

Chapter 17

Impacts of Up-Coming Deep-Sea Mining

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17.1 Introduction to Deep-Sea Mining

17.1.1 Manganese Nodules and R and D for Mining Technologies

Deep-sea manganese nodules are the first recognized deep-sea mineral resources (Cronan, 1980; Mero, 1965). The deepest of these occurrences are from 4 to 6 km (2.49–3.7 mi) in water depths. The nodules, been found in large quantities at the Clarion-Clipperton Fracture Zones (CCFZ) in the Pacific, have been focused as potential resources for Cu, Ni, Co, and Mn in the next generation (Cronan, 1980; Mero, 1965). For manganese nodules, international consortia conducted some form of tests of prototype mining systems and components in the 1970s (Bath, 1989; Kaufman, Latimer, & Tolefson, 1985; Welling, 1981). However, subsequent progress has been slow down since 1980, due to unfavorable metal-market conditions, which led to the virtual cessation of R&D activities by international consortia since the early 1980s. On the other hand, individual countries have entered the R&D arena since the 1980s as part of their national R&D programs (Herrouin et al., 1987; Hong & Kim, 1999; Muthunayagam & Das, 1999; Yamada & Yamazaki, 1998; Yang & Wang, 1997), because it was necessary to have an original mining technology for getting an exclusive mining claim for manganese nodules in the High Sea Area under the Law of the Sea. Consequently, they got their issued claims from the International Seabed Authority (ISA) as shown in Fig. 17.1 (<http://www.isa.jm/>). The general concept of mining system is shown in Fig. 17.2. Three major components of the mining system are: a mining vessel on sea surface, a lift system with pipe string and buffer, and a seafloor miner. The miner collects the nodules

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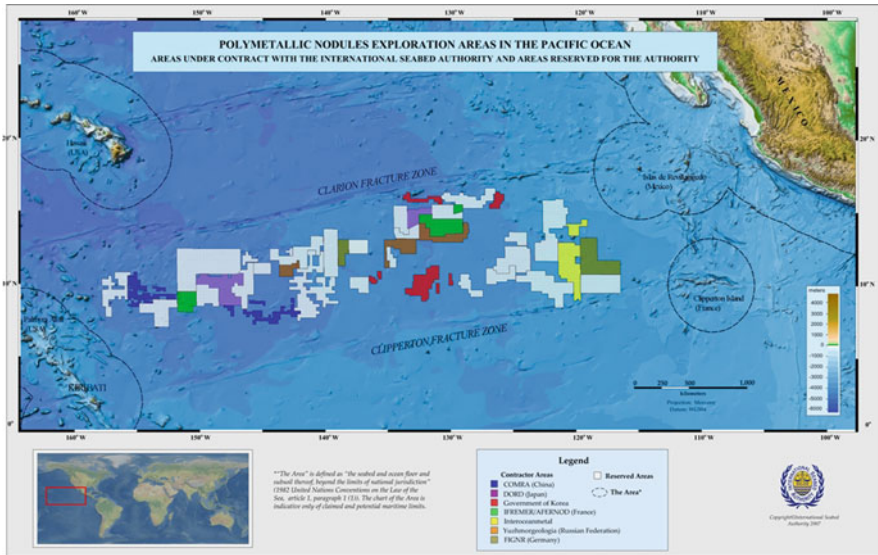


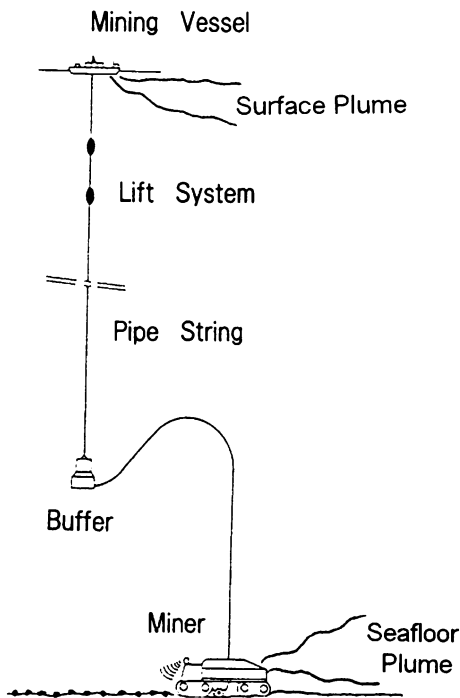
Fig. 17.1 Issued mining claims for manganese nodules from ISA in CCFZ. Note: India has one in the Indian Ocean

half-buried in sediments on seafloor and sends them via the lift system through the feed regulating buffer. A water flow generated by pumps through the pipe string lifts the nodules up to the mining vessel. The assumed production scales of a mining unit in commercial stage ranged from 5,000 to 10,000 t/d in the consortia’s and national R&D studies.

