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Combined Mining and Pulp-Lifting of Ferromanganese Nodules and Rare-Earth Element-Rich Mud around Minamitorishima Island in the Western North Pacific: A Prefeasibility Study

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Abstract: An examination of the technical and economic feasibility of the combined mining of the rare-earth element-rich mud (REE-rich mud) and ferromanganese nodules (FN) around Minamitorishima (Marcus) Island in Northwest Pacific is introduced. A previous study showed that the mining of REE-rich mud around Minamitorishima Island was not economically feasible. Therefore, in this study, three changes from the previous mining model to improve its economy are proposed. The first one is combined mining with FN in the area. The second one is introducing a pulp-lifting system that can lift both REE-rich mud and FN at high concentrations through a riser pipe. The third one is the reuse of waste mud and processed slag for construction materials. The economic evaluation results show a change from a slightly negative to quite positive economy depending on the mixing ratio of REE-rich mud and FN in the pulp-lifting. In addition, some technical approaches necessary to realize the combined mining method are introduced.

Keywords: deep-sea mining; pulp-lifting; ferromanganese nodule; rare-earth element-rich mud; western North Pacific

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1. Introduction

The presence of deep-sea rare-earth element-rich mud (REE-rich mud) in the Pacific seafloor which involves high contents of rare-earth elements was reported in a previous study [1]. Two areas with high contents of REE-rich mud in the range of 500–1500 ppm, such as off Hawaii in the northeastern equatorial Pacific and off Tahiti in the southeastern Pacific, were pointed out. The authors of the paper also suggested the areas' potential as locations of rare-earth element resources. Several feasibility studies were conducted on the mining of these elements [2–4]. However, because of the presence of an overlaid sediment layer that is several tens of meters thick with poor rare-earth element contents of less than 500 ppm, the results showed that the mud's 500–1500 ppm potential was not great enough for the mining to be economical. One paper [2] proposed an in situ chemical concentration for improving the economy. In 2013, another higher content area was found by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) near Minamitorishima (Marcus) Island in the Japanese exclusive economic zone (EEZ) [5]. In this area, there are rare-earth element-rich layers with 5000–6500 ppm contents within 10 m below the seafloor, which is 5600–5800 m deep. The distribution aspects of this area and its potential as a rare-earth element resource have been reported in detail [6,7]. The feasibility of mining REE-rich mud in the area using ferromanganese nodule (FN) mining technologies was examined by Yamazaki et al. [8]. The results showed a negative economy. In this study, FN mining technologies, including feasibility studies and metallurgy, were reviewed as the basis of the combined mining of REE-rich mud and FN, and the mining model and the results of the economic evaluation are presented.

2. FN and Research and Development Approaches to Mining

Many scientific, technical, and economical publications are available on FN, mostly because they are considered the primary commercial target in deep-sea mineral resources [9,10]. The geological distribution characteristics have been studied in detail by numerous researchers [11–14]. However, very little detailed information on the first mining target areas in the Clarion-Clipperton Fracture Zone (CCZ) was available even in the 1990s [15,16], though the international consortium had authorized their sites in US domestic law [17] and the Pioneer Investors with the International Seabed Authority (ISA) were placed there as contractors [18]. Without enough information, basic geological and geophysical factors had to be assumed in some previous economic feasibility studies on the development [19–21]. An economic feasibility study on cobalt-rich FN inside the Cook Islands EEZ [22] stood out, because the high cobalt content in FN and a mechanical lift were assumed in the mining model. The results of these four feasibility studies are summarized and compared in Table 1. Because the market demand for manganese in the 1980s and 1990s was only 40% of that in 2019 [23], the manganese recovery from FN mining was not considered in some economic analyses [20,22]. The price reduction in the market due to the large amount of manganese supplied by FN mining was thought not to recover the additional metallurgical processing cost.

Table 1. Summarization and comparison of earlier economic feasibility studies for ferromanganese nodule (FN) mining [19–22].

