

Environmental studies for Deep Seabed Mining

Rahul Sharma

National Institute of Oceanography, Dona Paula, Goa-403004

rsharma@nio.org

Abstract

Minerals from the deep-sea are potential sources of metals such as Cu, Ni, Co, Mn, Fe, that could be mined in future by developing suitable technologies for mining as well extracting metals from them. Several groups of environment scientists and mining engineers have been conducting studies for working out these minerals. These studies have revealed several unknown physical, chemical, biological and geological conditions under which the mining system will have to operate, and also the potential impacts that may occur.

Hence, the data generated through environmental studies would be useful not only in understanding the potential effects of large scale mining on marine ecosystem, but also in the development of various mining subsystems. However, owing to the uncertainty of the design of mining system and the difference in the scale of test mining as well as of the experiments conducted, many questions remain unanswered, which need to be considered in future.

Introduction

Deepsea mining has been a subject of interest around the world for over three decades, due to its potential for the economical recovery of large reserves of minerals, such as manganese nodules and crusts, which are considered as alternative source of strategic metals, such as Cu, Ni, Co, Pb, Zn, Cd besides Fe and Mn, for industrial development. The value of imports of ores and minerals during 1994-1995 accounted for ~21.5% of the total imports value of all merchandise to India and amounted to about 190 billion Indian rupees (Desa, 1999). The imports include the minerals and metals that also have a marine source. Demand for these minerals and metals has increased (Table 1), which are met either from domestic production or imports. In case of some of the metals and minerals, such as zinc, phosphorite, ilmenite and rutile, the domestic production has steadily grown. On the other hand, in case of metals such as cobalt and nickel, the entire demand is met from imports. Irrespective of the trend in domestic production, the imports have grown with years for all the metals, except for TiO₂, which is supplied from placer minerals. This indicates the growing demand of metals, for which there is an increasing need to look at the deepsea minerals as an alternative source, in the future.

A deep-sea mining operation would offer variety of challenges, owing to distant locations (thousands of miles from the coast), deep-sea mineral occurrences (5-

6 km of water depths), extreme physico-chemical conditions (high pressure, low temperature) and unknown environmental settings. However, due to the location of most of the potential mining areas in the international waters, it is a collective responsibility to ensure that no harmful damage is caused to the marine environment. As no deepsea mining activity has been started on a commercial scale, it is a favourable situation to foresee the likely effects and work out the means to minimize such effects by designing 'environment friendly' mining system in advance and plan mining operations accordingly.

This paper describes the environmental studies conducted by various groups around the world to understand the potential environmental impact of deepsea mining, evolve methods to conserve marine environment and also activities to be undertaken in future.

Status of deep seabed mining and related studies

Considerable progress by different groups of scientists and engineers has been made in all the 4 areas of deep seabed mining as follows:

Survey and exploration

The survey and exploration of deep-sea minerals has led to detailed studies on distribution and grades of these minerals, their genesis and mineralogy, petrology and sedimentology of associated substrates and bathymetry maps of the seafloor. In the quest for faster and more accurate survey and data collection, various survey equipment ranging from free-fall devices, mechanical equipment, remotely operated vehicles, tethered online cameras to remotely sensed backscatter and subbottom profiling data, have been developed and used. As a result, India, France, Japan, Russia, China, a consortium countries of eastern European countries (IOM) and Korea have claimed large areas in the Indian and Pacific Oceans.

Mining system development

International consortia had conducted tests of prototype mining systems and components in the Pacific Ocean in the seventies (DOMES, 1976). The subsequent progress in the development of mining technology for deep-sea minerals has been slow since 1980 due to unfavorable metal market condition. However, research groups have been working at designing different subsystems of the mining system and presently the

researchers have narrowed down to basically two miner/collector concepts: self-propelled seafloor miner vehicles (Brink and Chung, 1980;) and tow-sled collectors (Chung and Tsurusaki, 1994).