17.2 Outlines for Environmental Impacts Caused by Nodule Mining

Three major sources of in-situ environmental impacts are expected during the manganese nodule mining. They are direct miner tracking on seafloor, a seafloor plume created by discharged sediments from the miner, and a surface plume created by discharged sediments and water from the mining vessel as shown in Fig. 17.2. On the seafloor, a huge amount of deep-sea sediments is recovered with nodules by the miner (Yamazaki, Tsurusaki, & Handa, 1991). Most of the recovered sediments are separated from the nodules and discharged from the miner immediately. They make the sediment-water mixture, suspended near the seafloor as a sediment plume, and then settled on the seafloor again finally. Severe damage of seafloor benthos may occur with the direct miner tracking and the resedimentation, because the benthos is expected to be very weak. The sediment deposition rate is too quick compared with the one under the natural condition. It then shuts down the feed supply to the benthos and covers the seafloor like a very large blanket.

Fig. 17.2 Schematic image of manganese nodule mining system and the environmental impact sources



17.2.1 Environmental Impact Studies for Nodule Mining

17.2.1.1 DOMES

A pilot investigator of environmental impacts caused by manganese nodule mining was U.S. The Deep Ocean Mining Environmental Study (DOMES 1972–1981) Project, which was carried out by the National Oceanic and Atmospheric Administration (NOAA) in CCFZ, was only one pioneer systematic study of the environmental impacts. Three DOMES reports, which included an environmental baseline study (Ozturgut, Anderson, Burns, Lavelle, & Swift, 1978) and two environmental monitoring results of the nodule mining tests (Burns, Erickson, Lavelle, & Ozturgut, 1980; Ozturgut, Lavelle, Steffin, and Swift, 1980), were published. The monitoring was completed during two of the pilot-scale mining tests conducted by Ocean Mining Inc. and Ocean Mining Associates in 1978 in the Pacific Ocean. The concentrations of particulates in the discharges, and assessed the biological impacts on the surface, as well as benthic plumes were measured. Because no other monitoring of surface discharge during mining tests has been conducted since then, the results still have current value as being of interest. Post-mining monitoring of the deep-sea environment was investigated with the Scripps Institute of Oceanography in 1983 in the DOMES area. No change was found in the benthos from the observation and samplings (Spiess, Hessler, Wilson, & Weydert, 1987).

17.2.1.2 DISCOL

The Disturbance and Recolonization Experiment in a manganese nodule area of the Deep South Pacific Ocean (DISCOL) was started in 1988 by a German group. The numerical and biological analyses are both very important and interesting (Schriever, 1995; Thiel & Forschungsverbund Tiefsee-Umweltsschutz, 1995; Zielke, Jankowski, Sündermann, & Segschneider, 1995), though the disturbance scale created by a towed plough in 1989 was very small. The group observed the disturbed area in 1996, 7-years after the disturbance and found that still some impacts remained on the benthos (Bluhm, 1999; Schriever, Ahnert, Borowski, & Thiel, 1997). These results summarized some important proposals necessary for the environmental assessments of future commercial deep-sea mining activities (Thiel, Angel, Foel, Rice, & Schriever, 1998).

17.2.1.3 NOAA-BIE

The Benthic Impact Experiments (BIE I&II, 1991–1995) were conducted by NOAA in CCFZ under cooperation with Russia. After baseline studies in a pre-selected area, the Deep-Sea Sediment Resuspension System-DSSRS (Brockett & Richards, 1994) was used 49 times in an area of $150 \times 3,000$ m ($492 \times 9,842$ ft). The post-disturbance sampling with CTD, sediment traps, and core samples indicated changes in the faunal distribution in the area. The impact assessment after 9 months indicated that, while some of the meiobenthos showed a decrease in abundance, the macrobenthos showed an increase in their numbers, probably because of increased food availability (Trueblood, Ozturgut, Pilipchuk, & Gloumov, 1997). However, the project was stopped in 1995 and the complete results have not yet reported.

17.2.1.4 JET

In Japan, an environmental impact research on manganese nodule mining was initiated in 1989 (Kajitani, 1997). Following 5 years of planning and baseline studies of the environment in and around the Japan's mining claim in CCFZ, the Japan Deep-sea Impact Experiment (JET) was conducted in 1994 under cooperation with NOAA using DSSRS (Yamazaki & Kajitani, 1999). The detail is introduced in the following paragraph.

17.2.1.5 IOM-BIE

A benthic impact experiment (IOM-BIE) was conducted by the Interoceanmetal (IOM) Joint Organization in the Pacific Ocean's CCFZ in 1995, using DSSRS. In all, 14 tows were carried out on a site of $200 \times 2,500$ m ($656 \times 8,202$ ft) and the impacts were observed from deep-sea camera tows and sediment samples (Kotlinski & Tkatchenko, 1997). No significant change was observed in meiobenthos abundance and community structure in the re-sedimented area, but alteration in meiobenthos assemblages within the disturbed zone was observed (Radziejewska,

1997; Radziejewska & Modlitba, 1999). This finding indicates that the intensity of disturbance and the proximity to the site could have variable effects on the composition of the faunal assemblages. The review of baseline data and benthic impact experiment were reported (Radziejewska, Szamałek, & Kotlinski, 2003).

17.2.1.6 INDEX

The National Institute of Oceanography (Goa, India) conducted the Indian Deep-sea Environment Experiment (INDEX) for the Department of Ocean Development (Government of India) in 1997 in a pre-selected area in the Central Indian Ocean Basin after a detailed baseline study during 1995–1997. The DSSRS was used 26 times in an area of $200 \times 3,000$ m ($656 \times 9,842$ ft) (Desa, 1997). Post-disturbance impact assessment studies indicated vertical mixing of sediment, lateral distribution of suspended particles, and differential effects on microbial, meio and macrobenthos both inside and outside the disturbance track (Ingole, Ansari, Matondkar, & Rodrigues, 1999). The post experiment monitoring results after 5 years were reported by Sharma et al. (2003).

