Synthesis of Environmental Impacts of Deep Seabed Mining

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A synthesis of environmental data compiled over the past 25 years is reviewed and organized. We describe the anticipated activities associated with exploration for commercial deposits, with engineering tests of recovery and mining systems, and with basic metallurgical processing. Basic description of the manganese nodule oceanographic environment is presented, including the occurrence of nodule deposits, relative sediment properties, benthic currents, and biological community. Environmental impacts from previous studies are summarized. Studies to date support the original concerns for environmental impact identified in the DOMES research, including impact on the benthic community where nodules are removed; impacts of the discharged plume on the near-surface biota; and impacts on the benthos due to deposition of suspended sediment. Future studies should address the establishment of quantitative relationships between resedimented thickness and benthic community response; integration of mining-related research efforts on benthic communities; establishment of clear guidelines for monitoring of precommercial mining test; and comparison of impacts from deep seabed mining with alternative land-based mining scenarios.

Keywords Clarion-Clipperton Fracture Zone, environmental impacts, manganese nodules, seabed mining, The Area

A significant body of information has been acquired during the past 25 years on the environmental impacts of deep seabed mining. Small-scale mining equipment tests and mining simulation experiments have been carried out through collaborations of industrial, government, and academic workers, as well as baseline data collection by industrial explorers and government-funded researchers. Numerous

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oceanographic studies have been completed which relate directly to key environmental parameters of interest. These studies are summarized, referenced, and organized herein with the goal of providing primary direction and guidance for subsequent data collection efforts. This article describes expected activities related to seabed mining, and provides a description of the environment, and an analysis of potential impacts.

Expected Activities

The activities considered are restricted to exploration for commercial deposits, small-scale and prototype tests of commercial recovery mining systems, and metallurgical processing related to minerals from seabeds beyond national jurisdiction (The Area). At present, only exploration activities are currently ongoing, and these activities generally are not expected to cause serious environmental harm. Also, metallurgical processing is unlikely to take place at sea in the forseeable future.

Crucial to any environmental evaluation is consideration of the implications of an activity as well as the activity itself. Actions taken in the near future by explorers, such as collection of baseline data, and investments in technology development, have basic implications for the ultimate characteristic of the seabed mining industry and thus its environmental impacts. While the focus of this article is clearly on describing the impacts of the activities anticipated, a brief description of the entire industry is provided, as well as it is defined at this early, precommercial stage. First, the assumptions of scale and size, so necessary for environmental assessment, are delineated as they exist to date. Then, brief narratives of the types of operations envisioned are presented.

Prospecting and Exploration

The major prospecting and exploration activities included here generally fall within the realm of oceanographic research. Though explorers for commercial manganese nodule deposits have refined and modified many procedures to fit their particular goals, their basic methods and backgrounds stem directly from the well-developed disciplines of geological, physical, and biological oceanography. Specific field techniques are listed in Table 1.

These techniques are initially employed to find the best mine sites and to map their extent. Such activities would probably continue throughout all but the last year or so of mining. After the mineral resources are mapped, the same techniques would be used at higher spatial densities but at lower overall levels of effort to delineate the actual path to be traversed by the mining device. The U.S. government has determined that these activities are not expected to cause serious environmental harm (15 CFR 970.701).

Scale and Prototype Mining Test

Prior to commercial operation, it is anticipated that at least 5 years of testing of a prototype mining system would be necessary to develop adequate operational control, to demonstrate system reliability, and to acquire sufficient ore for pilot-scale metallurgical processing tests. This estimate is based upon projections made by prospective deep seabed mining consortia and filed with the U.S. Department of

Table 1
Prospecting and exploration field techniques

Gravity and magnetometric observations and measurements
Bottom and subbottom acoustic profiling or imaging without the use of explosives
Mineral sampling of a limited nature such as those using either core, grab, or basket samplers
Water and biotic sampling
Meteorological observations and measurements, including the settling of instruments
Hydrographic and oceanographic observations and measurements, including the setting of instruments
Sampling by box core, small-diameter core, or grab sampler, to determine seabed geological or geotechnical properties
Television and still photographic observation and measurements
Shipboard mineral assaying and analysis
Positioning systems, including bottom transponders and surface and subsurface buoys

Commerce. The mining system for these tests is assumed to be similar to that described below, but would operate for much shorter periods of time. We estimate a required 60 days of full-scale operation during this 5-year period. As discussed below, these test operations will provide the first opportunity for the accurate assessment of environmental impacts.

Commercial Recovery

Considerable development of systems to recover deep seabed manganese nodules has been completed during the past 20 years by private and government-subsidized international consortia. Mining manganese nodules is unique for mineral extraction, not only because it involves transport of the ore through 4,500 to 5,000 m of seawater, but also because the deposits are essentially two-dimensional, with no overburden. Mining manganese nodules is much more analogous to harvesting potatoes than it is to strip-mining or open-pit operations for more conventional ores.

Mining operations consist of removing nodules from the seabed surface of fine-grained pelagic sediments (pickup), and conveyance to the ocean surface (lift). Many strategies have been tested to accomplish these two tasks, ranging in complexity from simple, towed dredges to self-propelled, highly maneuverable systems. The environmental impacts of these different systems are likely to be somewhat different. Impact assessment will depend very much upon the specific design proposed. Systems which have been tested in actual scale-model tests in the deep seabed include (1) several tests of different hydraulic systems, which pick up the nodules with a towed or self-propelled harvester and then lift the ore to the surface with simple hydraulic or air-assisted lift systems, and (2) a continuous-line bucket system, which consists of dragline buckets connected together on a loop. Other, more speculative types of systems have been conceived. Brief descriptions of several of these systems are included below.

Basic Assumptions. After extensive consultation with the initial commercial mining consortia, the U.S. government in its final environmental impact assessment for deep seabed mining (U.S. Department of Commerce, 1981, Appendix 3) settled on a number of assumptions regarding the scale of mining operations to be expected. These are essential for environmental impact analysis and are summarized here.

Industry estimates that vessels will mine 24 hours per day for an average of 300 days per year. The remainder of the year will be devoted to mechanical overhaul (about 30 days) and to transit and downtime for weather (about 35 days). Each mine site will be serviced by one or more ships designed to recover a total of 3,000 to 10,000 t (metric tons, 1 t = 1,000 kg) of nodules (dry weight) daily, or 900,000 to 3,000,000 t/year, with the lower limit described as that required for an industry which produces commercial manganese as well as copper, nickel, and cobalt, and the higher limit as that required for commercial production of the latter three metals. The larger tonnage operations will probably require at least two mining ships to operate efficiently.

Within a given mine site, mining will probably take place in one subarea at a time. For example, one year of mining with one vessel might take place in a 900-km^2 subarea (Ozturgut et al., 1981), approximately 25% of which could be unmineable due to topographic constraints on the collector apparatus. A 3,000,000-t/yr operation could involve twice this area, or 1,800 km^2.

The mining device, or "collector," will travel along depth contour lines covering about 100 km (54 nmi) daily, in such a manner as to sweep the bottom in nearly abutting swaths, in a similar manner to a farmer plowing a field. Based on developing collector technology, each swath could be up to perhaps 15 to 20 m wide for hydraulic systems and probably much wider for the continuous-line bucket system (CLB, described below).

Assuming a production of 5,000 t/day of dry nodules, the collector will contact 1.1 km^2 each day. An additional 0.8 km^2 will remain unmined owing to the inability of the system to sweep the seafloor in perfectly abutting swaths. The total area traversed daily would then be 1.9 km^2. On an annual basis that area may be inflated up to 25% due to topographic limitations or low nodule concentration. The daily throughput of the system is estimated in Table 2.

Table 2
Estimated mining system throughput

Component	Daily flux	Discharges	
		Benthic[a]	Surface
Nodules, dry t	5,500	250	250
Sediments, dry t	54,000	52,000	1,600
Biota, kg	783	760	23
Bottom water, m^3	58,000	—	—
Interstitial water, m^3	42,000	—	—
Total water[b], m^3	105,000	80,000	25,000

[a]Expected to be discharged within 20 m of sea floor.
[b]Includes bottom, interstitial, and some surface water.
Source: Modified from U.S. Department of Commerce (1981, p. 228).

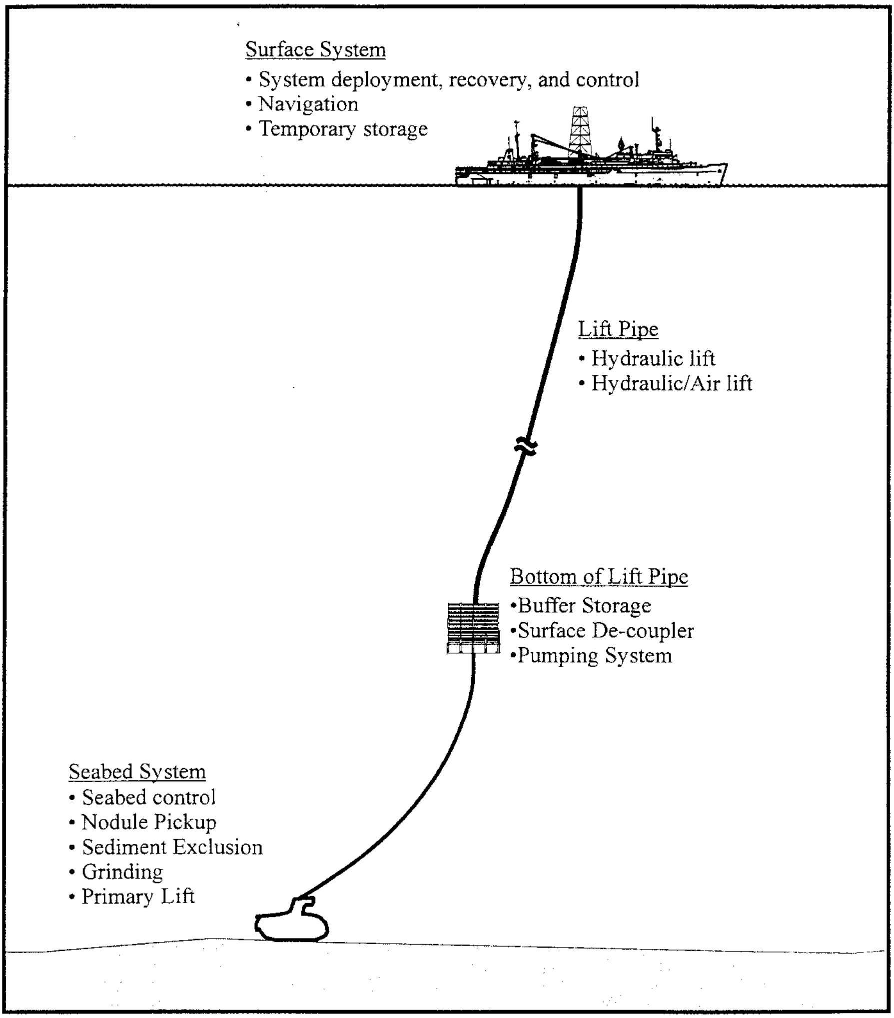


Figure 1. Hydraulic mining concepts.

Hydraulic Systems

Operating characteristics for hydraulic systems are well documented (e.g., U.S. Department of Commerce, 1981; Welling, 1981; United Nations, 1984). Hydraulic miners use hydraulic lift, either with or without injected air assistance, with towed or self-propelled collectors (Figure 1). Towed mining devices, or passive systems, are similar to a scraper or harrow being dragged over a plowed field. The first hydraulic system for recovery of deep seabed manganese nodules was tested by Deepsea Ventures, Inc., on the Blake Plateau during the summer of 1970 (Geminder & Lecourt, 1972). Active or self-propelled miners are more complex and may be fitted with separate propulsion, navigation, nodule pickup, and crushing systems. The complexities of the design for these systems are illustrated in Figure 2 for a hydraulic lift with a self-propelled collector as used by Ocean Mining

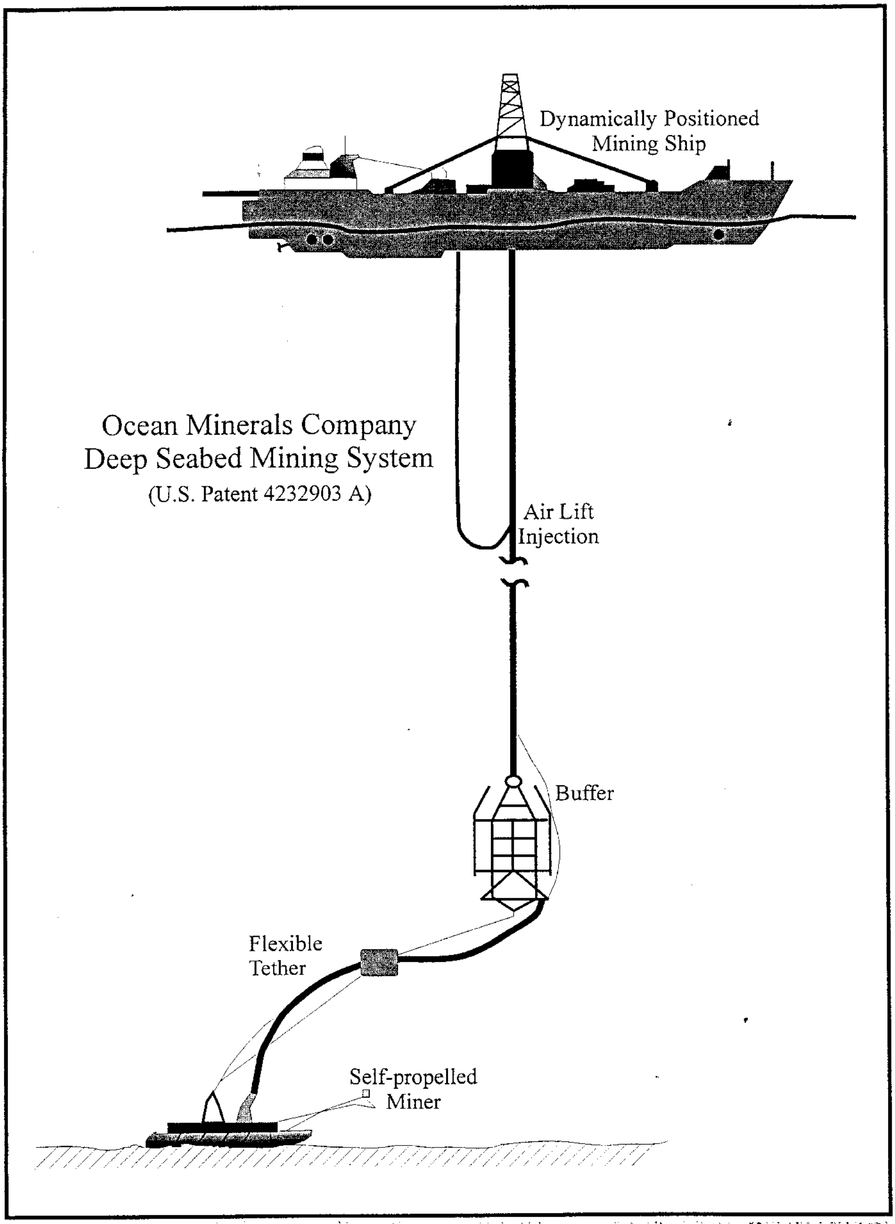


Figure 2. Complexity of design of hydraulic system.

Co. during successful tests in the Pacific (e.g., Welling, 1981; U.S. Patent 4,232,903, Nov. 11, 1980).

All tested systems used some means to separate the nodules from the sediment deposits in which they lie. In the Ocean Minerals Company design, nodules are picked up by tines at the front of the miner and fed into the suction pipe by conveyor belt or by the forward movement of the device. Separation of fine sediment is accomplished automatically by screening effect of the tines and use of a screen on the lifting part of the miner (Figure 3).

After the Deepsea Ventures tests, subsequent tests were completed by this group and several other international consortia between 1970 and 1980. Some tests were monitored by U.S. and other researchers to estimate potential environmental impacts. The results from this monitoring work are discussed below. For the purposes of impact assessment, the following distinctions among these tested systems are useful to consider.