Mineral processing

Some international consortia had developed manganese nodule processing techniques including pilot processing tests. However, the results were not made available to non-members. Recently, some of the research groups have conducted laboratory-scale tests (Zhong et al., 1999; Premchand and Jana, 1999), which may be scaled up to pilot-plant-scale in future. However, the unwanted tailings, depending on the type of processing, will amount to between 72% and 97% of the original ore (Black, 1982), but their safe disposal into the terrestrial or marine environment, or their alternative uses have not been studied to any sufficient extent.

Environmental studies

Owing to growing concern for the environmental impact of deep-sea mining, multi-disciplinary studies (oceanography, geology, geochemistry, ecology and geotechnical engineering) have been undertaken in different parts of the world oceans. Initial environmental impact studies were conducted during pilot scale mining tests for manganese nodules, in the seventies (DOMES, 1976, Burns et al., 1980; Ozturgut et al., 1980), followed by several experiments in the last decade, creating benthic disturbances in the Pacific and the Indian Oceans (Foell et al., 1990; Trueblood, 1993; Fukushima, 1995; Tkatchenko et al., 1996; Sharma and Nath, 1997). These studies include collection of baseline environmental data in the proposed mining areas, creation of an experimentally disturbed area comparable to future mining and monitoring its effects over a period of time. They aim at prediction of the intensity of mining impacts on different environmental parameters as well as evaluating the processes of restoration and re-colonization of deep-sea environment and animal communities. A comparison of the sediment resuspended during these experiments, shows that these were much smaller in scale than a commercial mining system (Yamazaki and Sharma).

Potential environmental effects of deep seabed mining

The impact of offshore mining is expected to be in the form of 'plume' at the seafloor, turbidity in the water column and addition of bottom sediments to the surface resulting in change in the marine ecosystem (Fig. 1). According to an estimate, an area of 300-600 sqkm will be disturbed every year for mining of 3 million metric tonnes of nodules per year (Sharma, 1993). With every tonne of manganese nodule mined from seabed, 2.5-5.5 tonnes of sediment will be resuspended (Amos and Roels, 1977). Hence, for an average 10,000 metric tonnes of nodules mined per day, about 40,000 metric tonnes of sediment will be disturbed (at 1 tonne nodule :

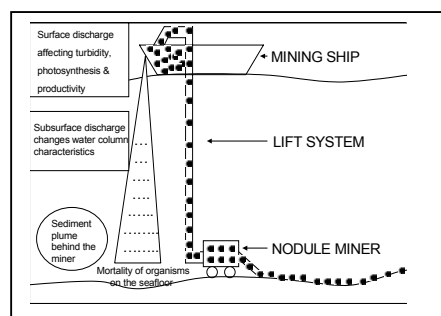


Fig. 1. Schematic for environmental impact of deepsea mining

4 tonne sediment). The adjacent areas will not only have higher sedimentation rates, but the suspended loads may remain for over long periods but also travel laterally, causing clogging of filter feeding apparatus of benthic organisms in the area. Sudden increase in the amount of suspended matter due to sediment plume and mining discharge, will increase the turbidity of these waters, and may also affect pelagic organisms (Morgan, 1981).

The debris and sediments mixed with water, which are lifted and transported with the minerals, will be discharged at the surface, and create turbidity. Their dispersion by currents will decrease the available sunlight for photosynthesis causing long term effects on biological productivity. At the same time introduction of bottom water, with its higher nutrient values, would result in artificial upwelling, increasing the surface productivity (Pearson, 1979).

A summary of the probable impacts at various levels in the water column have been given in the following section (from ISA, 1998):

Potential benthic impacts

It is anticipated that the primary benthic impacts caused by mining will be:

- direct impacts along the track of the nodule collector, where the sediments and associated fauna will be crushed or dispersed in a plume and the nodules removed;
- smothering or entombment of the benthic fauna away from the site of nodule removal, where the sediment plume settles; and
- clogging of suspension feeders and dilution of deposit-feeders food resources.

Potential water-column impacts

Discharge of tailings and effluent below the oxygen-minimum zone may cause some environmental harm to the pelagic fauna, such as:

- mortality of zooplankton species
- effects on meso-and bathypelagic fishes and other nekton, impacts on deep-diving marine mammals, on bacterioplankton and depletion of oxygen by bacterial growth on suspended particles.

