.238	8.594	9.119	9.205	9.739	+	+	ND	INC	7.89
Thallium	--	6.100	7.190	7.840	7.199	8.110	+	+	ND	NVA	11.62
Tin	9.196	9.819	11.322	11.653	9.153	11.303	-	-	11.136	INC	9.96
Titanium	9.414	10.127	11.385	12.115	11.667	12.388	+	+	10.404	INC	13.26
Yttrium	7.340	7.450	9.291	9.407	10.146	11.120	+	+	12.514	INC	13.19
Zinc	9.380	10.146	10.241	12.109	10.810	11.335	+	-	11.413	INC	10.72
Zirconium	8.342	8.179	9.447	10.604	11.375	12.104	+	+	ND	INC	--
Argon	8.269	8.681	10.206	10.495	0	0	+	+	ND		NA
Asbestos	8.704	9.302	10.374	11.200	9.172	9.862	-	-	0.000		9.32
Barium	8.204	8.574	10.102	10.398	9.887	10.222	-	-	11.121	INC	10.43
Boron	8.411	9.113	10.292	10.866	11.170	11.340	+	+	14.333	INC	9.58
Bromine	8.845	9.113	10.476	10.713	0	0	+	+	15.576		9.70
Calcium	9.364	10.111	11.238	11.749	0	0	+	+	15.235	INC	11.58
Chlorine	9.607	10.136	11.483	12.116	12.360	0	+	+	17.209		10.59
Clays	9.240	10.157	11.195	12.103	11.848	12.410	+	+	ND	NVA	--
Corundum and emery	6.400	7.900	8.294	9.150	8.720	10.100	+	+	0.000	NVA	--
Diamond, industrial	8.444	9.398	10.442	11.373	0.000	10.428	-	-	0.000		ND
Diatomite	8.275	9.103	10.207	11.102	11.348	12.116	+	+	ND	INC	--
Feldspar	7.820	8.263	9.627	10.207	10.620	11.124	+	+	ND	NVA	10.46
Flourine	8.646	9.180	10.527	11.166	9.540	10.388	-	-	13.199		11.33
Garnet	7.200	7.250	9.183	9.235	9.735	10.368	+	+	0.000	INC	--
Gem stones	9.510	10.114	ND	11.342[2]	ND	ND	+	+	0.000	INC	--
Graphite (natural)	7.300	8.265	9.173	10.196	8.500	10.520	-	+	0.000		10.19
Gypsum	8.574	9.204	10.330	11.118	11.734	12.367	+	+	0.000	INC	12.14
Iodine	7.530	8.149	9.402	10.113	11.189	11.945	+	+	13.181		9.30
Kyanite and related minerals	7.940	8.260	9.868	10.239	10.250	10.686	+	+	0.000	INC	10.33
Lithium	7.490	7.820	9.391	9.637	10.767	11.111	+	+	13.282	INC	11.23
Mica	7.760	8.193	9.338	10.485	LOW	NK	-	NK	0.000		--
Nitrogen	9.702	10.245	11.398	12.180	12.345	12.363	+	+	12.176		10.11
Oxygen	9.139	9.454	10.751	11.290	0	0	+	+	ND		NA
Perlite	7.410	7.890	9.280	9.485	10.790	11.296	+	+	0.000		--
Phosphorus	9.156	9.516	11.120	11.504	12.306	12.981	+	+	11.482	INC	11.22
Pottassium	9.119	9.478	11.104	11.411	11.127	13.366	+	+	15.140	INC	12.36
Pumice	7.610	8.237	9.471	10.200	10.158	11.158	+	+	--		--
Quartz crystal	6.200	6.400	7.640	9.778	0.000	NK	-	NK	0.000		--
Sand and Gravel	10.102	10.746	11.767	12.655	11.646	12.333	-	-	0.000	INC	--
Sodium	9.308	10.101	11.223	11.799	12.240	0	+	+	16.301		12.21
Stone	10.122	10.845	11.915	12.648	0	0	+	+	0.000		--
Strontium	6.500	6.600	8.252	8.488	8.554	9.245	+	+	13.977		10.91
Sulfur	9.382	10.144	11.253	12.104	11.128	12.104	-	-	15.504		10.81
Talc, soapstone and prophyllite	7.620	8.318	9.407	10.274	9.623	10.350	+	+	0.000		--
Vermiculite	7.550	7.820	9.374	9.805	10.588	11.588	+	+	0.000		--

1. Theobold *et al* 1972
2. Gemstones 10.114 World
   Multiply x 30 11.342 World Over
3. INC: Included in Total. Circles implicate present in Mn nodules.
4. NVA: Present but no value assigned.
5. NA: Not applicable.
6. ND: No data.
7. NK. Not known

Unconsolidated Deposits

Resources of mineral commodities from unconsolidated deposits have been computed for the abyssal regions and are totalled in Table 15 by commodity. Where breakdown is not possible, the inclusion or exclusion of any commodity from the total is indicated.

Abyssal Deposits

Both surficial and substratal deposits are included in resource estimates for the abyssal depths.

Surficial Deposits - Ferromanganese Nodules

Only ferromanganese oxide nodules are considered here as a potential resource.

Estimates of reserves for the Pacific Ocean have been reported by Mero (1965) at 1,700 billion MT, later revised (1967) to 1,500 billion, and by Zenkovitch and Skornyakova (1961) at 90 billion MT. Mero's figures are based on measurement from 101 photographs, cores and grab samples, and, as he states, on the basis of these data, most of the calculations concerning manganese nodule tonnages are of the nature of speculation. Many more data are available now, though no more authoritative compilation of resources has been made yet. Assuming that economic nodule deposition is confined within the depth range 3,000 to 6,000 m where 10 Å manganite and 7 Å manganite coexist with δ MnO_2 (Bender, 1970), a concentration of 1 gm/cm^2 would yield 1,390 x 10^9 T in the Pacific Ocean. This figure falls between the previous estimates, nearer to Mero's. Bezrukov in 1962 gave estimates for 15 million km^2 of the Indian Ocean covered by the best nodule concentrations, ranging from 4.3 to 0.001 gm/cm^2. Allowing 1 gm/cm^2 would give a total product of 150 x 10^9 MT. No such figures are available for the Atlantic or Arctic Oceans, and any assumptions made at the present time would be little more than guesses. For the purpose of resource estimates, then, a world total of 1,700 x 10^9 T as reported by Mero (1965) and cited by McKelvey et al. (1969) is assumed (Table 15). This is reduced to 1,500 x 10^9 T in the Pacific (Mero, 1967), 150 x 10^9 T in the Indian Ocean and 50 x 10^9 T in the Atlantic, but estimates for the Arctic or small ocean basins are not made. Metal content of the deposits is computed from data reported by Bender (1970) and listed previously in Table 6. Bender lists abundances for 37 elements in his nodules. Of these, only 11 show concentrations more than two orders of magnitude greater than crustal abundance given by Barth (1962). The resource values cited in the Table are computed using these elements only.

Substratal Deposits

Allowing a thickness of about 200 m, Mero (1965) has calculated that there are some 10^{16} T of red clay on the seafloor and has tabulated the elemental distribution for this material (Table 16) as a mineral resource.

A comparison of the concentration of the contained elements in Mero's table with crustal abundance discloses (Table 17) that only four elements (Mn, Cu, Pb and Mo) have a concentration ratio greater than one order of magnitude and none as much as two orders of magnitude. These are not considered to be sufficient concentrations to warrant inclusion of red clay as a potential mineral resource on the basis of the elemental content. It seems unlikely that any other uses would evolve for the material as a bulk industrial commodity that could not be met from a more adequate alternative source. Estimates are, therefore, not included in the resource base.

The possibility of areas of higher mineral content due to local environmental conditions should not, however, be excluded. Mero (1965) indicates the inclusion of 1 to 2 percent Mn nodule grains in some areas, and Cronan and Tooms (1967) have calculated that buried nodules in the upper 2 m of sediment are approximately equal in number to those found at the sediment surface.

Diatom ooze, composed of the frustules of planktonic plants, covers about 21 million km^2 in the higher latitudes of the Pacific, Indian and Atlantic Oceans.

The deposits average close to 4,000 m (Mero, 1965) in thickness and contain in excess of 90 percent SiO_2. Mero (1965) has estimated about 10^{13} T of siliceous oozes on the ocean floor, assuming a bed thickness of 200 m. Allowing 1 percent mineable area would give potential resources of 10^{11} T SiO_2.

Radiolarian oozes, consisting mostly of skeletal remains of radiolaria, are distributed widely in the Pacific and Indian oceans over some 7 million km^2 and may contain between 50 and 60 percent SiO_2, but, because of the lower grade, no resource estimates are made for these materials.

Calcareous oozes cover 128 million km^2 of the ocean floor according to Sverdrup et al. (1942). Revelle et al. (1955) estimates an average thickness of 400 m which would mean a total of 10^{16} T of oozes in all oceans (Mero, 1965).

Allowing 1 percent mineable at 90 percent $CaCO_3$ would give a potential resource of 10^{14} T $CaCO_3$.

Political Restraints

Quite apart from the legal aspects, the political environment involves paramount issues of morals and human rights. It is the environment in which laws are formulated after the status quo has been disturbed. The path through the political environment is a delicate one requiring diplomacy and tact, and the quantification of its interactions is extremely subjective because the mood of the people makes the rules, and some people claim the sea as home.

Social Restraints

The social environment is more real to the individual than the political one. It is his personal environment. Disturbances are not always welcome—unless they bring great benefits. The basic consideration in the social environment is conflict of interest, promulgated in the multiple-use-of-the-sea concept. Like all psycho-human affairs, the ranking of multiple uses is highly subjective and will ultimately depend on assessment of the greatest benefit for the greatest number.

Much has been written lately on these matters of human ecology (301), and man's concern with his own environment is a matter of great impact. It is essentially one of survival. Ferromanganese nodules will figure largely in this scheme.

Legal Restraints

In many areas where social need has developed rapidly, and this applies particularly to deepsea minerals, national and international law has lagged behind. Thus, there is a need for creative revision of the laws to encourage development and result in social benefit. It is now widely recognized that mineral resources are not inexhaustible, that exploitation cannot be properly effective without our regard to resource conservation, and that conflicting requirements for use of the mineralized areas by others must be duly considered.

Technical Restraints

The technical environment which interfaces with technical operations can be regarded as largely one-sided. Its major impact on technology is in the form

TABLE 15
ESTIMATED WORLD RESOURCES OF ELEMENTS FROM UNCONSOLIDATED ABYSSAL DEPOSITS IN ORDER OF MAGNITUDE DOLLARS ($0M 14.221 = $0.221 x 10^{14})

	MINERAL VALUE $/T	PACIFIC* PPM	PACIFIC* CONC. FACTOR	INDIAN*[2]	ATLANTIC* PPM	WORLD VALUE $OM	OOZES[3] $OM
Energy Resources							
Anthracite							
Bituminous coal and lignite							
Carbon							
Geothermal							
Helium							
Hydrogen							
Natural							
Peal							
Petroleum							
Shale oil							
Thorium							
Uranium	2,078.40[1]	4	0.2				
Ferrous Minerals							
Chromium	58.50	10	NE				
Cobalt	4,077.00	3,200	3.1	1,900	3,300	14.221	
Columbium							
Iron	76.90	117,000	1.2	140,000	164,000	NVA	
Manganese	61.00,	193,000	3.2	140,000	138,000	14.200	
Molybdenum	3.67[1]	900	3.5			13.303	
Nickel	2,072.00[1]	6,600	2.8	6,300	4,200	14.233	
Rhenium							
Silicon							
Tantalum							
Tungsten	5,973.00	66	2.6			12.710	
Vanadium	3,747	550	0.5			NVA	
Nonferrous minerals							
Aluminum							
Antimony							
Arsenic							
Beryllium	136,648.00[1]	3	0.0			NVA	
Bismuth	6,816.00[1]	30	2.15			12.450	
Cadmium	5,406.00[1]	2	1.0			NVA	
Cesium							
Copper	930.00	3,890	3.8	5,400	1,300	13.615	
Gallium	1,199,681.00[1]	10				NVA	
Germanium	176,320.00[1]	6	0.3			NVA	
Gold							
Hafnium							
Indium							
Lead	298.00	900	2.6	1,300	1,800	12.465	
Magnesium	777.00,	17,000	0.0		17,000	NVA	
Mercury	15,512.00[1]	2	0.4				
Platinum-group metals							
Radium							
Rare-earth metals	3,306.00[1]	320	2.8			13.190	
Rubidium							
Scandium	461 x $10^{5(1)}$	10	0.2			NVA	
Selenium							
Silver	68,801.00[1]	3	1.3			NVA	
Tellurium	13,224.00[1]	180	7.0			13.337	
Thallium							
Tin	3,264.00[1]	267	1.9			NVA	
Titanium	2,909.00,	6,700	0.0	4,200	44,000	NVA	
Yttrium	123,424.00[1]	310	0.7			NVA	
Zinc	298.00,	470	0.7	570	560	NVA	
Zirconium	6,612.00[1]	620	0.4			NVA	
Nonmetalic minerals							
Argon							
Asbestos							
Barium	29.00,	1,800	1.4	3,700	4,900	NVA	
Boron	521.00[1]	290	2.9			12.257	
Bromine							
Calcium	4.00	19,000		14,000	33,000	NVA	15.423
Chlorine							
Clays							
Corundum and cm							
Diamond, industrial							
Diatomite							13.639
Feldspar							
Fluorine							
Garnet							
Gem stones							
Graphite (Natural)							
Gypsum							
Iodine							
Kyanite and related minerals							
Lithium							
Mica							
Nitrogen							
Oxygen							
Perlite							
Phosphorus	80.00	1,400	0.0	2,800	1,690	NVA	
Potassium	37.00	4,000			4,000	NVA	
Pumice							
Quartz crystal							
Sand and gravel							
Sodium	20.00	26,000			23,000	NVA	
Stone							
Strontium	54.00	810	0.2	860	1,100		
Sulfur							
Talc, soapstone and pyrophyllite						NVA	
Vermiculite		85[1]					
Niobium						12.257	
TOTAL					NVA	14.817	15.429

1. Minor element from Bender 1972, p. 877

2. From Bezrukov

3. After Mero 1965

* Estimated T x 10^9: Pacific Ocean - 1,500; Indian Ocean - 150; Atlantic Ocean - 50; Total - 1,700

TABLE 16
ELEMENTAL ANALYSES OF VARIOUS CONSTITUENTS IN RED CLAY (AFTER MERO, 1965)

ELEMENT	ABUNDANCE IN RED CLAY (WT. %)	AMOUNT IN RED CLAY[2] (TRILL. T)	RATE OF ACCUMULATION IN RED CLAY (MILL. T/YR)	WORLD[3] RATE OF CONSUMPTION (MILL. T/YR)	RATIO		WORLD[4] RESERVES IN 1953 (MILL. T)	RATIO AMOUNT IN RED CLAY WORLD RESERVES (X 10^3)
					AMOUNT IN RED CLAY ANNUAL CONSUMPTION (X 10^6)	RATE OF ACCUMULATION RATE OF CONSUMPTION		
Al	9.2	920.0	46.0	4.72	200.0	10	570	1,620
Mn	1.25	125.0	6.3	6.7	19.0	1	320	390
Ti	0.73	73.0	3.7	1.3	56.0	3	140	520
V	0.045	4.5	0.23	0.008	550.0	28	NA[5]	---
Fe	6.5	650.0	32.5	262.5[6]	2.5	0.1	1,350	480
Co	0.016	1.6	0.08	0.015	110.0	5	1.6	1,000
Ni	0.032	3.2	0.16	0.36	8.9	0.5	13.5	220
Cu	0.074	7.4	0.37	4.6	1.6	0.1	150	50
Zr	0.018	1.8	0.09	0.032	900.0	45.0	NA	---
Pb	0.015	1.5	0.08	2.4	0.6	0.03	43	35
Mo	0.0045	0.45	0.023	0.040	11.0	0.6	3	150

1. Based on an oceanic tonnage of red clay of 10^{16}tons and a rate of accumulation of 5-10 tons per year. All quantities express in metric tons.

2. After Goldberg and Arrhenius (1958).

3. From Encyclopedia Britannica Book of the Year (1963).

4. After McIlhenny and Balland (1963).

5. No dtat available with which to calculate statistic.

6. Primary iron.

TABLE 17
ABUNDANCE OF ELEMENTS IN RED CLAYS
(AFTER MERO, 1965) AND CONCENTRATION
FACTOR OVER ABUNDANCES IN LITHOSPHERE

ELEMENT	ABUNDANCES IN RED CLAY WT. % (1)	ABUNDANCE IN LITHOSPHERE WT. % (2)	CONCENTRATION FACTOR (3)
Al	9.2	8.07	21.0
Mn	1.25	0.10	12.5
Ti	0.73	0.40	1.8
V	0.045	0.011	4.1
Fe	6.5	5.05	1.3
Co	0.016	0.0023	7.0
Ni	0.032	0.008	4.0
Cu	0.074	0.0045	16.4
Zr	0.018	0.016	1.1
Pb	0.015	0.015	10.0
Mo	0.0045	0.0001	45.0

(1) In Mero, 1965; after Goldberg & Arrhenius, 1968.
(2) After Barth, 1962.
(3) Ratio Red Clay/Lithosphere

of disturbances to the system due to materials failure primarily affected by motion, pressure, corrosion and biological fouling.

The impact on the environment is relatively small. The operation will not affect the motion of the sea, the pressure of the depths, the means of corrosion or the fouling capabilities of the biota to any great extent — although there may be some very minor local effects which must be considered, due to large operations, which might involve mixing of water masses or introduction of solvents.

In this section some of the problems caused by the influence of the sea on a mining system are discussed. Materials and processes are affected by motion, corrosion and biological processes. Other factors such as pressure and temperature are ancillary and are not considered here. For the mining engineer, the nature of some of the problems may be given perspective by the following excerpt from Kanjana-vanit describing the corrosion problems of an offshore dredge in Thailand.

"Due to the salt water and salt atmosphere in which sea mining dredges operate, corrosion is a far more serious problem than on dredges operating in non-salt water. This corrosive attack takes the obvious form of rusting as well as pitting of underwater surfaces and erosion of pump casings and impellers which occurs as a result of electrolytic action.

"Rusting of exposed metal surface is combatted by the time-honoured method of chipping away the rust before painting. Although this is slow, expensive and far from satisfactory, there does not appear to be any alternative at this time. Rustless or rust-resisting steels are prohibitively expensive, although galvanized hull plating has been used on one dredge operating off the coast of Thailand. This dredge pontoon has been afloat for about 3 years, and no deterioration of the hull has taken place in this time.

"We are all familiar with the paint manufacturer's direction on the side of the can that 'surface should be clean and dry, etc.' Unfortunately, the dry condition is found all too seldom on dredges operating in the sea, so that too frequently paint is applied over metal surfaces which are not only damp but also salty. This occurs particularly around the treatment plant where the open flow of sea water over the jigs produces an atmosphere of salt mist. Rust will show through paint applied in these conditions within a week, no matter how effective the paint may be when applied under ideal conditions.

"One major source of salt mist is the screen used to break up and wash the spoil from the dredge buckets or dredging pump. These screens utilize high pressure water jets and part of the water is atomized into the atmosphere. On two Thai sea dredges, this has been largely overcome by totally enclosing the screen and employing extraction fans to remove the corrosive mist to the outside of the dredges through trunking. The steel trunking, not surprisingly, has a short life.

"Electrical equipment is damaged by the damp and salty atmosphere, so as much as possible is located away from the treatment plant in a dry position. One dredge has the generating switchboard in one air-conditioned compartment and all motor switches in a second compartment, also air-conditioned. At each motor throughout the dredge, a start-stop switch only is provided to actuate the remotely positioned starter.

"The arrangement greatly eases the electrical maintenance problem. Motors and switches which are of necessity located in damp places are totally enclosed, and motors or alternators which are not in use for more than a few hours are heated by external heaters to keep the insulation dry.