Authors Processing method	**Andrews et al. [19] Reduction and Hydrochloric Acid Leach Process**			**Hillman and Gosling [20] Cuprion Ammoniacal Leach Process**			**Charles et al. [21] Reduction and Hydrochloric Acid Leach Process**			**Søreide et al. [22] High-Temperature & High-Pressure Sulfuric Acid Leach Process**		
Subsystem (condition)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)	Mining (wet)	Trans. (dry)	Process. (dry)
Production (t/y)	2.3 M	1.5 M	1.5 M	4.2 M	3.0 M	3.0 M	2.3 M	1.5 M	1.5 M	1.1 M	0.7 M	0.7 M
Operation days	300 d/y	300 d/y	330 d/y	300 d/y	300 d/y	330 d/y	250 d/y					
Capital expenditure (CAPEX)	$180M	$176M	$513M	$590M	$310M	$727M	$282M	$188M	$470M	$127M	$93M	$271M
CAPEX ratio	21%	20%	59%	36%	19%	45%	30%	20%	50%	26%	19%	55%
Equity/Loan	100/0			100/0			50/50			30/70		
Operating expenditure (OPEX)	$45M	$25M	$165M	$77M	$37M	$111M	$48M	$36M	$156M	$21.8M	$13.5M	$22.9M
Loan interest	0%			0%						8%		
Survey cost	$6M			$3M						$1.9M		
OPEX ratio	19%	11%	70%	34%	16%	50%	20%	15%	65%	38%	23%	39%
Metal	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**	**Price**	**Recovery**	**Product**
Co	$5.5/lb	85%	3375 t/y	$8.53/lb	65%	5070 t/y	$6.8/lb	85%	3525 t/y	$20/lb	83%	2652 t/y
Ni	$3.75/lb	95%	18,525 t/y	$3.62/lb	92%	36,708 t/y	$3.6/lb	95%	19,730 t/y	$3.33/lb	98%	2548 t/y
Cu	$1.25/lb	95%	15,675 t/y	$1.17/lb	92%	28,704 t/y	$0.95/lb	95%	17,810 t/y	$1/lb	97%	1890 t/y
Mn	$0.4/lb	93%	404,550 t/y				$0.3/lb	93%	382,500 t/y			
Taxes	46%			Total 29%						10%		
NPV										−81M		
IRR	6.4%			7.4%			12%			9.6%		

The first stage of research and development (R&D) activities for FN mining was conducted by the international consortium in the 1960s and 1970s [24–26]. Though some of the consortium's technological results were reported [27–32], most of the technically important data and results remain secret. The second stage was followed by several national projects [21,33–37]. Many publications were available from the national projects and other studies regarding seafloor FN miner design [38–42], the hydraulic lifting characteristics of FN in a pipeline [43–47], and the hydro-dynamics of the pipeline [48–52]. Among the national projects, ones conducted by China, India, Korea, and InterOceanMetals are still active.

Some important results and reviews of FN metallurgical processing have also been reported [53–59]. Most of the proposed processing methods were examined in Kojima [56], and the smelting and chlorine leaching method (SCL) was concluded to have an advantage in the study, though its cost was relatively higher than that of some hydro-metallurgical methods because of its waste-free characteristics.

The specifications of mining 5000 t/d in dry conditions, the transportation and the metallurgical processing systems, and the capital and operation expenditures (CAPEX and OPEX) of FN production were discussed in the ISA workshop in Chennai, India, in 2008. About 50 specialists in FN mining technologies, metallurgical processing, economy, and international law of the sea attended. The ISA controls all mineral resources-related activities in the international seabed area by law. Mining and metallurgical processing methods and cost analysis models were presented at first, then three working groups related to the mining technology, the metallurgical processing, and the economic model were created and the working groups reviewed the past published R&D results and models. At the end of the workshop, CAPEX, OPEX, and methods for mining, transportation, metallurgical processing, and model selection in the working groups were reported. Four mining methods with different collectors and risers and one processing method with hydrometallurgy were included in the report. The four mining methods involved using (a) a passive collector, (b) a tracked collector, (c) a Chinese collector with a steel riser pipe, and (d) Indian small tracked collectors with flexible risers. Applying the results of the workshop, the results of the economic feasibility analyses, including manganese recovery conducted after the workshop, were distributed to the attendees of the workshop [60]. Only the summary was open to the public [61]. Though updated distribution models of the CCZ have been presented by the ISA in the last ten years [62,63], no effective economic feasibility study has been undertaken.