- effects on fish behaviour and mortality caused by the sediments or trace metals;
- mortality of and changes in zooplankton species composition caused by discharges;
- dissolution of heavy metals (e.g. copper and lead) within the oxygen-minimum zone and
- the possible clogging of zooplankton by filtering particles in the plume.

Potential upper-water column impacts

If tailings consisting of sediments (including clay) and effluent are discharged in near-surface waters then there are additional impacts to those listed above, will be e.g.

- the potential for trace-metal bioaccumulation
- reduction in primary productivity due to shading of phytoplankton and
- effects on phytoplankton from trace metals and
- on behaviour of marine mammals and especially the
- duration of tailing suspension, especially with at-sea processing.

Environmental studies conducted by different groups

A brief description of studies conducted so far is given in the following paragraphs.

DOMES

The DOMES (1976) (Deep Ocean Mining Environment Study: 1972-1981) conducted by NOAA (USA) monitored environmental impacts during two of the pilot scale mining tests conducted by the Ocean Mining Inc. and the Ocean Mining Associates (OMA) in 1978 in the Pacific Ocean (Burns et al., 1980; Ozturgut et al., 1980). During the study the concentration of particulates was measured in the discharge and the biological impacts in the surface as well as benthic plumes were assessed.

DISCOL and ATESEPP

The DISturbance and Re-COLonisation (DISCOL) experiment was conducted by the scientists of the Hamburg University, Germany in the Peru Basin in the Pacific Ocean from 1988 to 1998. Collection of pre-disturbance baseline environmental data was followed by the disturbance caused by a plow harrow in a circular area of 10.8 km² (Foell et al., 1990). Post disturbance studies were carried out to monitor the impact and recolonisation after 6 months, 3 years and 7 years using sediment cores, deep-towed photographic systems, current meters, and nephelometers. The results have shown that over a period of time, although certain groups of benthic organisms may show a quantitative recovery, the faunal composition is not the same as the undisturbed one (Schriever et al., 1997). This implies that complete re-colonisation is a slow process and some of the benthic organisms may need more time to re-establish themselves in the disturbed areas in terms

of density and diversity. The ATESEPP (German abbreviation of impact of technical interventions into the deep sea of the Southeast Pacific Ocean) project extended the DISCOL-results by additional information of impacts in oceanography (sediment transport in near and far field), soil mechanical and geo-chemical aspects. Heavy impacts were demonstrated on the geo-chemical regime after disturbance of the top 20cm sediment structure of the deep-sea floor. The results of this experiment demonstrated that the scale of disturbance and investigation was still too small. An experiment of this scale is cost-intensive and would require cooperation in sharing, not only development and operational costs, but also the expertise, manpower and other resources among the participating groups (Thiel et al. 1991).

NOAA-BIE

The benthic impact experiment (NOAA-BIE) by the National Oceanographic and Atmospheric Administration (NOAA, USA) was conducted in the Clarion Clipperton Fracture Zone (CCFZ) of the Pacific Ocean (1991 to 1993). After baseline studies in a pre-selected area, the Deep-Sea Sediment Resuspension System - DSSRS (Brockett and Richards, 1994) was used for 49 times in an area of 150x3000 m and the post-disturbance sampling with CTD, sediment traps and core samples indicated changes in the faunal distribution in the area (Trueblood, 1993). The impact assessment after 9 months indicated that, whereas some of the meiobenthos showed a decrease in abundance, the macrobenthos showed an increase in their numbers probably due to increased food availability (Trueblood et al., 1997). Hence, mixed effects of resedimentation on benthic organisms could be expected and the effects cannot be generalized. The resedimentation in turn would depend on the total volume of sediment resuspended and the prevailing current patterns in the area.