"Electrolytic corrosion of the hull plating is retarded by fastening sacrificial zinc anodes to various points on the under-water plating. This is fairly effective, but the anodes require renewing at intervals of from 1 to 2 years and the location of some of the anodes make them difficult to change underwater. Above the waterline the plating is protected as far as possible by painting, but sea conditions often prevent work on this area for months at a time.

"Pump impellers and casings can be severely damaged by electrolytic action. In bronze impellers with a significant zinc content, electrolytic, or galvanic, action is set up between the copper and zinc particles in the metal when immersed in sea water with the result that the zinc is eaten away. This causes a rough, pitted surface to develop on the impeller. Water scour of the rough-surfaced, revolving impeller causes erosion which accelerates the deterioration. In cast iron pump casings, graphitization of the metal may take place. As with the hull plating, sacrificial anodes are employed to minimize corrosion. These are usually fitted into some convenient places in the suction space of the pump and are commonly of zinc, but in all gunmetal pumps, mild steel anodes may be used. Coating the interior surfaces of cast iron pump casings with an epoxy resin compound, which is already used to extend the life of worn casings on some non-salt water dredges, may provide a useful measure of protection in seawater pumps.

"Although most corroded major parts of an offshore dredge may be renewed without much difficulty, the hull or pontoons cannot be easily replaced without dry dock facilities. Decision to retire an offshore dredge may be based mainly on the condition of the hull. It is possible that more consideration will be given to the possibility of using a reinforced-concrete hull in an offshore dredge which does not require high speed movement like a sea-going ship."

The Effects of Motion

Motion has a deteriorating effect on structures due to fatigue, but this is a problem common to non-marine engineering and can be dealt with by reference to pertinent literature elsewhere. The effect of motion on mining or metallurgical processes is a problem peculiar to the marine environment. However, up to this time, few data have been recorded, and each operation must be designed on a trial and error basis.

Corrosion and Cathodic Protection

Exposure to the marine environment may produce several forms of corrosion response, of which only a few can be quantified in a meaningful way. Resistance to fracturing and corrosion represent the two groups of design parameters for which standard methods of evaluation over the whole range of construction materials are not available (Table 18).

TABLE 18
MATERIALS SELECTION PARAMETERS (BROWN, 1968)

PARAMETER	CHARACTERISTICS
Strength, density and cost	Easily quantifiable by standard methods; data readily applied.
Fabricability, procurability	Not so easily quantifiable, but can be evaluated readily in a manner meaningful to the designer.
Resistance to fracture and corrosion	Readily quantifiable in some cases but, in many instances, both quantifying the parameter and interpreting the resultant data relative to design are problems at the leading edge of technology.

The resistance of materials to corrosion is greatly affected by composition. Corrosion of metals is considered to occur by an electro-chemical mechanism, at which oxidation (or corrosion) may occur at sites which may be far-removed from a corresponding reduction reaction. Corrosion may take the form of pitting, crevice corrosion, dezincification or selective corrosion and stress corrosion of a galvanic anode.

Galvanic Effects

In any galvanic couple, the corrosion of one metal is accelerated and the corrosion of the other is reduced. This can lead to trouble if the effect is not anticipated and provided for or can be beneficial if designed to provide built-in protection where survival with minimum corrosion is a critical requirement — as, for example, the seating surfaces of a valve.

The arrangement of metals in a galvanic series for seawater in Table 19 indicates which of the metals (the higher ones in the list) in a galvanic couple will suffer accelerated corrosion and which will have its corrosion reduced. The magnitude of the effects will be determined by several factors, including, most importantly, the relative immersed areas of the dissimilar metals, their polarization characteristics and the overall resistance of the electrical circuit, including the metallic path, the water and any films or deposits on the metal surfaces. The maximum accelerating effect occurs when the area of the more noble metal is relatively large as compared with that of the less noble metal; such combinations are most dangerous and must be avoided.

Large, complex or critical structures, particularly those not made of structural steel, require the services of specialists for the design of a corrosion control system.

Protective coatings are normally applied to exposed surfaces. There are many types available, and the reader is again referred to the literature.

Biological Fouling

About 2,000 species of animals and plants have been reported as fouling organisms. Table 20 indicates how fouling affects some submerged objects,

TABLE 19
GALVANIC SERIES OF METALS IN FLOWING SEAWATER
(La Que, 1968)

Anodic or least noble

Magnesium and Magnesium alloys
CB75 aluminum anode alloy
Zinc
B605 aluminum anode alloy
Galvanized steel or galvanized wrought iron
Aluminum 7072 (cladding alloy)
Aluminum 5456
Aluminum 5086
Aluminum 503.2
Aluminum 3003, 1100, 6061, 356
Cadmium
Aluminum 2117 rivet alloy
Mild steel
Wrought iron
Cast iron
13% Chromium steel type 410 (active)
17% Chromium steel type 430 (active)
18-8 Stainless steel type 304 (active)
18-12-3 Stainless steel type 316 (active)
Ni-resist
Lead
Tin
Muntz Metal
Manganese bronze
Naval brass (60% copper 39% zinc 1% tin)
Yellow brass (65% copper 35% zinc)
Copper
Silicon bronze
Red brass (85% copper 15% zinc)
Aluminum brass
Composition G bronze
Composition M bronze
Admiralty brass
90% Copper 10% nickel
70% Copper 30% nickel
Nickel
Inconel (78% nickel 13.5% chromium 6% iron)
Nickel-aluminum bronze
Silver
Titanium
18.8 Stainless steel type 304 (passive)
Hastelloy alloy C
Monel nickel-copper alloy
Type 316 stainless steel (passive)
Graphite
Platinum

Cathodic or most noble

TABLE 20
HOW FOULING AFFECTS SUBMERGED OBJECTS (MURAOKA, 1968)

OBJECT	EFFECT
Ship hulls	Fouling reduces a ship's speed and increases fuel consumption. Increases frequency of dry-docking periods.
Underwater sound equipment	Fouling reduces sensitivity and sound transmission, and decreases effectiveness of sound gear by increasing cavitation noise. Measurement of beam pattern and receiving response of fouled underwater transducers show reduction of axial sensitivity ranging from 0 to 10 db in frequency intervals of one to 20 kHz.
Salt water pipe system in vessels, industrial power plants, and desalting plants	Fouling on pipe surfaces reduces pipe diameter and water flow. Detached organisms (mussel shells) block water flow at valves and at constricted places in pipes.
Metallic surfaces	Pitting occurs under shells of dead barnacles, created by oxygen concentration cells. Conditions favorable to corrosion are produced by metabolic products--particularly acids and sulfides. Sulfate-reducing bacteria promote anaerobic corrosion.
Protective coatings	Fouling damages coating in several ways: when a barnacle shell adhering to the coating is torn loose for any reason, the underlying paint comes off with it; paint film is weakened at the site of attachment due to metabolic products; the sharp edges of barnacle shells cut into the coating as the animals grow, eventually exposing the underlying surface. Paints are also destroyed by seawater bacteria that attack constituents such as rosin, paraffin, alkyd, phenolic resin, and linseed oil.
Plastic glass and surfaces	Windows of underwater structures and camera lenses become blocked and require frequent cleaning.

and, again, the reader is referred to the literature for more specific details.

REQUIREMENTS IN EXPLORATION FOR MARINE FERROMANGANESE NODULES

Exploration in the practical context must be defined as the process of determination of the benefit cost ratio of any particular mining operation. It includes, therefore, not only the prospecting effort, which substantiates the presence of mineral values, but, also, the deposit characterization and environmental monitoring which will permit quantilification of the benefits and the costs in real terms. The benefits are obviously the utilization of the resource and all the externalities associated with having the resource. The cost is what it takes to provide the benefits in terms of money, technology and effects. Thus, exploration is a measuring process carried out for the purpose of making sound decisions on future exploitative processes. Two questions, therefore, must be asked: (1) What must be measured? and (2) How are these measurements made?

The Data Base

Many data are required to characterize a seafloor mineral deposit. Ferromanganese deposits are widely distributed throughout the world ocean, and it is evident that they exhibit wide variations in tenor and in environmental setting, even over moderately short distances. Thus, the characterization of deposits is dependent on a thorough knowledge of the geological, geotechnical, oceanographic, meteorological and ecological parameters, and the measurement of each of these is an essential part of any nodule exploration program.

In our survey of the literature, of unpublished reports and of our own files, we have established that there are, at present, insufficient data to characterize the potential nodule mining sites. Expansion of the present data base is, therefore, of paramount importance, and it must be done prior to commencing even pilot mining operations.

Geological Requirements

The more basic data requirement is that of the deposit and its seafloor environment. It is necessary to understand the topographic features of the deposit in both large and small scale in order to evaluate methods and develop costs for exploitation. The value of the ore is determined from its composition which may vary in relation to the geochemistry of the underlying seafloor and the superjacent waters. Costs of processing will also be dependent on the texture and mineralogy of the ore and gangue materials, and leads for further prospecting will no doubt be engendered by an understanding of the ore-forming process. Sampling is an integral requirement of the geological data base though many improvements in remote sensing are obviating some of this need.

Through the use of bottom photography, rock sampling (if exposures are present) and both grab samplers and core samplers, the geological-sedimentological regime at the potential site should be sampled and described. In regard to the sedimentary matrix which is, in fact, the principal gangue of the exploitable nodules, the mining operator needs to know both the physical as well as the chemical characteristics of the sediment. To acquire such data requires that either actual samples be taken or that some in situ sensing system be employed which, once calibrated, will provide the much-needed physical and chemical information. Just to solve this problem alone requires a new research and development effort in deepsea sensing and instrumentation.

Although empirical relationships are known to exist between certain engineering or geotechnical properties of bottom sediments and such sedimentological parameters as grain size, specific surface area, sorting and even gross mineral content, there is a need to collect physical samples of both the sediment and the nodules.

Geotechnical Requirements

The marine mining environment consists basically of the air-sea interface, the water zone, the seafloor and the subbottom. Characterization of this environment and an understanding of its interaction with the various mining systems is not yet fully understood, but such is one of the key requirements in developing successful marine mining technology. Depending on the type of deposit (dissolved, unconsolidated or consolidated) and its geographic location, each deposit will have a different environmental setting that must be described in order to define the specific interactions between the environment and the mining system. These are listed in Table 21.

TABLE 21
PARAMETERS TO BE MEASURED FOR COMPLETE CHARACTERIZATION OF A MARINE MINERAL DEPOSIT (AFTER CORP, 1970)

1. Charts, Large Scale
    - a. Bathymetric
    - b. Topographic of surrounding land
    - c. Bottom conditions
2. Index and Engineering Properties of Bottom
    - a. Grain-size distribution
    - b. In-place density
    - c. Water content or void ratio
    - d. Specific gravity--bulk and individual constituents
    - e. Atterberg limits
    - f. Shear strength and sensitivity
    - g. Compressibility
    - h. Permeability
    - i. Velocity and attenuation
3. Mineralogical and Geological parameters
    - a. Lithology
    - b. Mineralogy
    - c. Radiometric properties
4. Geophysical Parameters
    - a. Subbottom profiles
    - b. Magnetometer/gradiometer profiles
    - c. Seismic profiles
5. Environmental Parameters--Seasonal and During Test Periods
    - a. Wind speed and direction
    - b. Wave height, period and direction
    - c. Current speed and direction
    - d. Tides
    - e. Water turbidity
    - f. Water temperature
    - g. Ecology

There are compilations of oceanographic data on the air-sea interface and on the sea that can be used to provide environmental information for a potential mining operation in almost any Pacific area. However, published data on the engineering properties of the seafloor and its subbottom are not plentiful. Although extensive engineering properties investigations of offshore sediments have been conducted, the geographic areas covered by these studies do not include zones of potential nodule mining.

Currently, industrial emphasis has been placed on the development of geotechnical techniques for the delineation and exploitation of marine placer deposits. Similar development of techniques must eventually be made for materials associated with non-placer-type deposits, particularly manganese nodules.

In evaluating the economic feasibility of a commercial offshore placer operation—our basis for dredging investigations up to now—there are two main factors to be considered: (1) the value of mineralization available for extraction and (2) the cost of delineation and mining. The latter factor represents a major unknown which can only be answered by extensive analysis of the mining system components and their interaction with the environment. Successful marine mining systems will be possible only by achieving better operational control and a better understanding of the engineering properties of the deposit material being mined. Thus, characterization is basic to successful mining systems design.

The most important parameters affecting dredge performance and the most difficult to measure are those describing the material to be dredged. The usual method of determining dredging progress is to conduct hydrographic surveys before, during and after dredging and compute the volume of material removed. For control purposes during the actual dredging operation, continuous monitoring is required in order to evaluate the dredging equipment and the operating procedures and to ensure optimum productivity. This information can best be obtained by the use of performance monitoring instruments. The U.S. Army Corps of Engineers has made notable progress in up-grading dredge performance by utilizing production measurements and controls during hopper dredging operations. Mauriello and Dennis (1968) point out the relationship between the characteristics of subbottom materials and dredging capability. Iwata (1970) describes laboratory tests for grab dredging to relate ground characteristics to dredge performance. Van Baardewijk (1968) discusses in some detail the interaction between dredge and soil and presents a basic classification system established by the International Association of Dredging Contractors for identifying different soil types and the engineering measurements required for determining their dredgability. Even though the importance of the dredging parameters is recognized, their effects on system performance have not been closely studied, and much remains to be done in order to assess their full influence. For example, the frictional or strength properties of a soil are significantly affected by the rate of loading. Therefore, optimization in the speed of a dredge cutter could improve its performance. Water depth and the influence of pore pressure on the engineering behavior of the subbottom must also be considered. There is insufficient knowledge at present to justify extrapolation of shallow water classification data to deeper water depths.

Although the foregoing discussion stresses the importance of subbottom characteristics in assessing dredge performance, these characteristics are equally important in evaluating other subsystem components. Great improvements could be made if the effect of soil parameters on penetration rate, core recovery and sample reliability were better understood. Techniques are being utilized to determine true in-place density in conjunction with routine deposit delineation. This can be accomplished by controlled coring using very thin-walled tubes for short penetrations, by in situ penetration measurements based on a pre-established penetration-density index or by indirect means such as acoustic or nuclear-density measurements.

The design and performance of other subsystems are also affected by the deposit characteristics.

Transportation, beneficiation and waste disposal techniques require adequate information concerning the grain size and sedimentation characteristics of the excavated material as well as its consistency and plasticity grading in the disturbed state.

Problems with bottom slope stability will also need solutions in order to prevent contamination of the mining areas or burial of bottom-supported equipment as a result of slope failure. The use of equipment on the bottom will require knowledge of the seafloor-bearing capacity. Solution of these problems requires knowledge of sediment shear strength and compressibility. Sonic velocity characteristics of the deposit material are needed for the interpretation of subbottom profiles.

At present there is no way of knowing which index or engineering parameters will correlate with system performance and will have the controlling effect on system design. It is necessary, therefore, that a preliminary characterization of marine deposits incorporate as many index and engineering parameters as possible. A sample of the current data sheet used at MMTC for marine placer classification is shown on Figure 12. The terms under the general description section have been proposed by Arthur Casagrande at Harvard and give an extremely indicative insight into engineering behavior. Similar investigations have recently been initiated by the Underwater Minerals Program at the University of Wisconsin, and their early review of data suggests that such measurements are basic to designing the mining systems for deepsea nodules as well as for onshore placer deposits.

Oceanographic Requirements

Measurement of physical and chemical oceanographic variables is a necessary adjunct of deepsea mineral exploration for a number of reasons. The mineral content of the deposits may be influenced by the nature of the water interface; operations will be strongly influenced by the dynamics of the water mass, and the biomass is "water dependent" in a variety of ecological niches, any of which could be affected by disturbance caused by mineral exploitation.

The state-of-the-art for many of these measurements, particularly on a widely dispersed, synoptic basis, is not sufficiently advanced for mining use. There are, for example, few reliable measurements of bottom currents in the deep ocean. Most estimations have been made from the configuration of sediment ripples or the amount of sediment coating on jutting rocks or nodules as observed in photographs or from theoretical considerations. Cyclical or seasonal measurements are virtually nonexistent.

The art of measuring sea state is a little more advanced, but prediction is not yet fully reliable. The geochemistry of ocean waters and the identification and measurement of particulates is again in a primitive technological state with regard to the deepsea. Programs such as the Geochemical Ocean Sections Study (GEOSECS) of the IDOE will do much to improve capabilities in this regard, but the very vastness of the deepseas will make significant coverage a formidable task.

Our review of the available information leads us to suggest that the measurement of oceanographic variables should be by automatic, self-recording in-situ sensing systems.

Meteorological Requirements

Most data on weather and climate are required in order to evaluate available working time in areas adversely affected by weather conditions and also to reduce the risk of loss of life and property. The weather is mostly a surface phenomenon, and, because of its very substantial impingement on operations at sea, good meteorological data such as outlined earlier are of paramount importance. All this could be obviated in the deepsea, however, by placing the operations in a submerged mode and making use of the predictable "climate" of the seafloor environment. Thus, prior to iniating a major meteorological program, some serious study should be given to the possibility of placing parts of any nodule mining system on the deepseafloor or, at least, to submerging parts of the system beneath the surface of the sea.

Ecological Requirements

The collection of data on the life on the deepsea and the understanding of environmental change is a complex and formidable task. The basic requirement for evaluating the influence of a mining is a knowledge of existing life in the water and on the seafloor. The food chain cycle has to be determined from the surface layers of primary photosynthetic production to the detritus dependent creatures in and on the bottom. Natural changes must be recorded and the effects of artificial change predicted and superimposed. The ecological data base is virtually unknown in the deepsea and new techniques will have to be developed in order to obtain the necessary data.

In the exploitation of ferromanganese nodules, three major types of disturbance can be anticipated, according to the present state-of-the-art. Hydraulic systems will bring up cold water and seafloor sediment from the depths and disperse them over the surface waters. Mechanical systems will disperse a sediment plume from the bottom to an indeterminate height, and both systems will cause overturning of sediments in place. In the exploration phase, then, measurements will have to be made of baseline conditions and populations. Disturbances will need to be monitored, and post-mining monitoring will have to be maintained for about a year. With the current lack of operations to allow for post-operational monitoring, it may be possible to acquire some useful data from the examination of previous exploration areas. This would require a careful search to locate previous sites of experimental nodule mining.

Operational Prerequisites

For all mining activities at sea, whether exploration or exploitation, there are certain basic operational prerequisites. These include a knowledge of the weather, a platform from which to carry out the mission, a source of power and a knowledge of precise location. Lastly, the ability to maintain position at any desired location is mandatory for the accomplishment of most activities requiring contact with the seafloor. The state-of-the-art for each of these functions varies — in some cases, being well advanced as in navigation and, in some cases, being in a more primitive state as in environmental forecasting. What sets these functions apart is that their technological development will not be dependent on the viability of mineral resource exploitation, and the costs of innovation will not be a charge against the minerals resources base.

Environmental Predictions (after Baer and Crutcher, 1973)

The best long-range estimates of future environmental conditions are provided by statistical summaries of past occurrences. Such information is commonly presented in atlas form (Figure 13). The contours define the absolute magnitude of the various mean surface wind velocities at different times of the year. Table 22 lists the number of available references which provide similar information for other characteristics and parameters, and a more comprehensive summary of atlases has been published by Rigby (1968).

Marine Minerals Technology Center

Sample Information:
Sample No.________. Container____of______.
Date taken________. Person______________.
Depth____to____. Water depth____________.
Condition of sample_____________________.
Method of sampling______________________.
Other___________________________________.

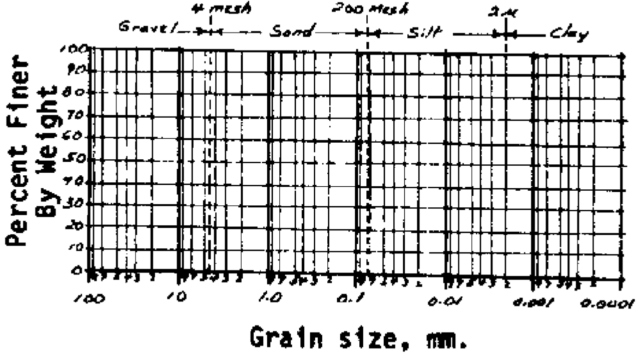
Geologic Information:
Description_____________________________
____.
Origin__________________________________
____.