3. Previous Economic Evaluation of REE-Rich Mud Mining

In the previous study [8], a production scale of 4000 t/d for REE-rich mud in dry conditions was assumed. Among the specifications for the mining, the transportation, the metallurgical processing systems, and CAPEX and OPEX for 5000 t/d of FN production in dry conditions in the ISA workshop report [60], the same tracked collector and lift sub-systems for FN were assumed as the ones for REE-rich mud. The CAPEX and OPEX for a larger production scale of FN than the ones for REE-rich mud were thought to cover some additional expenditures for REE-rich mud sub-systems. On the other hand, the mining vessel and many of the onboard facilities were newly examined and roughly designed in the study. Additionally, an acid leach and solvent separation process similar to that of Abe et al. [3] was assumed in the rare-earth element recovery. The similarities and differences between FN and REE-rich mud mining assumed in the study are summarized in Table 2. Though the mud excavator is different in terms of the nodule collector and the depth is more than that in the ISA model, all the CAPEX and OPEX of the system components such as excavator, riser, and pump and some of the onboard facilities were assumed to be the same as in the ISA model for the tracked collector and lift sub-systems. If the water content of REE-rich mud is assumed to be 66.7%, roughly estimated value from photos the core samples, the bulk density becomes about 1.5 g/cm^3. Because of the high cohesiveness of REE-rich mud, the spatial concentration in the riser is kept similar to that in the ISA model. Thus, the daily production of REE-rich mud in the same mining system with the ISA model becomes about 4000 t/d in dry conditions under a 40,000 m^3 daily volume of mud and water mixture lifted. The volumetric concentration is 6.67%. Because the mining site is in an open ocean area and close to equator, the total operation days per year were assumed as 250 days from the data used for the Japanese FN collector test near Minamitorishima Island [35]. The thickness of the excavated sediment layer was assumed to be 5 m from the seafloor and the average rare-earth element content was assumed to be about 2000 ppm.

Table 2. Similarities and differences between rare-earth element-rich mud (REE-rich mud) and FN mining.

Item	REE-Rich Mud	FN
Water depth	5600–5800 m	about 5000 m
Seafloor excavation	Hydraulic cut and suction	Hydraulic suction
Lift	Pump hydraulic in riser	Pump hydraulic in riser
Dewatering	Settlement and dry-up	Separation and dry-up
Transport	2000 km by cargo carrier to Japan's main land	2000–5000 km by cargo carrier to North America
Processing	Acid leach and solvent separation	Hydro-metallurgy

The mining vessel herself and many of the onboard facilities were assumed to be different from those of the ISA model. The most important point in the design of the onboard facilities is how to concentrate the mud and water mixture. The easiest and cheapest method for concentration is gravity settling in a tank. Because REE-rich mud is classified into silty clay from a water depth of 5600 to 5800 m, it is difficult to achieve gravity settling. However, the cohesion of clayey particles accelerates the settling process [64]. Therefore, the use of a four-tank concentration and dewatering system for 4 days was proposed and assumed. One of the tanks was used for receiving the mud and water mixture on the first day. Then, on the second day it was used for gravity settling for 1 day. The supernatant water was discharged from the tank into the middle water column at a depth of 500 m because no chemical treatment was applied. The water content of the settled REE-rich mud at this stage became about 90% and the specific density is 1.15 g/cm^3. The dry-up dewatering operation was separated into two stages. At first, a moderate temperature of 60–80 degrees in Celsius (°C) was applied to the settled mud for 1 day, then a temperature of 110 °C was used for 1 day in the same tank. The 1-day products stayed in the same tank. It was necessary to install water discharge and dry-up facilities in all the four tanks. Because of these installations, however, mud transfer among the tanks was not necessary. At the end of the concentration and dewatering after 4 days, the dried mud cakes were transferred and stored until they had to be loaded into a transportation vessel. The size of the mining vessel had to be large because of the four tanks, storage area, and other onboard facilities necessary.

Three economic measures calculated in the previous study were the net present value (NPV), the internal rate of return (IRR), and the payback period (PP). Though the rare-earth element prices given in the study were considered to be very expensive ones in 2012 and the waste disposal cost was not included, the results presented were minus $549M in NPV, minus 2.73% in IRR, and N/A in PP. None of these are good values in terms of economy. The main reasons for these values were the use of the large mining vessel, the lower concentration of slurry in the riser, and the lower income from rare-earth element sales.

