Environmental aspects of manganese nodule mining

Anthony F. Amos and Oswald A. Roels

The authors describe the environmental baseline conditions in the 'nodule zone', with emphasis on those parameters that might be affected by nodule mining. They consider the impact of full-scale mining operations on that environment and, finally, put forward recommendations to minimise adverse impacts and so to make deep-sea mining environmentally acceptable.

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Much of the information contained in this article is considered in depth in a chapter by A.F. Amos *et al* in *Marine Manganese Deposits* (in press), Elsevier, Amsterdam, edited by Geoffrey P. Glasby.

The mining of manganese nodules from the floor of the deep ocean has no historical parallel to draw upon for an evaluation of the possible environmental effects. Mining sites will be located thousands of kilometres from land, on the high seas, with 5000 metres of ocean water between the mining platform and the minerals being mined. The complex interactions between atmosphere, ocean water, and ocean floor (physics, chemistry, biology and geology) must be examined before the effect of nodule mining on the environment can be ascertained. As deep-ocean mining is without historical precedent, discussion on the subject should focus on the consideration of operations that are already in the planning and testing stages rather than the presentation of a general treatise on nodule mining by any method in any ocean. Only those locations where nodule deposits of known commercial value are found are discussed here.

The area of prime interest to the mining industry is the eastern equatorial Pacific Ocean, specifically the radiolarian (siliceous) ooze sedimentary province. This 'nodule zone' lies between the equator and the 30°N parallel and extends east to west from the 100°W to the 160°W meridian (Figure 1).

Within the nodule zone, specific sites have been selected for study by a US governmental-academic-industrial panel. Site C has been declared by Deepsea Ventures, Inc to be their prime site for future mining operations. Several cruises under the auspices of the US Department of Commerce, NOAA, Deep Ocean Mining Environmental Study (DOMES) project, have already been undertaken to study environmental baseline conditions before mining starts (Table 1).

Three basic mining systems are considered here: (a) the continuous-line-bucket (CLB) system; (b) the airlift or suction-dredge system using a towed dredge-head; and (c) as (b) above, but using a self-propelled dredging device.

It must be emphasised that important data concerning the magnitude and methods of mining operations are only available through a few published reports, copies of patents, and news releases. Such proprietary information is closely guarded by the mining companies.[1]

[1] Critical figures, such as volume of sediment disturbed by the different techniques and volume of effluent disturbed at the sea surface, have been obtained from a 1975 US National Research Council report with industry inputs.

Environmental conditions in nodule zone

While many physical, chemical, and biological measurements have been made in the equatorial Pacific Ocean, detailed measurements in the open ocean areas where nodules will be mined are lacking,

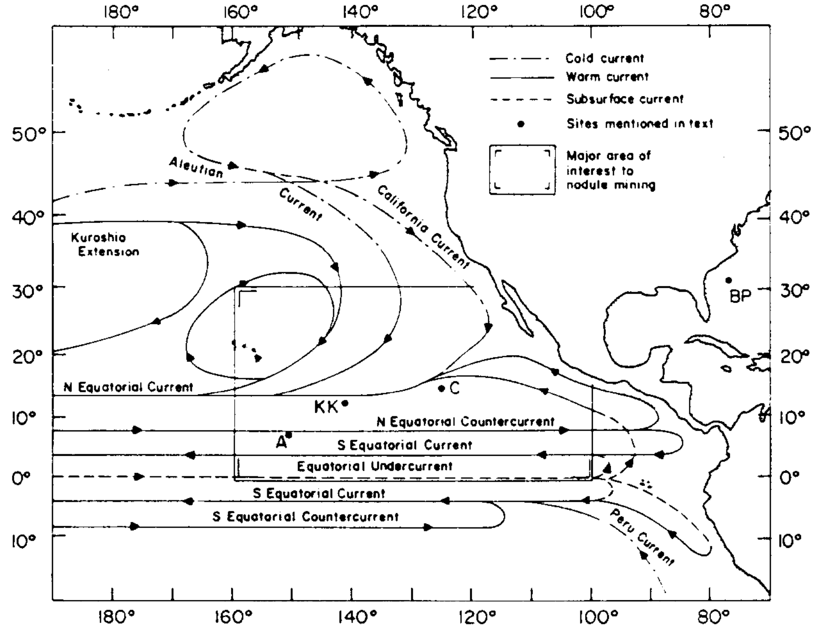

Figure 1. The eastern North Pacific Ocean, showing the manganese nodule zone, the location of test sites mentioned in the text, and the surface and subsurface currents.