Mineralogical and Chemical Information
____
____
____
____
Organic carbon content__________________
Soluble salts___________________________
Carbonate content_______________________

Other Information:
____
____
____

General description: fill in or circle applicable terms.
Color____________________. Odor__________________.
Grain size--very coarse, coarse, med.-coarse, med.-fine, fine, very fine.
Fine grains visible (less than 0.05 mm)? -- yes or no
Dust sizes present? -- yes or no
Gradation -- very uniform, uniform, poorly graded, fairly well graded, well-graded, very well graded.
Compactness (cohesionless materials) -- very loose, loose, med. dense,dense(firm), very dense (well compacted).
Consistency in undisturbed state -- soft, spongy, brittle, friable, elastic, sticky, stiff, hard,____________________
Consistency in remolded state -- sticky, soft, medium stiff, stiff, hard.
Plasticity grading -- nonplastic, trace of plasticity, med. plastic, highly plastic.
Consistency near plastic limit -- weak, soft, low toughness, medium toughness, high toughness,____________________
Fingernail rub test -- dull, shiny, very shiny
Dry strength -- none, very slight, slight-medium, high, very high
Reaction to shaking test -- none, slight, good, very good
Other -- ____

Index Properties:
Specific gravity -- (water at 1 gm/cc)
apparent (natural state)__________.
absolute (ground to -200 mesh)__________.
Dry density --
natural_______. remolded________.
Proctor max.______. optimum moist.______.
Proctor min.______.
relative density__________.
Grain size data --
effective size________.
coefficient of uniformity________.
other____________________________.



Water content______. Void ratio______
Degree of saturation__________.
Penetrometer reading -- Pocket______
Proctor________. Needle size______
Torvane________.
Atterberg limits -- Liquid limit______
Plastic limit_____. Sticky limit____
Plasticity index______.
Symbol designation on Unified Classification System__________

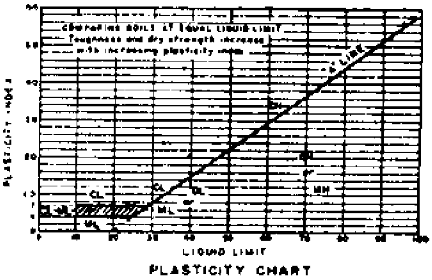


Figure 12. Marine placer classification data, Part 1

Engineering Properties

Unconfined Compression Test:

Compressive strength undisturbed________.

Water content, w = _______.

Compressive strength remolded__________.

Water content, w = _______.

Sensitivity______. Loading rate________.

Moduli of deformation, M_o=_____,M_{50}=_____.

Remarks________________________

Vane Shear Test:

Shear strength_______. Loading rate_______.

Remarks________________________.

____

Consolidation Test:

Coefficient of compressibility,

a_v = ________.

Coefficient of consolidation,

C_v = ________.

Compression index, C_c = ________.

Coeff. of Permeability, k = ________.

Time for 100% primary consolidation,

t_{100} = ____________.

Preconsolidation pressure,p_p = _____.

Remarks________________________

____

Direct Shear Test:

Peak angle of internal friction, ϕ_m =_____.

Shear displacement at peak____________.

Normal displacement at peak____________.

Ultimate angle of intermal friction,

ϕ_u = ___________.

Shear displacement at ultimate__________.

Normal displacement at ultimate_________.

Remarks________________________

Permeability Test:

Type of test__________

Coefficient of permeability, k=______.

Remarks________________________

Sonic Velocity Test:

____

____

____

____

Triaxial Test:

Type of test______________. Sample condition______________

Run Number	No.1	No.2	No.3	No.4	No.5	No.6	Average
Water content at start, w_o							
Water content at end, w_f							
Initial dry unit wt., $_d$							
Initial void ratio, e_o							
Initial degree of saturation, G_w							
Confining pressure,σ_c							
Time of loading							
Rate of strain							
Max. compressive strength,$(\sigma_1-\sigma_3)_{max}$							
Max. principal stress ratio, $(\sigma_1/\sigma_3)_m$							
Moduli of deformation, M_o							
M_{50}							
Max. neutral stress, $(u-u_o)_{max}$							
Cohesion intercept, c							
Angle of failure plane,α_f							
Angle of internal friction, ϕ							
Other information							

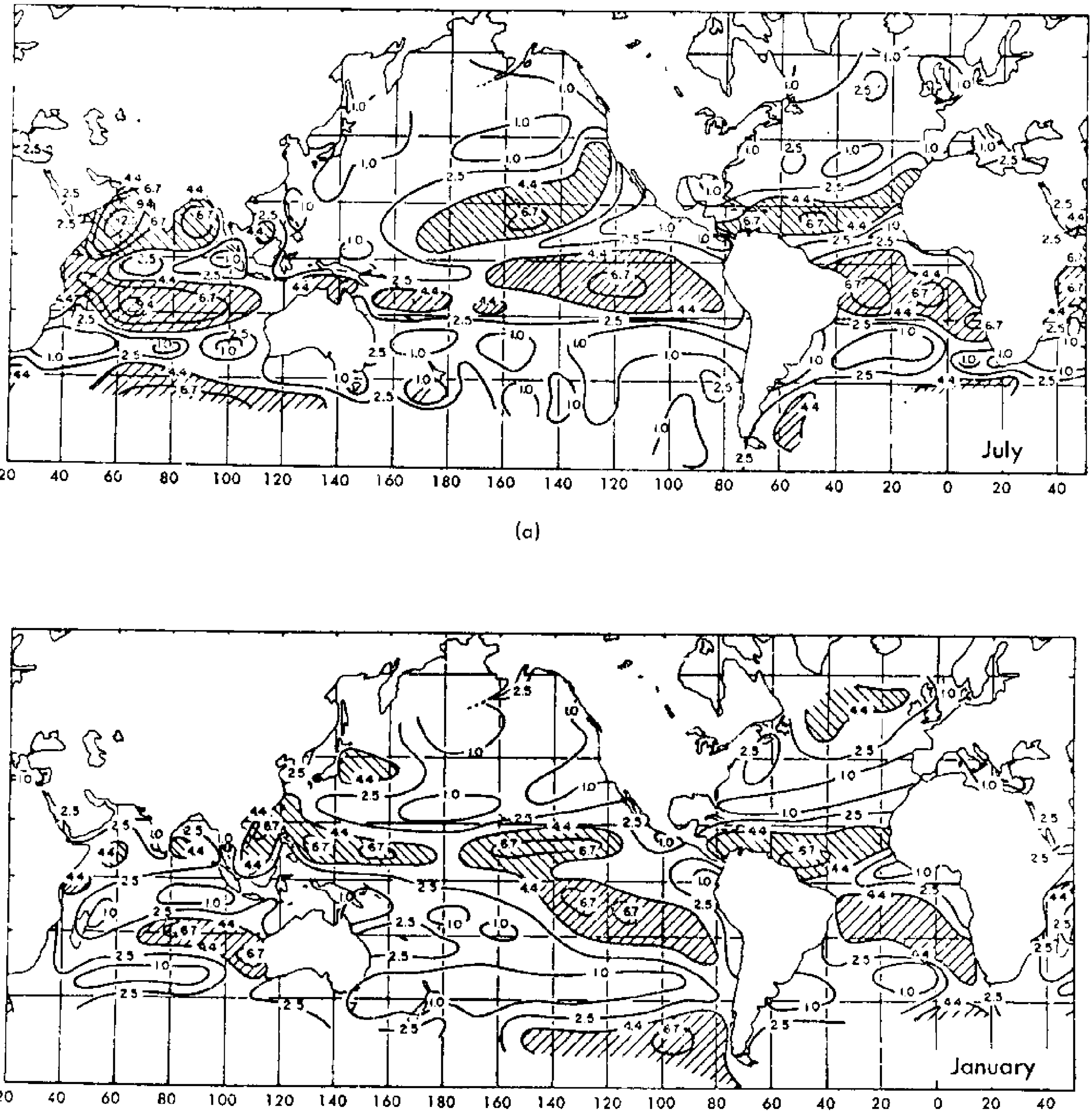
Remarks____

____

____

Other Information:

Figure 12 (cont'd). Marine placer classification data, Part 2



Magnitude of the mean surface wind in (a) July, (b) January. The contours show the magnitude of the mean vector wind at 10 meters anemometer height in m/sec. [From Y. Mintz and G. Dean, 1952, *Observed Mean Field of Motion of the Atmosphere*, Geophysical Research Paper 17, Geophysics Research Directorate, Air Force Cambridge Research Center.]

Figure 13. Mean surface wind speeds

TABLE 22

CLIMATOLOGICAL DATA GENERALLY AVAILABLE IN REFERENCE FORM REGARDING WEATHER PREDICTION (AFTER BAER & CRUTCHER, 1973 (IN PRESS))

PARAMETER	DATA PRESENTED	NO. OF REFERENCES
Barometric Pressure	Mean Isobars	11
	Frequency Distributions	10
Visibility	Percentage Time Visibility Below Specified Values	10
Winds	Wind Roses - Percent Frequency Gales, etc. Wind Components Only	13
Temperatures (Air)	Frequency Distributions Means Only	12
Temperatures (Water)	Isotherms of Sea-Air Temperature Differences	16
Ice	Limits of Ice Extent	13
Long Period Waves (Tides)	Entire Pub. on Tides and Currents	3
Wind Waves	Entire Pub. on Sea and Swell	5
Large Scale Currents	Maps Depicting Prevailing Current Direction and Mean Speed Range	3

Climatological atlases can provide a general insight into the gross conditions expected in the area but do not provide detailed enough information for solution of specific design or planning problems for specific locations. Such information usually requires a detailed analysis of original observational data, theoretical computations and interpretations.

When the duration of local observations is not adequate, theoretical diagnostic procedures similar to those used in short-range forecasting may be applied in a procedure termed "hindcasting." The accuracy of hindcasting can be improved significantly when actual local observations are available for a duplicate time period. These become even more important when short-term forecasting is planned or when high accuracy is needed. Therefore, an observation program should be established prior to any operations. The program may vary somewhat according to the information needed but should generally include a six hour minimum frequency of observation.

Observing Techniques

Following are brief descriptions of observing techniques which are commonly used.

Barometric Pressure

Normally, this variable is recorded continuously on a microbarograph which is calibrated periodically against a mercurial or precision aneroid barometer. These data are needed in conjunction with other simultaneous pressure data to predict surface wind conditions.

Visibility

Ordinarily visually observed and manually recorded though some locations may be instrumented adequately. Importance is the regular occurrence of haze or fog.

Wind

Either continuous recordings should be made or both mean and instantaneous gust values recorded. Means should be averaged over at least 15 minutes. The vertical profile of wind velocity varies significantly with altitude so that the same elevation must be maintained. There would be an advantage in multiple elevations which would be optimally spaced at approximately double the elevation of the one below. Great care must be used to locate the sensors where they are exposed to an unobstructed wind, remembering that new shore conditions are different from open ocean conditions.

Atmospheric Temperature

Many types of instruments are available to record temperature. Special attention must be given to achieve adequate aeration of the sensor while protecting it from spray and direct or reflected sunlight.

Water Temperature

The instrument should have a time constant of at least 10 minutes and accuracy of 0.1°C. Sharp gradients occurring in the vertical may be helpful in determining water currents.

Ice

In those high latitudes where ice is common, its thickness and coverage should be recorded. Photographs taken by aircraft should be of great help in describing such conditions.

Currents

Currents are difficult to record directly because of poor instrumental reliability. They vary with tides, waves, winds and depth and location. New current meters are needed.

Long Period Waves

Tides are the best-known, long-period waves. They may be recorded by bottom-mounted pressure sensors. Local resonant oscillations called "seiches" can occur in bays. Trapped "edge waves" can move along shorelines. Hurricanes and other storms cause large "storm surges" near shore.

Wind Waves

These are best recorded by staff, bottom-mounted pressure gage or free floating accelerometer. None of these methods is reliable for long-term operation. In shallow water, waves vary significantly with location because they are affected by bottom topography. Waves are best described by spectral statistics but can be summarized by "significant height" which is four times the square root of the variance of the record. Individual wave heights are approximately Rayleigh distributed (Longnet-Higgins, 1952) which can be used to estimate extreme individual waves from the significant height that most atlases present. Nevertheless, much of the current wave research is not directed toward solving ocean mining operational problems. Accordingly, we recommend that new research promulgated in response to the mining needs be directed towards specific problems such as waves attenuated by wave traps around mining barger, waves against ore carriers and, certainly, better wave prediction systems.

Platforms

A platform (ship, barge, etc.) is the fundamental requirement of any operation at sea. There are three basic functions of platforms used in marine exploration and exploitation: (1) the support of equipment for observation and measurement,

(2) the support of tools and equipment for working with seafloor materials and (3) the transportation of people and materials (Table 23). Platforms may be air airborne, floating or in contact with the bottom; they may be self-propelled or stationary, or they may be manned or unmanned. Floating platforms size ranges from massive bulk carrier units weighing upwards of 300,000 T to an individual diver weighing a few tens of pounds. Many of them, such as the hovercraft, perform across the interface and may thus be used in several modes.

TABLE 23
CLASSIFICATION OF PLATFORM TYPES IN USE AT
PRESENT (1970) ACCORDING TO FUNCTION

PLATFORM FUNCTION	AIRBORNE	SEASURFACE	SUBMERGED	BOTTOM CONTACT
Measuring	X	X	X	X
Exploration	X	X	X	X
Survey	X	X	X	X
Environmental Monitoring	X	X	X	X
Handling				
Drilling	-	X	-	X
Dredging	-	X	-	X
Construction	X	X	X	X
Transporting				
Personnel	X	X	X	-
Supplies	X	X	X	-
Products	-	X	-	-

Airborne Platforms

The use of airborne vehicles is common for support of marine mining operations. These may include fixed wing aircraft (Webb, 1965) and helicopters (Jenkins, 1973), hovercraft for exploration and survey (Eggington and George, 1970) and satellites for survey, navigation and environmental monitoring.

Floating Platforms

A large variety of floating platforms is available for all functions at sea. They include survey vessels, drill ships, dredges, transports, semisubmersible platforms and submarines of various configuration and purpose. Where conditions are suitable, ice cover may be used as a base for working (Daily, 1969).

Submerged Platforms

The use of manned deepsea submersible vehicles is becoming more widely accepted as depth and payload capabilities increase, but the state-of-the-art is still not sufficiently advanced for their use as an economic exploration tool. Towed, unmanned platforms are an intregal part of any deepsea exploration program for manganese nodule deposits, and they carry such instruments at T.V., stereo cameras, bottom samplers and acoustic probes. However, they lack the capability of high speed towing and, for the most part, are in a somewhat primitive stage of development. Unmanned and untethered submersibles controlled by acoustic telemetry are also in the development stage but, as yet, unperfected.

In regard to development of submerged platforms, we believe that engineers at Scripps Institute of Oceanography, Woods Hole Oceanographic Institute and the University of Hawaii could make significant advances in closing the gap between what is available and what is needed. There is also a role for industry, and cooperative ventures between these academic institutions and such firms as Westinghouse, for example, would greatly enhance early successful development.

Bottom Platforms

Platforms in contact with the bottom are suitable for many purposes, particularly when sea motion is to be avoided or a large machine base is required. They include the many types of drilling platforms, artificial islands and a number of bottom crawlers being constructed for the development of marine resources.

The choice of platform is made only after consideration of the following factors:

Major function
Operational environment
Ancillary functions
Magnitude of effort
Mobility
Cost

Design Considerations

The design of marine platforms is a very specialized subject, and consideration of different factors is required for floating platforms and for platforms in contact with the bottom. (Airborne platforms are not considered here.)

Four steps are involved in the design of floating platforms:

1. Specification of requirements based on the analysis of the task to be performed and the geographic limits of the platform operations. In tasks requiring contact with the bottom such as drilling or dredging, it will be necessary to specify the maximum water depths and maximum penetration depths required as well as anticipated subbottom characteristics.

2. Preliminary design should allow for the problems of internal forces, motion and working environment that must be considered in the selection of the type of platform. The effect of wind, waves, current, drag and inertia are all significant with regard to anchoring and platform motion. Suppression of motion is of extreme importance in most operations. Other environmental factors which must be considered are biological fouling and corrosion. Special equipment for the operations must be specified at this time and limiting factors disclosed. The propulsion power required, allocation of space, platform weight and checks of stability, strength and free board are also needed during preliminary design and the principal configurations and dimensions optimized.

3. Contract design involves the preparation of drawings and specifications of the platform which are sufficiently detailed to be used as a basis for preparing or soliciting bids for fabrication.

4. Detailed design and construction is generally carried out by the builder's yard and includes the preparation of working drawings, construction and launching. There is no treatise on mining dredges, but the reader is referred to the many references (629.12) dealing with the ship design, many of which are directly related to mining vessel design.

Platforms in contact with the bottom do not as yet constitute a major requirement in marine mining plat design, but they are used in the extraction of sulfur offshore by the Frasch process (Lee et al., 1960) and in the development of underground mines from artificial islands offshore (Beki, 1970). Crawlers have a potential use in the exploration phase, and they should be so considered.

In addition to the environmental considerations discussions for floating platforms, the design of fixed offshore structures should provide for extraneous loads due to earthquakes and for reduction in structural integrity due to fatigue and corrosions. Design factors for the deepsea are virtually unknown — a significant gap.

Acquisition of Platforms

Although construction of new platforms to suit each particular task is technically desirable, conversion of existing platforms will probably be necessary. The charter of vessels for ocean operations is a transaction that requires specialized knowledge to ensure that the mining company obtains a vessel suited to its needs. To protect themselves, companies should always use the services of a competent admiralty attorney before making any commitment. We suspect that even in the law there are gaps that must be closed.

Conversion of sea-going vessels to exploration or mining platforms has been done in only a few cases. Thus, the trade-offs of conversion or new construction should be considered very carefully in a production operation where the additional stresses of mining are added to those of seakeeping.

The Diver as a Platform

Divers are used as an adjunct to marine mining operations in all three basic modes: to observe and measure, manipulate tools and equipment and transport people and things.

However, for deepsea work their use is limited to maintenance and support of equipment on and near the sea surface. We do not detect any important gap in this effort.

Costs

The costs of operation of platforms at sea vary widely. Tables are useful as indications of ownership cost, and Tables 24, 25 and 26 give an estimate of the cost range for large tonnage sea-going transports. As with most structures, the greater the size, the lower the unit cost. In order to advise would-be mining groups in terms of real costs, we would recommend that only a team of economists, accountants and mining engineers could make reasonable estimates of total costs.

Power

Power sources for use in deepsea operations are subject to many of the same limitations applying to remote sites on land. Selection of the optimum power source must be weighed against the following factors.

1. Amount of power required, including peak power and sustained load.
2. Availability of suitable generating equipment.
3. Cost.

Power sources for marine use are many and varied and are constantly being improved. Most existing mining operations offshore use conventional power sources such as portable diesel electric generators, and there is a trend to the use of gas turbine generators in the offshore oil industry. These should be considered in any similar mining venture.

A serious limitation associated with the transmission of electric power at great ocean depths is the difficulty of providing watertight cable connectors. The trade-offs between high voltage AC and high voltage DC should be considered also with regard to transmission loss. The use of nuclear energy has been considered for future marine operations, and the utilization of energy from the ocean itself should be considered. For submerged instrumentation and measurement, many small portable power sources are available and reliable, and continuous supply of power aboard floating platforms is available using conventional sources.

Figure 14 shows approximate costs of marine systems in 1965. Small power sources such as batteries, fuel cells or certain isotopes can operate successfully in the submerged mode. Fuel cells and batteries generally cannot operate for more than a few weeks without recharging or refueling. Systems with large energy requirements may require a nuclear reactor power source. They allow long-term operation at any depth, assuming pressure containers can withstand the depth.