4. Mining Model: Combined Mining of REE-Rich Mud and FN by Pulp-Lifting

In 2016, a vast FN area of co-distribution with REE-rich mud was found by JAMSTEC near Minamitorishima Island in the Japanese EEZ. The location and nodule distribution aspects were introduced [65]. The area size was expected to be 44,000 km^2 at the time, and updated information for nodule distribution in this area has been reported [66]. The metal contents of FN were similar to those of the cobalt-rich ferromanganese crusts on the Pacific seamounts [67]. The same type of co-distribution area—FN with REE-rich mud—has been found beyond the Japanese EEZ around Minamitorishima Island, and China was authorized a third FN contract in the co-distribution areas next to the Japanese EEZ from ISA in 2019 [68].

Because of the co-distribution, a unique lift method is applicable for the combined mining of REE-rich mud and FN. The method is called pulp-lifting. It was investigated in a French FN R&D program in the 1980s [43]. A non-Newtonian solid–water mixture with a high solid volumetric concentration of 55~60% was created by mixing crushed FN, deep-sea sediments, and water. Then, the mixture was circulated in a 15 m vertical experimental pipeline by a piston pump. Because of the drastic reduction in frictional resistance between the pipe wall and the high-concentration pulp, it was clarified that the pipe diameter would be about half of the one needed for a same-nodule mass transportation under a normal solid–liquid slurry. The pump power necessary was found to be lower than one needed for the same mass transportation one under solid–liquid slurry conditions. Pulp-lifting has never been used in any deep-sea mining programs, but the method is popularly applied for coal–water mixtures (CWMs) in many coal electricity power stations. CWM created by powder coal and water with a mass concentration of about 70% is supplied to a boiler through a pipeline [69].

In the mining model of REE-rich mud and FN proposed in this study, the following assumptions were selected as basic conditions from the reviewed FN mining technologies, including feasibility studies, metallurgy, and other factors:

- Production rate of 6000 t/d in dry conditions in REE-rich mud and 3000 t/d in dry conditions in FN;
- Hydraulic cut and suction for REE-rich mud excavation;
- Hydraulic suction for FN collection then crushing;
- Mixing and pulp-making then feeding to a piston pump;
- Pumping up through a riser;
- Solid volumetric concentration of 55% and seawater concentration of 45% in pulp;
- Water depth of 5800 m;
- Drying lifted pulp then transferring it to carrier vessels;
- Transportation distance of 2000 km from Minamitorishima Island EEZ to the leaching and processing location in Japan's mainland;
- Separation of REE-rich mud and crushed FN;
- Leaching by HCl and solvent extraction with recovery ratios of 24% for Ce and 92% for other rare-earth elements in REE-rich mud [3];
- Brick making by adding cement powder to the leached mud after neutralization and desalting then providing it for construction material free of charge;
- Processing by SCL with recovery ratios of 80% for Mn and 94% for the other three metals in FN [56];
- Processed slag sales as concrete aggregate in 100 $/t;
- Calculating the CAPEX and OPEX of the mining model except for the brick-making and processing using an equation based on ones in the previous study [8]:

$$C_A = C_B \left(\frac{a_A}{a_B} \right)^n \tag{1}$$

  where C_A = the value in this study; C_B = the value in the previous study; a_A = the total mass in this study; a_B = the total mass in the previous study; n = 0.6 scale factor [70].
- Calculating the CAPEX and OPEX of the brick-making on the basis of Tsuji et al. [71];
- Calculating the CAPEX and OPEX of the processing using Equation (1) on the basis of Kojima [56] and Park et al. [72].