17.3 Detail of Japan's Research in Nodule Claim

17.3.1 Baseline Studies

For surface water column, 0–200 m (0–656 ft) in depth, CTD profiling, plankton and water sampling were conducted at every degree of latitude between 5°N and 15°N along the 147°W longitudinal line. The depths of thermoclines, species and sizes of phyto- and zooplankton, and nutritive salt concentrations were also examined (Kajitani, 1997).

For the bottom water column, 0–50 m (0–164 ft) in height above seafloor, current profiling was conducted and background sedimentation rates were measured. For deep-sea sediment layers, physical and chemical properties, and the abundance of benthos and bacteria were clarified (Kajitani, 1997). A sediment core sampler, multiple-corer (MC), originally developed for the German study, was used and the effectiveness for surface sediment layer was certified. The corer installed eight sub-core tubes, 95 mm (3.74 in) in inner diameter and 610 mm (24 in) in length, into the frame. In the meiobenthos, the size ranges 32–300 μm in deep-ocean area was found to be a good indicator of benthos with MC sampling; the background abundance was also clarified (Shirayama & Fukushima, 1997a).

17.3.1.1 JET

An artificial near seafloor sediment plume was created in August 1994 with DSSRS; it was a kind of model collector called “disturber.” The schematic arrangement is summarized in Fig. 17.3. The disturber recovered 352 tons of deep-sea sediments

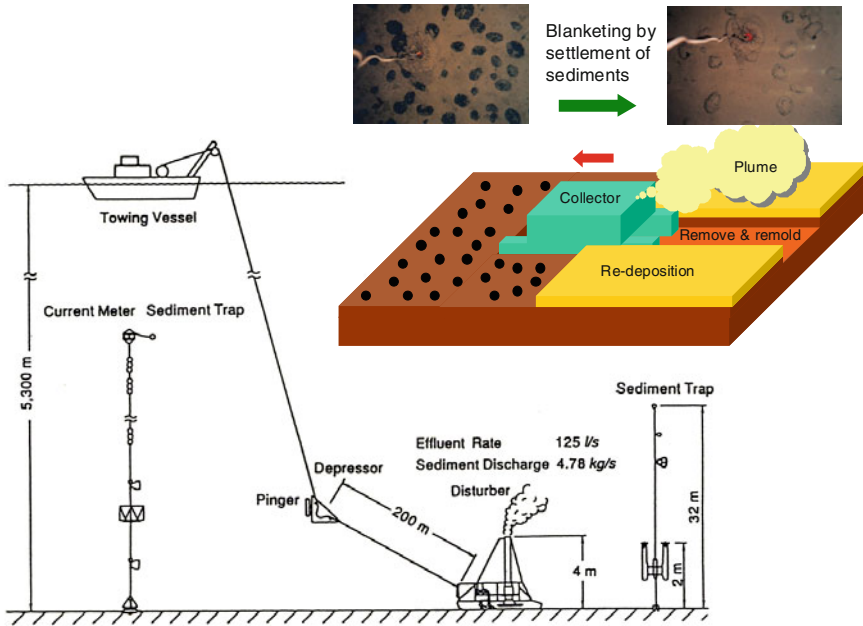


Fig. 17.3 Schematic arrangement of JET

in dried weight during a 20 h-and-27 min operation and flushed them out from a chimney-like duct pipe (Barnett & Yamauchi, 1995). Twelve mooring systems around the tow zones were deployed based on the pre-measured near-bottom current profile. The re-suspended sediments were collected in sediment traps and the current speeds and directions were measured by current meters in the mooring systems during the experimental period (Fukushima, 1995).

Pre-experiment observation (J1) was conducted a few weeks before the experiment to determine background conditions of the experimental area and the ambient seafloor. Samplings of deep-sea sediments for biological, chemical, and physical analyses by MC were the main operations in the period. Thirteen trials were there in the test site. Post-experiment observation was separated into three periods such as just after the experiment (J2), about 1 year after (J3), and about 2 years after (J4). The observation efforts concentrated on the sediment samplings and inspections of the seafloor via a camera system, because monitoring of the benthos covered by the resedimentation was considered to be the most important in these periods. An example of a seafloor photo of the disturber track is shown in Fig. 17.4. Fourteen, 12, and 12 were numbers of the sampling trials in J2, J3, and J4 respectively.

17.3.2 Evaluation of Impacts

The resedimentation was analyzed using three methods. Using the data from the mooring systems and an interpolation method, the areal distribution was calculated



Fig. 17.4 Disturber track

2.5 km (1.55 mi) long and 1 km (0.62 mi) wide, and the maximum thickness 2.6 mm (0.1 in) in re-disposition (Barnett & Suzuki, 1997).