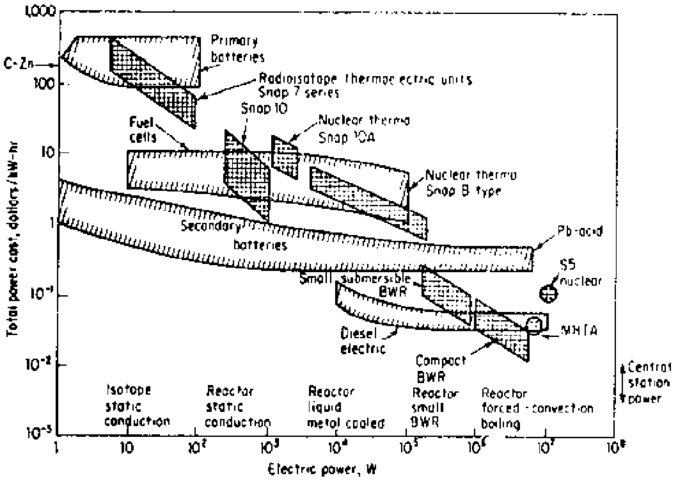


Figure 14. Marine power costs for exotic systems based on 1965 data (Cohn and Wetch, 1969)

Navigation and Survey (largely after Barnes, (1972)

Standard Navigation Techniques and Instruments

Techniques for precise positioning a ship at sea are crucial to exploration and recovery. Determining the position of a vessel at sea can be accomplished in a variety of ways, the choice of which will depend on the scope of the operation, accuracy required, system mobility, distance from shore, cost and whether it meets the engineering requirements of the task.

The methods of position determination can be broadly categorized as: dead-reckoning, bottom sounding, satellite, acoustic Doppler, inertial guidance, automatic star and sun-moon trackers, visual onshore objects, astronomical and electronic. The older methods of positioning by dead-reckoning and simple use of contoured bathymetry charts in conjunction with echo sounders give, at best, only

TABLE 24
CAPITAL AND OPERATING COSTS FOR SOME WORK PLATFORMS AT SEA (COMPILED BY AUTHOR)

	INDUSTRIAL RESEARCH SHIPS AND WORKBOATS	HYPOTHETICAL WORKBOATS			ACADEMIC RESEARCH SHIPS	SUBMERSIBLES (WESTINGHOUSE)
Platform Details	Less than 200 ft.; Less than 3,000 T displacement	75 ft. 10 knots	125 ft. 11 knots	175 ft. 12 knots	750-800 T Gross	
Accom. Crew		6	8	12	18-20	
Technical Staff		4	6	16	10-14	
Capital Costs $		300,000	400,000	850,000	200,000 to 1,000,000 (Acquisition or conversion)	3,000,000
Operating Costs		1968	1968	1968	1968	1968
Amortization	25% Cap	12,000	16,000	34,000	*	50,000
Insurance		2,500	3,000	5,000	24,000	9,000
Capital Items	3% Cap	1,500	2,000	3,000	43,000	10,000
Insurance	3-4%					
Maintenance	6-7% 0.01% Cap/day	5,000	6,700	9,000	84,000	21,000
Crew	$50-75/man/day	19,000	24,000	42,000	212,000	40,000
Food	$5/man/day	3,000	4,200	8,000	29,000	
Fuel	$0.15/Hp/day	4,500	5,000	7,500	25,000	2,000
Other	1% Cap 0.02% Cap/day	3,000	5,000	10,000	29,000	10,000
Management/Prof.	10% Cap				49,000	28,000
Total		50,500	65,900	118,500	495,000	160,000
Day cost		1,000	1,300	2,450	1,575	8,000
Remarks	Operating cost estimates detailed above are for ownership.	Working 1,000 miles from homeport, 50% working, 50% moving, 60 days total.			45 operating days, 7 ships	Monthly cost, 15-20 dives, 40-60% usage.

*not included

TABLE 25
AVERAGE COSTS OF OWNING AND MAINTAINING MARINE EQUIPMENT IN THE U.S. (ASSOCIATED GENERAL CONTRACTORS OF AMERICA, INC., (1966).

COASTWISE CRAFT	AVERAGE ANNUAL EXPENSE PERCENT OF CAPITAL INVESTMENT WITHOUT FIELD REPAIRS				AVERAGE USE MONTHS PER YEAR	EXPENSE PER WORKING MONTH PERCENT	APPLICATION OF A.G.C. SCHEDULE TO OWNER'S VALUES	
	Depreciation	Overhauling Major Repairs Painting	Interest Taxes Storage Insurance	Total Ownership Expense			Value Dollars	Expense Per Working Month Dollars
Derrick Boat	10	8	16	34	8	4.3	(Fill in your own values)	
Dredge, Clamshell	8	6	16	30	8	3.8		
Dredge, Dipper	12	16	16	44	8	5.5		
Dredge, Hydraulic	10	7	16	33	9	3.7		
Drill Boat	8	11	16	35	10	3.5		
Lighter	10	8	16	34	10	3.4		
Mixer Boat	13	16	16	44	8	5.5		
Pile Driver	12	8	16	36	8	4.5		
Scow	8	6	16	30	10	3.0		
Scow, Dump	12	11	16	39	8	4.9		
Tug	10	13	16	39	10	3.9		

Note: Column Three is a summation of the following: Interest 5%, Taxes 1.5%, Storage and Incidentals 4.5%, Insurance 5%.

an approximate location. Positioning with advanced instrumentation such as used in satellite radio telemetry, acoustic Doppler, inertial guidance and tracking systems require large initial expenses and may be economically impractical. Visual positioning employing transit and sextant instruments to calculate distances by triangulation and three-point fix onshore markers has long been adequate although limited to near shore. Such could be used near islands. Astronomic positioning by fixing to celestial bodies has been used to locate offshore installations beyond the limit of visibility of shore stations or reliable electronic control. Astronomic positioning is a time-honored system of navigation, but it is gradually giving way to more advanced instrumentation as experimental electronic systems become more operational and less expensive.

Electronic Systems

Present operational electronic methods of position determination are developed to the point where they are practical, economical and, in fact, essential to deepsea research and survey work. The advantages of greater efficiency and accuracy at reasonable cost are increasing the adoption of electronic methods of navigation and positioning for many mining survey projects.

There are at least 50 systems for electronic position determination. These range from world-wide coverage utilizing a network of shore stations, to local systems with but two portable shore stations; and, in cost, from millions of dollars to a few thousands of dollars; and, in accuracy, from a general location (with a few nautical miles) to accurate locations (within a few meters).

Table 27 tabulates the electronic methods available by system, equipment specifications, capability and cost and gives information regarding the types of equipment available and the selection of the system suited to various marine navigation and survey operations.

Deepsea Navigation

The accuracy of navigation required becomes greater as exploration and delineation become more refined. In broad exploration programs, satellite navigation or even dead-reckoning and star sights may be utilized to advantage, but once deposit delineation or characterization is required then accurate position fixing within meters or less is mandatory. This can only be accomplished by reference to a fixed point or points on the bottom, and, as yet, the technique of accurate survey as on land has not been perfected for the deepsea on a non-military basis.

Short range systems such as radar, visual fixing or Raydist may be used between vessels for establishing relative positions among operations employing a number of platforms.

There is also a need to provide accurate navigation for conservation measures. To mine in a patchy manner is neither good conservation nor good business practice.

TABLE 26

CONSTRUCTION DATA FOR BULK TRANSPORT CARGO VESSELS (MADDEN, 1970)

DEADWEIGHT TONS	200,000	20,000
CONSTRUCTION ($/DWT)	$ 70	$ 220
HORSEPOWER	300,000	9,000
TONS/HORSEPOWER	6.7	2.2
HORSEPOWER/TONS	.15	.45

Navigation of Undersea Platforms

While using basically the standard methods of electronic positioning for surface movements, submersible platforms require altogether different navigational aids for positioning on the bottom. These generally relate the position of the submerged platform to the surface support platform or to some local grid. Existing systems depend on support ship tracking systems, dead-reckoning or the use of local bottom markers. Many factors must be considered to determine the best system for any particular job. Platform specifications such as power, payload, dimensions, environment characteristics such as depth, bottom features, quality of the water and availability of systems must all be considered before selection. Some of the systems are illustrated in Figure 15. Obviously, considerable research remains to be done in order to provide accurate but reasonably inexpensive navigation systems for nodule mining.

Seafloor Survey

Mapping the seafloor is obviously much more difficult than mapping on land. Visibility is limited, and bench marks must be set under water if they are required.

There are basically two kinds of base maps — or charts — needed for marine minerals operations depending on the nature of the operation: its whereabouts and whether the user is conducting an exploration-type operation or engaged in the exploitation of a deposit. Geodetic control at the sea surface is attainable to varying degrees of accuracy using electronic positioning systems discussed previously, but establishing a marine geodetic control point on the seafloor, however, requires application of new methods not previously encountered on land. Experiments conducted by Mourad (1970) indicate " . . . the feasibility of man ultimately being able to establish geodetic reference points at sea to an accuracy comparable to that achievable on land . . . " Perhaps then, it is incumbent on an international body to establish and maintain seafloor bench marks.

In marine mineral exploration, the primary base map is a bathymetric chart; this is true regardless of area and water depth. Ideally, a scale of at least 1:24,000 and preferably larger is required. Available bathymetric charts may be dated, and very few reflect the scale required unless they were made in shallow waters of bays or estuaries. Charts made prior to World War II, when modern electronic positioning systems were nonexistent, generally lack sufficient accuracy for mining control. Conversion of scale by photo enlargement to required size will yield, at best, the general or average relief of bottom topography even if accuracy of position is assured. In most cases, the miner will need to re-survey the area and produce his own version designed on close grid profiles. Normally, bathymetric control lines along the Continental Shelf are spaced on five-mile intervals. In the slope and deepsea regions, line spacing may be, at most, 10 miles. Considering the possibility that a mineral deposit may not exceed 30 to 40 square miles in area, it is highly improbable that line densities of these magnitudes will suffice for detail delineation and characterization of a deposit. The target area should be defined by a bathymetric survey on a grid consisting of not more than 1/4 mile line spacing at a resolution of at least one percent of the water depth from 50 to 600 ft, with increased tolerance for greater depths. Control of this tolerance can be greatly enhanced by the use of submersibles. The value of tight grid high resolution surveying for bathymetry is emphasized by the interpretation of the morphology depicted in the contoured data. High yield concentrations of minerals (i.e., phosphorite, manganese, heavy metals) are in many cases controlled by tectonics and geo-

TABLE 27
ELECTRONIC POSITIONING SYSTEMS

NAME	RANGE	ACCURACY
Satellite Systems	Global	155
MX-702 h.p.		155.0 ft
Update Geo Navigator		200.0 ft
4007 AB		0.1 nm
Hyperbolic Systems (Long Range)		
Omega	Global: each station covers 5,000 miles	1-2.0 nm abs.
Omega-1		
Omega R010 &R011		
Omega OR-100A		
Loran-A	700 nm (day) 1,400 nm (night)	2.0 nm
Loran-C	1,200 nm	250-1,500.0 ft
Hyperbolic Systems (Medium Range)		
Decca Navigator	250 nm	0.25-2.0 nm
Lorac-A	200 nm	15-400.0 ft
Lorac-B	200 nm	15-400.0 ft
Decca Survey	200 nm	25-300.0 ft
Hi-Fix (2 range or hyperbolic)	25-200 nm	3.7 ft (hyp.) 2.5 ft (2-range)
Rana F & G	50-76 nm	30-75.0 ft
Toron	400 nm	3-100.0 ft
Azimuthal		
Consol	700 nm	+6.0 nm
Sextent		
Various	1-2 miles	
Radar Ranging (Example)		
Model 436	420,000 ft	±5.0 ft
Ranging Systems		
LAMDA	150-400 nm	15-40.0 ft (day)
Hydrodist	25 nm	5-100.0 ft
Shoran	12-40 nm	30-50.0 ft
EPI	12-400 nm	135-1,500.0 ft
Raydist DR-S	250 nm (day) 150 nm (night)	"few meters"
Autotape DM-40	62 miles	50 cm + 1 100,000 x range
Acoustic Systems		
MRQ-2015A Doppler Sonar	1-600 ft depth	0.2%-400 ft 0.5% 400-600 ft distance travelled
APRS	to 3,000 ft depth	0.5-1% depth
Deep Water Fixing & Command Retrieval	20,000 ft depth	
Underwater Location Equipment	to 1,200 ft depth	±50 ft radius from beacon
TIP	to 20,000 ft depth	
Acoustic Position Measurement (APMS)	50-20,000 ft depth	0.25-1% depth
Navtruk 435	600 ft depth	0.5% distance

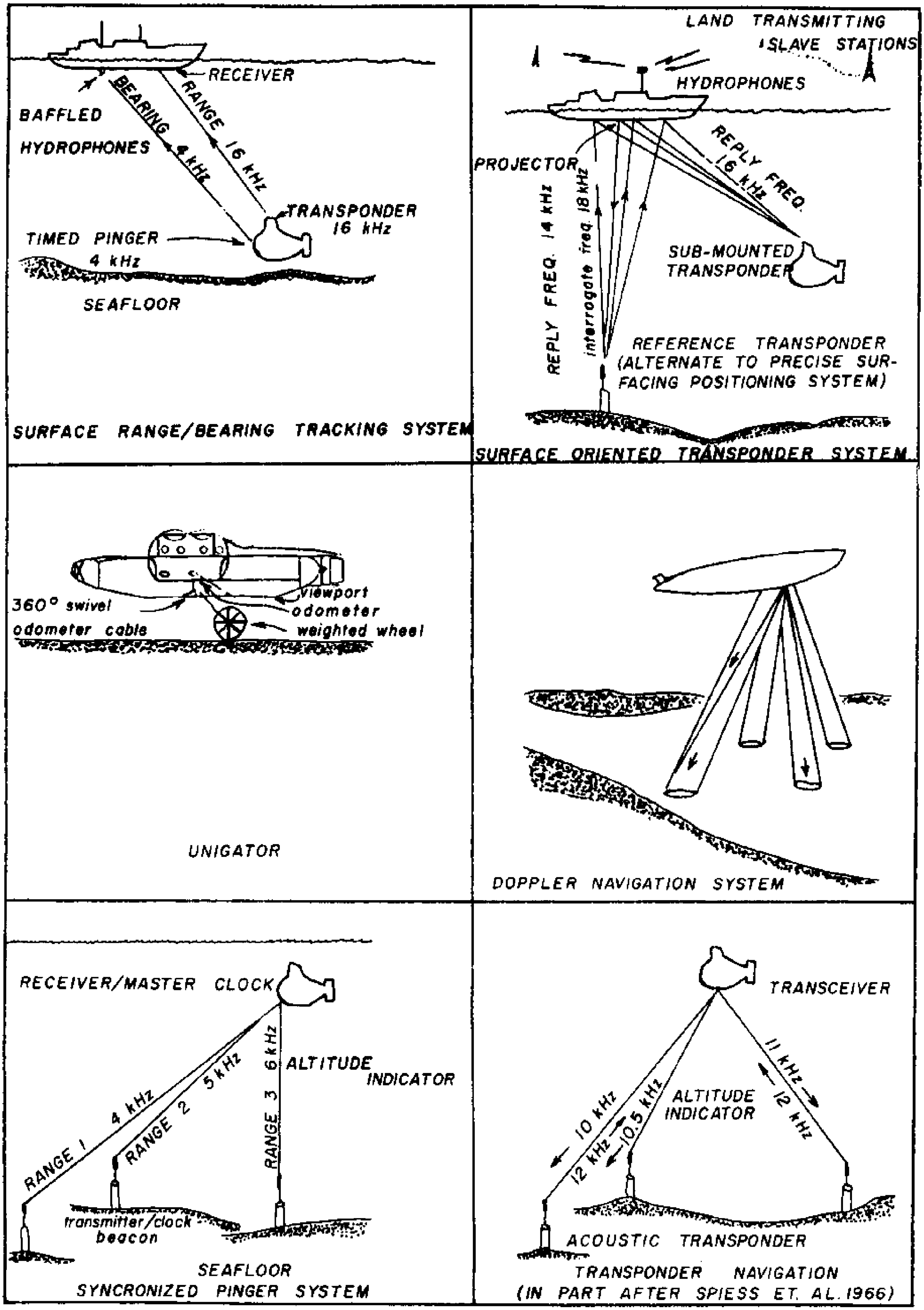


Figure 15: Submersible platform navigation systems (after U.S. Naval Oceanographic Office, 1970)

logic features reflected in the surface relief (Barnes, 1970).

Once the mine site location has been determined and mine survey control is required for exploitation, a new approach to seafloor geodetic control is required. The Pacific experiment conducted by Mourad (1970) is a good example of present thinking on the approach. Three acoustic transponders were planted in about 6,200 ft of water, as illustrated in Figure 16. Each transponder operated at a different frequency using both battery and nuclear power sources to supply energy. An equillateral triangle formed the bottom geometry from which the coordinates of a control point were determined. Four techniques were used to ascertain the coordinates: LORAC airborne line-crossing, satellite, ship inertial and acoustic. The shore-based stations served as the trilateration network from which a land geodetic reference was taken. By positioning a ship directly above the submerged signalling devices, it was possible to use the four techniques to locate the points precisely and establish a marine control point from which submerged mapping exercises could be referenced. The standard point error in ship geodetic position was determined to be between ±50 to ±60 ft. To give some idea of how electronic systems have increased the accuracy of measurement, Mourad notes that the final adjusted coordinates of the control point improved by about 1,600 to 2,000 ft from the original position determined during the installation of the underwater transponders. This is significant in that it implies that location of equipment or markers on the seafloor by other than properly related geodetic measurements will not stand the test of property (mining leases) surveys as to right of ownership.

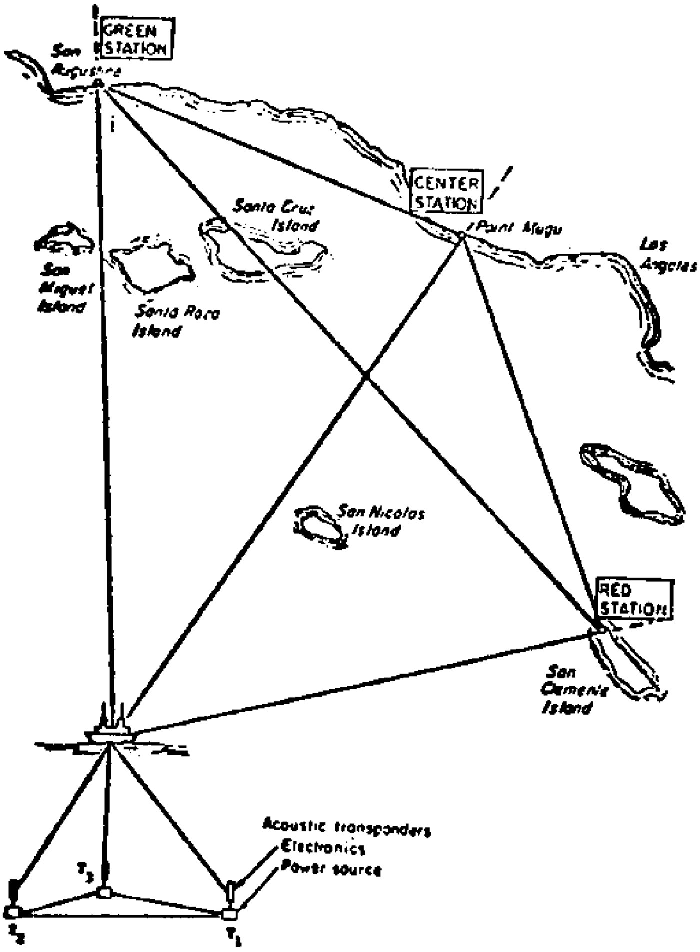


Figure 16: Pacific geodetic control point

Submerged Mapping

As water depth increases, bathymetric mapping problems increase proportionately. Echo sounding methods encounter problems in transmission velocity variations due to density changes (i.e., scattering layer). True depth dimensions in the abyssal regions of the ocean become distorted accordingly. The advent of deep diving research submersibles lend added capability to the marine miner in that he can compensate for these variations that change the detail resolution that can be attained in shallower water.