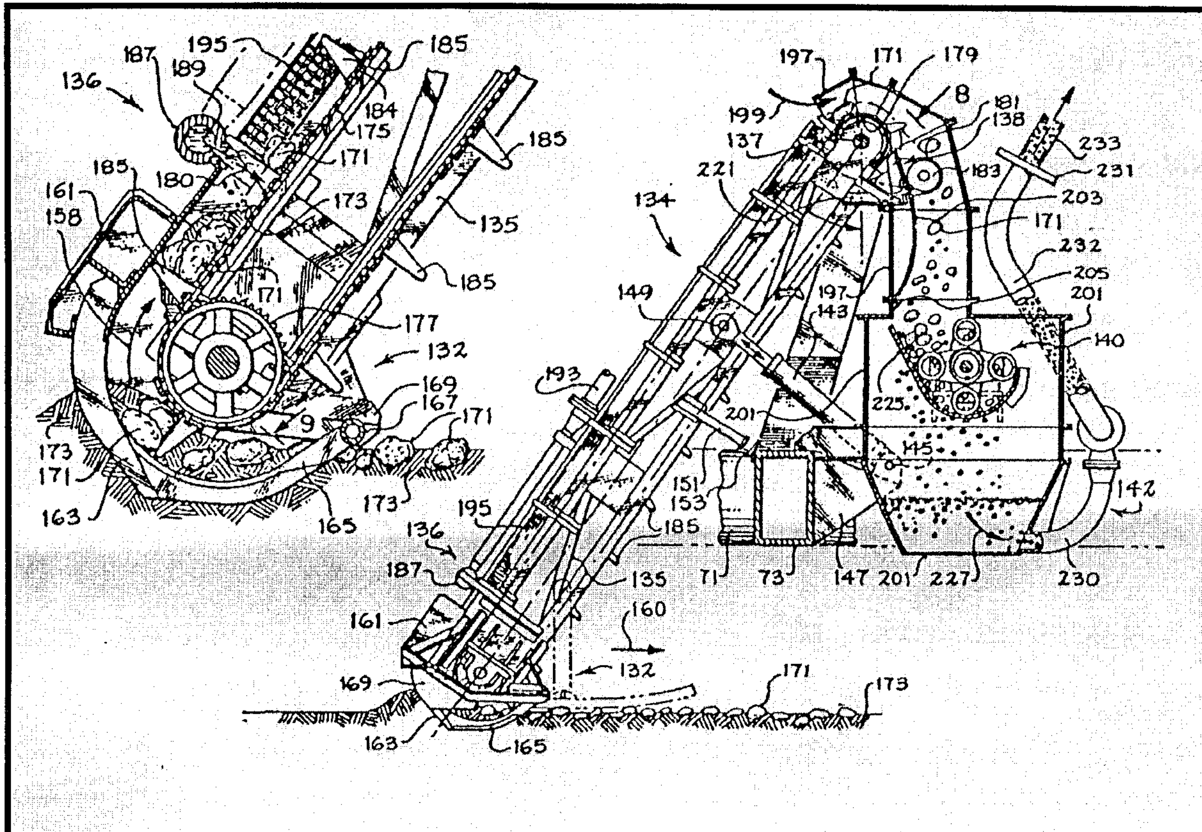
Precision of Mining Track. Some systems tested were simply towed from the surface. Others had passive controls on the seabed collector to provide some steering capability. Still others were entirely self-propelled, with interactive, real-time steering. From the perspective of the miner, the design is a trade-off between the degree of control attained and the cost and complexity of the design. From the perspective of impact assessment, two factors are important. High precision allows efficient recovery and conservation of the mineral resources and also permits accurate avoidance of areas deemed to be worth preserving. However, it also leaves less of the original site untouched. Technological advances which have occurred since these tests were carried out, particularly with regard to telemetry and control systems, strongly suggest that future hydraulic systems will be steerable with high (submeter) precision.

Separation of Nodules from Sediments. All systems are designed to minimize the amount of sediment which is lifted along with the nodules. Nodules have been raked up and/or washed before being collected. For the miner, the trade-offs are concerned with energy costs, maintenance costs, and reliability. For environmental assessment, the main concerns are with the efficiency of the collection and separation and with the dispersion of sediments in bottom waters. The optimal design must provide an acceptable balance among these potentially conflicting concerns.

Discharge of Suspended Solids. After collection, the nodules will be lifted to the surface, probably after being crushed to cobble-sized or smaller dimensions. The dynamics of slurried solids require fairly uniform dilutions in seawater and subsequent discharge of the lifted seawater along with some fraction of suspended solids. All recovery systems will seek to minimize the amounts of sediments and fine-grained nodule fragments in this discharge stream for simple economic reasons, but some suspended-sediment discharge is likely to be required with any design. However, the miner is likely to have relatively complete control over the depth at which this discharge is set (U.S. Minerals Management Service, 1990). Thus, a primary concern for impact mitigation, discussed below, will be the selection of the receiving waters for these discharges.

Continuous Line Bucket (CLB) System

The CLB system (Figure 4) has been tested for possible use in recovering manganese nodules (Masuda et al., 1971) and is described in NOAA's EIS for deep seabed mining (U.S. Department of Commerce, 1981). The CLB system has also been proposed for mining phosphorite nodules and slabs and for cobalt crust



Ocean Minerals Company Nodule Pick-up System (from U.S. Patent 4232903 A)

Figure 3. Separation of fines.

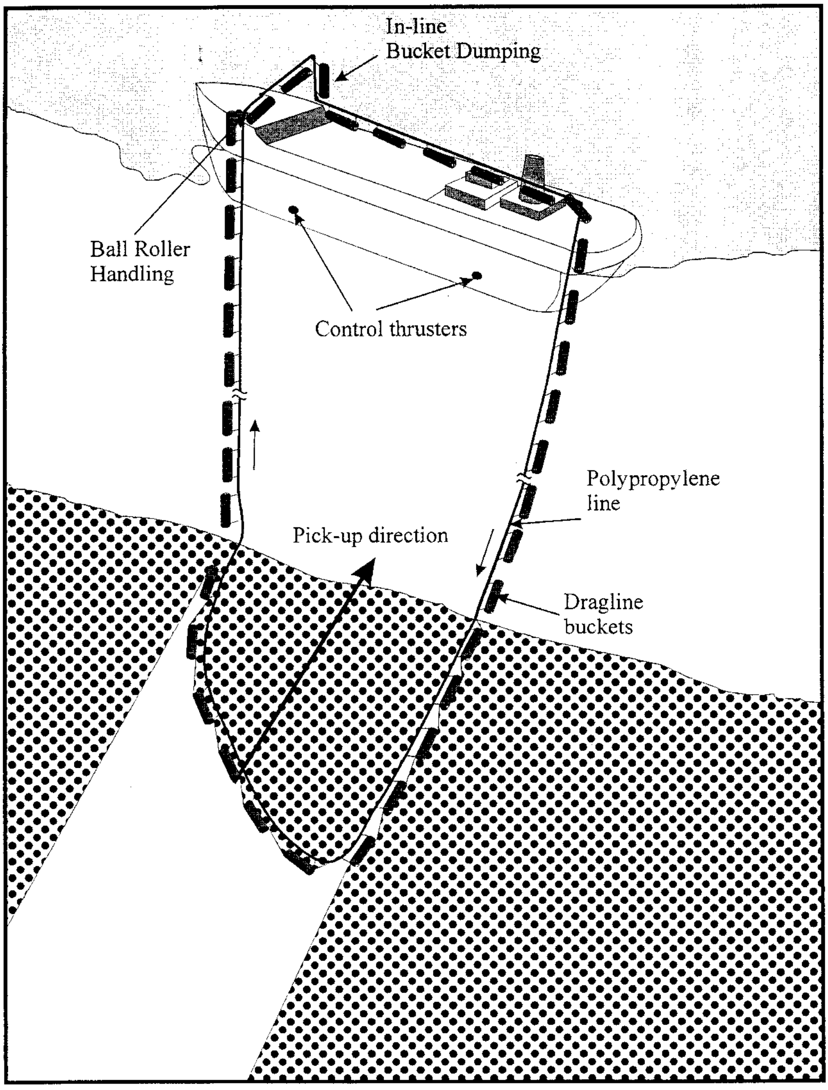


Figure 4. Continuous line bucket (CLB) manganese nodule recovery system.

mining. The original CLB system concept used one ship, with empty buckets going down from the stern and partially filled buckets coming in at the bow. The distance between the downward-moving and the upward-moving parts of the loop of rope is dependent on the length of the ship and thus cannot be altered. Entanglement can be avoided by achieving an optimum combination of ship speed and length of line or by use of hydrodynamic deflectors. The optimum combination may be influenced by various other factors including the nature of the seabed, underwater currents, variations in the ship's course because of weather heading, or bad weather conditions.

To minimize these disadvantages and to add to the flexibility of operation, a two-ship system was designed where the empty buckets go down to the seabed from one ship and are brought up to a sister ship nearby. The distance between the descending and ascending parts of the loop and the curve of the loop can be influenced by the relative positioning of the two ships (United Nations, 1984).

Speculative Deep-Water Systems

Other, more speculative systems have been suggested but not tested. One in particular, a deep submersible modular system, would mine and transport manganese nodules from the seabed to an attendant platform on the surface. An autonomous collector vehicle would be launched with ballast material such that the weight of the ballast in water is equal to the weight in water of the nodules to be collected. The collector would be designed to have sufficient buoyancy so that the vehicle is weightless in water. Thus, in descent, thrusters propel the unit down steadily against hydrodynamic resistance alone. On the bottom, the collector is propelled over the bottom, and as collection proceeds, ballast material is simultaneously ejected on an equal weight-in-water basis. In this manner, a small net weight in water of the collector is maintained. Mining is terminated shortly before ballast material ejection. Ballast material ejection is continued until the weight of the vehicle is zero or slightly negative. Finally, the vehicle is propelled by thrusters to the surface, docked with the surface ship, unloaded, serviced, and reballasted for a new mining cycle. In theory, very little onboard power is required to collect the nodules because the major source of energy is the potential energy of the ballast material. The operating principle of this system is illustrated in Figure 5 (United Nations, 1984). Processed tailings have been suggested for use as ballast. Advantage might be taken of ambient currents to propel the vehicle similarly to a sailplane or glider.

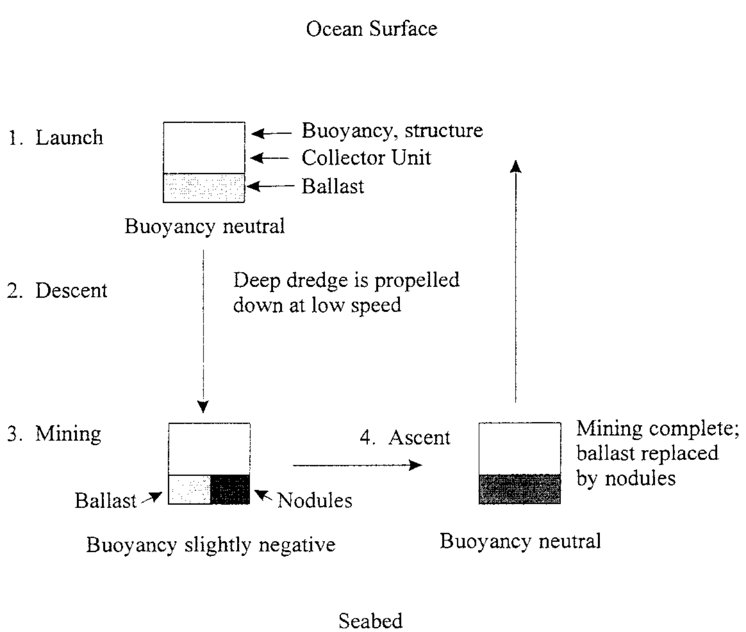


Figure 5. Speculative deep water system.

This concept for a mining system and others are certainly possible candidates and cannot be ruled out at this early stage of development. They are not defined well enough to permit confident environmental assessment and illustrate the need to keep regulatory development apace with commercial development. Premature prescriptive rules about discharging, mining patterns, or other mining activities might limit or even curtail potentially superior methods for commercial recovery.

Ore Transfer and Transportation

Manganese nodules raised from the seabed may be transferred at sea from the lift ship to the transport ship. Conventional dry-bulk handling methods using belt or screw conveyors and buckets may be satisfactory to handle the material as raised. For ship transport, the water should be drained after loading to reduce transport weight and to assure stable cargoes that do not shift at sea. Unfortunately, manganese nodules tend to disintegrate into small particles during handling and when stacked in large piles and in ship holds. Thus, a persistent problem to be expected at every point of transfer is the suspension of fine-grained ore particles in discharge waters.

Transportation of ore and other materials is also an important consideration for environmental impacts. However, vessels for transportation of manganese nodules can be described only in generalities until the specific features of the mining system are delineated, the destination ports determined, and other uses of the transport are defined. The ores may be carried in ore-carrier hulls which restrict the centerline cargo holds to a small part of the available hull space, or in standard bulk carriers which load dense ores in some of the cargo holds only, leaving others empty. In either configuration, extra steel is needed to provide compartmentalization and adequate hull strength for concentrated loads of dense ore. Combination ships may be able to carry any ore, bulk or oil. Such ships are flexible for carriage and pumping of other liquid cargoes. If ocean dumping of processing wastes is the selected disposal technique, ore carriers could transport wastes from shore to the disposal site.

Ore carriers normally have no cargo-handling gear, although many ships are equipped with cranes and a few have self-unloading conveyors. If the nodules are fragmented into small pieces, as would be necessary for a hydraulic-lift system, they can be transferred to the ore carrier through a slurry hose. For a CLB system, other options, such as conveyor belts, could be employed with the whole nodules. It is likely that the handling gear employed would be housed on the mining vessel and at the offloading port site.

Dry-bulk ships are usually gearless, house-aft, diesel-propelled, single-screw designs. The ships have multiple cargo holds, increasing with larger size, and power-operated, rolling hatch covers. Bow thrusters are now common for ease of docking operations. An ore-carrying-type ship with reduced hold width and lower hold center of gravity is needed for proper stability. Whether slurry or dry form, the ore-carrying configuration is essential. In addition, a capability for transport of fuels, supplies, and waste by the ore carrier would probably be necessary.

The water depth available inside major harbors is generally about 40–45 ft in salt water at low tide. Allowing for tidal rise and deeper dredging at berths, ships with about 12–13.5 m ft of draft would be the maximum size that could be fully laden and still transit most large harbors. These are equivalent to about 65,000 dwt, to over 100,000 dwt for recently proposed shallow-draft designs. Deadweights are typically less for older ships with higher speeds and relatively deep drafts.

Metallurgical Processing

The primary way in which the manganese nodules differ from most land ores of base metals is that they are oxides and not sulfides. This imposes basic differences on the treatments required to extract the metals from the ore and also results in very different waste products. The land ores most similar to the nodules and crusts are laterites which occur as surficial sedimentary deposits, mostly in tropical rain forests. The processing methods which have been proposed and tested for nodules are mostly modifications of techniques originally developed for laterites.

Of the various types of processing schemes available for manganese nodule processing, five are considered most probable for first-generation commercial applications (Haynes & Magyar, 1987) as follows:

1. Gas reduction and ammoniacal leach (modified Caron)
2. Cuprion ammoniacal leach
3. High-temperature and high-pressure sulfuric acid leach
4. Reduction and hydrochloric acid leach
5. Smelting and sulfuric acid leach

The two ammoniacal and high-temperature and high-pressure sulfuric acid processes are designed to recover three metals (cobalt, copper, and nickel), and the other two hydrometallurgical processes are designed to recover four metals (cobalt, copper, nickel, and manganese). In the three-metal processes, manganese could also be recovered from the tailings if favorable economic conditions exist.

Wastes generated by these processes will of course depend very much on the actual process scheme used. Haynes and Law (1982) examined the above process types and produced estimates of the various major, minor, and trace components which would result in the waste streams for each. In comparison with wastes produced from sulfide ores, it is important to recognize that waste from nodules or crusts would generally be more stable and less liable to release toxic metals into the environment. The potential for sulfuric acid production does not exist for these oxides.

Probably the most common of the processes proposed to date is the sulfuric acid leach. Table 3 presents estimates of the major inputs and outputs of metals that would be expected from this process, assuming a throughput of 3,000,000 t of ore (dry weight) and the same process stream as that used in the processing scenario developed for manganese crusts (U.S. Minerals Management Service, 1990, Appendix A). The nodule composition used in this table comes from Haynes and Law (1982). The waste streams include the filtered wash water (elutriate), consisting of sea salts diluted in fresh water, and the dissolved and solid tailings which must be discharged (leach liquor and leach residue).