To increase data points for an analysis of the resedimentation, an image analytical technique was developed and applied to the seafloor photos (Yamazaki, Kajitani, Barnett, & Suzuki, 1997). The areal distribution was estimated approximately 3 km (1.86 mi) long and 2.5 km (1.55 mi) wide. It also showed that the heavy resedimentation area, which was thicker than 0.26 mm (0.01 in), was within 100 m (328 ft) of the towed tracks. The extent of the resedimentation area calculated by a computer simulation to qualify the dispersion analysis of re-suspended sediments agreed with these analyses (Nakata, Kubota, Aoki, & Taguchi, 1997). The average thickness of the deep-sea sediment layer recovered by the disturber was calculated to be about 50 mm (2.36 in) from the recovered weight and a stereo photogrammetric analysis (Yamazaki et al., 1997).

A quick decrease in the abundance of resedimentation in the meiobenthos community just after the experiment (J2) in the areas and in the recovery about 2 years after (J4) are summarized from J1 to J4 observations by Shirayama and Fukushima (1997b).

17.3.3 Scale Consideration of Experiment

The thickness of deep-sea sediment layer recovered by a commercial scale collector was calculated at 57 mm (2.24 in) based on vertical profiles of vane-shear strength and sensitivity of the layer, and 1 kPa of nodule pick-up resistance (Yamazaki et al., 1991). The volume of sediments recovered by the collector and discharged on the

seafloor was estimated at 54,000 m³/d from the recovered thickness, 10,000 t/d nodule production rate in wet condition, and 10 kg/m² nodule abundance in wet conditions in the calculation (Yamazaki & Sharma, 2001). The total volume of recovered sediments by the disturber was calculated at about 1,400 m³ based on sampling results of discharged water-sediment mixture content from the disturber, discharged rate of the disturber, the total operation time, and about 80% water content of the sediments in-situ (Yamazaki & Sharma, 2001). Thus, the volumetric scale of discharge in JET was only 2.6% of the daily one in 10,000 t/d production rate of commercial mining.

17.4 Japan's Further Research in Seamount Area

17.4.1 DIETS

Because the disturber was towed fewer times than originally planned in JET, it failed to create as dense a tracking zone as expected. The post-experiment core samples were only collected from the resedimentation area, and no data at all were obtained related to the direct destruction of the ecosystem that occurred in the running tracks of the nodule collector. Therefore, a separate experiment was needed to analyze the impact of such activity on the seafloor ecosystem.

In another attempt to gather appropriate data, an artificial impact experiment that focused on analyzing the direct destruction of benthos occurring in the running tracks of a nodule collector was conducted in a terrace on the same seamount where the nodule collection test had taken place in the southeast region of Marcus Island in 1999 (Yamazaki, Kuboki, & Matsui, 2001). The experiment was called DIETS (Direct Impact Experiment on Seamount). The depth was 2,200 m (7,218 ft), and the nodule population was 15 kg/m² in the terrace. A towed system called a “scraper” was used in DIETS. The outline of the scraper tow operation is summarized in Fig. 17.5. The nodules and sediments along the track were removed and piled with the tow in accordance with the system design.

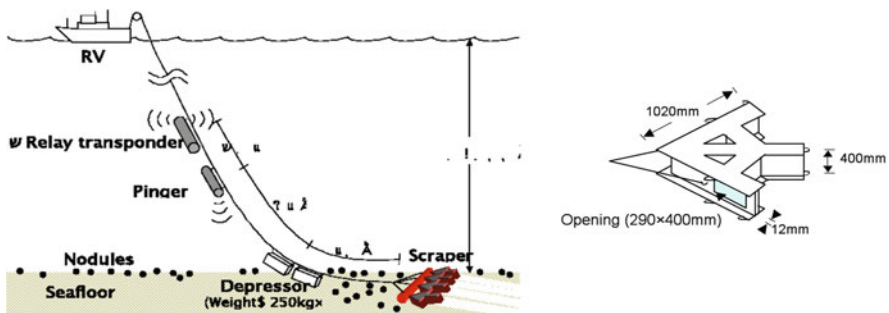


Fig. 17.5 Outline of scraper tow (left) and the unit configuration (right)

Because the Differential Global Positioning System for the R/V navigation and the Long Base Line underwater acoustic positioning method deployed with the bottom transponders in advance of the scraping on the seafloor were used in DIETS, the position accuracy of the scraper on the seafloor was presumed to be about 10 m (32.8 ft). The length of one tow was scheduled to be 700–1,000 m (2,297–3,281 ft). A dense tow zone of 100 m (328 ft) in width and 200 m (656 ft) in length was set up to make the post-experiment sediment core sampling easy from the places where the nodules had been removed, and a total of 15 tows was planned for this area. That is, if each tow was 6 m (19.68 ft) wide with no overlapping, the width of scraping totals 90 m (295 ft). Even when the tows overlapped an average of 50% of the scraper width, 67.5 m (221 ft) in total or two-thirds of the zone width was covered with the piling. Therefore, the probability of effective sampling from the direct destruction area with MC increased.

17.4.2 Post-experiment Observation and Sampling

Successful scraping was confirmed from the seafloor observations as shown in Fig. 17.6. The horizontal extent and the thickness of the resedimentation created by DIETS were detected approximately 200 m (656 ft) to the north and 240 m (787 ft) to the south from the dense tow zone and 0–0.18 mm (0–0.70 in) for increase of sediment cover on nodules, respectively. These were measured by applying an image analysis technique of seafloor photos developed for quantification of resedimentation (Yamazaki, Kuboki, & Uehara, 2001). The extent was quite smaller than the one created in JET. The functional differences between the scraper and the disturber, and the size differences of the two sediments, were considered the main reasons.