See A.F. Amos, O.A. Roels, C. Garside, T.C. Malone, A.Z. Paul, 'Environmental aspects of nodule mining in *Marine Manganese Deposits* (in press), Elsevier, Amsterdam, edited by Geoffrey P. Glasby.

particularly in fields such as nutrient chemistry, phytoplankton productivity, and benthic ecology. Deep and bottom measurements in the water column are sparsely located throughout the area. Project DOMES cruises have recently studied the seasonal baseline conditions of the physical, geological, chemical, and biological oceanography at the test sites shown in Figure 1 and Table 1.

Water column

The water depth in the manganese nodule belt varies from 2300 to 6000m but with an average depth of 5000m. High-grade nodules are generally found in depths from 4000-6000m and mining systems will have to operate at these depths. Most of the area consists of a rather flat plain trisected by the E-W trending Molokai, Clarion, and Clipperton Fracture Zones. With the exception of the fracture zones, the abyssal topography shows less than 200m relief with rather

Table 1. Test sites and cruises referred to in text.

Test site	Location	Ship	Cruise	Dates	Reference
BP	31°02'N; 78°24'W Blake Plateau	Deepsea Miner	–	August 1970	Amos *et al*, 1972[a]
KK	13°N; 141°W	Kana Keoki	72–1	August-September 1972	Roels *et al*, 1973[b]
A	8°27'N; 151°47'W	Moana Wave	74–2	April-May 1974	Amos *et al*, 1975[c]
C	15°N; 126°W	Oceanographer	RP–6–OC –75	April-June 1975	Amos *et al*, 1976[d]
GEOSECS (Profile)	14°3'S; 126°16'W to 28°31'N; 121° 30'W	Melville	GEOSECS LEG 10	May-June 1974	Broecker and Mantyla, 1974[e]
GEOSECS (Test station)	28° 29'N; 121° 38'W	Thomas Washington	–	September 1969	Craig and Weiss, 1970[f]

[a] A.F. Amos, D. Garside, K.C. Haines, and O.A. Roels, 'Effects of surface-discharged deep-sea mining effluent', *Journal of the Marine Technology Society*, Vol 6, No 4, pp 40-45.

[b] O.A. Roels *et al*, 'Environmental impacts of deep-sea mining', Progress Report: NOAA Technical Report No ERL 290-OD11, Washington, DC, 1973.

[c] A.F. Amos *et al*, 'Report on a cruise to study baseline conditions in a manganese nodule province', Seventh Annual Offshore Technology Conference, Houston, Texas, 5-8 May 1975, OTC Preprint No 2162. 'The environmental impacts of deep-sea mining', Cruise Report 'Moana Wave', microfiche, NOAA, US Department of Commerce, Boulder, Colorado, 89302, USA, 1975.

[d] A.F. Amos, O.A. Roels, and A.Z. Paul, 'Environmental baseline conditions in a manganese nodule province in April-May 1975', *Proceedings of Offshore Technology Conference*, Vol 1, 1976, pp 341-356.

[e] W.S. Broecker and A.W. Mantyla, 'GEOSECS', Pacific Expedition Preliminary Report, LEG 19, Papeete-San Diego, 13 May-10 June 1974, unpublished, Institute of Oceanography.

[f] H. Craig and R.F. Weiss, 'The GEOSECS 1969 intercalibration station: Introduction, Hydrographic features, and CO_2-O_2 relationships, *Journal of Geophysical Research*, Vol 75, pp 7641-7647.