New methods of processing for manganese nodules are under development. Choi and Sohn (1996) investigated the leaching characteristics of manganese nodules in ammonium chloride solution by using sodium sulfite as a reductant. Experiments were conducted in leaching of manganese, cobalt nickel, copper, and iron using sodium sulfite in the ammonium chloride solution. It was found that the leaching behavior of manganese, copper, cobalt, and nickel depended on the

Table 3
Estimated throughput from manganese nodule processing (sulfuric acid leach processing)

Component	Wt.%	ppm	t/yr	Elutriate	Liquor	Residue
A. From the ore						
Aluminum	2.9		87,000		8,700	78,300
Antimony		37	111			112
Arsenic		159	477			471
Barium	0.3		8,310			8,310
Cadmium		12	37			39
Calcium	1.7		51,000			51,000
Carbon	0.2		5,700			
Cerium		532	1,596		5,700	1,596
Chlorine	0.5		15,900			
Chromium		27	81		15,900	73
Cobalt	0.2		7,200			1,009
Copper	1.0		30,600			6,393
Iron	6.9		207,000		4,140	202,860
Lead		450	1,350			1,350
Magnesium	1.7		49,500		42,075	7,425
Manganese	25.4		762,000		38,100	723,900
Mercury		0	0			0
Molybdenum		520	1,560			1,638
Nickel	1.3		38,400			4,178
Phosphorus	0.2		6,900		6,900	
Platinum		0	0			
Potassium	0.7		21,000		4,200	16,800
Silicon	7.6		228,000		6,840	221,160
Silver		0	0			0
Sodium	2.8		83,700		66,960	16.740
Strontium		450	1,350			1,221
Sulfur	1.8		55,200			55,200
Thallium		5	16			16
Titanium	0.5		15,900			15,900
Vanadium		470	1,410			1,504
Yttrium		21	62			57
Zinc	0.1		4,200		3,831	429
B. From associated seawater						
Barium		70	210	189	21	
Calcium		400	1,200	1,080	120	
Chlorine	2.0		60,000	54,000	6,000	
Fluorine	0.3		9,000			9,000
Magnesium	0.1		3,900	3,510	390	
Potassium		400	1,200	1,080	120	
Sodium	1.1		33,000	29,700	3,300	
Sulfur		900	2,700	2,430	270	

Source: U.S. Mineral Management Service (1990), Appendix A.

amount of added sodium sulfate. The sodium sulfite has been found to be an effective reductant for extracting more than 95.8% of Mn, 93.5% of Ni, 98.5% of Cu, 89.1% of Co, and 3.1%of Fe when leached in 5N NH_4Cl at 80°C for 2.5 h.

A unique biological processing concept has been proposed by Konishi and Asai (1996). Sulfurous acid and sulfuric acid are produced biologically from elemental sulfur and used simultaneously as leaching agents. The thermophile bacterium *Acidianus brierleyi*, growing on elemental sulfur at 65°C, is effective in solubilizing the value metals in nodules.

The idea of metallurgical processing at sea was evaluated seriously by industrial consortia in development projects during the 1970s and 1980s. There would be significant economic advantages to the reduction of the ore to the 3% or so of the value metals (excluding manganese) before transportation. At that time such ideas were ultimately rejected because of the serious complications caused by the restrictive areas available on conventional vessels at sea and by the need to compensate for the inevitable motion of the ship. It is important to note, however, that marine technologies and metallurgical processing technologies are constantly improving, and it is quite possible that processing at sea will be viable when seabed mining becomes a commercial reality.

Description of the Environment

Two regions in the deep seabed currently have exploration claims registered with the International Seabed Authority. The Government of India has claimed an area in the South Central Indian Ocean between 10°S and 17°S latitude and between 72°E and 82°E longitude, while seven international groups (China, France, India, Japan, Korea, Russia, and an Eastern European group) have claims in the Northeastern Tropical Pacific (the Clarion-Clipperton Zone) between 7°N and 18°N latitude and between 157°W and 118°W longitude (see Figure 6). Though these two regions are more than 13,000 km distant from each other and must be considered separately in any site-specific environmental analysis, they do share key similarities which are probably related to the occurrence in both regions of manganese nodule deposits of relatively high abundance and high metal content.

The following description of the environment focuses on these similarities because they are also generally the key factors of importance for assessment of environmental impacts. In this section, a brief discussion of the geologic factors which appear to cause the occurrence of high-grade deposits is presented and then the general physical, chemical, and biological factors of importance in these marine environments are outlined.

Occurrence of Commercial Nodule Deposits

Manganese nodules are common worldwide in both marine and freshwater systems. They form along gradients of ambient water chemistry in which waters traverse from relatively acidic and low oxygen levels into relatively high levels. Acidic, poorly oxygenated waters can contain significant amounts of dissolved and organically complexed metals. Where these waters pick up oxygen and usually at the same time lose some acidity, many metals will rapidly oxidize and precipitate out. This situation commonly occurs at the water/sediment interface in lakes and the ocean, which is where manganese nodules are usually found. Iron and man-

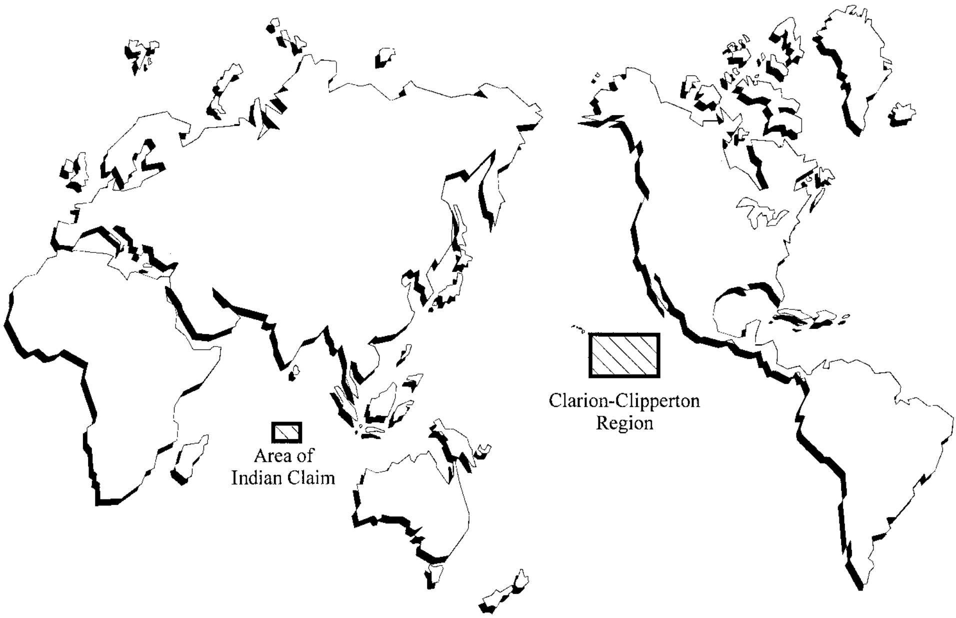


Figure 6. Areas with current claims under the International Seabed Authority.

ganese are the most common transition metals in the earth's crust, and thus form the bulk of the precipitated material. Manganese oxides also have special surfaces which are particularly effective at collecting and holding more manganese and other metals, scavenging them preferentially from the bypassing water flow.

In addition to these basic gradients, conditions which particularly favor high abundances of manganese nodules with relatively high concentrations of the value metals copper, nickel, and cobalt include (1) relatively high inputs of dissolved and organically complexed metals; (2) relatively low levels of other types of sedimentation, such as aluminosilicates and carbonates; and (3) long-term stability of the seabed surface to permit time for deposit accumulation.

As discussed below, these characteristics are well developed on the seabed under the tropical oceans in particular areas which have high primary productivity in surface waters, which are far from land sources of sediments, and which are deep enough so that carbonate sedimentation is mostly dissolved before it accumulates. Thus, it is probably no coincidence that the highest abundances and grades of manganese nodule deposits, as evidenced by the locations of the existing international exploration activity, fall in the areas of the world's oceans which are farthest from land.

Local conditions of topography also exert significant control over manganese nodule distributions in both areas, and the best deposits are found in gently sloping regions which are partially sheltered from major inputs of bedload-derived sediments (Demidova et al., 1996).

Relevant Sediment Properties

Manganese nodules are believed to be different morphologically from manganese crusts or pavements primarily because they form on sediments rather than on hard substrates. Unconsolidated sediments are much more susceptible than hard substrates to disturbance from tectonic activity, benthic currents, and biological mixing by burrowing organisms (bioturbation). Extensive examinations of manganese nodules from many environments show that the nodules experience repeated overturning during their growth to result in their characteristic, onionlike morphology.

The sediments from the Indian Ocean site and from the Clarion-Clipperton region of the Pacific consist mostly of clays and siliceous biological casts. Sands and larger sediments generally are not found so far from land, and the commonly formed carbonate biological casts dissolved on the seabed in these deep-water regions faster than they accumulate. In the Central Indian Basin, the sediments are primarily siliceous sediments and contain an average of 5.5% by weight of radiolarian tests (Roonwal et al., 1994).

The upper centimeter or so of the sediments is high in water content and the water chemistry is very similar to that of overlying waters. Most of the benthic fauna reside in this zone. Sediment permeability is determined by grain size and shape, sorting, packing, and other factors which in turn determine suitability of the sediments as habitat for deep-sea infauna. Biological disturbance of the sediments in turn affects pore water equilibria.

Generally, bottom-sediment chemistry is stable. Bacterial activity acts to oxidize the organic material present, and oxygen concentrations decline with sediment depth. Ammonia concentrations in DOMES sediment samples showed significant enrichment over near-bottom water, presumably a direct result of metabolic activity.

Detailed sampling of the bottom in the Clarion-Clipperton region has been carried out and is reported by Baturin et al. (1991), Bischoff and Piper (1979), Murdmaa and Skornyakova (1986), and others. These collections indicate that there are predominantly recent and Pleistocene pelagic radiolarian, calcareous-argillaceous, and argillaceous oozes with highly variable nodule abundances (from 0 to more than 15 kg/m^2). The bulk density of the sediments may vary within the range 1.1–1.62 g/cm (mean value 1.19 g/cm), moisture content 52–85% (mean of about 76%), and porosity 71–93% (average porosity about 87%). The diatomaceous-argillaceous ooze pelite fractions (< 0.01 mm) comprise 50–85% of the sediments, and have a dry specific gravity of 0.4–0.9. The argillaceous ooze can consist of more than 90% pelite and 40% or more subcolloidal fractions of a size less than 0.001 mm.

Sharma and Rao (1991) report that the seabed in the Indian claim area consists primarily of biogenic sediments, manganese nodule deposits, massive rocky exposures, and associated ferromanganese crust deposits. Siliceous ooze is the primary component of the sediments, with a thin strip of calcareous foraminiferal and coccolithid ooze in the west and some red clays in the south.

It is important to note that much of this fine-grained material is probably delivered to the seabed in the form of much larger (0.1–1 mm) fecal pellets from zooplankton and larger animals in the water column. Researchers who have had extensive experience handling material from box cores and other relatively undisturbed sediment samples from the region consistently note the surprisingly coarsegrained feel of the material before it is disaggregated for various analytical testing procedures. Thus, we can expect the in-situ behavior of the material to approximate a bimodal mixture of very fine-grained clays and much coarser aggregations of particles.

Benthic Currents

The benthic and deep waters of the Indian Ocean are believed to be derived in large part from the Atlantic, with some contributions from the South Australian Basin and from the Wharton Basin (Kolla et al., 1976). Recent work funded through the World Ocean Circulation Experiment (WOCE) has retrieved benthic current data from one current-meter array located in the southwest corner of the area of the Indian claim (20°S, 72°29.2′E; Nowlin et al., 1997). These data are currently being processed by the investigators involved and are not available for general distribution. Summaries of the data retrieved from the meters at 99 m and 1,099 m off the sea floor have been made available and are presented in Table 4. The currents appear to be generally southerly, with mean speeds of a few centimeters per second and maxima > 10 cm/s. As discussed below, these means and maxima are consistent with the currents in the Clarion-Clipperton zone, which are discussed further below.

Much more examination of the benthic currents in the Clarion-Clipperton region has been carried out. Benthic currents have been documented by a number of authors (Demidova et al., 1990; Demidova & Kontar, 1989; Hayes, 1979, 1980; Gardner, et al., 1985; Amos et al., 1977; Johnson, 1982) on and between abyssal hills (see Figure 7).

Table 4
Benthic currents in the South Central Indian Ocean[a]

Parameter	Minimum	Mean	Maximum	Std. Dev.
Meter at 3,014 m				
Speed (cm/s)	0.93	2.23	10.30	1.72
Direction (deg true)	0.30	189.43	359.93	100.76
u component (cm/s)	−7.94	−0.15	9.43	1.94
v component (cm/s)	−9.54	−0.13	10.26	2.03
Temperature (°C)	1.47	1.55	1.64	0.02
Pressure (db)	3,069.89	3,073.49	3,077.24	0.65
Meter at 4,014 m				
Speed (cm/s)	0.93	2.04	8.01	1.33
Direction (deg true)	0.07	186.68	359.71	109.05
u component (cm/s)	−5.58	0.01	7.94	1.72
v component (cm/s)	−6.08	0.19	6.49	1.72
Temperature (°C)	1.42	1.44	1.48	0.01

[a]Water depth 4,113 m; deployment 14 May 1995–26 January 1997
Source: WOCE Program, Nowlin et al. (1997).

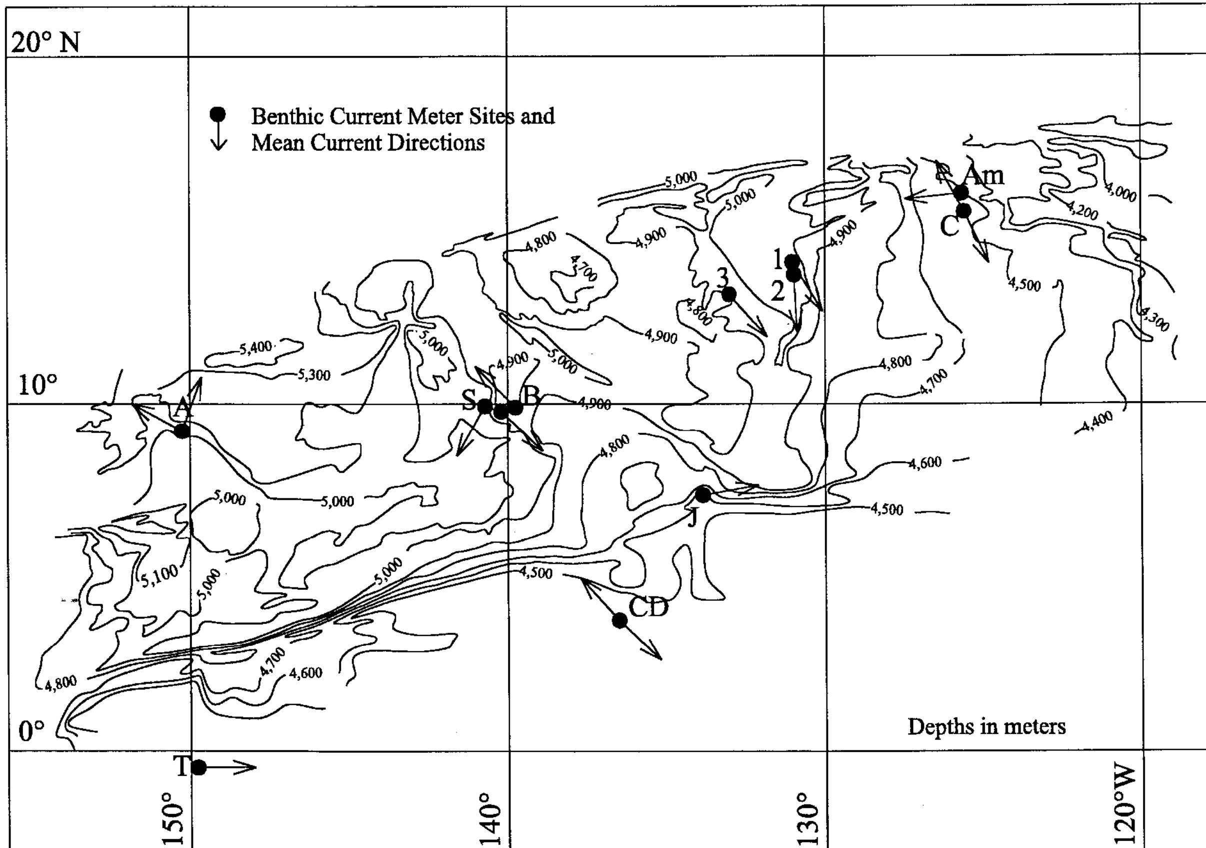


Figure 7. Benthic currents in the Clarion-Clipperton region.