The removal of the top surface sediment layer and the impacts and recovery were clearly detected from some sediment core analysis data (Ohkubo & Yamazaki,

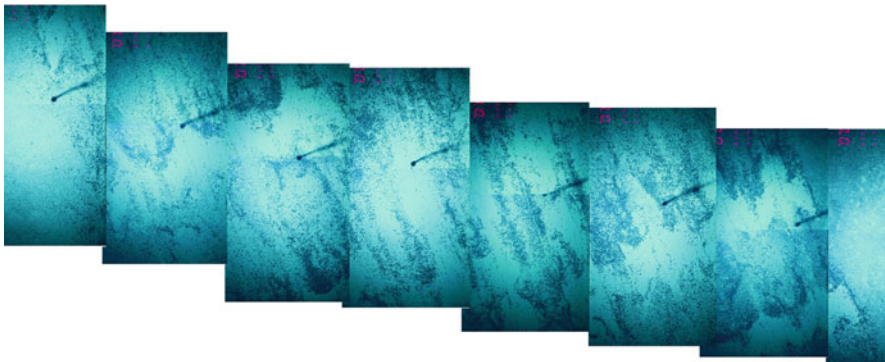


Fig. 17.6 Observed image of scraper tow tracks

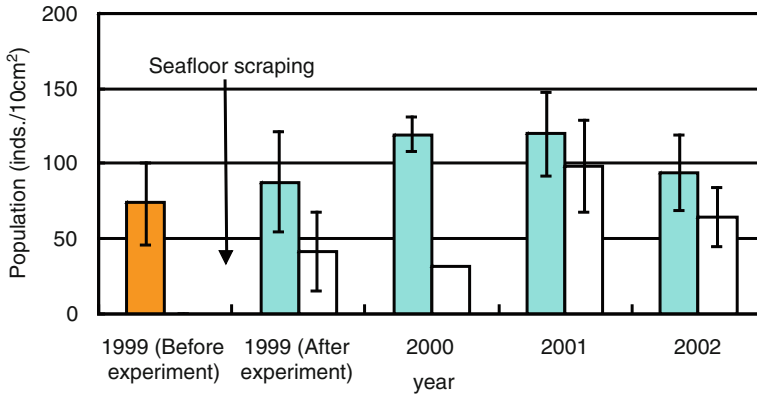


Fig. 17.7 Population change of meiobenthos before and after experiment

2003). The water content profiles showed that the top surface sediment layer (1–2 cm (0.39–0.78 in) deep), in which the water content of background is quite high, was cut and taken away. The removal is also recognized from the biological analysis as summarized in Fig. 17.7. Background population of meiobenthos, mainly composed of nematode, was 70/10 cm² in the DIETS site. The population, immediately and 1 year after, decreased drastically in the nodule removed locations. However, 2 years after, it increased more than the level of background. The reasons of these changes are suggested as follows:

- Initially the meiobenthos in the top sediment surface layer is the richest part in population and is removed with sediments and also destroyed. The reduction in the population is observed in this stage.
- They return from the surrounding area and/or breeding of the remaining ones occurs. The increase in the population is observed in this stage.

The overshooting more than the background level in meiobenthos was also observed in the post-experiment monitoring of JET (Shirayama, 1999). The timing was the same, 2 years after the experiment. However, this occurred in the resedimentation area. The 2 years might be a necessary duration for the reproduction at meiobenthos level from destroyed and dead organisms in the benthic ecosystem. From this viewpoint, much of the amount of dead organisms was considered the reason of the overshooting.

17.4.3 Numerical Modeling

Numerical modeling in this research is classified into two parts. The first one was to revise the diffusion model used for the seafloor plume dispersion, re-settlement, and resedimentation in the previous program. Data obtained during NOAA-BIE

(Trueblood et al., 1997) were introduced into the model and some trial calculations were conducted for the improvement (Doi, Nakata, Kubota, & Aoki, 1999). The model with wider applicability was finally developed.

The second effort one was to create a benthic ecosystem model and to combine it with the seafloor plume diffusion and resedimentation model. The ecosystem model was created based on a carbon mass balance in the bottom layer. Then a series of preliminary test calculations under the resedimentation and the direct destruction conditions were conducted introducing the JET and DIETS data, respectively.

17.5 Expected Environmental Impacts Caused by Seafloor Massive Sulfide Mining

17.5.1 *Seafloor Massive Sulfide Mining*

Kuroko-type seafloor massive sulfides (SMS) in the western Pacific have received as much attention as resources for gold, silver, copper, zinc, and lead for the commercial mining by private companies (<http://www.nautilusminerals.com>; <http://www.neptuneminerals.com>). Since the end of the 1980s, SMS have been found in the back-arc basin and on oceanic island-arc areas at 1–2 km (0.62–1.24 mi) of water depths. The typical representatives found are in the Okinawa Trough and on the Izu-Ogasawara Arc near Japan (Halbach et al., 1989; Iizasa et al., 1999), in the Lau Basin and the North Fiji Basin near Fiji (Bendel et al., 1993; Fouquet et al., 1991), and in the East Manus Basin near Papua New Guinea (Kia & Lasark, 1999) as shown in Fig. 17.8. The higher gold, silver, and copper contents in one of the areas have increased the likelihood that mining would be profitable, and a pioneer commercial mining venture is scheduled to start in 2012–2013 (<http://www.nautilusminerals.com>). The planned production scale is 6,000 t/d. The mining system is a similar one like manganese nodules in Fig. 17.1 except the miner and the discharge point of lifted sediments and water. The miner is necessary to add cutting and crushing functions for the SMS ore body. The lifted sediment and water are planned to return to the bottom via pipeline and those discharged near the seafloor.