JET

The Japan deep-sea impact experiment (JET, 1994 - 1997) was conducted by MMAJ (Metal Mining Agency of Japan) in the CCFZ of the Pacific Ocean in 1994 with the DSSRS. Disturbance was created during 19 transects over two parallel tracks of 1600 m length (Fukushima, 1995). The impact was assessed from sediment samples, deep-sea camera operations, sediment traps, and current meters and the results show that the abundance of meiobenthos decreased in deposition areas immediately after the experiment and returned to original levels 2 years later, but the species composition was not the same; whereas the abundance of certain groups of mega and macro-benthos was still lower than the undisturbed area (Shirayama, 1999). This observation shows that certain groups are more susceptible than others to adapt to the changed conditions on the seafloor.

IOM-BIE

A benthic impact experiment (IOM-BIE) was conducted by Interoceanmetal (IOM) Joint Organisation, in CCFZ in Pacific Ocean in 1995, using DSSRS. In all, 14 tows were carried out on a site of 200x2500 m and the impact was observed from deep-sea camera tows and sediment samples (Tkatchenko et al., 1996). The results have shown that whereas no significant change was observed in meiobenthos abundance and community structure in the re-sedimented area, alteration in meiobenthos assemblages within the disturbed zone was observed (Radziejewska, 1997). This indicates that the intensity of disturbance and the proximity to the site could have variable effects on composition of the faunal assemblages.

INDEX

The Indian Deep-sea Environment Experiment (INDEX) was conducted by National Institute of Oceanography (Goa, India) in 1997 in a pre-selected area in the Central Indian Ocean Basin after a detailed baseline study from 1995-97. The DSSRS was used 26 times in an area of 200x3000 m, during which about 6000 m³ of sediment was resuspended (Sharma and Nath, 1997). Photographic surveys showed destruction of benthic organisms due to the movement of the disturber on the seafloor as compared to that before the experiment (Fig. 2, 3). The post disturbance impact assessment studies have indicated that the effects of disturbance are the highest in and around the disturbance area (Sharma et al., 2001) and differential effects on microbial, meio and macrobenthos within and outside the disturbance track (Ingole et al., 1999, Nair et al., 2000). Longterm monitoring of re-colonisation and restoration of the benthic environment has indicated that natural conditions have set in over a period of time.



Fig. 2. Benthic organisms observed before the disturbance experiment

Environmental considerations for deep seabed mining

It is anticipated that the environmental impact will be greatest at the seafloor and at the depth zones of discharge of mine tailings and effluent (Thiel et al., 1997). Although, the impacts at the seafloor and in the water column cannot be avoided, they must be taken into account during the development of the mining equipment and in designing the mining operations to minimize the effects. As there is a higher potential for environmental

harm in the depth zone from the surface to 1,000 m, it is advisable that discharges should be released below the depth of the oxygen-minimum layer (e.g. in 1,000 m in many parts of the Pacific Ocean), and which has to be evaluated early in advance of commercial mining activities.

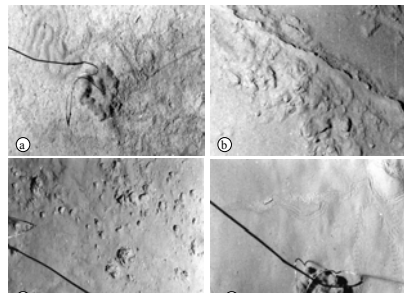


Fig. 3: (a) Seafloor with animal tracks before the disturbance, (b) 'disturber' track on the seafloor, (c) sediment lumps close to the disturber track, (d) resedimented surface after disturbance experiment.

In order to limit the impacts to minimum levels, the following measures need to be taken in the design considerations of the deep-sea mining system:

- minimizing sediment penetration of collector and mining vehicle,
- avoiding the disturbance of the more consolidated suboxic sediment layer,
- reducing the mass of sediment swirled up into the bottom-near water layer,
- inducing a high rate of resedimentation from the plume behind the miner,
- minimizing the transport of sediment and abraded nodule fines to the ocean surface
- reducing the discharge of tailings into bathyal or abyssal depth, and
- reducing the drift of tailings by increasing their sedimentation rate.

Certain environmental factors must be considered to predict and control the negative impact of offshore mining (Sharma and Rao, 1991). These are :

- i) The proportion of total area that will be affected, with respect to total area of the waterbody.
- ii) Influence of surface and subsurface currents in different seasons
- iii) Distance of coastal belts and inhabited areas from the area of influence.
- iv) Existence of fishing potential or any other commercial activity in the area of influence.