Classification of Benthic Currents. The summary statistics of the benthic current measurements available for the Clarion-Clipperton region are presented in Table 5. Mean values of current speed and velocity depend on the duration of measurement. Hayes found average speeds over periods of 143–197 days to be between 1.5 and 2 cm/s. High variability in speed and direction was noted in all studies.

Three dynamic regimes are in evidence in the Clarion-Clipperton region (Figure 8):

1. *Calm periods*, characterized by minimal current speed (0–3 cm/s), moderate to low variance, and low tidal activity. In our experiment, reported in Demidova et al. (1992) and Demidova and Kontar (1989), this time interval lasted about 11 days, from the 11 February to 21 February 1988.
2. *Intermediate*, mostly tidal periods, characterized by the alteration of current speed (0 to 5–6 cm/s) and velocity with a corresponding increase in the variance of the data but with the same minimal values as in the first case. In

Table 5

Benthic currents in the Clarion-Clipperton region

Location			Water depth (m)	Above seabed (m)	Duration (d)	North (variance)	West (variance)	Ave. speed (cm/s)	Ave. dir.	Max. speed (cm/s)
ID[a]	N. Lat.	W. Long.								
1	14°20.5′	131°00′	4,950	35	13	−1.5	−0.1	1.5	183	9
						1.2	1.9			
				25	13	−2.2	0.7	2.3	163	10
						1	2.2			
2	13°56.5′	131°01′	4,980	35	13	−1	−0.4	1.1	200	9
						1.3	1.3			
				25	13	−2.8	−0.2	2.8	183	7
						1	0.7			
3	13°31′	132°57′	4,920	6	13	−3.1	3	4.3	155	13.5
						2.4	2.9			
A	8°27′	150°49′	5,200	50	143	0.19	−0.29	0.35	50	12
				30	143	0.29	−0.49	0.57	59	10
A1	9°27′	151°17′	5,200	4	40	1.4	−2.7	3	63	15
A2	9°26′	151°17′	5,190	8	40	2.3	−2.4	3.3	46	15
				4	40	1.6	−0.24	2.9	9	
A3	9°21′	151°17′	5,093	4	40	1	0.5	1.1	333	
B	11°42′	138°24′		30	197	1.3	−1.68			14.5
C	14°38′	125°29′	4,508	30	156	1.7	−0.62		331	15
				6	156	1.8	−0.81		324	13
S2	11°02′	140°06′	4,906	4.7	123			5.25		12.5
S3	11°03′	139°59′	4,873	4.7	200			4.45		11.2
CD	4°00′	136°01′	4,469	4.7	195					10.1
Am	15°13′	125°58′	4,655	10	11	0.3	−6.1	7	273	
						3.2	3.6			
J	7°40′	134°00′	4,705	25	4			4.8	56	8.3
			4,590	19	4			5.4	99	9.6
			4,700	5	4			4.5	63	8.1
T	1°02′S	149°50.7′	4,647	1,500	152	0.1	3.9		87	

[a]See Figure 7.

Source: Demidova, et al. (1996).

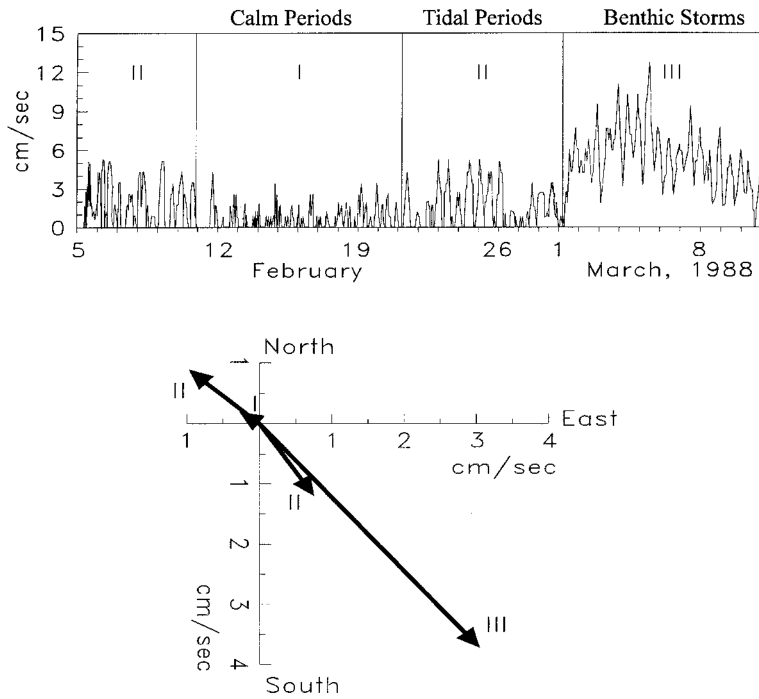


Figure 8. Benthic current regimes in the Clarion-Clipperton region.

our experiments this regime was revealed between 4–11 and 21–29 February.

2. *Benthic storms*, associated initially with a sharp increase in current speed which can maintain relatively stable speeds to produce 24-h means of as much as 8 cm/s, reported in Demidova and Kontar (1989), and 1-h means of between 13 and 15 cm/s, reported in Hayes (1979). These events can be termed "benthic storms." The benthic storm measured in our study lasted about two weeks (the first two weeks of March). Approximately the same time intervals (several weeks) of increased velocity have been found in the more long-duration observations by Hayes (1979) as well.

Current Directions in the Clarion-Clipperton Region. The general direction of near-bottom currents in the province is postulated by Wong (1972) and Sokov (1991) to be dominated by the flow of Antarctic bottom water (AABW) to the northeast. This water is introduced to the region through the deep Clarion and Clipperton passages. Flowing along the main fault zones to the northeast, a part of it presumably branches off in the numerous seabed valleys and depressions, potentially influencing local current distributions. However, as shown in Table 5, the measured benthic currents available to this study all indicate current directions in direct opposition to the north-northeast direction predicted by indirect methods. At the site of the bottom station BS-3, north-northwest (NNW) and south-south-east (SSE) directions dominated the observations. This direction is consistent with the bearing of isobaths at the site. The mean velocity vector for BS-3 is southeast. Analogous results are obtained as well for the other two stations, where the mean velocity vector is also directed along the major isobaths. Thus, consistent with this study and others, local bottom-water advection at the scales of hours to months appears to be controlled by bottom relief.

In the central and west parts of the Clarion-Clipperton region this relief is, with some exceptions, made up of elongated hills separated by gentle valleys which are oriented transversely with respect to the major fault zones. According to several recent studies by Morel and LeSuave (1986) and by Demidova et al. (1996), the submeridional valleys of erosional nature are widely developed in these parts of the province. According to all the observations to date, the calm and active regimes discussed above are characterized by opposing current directions. The mean direction at the period of low activity is often NNW, consistent with the basic advection of AABW, whereas the flow during benthic storms is often SSE. Hayes (1979, 1980) reports earlier experiments of longer duration, in which this same trend of current reversal during different regimes is evident. Interestingly, this inferred direction of sediment transport along the seabed valleys to the SSE corresponds to the direction of general decrease of ocean depths rather than their increase.

Benthic Currents and Sediment Transport. The results presented above strongly suggest that benthic currents in the Clarion-Clipperton region are effective in transporting sediments along the seafloor valleys. The benthic storms noted in this and other studies are clearly capable of lifting and transporting fine-grained materials which have been disaggregated by detrital feeders and other mechanisms (see, e.g., Kennett, 1982; Trueblood & Ozturgut, 1992; Baturin et al., 1991). These currents are sufficient to suspend and transport significant quantities of the very fine-grained, relatively low-density, uppermost pelagic sediments which predominate in this region.

The alternating intermediate tidal currents are also likely to be effective in transporting sediments. The threshold speed of beginning of erosion depends both on sediment properties in a site under investigation and on benthic current peculiarities there. For instance, there is good evidence, reported by Gross et al. (1988) that for the same benthic current speed, erosion does not occur if the direction of the current is stable and it arises immediately with sharp direction change.

The calm periods provide conditions for subsequent accumulation of sediments. During the interspersed periods of low-speed currents (0–1 cm/s), which can last for several days, even the most fine-grained sediments (up to subcolloidal particles) transported by the currents will redeposit on the seabed. Based on Hayes' estimates of monthly averaged current speed (2 cm/s), this would result in a net bedload transport of 50 km per month if the high-speed currents effecting the transport are always in the same direction. This transport occurs in quasi-periodic regime, so the nepheloid layer arising during benthic storms and maintained by inertial-tidal alteration and by variability of smaller scales may exist for several years and transfer to hundreds of kilometers, as was shown by Gross et al. (1988). Finally, currents at the velocities observed can also facilitate and generate turbidity flows of a semifluid layer of sediments along the inclines, while simultaneously entraining a fraction of the material into the flow, as suggested by Craig (1979).

It has been demonstrated by Demidova et al. (1992) and by Sokov and Demidova (1992) that the reason for the acceleration of the benthic currents observed by the Russian studies was an anticyclonic eddy more than 200 km in diameter which was moving through the area from the east-southeast (ESE) to the west-northwest (WNW) and penetrating to the bottom. The finite speed of the eddy to the WNW, possible declination of its axis, and reference of the sites to different sectors of the eddy were probably responsible for some shifts of the prominent features of the current time series at the sites during the benthic storm. At the same time there was weak agreement of the corresponding time series before the benthic storm during the first and the second current regimes, possibly because of the significant influence of local seafloor relief.

It is important to note that the region is known for steady average winds which are mainly representatives of the Northeast Trade winds and, connected with the wind and pressure fluctuations, with its significant synoptic eddy activity, which could be the reason for the majority of benthic storms. Spatial-temporal scales of the eddies provide benthic storms occurring more or less regularly and developing over the large part of the province. The main direction of movement of the eddies across the province and the circular movement of the water in them should determine the predominant direction of benthic currents during benthic storms, whereas the local direction at specific points and current directions during calm time intervals probably depends on the local bottom topography.

Geologic Indicators of Benthic Currents and Sediment Transport. Extensive sampling photography of nodule deposits have also been completed in this area in commercial development efforts. This work indicates that benthic currents may be very important to nodule deposit formation and also suggests a mechanism which may be central to the process.

Many researchers in recent years have noted the high degree of local variability in the overall abundance, composition, and surface morphology of deep-seabed manganese nodules in the Clarion-Clipperton region of the northeast Tropical Pacific. This high local variability is attributed to such factors as the local seabed topography, benthic current structure, and sediment type (e.g., Morgan et al., 1993; Keating & Bolton, 1992; Baturin, 1988; Usui et al., 1987; Murdmaa & Skornyakova, 1986; Dymond et al., 1984; Piper & Blueford, 1982).

Investigators in the Clarion-Clipperton region have discovered persistent evidence of active bedload transport, both with recent measurements of artificially induced dispersion of benthic sediments, reported by Trueblood and Ozturgut (1992), and through identification of recent and ancient erosional surfaces using photography, acoustic subbottom reflection profiling, and direct sampling, reported by Usui et al. (1987) and by Piper and Blueford (1982). Recent Russian and French studies cited above have shown (in the region defined by 133°40′W and 136°40′W longitude and 11°N and 14°N latitude) that these surfaces are arranged in a system of erosional elements revealed morphologically as long, relatively flat valleys (several hundred meters wide by several tens of kilometers long) with depths of several tens of meters and flanked by steep (to 45°) slopes. The valleys generally have southerly down-slope directions.

The valleys are filled mostly by Pliocene to Pleistocene siliceous clays, with the depth of recent sedimentation increasing distinctly from north to south (Demidova et al., Yubko, 1996). Because the regional bathymetry becomes progressive deeper toward the north-northwest, gravity-driven sediment transport is not possible toward the southeast. Thus, the evidence strongly indicates a net southward bedload transport by benthic currents.

Benthic Communities

Adequate characterization of the benthic communities in the Clarion-Clipperton region or the Indian Ocean claim area has not yet been achieved. Generally, in both of these deep seabed areas, as well as in other deep ocean basins, the communities are essentially dependent for their nutrition on the organic content of falling detrital material from surface waters. No active hydrothermal vent communities are known in these areas, and obviously no photosynthesis is possible. As discussed below, environmental impacts of mining on the benthic communities are probably the most poorly understood class of impacts to be considered. The following sections summarize the available data for the Indian Ocean claim area and the DOMES data for the Clarion-Clipperton region. Other collections have been made in the Clarion-Clipperton region (e.g., see Kaneko et al. 1997; Trueblood & Ozturgut, 1997) and in the Peru Basin of the South Pacific (Schriever et al., 1997), which show similar taxa in similar relationships. It is beyond the scope of this synthesis to resolve the differences and similarities among these studies, but such an undertaking would greatly enhance our general understanding of deep-seabed biological communities.

Benthic Fauna in the Indian Ocean Claim. Sharma and Rao (1991) present a qualitative description of the megafauna observed in the Indian Ocean area which is summarized in Table 6. More recent assessments of the infauna densities have been made by Sharma et al. (1997) from examination of box cores. These examina-

Table 6
Megafauna observed in the Indian claim area

Phylum	Taxonomic groups
Coelenterata	Actinarians, Cnidaria, Hexacorallids, Madreporites, Pennatulids, Scleractinarians
Porifera	Hydrazoans, Sponges
Annelida	Oligochaetes, Polychaetes
Arthropoda	Amphipods, Arthropods, Cirrepeds, Copepods, Crustaceans, Cumaceans, Decapods, Isopods, Mysidaceans, Ostracods, Tanadaceans
Mollusca	Alacophora, Brachiopods, Cephalapods, Gastropods, Octopods, Pelecypods, Scaphopods, Squid
Echinodermata	Asteroids, Brisingids, Crinoids, Echinoids, Holothurians, Ophiuroids
Echiurida	Echiurids
Ectoprocta	Bryozoa
Sipunculida	Sipunculids
Platyhelmenthis	Platyhelmenthes
Rhizopoda	Agglutinating rhizopod protozoans
Hemichordata	Tunicates, Ascidaceans
Chordata	Anoumarids, Brachiurids, Fish, Macrourids, Pycnogonids

Source: Sharma and Rao (1991).

tions indicate a dominance of polychaetes and nematodes in the cores in six macrofaunal and three meiofaunal taxa.