The submersible equipped with sonar, capable of scanning athwartship segments right and left from the fore and aft axis, can obtain the high resolution bathymetric data required. The elements involved in the survey were:

1. A surface ship fitted with an acoustic ship position measurement system.
2. A shore-based range system to permit the surface ship's position to be accurately known with respect to the shore.
3. A submersible fitted with a precision sonar capable of scanning athwartship segment right and left 30° from the submersible's fore and aft axis and a pinger.
4. A pinger, compatible with the acoustic position measurement system, placed on the bottom in the survey area.

The ship's position is monitored continuously and the input ranges from the shoreline stations recorded. Thus, the position of the submersible relative to the ship is also monitored continuously and the input time differences recorded continuously. Actual survey data are calculated on the submersible's position with reference to an expendable bottom pinger whose position relative to the ship is established by repetitive measurements employing the electronic positioning system and the acoustic ship measurement system. (Estimated 1° circular probable error after one hour measurement <20 ft.)

Using the system described above, the submersible's position essentially is known continuously and is plotted every two minutes during each run (approximately every 300 ft along its track). The depth from the bottom to the submersible is sampled every 4.8 sec (~15 ft) and the submersible's depth recorded continuously. Thus, it is possible to make a first-order plot after each dive to check the data and plan further dives. The submersible transverses the mine site about 430 ft above the bottom at a speed of about 1.5 knots on a series of straight headings, directed from the surface by underwater telephone.

The surface ship holds to immediately above the fixed bottom pinger to minimize acoustic ship position measurement errors. The submersible's actual position is measured and plotted relative to that pinger. The single ping accuracy of the submersible's measured position is within 20 ft relative to the pinger and 10 ft relative to the onshore stations.

The submersible's sonar sweeps back and forth 30° either side of the vertical line from the sonar to the bottom and thus describes a zig-zag path on the bottom about 500 ft wide and spaced about 15 ft between parallel sweeps (Figure 17).

The path coverage of the bottom is 100 percent over the width of about 500 ft as compared to a 63 ft sweep width for a 6° beam towed depth sounder or about 10 ft for a 1° beam width unit (in both cases assuming the towed fish is towed 600 ft above the

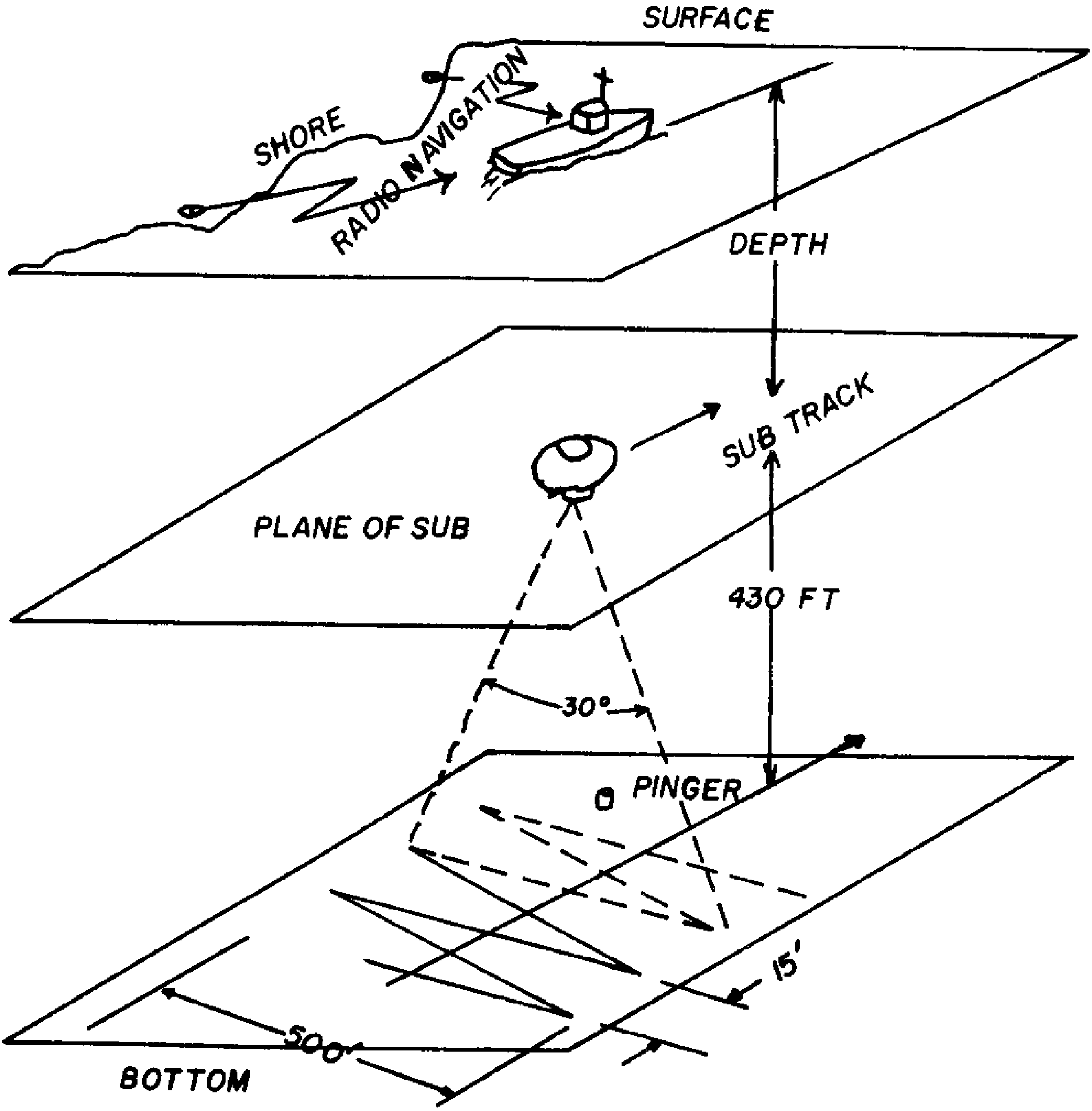


Figure 17: Submerged mapping technique[1]

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1. Technique was developed by the Delco Electronics (formerly Ac Electronics Defense Research Laboratories) General Motors Corporation, using their research submersible the Deep Ocean Work Boat (DOWB).

bottom).

The major advantage of submersible application to bottom surveying is that, with a lane spacing of 500 ft, large areas and prominent bottom features important in submerged mining operations can be observed that otherwise are not noticed using surface echo sounding techniques.

Inderbitzen and Simpson (1970) conducted a field reconnaissance on an area about 15 miles west of Del Mar, California. Surveys were made of bottom sediment and bathymetry using the Lockheed Missiles and Space Company deepsea submersible DEEPQUEST. They reported locating several deeply entrenched submarine gullies. Figures 18 and 19 provide a contrast of bathymetric data made using the submersible with data taken by a surface vessel a few years earlier.

Bathymetric data shown on Figure 19 are examples of the excellent resolution obtainable from a submersible. The submersible made it possible to obtain such detail and also provided an opportunity for direct observation of the bottom topography. It is doubtful the core drill sites could have been selected and drilled in geologically important areas along the sloping terrain using a surface platform alone.

The mapping technique used by Inderbitzen and Simpson was similar to the technique described by Momsen (1969) and employed in sea operations using the Delco Electronics Deep Ocean Work Boat (DOWB). The Lockheed technique employs either a single or multiple number of transponders moored at selected points on the seafloor. Surface buoys linked to the transponders are located by electronic precision positioning instruments aboard the surface tender. These positions are referenced to onshore triangulation sites which give the sea fixes geodetic control of something less than third order triangulation accuracy. Periodic fixes are taken during a dive day to compensate for variations of position due to drift caused by currents, wind and wave action.

A simpler technique has been used by the Westinghouse deepsea submersibles (DEEP STAR 2,000 and 4,000). A transponder is mounted to the hull of the submersible, and, while on the bottom, a high frequency signal is generated by the transponder (active or passive modes available). At the surface a small skiff with a receiver is sent out from the tender. Aboard the skiff is a receiver unit which is tuned to the transponder frequency. The sensitivity of the receiver is peaked to maximum amplitude when the skiff is directly over the submersible. The tender can then use radar (range and bearing) to fix the position of the skiff and, therefore, the bottom fix of the submersible. This technique has accuracies limited to the accuracy in obtaining fixes by radar but offers distinct advantages, both in cost and time. Submerged mapping of large areas is unlimited as to mobility and is independent of physical arrangements of bottom transponders and distance from the seafloor triad or single transponder units. Obviously surface conditions due to inclement weather are a disadvantage.

Position Control

Maintaining and relocating the position of a vessel or platform at sea to any degree of accuracy is a complicated operation even under ideal conditions. Some of the factors that affect this position maintenance are (abstracted largely from a compilation by Jenkins, 1973):

1. Sea state (wave heights, periods, etc.)
2. Seafloor properties (type, strength, etc.)
3. Weather (wind force, etc.)
4. Anchor (type, size, holding power, etc.)
5. Mooring lines (cable and chain, etc.)
6. Mooring configuration (three point, eight point anchoring, etc.)
7. Vessel characteristics (size, natural periods, etc.)
8. Tensions in mooring lines
9. Currents (speed, direction)
10. Electronic equipment (computer, sonar, etc.)
11. Vessel propulsion system (number of engines, horsepower rating type, bow thrusters, etc.)

Some of these factors are known, some estimated and some will have to be determined with models if the accuracy of the position is to be maintained within a few feet, under a variety of sea and weather conditions.

For more detailed discussion of the different aspects of position control at sea, the reader is referred to the references in the bibliography.

Relocation of a position can be achieved by standard navigation and survey methods and by relative positioning with acoustic and/or buoy markers.

Less expensive systems are radar reflector buoys (Figure 20), taut-wire, single acoustic beacons and bottom topographic markers. Wind, wave and currents cause movements of the buoys, and the accuracy of the position to be maintained is a function of this movement. Generally, in shallow water or near islands, the buoys have less movement, and accuracy of positioning is higher.

A taut-wire system consists of an anchor, thin wire and tiltmeter unit (Figure 21). Some marine surveyors consider this to be the most practical, easiest and quickest system in use.

Williams (1967) describes a single acoustic transponder beacon that is accurate enough to pick up movements of a few feet once the vessel is on station over the beacon. This system only gives the range to the beacon so a trial and error technique is needed to get back on station once the ship has moved off.

The two main methods of maintaining position are by static anchoring and by dynamic anchoring, but for the deepsea the latter is generally feasible. A few of the various mooring systems are shown in Figure 22. Comparisons between dynamic and static anchoring with reference to recent operations are shown in Table 28. Figure 23 shows the use of three transponder beacons for position fixing.

Exploration and Characterization

Over the past ten years, marine mineral exploration programs have increased many fold and valuable papers have been written on the tools and techniques used. Over 70 new or ongoing exploration programs were reported in 1972 and included operations in three major oceans and off the shores of 20 countries (Table 29). Major emphasis was on tin, titanium minerals and gold, all in near-shore, relatively shallow areas. There have been selective projects in deep water to sample manganese nodules in the Atlantic and Pacific Oceans and metalliferous muds in the Red Sea.

The exploration effort may be broken down into five major categories: (1) mapping, (2) geophysical sensing, (3) sampling, (4) characterization and (5) deposit evaluation. These are generally carried out in sequence. Overall costs per square mile are generally higher offshore than on land. Table 30 gives approximations of mineral exploration costs

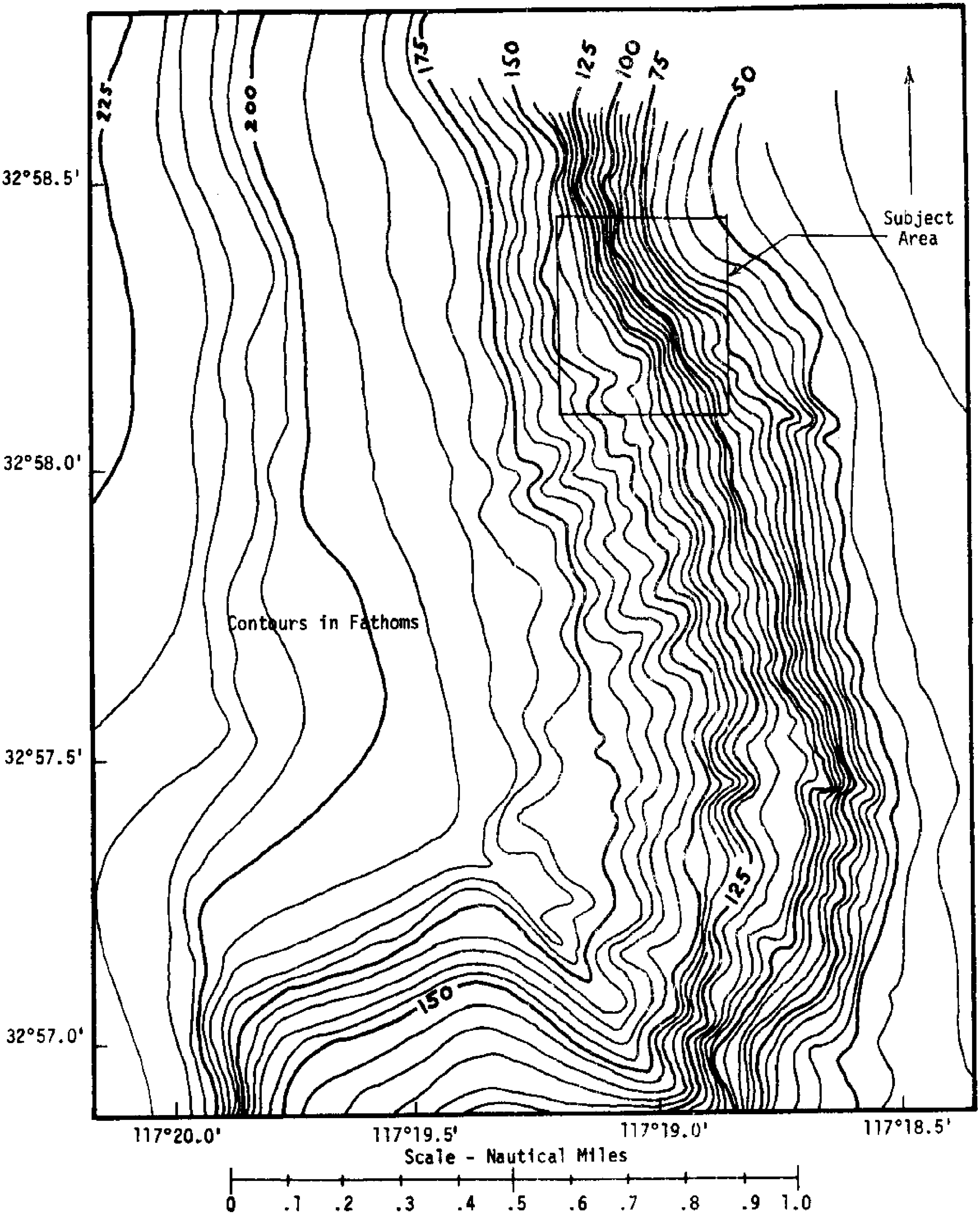

Figure 18: Bathymetry of the San Diego trough slope in the vicinity of the subject area. Contours prepared by Inderbitzen (1965) based upon a surface ship survey.

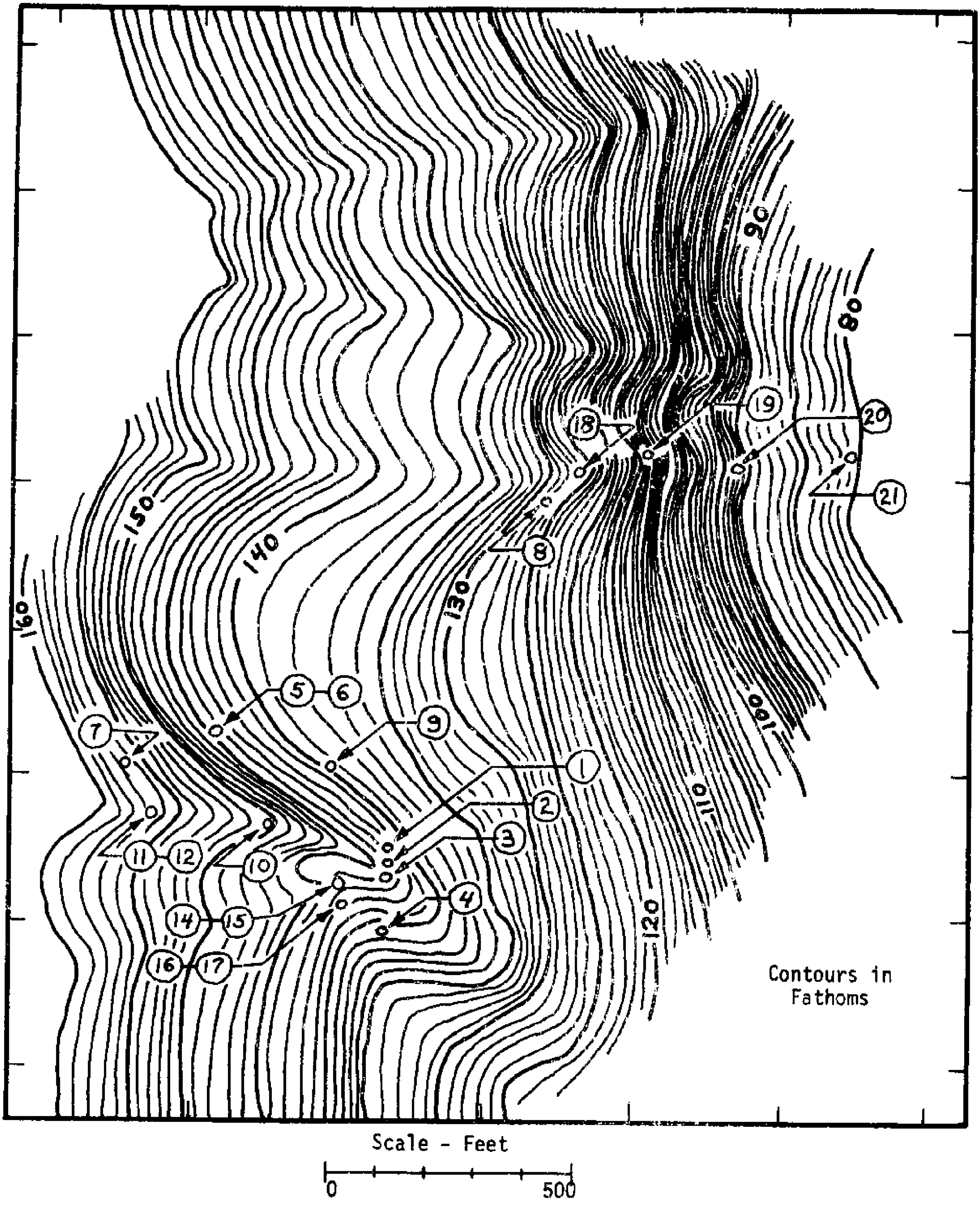

Figure 19: Bathymetry of the subject area based upon data obtained during the reported deep quest dives. Contours are in fathoms and distances in feet for ease in comparison with the original chart prepared in 1965 (Figure 5). The black dots denote the locations of cores obtained during the study.