Some of the unanswered questions

In spite of all experiments conducted and calculations based on still limited data for the possible effects of future mining activities, many questions remain unanswered, due to the limited scope of these studies (Chung et al, 2001). Some of the questions are:

1. What would be the effects of surface discharge of effluents or debris mixed with bottom waters?
2. What would be the effects of movement of a collector mechanism or miner/collector vehicle tracking on the seafloor?
3. What should be the acceptable water level of discharge of effluents in the water column below the free surface?
4. What would be impacts of discharges from nodule-transport pipe and other sub-systems (for example, buffer) suspended in the water column?
5. How would the resettlement or redistribution of suspended sediments occur close to the seafloor?
6. What would be the net effect on the marine food chain of different subsystems / activities of deep-sea mining at various depth zones?
7. Could alternative uses be found for the large quantities of debris from deep-sea minerals?
8. What would be an ideal size of each mining area to allow re-colonisation and restoration of the benthic communities?
9. What alterations in the mining system design could be used to minimize the effects on the marine ecosystem? What engineering data should the environment experiment provide?
10. Which key parameters would be useful as indicators of environmental impacts and how do we prioritize them?
11. What results, data and statements each contractor would be required to deliver in order to claim mining regions?
12. What will be a likely mining system or systems in next 20 years to determine a basis of environmental tests? How do we categorize and define potentially real mining system and miner or collector systems, and narrow down to one or two systems?
13. What else environmental parameters do we expect in case of at-sea processing?
14. How do we categorize and identify pollutant or effluent discharges from the ship, pipe, buffer and miner/collector for land processing and at-sea processing?
15. Upon generalizing the 13 and 14 above, how do we develop an approach to develop a disturbance flow simulation model or component disturbance tests, and verify the simulation model?
16. How do we prepare disturbance and fine discharges and generalize the test parameters from the tow-sled collector and miner/collector vehicle?
17. How much room do we leave in environment test planning for unidentified deep-sea questions?
18. How do we integrate the test data of bottom disturbance with other effects?

The following questions would also affect the engineering design and have not yet been addressed. For example:

1. What will be a likely mining system or systems in next 20 years that can be a basis of environmental tests? It is difficult to specify "commercial-scale" now but should assume instead, because commercial system size and type are likely different depending upon the

use of nodule elements and can vary with metal market situation.

2. How do we generalize the test parameters from the tow-sled collector and miner/collector vehicle?
3. How much room do we leave in environment test planning for unidentified deep-sea questions?
4. How do we integrate the test data of bottom disturbance with other effects in a more environmental friendly mining system design and operations?

Conclusions

Since, offshore mining may become essential in order to replenish the mineral resources for industrial development in future, steps should be taken to arrive at such design parameters that the mining operation will cause least possible damage to the marine environment. Marine biological communities survive in a fragile ecosystem by maintaining a very delicate balance with their environment. The marine environment supports optimum life on every square meter and any sort of major change due to mining operations, could upset the whole marine ecosystem. Time series collection of data on various oceanographic parameters (geological, biological, chemical, physical, meteorological etc.) before, during and after the offshore mining activities will have to be collected to assess the effects of mining as well as in the design of the mining system.

However, the scale of the experiments conducted so far is too small for the potential disturbance caused by a nodule mining system. The time scales for the re-establishment of geochemical and ecological conditions after commercial mining disturbance will be very long, may be in the order of decades. Hence all the results of these experiments cannot be extrapolated to future mining activities. There are many more questions that must be answered and more problems to be solved prior to the commencement of a commercial mining operation. Environment scientists and engineers should form a team in their efforts so as to achieve the ultimate target of recovering minerals from deep ocean with acceptable environmental impacts.