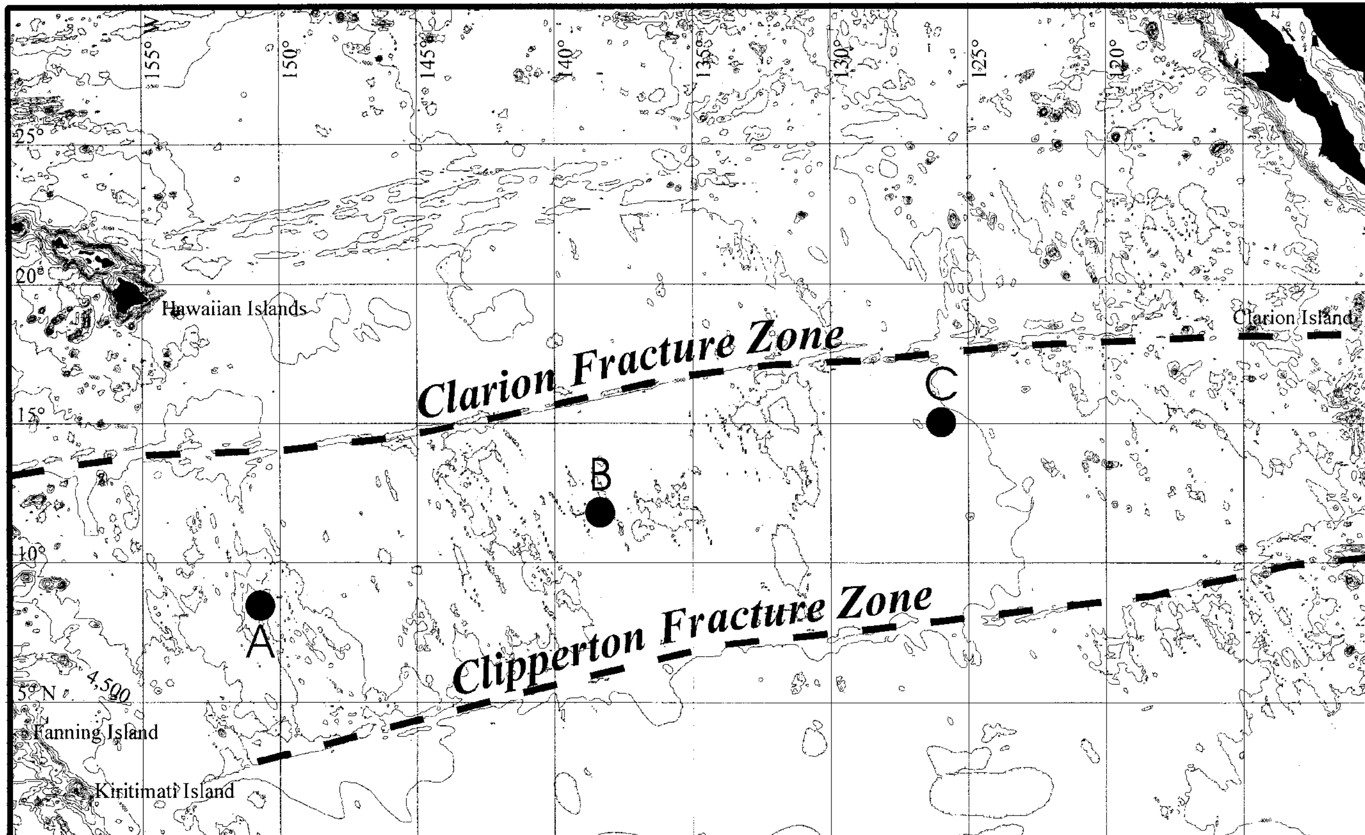
The population density ranges from 8 to 64 organisms/m^2 for the macrofauna and from 3 to 45 organisms/10 cm^2 for the meiofauna. The meiofauna consisted entirely of nematodes in some cores, with associated harpacticoid copepods and larvae in others. With some exceptions, nematodes were concentrated toward the top level in all cores, but they were found throughout the cores. The harpacticoid copepods were generally confined to the top 5 cm.

The polychaetes dominated the macrofaunal assemblage in the cores, followed by peracarid crustacans (amphipods and tanaidacea), Bryozoa, and Rhizopoda. Estimated biomass was dominated by the presence of a few crustaceans in some samples. No depth distribution was evident in the cores. These general taxa are the same ones found in the Clarion-Clipperton region, discussed in the next section.

Benthic Fauna in the Clarion-Clipperton Region. The benthic fauna in the Clarion-Clipperton region was studied to some level of detail in the U.S. government-sponsored Deep Ocean Mining Environmental Study and are described in the Deep Seabed Mining Final Programmatic Environmental Impact Statement (DOMES; U.S. Department of Commerce, 1981). The following summary has been abstracted and modified as appropriate.

Benthic organisms were surveyed at three sites in the region, labeled DOMES Sites A, B, and C (see Figure 9). Photography, box cores, free-fall baited traps, and bongo-net tows were used to observe and collect specimens. The near-bottom macro-zooplankton include primarily crustaceans (copepods, ostracods, amphipods, and decapods) and exhibit very low concentrations; fewer than five individuals were caught per sample in net tows. This indicates highly dispersed populations near the bottom compared with upper waters. Bottom scavengers trapped in the area consisted of two families of fish (rat-tails and liparids) and amphipod crustaceans. Amphipods collected during DOMES were found in large numbers (about 50,000 individuals in the 73 samples obtained) and represented 10 species. Photographic surveys generally show only the larger organisms (termed macrofauna or megafauna, though the distinction between these two classes is not applied consistently among researchers) and are not representative of the true abundances of the benthos.

In these surveys, more than 90% of the macrofauna were sea stars, brittle stars, sea anemones, sea cucumbers, or sponges. Box cores were analyzed for the infauna, which generally comprise the numerical majority of the benthos. The relatively large organisms in this collection (average wet weight 1.6 mg) are found in average densities of from 92 to 152 individuals/m^2. The majority of the infauna are minute (less than 1 mm) and live in the upper 1 cm of sediments. Forty percent of the macrobenthos collected were polychaete worms (underestimated due to sampling problems), 19% tanaids, and 11% isopods. Sponges, bryozoans, gastropods, sea cucumbers, sea urchins, bivalves, sea anemones, brittle stars, brachiopods, and miscellaneous nonpolychaete worms comprised the majority of the remaining organisms (see Table 7). Some of the organisms collected apparently live on the surface of the manganese nodules, including foraminifera, bryozoans, coelenterates, and serpulid worms. The faunal characteristics of the three sites (including the weight of the large epifauna) varied in terms of average biomass, average density of macrofauna and meiofauna, and the percentage of suspension



Clarion-Clipperton Region Bathymetry
Contour Interval 500 m

Contours generated from 5' grid data distributed
by the U.S. National Geophysical Data Center, Boulder, Colorado

DOMES Site: ●

Figure 9. DOMES sites in the Clarion-Clipperton region.

Table 7
Clarion-Clipperton region benthic fauna

	DOMES A		DOMES B		DOMES C		Total	
	No.	%	No.	%	No.	%	No.	%
Macro- and Megafaunal taxa								
Polychaeta	189	38.6	239	46.4	542	38.2	970	40.1
Tanaidacea	121	24.7	77	15.0	274	19.3	472	19.5
Isopoda	57	11.6	30	5.8	197	13.9	284	11.7
Bivalvia	40	8.2	73	14.2	90	6.4	203	8.4
Gastropoda	13	2.7	25	4.9	23	1.6	61	2.5
Ectoprocta	25	5.1	8	1.6	97	6.8	130	5.4
Porifera	4	0.8	16	3.1	55	3.9	74	3.1
Hydrozoa	3	0.6	2	0.4	3	0.2	8	0.3
Stephanoscyphus	1	0.2	10	1.9	2	0.1	13	0.5
Actiniaria	3	0.6	—	—	15	1.1	18	0.7
Brachipoda	10	2.0	9	1.7	31	2.2	50	2.1
Hemichordata	—	—	1	0.2	1	0.1	2	0.1
Sipunculoidea	3	0.6	4	0.8	14	1.0	22	0.9
Echiuroidea	—	—	—	—	3	0.2	3	0.1
Ophiuroidea	9	1.8	—	—	10	0.7	19	0.8
Echinoidea	—	—	3	0.6	1	0.1	4	0.2
Crinoidea	1	0.2	—	—	7	0.5	8	0.3
Holothuroidea	1	0.2	—	—	2	0.1	3	0.1
Aplacophora	2	0.4	2	0.4	2	0.1	6	0.2
Polyplacophora	1	0.2	—	—	5	0.4	6	0.2
Monoplacophora	1	0.2	—	—	—	—	1	—
Scaphopoda	1	0.2	—	—	1	0.1	2	0.1
Oligochaeta	—	—	—	—	8	0.6	8	0.3
Pycnogonida	—	—	—	—	3	0.2	3	0.1
Cumacea	—	—	4	0.8	3	0.2	7	0.3
Amphipoda	2	0.4	5	1.0	14	1.0	21	0.9
Cirripedia	—	—	—	—	3	0.2	3	0.1
Ascidacea	3	1	7	1.4	7	0.5	17	0.7
Unknown	—	—	—	—	4	0.3	4	0.2
Total	490	99.9	515	100.2	1,417	100.0	2,422	99.9
Total per core	22		25		37			
Meiofaunal taxa								
Nematoda	1116	87.3	1,486	87	709	69.1	3,311	82.5
Ostracoda	77	6	82	4.8	226	22.0	385	9.6
Copepoda	84	6.6	138	8.1	81	7.9	303	7.5
Acarina	—	—	2	0.1	8	0.8	10	0.2
Turbellaria	2	0.2	—	—	1	0.1	3	0.1
Kinorhyncha	—	—	1	0.1	1	0.1	2	—
Total	1,279	100.1	1,709	100.1	1,026	100	4,014	
Total per core	58		85		27			99.9

Source: U.S. Department of Commerce (1981).

feeders. The statistics for the DOMES area are comparable to similar statistics for the abyssal benthos elsewhere in the oceans.

In the mid-1960s, marine ecologists were surprised by their discovery of the very high diversity of the fauna in the deep sea. The 80 box-core samples from the DOMES sites illustrate this high diversity, with 2,422 individuals of 381 macrofaunal species. Nearly three-fourths of the species were represented by four individuals or fewer; 131 species were represented by only one individual, with an average density of less than one individual per 20 m^2. The diversity of this habitat is so high that even with 80 samples, the number of species versus number of samples curve has not leveled off. In other words, if more samples were taken, one would expect to find more species. A familiar land analogy of this diversity is not readily available, but one can imagine a 20-m^2 field with over 2,000 stalks of grass representing more than 350 species.

One of the important features of any detritus-based system is the continuous recycling of materials. In the abyssal benthos, neither the rates at which important processes occur, the factors that control the trophic directions of energy flow, nor the factors that control the taxonomic directions of the energy flow are understood. Preliminary indications, however, are that these processes occur relatively slowly in the deep sea. Present knowledge indicates that nutrients in the bottom water can be returned to the surface waters by two mechanisms: the long-term (about 2,000 years) movement of bottom waters to the surface and the vertical migration of bottom-dwelling animals which are consumed by predators occurring higher in the water column. Rat-tail fish and amphipods are two bentho-pelagic organisms found in the DOMES area that are known to migrate vertically to shallower depths. Rat-tails have been caught from 50 to 730 m and amphipods up to 400 m above the abyssal floor of the North Pacific Ocean (Smith et al., 1979). In the deep sea, the organic detritus that is not utilized by the benthos, bacteria, or other bottom microorganisms is lost forever to the ecosystem by burial in the sedimentary column.

Meteorology and Water Column Characteristics

The Indian claim area and the Clarion-Clipperton region represent the most remote sites from land on the planet. As discussed previously, the formation of commercial-grade manganese nodules appears to require minimal inputs of terrigenous sedimentation and very deep water, below the carbonate compensation depth (CCD). The following sections describe the key features of the ocean and air which overlie these deposits and which would be directly relevant to environmental impact assessment.

Central Indian Ocean. The following sections outline the general aspects of climate, ocean circulation, and water chemistry which influence activities in the Indian claim area. These data are much less complete than the corresponding information outlined for the Clarion-Clipperton region, below. However, data from the Indian Ocean component of the World Ocean Circulation Experiment (WOCE), begun in 1994, are expected to be widely available soon and will greatly help to augment our general understanding to the Central Indian Ocean environment.

Climate. The climate is dominated by the monsoon seasons, including the northeast monsoon (December to April), and southwest monsoon (June to October). Tropical cyclones occur during January to February. Major international research is currently underway through the WOCE to characterize and understand the El Niño/Southern Oscillation phenomena which have been documented in the area.

Ocean Circulation. There are several currents which make up the Indian Ocean's current system. The North Equatorial (from November to April), South Equatorial, Monsoon Drift, the Northeast Monsoon (in April) and the Antarctic Circumpolar Current all impact the flow of the Indian Ocean. In the Indian claim area, these result in a net westward flow of the surface currents year round (Sharma and Rao, 1991). The recent WOCE Cruise *I8N* recorded acoustic doppler current profiles (ADCP) along a north-south transect during March and April of 1995. These show predominantly southerly current (Figure 10).

Climatological surface heat flux data suggest that there is a large heat exchange that takes place between the atmosphere and the Indian Ocean. Because the Indian Ocean extends northward only to low latitudes, no cold water masses are formed at its surface. Therefore, if the net heat gain is to be transported to the south by meridional mass overturning, cold water must be drawn from the south at depth, be transported by upwelling to the surface, and then flow southward. Hydrographic analysis by Warren (1981) implies that there is a strong overturning cell with a large net northward flow below 2,000 m near 18° S. If this cell exists, it would imply an average upwelling rate at the 2,000-m level several times larger than that of the Pacific Ocean. However, the summary benthic current data from almost two years of deployment and summarized above (Table 4) suggest a net southerly trend for the deep currents.

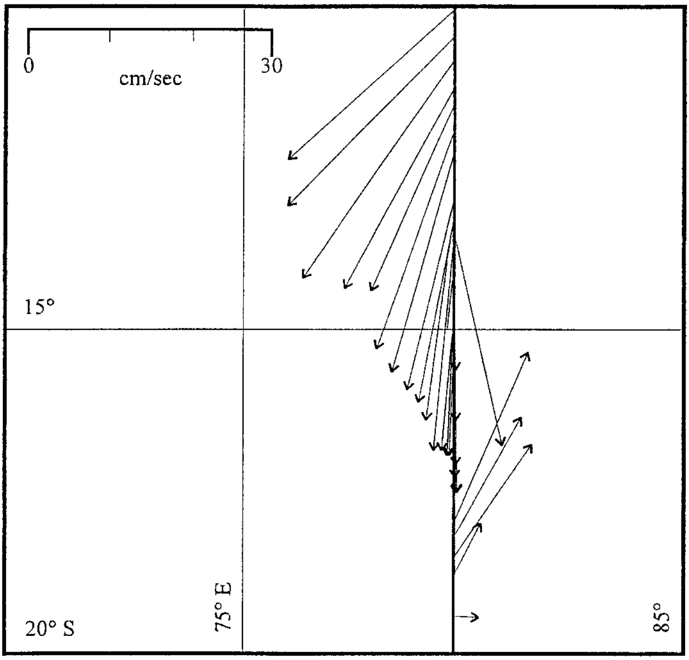


Figure 10. WOCE ADCP surface currents in the Indian claim area.

Seawater Characteristics. General sea water components are presented in Table 8. They are representative of the low nutrient, oligotrophic tropical environments typical of both the Central Indian Ocean and the Clarion-Clipperton region. Long term averages of chlorophyll in surface waters, as inferred from the Coastal Zone Color Scanner (CZCS) instrument flown aboard the Nimbus-7 satellite from October 1978 through June 1986, are presented in Figure 11.

Clarion-Clipperton Region

The following sections outline the general aspects of climate, ocean circulation, and water chemistry which influences activities in the Clarion-Clipperton region.

Climate. Ocean temperatures vary widely geographically and with depth. On the basis of temperature, the water column can be divided into three layers: (1) the mixed layer, (2) the thermocline, and (3) the deep layer. The mixed layer, extending downward from the surface, is directly influenced by winds and waves. In the central North Pacific, the average sea surface temperature is 25°C. At the thermocline, which begins at the bottom of the mixed layer, there is a rapid decrease in temperature with increasing depth. The temperature change through the thermocline can be as much as 12°C. In the deep layer, the temperature continues to decline at a steady, but slower, rate. At depths of 1,000 m, the temperature drops to a few degrees (Ozturgut et al., 1978).