Table 2. Major currents in the manganese nodule zone.

Name	Where found	Velocity (cm/s)	Depth (m)	Transport ($10^{12} cm^3/s$)	Remarks
North Equatorial Current	8°N–30°N across entire region	Westerly; 15	Surface to > 300	27	Major surface current in the manganese nodule zone
North Equatorial Counter-Current	7°N–12°N across entire region	Easterly; Avg 20–30 Max 120	Surface to 200	15	Seasonally variable due to shift in the Intertropical Convergence Zone; subsurface to 85°W
South Equatorial Current	10°S–4°N across entire region	Westerly; 35–45	Surface to 50 N of equator to 200 S of equator	49	Seasonally variable N of equator; divergence N and S of equator of this current causes equatorial upwelling
California Current	30°N–15°N 1000 km off coast	South, then south-westerly; 15	Surface to 100–300	17	During February-June supplies most of the water to N Equatorial Current
(Peru Oceanic Current)	30°S–5°S	North, then north-westerly	Surface to 700	14	Not directly in area of interest, but supplies water to S Equatorial Current
Equatorial Undercurrent	2°N–2°S across entire region	Easterly; 120–150	50–300	35	Branches N and S east of Galapagos Islands to supply water to N and S Equatorial Currents

See work cited in note to Figure 1.

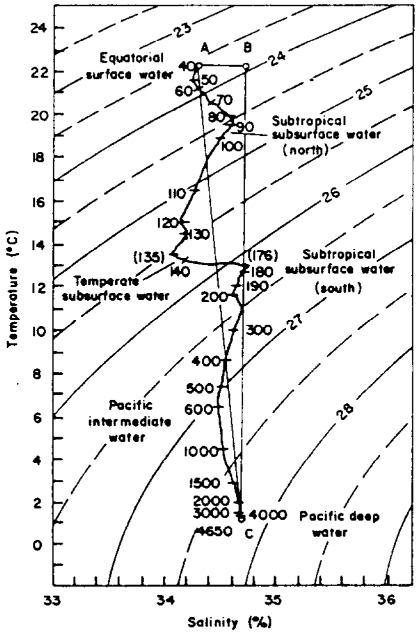

Figure 2. Typical temperature-salinity curve at site C.

Water masses are identified at their core-layer values. Depths (m) are marked along the temperature-salinity curve. Curved lines are isopycnals annotated in σ_t units. A = surface water; C = bottom water; B = bottom water in temperature equilibrium with the surface water. Area within triangle ABC contains all possible mixtures of surface and deep water at any temperature between the two.

closely spaced abyssal hills. A few widely spaced seamounts are found throughout the area.

A system of zonal currents characterises the surface and near-surface flow (Table 2). They represent the equatorial extensions of the huge subtropical anticyclonic gyres that dominate the middle-latitude circulation.

Bottom currents in this region distant from continental margins are generally the result of the slow northward movement of dense, cold water that originally formed at the surface in the Antarctic. Indirect and direct evidence shows that bottom currents in parts of the world's oceans flow at much higher velocities than was previously supposed. Significant oscillations superimposed on the net-drift are caused by the deep ocean's response to tidal forces. Peak velocities strong enough to erode and transport sediment have been measured at sites A and C. The general drift of bottom water in the area is thought to be toward the northeast. Fairly extensive (compared to what was previously known for the area) bottom and mid-water current measurements were made during the baseline studies of DOMES.

A typical temperature-salinity curve is given in Figure 2. Typical profiles for nutrients, dissolved oxygen, and light-scattering are shown in Figure 3.[2]

Trace metals are present in very low concentrations in the water column (hardly within the limits of sensitivity of present analytical methodology). Measurements of dissolved radon indicate very low rates of vertical diffusion from the sediment.

Phytoplankton and zooplankton productivity (biomass, taxonomic composition) are poorly documented in this area, generally less than 150mg C/m^2/day.