One of the most important assumptions is the production rate of 6000 t/d in dry conditions in REE-rich mud. This was calculated from Japan's domestic rare-earth element consumptions and the rare-earth element contents of the REE-rich mud recovered. The production rate of 3000 t/d in dry conditions in FN was selected as half of REE-rich mud. Japan's domestic consumptions of the four metals are quite a lot larger than the masses recovered. Because higher concentrations of REE-rich mud and crushed FN and lower amounts of seawater from the pulp-lifting come up to the mining vessel, everything underwater and the onboard facilities including the vessel herself are smaller than those used the previous studies [3,8,60]. The direct drying of the lifted pulp is also induced from the higher concentrations. The separation of water from the pulp is difficult but the drying process is easy. One more important point is the selection of the metallurgical processing method. The SCL is a waste-free method and the best choice for Japan's social and geographical situation. The slag is reused after smelting for aggregate and the sulfur liquid after the leaching is refreshed and reused for leaching. The CAPEX and the OPEX of the mining system are less expensive, as shown in Table 3. In the recovery of REE-rich mud on the seafloor, it is difficult to remove the overlaid sediment layer with smaller rare-earth element contents. An averaged rare-earth element content from the seafloor surface to the target depth of about 1000 ppm, the same as in Abe et al. [3] shown in Table 4, is assumed in the mining model. For example, the average top 5 m of the sediment column becomes 1000 ppm in the case of 0 ppm from the seafloor surface through to 4 m and 5000 ppm from 4 through to 5 m. The metal contents of FN presented by JAMSTEC [65] and shown in Table 5 are assumed in the mining model. They are cobalt-rich, copper-poor, and nickel-poor, similar to the cobalt-rich ferromanganese crusts on the Pacific seamounts and different from the FN in the CCFZ.

Table 3. Estimated capital and operating expenditures (CAPEX and OPEX) under basic conditions.

	CAPEX ($M)	OPEX ($M)
Mining	179.7	80.7
Transportation	223.8	33.7
Leaching (REE-mud)	198.3	261.9
Brock making	155.6	226.0
Processing (FN)	863.6	110.8
Total	1621.0	713.1

REE-mud: rare-earth element-rich mud; FN: ferromanganese nodule.

Table 4. Element contents in REE-rich mud assumed from Abe et al. [3].

Element	Content (ppm)
Ce	177.9
La	154.0
Pr	46.2
Nd	192.6
Sm	44.9
Eu	11.1
Gd	49.0
Tb	7.3
Dy	45.4
Y	277.2

Table 5. Metal contents in FN assumed from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) [65].

Metal	Content (%)
Ni	0.4
Cu	0.2
Co	0.5
Mn	20.0

5. Economic Feasibility of the Combined Mining of REE-Rich Mud and FN by Pulp-Lifting

5.1. Results of Basic Condition

Data on prices of rare-earth elements are available through paying member sites [73,74]. In this study, based on the 5-year average prices of rare-earth elements in the period 2013–2017 [75] (to exclude the higher ones in 2012), the 10-year average prices of the four metals in the period 2008–2017 [75], the contents in Tables 4 and 5, and their recovery ratios assumed in the mining model, the revenues of the mining model under the basic conditions are calculated as shown in Table 6. It is obvious that the revenues from FN are 4.7 times more than the ones from REE-rich mud under the basic conditions of the combined mining model. In the economic evaluation, the first 3 years are assumed to be devoted to construction with no income, while the fourth year is assumed to be used for test operations with 50% income. Then, the next 16 years, from the 5th year to the 20th year, are assumed to be used for full mining, with 100% income. The total yearly income is calculated as about $780M, because the revenues listed in Table 6 and about $50M from the slag sales are the total. The same three economic measures—NPV, IRR, and PP—are calculated as shown in Table 7. The results show a slight negative economy.

Table 6. Assumed prices and estimated revenues with their production under the basic conditions.

Element and Metal	Price ($/t)	Yearly Revenue ($M)
Ce	15,000	1.2
La	15,000	3.8
Pr	125,833	9.6
Nd	83,333	26.6
Sm	35,000	2.6
Eu	1,500,000	27.6
Gd	100,000	8.1
Tb	1,033,333	12.5
Dy	508,333	38.2
Y	56,666	26.0
Ni	16,121	51.8
Cu	6678	11.3
Co	34,698	155.6
Mn	2463	354.7
Total		729.6

Table 7. Result of the economic evaluation under basic conditions.

NPV ($M)	IRR (%)	PP (year)
−526.7	3.66	15

5.2. Sensitivity Analyses by FN Production Rate

Because the revenues from FN shown in Table 7 have larger effects on economy, sensitivity analyses using the FN production rate are examined. In the analyses, the production of REE-rich mud is fixed as 6000 t/d and the one for FN is increased from 3000 to 7000 t/d. In each of the analyses, CAPEX, OPEX, and the income are recalculated. The results of the NPV are summarized in Figure 1. About 4000 t/d is found as the point of NPV = 0.

