Presentation for Workshop on Mining Cobalt-rich Ferromanganese Crusts
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Technological issues associated with commercializing cobalt-rich ferromanganese crusts deposits in the Area

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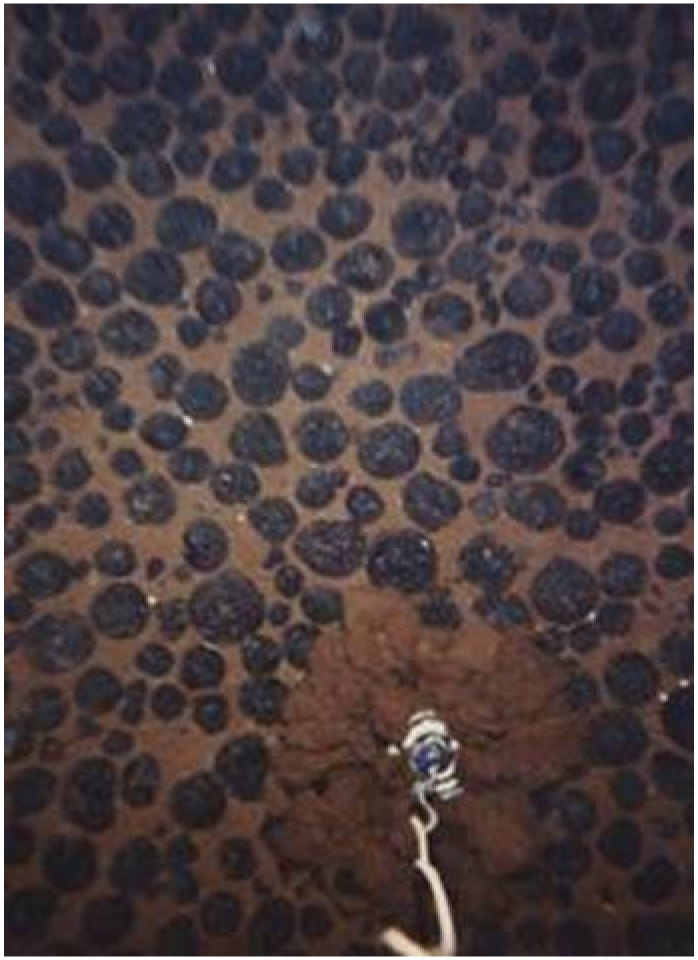
Today's topics:
1. Fundamentals (background and geotechnical properties)
2. Preliminary technical and economic evaluation and analyses
3. Chances for crust mining and problems to be solved

Keywords: Cobalt-rich ferromanganese crust, Economic analysis, Manganese nodule, Microtopography, Mineral dressing, Platinum recovery, Substrate rock, Sensitivity analysis, Technological issue.

Introduction of nodules and crusts

Fundamentals



Manganese nodules
Half buried in soft sediments on ocean floor in about 5,000m deep
Public sea and EEZ

Cobalt-rich manganese crusts
Pavement on substrate rock on seamounts in 800-2,500m deep
EEZ and Public sea

Fundamentals

Previous FS for manganese nodules

- Texas A&M Univ., USA in 1983

Andrews, B. V. et al. (1983). *Economic Viability of a Four-Metal Pioneer Deep Ocean Mining Venture*, US Dept. of Commerce, PB84-122563, 201p.

- Bureau of Mines, USA in 1985

Hillman, C. T., and Gosling, B. B. (1985). *Mining Deep Ocean Manganese Nodules: Description and Economic Analysis of a Potential Venture*, US Bureau of Mines, IC 9015, 19p.

- IFREMER/GEMONOD, France in 1989

Charles, C. et al. (1990). "Views on Future Nodule Technologies Based on IFREMER-GEMONOD Studies," *Materials and Society*, Vol. 14, No. 3/4, pp. 299-326.

- Norwegian group for cobalt-rich nodules in Cook Is. EEZ in 2000

Soreide, F. et al. (2001). "Deep Ocean Mining Reconsidered: A Study of the Manganese Nodule Deposits in Cook Island," *Proc. 4th ISOPE Ocean Mining Symp.*, Szczecin, pp. 88-93.