Vertical profiles of phytoplankton productivity and chlorophyll *a* showed little variability between stations at site A.[3]

Geographic and seasonal variations in zooplankton standing stock

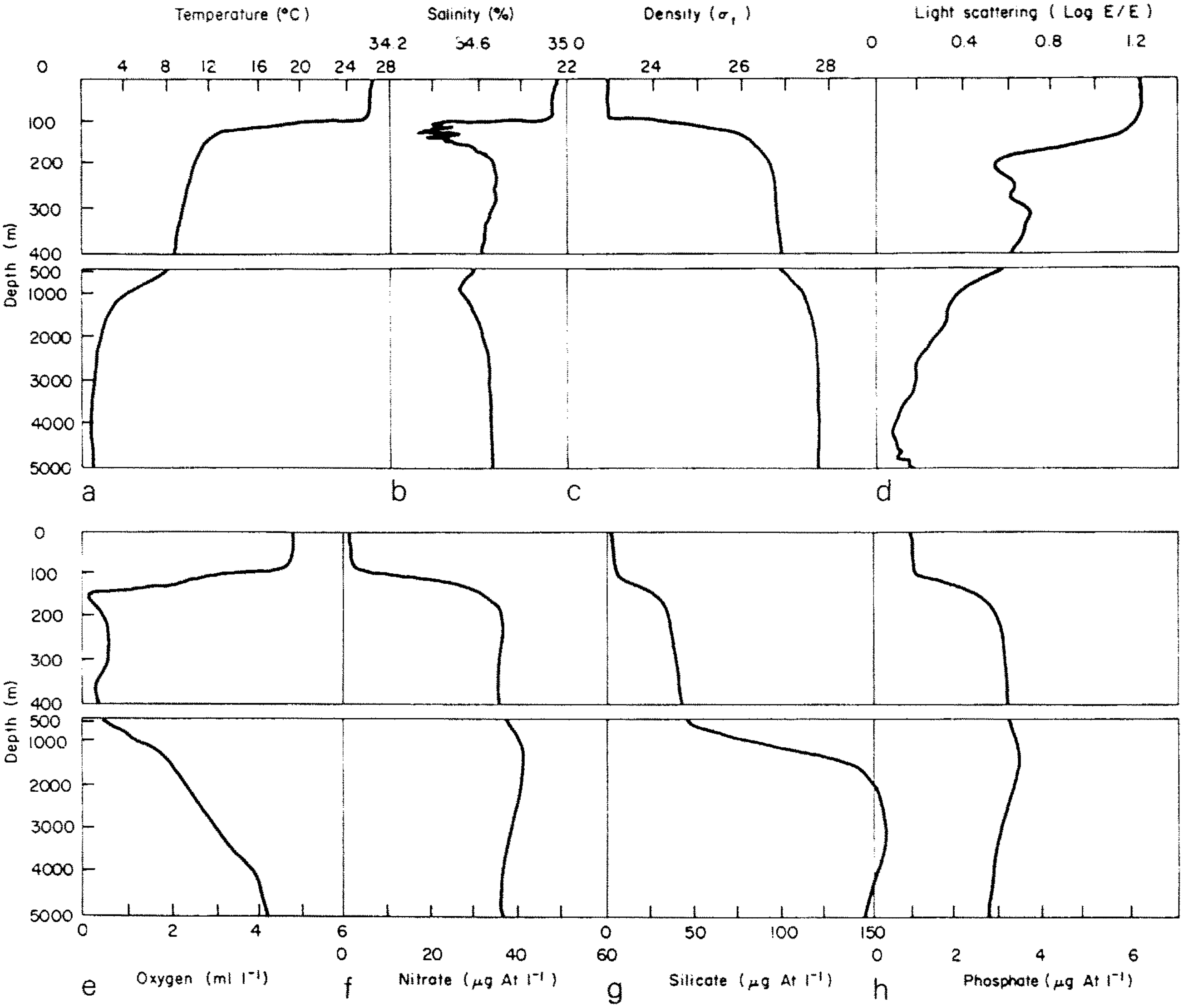

Figure 3. Vertical profiles of physical and chemical parameters in the water column at site A in April and May 1974.