References

- Amos, A. F. and Roels, O.A. (1977). Environmental aspects of manganese nodule mining. *Mar. Pol. Int. Bull.*, 1, pp. 160-162.
- Black, JRH. (1982). "Metals Recovery from Manganese Nodules: A Review of Processing Schemes," in Humphrey, PB, ed, *Marine Mining: A New Beginning*, pp 93-107, Department of Planning and Economic Development, State of Hawaii (USA).
- Brink, AW, and Chung, Jin S. (1980). "Automatic Position Control of a 300,000 Ton Ship Mining Systems," *Proc Offshore Technology Conf*, Houston, 1980; also in ASME Trans. *J Energy Resources Technology*, 1982.
- Brockett, T., and Richards, CZ (1994). "Deep-Sea Mining Simulator for Environmental Impact Studies," *Sea Technology*, August, pp 77-82.

- Burns, RE Erickson, BH Lavelle, JW, and Ozturgut, E (1980). "Observation and Measurements During the Monitoring of Deep Ocean Manganese Nodule Mining Tests in The North Pacific, March-May 1978," NOAA Technical Memo ERL MESA-47, National Oceanic and Atmospheric Administration, Colorado (USA), 63.
- Chung, JS, Schriever, G, Sharma R, Yamazaki, T (2001). Deep seabed mining environment : preliminary engineering and environmental assessment. Proceedings of Int. Symposium on Ocean Mining, Szczecin (Poland), 8-13.
- Chung, S.S. and Tsurusaki, K., 1994. Advance in Deep-Ocean Mining Systems Research. Proc. of the Fourth International Offshore and Polar Engineering Conference, pp. 18-31.
- Desa, E. (1999). Opportunities for offshore minerals exploration in Indian Ocean. Proceedings of Int. Symposium on Ocean Mining, Goa (India), 6-13.
- DOMES (1976). "Summary of the Minutes of the DOMES Mining Industry Meeting," NOAA Pacific Marine Environmental Lab., Seattle, USA, 12 pp.
- Foell, EJ, Thiel, H, and Schriever, G (1990). "DISCOL: A Longterm Largescale Disturbance – Recolonisation Experiment in the Abyssal Eastern Tropical Pacific Ocean," Proc of Offshore Technology Conference, Houston, USA, Paper No. 6328, pp 497-503.
- Fukushima, T (1995). "Overview "Japan Deep-sea Impact Experiment = JET," Proc. of 1st ISOPE Ocean Mining Symp, Tsukuba, Japan, ISOPE, pp 47-53.
- Ingole, B.S; Ansari, Z.A; Matondkar, S.G.P; Rodrigues, N. (1999). Immediate response of meio and macrobenthos to disturbance caused by benthic disturber. Proc. of the 3rd ISOPE – Ocean Mining Symp., Goa (India), Int. Soc. Offshore and Polar Eng., 191-197.
- ISA (1998). "Draft Guidelines for the Assessment of the Possible Environmental Impacts Arising from Exploration of Deep-Seabed Polymetallic Nodules from the Area," Workshop by the International Seabed Authority ISA), Sanya, Hainan, China, 1-5 June 1998.
- Morgan, C. (1981). "Environmental impacts of deep-ocean mining – the importance of manganese". In: R.A. Geyer (Editor) Marine Environmental Pollution (2), Dumping and Mining, Elsevier Oceanography Series, Elsevier, New York, 415-435.
- Nair, S, Mohandass, C.Loka Bharati, P.A, Sheelu, G, Raghukumar, C. (2000). Micro-scale response of sediment variables to benthic disturbance in the central Indian Ocean Basin. Marine Georesources and Geotechnology, 18 (3) :273-284.
- NOAA (1981). "Deep Seabed Mining: Final Programmatic Environmental Impact Statement," National Oceanic and Atmospheric Administration, Washington, DC, Vol. 1.
- Ozturgut, E, Lavelle, JW, Steffin, O, and Swift, SA (1980). "Environmental Investigation During Manganese Nodule Mining Tests in the North Equatorial Pacific, in November 1978," NOAA Technical Memorandum ERL MESA-48, National Oceanic and Atmospheric Administration, Colorado (USA), 50.