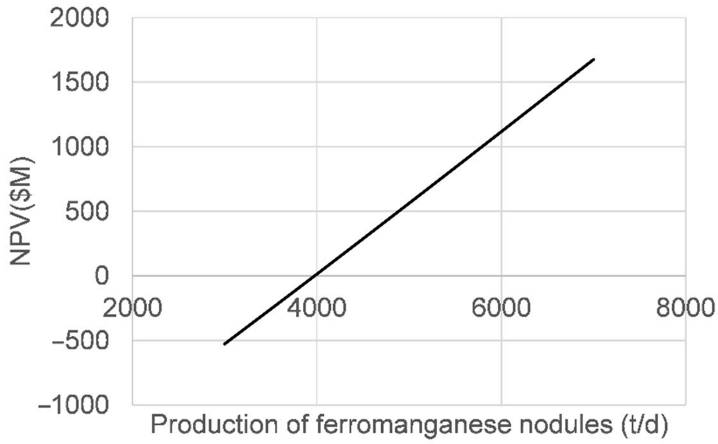


Figure 1. Sensitivity analyses of net present value (NPV) using FN production rates.

6. Expected Geotechnical Characteristics of REE-Rich Mud

Because the water depth, 5600–5800 m, is deeper than the carbonate compensation depth (CCD), REE-rich mud is composed of siliceous particles and classified into pelagic clay. No geotechnical data such as water content and cohesiveness are available to examine technical problems for REE-rich mud excavation on the seafloor. Though some data are available on deep-sea siliceous sediments [76,77], the technical problems expected for the excavation were examined based on the little data available. Example geotechnical properties of siliceous deep-sea sediments in shallow layers are shown in Figure 2 [76] and properties from shallow to deep layers are shown in Figure 3 [77]. Using recovered box-core samples, 50 cm square and 30–40 cm in height, the vane shear strength, sensitivity, water content, and cone penetration resistance were measured in the core column, as shown in Figure 2 [76]. In the vane shear strength and the sensitivity, the relationship is defined by Equation (2) [78]. In Figures 2 and 3, the water content was calculated by Equation (3). The relationships among the geotechnical strength characteristics of clayey sediments are generally given by Equation (4) [79]. Using a recovered gravity-core sample that was 11 cm in diameter and 261 cm in height, measurements of some geotechnical factors were conducted. From these factors, the solid density, bulk density, and water content were calculated, as shown in Figure 3 [77]. From the obtained results shown in Figure 3, the highly cohesive and clayey nature of the gravity-core sample was recognized.

$$S_t = S_{vo}/S_{vr} \tag{2}$$

where S_t = sensitivity, S_{vo} = original undisturbed vane shear strength, S_{vr} = remolded vane shear strength.

$$w = (W_W - W_O)/W_O \times 100 \tag{3}$$

where w = water content, W_w = water-saturated weight in air, W_o = dried weight in air.

$$q_u = 0.2 \times q_c = 2 \times S_{vo} \tag{4}$$

where q_u = undisturbed uniaxial strength, q_c = cone penetration resistance.