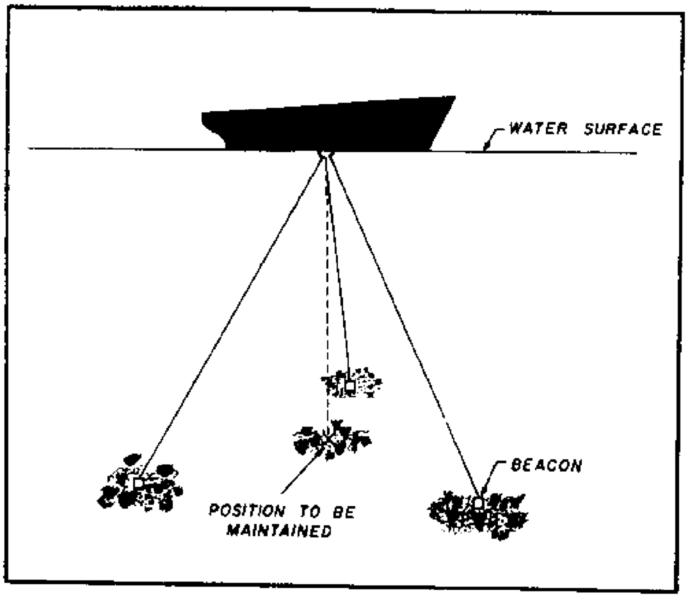

Figure 20: Use of three transponder buoys with radar detectors for position fixing (after Welling and Cruickshank, 1960)

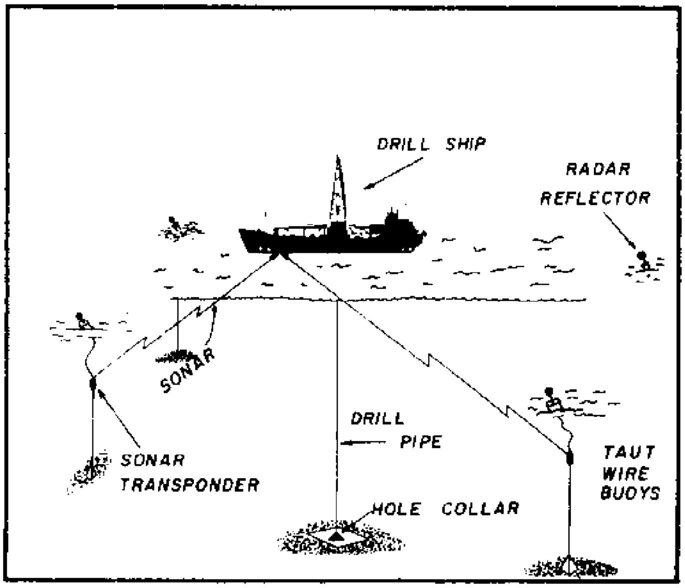

Figure 21: Taut wire system for dynamic anchoring (after Smith, 1965)

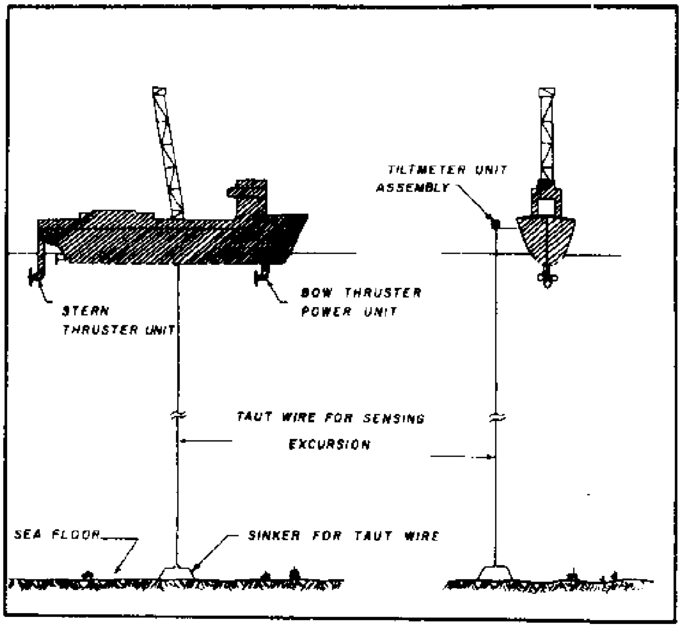

Figure 22: Mooring systems in common use (after Jenkins, 1973)

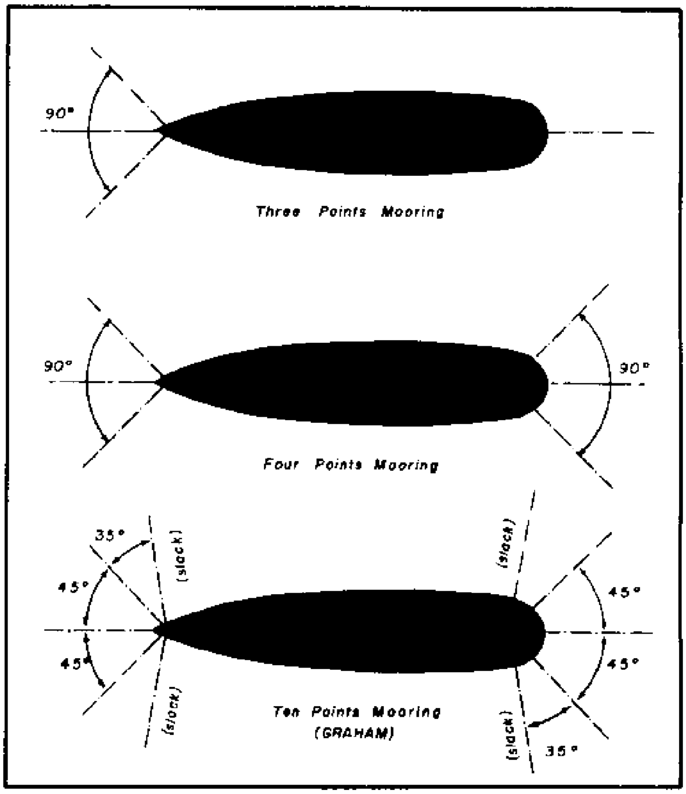

Figure 23: Use of three transponder beacons for position fixing (after Williams, 1967)

TABLE 28
COMPARISON OF STATIC AND DYNAMIC ANCHORING SYSTEMS IN USE (AFTER MULLER AND MOUROT, 1970)

VESSEL NAME	TYPE	FUNCTION	DESIGN REQUIREMENTS	SYSTEM COMPONENTS	OPERATIONAL EXPERIENCE
Reforma	Center-well floating barge	Offshore exploratory drilling		Eight-anchor array 20,000 lb. Danforth type anchors, wire cable, fairleaders, and four double drum mooring winches.	
E.W. Thorton	Self-propelled Catamaran	Offshore drilling	Water depth 600 ft. Drilling depth over 20,000 ft.	Eight-anchor array 20,000 lb. anchors, wire cable and 8 mooring winches.	Array set to permit 45° rotation in either direction about well center to compensate for changes in wind direction. All expectations reported to be met during initial 7 months operation.
Wodeco V	Center-well floating barge	Offshore drilling		Eight-anchor array, 10,000 lb. anchors, wire cable.	
Blue Water No. 2	Column-Stabilized semi-submersible	Offshore drilling		Eight-anchor array, 22,000 lb anchors, wire cable.	
Glomar Sirte	Self-propelled ore carrier conversion	Offshore drilling		Eight-anchor array, 20,000 lb. Danforth type anchors, chain.	Mooring system has equalled all expectations. Successful operation in Sea State 6.
Toto 2	Second tongue of the ocean. Moor	Provide permanent anchorage for cruiser sized ships	Water depth 5,500 ft.	Three-point moor, 6,000 lb. INT anchors, chain and wire, intermediate and main buoys, anodes.	Installation required services of 6 ships and 3 work boats. Moor failed after 4 1/2 service; primary cuase of failure was corrosion in wire ropes.
Pigeon Ortolan	Self-propelled Catamaran ASR2./22.	Conduct rescue/ salvage operations	Water depth 1,000 ft.	Four-point moor, 5,000 lb. INT anchors, chain buoys.	

DYNAMIC ANCHORING

VESSEL NAME	TYPE	FUNCTION	DESIGN REQUIREMENTS	SYSTEM COMPONENTS	OPERATIONAL EXPERIENCE
Glomar Challenger	Conventional ship hull form	Exploratory drilling as part of NSF Deep Sea Drilling Project	Water depth 3,000-18,000 ft. Accuracy of station keeping-radius equal to 3% water depth.	Two bow and two stern tunnel mounted side thrusters and two main screws.	System behavior reported to be excellent. Limiting environmental conditions: Approx. 30-40 kt. winds and 2 kt. surface currents.
Mission Capistrano	Sonar research ship	Accoustical studies	Water depth 20,000 ft. Accuracy of station keeping-1,000 ft. radius with concurrent beam winds of 25 kts. and 1 kt. surface currents.	Two self-contained 60 T, 1,250 hp. Murray and Tregurtha thruster pods.	Ship was maintained at an std. deviation of 142 ft. from desired location in 13,000 ft. of water with 28 kt. wind and 11 ft. swells.
Cuss I	Converted Navy YFNB	Experimental drilling	Water depth 20,000 ft. Max. conditions under which drilling is to continue: wind velocity 20 kts. surf. current 0.5 kts. deep current 0.2 kts.	Four Harbormaster outboard propulsion and steering units mounted port and stbd. at fore and aft main deck extremities.	
R.V. Melville R.V. Knorr	Conventional ship hull form AGOR 14/15	Oceanographic research	Ship to remain stationary over a fixed point in 35 kt. winds and heavy seas.	Vertically mounted, multibladed, cycloidal propellers, one at bow and one at stern.	Main propulsion also furnished by cycloidal units; no rudders required.
Project Mohole	Column Stabilized semisubmersible	Exploratory drilling	Maintain station with 3 kt surface current and simultaneous 33 kt. wind with 50% reserve power for maneuvering.	Six rotatable propulsion units and two main screws.	

TABLE 29
MARINE MINERAL EXPLORATION ACTIVITIES (FROM CRUICKSHANK, 1972)

LOCATION	COVERAGE	PURPOSE OF EXPLORATION	COMPANY	STATUS REPORTED
Deep Seas				
Atlantic Ocean	Not specified	Manganese nodules	Deepsea Ventures, Inc.	Active
Pacific Ocean	Area SE of Hawaii 1700 km S of Los Angeles	Manganese nodules	Sumitomo Shell Co.	Completed test, 1 ton sample obtained
Red Sea	Approximately 21°N38°E	Metalliferous muds	International Geomarine Corp., Ocean Science and Engineering, Inc.	Active
Indian Ocean	Arabian Sea	Mineral exploration	Society for Field Research on Substrate, GmbH. Hanover	Active sampling
Red Sea	Approximately 21°N38°E	Hot brine investigation	Woods Hole	Active
Europe				
United Kingdom	S Irish Sea off Welsh Coast, N Wales and Lancashire	Not specified	Seismograph Svc (UK), Institute of Geological Sciences, University of Wales	Samples taken
	50,000 acres off Yorkshire coast	Potash	Yorkshire Potash Ltd. (Rioeinto Zinc Corp.)	Active
	Continental Shelf	Mineral assessment	Institute of Geological Science	Planning permission applied for
	N Coast Cornwall	Tin	Alpine Geophysical Assoc.	In process
	W Coast Continental Shelf	Geologic mapping	George Wimpey and Co. for Institute of Geological Science	Active
	Mawddach Estuary, N Wales	Au placers	Rio Tinto Zinc Corp.	Active 5 year program
	N Sea	Aggregates	P & O group (UO), Van Hattumen, Plankevoort NV (Holland)	Exploration permit granted
Greenland	Continental Shelf	Chromite, rutile platinum	Marine Resource Consultants, Inc.	4 month program activated
U.S.S.R.	Baltic Sea Coast	H.M. sands, rutile, ilmenite, zircon	USSR Federal Research Institute for Maring Geology	Discovery report
	All seas	All minerals	All-Union Scientific Research Institute for Ocean Geology and Geophysics	Active
	Black Sea, Kalamit Bay, New Yevpatoria, Sea of Azor	H.M. sands, Fe, Mn	Marine Geology Lab, Moscow University	Under development
	Kamchatka and Sakhalin Islands	Au, Sn	NK	Discovery report, commercial grade
	Sea of Ohkotsk	NK	NK	Operating
	Kamchatka, Chukotka, Kirvele Islands, Sahkalin	Cu (Coastal?), Titanomagnolite	NK	Discovery report in 82' water
	Sea of Japan, Siberian Coastal Waters	Au, H.M. sands	NK	Discovery report
	Laptev and E Liberian Seas	Tin	NK	Sole rights to exploit applied for
Sweden	Gulf of Bothnia	All types of mineral ore, excluding oil, gas and salt	Boliden A.B.	Being undertaken
Greece	Sea bed of coastal zone	Mineral resources	Hellenic Government	Discovery reported in 80' water
Africa				
South Africa	Plettenburg Bay	Bentonite	NK	Active sampling
	Continental Shelf, Capetown to Port Elizabeth	Phosphorite	Phosphate Development Corp. Ltd (FOSKOR) and University of Capetown	3 established concessions
Mozambique	16°-30° S Coastal beaches	H.M. sands	Minerais de Marracuene, Geotecnica a Minas Lda, Minerais Basicos de Mozambique Lda	Plans announced for mobile sub base
Asia, Far East				
Japan	NS	Underwater mineral surveys	Hitachi Shipbuilding and Engineering Co., Mitsubishi Heavy Industry Ltd, Mitsubishi Electric Co., Nakamura Takkosha Co.	Recommended crash program
	Japan Continental Shelf	Mineral resources	Oceanographic Science and Technology Council	Will shortly undertake exploitation
India	Chavara in Quilon District of Kerala, beaches	Monazite	A Calcutta company in collaboration with American, Canadian, Japanese and French interests	Will shortly undertake exploitation
	N Andaman Islands	Phosphorite	Geological survey of India	Preliminary survey recomm
	Laccadive Islands	Calc sands	Geological survey of India	Survey completed 16 x 10^6 reported
Malaysia	Malacca, five mile stretch of coast	Sn	Placer Ltd. (Canada) Sharikat Lombongan dal Perusahan Melayu (Malaysia)	Disc. of rich dep. announced. Cost: $M400k Work ceased pending decision on rights
	I. Perlis and Kedah II. Perak, Selangor, Penang III. Malacca, Johore, Negri Sembilan	Sn	I. Ocean Mining (US) II. Conzinc Rio Tinto III. Billiton	Confirmed previous declaration of interest by Government to award lease rights
	Malaysia W Coast, between Kuantan and Pulau Tioman, 6,000 m^2	Sn, sand, gravel	Royal Malaysian Navy, University of Malaysia, Imperial College (London)	10 day survey completed
Thailand	Offshore NS	Mineral resources	US Naval Oceanographic Office (ECAFE)	Preliminary survey completed
	NS	Tin	Eastern Mining Co. (US-Thai)	Concession secured
	NS	Tin	Comatain (Fr)	Active drilling
	W Coast	Tin	Tronoh Mines	Active drilling
	Andaman Sea, W Coast Phuket	Tin	NS	Rich discovery report
	N Coast, Ko Phangan	Tin	Billiton Co.	Exploration program began
	W Coast, Ranong	Tin	Siamese Tin Syndicate	Drilling active

TABLE 29 (con't)

North America				
Canada	Canadian Continental Shelf	Mineral resources	Canadian Department of Energy, Mines and Resources	1 year program (Hudson 70) beginning 11/69
Central America				
Puerto Rico	S and SW Coast, 1,500 m^2 Continental Shelf	Heavy minerals	Industrial Development Administration, P.R. US Geological Survey	Being undertaken
Panama	Panamanian Coast, Bay of Montijo	Rutile, Au, Hg	North American Resources Corp.	Concession rights obtained
	Rivers	Au	Sandia Metals Corp.	Active
	Baboa District	Magnetite (62% Fe)	Panama Iron Sand Development Corp.	Completed 2.5 x 10^6 T reported
USA				
Maine	Long Island in Casco Bay	NS	King Resources Corp.	Establishing base
New England	Long Island and New Jersey Continental Shelf	Sand and gravel	Woods Hole Oceanological Institute, US Geological Survey	Report
New Hampshire	Continental Shelf	Mineral resources	University of New Hampshire Raytheon Co.	Active survey, $90,000 Sea Grant
Michigan	Green Bay, Lake Michigan	Mn	Michigan Technological University	Samples retrieved, 5 T
Louisiana	165,000 acres offshore	Phosphate	Kerr McGee Corp., Georgia Department of Mines, Mining and Geology	Lease sale of 119 tracts scheduled 5/69
California	S San Francisco Bay	Oyster shells	California Division of Mines and Geology	Active investigation
Alaska	Offshore 5 m W of Nome 22,000 acres	Au	Shell Oil Co., American Smelting, Mining and Refining Co.	Drilling from the ice, winter 1969
	Goodnews Bay	Pt	US Geological Survey, US Coast Guard	Active, summer 1969
	Eastern Bering Sea	Au, heavy minerals	US Geological Survey, Coast and Geodetic Survey, University of Washington	Active, summer 1969
	Chukchi Sea	Mineral resources	US Geological Survey, US Coast Guard	Active, summer 1969
	Goodnews Bay, 20,000 acres offshore	Pt	Apco Corp., Inlet Oil Corp.	Disc. report from 7 of 50 holes. Resume 70
	50 M W Prudhoe Bay	Placer An and Pt	NS	Planning investigations
Hawaii	Oahu, Makua to Honolulu, 30 m	Sand inventory	Institute of Geophysics, University of Haw.	Completed 1969
South America				
Uruguay	Aguas Dulcas, beach, 200 km N of Montevido	Limenite, rutile, monazite	Administration Nacional de Combustibles, Alcohol y Portland (ANCAP)	Formation of national/foreign companies authorized for development
Parts of Pacific				
Eastern Pacific	Selected areas NS	Tin, Au, chromite, Fe	Marine Resource Consultants, Inc.	Active
	Beaches in Malaysia, Korea, Tai-Taiwan Philippines	H.M. sands	Private consultant, ECAFE	Active
Indonesia	Selected areas offshore, Belitung and Bangka	Tin	Oceanological Science and Engineering, Inc. (US), Amerada Petroleum Corp. (US), Kathleen Investments (Aust.) UK, Dillingham Overseas Corp. (US), Signal Oil and Gas Co. (US)	Draft No. 2 under study
	Riau and NW Singkep offshore	Tin	Rio Tinto Zinc Corp. (UK), Bethlehem Steel Corp. (US)	Draft No. 1 under study
	Offshore between Billiton and Singkep and off coast of W Kalimantan (Karimata)	Tin	NV Billiton, Maatschappij	Exclusive contract to explore and develop
	Offshore areas of Central and S Sumatra, Kalimantan and Sulawesi	Heavy minerals	Ocean Mining, Inc.	Contracts under discussion
	Offshore Bangka and Billiton	Tin	United Nations, Indonesian State Mines	Active
Pacific Islands	3 major archipelagoes in 3 million m^2 of ocean	Resource mapping	US Geological Survey, Territorial Gov's.	Reported planned
Fiji	Selected areas	Mineral survey	Barringer Research (Can)	$M2 agreement with Fiji Government signed
	Offshore Viti Levu and Vanua Levu	Au and other	Crawford Marine Specialists	Active
New Guinea	Deltas and offshore Gulf of Papua, 2,000 m^2	Magnetite sands	James Wallace Exploration Party, Ltd. (Aus.)	Application subject to approval
New Zealand	E Coast Banks Peninsula to Rangitata River 100 m	Au	Kaiser Aluminum and Chemical Corp.	Permit approved
	W Coast, S Island, 150 x 10 m, Terramakau River to Waiho River	Au	Marine Mining Corp.	Commenced drilling, seismic completed
	N Island between Waverley and Patea	Iron sands	Adaras Developments Ltd., for Marcona Developments (NZ) Ltd., Subsidiary of Marcona Corp. (U)	Work in progress, 60 to 100 million T concentrate estimated
	Golden Bay area, Westport, Parapare inlet to Pakawau, including Aorere River, 8,600 acres	60 minerals of interest	Kaiser Mining and Development Ltd.	Applied for prospecting
	Otago Coast	Au	Alpine Geophysical Associates	Survey in program
Australia				
W Australia	Beaches near Bunbury	H.M. sands	Coastal Titanium Party, Ltd.	Will explore
	William Bay, 760 acres	H.M. sands	Hill 50 Consolidated, Homme Gold Miles, NW Mining Co.	To prospect
	Shark Bay, 2 million acres	Potash and other	Magellan Petroleum Australia, Ltd.	Drilling commenced
Queensland	Burdekin River area, beaches, 30 m, to be 1,700 m^2	Au	Amad N. L., Yam Ltd.	To prospect, Scout drilling completed, 0.33 dwt/yd^3
	Offshore Port MacQuarie to Hat Head	Rutile	Laser Electronics Party Ltd. for Planet Metals Ltd.	Completed initial program. Drilling will follow
	Point Plommer and Crescent Head	H.M. sands	Planet Metals Ltd.	Scout drilling completed
	S. Queensland and N N.S.W.	H.M. sands	Offshore Research and Development Party Ltd., for Planet Metals, Inc.	Drilling in progress. 120 line rules SBP completed
	Cape York Peninsula, coastal	Tin sands	Consolidated Mining Industries Ltd.	320 holes, 21 mil y^3 indicated, 13 oz/y
	Great Barrier Reef	Minerals NS (coral)	Queensland Government	Investigating
Tasmania	Selected offshore areas	Tin	Ocean Mining A.G.	Phase II completed; Phase III in preparation
NSW	N Coastline	Rutile, zircon	Planet Metals Ltd.	3.5 x 10^6 T deposit drilled
N Australia	Gulf of Carpenteria	Bauxite	Ocean Resources N/L, Canadian Superior Mining (Aust.) Party Ltd.	Initial SBP and coring complete, permits applied for