In the DOMES study area, a strong permanent thermocline was found to separate surface and intermediate waters. Mixed layer depths varied between 36 m

Table 8
Major variables in the water column, Indian claim site

Depth (m)	Temp. (°C)	Salinity (g/kg)	Dissolved oxygen (mL/L)	Phosphate (μM)	Nitrate (μM)	Silicate (μM)
0	23.0–30.0	33.5–35.5	4.3–5.0	0.1–0.3	0.4–1.0	2.0–6.0
100	18.0–24.0	34.8–35.4	2.05–5.0	0.1–1.0	0.5–15	3.0–15
200	13.0–19.0	34.6–35.6	1.05–5.0	0.3–1.6	1.0–25	3.0–22
300	10.0–17.0	34.7–35.7	2.0–5.0	0.3–2.0	4.0–30	3.0–35
400	10.0–13.0	34.8–35.4	2.0–5.5	0.6–2.0	5.0–30	5.0–40
500	8.0–11.0	34.7–35.0	2.0–5.5	0.8–2.2	10–30	5.0–45
600	7.5–10.0	34.6–34.9	1.5–5.5	1.0–2.6	15–35	5.0–55
800	6.0–6.5	34.5–34.8	1.5–4.5	1.5–2.8	25–40	30–75
1,000	5.0–5.5	34.6–34.8	1.5–3.0	2.4–2.6	30–40	60–95
1,200	4.0–5.0	34.6–34.7	2.0–2.5	2.4–2.8	30–40	70–110
1,500	3.0–4.0	34.7	2.5–3.0	2.6	35	80–115
2,000	2.2–2.4	34.7–34.75	3.2–3.4	2.4–2.6	30–35	90–125
2,500	1.7–1.8	34.74	3.4–3.8	2.2–2.5	30–35	100–120
3,000	1.4–1.5	34.74	3.8–4.0	2.4	30–35	115–135
4,000	1.05	34.73	3.90	2.36	34	120–150
5,000	0.95	34.70	4.14	—	—	—

Source: Sharma and Rao (1991), after Wyrtki (1971).

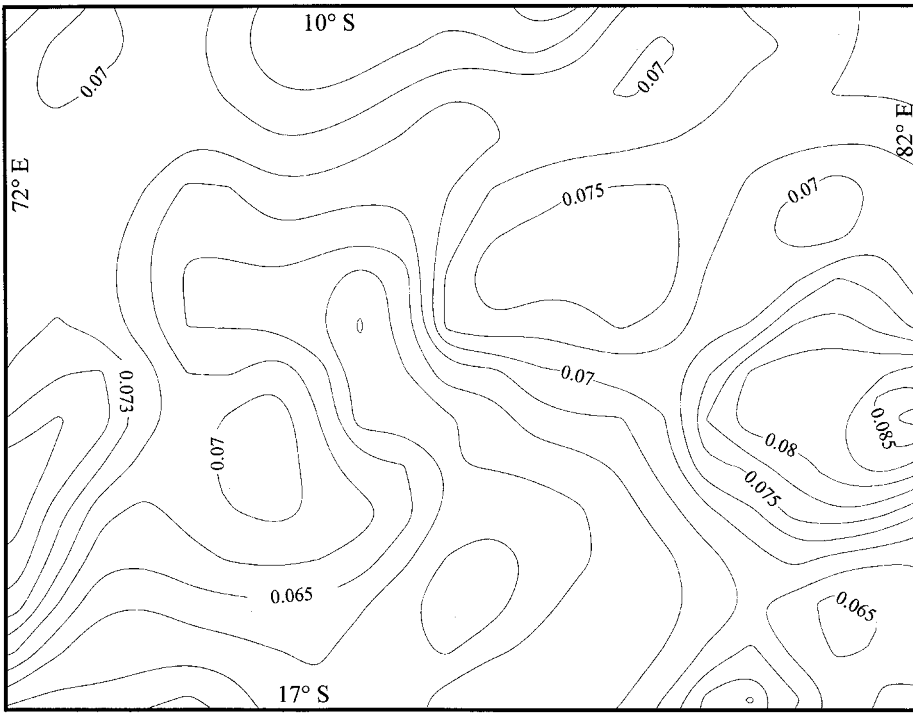


Figure 11. Chlorophyll concentrations (mg/m^3) in surface waters in the Indian claim area.

(summer) and 55 m (winter) while the thermocline extended to 150 m in summer and to 130 m in winter (U.S. Department of Commerce, 1981). Temperatures at the base of the thermocline averaged 12–13°C. Below this depth, temperatures decreased more slowly to about 4.5°C at 1000 m (Ozturgut et al., 1978).

Surface temperatures typically revealed parallel isothermal structures between November and April with a latitudinal temperature gradient of about 0.6° to 0.8°C per degree of latitude (Seckel, 1962). These parallel isotherms break down in the summer. Minimum and maximum temperatures generally occur in March and September, respectively. The annual range in surface temperature at latitude 12°N was only 1.7°C, but at 26°N it increased to 5.3°C. Below the mixed layer the average temperature gradient is about 15°, 6°, and 5°C per 100 m at latitude 10°, 20° and 30°N, respectively. Seasonal and diurnal thermoclines may be superimposed on the permanent thermocline.

Ocean Circulation. As speculated for many years and confirmed in the Deep Ocean Mining Environmental Studies program (Halpern, 1978) and later in the TOPEX/POSEIDON program, the North Equatorial Current dominates surface water movement in the study area (see Figure 12). The North Equatorial Current is a broad current flowing east to west extending between 9° N and 20° N latitude, and has an average speed of about 10 cm/sec. The surface water mass in this area, called the North Pacific Subtropical Waters, is between 50 and 200 m thick. Beneath the North Pacific Subtropical Waters lies a 1,000 m thick layer of colder water called the North Pacific Intermediate Waters. This layer is characterized by a salinity minimum. The water originates at high latitudes in the Pacific Ocean and

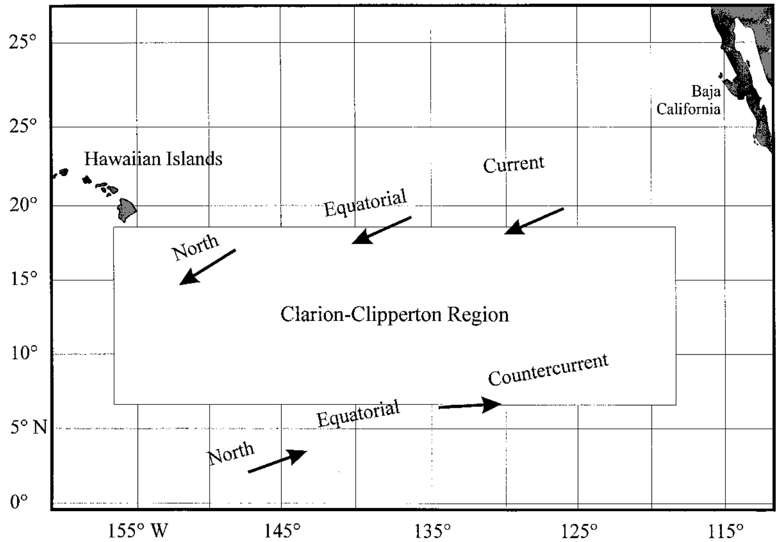


Figure 12. Surface currents in the Clarion-Clipperton region.

sinks beneath the North Pacific Subtropical Waters in a broad area north of approximately 45°N latitude.

The nearly homogeneous Pacific Deep Water is found in a zone approximately 3,600 m thick beneath the North Pacific Intermediate Water. Pacific Deep Water originates in the North Pacific Basin and flows very slowly southward. Antarctic Bottom Water is found close to the seafloor in a zone several hundred meters thick. Antarctic Bottom Water originates in the Antarctic Ocean and moves slowly northward.

The wind-generated open ocean wave climate can be typified by four general wave types: northeast trade wind waves, South Pacific and North Pacific swells, and hurricane-generated waves. Simultaneous arrival of waves from more than one source is common. Trade wind waves may occur throughout the year, but they dominate from April to November when they are present 90 to 95% of the time as compared to 55 to 60% of the time from December through March. Waves generated by these winds typically have periods of 5 to 8 s with heights of 1 to 4 m. They usually approach from the northeast, east, or southeast. South Pacific swells resulting from storms in the southern hemisphere occur between April and October. They produce swells (the Southern Swell) from a southern quadrant with long periods (14 to 22 s) and low amplitudes (approximately 1 m).

Major Water Chemistry. Water chemistry and primary productivity studies in the region show that the Northern Equatorial Current carries a distinct but diffuse plume of nutrients and fine-grained materials westward from terrigenous and upwelled sources off the North American continent. Due to the normal increase of solar energy inputs to surface waters with decreasing north latitude, primary productivity generally follows an increasing trend toward the equator. However, because of the nutrient influx from the west in the area of interest, the gradient here is dominated by a trend of decreasing primary productivity to the west. This gradient is clearly expressed in the contoured overall mean values of the primary productivity estimates of ocean chlorophyll concentration in the eastern part of the Clarion-Clipperton region, derived from the Coastal Zone Color Scanner (CZCS) instrument flown aboard the Nimbus-7 satellite from October 1978 through June 1986 (Figure 13).

Seawater density varies inversely with temperature, directly with salinity, and, to a minor degree, directly with pressure. Density of seawater controls oceanic stratification. According to DOMES data, the sea surface density in this region is about 1.022 grams per cubic centimeter (g/cm^3). At depths of 1,000 m and more it is about 1.0275 g/cm^3. These small changes are significant so density is usually expressed by the quantity "Σ_t" which is a dimensionless unit calculated by subtracting 1.0 from the density and multiplying by 1,000. In the above case, Σ_t would vary from 22.0 to 27.5. The rapid increase in density that coincides closely with the thermocline and the halocline (the zone of rapid salinity increase) is called the pycnocline.

The pycnocline/halocline/thermocline is an important mid-water layer because it retards vertical diffusion and sinking. Thus, as animals and plants in the mixed layer die and sink, they tend to accumulate and decay in this zone. This concentrated decomposition depletes available dissolved oxygen creating an oxygen minimum.

DOMES project data (Figure 14) reveal typical oceanic salinity and temperature profiles with little seasonality (Anderson, 1979). The average mixed layer salinity was 34.3 grams per kilogram (g/kg) of seawater. Below this are found two minima and maxima within the upper 1000 m. A maximum range of about 2 g/kg through the water column was typical.

In the ocean, pH is maximal at the surface due to the combined effects of carbon dioxide uptake and oxygen evolution in the photosynthetic process. With increasing depth, photosynthesis decreases while decomposition and respiration

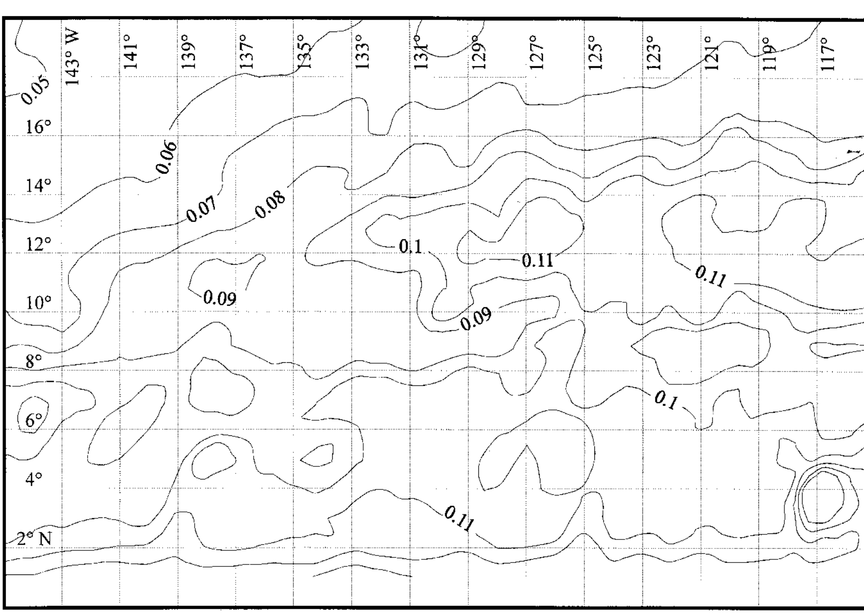


Figure 13. Chlorophyll concentrations (mg/m^3) in the Clarion-Clipperton region.

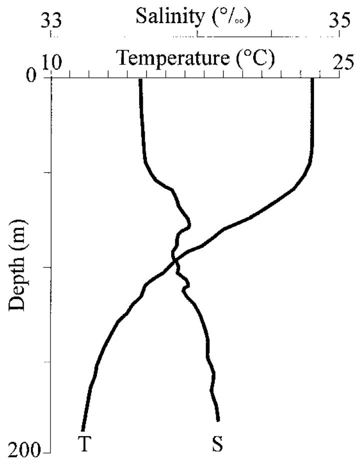


Figure 14. Salinity and temperature profiles in the Clarion-Clipperton region.

increase, consuming oxygen and depressing pH. A pH minimum generally coincides with the oxygen minimum. DOMES results for dissolved oxygen are typical of oceanic conditions in the proposed exploration areas, showing essentially saturated concentrations of dissolved oxygen within the mixed layer and slight supersaturation [400–500 μM] just below the mixed layer resulting from a thin layer of enhanced photosynthetic activity where phytoplankton biomass accumulates.

Below the thermocline, oxygen concentrations rapidly decrease to a minimum. Between 300 and 500 m, concentrations as low as 1 μM have been measured. Below the minimum, concentrations increased to about 350 μM near the bottom (5,000 m; Ozturgut et al., 1978).

Marine plants, or algae, require certain elements for their growth, as do their terrestrial counterparts. Some of these elements, particularly nitrogen, phosphorus and silicon, are required in relatively large amounts and are termed macronutrients. Most of these elements are abundantly available in seawater; however, in tropical and subtropical surface waters iron, nitrogen and, to a lesser extent, phosphorus, can be present in concentrations limiting to algal growth. Ambient nutrient concentrations reflect a dynamic balance among the forces of water mass advection, diffusive mixing, and biological cycling. Nitrate concentrations in the DOMES study area were low in the mixed layer (typically about 1–2 μM) reflecting active uptake by phytoplankton (Ozturgut et al., 1978). In the thermocline, nitrate concentrations increased with depth to about 35 μM. Occasionally a nitrate maximum was detected near the base of the thermocline. Anderson (1979), in a summary of the DOMES nutrient chemistry investigations, reported a resistant nitrate maximum (approximately 45 μM) at the interface between the oxygen minimum layer and the "upper deep water" at depths of about 800–1,000 m. Below this layer, concentrations gradually decreased to about 41 μM and about 36 μM at 4,000 m. Within 20 m of the bottom there was a further, abrupt drop to less than 30 μM (Roels et al., 1973).

Trace elements, or micronutrients, include metals and organic substances such as vitamins and their precursors which are necessary for algal growth. Values from a station to the north of the DOMES area (32°41′N, 145°00′W) (Bruland, 1980; Landing and Bruland, 1980) show maxima in manganese concentrations at the surface (0.62 nanogram-atom per kilogram) and in the oxygen minimum (0.71 nanogram-atom per kilogram). Copper and nickel levels increased with depth.

Suspended particulate matter (SPM) includes living and non-living, organic and inorganic particles. The non-living portion is called detritus. However, even inorganic detritus has bacteria and other microorganisms associated with it, and the term “organic aggregate” is sometimes applied. SPM is an important component of the planktonic food web because it is present in sizes commonly ingested by zooplankton. DOMES results (Baker et al., 1977) showed mixed layer concentrations of SPM of about 47 $\mu g/l$ and maxima (to 110 $\mu g/l$) just above the thermocline. Concentrations below 200 m were very uniform at about 10 $\mu g/l$ with a slight increase (to about 12 $\mu g/l$) within 400 m of the bottom. The inorganic fraction of the SPM increased near the bottom suggesting sediment resuspension by the bottom currents.

Pelagic Biota

Within the proposed contracts areas, the environment includes expanses of oligotrophic subtropical ocean. Data were not available for the Indian Ocean claim area in particular, but the environment is similar and can be expected to have the same or similar types of biological resources as those found in the Clarion-Clipperton region.

Bacteria. Bacteria are found throughout the water column as well as in the sediments. These microbial decomposers are concentrated at the sea surface, in the oxygen-minimum zone, and in the sediments. They are associated, as organic aggregates, with all detritus, and their remineralization of organic matter provides a major source of nutrients for use by algae. Sorokin (1971) found that bacterial aggregates constituted 20–40% of oceanic particles, with little depth variability other than a slight concentration at the bottom of the thermocline. The size of the aggregates (larger than some small phytoplankton) makes them easily available as substrate for fine-filter feeders, but also for coarse-filter feeders and even selective feeders such as larval fish. He estimates that “bacterioplankton” are as important as algae as a primary food substrate.