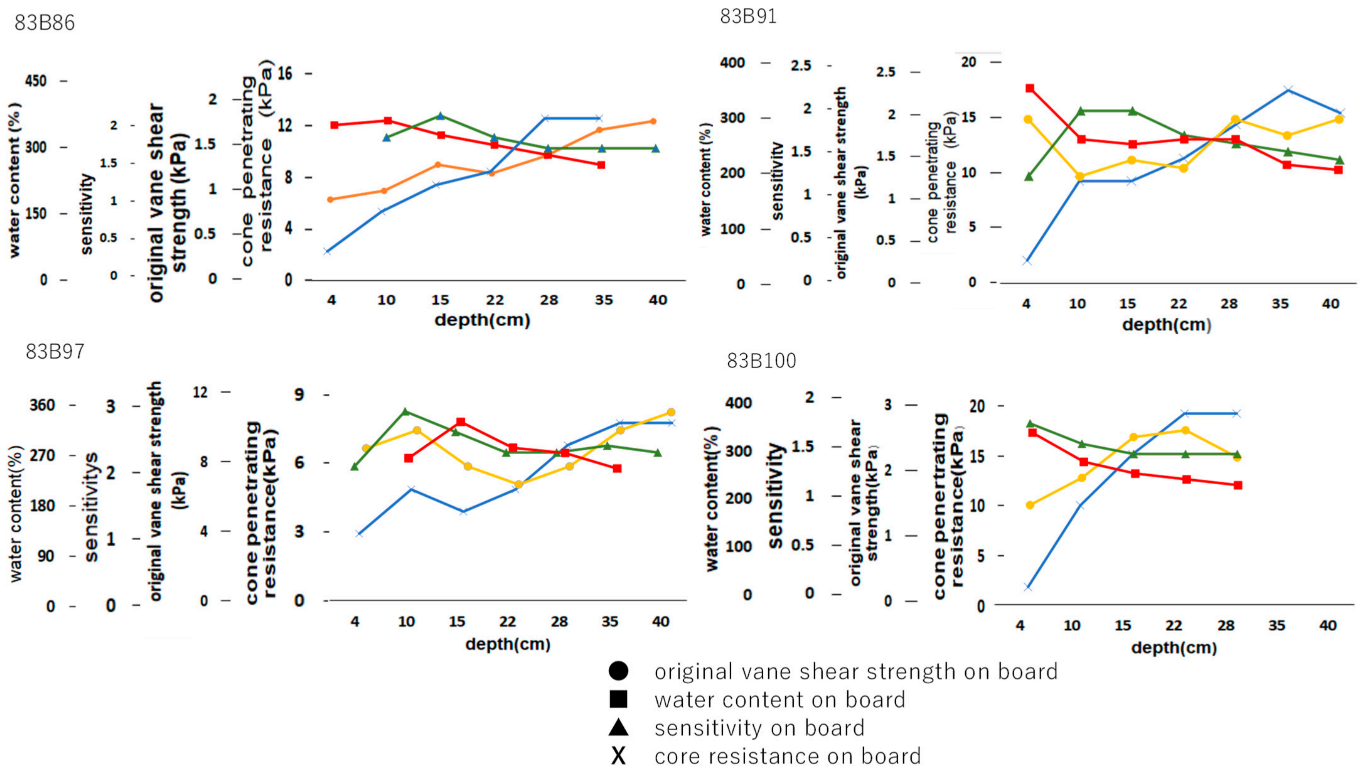
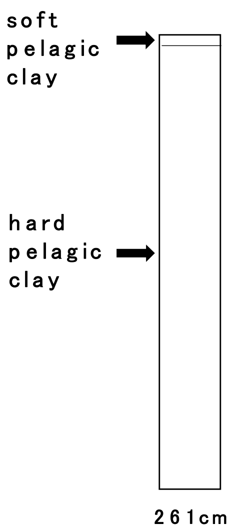


Figure 2. Example geotechnical properties of siliceous deep-sea sediments in shallow layers at Penrhyn Basin, South Pacific, about 5200 m deep [76].



Depth (cm)	Solid density (g/cm³)	Bulk density (g/cm³)	Water content (%)	Cohesion (kPa)	Friction angle (degree)
0–30	2.65	1.13	489	15	3.6
50–80	2.62	1.11	493	12	9.0
100–130	2.62	1.12	396	13	4.4
150–180	2.64	1.17	343	21	10.0
200–230	2.63	1.16	330	18	10.4

Figure 3. Example geotechnical properties of siliceous deep-sea sediments from shallow to deep layers in the Japanese FN contract area in the Clarion-Clipperton Fracture Zone (CCZ), North Pacific, about 5200 m deep [77].

7. Technical Considerations

The solid density of 3.25 g/cm^3 and the porosity of 55% were reported for FN [80]. From these values, the volumetric concentration of about 45% for FN was calculated. From the water contents, 200~350% in Figure 2 and 330~493% in Figure 3, the volumetric concentration of 7~16% is expected for REE-rich mud. The value of 45% for FN is not bad, but the value of 7~16% for REE-rich mud is quite low compared with the one of 55~60% in the French pulp-lifting experiment [43]. To create a good pulp condition, the question of how to reduce seawater in REE-rich mud on the seafloor is considered to be of primary importance. The high cohesiveness of 12~21 kPa in Figure 3 is the secondary problem, but the sensitivity of about 3 in Figure 2 looks to be helpful to reduce the cohesiveness by remolding REE-rich mud during the excavation. The question of how to crush FN and make smaller particles on the seafloor is the third problem. Meanwhile, how to mix REE-rich mud and the crushed FN particles is the fourth problem and how to feed the mixture to a piston pump is the fifth. A good water content of REE-rich mud and a good size distribution of crushed FN for pulp-lifting must be experimentally clarified at first.