(a), (b), (c), and (d) are typical continuous profiles at one station; (e), (f), (g), and (h) are averages of all discrete sample data collected at site A.

(displacement volume) in the upper 150m of the water column are positively correlated with phytoplankton standing crop in the eastern tropical Pacific. Seasonal cycles of chlorophyll *a* and zooplankton are low in amplitude and nearly identical in phase.

In summary, primary productivity, phytoplankton standing crops, and zooplankton standing stocks are low and show little seasonal variability. All the evidence reported to date suggests that epipelagic communities in prospective manganese nodule mining areas are in approximate steady state, and phytoplankton and zooplankton productivity are closely coupled.

Despite the low overall surface productivity in the nodule zone, wide-ranging pelagic animals are found throughout the region, sometimes in large numbers.[4] Many of the pelagic species of birds associate where food supplies are plentiful and a feature of their distribution is a distinct zonation of alternating high and low population densities. Mining will have little effect on these species.

Ocean floor

At study sites KK, A, and C, probably typical of the whole region,

[2] Silicate, another important nutrient for diatom growth, has a rather different distribution, increasing to a maximum concentration of about μg–at l⁻¹ at 3000m.

[3] The chlorophyll *a* maximum occurred between 30 and 50m, while chlorophyll *a* specific productivity peaked between 10 and 20m.

[4] Typical of these are squid, flying fish, shark, dolphin (fish), birds, porpoises and whales.

nodule coverage is extremely variable: from no to dense coverage to pavement on occasional outcroppings. Even over small distances, the nodule coverage is often very patchy.

The most direct effect of manganese-nodule mining will be on the bottom-dwelling communities which will be destroyed when buckets and dredge-heads scoop up both nodules and bottom-dwellers from the ocean floor. All of the abyssal fauna live on the sea floor or within the upper few centimetres of the sediment. They range in size from bacteria to large holothurians up to 0·5m in length. A limited population of free-swimming animals (fish, cephalopods) is present, presumably occurring near the ocean floor where they feed on the abyssal fauna. The larger organisms dwelling on the sediment surface can be studied by underwater photography. Smaller surface-dwellers and subsediment-dwellers can be studied by dredging or box-coring, while total population densities can be determined by box-coring only.[5]

[5] The 'Challenger' expedition of 1872-76 obtained two bottom dredges. In 1891, Alexander Agassiz, aboard the 'Albatross' of the US Fish Commission, obtained nine dredges. In 1975 aboard the 'Oceanographer' at sites A, B, and C, A.Z. Paul obtained 7863 bottom photographs covering an area of 81 355m^2 revealing 1807 macrofaunal organisms or 2/100m^2 and 5 replicate box cores (of 0·25m^2 each) at 7 stations at site C for a total of 35 box cores, 25 of which have been partially analysed. These 25 cores cover an area of 6·25m^2. The total weight of organisms collected from these box cores was 5·39g, corresponding to a biomass of 860 mg/m^2.