Phytoplankton and Photosynthesis. El Sayed and Taguchi (1979) examined water samples from the DOMES area and identified 163 types of diatoms, 122 dinoflagellates, 48 coccolithophorids, and 15 other types. The coccolithophorid *Gephyrocapsa huxleyi* was the dominant species of phytoplankton at the depth of the chlorophyll maximum. Surface concentrations of chlorophyll are presented for the Indian claim site in Figure 11 and for the Clarion-Clipperton region in Figure 13.

In subtropical surface waters, nutrient concentrations are low and phytoplankton populations, measured by either cell counts or chlorophyll *a* concentrations, are sparse. Daily primary productivity is low, 100–200 mg carbon/m^2. A subsurface maximum is seen in chlorophyll *a* concentrations below the mixed layer. Concentrations of about 0.06 mg/m^3 are found in the mixed layer, but are three to four times that at 70–80 m. Typically production is limited by the low availability of nutrients in near-surface waters and by the decreasing availability of light at greater depths. Surface light at these latitudes is generally so intense that a thin layer at the surface experiences photo-inhibition. The highest values of gross primary production are found at about 40 m, while the most efficient productivity (maximum production per unit of chlorophyll) is usually found below 50 m. The photic zone, defined as the depth at which 1% of the surface light intensity remains, generally reaches about 90 m in these clear, oligotrophic waters. The concentration of chlorophyll *a* and suspended particulate matter (SPM) creates a discontinuity in light attenuation at the top of the pycnocline.

Zooplankton and Micronekton. Hirota (1977) sampled zooplankton and micronekton in the DOMES area. Microzooplankton and nanozooplankton were sampled from waters to a depth of 200 m deep. Macrozooplankton were sampled to 1100 m, and micronekton were collected with a midwater trawl.

Micronekton biomass ranged from 280 to 580 g/100 m^2 (median 358 g/100 m^2), with greater than half accounted for by fish, particularly myctophids (lantern fish). Macrozooplankton concentrations were highest (10 g/1,000 m^3) in the upper 150 m, lowest at about 200 m in the oxygen minimum, and intermediate between 200 and 900 m. Maximum concentrations of neuston (surface-dwelling macrozooplankton and fish larvae) were 50 to 100 mg/m^3. Most taxa of micronekton showed density maxima within the upper 100 m of the water column.

Among the filter-feeding macrozooplankton (mostly herbivores), the most important are the calanoid copepods and larvaceans. The somewhat larger omnivores, mainly medium-sized copepods and adult euphausiids, are more important in terms of energy flux through the community because of their greater vertical range and diurnal migrations. Carnivorous macrozooplankton include larger copepods, larval fish, and chaetognaths, with the latter the most abundant.

Nekton. Noncommercial nekton common in the DOMES area included some squids, lancet fishes, flying fishes, lantern fishes, rat-tail fishes, pelagic shrimp, and euphausiids.

Commercial fish species, including tunas, tune-like species, and billfishes, are found all across the Pacific Ocean at tropical and subtropical latitudes. The following species, due to their commercial importance, are of primary interest: yellowfin tuna (*Tunnies albacares*), bigeye tuna (*T. obesus*), skipjack tuna (*Katsuwonus pelamis*), albacore tuna (*Tunnies alalunga*), blue marlin (*Makaira nigricans*), striped marlin (*Tetrapterus audax*), shortbill sportfish (*Tetrapterus angustirostris*), ono or wahoo (*Acanthocybium solandri*), and mahi mahi (*Coryphaena hippurus*).

Most billfishes and tuna-like species are top-level predators like the tunas although they occur in the same open-habitat. The billfishes and tuna-like species are solitary rather than schooling fish. Most species are regarded as being as highly migratory as the tunas. Like the tunas, their latitudinal range is seasonal, with movement to higher latitudes in warm seasons and to lower latitudes in cold seasons.

Tunas (and some billfishes) are distributed vertically to great depths. The depths of greatest concentrations are stratified, with some overlap among species. Striped marlin are taken mostly at 150–290 m, yellowfin tuna at 150–300 m, and bigeye tuna at 290–380 m (Saito, 1973; Saito & Sasaki, 1974). Skipjack tuna usually occur in surface schools accompanied by flocks of seabirds. Although small yellowfin tuna tend to school at the surface, either as mixed schools with skipjack or as discrete schools of their own kind, larger yellowfin are deep-swimming.

Although the distribution range of tuna larvae is less extensive than that of the adults, skipjack tuna and yellowfin tuna larvae are most abundant around Hawaii in the summer (as are blue marlin, mahi mahi, and wahoo larve), and bigeye tuna larvae are distributed as far north as 25°N latitude in the central Pacific. The distribution of billfish larvae somewhat resembles that of bigeye tuna in the central Pacific (Matsumoto, 1984). Spearfish larvae are found across a broad area of the subtropical North Pacific. Tuna larvae are distributed vertically to depths of 130 m or more, but most are confined to the upper 50 or 60 m (Matsumoto, 1984).

Larval fish collected in the DOMES area included members of commercially important pelagic species, but were primarily representatives of midwater and near-surface species of no commercial significance. Larvae of commercially important species were more concentrated in the upper 200 m and especially in the neuston. Few larval fish were found in the range 200–1,000 m (Hirota, 1977).

Marine Mammals. Several marine mammals have been sighted in the Clarion-Clipperton region. They are briefly described in the following sections.

Dolphins. A number of species of dolphins have been spotted in the northeastern Pacific and may be present in the contract areas, though most species are most often spotted closer to land. The Pacific bottlenose dolphin (*Tursiops truncatus*) occupies a variety of habitats, especially in the seaward edges of banks surrounding islands. Individuals grow to a size of 4 m and more. The spotted dolphin (*Stenella attenuata*) is very common in Hawaii, but is nearly always found at least 3 km from shore and may be present in the Area. The spinner dolphin (*Stenella longirostris*) is also found throughout in the eastern tropical Pacific. Schools tend to remain in well-defined home ranges. These dolphins eat primarily mesopelagic fish and epipelagic/mesopelagic squid. The rough-toothed dolphin (*Steno bredanensis*) is common and likely in the Area.

Whales. All of the large baleen whales move from polar or temperate regions in spring and summer toward the equator in fall and winter; however, neither the migratory routes nor the seasonal distribution of blue whales are well mapped. Blue whales (*Balaenoptera musculus*) are distributed south from the southern Chukchi Sea to waters off Panama. Leatherwood et al. (1982) report that substantial numbers have been reported recently at 1,300–2,800 km off Central America at latitudes between 7°N and 9°N in February, March, and June. Leatherwood et al. also reports that blue whales have been observed far offshore of northern California in May.

The fin whale (*Balaenoptera physalus*) summers in northern waters of the Bering Sea and south as far as central Baja California. Leatherwood et al. (1982) report that in winter their distribution extends at least from the Big Sur area off central California south to Cabo San Lucas, Baja California. The authors state further that much of the population is believed to winter far offshore and thus these whales are probably present in the Clarion-Clipperton region at least during the summer months.

Determination of the range of the sei whale (*Balaenoptera borealis*) is hampered by historical lumping of this species with the Bryde's whale in whaling logs. It is primarily a pelagic temperate-latitude species, but the winter range extends to at least off Baja California. Leatherwood et al. (1982) report recent sightings in the eastern Tropical Pacific.

The sperm whale (*Physeter maerocephalus catodon*) is found throughout the eastern North Pacific, but south of latitude 40°N during the winter (Leatherwood et al., 1982).

Environmental Impacts

In 1981 the U.S. government published its programmatic environmental impact statement for deep seabed mining in the Clarion-Clipperton region (U.S. Department of Commerce, 1981). The impact predictions were based primarily on the DOMES results, monitoring of a few small-scale mining development tests, and certain related research studies. Since the completion of this study, several additional international efforts have been undertaken to develop better predictive capability. Thiel et al. (1991) produced a comprehensive and well-organized discussion of all available studies related to the subject. This section summarizes the primary results of these two excellent studies which are related directly to the formulation of guidelines for future work. It also incorporates the relevant results from available efforts which have been completed since the 1991 report was assembled.

DOMES Impact Predictions

The results of the DOMES research are summarized by Bischoff and Piper (1979) and also in a dedicated issue of the journal *Marine Mining*, Volume 3, published in 1981. The final programmatic impact statement (U.S. Department of Commerce, 1981) predicted minimal environmental effects from deep seabed mining, particularly when compared to land-based open-pit mining in the tropics, the most likely environment of new land mines for the same base metals. The work also concluded, however, that these predictions must be confirmed by thorough and well-designed monitoring of precommercial mining tests. The DOMES program identified three areas of concern which merit further early consideration, independent of mining-test monitoring:

1. Impacts on the benthic communities proximate to the area where manganese nodules are removed
2. Impacts on the near-surface biota, particularly fish larvae, due to the discharge plume of suspended sediments and other foreign materials in the water column
3. Impacts on the benthic communities due to the deposition of suspended sediments

Subsequent research efforts have focused on these impacts. The DOMES program concluded that other areas of concern (e.g., bioaccumulation of metals, pycnocline accumulation of suspended sediments, dissolved-oxygen depletion, phytoplankton blooms) fall into two categories. These include (a) effects of the operation which have very little potential for causing serious environmental harm; and (b) those which have some potential for harm but which cannot be adequately evaluated in advance of ongoing precommercial recovery operations and which can be resolved in a timely manner by careful monitoring of such operations.

While the nodule collector will be likely to cause serious harm to the benthic organisms which are caught in its path (item 1), the assessment concluded that this impact will probably not cause serious environmental harm, since the mining will encounter only a very small percentage of the benthic community in the area.

It may be argued that the impacts of the surface plume (item 2) should be included in the group (b), since the specific configuration of the discharge plume will completely determine the magnitude of these impacts and is not amenable to examination until precommercial recovery operations are conducted. This area of concern is retained as worthy of early examination because its resolution depends on a presently inadequate understanding of the ways in which fine-grained particles travel through the water column to the seabed and their associated interactions with pelagic biota.

The most significant at-sea environmental issue remaining after DOMES project concerns the effects of the benthic sediment plume created by the nodule collector (item 3). Besides burying benthic fauna very close to the operation, fine sedimentary particles from the plume will be carried unknown distances from the site by benthic currents, eventually settling and interacting with the benthic environment in unpredictable ways. The tremendous diversity of benthic communities and the possibly long-term responses to rapid increases in sedimentation rates make confident prediction of the potential environmental harm a major challenge.

Subsequent Studies

Several internationally supported research efforts have been undertaken to further our understanding of the environmental impacts of seabed mining. In general, this work supports the DOMES conclusion and emphasizes the need for well-designed examinations of the benthic environment. The objectives and results of these efforts are described in the following sections.

U.S. Sponsored Studies after DOMES. The U.S. government sponsored several scientific attempts to address the problems identified above related to benthic responses to sedimentation in the deep seabed. These studies are outlined below.

ECHO-1. In June 1983, the Scripps Institution of Oceanography vessel *R/V Melville* examined the area near DOMES Site C where one of the small-scale mining tests (conducted by Ocean Management Associates, OMA) had been carried out (see Figure 9; Hessler & Wilson 1985; Spiess et al., 1984, 1987). The intent was to examine benthic recolonization by sampling (using a 0.25-m^2 box corer) areas within or near the test mining tracks and more distant areas not affected by the mining to see if there were any significant differences between the seabed areas some 5 years after the test mining. Both macrofauna and meiofauna were analyzed and no consistent differences between samples from near the mining tracks and from a nearby control area were found. Dick and Foell (1985) determined that these tests were inconclusive due to the limited temporal and areal extent of the mining operations and the inability to sample accurately within or near the 2-m-wide mining track using the techniques then available.

The Acute Mortality Experiment. Using the Remote Underwater Manipulator, version 3 (RUM-III; Kukert, 1989; Kukert & Smith 1988; Smith et al., 1988), known amounts of sediment were added to corers positioned on the seabed with the expectation that later recovery would allow determination of the amount of sediment that would produce complete mortality of the benthic community. Technical problems with RUM-III limited recovery to only four cores within the areas treated by known amounts of sediments and two control cores from unaffected areas. The cores from the affected areas had to be retrieved after only 6 days, and the small number of replicates precluded confident inferences being made.

General conclusions were that there was little evidence of serious disturbance to macrofauna when subjected to burial under 1 cm of sediment. In contrast, burial under 4 cm of sediment appeared to cause entombment of 25–50% of the macrofauna in 6 days. Smith et al. (1988) recommended some modifications to the design of the experiment to be held near DOMES Site C in 1990, namely, (1) incubation time of burial experiments should be greater than 6 days to allow for either upward escape or burial mortality to take place; (2) burial treatments should be sampled to permit horizontal sectioning along the burial interface; and (3) a maximum dose of 5 cm may be necessary to produce near-total burial mortality.

In addition to reporting results of this test, Smith et al. (1988) reviewed the literature for what was known about burial effects (acute and chronic) on the shallow-water macrobenthos and carried out simple modeling of burial depths and times that may be required to produce mortality at DOMES Site C. However, it should be noted that shallow-water macrofauna results are not directly transferable to the deep sea (Nichols et al., 1978).

The QUAGMIRE II Expedition. In a cruise of the Scripps Institution vessel *R/V New Horizon* in April–May 1990, several studies with immediate relevance to ocean mining were attempted (Wilson, 1990). An international team of scientists attempted to deploy the recently modified RUM-III vehicle to sample precisely within the mining track from which nodules were removed during the OMA prepilot mining test campaign in 1978. Using 0.09-m^2 Ekman corers, this remotely controlled robot vehicle attempted to utilize its television, photographic, sonar, and remote manipulation capabilities to achieve the accurate sampling placement that was lacking and which precluded definitive conclusions from being made during ECHO-1. This expedition also attempted to carry out a critical-dose experiment to determine the sensitivity of benthic fauna to sedimentation levels (Taghon, 1985; Taghon et al., 1988). Unfortunately, RUM-III succeeded in obtaining only 8 cores, and the major cruise objectives were not achieved.

DISCOL

In February 1989 the Federal Republic of Germany (FRG) initiated a large-scale *dis*turbance-re*col*onization experiment (DISCOL) in the Peru Basin of the eastern tropical South Pacific Ocean near an existing mining claim under German domestic law (Schriever et al., 1997). The research ship *F/S Sonne* was used in a 2-month campaign that included site selection, pre-impact baseline data acquisition, creation of an impact, initial post-impact data acquisition, and deployment of long-term instrument arrays. A second cruise in September 1989 obtained another set of post-impact data about 6 months after the initial disturbance.

After selecting a suitable location (centered upon 7°04.4′S, 88°27.6′W), baseline data-gathering operations began. The DISCOL experimental area is a circle with a diameter of 3,704 m, approximately 10.8 km^2 in area. It is subdivided into 8 pie-shaped sectors, with the center of each oriented along the 8 cardinal points of a compass. The area is further divided by concentric circles with radii at 1,000 and

1,350 m from the center. This creates three zones in each sector: an inner or central zone from 0 to 1,000 m from the center and an outer or peripheral zone from 1,350 to 1,852 m from the center, separated by a 350-m-wide buffer zone. Sampling locations were selected randomly at five central and five peripheral positions located along the midline of the sectors at 500 and 1,600 m from the center.

The disturbance was created using a specially designed device termed the "plow-harrow." This gear was towed across the area for a total of 78 transects and disturbed the sediments to a depth of at least 10–15 cm. Due to crowding of disturber tracks in the central region and proportionately greater distance between disturber tracks in the periphery, the central area is believed to have been more severely affected than the peripheral area.

Inspection of the disturbed area using television and photography indicated that up to 20% of the area was directly impacted by use of the plow-harrow, while about 70% was covered by various thicknesses of sediment that had been suspended during the disturbance, driven downstream by the near-bottom currents, and resettled at some distance from the directly disturbed areas. The remaining 10% of the area, primarily in the southern quadrant, was not believed to have been affected to any significant extent, since few tracks crossed this area and since the prevailing north-to-northwesterly currents preclude extensive sediment redeposition.

Both pre- and post-impact sampling schemes followed the same pattern. At each selected sampling location, a minimum of three 0.25-m^2 box cores and one multicorer (with eight 9.5-cm inner-diameter core tubes) were obtained. At certain sampling locations, additional box corers and multicorers were taken to provide supplementary sample material for geologic, chemical, and microbiological analyses. Baited trap chains with traps at 0, 5, 10, 30, 50, and 100 m above the seabed were used to obtain epipelagic, macro- and megafauna from the near-bottom water layer. A free-fall benthic observation system was deployed with and without bait or a baited trap to acquire photos at preset time intervals.