The next important is the service lifetime of the riser pipe. From the viewpoint of economy, usually the usage of a steel pipe is assumed in deep-sea mining models [2–4,8,19–21,60,72] and in this study, except in the mechanical lift model [22]. The other technological studies introduced as references in this study are related to the lift conditions in the steel pipe and the pipe dynamics of the steel pipe, except for the studies on metallurgical processing. However, the relatively short time of 2-5 years was reported in the case of the 1700 m water depth and several hundred tons in weight, including a submerged pump under a maximum wave height of 6 m for massive seafloor sulfide mining in Papua New Guinea [81]. In the case of deeper and rough wave conditions for the combined mining of REE-rich mud and FN, a shorter service lifetime is expected. Depending on the lifetime, it should be concluded that there would be greater OPEX for the steel riser pipe. The clarification of this problem is necessary.

Some other technical efforts such as clarifying the brick-making process by adding cement powder to the waste mud and checking the engineering properties of the processed slag as concrete aggregate are also important, because these are key points in their reuse.

After these technical clarifications, a realistic economic feasibility analysis will be conducted. We note that although detailed and useful geological data of REE-rich mud have already been published [82–85], the geotechnical data corresponding to geological variations are not available currently.

8. Mining Area Management Plan

The mining area sizes necessary for the combined mining of REE-rich mud and FN are different. If the average FN population in the co-distribution area is the same as the one in CCFZ—10 kg/m^2 in wet conditions—the population in dry conditions becomes 7.2 kg/m^2 for the solid density and porosity of FN. Under the FN population, 417,000 m^2 per day must be covered for an FN production of 3000 t/d. In case of an REE-rich mud production of 6000 t/d under the mining model and geotechnical characteristics detailed in this study, 4000 m^2 per day must be excavated up to 5 m deep. The area size for REE-rich mud is only about 1% of that for FN. To minimize the horizontal transportation distance, the mining site for REE-rich mud should be placed at the center of the one for FN. The daily mining area management is expected to be similar to that in Figure 4. The area size of the co-distribution of REE-rich mud and FN increased from the first press release value of 44,000 km^2 [65] to the updated value of 70,500 km^2 [66]. From the area size necessary for daily FN mining, about 560 years (under 300 days of operation per year) is the expected lifetime of the combined mining under the basic conditions in the Japanese EEZ around Minamitorishima Island.

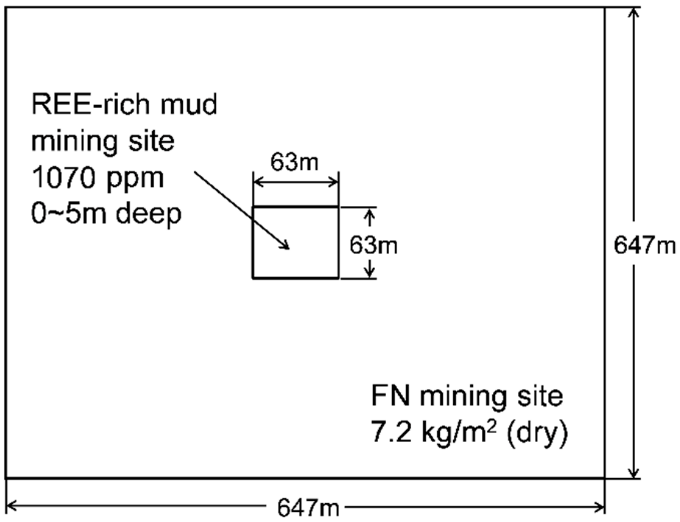


Figure 4. Daily mining area management for the combined mining of REE-rich mud and FN (not in an accurate scale).

9. Concluding Remarks

The area of the co-distribution of REE-rich mud and FN in the Japanese EEZ has a chance to be used for commercial mining. The following three innovative changes in the mining model have improved the economy of the mining:

- Combined mining with REE-rich mud and FN;
- Pulp-lifting;
- Reuse of waste mud and processed slag as construction materials.

The production ratio of 6000 t/d for REE-rich mud versus 3000 t/d for FN is slightly negative in economy. More FN in the pulp concentrates is necessary for a better economy. An appropriate water content of REE-rich mud and a good size distribution of crushed FN for pulp-lifting must be clarified first.

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