Abbreviations: NK: Not known
NS: Not specified

TABLE 30
COMPARATIVE DATA ON ONSHORE AND OFFSHORE MINERAL EXPLORATION COSTS (AFTER LAMPIETTI, 1970)

LOCATION	COMPANY	METHOD	MINERALS	EXPLORATION AREA, SQ. MI.	GROSS VALUE*, U.S. $\$X10^6$	APPROX. COSTS U.S. $\$X10^6$	TIME, YEAR	WAS TARGET FOUND	COST, $ PER SQ. MI.
OFFSHORE									
Tasmania, Australia	TOEC	Seismics & drilling	Tin & other Tin & other	1,500	50	0.050	1	No	433
S.W. Thailand	U.C.	Seismics & drilling	Tin	500	200-300	1.0	3	Yes	2,000
S.W. Africa	C.D.M.	Seismics & drilling	Diamonds	2,500	300	2.5	2	Yes	1,000
Red Sea deeps	WHOI & priv. ind.	Geophysics & deep coring	Base-metal sulphides	50	1,000-2,000	0.750	2	?	15,000
ONSHORE									
Kidd Creek, Ontario	Texas Gulf Sulphide	Geophysics & coring	Silver, copper, zinc	25,000	3,000	2.0	5	Yes	80
Bougainville	RTZ	Geochemics	Gold, Copper	3,500	50,000	NA	3+	Yes	--
Sierra Leone, W. Africa	Sherbro Minerals	Drilling	Rutile	2,000	2,000	NA	10	Yes	--
Trailridge, Florida	duPont	Mapping, sampling, drilling	Ilmenite	600	100	NA	2	Yes	--
Carlin, Nevada	Newmont Mining Corp.	Mapping, drilling, trenching, sampling	Gold	25	100	0.5	3	Yes	20,000

*Refers to gross value discovered for onshore and expected target for offshore.

for some onshore and offshore programs. The cost range of $20,000 to $80,000 per square mile onshore and $15,000 to $443,000 offshore, though mostly in shallow water, emphasizes that the great disparity of costs between different deposits is due largely to environmental factors. In other cases, a particular advantage obtained offshore in all depths of water is the greater use that can be made of integrated geophysical sensing systems which form a useful and highly mobile exploration tool. Sampling, particularly of unconsolidated materials, and especially in the deepsea, is one of the greatest problems still to be overcome, and developments to improve the accuracy and lower the cost are critically needed at this time.

Sampling Systems

Evaluation of marine mineral deposits requires complete environmental characterization which involves the sampling of the superjacent waters, the seafloor and the subbottom. Different tools and techniques are required for each area, and a wide variety of off-the-shelf equipment is available. Nevertheless, the sampling of mineral deposits entails technical problems of characterization and evaluation which have not been solved. Specific nodule samplers are not yet commercially available.

Superjacent Waters

Water samples may be required for trace element analysis, pollution control monitoring or characterization of water masses.

A particular layer in the water column may be sampled in bulk with a suction apparatus. A weighted hose is lowered to the desired depth and hydraulic pumps on board the vessel bring the water to the surface. Discrete water sample bottles are available with capacities of up to five gallons. A number of these are attached to a hydrographic wire at predetermined intervals. The bottles are open to the free passage of water while being lowered and are closed sequentially by messenger weights. Usually, a set of reversing thermometers is attached to each bottle and furnishes information as to depth and water temperature where the bottle was closed. Still, sampling procedures and interpretation of the data are largely for physical oceanographic studies.

Seafloor

Surficial sampling of the seafloor is usually carried out using drag dredges or some form of mechanical grab. Dredges vary in recovery volume from a fraction of a yard to several cubic yards and are generally designed to be dragged along the seafloor while the vessel is under steam. Bulk samples of bottom surface materials are taken during tows lasting up to several hours, and the dredging has an averaging effect on the samples. Large diameter pipe may be used to collect hard rock from the walls of steep submarine slopes or bottom. This requires towing the dredge with a strong cable and enough speed to break off outcropping rocks. The source of the sample may not be certain because of the lengthy haul required. It is essential that the dredging system be provided with a means of measuring cable tension and also with adequate safety releases on the bucket in case the safe working load limit is exceeded.

The grab will take gross samples of the seafloor surface, and the size is limited generally by the capacity of the hoisting equipment. The device is armed at the surface and lowered to the seafloor using a winch. In deep water, the device may tumble and require a five minute stop in lowering at a point about 100 ft above bottom to allow for stabilization of the device before the final plunge to bottom. Tripping is automatic when the bottom is reached. The jaws are drawn shut as slack is taken during retrieval, unless spring loaded, whereby the clam or bucket is closed automatically.

Subbottom - Fine-Grained Sediments, Unconsolidated

Tube-type corers are used for seafloor sampling and range from simple open tubes (free-fall) to piston corers with liners. All operate on the concept of an open tube caused to penetrate into the sediments and retain a sample of the material which is then brought back to the deck.

Open-tube gravity corers consist of an open tube with weights on top and a core catcher on the bottom. The device is lowered onto the seafloor as fast as the winch can safely be played out. The sample is retained in the tube by the core catcher. Recovery is sometimes aided by a ball valve at the top of the tube that, when closed, seals the tube and creates a partial vacuum if the sample starts to fall out.

Free-fall piston corers utilize a piston placed in the tube at the water/sediment interface. On impact the tube passes down around the piston and into the sediments. The stationary piston prevents the compressional forces of the expelling water from acting on the sediments and, by suction, prevents the sediments, in part, from being compressed.

Subbottom - Coarse-Grained Sediments and Rock

Interlocking grains of sand and gravel make it necessary to apply mechanical power for drilling or vibrating. This may be applied as impulsive, percussive, vibratory, rotary or oscillatory jet motion, or it may involve high pressure water or air jets or a combination of these. Depths of penetration and water depth capabilities are limited.

Quantitative sampling of consolidated deposits has been perfected for petroleum exploration but, as yet, is too costly for mineral exploration. Deposits of high unit value materials may be sampled by core drilling, whereas low unit value materials are usually sampled by gravity coring and/or sludge sampling.

Sampling of manganese nodules has utilized the three basic methods of drag dredging, coring or box coring, the latter two more recently on a free-fall basis (Schatz, 1971; Kauffman and Siapno, 1972). One of the problems of this type of sampling is the time of trip which, at a velocity of 300 ft/min and a rise velocity of 100 ft/min, would take 90 min in 18,000 ft of water. Bulk sampling requires the use of a large dredge and heavy winch and, with much lower speeds, might require several hours per round trip.

Visual "sampling" is carried out by photographic camera or T.V. These are more or less primitive and dependent on the type of carrier to which they are attached. In either case, ground coverage is very low and, considering the high cost of ship time, very expensive.

We judge from our own studies, as well as from a review of the literature, that the sampling problem is still far from solved. We would recommend that small tool or machine works, in cooperation with mining engineers, could revise new sampling tools for the nodule explorationist.

Sampling for Mineral Evaluation

Mineral deposit sampling involves two stages. Firstly, qualitative sampling to indicate the nature and probably extent of a deposit and, secondly, quantitative sampling for characterization and evaluation. Accurate sampling requires sophisticated equipment, and, for marine work, there are few systems that are reliable and accurate.

Qualitative sampling of marine deposits will involve such simple devices already described as snappers, drop corers, drag dredges, etc. Accuracy of positioning is not so critical at this stage but, of course, is dependent on the type of deposit being sampled. Any system which will give quantitative samples may be used for qualitative sampling.

In the development of sampling systems for marine deposits, sampling equipment should be chosen, developed or designed for a specific set of conditions. Variables such as ground type, mineral type, depth of sample, volume of materials, depth of water and reliability required must all be considered. No one system will suit all conditions, and it would be optimistic to assume that one could be built. We recommend that specific samplers be designed for specific depositional conditions, including variations in nodule size and matrix sediment.

Deposit characterization sampling is also done to determine the engineering properties of the seafloor and subseafloor materials and to relate these to geophysical survey data and subsequent mineral evaluation and even to design of the mining system. Fewer samples will be required than for evaluation, but they must be undisturbed samples to be meaningful.

Sampling costs offshore are normally much greater than for comparable situations on land. Tables 31 and 32 indicate costs in drilling for characterization in each case prior to the installation of engineering works. Costs are not available for comparable situations for manganese nodules.

Geophysical Sensing Systems

Prospecting for mineral deposits, including nodules, and geologic structures and describing environmental characteristics may be accomplished by geophysical surveys. Most subsurface structures and mineral deposits can be located if detectable differences in their physical properties exist, and many characteristics of the environment can be correlated with measurable physical variables.

The major classical methods of geophysical sensing involve the in situ measurement of density, magnetism, electrical conductivity (S.P., resistivity and I.P.) and elasticity (proportional to the velocity of wave propagation). Other methods involve the measurement of both natural and induced radioactivity, thermal conductivity and chemical activity. Although the latter are not so widely practiced in mining exploration, their use is becoming more widespread with refined technology. Not so often considered are optical methods of sensing which include visual observations, using submersibles, T.V. or cameras. Although well-developed for terrestrial monitoring from space craft, the state-of-the-art is not so well-advanced at sea, even for pollution monitoring.

All of the methods are applicable to the subsea environment, but they have not all been applied in practice. For the purposes of exploration for marine alluvial deposits, only those dependent on elastic, magnetic and optical properties are freely applicable with existing equipment.

Echo sounders were developed prior to World War II to detect enemy submarines as well as depth to the

TABLE 31
DATA ON CHARACTERIZATION SAMPLING FOR OFFSHORE ENGINEERING PURPOSES
ENGINEERING CORING CASE HISTORY

YEAR	1957	1962	1964
LOCATION OF OPERATION	Upper New York Bay	Narragansett Bay	San Francisco Bay
PURPOSE OF DRILLING	Foundational Exploration	Foundational Exploration	Soil Sampling for Barto Tube
TYPE OF GROUND	Schist, Silt & Sand	Silt, Sand, Clay & Shale	Bay Mud, Clay & Rock
RANGE OF WATER DEPTH (FT)	55	50-100	0-100
RANGE OF HOLE DIAMETER (IN)	14-10, 6-4 & NX-Bx	10-8-6	2-8
TOTAL FOOTAGE DRILLED	2,000	1,500	3,200
TOTAL TIME ON SITE (DAYS)	168	85	25
AVERAGE COST ($/FT)	92.00	210.00	19.50
TOTAL COST ($)	184,000	315,000	52,400
COST PER DAY ($)	1,100	3,800	2,100
FOOTAGE PER DAY	12	18	125

TABLE 32
DATA ON ESTIMATED COSTS (1964) FOR CHARACTERIZATION SAMPLING IN SAN FRANCISCO BAY (STATE OF CALIFORNIA DIVISION OF BAY TOLL CROSSINGS)

TABULATION OF BIDS CONTRACTORS →	THE DUNCANSON HARRELSON COMPANY		RAYMOND CONCRETE DIVISION		BEN C. GERWICK INC.	
	Unit Cost ($)	Total ($)	Unit Cost ($)	Total ($)	Unit Cost ($)	Total ($)
MOBILIZATION AND DEMOBILIZATION	L.S.	8,900	L.S.	45,700	L.S.	19,700
FLOATING RIG SETUPS FOR SEDIMENT BORINGS	500	10,500	900	18,900	900	18,900
LINEAR FEET SEDIMENT BORINGS*	14	41,000	11	32,285	26	76,310
UNDISTURBED SAMPLES	8	3,576	12	5,364	20	8,940
SETUPS FOR WASH BORINGS**	125	4,625	600	22,200	230	8,510
LINEAR FEET OF WASH BORINGS	4	7,200	10	18,000	7	12,600
TOTAL BID		75,801		142,449		144,960

* Boring at 21 designated sites, maximum 225 feet deep, totalling 2,935 ft
**Wash borings totalling 1,800 ft

bottom. An acoustic signal was sent out at regular intervals, and, if a reflector was present, a return wave was reflected back to the receiver. The half time between signal and echo was a measure of the distance from the reflecting body, assuming a constant velocity. This was later applied to the more sophisticated bottom profilers. The velocity of sound in seawater is a function of the depth and the distribution of temperature and salinity. Most acoustic depth sounding instruments are adjusted for a constant sounding velocity, usually 800 to 820 fathoms/sec. In those cases where it is desirable to correct the readings to true depth, such can be done if the distribution of temperature and salinity are known but not without complications. Accuracy is the key to the selection of instruments and methods, and much money can be saved by requiring only that level of accuracy required for mining on exploration.

In the search for marine placer deposits of heavy minerals, the subbottom profiler is probably the most useful of all the exploration aids. It may also become useful in nodule exploration. A variety of energy sources may be employed, including electric spark, compressed air, gas explosion, acoustic transducers and electro-mechanical (Boomer) transducers. The return signals as recorded usually show a recognizable section of subbottom. Shallow layers of sediment, configurations in the bedrock, faults and other features are clearly displayed and require no sophisticated approach for interpretation. The maximum theoretical penetration is dependent on the time interval between pulses, the wave velocity in the subbottom and nature of the deposits. A pulse interval of 1/2 sec and an average velocity of 8,000 ft/sec will allow a penetration of 2,000 ft under ideal conditions. The actual penetration achieved is dependent on the wave velocity, the pulse frequency and the pulse energy. The resolution of the recorded data is largely dependent on the pulse frequency and the recording system. Band filters are commonly used to clarify the recorded signal.

Penetration and resolution are widely variable features on most models of wave velocity profiling systems. In general, high frequencies give high resolution with low penetration, while low frequencies give low resolution with high penetration. The general range of frequencies is at the low end of the scale and varies from 150 to 300 cps, and the general range of pulse energy is from 100 to 25,000 joules for non-explosive energy sources. The choice of a system for nodule investigations will depend very much on the requirements of the survey, but for the location of shallow placer deposits on the Continental Shelf the smaller low-powered models, such as the Rayflex Sonoprobe and Huntec Hydrosonde, have been used with considerable success. We feel that there is a need, however, to develop a system, perhaps to be towed at depth, exclusively for deepsea nodule surveys. Moreover, from our review of the available literature and our discussions with industry engineers, we have also identified the need for early experimental development of totally new seismic survey systems. Most surface-towed acoustic profilers do not provide sufficient resolution of nodule deposits; thus, the advanced development of deep-towed systems, such as is being pursued at Scripps Institute of Oceanography, at the University of Wisconsin and in the industrial sector, should be expanded.

Geochemical Systems

Sensing systems for the measurement of geochemical variables in the deepsea are unsophisticated. In fact, for most cases, samples are required, and these are usually processed in a laboratory ashore by standard analytical methods. The most promising advance for in situ analysis on the seafloor is neutron activation analysis which appears applicable to the exploration for manganese nodules. The literature is surprisingly extensive, and some promising starts have been made (550.4:543.5).

Professor John Noakes and his associates at the University of Georgia have already conducted some successful underwater tests in the shallow waters of the Continental Shelf, and they are presently extending the intermediate depth range of their in situ analysis system using submersibles. In regard to neutron activation analysis of deepsea deposits, particularly nodules, Noakes has devised a system whereby samples are analyzed on deck using a portable activation source. While this technique is useful in broad exploration surveys, close-control surveys during actual mining will require in situ measurement of copper, cobalt, nickel, manganese and, perhaps, iron. Moreover, in situ measurement of selected trace elements (those of economic interest) may become necessary as the commercial recovery of trace elements from the nodules becomes a routine process.

In short, the need is for early development of a reliable, in situ neutron activation analysis system that can be either towed near the bottom during exploration or attached to the mining unit during exploitation.

Data Processing Systems

Shipboard processing of data is an important aspect of development in deepsea exploration. Real time output on positions, environmental characteristics and deposit characteristics would enhance the survey or exploration operation immeasurably. The trend is toward this type of system, with integrated geophysical sensors combined with environmental sensors, feeding to a control data processing bank on board ship. At the present time, the cost of these systems is still excessive.

Perhaps an alternative to an on-board computer would be a radio-telephone link using a portable terminal such as that designed and marketed by Texas Instruments Company. While such a terminal may not allow total flexibility, its use has the decided advantage of inexpensive terminal installation aboard ship, and it can be linked to much larger computers than would normally be found on mining ships.

While computer facilities aboard ship are highly desirable, they may not be necessary in the early stages of nodule exploration, except, perhaps, for vessels that use satellite navigation. However, in the second (or mining) stage, computers will be necessary in order to maintain quality control during mining and any at-sea processing, to monitor environmental variables and to provide routine record-keeping and engineering data handling.

THE TECHNOLOGIC GAPS

In order to identify the gaps in technology, it is first necessary to identify the needs. These we have presented. As previously pointed out, the exploration process is one of measurement and procurement of knowledge. First, the knowledge gap must be assessed, and, from an assessment of the state-of-the-art of data acquisition and handling, the priorities for improving technology may then be determined. Priorities have been assigned according to the assumptions listed in Table 33.

TABLE 33
PRIORITY RATINGS FOR TECHNOLOGICAL GAPS

DEEPSEA MINERALS ENVIRONMENTAL DATA REQUIREMENTS	TECHNOLOGICAL SYSTEMS REQUIREMENTS (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
GEOLOGICAL										
Topographic Mapping										
Macro	2	2	2	4	4			2		2
Micro	1	1	1	4	1			1		1
Morphology	2	2	2	4	4			2		2
Petrology	1	1	2	4	4	2	2	1	2	1
Mineralogy	1	1	1	4	4	2	2	1	2	
Geochemistry	1	1	1	4	4	2	1	1	1	
Geodynamics										
Sediment transport	1	1	1	4	1	2	1	1		
Interstitial waters	1	1	1	4	4	2	1	1		
Ion exchange	1	1	1	4	4	2	1	1		
GEOTECHNICAL										
Index Properties	1	2	2	4	4	2	2	1		2
Engineering Properties		1	1	4	4	2	1	1		1
Strength	1									
Compressibility	1									
Permeability	1									
Sonic properties	1									
OCEANOGRAPHIC										
Currents										
Surface	2	2	4	4	2	2		4		2
Bottom	1	1	4	4	1	2		1		2
Sea States	2	2	4	4	4	2		4		2
Water Quality										
Particulates	1	1	1	1	1	2	1	1		2
Solubles	1	1	1	1	1	2	1	1	1	2
METEROLOGICAL										
Precipitation	2	4	4		4			4		4
Winds	2	4	4		4			4		4
Storms	2	4	4		4			4		4
Visibility	2	4	4		4			4		4
Humidity	2	4	4		4			4		4
ECOLOGICAL										
Nekton	1	2	4	4			4	4		4
Plankton	1	2	4	4			4	4		4
Epi Fauna	1	1	1	4	1		1	1		1
In Fauna	1	1	1	4	1		1	1		1

(1) Environmental Data
(2) Environmental Predictions
(3) Platforms
(4) Power
(5) Navigation and Survey
(6) Position Control
(7) Sampling Systems
(8) Geophysics Sensing Systems
(9) Geochemical Systems
(10) Data Process Systems

Data Requirements

In Table 33 the various environmental parameters which are involved in the "need to know" are listed in the first column, and the technological systems involved in the data acquisition are listed horizontally. Those requirements involving ratings of highest priority are:

Microtopographic mapping

Petrology

Mineralogy

Geochemistry and geodynamics of the deposits and associated seafloor

Engineering properties, including trafficability of the seafloor

Information on bottom currents and water quality throughout the water column, particularly in a narrow seafloor and surface interface zone

Baseline data on marine life throughout the water column, particularly on bottom fauna and the effects of mining disturbance on it

Technological Research Priorities

Using the same system of rating as for the data requirements, the technologic gaps appear in Table 34 as items of first priority. In this matrix, the systems are listed in column one, and the environments of use are listed horizontally. Prime needs are shown for the following.