17.5.2 *Ecosystem Around Seafloor Massive Sulfides*

A unique large biomass ecosystem has been found around active hydrothermal vents (<http://www.whoi.edu/oceanus/viewArticle.do?id=2420>). They are *Beggiatoa*, *Calypptogena*, *Bathymodiolus*, tubeworms (*Riftia pachyptila*), amphipods, copepods, snails, shrimps, crabs, sea urchins, sponges, and fishes. All SMS in the western Pacific mentioned above are accompanied by many active hydrothermal vents. The primary productions in the ecosystem are sulfur oxidation using hydrogen sulfide supplied from the venting water and immobilization. The filamentous, colorless

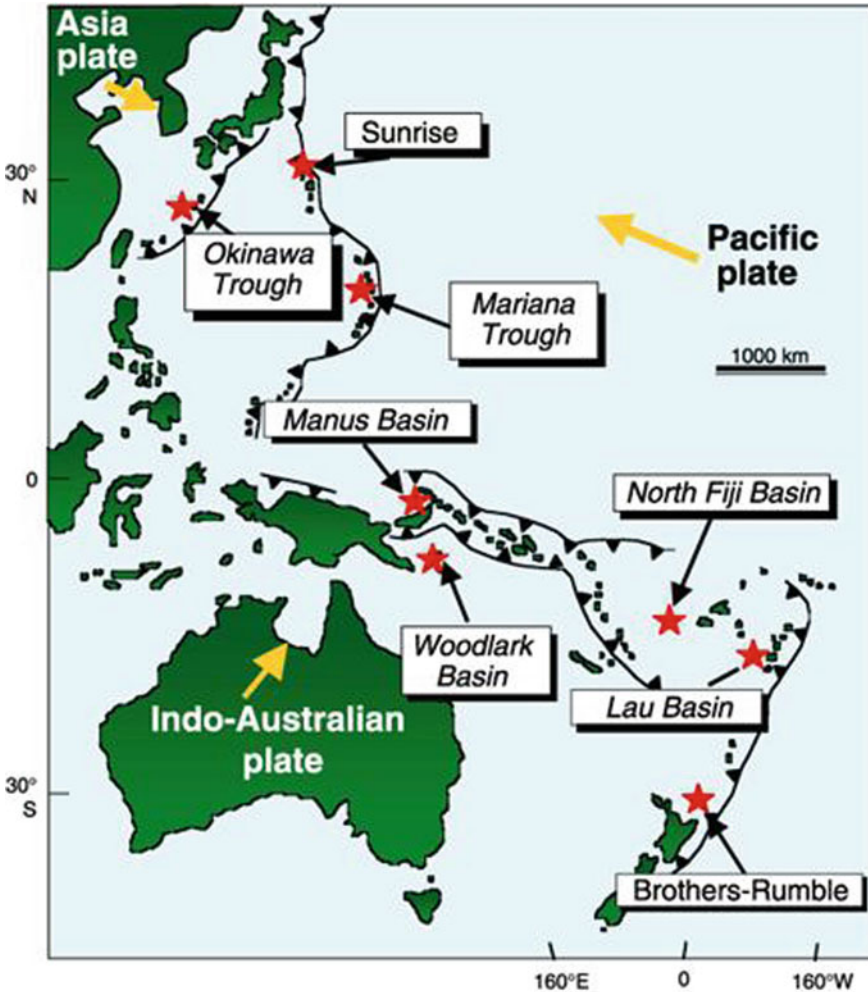


Fig. 17.8 Distribution of known active SMS sites in the western Pacific

sulfur oxidizing bacteria *Beggiatoa* spp. often grows abundantly on top of sulfide-rich sediments. They are found around hydrothermal vents throughout the world's oceans, and may form mats on marine sediments ranging in size from a few millimeters to several meters (Fenchel & Bernard, 1995). *Calyptogenia* spp., which harbors sulfur oxidizing bacteria in their gills, is thought to be sustained by chemosynthetic energy sources under immobilization. *Bathymodiolus*, and tubeworms (*Riftia pachyptila*), have the same functions like *Calyptogenia*. They are either found adjacent to hydrothermal vents and *Beggiatoa* fields. The mass balance in the bacteria mat and the bivalve fields are illustrated in Fig. 17.9. Only the function of chemosynthetic sulfur oxidation is considered in this figure. The mass balance ecosystem

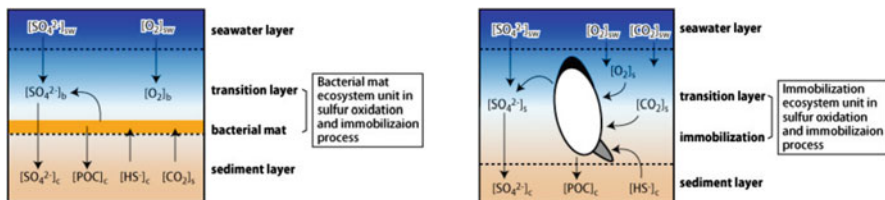


Fig. 17.9 Structural outline of sulfur oxidizing in bacterial mat field (left) and bivalve field (right)

model of chemosynthetic sulfur oxidation around natural cold seepages has been created (Takeuchi et al., 2007). The model is also applicable for hydrothermal chemosynthesis.