A seabed observation system was utilized to obtain real-time television and photograph images of the seabed and megafauna. Several biological trawl hauls were used to obtain specimens of the larger faunal elements. These trawl collections resulted in rather limited material because, although several modifications of the trawl were attempted, most animals were ground up between the nodules that were gathered and which filled the cod end to near capacity. The corers provided samples for further biological studies of the benthos, particularly the macrofauna and meiofauna.

Further data collected included sediment vane shear strength, near-bottom current measurements, and hydrographic measurements using the multisonde, a rosette sampler equipped with remotely controlled water sampling bottles as well as pressure, temperature, conductivity, light transmission (nephelometer), dissolved oxygen, and sound velocity sensors. Weather logs were also maintained at 2-h intervals.

Four randomly sampled post-impact data sets were collected, immediately after the impact, 6 months later, after 3 years, and after 7 years. Due to the impact, the abundances of all faunal taxa decreased significantly and, except for the bacteria, did not reach the values of undisturbed sediment half a year later. Three years after the impact, densities of the major faunal groups (mega-, macro-, and meiofauna) significantly exceeded these determined for the baseline study. The sample processing for the fourth post-impact investigation is still in progress. A summary of the completed results and some initial observations from the last expedition to the site were presented by Schriever et al. (1997), and are abstracted and summarized here.

General Observations. Heavy impacts were created within and adjoining the plow tracks, which covered approx. 20% of the site. The semiliquid uppermost sediment material was removed from the surface, and the exposed clayish sediments from deeper layers initially formed sharp-edged track contours. The sediment cloud created by the passage of the plow-harrow resettled and blanketed large areas. Soft, surficial sediments, transported by benthic currents, progressively refilled the artificial seabed depressions along the plow-harrow tracks and softened their relief with passing time. As soon as 3 years after impact, the thickness of the semiliquid upper layer in some disturbed sediment samples exceeded natural conditions. However, the tracks remained clearly recognizable for the entire period of investigation. In the sediment samples, the disturbance impact was recognizable by the presence of lighter-colored carbonate-rich clay and uneven sample surfaces, even after 7 years had passed.

Impacts on Megafauna. Images from the baseline study and from later observations collected outside the experimental area represent the undisturbed situation of the animal community. The megafauna densities in these undisturbed areas remained on a more or less constant level during the entire period of investigation. This indicated that, apart from the experimental impact, no detectable ecological factors had affected the megafauna.

The plow-harrow apparently destroyed or buried the majority of the megafauna in its path. Half a year later, highly motile animals had repopulated these areas. Three years after the impact, megafauna densities in the tracks had reached the level of the baseline study. However, the diversity was still low, and highly mobile animals such as Ophiuroidea, Holothurioidea, and Crustacea (mainly *Probeebei mirabilis*) were dominant. Less motile animals (e.g., Lophenteropneusta, Asteroidea, and Actiniaria) occurred only in the photographs from the 3-year post-baseline expedition in 1992. At this time the animal densities had declined to levels lower than those of the baseline study. The plowing had buried the manganese nodules and thus had in effect removed the hard substrate from within the disturber tracks. Animals such as Porifera and Crinoidea, which depend on hard substrates, did not survive this procedure, and were also unable to recolonize the nodule-free areas again. The megafauna in the plow-harrow tracks thus changed from the typically mixed to a pure soft-bottom assemblage. Within the seabed area which was not directly impacted by the plow-harrow, the megafauna densities remained at the baseline level during the early post-impact investigations. Three years after the impact, however, the abundances, especially of highly mobile soft-bottom animals, increased remarkably.

Impacts on Macrofauna. Polychaeta, Tanaidacea, Isopoda, and Bivalvia dominated the macrofauna and together included more than 90% of all animals in this size class in the baseline and reference samples. Immediately after the plowing disturbances, these groups were significantly reduced in samples from the impacted area, and the overall macrofaunal density decreased to 38.6% of that in undisturbed sediments. The intensity of the impact on the different groups can be regarded as a function of the average dwelling depths in the sediment. Shallow-dwelling Bivalvia were decimated to 9.8% of their original abundance, whereas the impact had a lesser effect on the deeper-dwelling Polychaeta (48.6%). The lower impact on the Polychaeta may also reflect the relatively high mobility of these animals.

This mobility may also have facilitated the observed rapid initial recolonization in the plow-harrow tracks from the unplowed between-track areas. The recovery started rapidly. Only half a year after impact, the macrofaunal densities in the in-track samples rose to 81.8% of the undisturbed values, and for the following years, further leveling between the different sample types was expected. Three years after the impact, however, balanced abundances between disturbed and undisturbed samples were observed only for the Tanaidacea, whereas the recovery of all other taxa stagnated or, in case of the Isopoda, even regressed. At this time, the macrofaunal depth distribution in disturbed samples had shifted significantly into deeper sediment layers. The scientists found very high animal densities in those samples which corresponded to tracks refilled with semiliquid material.

Seven years after the impact, disturbed abundances equalled undisturbed levels for the Isopoda, but for the Tanaidacea and the Bivalvia the disturbed values still displayed high variability. The polychaete data analysis of the most recent observations is still in progress, and examination of the other taxa (and therefore also for the whole macrofauna) still remains incomplete.

Impacts on Meiofauna. Foraminifera, Nematoda, and Harpacticoida abundances were estimated to determine the recolonization process of the meiofauna. Immediately after the impact, the densities of these three groups decreased to approximately 50% of the baseline study. Half a year later, this process continued for the Nematoda and the Harpacticoida, while Foraminifera densities increased slightly. Three years after the impact, the situation had changed. The densities of the Nematoda had increased to levels more than twice those of the baseline study, while Harpacticoida had increased by more than 60%. However, in contrast to the megafauna, meiofaunal densities had also increased at the reference site. This may be due to an additional food input from the euphotic zone, and appears to have occurred as well at the sites within the plow-harrow tracks. Thus interpretation is ambiguous; recolonization cannot be distinguished from enhanced food supply for this group.

Preliminary results of the sampling 7 years after the impact again showed decreased densities of the Nematoda and Harpacticoida. Nematoda densities were still 50% higher than the baseline values, while those of the Harpacticoida exceeded baseline levels by 15%. At the reference station, the densities of both groups nearly equalled those of the baseline study. Faunal analysis of separate depth intervals from selected sediment cores revealed that 70–95% of the metazoan meiofauna in the undisturbed area dwell in the top 2 cm of the sediment. A comparison of undisturbed samples and those from the plow-harrow tracks after 7 years showed inverse abundance relationships for the Nematoda and Harpacticoida: the density of the Nematoda was higher in in-track samples compared to those outside the tracks, whereas the opposite situation was observed for the Harpacticoida. Samples collected from outside the experimental area exhibited intermediate densities for both taxa.

Benthic Impact Experiment (BIE)

The Benthic Impact Experiment (BIE) was designed to address the effects of sediment redeposition through artificial generation of suspended sediments on the seabed (Trueblood & Ozturgut, 1997). The work was conducted in collaboration with Russian scientists from the Yuzhmorgeologiya Association aboard the vessel *R/V Yuzhmorgeologiya*. The means for suspension of seabed sediments was provided by the Deep Sea Sediment Resuspension System, built for the U.S. government's National Oceanic and Atmospheric Administration (NOAA) and the Japanese government by Sound Ocean Systems, Inc. (Brockett & Richards, 1994). Initial trials and experiments with the system were conducted in 1991 and 1992. However, the sediment redeposition results were not satisfactory, and a second generation system was manufactured and tested in 1993. The new system (termed the "Disturber") mixed surficial sediments with ambient seawater, lifted the resultant slurry, and discharged it 5 m above the seafloor.

In July 1993, the NOAA started the BIE with baseline studies which included deployment of a transponder net and current meters, and side-scan sonar and camera surveys in the study area. In August 1993, the baseline current meters were recovered, baseline box-core samples were randomly collected from the study area, and sediment traps and current meters with optical-beam transmissometers were deployed.

Following these baseline data collection efforts, the 4,900-m deep experimental area (located approximately at 12°55′N, 128°35′W) was blanketed with sediment by towing the Disturber 49 times through a 150-m by 3,000-m zone oriented in a northeast/southwest direction parallel to the normal Trade Wind weather. This resulted in the suspension of approximately 4,000 m^3 of sediment. Northerly currents at the time of disturbance transported the bulk of the suspended sediment to the north, as indicated by the sediment trap and transmissometer data. Results indicate that the discharged sediment did not travel far, settling quickly as a sediment-laden fluid flow.

Samples were randomly collected in the area of heaviest accumulation of the suspended sediments to determine the impacts on macro- and meiofauna, both immediately after towing and 1 year later, in 1994. Meiofaunal analysis indicates that nematodes exhibited a significant decrease in abundance in the sediment redeposition area 9 months after the Disturber operations.

Of the 71 macrofaunal families analyzed, only Sabellid polychaetes and Macrostylid isopods exhibited a significant treatment affect that could be attributed to the sediment redeposition. Overall species diversity remained unaffected by sediment redeposition.

Unfortunately, a key parameter for this work, the resultant sediment thickness added by the disturber at the sample sites, was not attainable because the amounts of sediment suspended were so widely dispersed that no significant accumulation was measurable outside the actual area disturbed. Thus no relationship between faunal succession and sediment was attained.

Japan Deep-Sea Impact Experiment (JET)

The Japan Deep-Sea Impact Experiment (JET) used the same device as the BIE in a western location (5,300-m water depth; 9°14.5′N, 146°15.5′W) similarly to explore faunal succession as a function of rapid resedimentation (Kaneko et al., 1996, 1997). In 1994, 13 samples before the artificial disturbance (JET1) and 14 samples following the disturbance (JET2) were collected at the site. One year later, 12 samples (JET3) were collected in the same area. The abundances and vertical distributions of meiofauna and bacteria were studied using those samples. Again, no quantification of the thickness of resedimentation in the sampled area was achieved, but clear indications of impacts to the infauna were made and are summarized below.

In general, the study shows that the average abundance of nematodes decreased significantly at JET2, while those of copepods and bacteria increased significantly at JET3. In a 3-year baseline study prior to the experiment, more than 95% of the total metazoan meiofauna were distributed in the upper 5 cm of the sediments, and about 90% were located in the upper 3 cm, with most organisms concentrated close to the sediment surface (Kaneko et al., 1997). Thus, it was only necessary to analyze the upper 3 cm of sediment for each sample. Cumulative percentage curves indicate that most organisms were concentrated in the top 1 cm of sediment in (50–80%). Also, the percentage of copepods in the upper layer of sediment was higher than that of nematodes and bacteria.

The average abundances of metazoan meiofauna and bacteria in each sediment layer in the JET1, JET2, and JET3 samples were compared statistically. Although there were significant differences in the nematode abundances among the three JET samples, the results of comparisons in each sediment layer showed a similar density in the top 3-cm layers for JET1 and JET3. However, the nematode abundances in all sediment layers for JET2 had significantly lower densities than in the JET1 sample ($p < 0.001$ in all sediment layers).

JET3 samples had significantly greater abundances of copepods than JET1 ($p < 0.001$) only in the top 1-cm sediment layer, whereas bacteria were significantly more abundant at each depth ($p < 0.001$) for the same samples. Copepod abundances of the first 0.25-cm layer in the JET2 samples and bacterial abundances of the top 0.5 cm were lower than those of JET1 samples, although they were not significantly different ($p < 0.2$). Vertical distributions in the sediment profile indicated that the extended effects of disturbance on the average abundance were different for each faunal component, but that changes in abundance of total fauna were greater in the upper layers.

IOM-BIE

Kotlinski and Tkatchenko (1997) presented preliminary results of Interoceanmental Joint Organization (IOM) research efforts. Cooperating with the China Ocean Mineral Research Association (COMRA), the IOM researchers surveyed two areas within the Clarion-Clipperton Zone. Monitoring changes in the ecosystem following a sediment disturbance, their results indicate that immediately after a disturbance, megabenthos were observed to intensity feeding activity due to the presence of additional food resources. Meanwhile, meiobenthos abundance decreased and meiobenthos vertical distribution was altered.

Kotlinski and Tkatchenko point out that their preliminary results indicate changes in zinc, lead, cadmium, and copper concentrations in pore water and near-bottom water. They caution against assumptions of anthropogenic source, since episodic plumes from subsea volcanic activity and sediment flows on slides of

3–4° slopes were noted in the region. Temperature inversions and increased concentrations of heavy metals accompany discharges of mineralized water from volcanic and hydrothermal activity.

Indian Deepsea Experiment (INDEX)

The Deepsea Experiment (INDEX) in the central Indian Ocean (10°S, 76°E) utilized the Deep Sea Sediment Resuspension System (Brockett & Richards, 1994) to resuspend > 6,000 m^3 of sediment over a 9-day period in August 1997 (Desa, 1997; Sharma et al., 1997). Monitoring of this disturbance will continue for the next 3–5 years.

Summary

All studies concluded to date support the original first-order concerns about environmental impacts identified in the DOMES research. These are repeated here for convenience:

1. Impacts on the benthic communities within the area where manganese nodules are removed
2. Impacts on the near-surface biota, particularly fish larvae, due to the discharge plume of suspended sediments and other foreign materials in the water column
3. Impacts on the benthic communities at some distance from removal operations, due to the deposition of suspended sediments

As discussed above, post-DOMES work has focused on the benthic communities, due to the expected long-term processes which will be involved in faunal succession after benthic impacts. The U.S.-funded research subsequent to the DOMES work, including the BIE, primarily demonstrated the extreme technical difficulties which must be overcome before meaningful results can be obtained. The DISCOL program clearly shows significant changes in the benthic habitat within tracks of a plow-harrow device which may or may not be representative of a real mining system. The JET results indicate significant impacts, particularly on meiofauna, in areas where significant resedimentation is known to have taken place.

None of these studies has been able to establish quantitative relationships between burial depth and faunal succession. Such relationships must be defined before predictive capability can be achieved.

As discussed above, with the exception of a few pioneering efforts (e.g., Bluhm, 1994), very little work has been completed which compares and contrasts the baseline information obtained from the different sites. Many more such studies are necessary before it will be possible to estimate the true sizes of these benthic habitats, provide comparability in impact predictions which can be expected from site to site, and guide selection of long-term experimental reference sites as benchmark for all benthic studies.

None of this work addresses directly the concern expressed in item 2 related to surface-discharge impacts. Though significant efforts to model surface discharges have been completed, very little progress has been made in mining-related studies to understand the actual fates and effects of suspended solids in the deep-sea surface waters of potential mine sites. As discussed above, the majority of the sediments which reach the deep seabed show clear signs of biological interaction; fine-grained sediments do not appear to settle out of the water column until they are incorporated into fecal matter by zooplankton and larger animals. Understanding of the primary pathways whereby sediments are naturally removed from the water column is a basic problem in oceanography and is an active subject of research worldwide. Incorporation of the results of this work will be essential for the design of future monitoring efforts and for impact predictions.

Finally, none of the work completed to date examines the generality of the DOMES conclusion that seabed mining is possibly more environmentally benign than the alternatives of land-based recovery from new mines. This topic must be pursued on a case-by-case basis within the context of specific development plans. It is an important aspect of impact analysis which has not been given adequate attention to date.

The above observations suggest the following priorities for future work in this area:

1. The establishment of quantitative relationships between resedimentation thickness and faunal succession in benthic communities
2. The unification of mining-related research efforts on benthic communities by (*a*) synthesis of existing studies to isolate similarities and differences; (*b*) establishment of common rules for taxonomic reference and, hopefully, a single site for holding of specimen collections; and (*c*) establishment of long-term experimental reference sites for common comparison of techniques, acquisition of baseline data, and monitoring of natural variability within each region
3. The establishment of clear guidelines for monitoring of precommercial mining tests by (*a*) application of items 1 and 2 to the definition of benthic monitoring requirements; and (*b*) synthesis of ongoing oceanographic studies of suspended particles in the oligotrophic ocean surface waters with physical modelling work to establish monitoring guidelines for surface discharges
4. Case-specific comparisons of impacts predicted from deep seabed mining with those anticipated from alternative, land-based methods for obtaining the same quantities of minerals.

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