Environmental Predictions

The gaps here are techniques of observation for ecological baselines and the forecasting of change due to natural effects and to disturbances of the natural regime. Systems of observation and measurement have been particularly neglected at abyssal depths and for predictive analysis will require careful multicyclical monitoring. With the possibility of acyclical life occurring at these depths, predictive techniques may require some new approaches.

Environmental predictions for weather and sea water, although not ideal, are well under active development, and they must be accepted at the present state-of-the-art.

Platforms

There is a considerable need to improve the rate of ground coverage for most exploration tasks, and, while this is sometimes dependent on the methods of sensing, there is a definite inability to perform high speed traversing near the bottom due to the lack of a suitable vehicle. Manned submersibles with speeds of 20 knots would greatly improve capabilities. On a less ambitious scale, further developments of existing towed platforms or unmanned submersibles controlled by acoustic telemetry would be most helpful. Bottom vehicles such as RUM, designed for geo-data collection, are also needed—again, controlled by cable from surface ships.

Navigation and Survey

Navigational aids for tight grid exploration control within normal terrestrial survey limits required for characterization will have to be placed on the seafloor. Such hardware is not yet readily available.

Sampling Systems

Deepsea quantitative sampling systems for unconsolidated material are inadequate for low-cost deposit evaluation, geotechnical properties measurement and ecological assessment. Sampling by bore hole of consolidated material is possible in most cases but not on an economic basis. Methods of sampling both shallow and deep deposits of ferromanganese crusts in crustal areas beneath glacial till or volcanic flows are urgently required if the full spectrum of ferromanganese deposits are to be considered.

Geophysical Sensing Systems

Television and camera systems are well-advanced in use but by no means perfected as a quantitative tool in fast surveys. Further extensive research is required to improve these tools, with regard to their ground speed and data output mode.

Acoustic scanning utilizing the elastic properties of the earth media as in depth recorders, subbottom profilers and side scanning sonar is a vital and versatile exploration technique. Improvements in these systems is needed, particularly in spectral analysis leading to correlative indicator recognition and nodule signature definition. It is also of extreme importance to increase the range of these techniques—again, with the objective of increasing ground coverage and lowering costs.

Methods of survey utilizing induced radioactivity have been indicated to have a valid potential for in place, quantitative, elemental analysis. The perfection of these techniques would come near to approaching an ideal system and should be given a high priority in future development work.

Geochemical Systems

Most analytical work is carried out in laboratories ashore. Improved systems for shipboard analysis should be sought, but their lack does not presently constitute a serious gap. Neutron activation analysis research on in-situ seafloor analysis should be given priority at this time.

Data Processing Systems

Integrated systems for in-situ measurement and shipboard analysis of all geo-, oceano- and ecologic phenomena should be developed specifically for ferromanganese deposit exploration. Continual improvement of these systems would be made to the basic system which ideally would allow for instantaneous display in analog and digital form of all parameters of depositional and environmental characterization at a reasonably rapid traverse speed.

DISCUSSION AND CONCLUSIONS

In the preceding pages of this report we have outlined the more important environmental and technical/operational problems facing the explorationist. By assessing the present knowledge, the environment of probable nodule sites, and the present state-of-the-art of exploration technology, we have identified those gaps which must be bridged before deepsea nodule mining can become a viable industry. While the principal conclusions of our investigation have been largely discussed in the preceding chapter, i.e., as needs to meet the exploration gaps, there are several other pertinent aspects that warrant discussion. Among these are some of the viewpoints of industry, and our suggestion for an alternative approach to solving technological problems.

During the course of preparing this report, we visited with several industrial firms in North America that are committed to the exploration for, and the exploitation of, deepsea manganese nodules. In these several conversations with both management and engineering staff personnel, we were informed of

TABLE 34
PRIORITY RATINGS FOR TECHNOLOGICAL GAPS

TECHNOLOGICAL SYSTEMS			ENVIRONMENT IN WHICH USED Oceanologic							
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
OPERATIONAL PREREQUISITES										
Environmental Predictions	Observing techniques		1			2	2	2	2	1
	Forecasting		1				2	2	2	1
Platforms:	Airborne platforms						4	4	4	4
	Floating platforms			2	2	2	2	2	2	2
	Submersible platforms		1	1	2	2	2			2
	Bottom platforms		1	1	1	1				1
	Divers			4	4	4				4
Power:						4	4	4		
Navigation and Survey:	Optical systems									
	Electronic systems		1			1		2		
Position Control:	Seafloor survey		1	1	1	1		2		1
	Static anchoring			2	2	2	2			2
	Dynamic anchoring						2			2
EXPLORATION AND CHARACTERIZATION										
Sampling Systems:	Superjacent waters						2			
	Seafloor		1	2	1					
	Subbottom		1	1	1					
Geophysical Sensing Systems:	Optical	Transmissivity								
		Reflectivity	1				1			
	Mass;	Density								
		Gravitation								
	Magnetism;	Terrestrial								
		Atmospheric								
		Electromagnetic				3				
	Electrical;	Conductivity		3						
		Self potential				3				
		Induced polarization				3				
		Resistivity		3						
	Thermal;	Heat flow		3						
		Thermal anomalies		3						
	Elasticity;	Seismic velocity		2						
		Reflection	1	1	1	1				1
		Refraction		2						
	Radioactivity;	Natural				3				
		Neutron induced	1		1	1				
		Gamma backscattering				3				
		Gamma spectroscopy				3				
Geochemical Systems:	Wet chemical							2		
	Neutron activation		1	1						
	X-ray diffraction			3		1				
	Mass spectroscopy			3				2		
	Atomic Absorption			3				2		
	Fluorescence spectroscopy			3				2		
	Other									
Data Processing Systems:	Shipboard		1	1	1	1	1	2	2	1
	Remote		1	1	1	1	1			1

(1) Technical Gaps
(2) Geological
(3) Geotechnical
(4) Seafloor Interface
(5) Water Mass
(6) Air Interface
(7) Meteorological
(8) Ecological

TABLES 13 AND 14: KEY PRIORITIES IN FILLING THE TECHNOLOGICAL GAPS IN EXPLORATION OF MARINE FERROMANGANESE DEPOSITS

Priorities are allocated to each component using the following numerical ratings:

PRIORITY 1

The highest priority. Knowledge which should have already been gained or technology which lags seriously behind in any part of an interdependent system is included here.

PRIORITY 2

This includes projects which are necessary for the improvement of the total system, but for which there are temporary substitutes.

PRIORITY 3

Basic research of more academic interest. This work is vital to an understanding of the natural system and could return substantial dividends by nature of its discovery potential.

PRIORITY 4

Needs which are not in themselves a unique requirement of Mn nodule exploration but of which research awareness should be maintained. No substantial input can be made from this program.

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specific needs that industry would like to see fulfilled, or of specific problems outside those identified in our original assessments. Perhaps it is best that we consider briefly and in a composite manner some of the industry problems and then discuss an alternative approach to segmented research projects.

One of the first needs brought to our attention was that of providing a reliable *in situ* sensing system which could quickly determine the copper, nickel, cobalt, and manganese values of the nodules in any given survey area. The idea being that it is a definite enhancement of the total mining system when only the highest grade nodules are mined. While we do not know if there are significant variations in the metal content over several hundred feet, such variations are known to be present on a larger scale. Thus, the mining vessel engaged in recovery could profit by raising or lowering its collecting device to conform with changes in metal grade on the bottom. Such a system would also be used in the exploration phase, which, for large areas of the Pacific, would save many months of costly laboratory analysis time. Interestingly, this idea was expressed by several workers in the field who are academically oriented, for such a tool would also provide much needed data for large areas where, at present, only a few samples have been collected.

A second need expressed by industry personnel is that of obtaining extensive data on the chemical composition of nuclei of manganese nodules. Although many nodules upon splitting are found to possess only a small nucleus, sometimes only a sand grain, there are areas where metal-rich nodules have been sampled and found to contain large nuclei of different rock types, shark teeth, clay lumps, and altered volcanic material. Since the nodules will be mined and probably returned to a shore processing plant before processing, it behooves the miner to return nodules with small nuclei and, hopefully, uniform chemical composition. The chemical processing systems now proposed involve some rather costly acids and other compounds, and if the nuclei are sufficiently variable in their gross composition, considerable economic loss would be brought about through undue waste of processing liquors. Moreover, knowledge of the variability of the nucleus material is important to the explorationist who must concentrate his initial efforts, at least, on those areas where the nuclei are most favorable to his particular exploration scheme. Basic research on the precipitation of nodule material on the nucleus is warranted, and it appears that such research could provide clues to other nodule characteristics. While an initial research effort is underway on this problem at the University of Wisconsin, much more work needs to be done, particularly in consort with companies and agencies who have large collections of nodules for analysis. Surprisingly, there has been very little attention given to the role of the nucleus in the origin of the nodule, and in the nucleus as a factor in ore grade.

A third problem brought to our attention by both industrial and academic investigators is that of the paucity of nodule samples presently available for basic research and for process or pilot plant testing. At this time, academic investigators and even some industrial research and development laboratories are dependent on existing samples which are in museums, sample repositories, and agency collections. Several major companies have collected extensively and have assembled samples from both the Atlantic and Pacific nodule areas, but, for the most part, these samples are difficult to obtain and any analyses must be released only with the permission of the donor. Such proprietary restrictions have placed an undue hardship on the research community, and we suspect that this situation will prevail in the year ahead. It seems to us, however, that an alternative would be to have either a national or an international agency engage in extensive collecting of large bulk samples solely to provide material for the many investigators in this field. Such an effort would require the cooperation of the several sea-going institutions as well as international support in the form of both funding and logistical aid. Even one dredging ship, in one year, could provide sufficient bulk nodule samples to satisfy the international research community for this decade. This is readily apparent when one considers the rapid strides that have been made in nodule research using only those samples obtained by small grabs or from museum and repository collections. Furthermore, even a single ship could obtain closely spaced samples over a large part of the central Pacific if it were funded for a continuous two or three-year period. In short, much research is being held back not because of personnel or laboratory limitations, but simply because there is an insufficient supply of nodule samples in the common domain.

A fourth problem is one that was more apparent than specified. This is the problem of communication between the many workers in the international community of nodule investigators. Admittedly, the commonplace system of reporting research in scholarly journals should serve to communicate new data, new concepts, and new findings throughout the world. In practice, however, the nodule investigators must compete with all other scientists in the race to convey edited papers to their colleagues. Even more important is the lack of a central information center on manganese research, a center where all data are available, from which new data are rapidly disseminated among the profession, and where contributions in foreign languages are readily available in any of several translations. One of us spoke with an investigator in an American university who was engaged in a project on nodule chemistry which was, unknown to him, already being pursued at a foreign institution. Such duplication of effort is costly and unnecessary. Moreover, we detected that investigators in academic institutions were seldom familiar with research going on in industrial laboratories. In fact, we met one investigator on the East Coast, who was far more familiar with a fellow scientist's work in New Zealand than he was with an American industrial research and development laboratory engaged in manganese nodule studies only a few miles away. Perhaps the problem of communication and dissemination of nodule data and information is no different than that faced by other scientists, but we believe that it is sufficiently different and sufficiently international in scope and importance to warrant the organization of a central information center. Such an effort, appears, to us, to be a worthy I.D.O.E. objective.

A fifth need expressed by industry discussants is the acquisition of pre-mining site data at the likeliest sites for nodule exploration and, ultimately, exploitation, in both the Atlantic and Pacific Oceans. Although we identified this as an exploration gap in our preceding assessment, it is noteworthy that such a need was also expressed by industry personnel. Thus, it would seem that one of the earliest efforts under I.D.O.E. sponsorship would be to measure the several environmental parameters at selected Pacific mining sites. Inasmuch as some parameters may be cyclic in nature, we suggest that the initial survey be conducted at intervals over a twelve months' period, and if funding permits, over a full two-year period. It is better that an independent organization, i.e., one with no commercial ties, make such a base-line survey rather than place the burden of a pre-mining survey on any economically oriented group.

Clearly, the above observations are in line with the objectives of the I.D.O.E. Program, and while they might have been covered in broad discussion of some of the earlier proposed research, we feel that they deserve specific attention. The problem of defining the mining environment is critical, and the resulting data are of immediate use to all parties involved in manganese nodule exploration. Our attempt here is to place some emphasis on those problems which both the industrial and academic/international sectors alike are concerned with. In spite of our rather exhaustive survey of the literature and our many discussions with others in this field, we still believe that certain technological gaps will not become fully apparent until actual exploration and exploitation are initiated. Accordingly, we have considered an alternative approach, and this is described below.

The axiom which states that experience is the best teacher suggests to us that the most direct approach to identifying exploration and exploitation problems and to providing the most timely solutions to these problems is to go out and explore for, and then mine, manganese nodules. We visualize that such a project could be conducted with the full cooperation of both national and international groups and including both the academic and industrial sectors. Moreover, by encouraging the I.D.O.E. Office to sponsor and to oversee (but not manage) such a program, the knowledge gained would be freely available to the international community. We have, at this time, more than adequate expertise and physical resources to conduct such a test mining program and, indeed, given early support such a program could be implemented within the year. Time and again we have heard from our colleagues that no one knows the full extent of the problems to be encountered nor the remedial actions to be taken until an actual deepsea nodule mining program is underway. We subscribe to this idea, and we encourage the I.D.O.E. Office to consider such an idea as a valid one for a major research and development program. Additionally, we would point out that such a project would bring the efforts of many scientists and engineers, both in this country and abroad, to bear on a common task. As we see the evolution of the "International Manganese Program" from a modest meeting in Harriman, New York, in 1972, to a major collection of individual project reports in 1973, we are struck with the disparity of effort and the often misunderstood objectives. Perhaps the nature of scientists is such that they do prefer to follow their own directions, and for however fruitful such a philosophy may be in some disciplines, the study of manganese nodules is truly interdisciplinary and must, by necessity, bring to bear the combined efforts of chemists, engineers, geologists, oceanographers, and others for solving the common problem of exploring and exploiting deep-sea nodules. Accordingly, we propose that a second step in the I.D.O.E. Program be to support a full scale exploration and mining program, as a test, and that it seek national and international cooperation and input. We would also point out that the sale of mined nodule ore would provide some considerable financial return to the program which should be used solely to offset the expenses of the project itself. While it is not our prerogative to specify funding levels, nor select sites, nor recommend the co-investigators in such a program, we do encourage the I.D.O.E. Office to be receptive to such a proposed program and if accepted, to designate a managing committee to consider the operational details at an early date.

In concluding this report, we would simply state that it is our view that we must bridge the high priority technologic gaps that have been identified herein. (As these are specifically identified in the preceding chapters, we see no reason to reiterate them here.) Our intention throughout this study has been to determine the technologic gaps from as careful and as broadly based an inquiry as it has been possible within the limited budget and time of our study. We do not suggest that we have investigated every technologic gap that has been brought to our attention, but we do believe that the significant problems attendant to early exploration and initial exploration of manganese nodules have been identified. In that this report will be of concern to many professionals and to some laymen in disciplines outside of marine science, e.g., international relations, law, economics, and politics, we have endeavored to provide a reasonable background coverage of both the environment and the technology. We trust that our colleagues engaged in nodule studies and underwater minerals exploration, in general, will view tolerantly our preceding descriptive passages. We have endeavored to avoid any personal bias, but inasmuch as our own views frequently matched those of our colleagues in applied investigations, we have probably given unintentional emphasis to some few recommendations.

Finally, we would encourage the I.D.O.E. Office and our fellow nodule enthusiasts to consider our proposal carefully. We firmly believe that the best way to identify and to solve the real problems in nodule exploration and exploitation is to find the nodules and mine them. Our idea for an I.D.O.E.-supported exploration and exploitation project, we believe, satisfies the spirit of the individual investigators and the purpose of the National Science Foundation's I.D.O.E. Program. Accordingly, we seek your concern, your counsel, and, we hope, your support.

BIBLIOGRAPHY ON FERROMANGANESE NODULES AND MARINE MINING GAPS

It was the authors' original intent to append an extensive bibliography to this report. However, because of its size (approximately 500 pages) this bibliography, covering all aspects of ocean mining and related subjects, will be published as a separate technical report under the present I.D.O.E. program.

The Universal Decimal Classification (UDC) used throughout the bibliography was originally derived from the Dewey Classification (DC) and has been and is still being extended for use in classifying articles in periodicals, monographs, and documents of all kinds, under the auspices of the Federation Internationale de Documentation (FIC) which authorizes publication of international editions in fourteen different languages including French, German, Spanish and Japanese. An outline of the main divisions is given in the Abridged English Edition B.S.1000A: 1961. It may be obtained from the British Standards Institution in London. The volume contains a complete explanation of the system.

The format of the bibliography was drawn up in collaboration with the U.S. Bureau of Mines, Division of Automatic Data Processing at Denver. It is based on the Finder System, developed for the library cataloguing at the Marine Minerals Technology Center. The bibliography is in five sections listing subjects, key words, references and authors, each keyed to the UDC subject number.

All references relating to the deepsea ferromanganous deposits have been collected together under a group prefix 622*70(26):

622	mining industry
*70	non UDC regionalization referring to manganese; see subdivision of 546 (inorganic chemistry)
(26)	oceans
:	relates prefix to following subject number

Further breakdown by subject is denoted in the subscript, as for example: 622*70(26):546(265)

622*70(26):	marine ferromanganese mineral industry
546	composition
(265)	distribution W Pacific

The bibliography, when published, will contain the following sections:

Section I

UDC SEQUENTIAL NUMBER LISTING. Lists subject headings according to Universal Decimal Classification in numbered sequence (15 pages, approximately 750 entries).

Section II

ALPHABETICAL SUBJECT LISTING. Lists subject headings alphabetically and refers each subject to its appropriate UDC number. Multiple word subject headings are listed for each word (52 pages, approximately 3000 entries).

Section III

KEY WORD LISTING FOR MANGANESE NODULE LITERATURE. Lists key words in manganese nodule literature in bibliography and refers each key word to its appropriate source or sources by author, year and UDC subject number (37 pages, approximately 2000 entries).

Section IV

BIBLIOGRAPHY. Lists bibliographic references for each UDC subject number alphabetically by author within each number sequence. References on manganese nodules are grouped under the prefix 622*70(26) MANGANESE NODULES (303 pages, approximately 3000 entries).

Section V

AUTHOR LISTING. Lists authors first alphabetically and then by year. Refers each entry to its appropriate UDC subject number and subject (81 pages, approximately 4300 entries).

ACKNOWLEDGEMENTS

Acknowledgement of support and assistance in the preparation for this report is sincerely made to the staff of the Marine Research Laboratory of the University of Wisconsin at Madison, the Director and Staff of the Marine Minerals Technology Center, Environmental Research Laboratories of NOAA at Tiburon, and to the staff of the Automatic Processing Center of the U.S. Bureau of Mines at Denver.

Much of the original bibliographical collection on manganese nodules was compiled by Mr. Gale Hubred of the University of California.

Particular thanks go to Charles Morgan, Morton Wakeland and Laurie Mann at the Marine Research Laboratory for their able assistance in drafting, collation and typing.

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