The other animals found around active hydrothermal vents, such as amphipods, copepods, snails, shrimps, crabs, sea urchins, sponges, and fishes, are the secondary species categorized as the chemosynthesis-affected ecosystem on the organic carbonate creation with the chemosynthetic members (<http://www.pmel.noaa.gov/vents/nemo/explorer/concepts/chemosynthesis.html>). The food web structure around hydrothermal vent is illustrated in Fig. 17.10 and is compared with the one in normal benthos. Because of additional primary production from the chemosynthesis, the biomass around the hydrothermal vent is quite richer than the one in normal benthos.

17.5.3 Expected Environmental Impacts Caused by SMS Mining

Both the direct destruction of the ecosystem that occurred on and in the SMS ore body to be extracted and recovered, and the blanketing of the ecosystem in the surrounding area of the SMS ore body with the resedimentation of fine particles separated from the SMS ore, are the expected environmental impacts caused by the SMS mining on the seafloor. Not only the active hydrothermal vents, but also the sites,

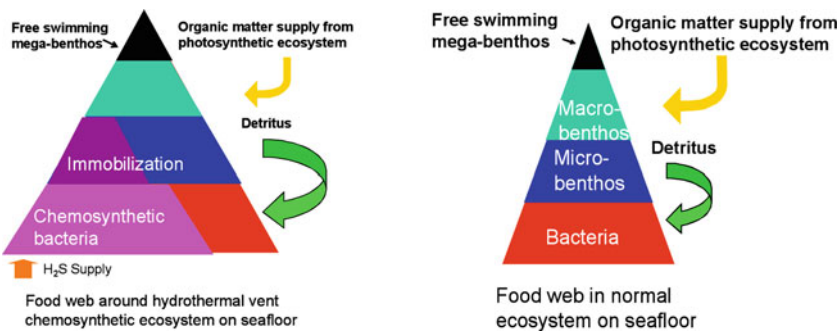


Fig. 17.10 Comparison of food web structures around hydrothermal vent (left) and in normal benthos (right)

where small chemosynthetic communities are present, are recognized as dangerous zones for the seafloor miner. The vents and the sites have active hydrothermal flux routes through fissures and/or faults and high temperature and high corrosive water may be increased and/or induced with the mining activity. The miner's robotic control mechanism and sensors are too weak against the high temperatures though it is 40–50°C (104–122°F). The high corrosive atmosphere is also not good for hardware on and around sea floor. Thus, no direct destruction of chemosynthetic community is expected. However, the direct destruction of the chemosynthesis-affected ecosystem and the blanketing of the chemosynthetic community, the chemosynthesis-affected ecosystem, and the normal ecosystem are expected.

17.5.4 Environmental Assessment of SMS Mining

Because the chemosynthetic communities around hydrothermal vents are unique and different from the normal ecosystem, the quantitative distribution and abundance data are necessary for baseline analysis. The data on the chemosynthesis-affected ecosystem are necessary, too. However, at present only many scientific and biological studies, such as the chemosynthesis mechanism and DNA analyses, are available in the literature. Therefore, a baseline survey from the chemosynthetic community on the active hydrothermal vent near the target mining site, through the chemosynthesis-affected ecosystem in the transition zone to the normal ecosystem far away from the mining site, are required.

As learned from some previous research mentioned in the previous paragraph is that an artificial impact experiment and the post experiment monitoring are both necessary for a deeper understanding the SMS mining impacts on seafloor ecosystem. A small scale extraction and recovery of the SMS ore body such as a pilot or trial mining test is a good chance to evaluate the mining impacts. Both the direct destruction of the ecosystem and the blanketing of the ecosystem must be monitored at least a few years after the experiments. Because of the richer biomass around active vents and continuous hydrogen sulfur supply, the recovery rates of the chemosynthetic community and the chemosynthesis-affected ecosystem are expected to be quicker than the ones observed in manganese nodule areas. However, the actual observation data are necessary and the recovery rate of the surrounding normal ecosystem is impossible to expect. In addition to the biological and physical phenomena, some chemical impacts on the ecosystem may occur, because the SMS ore itself contains many metals. Thus it must also be clarified through the experiment and the monitoring.

On the basis of the understanding of the baseline conditions, a numerical ecosystem model around hydrothermal vents should be developed that includes the chemosynthetic community, the chemosynthesis-affected ecosystem, and the normal ecosystem. By applying the experiment and the monitoring data, the model will be improved to simulate the mining impacts and the recovery process. Thereafter, the model is used as an effective tool for expecting scale-upped mining impacts and for assessing environmental impacts with proposed deep-sea mining.