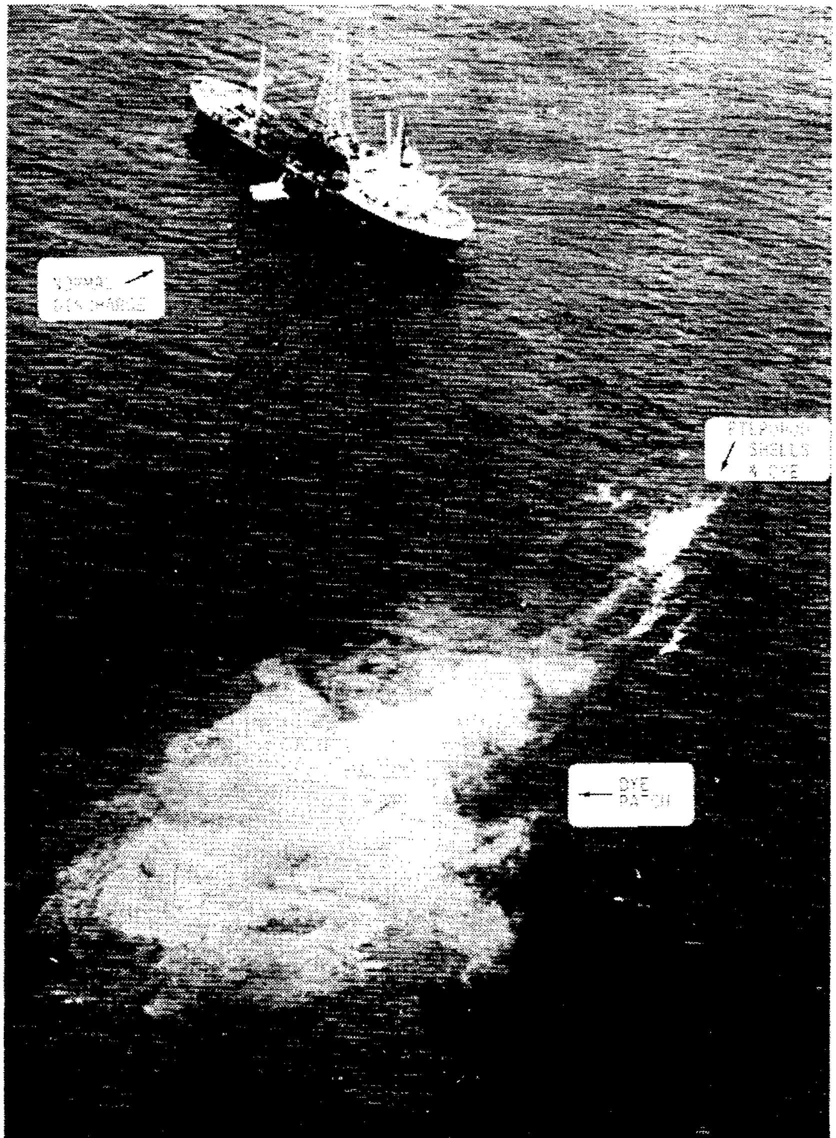

Figure 4. Aerial view of dye-marked mining effluent.

Taken 8 minutes after a 3-minute injection of dye into the outboard discharge of the 'Deepsea Miner' during mining tests on the Blake Plateau in August 1970.

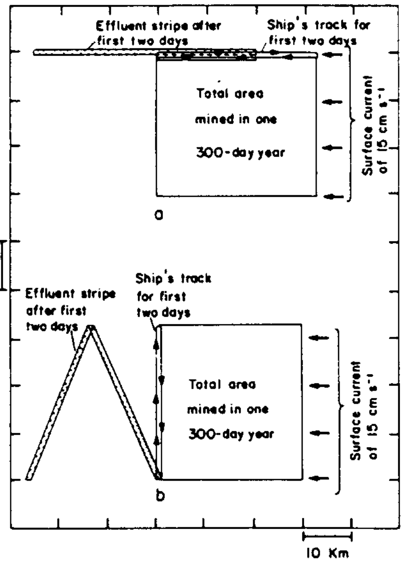

Figure 5. Configuration of effluent stripe after two days of mining with surface current (a) parallel to the ship's track, and (b) normal to ship's track.

Separation of ship's track and width of effluent stripe are 100m and are exaggerated 10 times here for clarity of illustration.

Environmental impact of nodule mining

In each of the three basic mining systems there will be some disturbance of sediments at the ocean floor as the collecting device moves along the bottom. Resuspension of sediment in the near-bottom water will occur. The mining companies will try to avoid transporting metallurgically worthless sediments to the surface with the nodules. Practically, it will not be possible to separate all the sediment from the nodules.[6]

After the nodules have been collected from the sea floor they are transported through the water column to the surface-mining vessel either in the buckets of a continuous line dredge or in a water stream through a pipeline. In both modes of transport some or all of the entrained sediment and near-bottom water may be discharged, either at the surface or at intermediate depths in the water column.