- Pearson, J.S., 1979. Ocean Floor Mining, Noyes Data Coprn., N.J. 201.
- Premchand; Jana, R. (1999). "Processing of Polymetallic Sea Nodules - An Overview," Proc. of 3rd ISOPE Ocean Mining Symp, Goa, India, ISOPE, pp 237-245.
- Radziejewska, T (1997). "Immediate Responses of Benthic Meio- and Megafauna to Disturbance Caused by Polymetallic Nodule Miner Simulator," *Proc Int Symp Environmental Studies for Deep-sea Mining, Metal Mining* Agency of Japan, Tokyo, Japan, pp 223-236.
- Schriever, G, Ahnert, A; Borowski, C, and Thiel, H (1997). "Results of the Large Scale Deep-sea Impact Study DISCOL during Eight Years of Investigation," *Proc Int Symp Environmental Studies for Deep-sea Mining, Metal Mining* Agency of Japan, Tokyo, Japan, pp 197-208.
- Sharma, R., (1993). Quantitative Estimation of Seafloor Features from Photographs and Their Application to Nodule Mining. Proc. of Marine Georesources and Geotechnology, Vol. 11, pp. 311-331.
- Sharma, R, and Nath, BN (1997). "Benthic Disturbance and Monitoring Experiment in Central Indian Ocean Basin," *Proc 2nd ISOPE Ocean Mining Symp*, Seoul, Korea, ISOPE, pp 146-153..
- Sharma, R, Nath, B.N., Parthiban, G., Sankar, S.J. (2001). Sediment redistribution during simulated benthic disturbance and its implications on deep seabed mining. Deep-sea Research II, 48, 3363-3380.
- Sharma, R. and Rao, A.S. (1992). Geological factors associated with megabenthic activity in the Central Indian Basin. Prod. of Deep-Sea Research, Vol. 39, No. ¾, pp. 705-713.
- Shirayama, Y (1999). "Biological Results of JET Project: an Overview," *Proc 3rd ISOPE Ocean Mining Symp*, Goa, India, ISOPE, pp 185-190.
- Thiel, H (1991). "Environmental Impact Resulting from Deep-Sea Mining and Risk Assessment," pp. 87-96 in *Law of the Sea at the Crossroads*, R. Wolfrum, Ed. "The Continuing Search for a Universally Accepted Regime," *Proc an Interdisciplinary Symp of the Kiel Institute of International Law*. Veroeffentlichungen des Instituts fuer Internationales Recht an der Universitaet Kiel.
- Thiel, H, Angel, MV, Foell, EJ, Rice, AL, and Schriever, G. (1997). "Environmental Risks from Largescale Ecological Research in the Deep-Sea," EC Report, Bremerhaven, Germany, pp 210.
- Tkatchenko, G, Radziejewska, T, Stoyanova, V, Modlitba, I, Parizek, A (1996). "Benthic Impact Experiment in the IOM Pioneer Area: Testing for Effects of Deep-sea Disturbance," *Int Seminar on Deep Sea-bed Mining Tech*, China Ocean Mineral Resources R&D Assoc., Beijing, China, C55-C68.
- Trueblood, DD (1993). "US Cruise Report for BIE— II Cruise. NOAA Technical Memo OCRS 4, National Oceanic and Atmospheric Administration, Colorado, USA, pp 51.
- Trueblood, DD, Ozturgut, E, Pliipchuk, M, and Gloumov, IF (1997). "The Echological Impacts of the Joint U.S.–Russian Benthic Impact Experiment," *Proc. Int. Symp. Environmental Studies for Deep-sea Mining, Metal Mining* Agency of Japan, Tokyo, Japan, pp 237-243.
- Yamazaki, T, and Sharma, R (2001). "Estimation of Sediment Properties during Benthic Impact Experiments, " *Marine Georesources and Geotechnology*, (in press).
- Zhong, X, He, Z, Shen, Y, Mao, Y, Qu, S, and Li, X (1999). "The Smelting-Rusting Solvent Extracting Process to Recover Valuable Metals from Polymetallic Nodules," *Proc 3rd ISOPE Ocean Mining Symp*, Goa, India, Int Soc Offshore and Polar Eng, pp 227-231