17.6 Economic Impacts on Metal Markets

17.6.1 *Economy of Deep-Sea Mining*

On the basis of the R&D efforts that examine the potential markets for manganese nodules, the economic feasibilities of the mining venture in CCFZ (Andrews, Flipse, & Brown, 1983; Charles, Herrouin, Mauviel, & Bernard, 1990; Hillman & Gosling, 1985) and the inside of Cook Islands EEZ (Soreide, Lund, & Markussen, 2001) were evaluated. The conditions and results are summarized in Table 17.1. Another feasibility for deep-sea mining of the Red Sea sulfide mud at about 2 km (1.24 mi) of water depth was examined (Amann, 1985; Nawab, 2001). All these old results suggested less economic attractiveness of the deep-sea mining.

Referring to the previous feasibility studies on capital costs and applying the economic parameters for operating costs, some economic potential analyses of mining manganese nodules, cobalt-rich manganese crusts, and SMS for Japan have been conducted (Yamazaki, 2007; Yamazaki & Park, 2005; Yamazaki, Park, Shimada, Iizasa, & Shiokawa, 2003; Yamazaki, Park, Shimada, & Yamamoto, 2002). The studies conclude SMS mining might be economically attractive.

In February 2008, ISA held a Workshop on Polymetallic Nodule Mining Technology – Current Status and Challenges Ahead in Chennai, India. An updated manganese nodule mining venture model was discussed and created with many experts in mining technology, metallurgical processing, and economy being present. Based on the model, applying current economic parameters, the economies of nodule mining were re-evaluated and opened to public via the ISA homepage (<http://www.isa.org.jm/files/documents/EN/14Sess/LTC/ISBA-14LTC-3.pdf>). It included an updating of the construction costs of mining system and a metallurgical processing plant in 2007 as the most important components of any re-evaluation. The results, 14.9–37.8% in IRR (Internal Rate of Return), highlighted a larger interest in manganese nodule mining.

17.6.2 *Metal Markets*

World metal production in 2006 and the abundance of metals in the earth's crust are shown in Table 17.2. It is realized the most unbalanced popular metal in the production versus the abundance is copper from Table 17.2. Comparing the planned metal productions from manganese nodule mining in Table 17.1 with the world production in Table 17.2, it is recognized a few cases the values of cobalt and manganese are more than 5% of the market demands. These are no good situations in keeping the metal prices high enough for a new mining venture.

In case of the coming SMS mining, the planned metal productions are considered acceptable and smaller than the market demands. On the basis of the production rate and the metal contents of SMS mining announced in the web (<http://www.nautilusminerals.com>), and assuming the total metal recovery ratios in

Table 17.2 World metal production and abundance in earth's crust

Metal or product	World production in 2006 (metric ton)	Abundance in Earth's crust (ppm in weight)
Platinum	518	0.01
Mercury	1,480	0.08
Gold	2,460	0.004
Silver	20,200	0.07
Cobalt	67,500	25
Molybdenum	185,000	1.5
Tin	366,000	2
Magnesium	584,000	23,300
Nickel	1,580,000	75
Lead	3,470,000	12.5
Zinc	10,000,000	70
Copper	15,100,000	55
Manganese ore	33,400,000	950
Aluminum	33,700,000	82,300
Steel	123,000,000	56,300

Remark: Manganese ore contains about 40% manganese (Source of production data: http://minerals.usgs.gov/minerals/pubs/commodity/statistical_summary/myb1-2006-stati.pdf
Source of abundance data: Geological handbook, Heibon-sha, Tokyo, Japan)

ore-dressing and metallurgical processing as 95%, the expected metal productions from the first commercial mining are estimated to be about 128,000 t/y in copper, 14,000 t/y in zinc, 12 t/y in gold, and 63 t/y in silver. These values are the maximum results from one mining unit. All the productions are less than 1% of the market demands. These have less effect on metal prices.

17.7 Summary Remarks

Through 37 years of research on the environmental impacts caused by manganese nodule mining, much important knowledge on this mining and other deep-sea mining possibilities have been accumulated. The deep-sea baseline survey, the benthic impact experiment, the post experiment monitoring, and the numerical modeling are all recognized as the important components for the environmental assessment of deep-sea mining.

In summary, the following environmental impacts for deep-sea mining are:

1. Careful and sufficient benthic baseline data accumulation is required to evaluate their variations of fluctuation;
2. Developing a benthic ecosystem model as an effective tool to evaluate the quantitative ecosystem reaction against environmental impacts caused by an artificial disturbance (mining operations);
3. A benthic impact experiment is necessary to improve the ecosystem model;

4. Scale and rate viewpoints of the benthic impact experiment against the actual exploitation are necessary in order to apply the ecosystem model as a part of any quantitative environmental assessment, and.
5. Quantitative environmental guidelines and assessments are also helpful for the developer of deep-sea mineral resources, because satisfying the present guidelines and assessments are clear and fair.

Some uncertainties will always remain in understanding the benthic ecosystem. Though the deep-sea ecosystems are different from place to place, international collaboration in establishing standard approaches and methods for the needed environmental assessment is necessary.

From the economic feasibility studies conducted on manganese nodules and the seafloor massive sulfide mining, the more attractive choice today is considered the seafloor massive sulfide mining especially in the current metals' economies and impacts on the markets for metals.

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