To be economically feasible, a mining unit (single mining ship or platform) must harvest at least 5000 (wet) metric tons per day. With a concentration of 10kg nodules m^{-2}, an area of 5×10^5 m^2 day^{-1} must be mined. These numbers are typical of estimates found in the literature on the economic aspects of nodule mining.[7] Nodule abundance is frequently quoted in terms of percentage of sediment covered by nodules as revealed by bottom photographs.

Surface-discharged effluent

Dilution of the deep-water effluent with surface water is very rapid. Complete flushing of the area by prevailing surface currents would take only eleven days along the long axis of a 30 x 150km mining area with a current speed of 15cm s^{-1} (North Equatorial Current). The rapidly expanding plume from a test in the Blake Plateau in 1970 (Figure 4) had already been diluted to approximately 0·05% of its original concentration eight minutes after discharge.[8]

Transport of the effluent by currents would make the concentration very patchy. A hypothetical effluent distribution is shown in Figure 5 for a track-line of 32·8km long with a separation of 100m and a prevailing current of 15cm s^{-1}. Ultimately the volume of water 5m deep to be transported past the mining vessel during one year would contain 9ppm effluent.

It is unlikely that a measurable effect on productivity, oxygen demand, or nutrient concentration would result from this kind of mining activity, although the possibility remains of a change in species composition of phytoplankton caused by the transport of dormant spores from the bottom to surface waters.

Of the vast quantity of sediment disturbed by the dredges at the ocean floor quoted by the National Research Council,[9] all but a very small percentage would have to be rejected at the dredge head. According to their figures, the quantity of sediment disturbed by a towed dredge would be $2\frac{1}{2}$ times the volume of *all* the material pumped to the surface and $5\frac{1}{2}$ times with a self-propelled device. If all this material goes into suspension in the bottom 10m of the ocean (Table 3) and the resulting sediment-water mixture is pumped to the surface with the nodules, then the surface-water plume will contain 11·5ppm sediment (towed dredge) and 22ppm sediment (self-propelled dredge). This is an increase in suspended material of between two and three orders of magnitude over the normal surface-water turbidity. If the sediment screens can remove 80% of the sediment disturbed and redistribute it in the near-bottom water before

[6] In the CLB system some of the sediment collected with the nodules in the buckets will wash out as the buckets move through the water column on their way to the surface. The other systems propose to use towed or self-propelled bottom-gathering devices connected with hydraulic or airlift pumping systems to transport the nodules through a pipeline system.

[7] The following assumptions were made in the authors' calculations: nodules of 2-4cm diameter; 25% of the sea floor covered with nodules; 10kg nodules/m^2; 300 mining days operation per year.

[8] The discharge rate during this experiment was half the rate of proposed full-scale operations.

[9] US National Research Council report, 1975.

Table 3. Amount of sediment disturbed at the ocean floor by dredging.

Type of dredge	Separation of track lines (m)	Mining efficiency (%)	Nodules mined per day (metric tons)	Per 300-day year: Volume of sediment + nodules removed ($m^3 \times 10^7$)	Volume of sediment alone ($m^3 \times 10^7$)	Volume of water affected ($m^3 \times 10^9$)	Suspended solids in bottom 10 m of water (ppm)
Towed	0	100	4920	1·48	1·40	1·48	9460
	50	30	4920	1·48	1·40	4·91	2850
	100	15	4920	1·48	1·40	9·81	1430
	500	3	4920	1·48	1·40	48·50	290
Self-propelled[a]	0	100	4600	3·26	3·19	1·73	18440
	50	35	4600	3·26	3·19	4·91	6500
	100	18	4600	3·26	3·19	9·81	3250
	500	3·5	4600	3·26	3·19	48·50	660

[a] Using a track width of 17·6m (3·6m for propulsion device which interacts with ocean floor) and a computed width of 14m to mine 4600 metric tons day $^{-1}$.
Source: National Research Council Report, 'Mining in the outer continental shelf in the deep ocean', National Academy of Sciences, Washington, DC, 1975.

pumping to the surface, then these quantities would still amount to 2·3ppm and 4·4ppm, respectively, for the two systems.[10]

Disturbances on ocean floor

Mining operations will undoubtedly stir up clouds of sediment in the near-bottom waters, and bottom currents and turbulent processes in the area are sufficient to keep it in suspension. However, there seems to be no evidence of increased turbidity in pilot mining operations. Moreover, the mining industry has developed systems that, allegedly, will screen-out 80–90% of the sediments at the dredge head.

Probably no more than 40% of a given area will be mined, and recolonisation by benthic organisms of the mined sea floor from adjacent, untouched zones will undoubtedly occur, although this may take a very long time.

Near-bottom sediment plumes will occur and their behaviour is the greatest unknown factor associated with the effects of ocean-floor mining.

Conclusions

Present knowledge of the basline conditions in the oceanic environment is still largely incomplete in manganese nodule provinces.

Knowledge of the impact of mining on the oceanic environment is growing, but it remains difficult to forecast precisely the environmental effects of full-scaie mining operations.

To ensure the safe development of this marine resource, and to avoid costly and drawn-out legal wrangling based on the unsubstantiated opinions of 'experts' for opposite viewpoints, it is clearly necessary that an orderly procedure be followed and that all environmental factors related to deep-sea mining be well documented. The following procedure should be adopted:

1. The establishment of baseline conditions in the potential mining areas. This study is underway[11] and could be continued and completed, if necessary, simultaneously with the subsequent phases of the procedure.
2. The environmental monitoring of pilot and/or full-scale mining operations.
3. The documentation of changes induced in benthic and pelagic

[10] These calculations assume that the sediment remains with the surface plume and is diluted proportionately, for an effluent concentration of 0·12% (deep water in surface water). For 'Deepsea Miner' (in the 1970 Blake Plateau test) this was 0·05%.
[11] Deep Ocean Mining Environmental Study, NOAA, US Department of Commerce.

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ecosystems by deep-sea mining and evaluation of their implications in relation to current and potential marine resources.
4. If necessary, the recommendation of changes in mining methods and equipment use, based on the facts established in (2) and (3).
5. The formulation of environmental criteria and regulations for future mining operations to minimise harmful environmental effects while enhancing the development of potentially beneficial by-products.
6. The monitoring and enforcement of (5).

This procedure could be implemented rapidly by most interested nations and should then serve as a model for possible international adoption. There is no other way to develop this resource and preserve and protect the quality of the marine environment.

The preliminary results of studies of the environmental impact of deep-sea mining indicate that the impact of the mining itself is very likely to be small compared with the potential environmental impact of processing nodules at sea, or in the coastal zone. High priority should be given to studies of these aspects of manganese nodule mining. It is also very important that a comparative study is undertaken of the environmental impact of producing copper, cobalt, nickel and manganese from land-based and ocean-based deposits.

1972, pp 49-62; Report of the Task Group on Continuously Sampled Data to the Ocean Science Committee, National Academy of Sciences/National Research Council, Washington, DC, 1973; and the work cited in the footnote to Figure 1.

Oswald A. Roels was previously Professor at the City College of the City University of New York and Senior Research Associate, Lamont-Doherty Geological Observatory of Columbia University. His main publications, in the field of deep-ocean mining, include 'Will nodule mining disturb the marine environment?', Marine Technology Society Journal, Vol 8, 1974, pp 17-20; 'The environmental impact of deep-sea mining: a suggested approach to ensure the safe development of deep-sea mining', Second International Colloquium on Exploitation of the Oceans, Bordeaux, 1-4 October 1974, Vol 4, Bx-203; and (with various authors headed by A.F. Amos) 'Report on a cruise to study baseline conditions in a manganese nodule province', Seventh Annual Offshore Technology Conference, Houston, Texas, 5-8 May 1975, OTC Preprint No 2162.