Fundamentals

Summarization of previous FS for manganese nodule mining

	Soreide et al. (2001) High-Temperature and High-Pressure Sulfuric Acid Leach Process			Hillman and Gosling (1985) Cuprion Ammoniacal Leach Process			Andrews et al. (1983) Reduction and Hydrochloric Acid Leach Process			Charles et al. (1990) Reduction and Hydrochloric Acid Leach Process		
	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)	1.1M	0.7M	0.7M	4.2M 300d/y	3.0M 300d/y	3.0M 330d/y	2.3M 300d/y	1.5M 300d/y	1.5M 330d/y	2.3M 250d/y	1.5 M	1.5 M
Capital cost	127M$	93M$	271M$	590M$	310M$	727M$	180M$	176M$	513M$	282M$	188M$	470M$
Capital cost ratio	26%	19%	55%	36%	19%	45%	21%	20%	59%	30%	20%	50%
Equity/Loan	30 : 70			100 : 0			100 : 0			50 : 50		
Operating cost Loan interest Survey cost	21.8M$ 8% 1.9M$	13.5M$	22.9M$	77M$ 0% 3M$	37M$	111M$	45M$ 0% 6M$	25M$	165M$	48M$	36M$	156M$
Operating cost ratio	38%	23%	39%	34%	16%	50%	19%	11%	70%	20%	15%	65%
Metal Co Ni Cu Mn	Price $ 20/lb $ 3.33/lb $ 1/lb	Recovery 83% 98% 97%	Product 2,652t/y 2,548t/y 1,890t/y	Price $ 8.53/lb $ 3.62/lb $ 1.17/lb	Recovery 65% 92% 92%	Product 5,070t/y 36,708t/y 28,704t/y	Price $ 5.5/lb $ 3.75/lb $ 1.25/lb $ 0.4/lb	Recovery 85% 95% 95% 93%	Product 3,375t/y 18,525t/y 15,675t/y 404,550t/y	Price $ 6.8/lb $ 3.6/lb $ 0.95/lb $ 0.3/lb	Recovery 85% 95% 95% 93%	Product 3,525t/y 19,730t/y 17,810t/y 382,500t/y
Taxes NPV IRR	10% -81M 9.6%			Total 29% 7.4%			46% 6.4%			12%		

Fundamentals

Competitive relationship between nodules and crusts

	Depth	*Location*	*Metals*
Crusts	800-2,500m	Equatorial Pacific	Co: 0.64%
		In- & out-side of EEZ	Ni: 0.50%
			Cu: 0.13%
Nodules	4,000-6,000m	CCFZ in Pacific	Co: 0.20%
		Out-side of EEZ	Ni: 1.44%
		(Sometimes in EEZ)	Cu: 1.12%

- Both are ferromanganese oxides and the metallurgical processing methods are expected to be similar.

- Their mining methods are different depending on the distribution aspects. The crusts is necessary to cut, slice, and fracture before the collection into the miner. Ore dressing process may be necessary to separate the crusts with the substrates before the metallurgical processing.

Purpose of study

Fundamentals

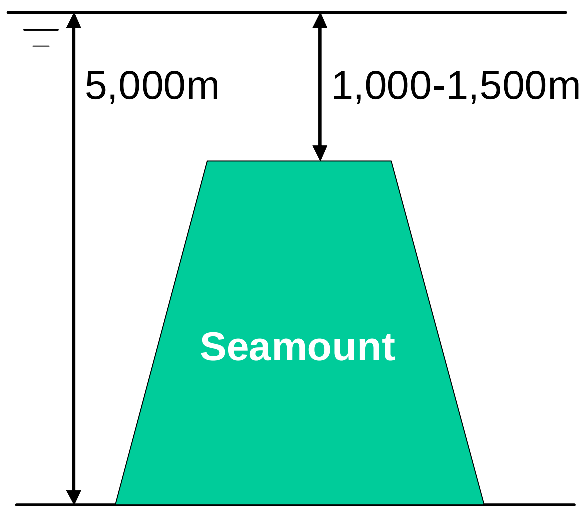
- Because similar metals (Co, Ni, Cu, and Mn) are contained in nodules and crusts, future needs may require that we select one of them.

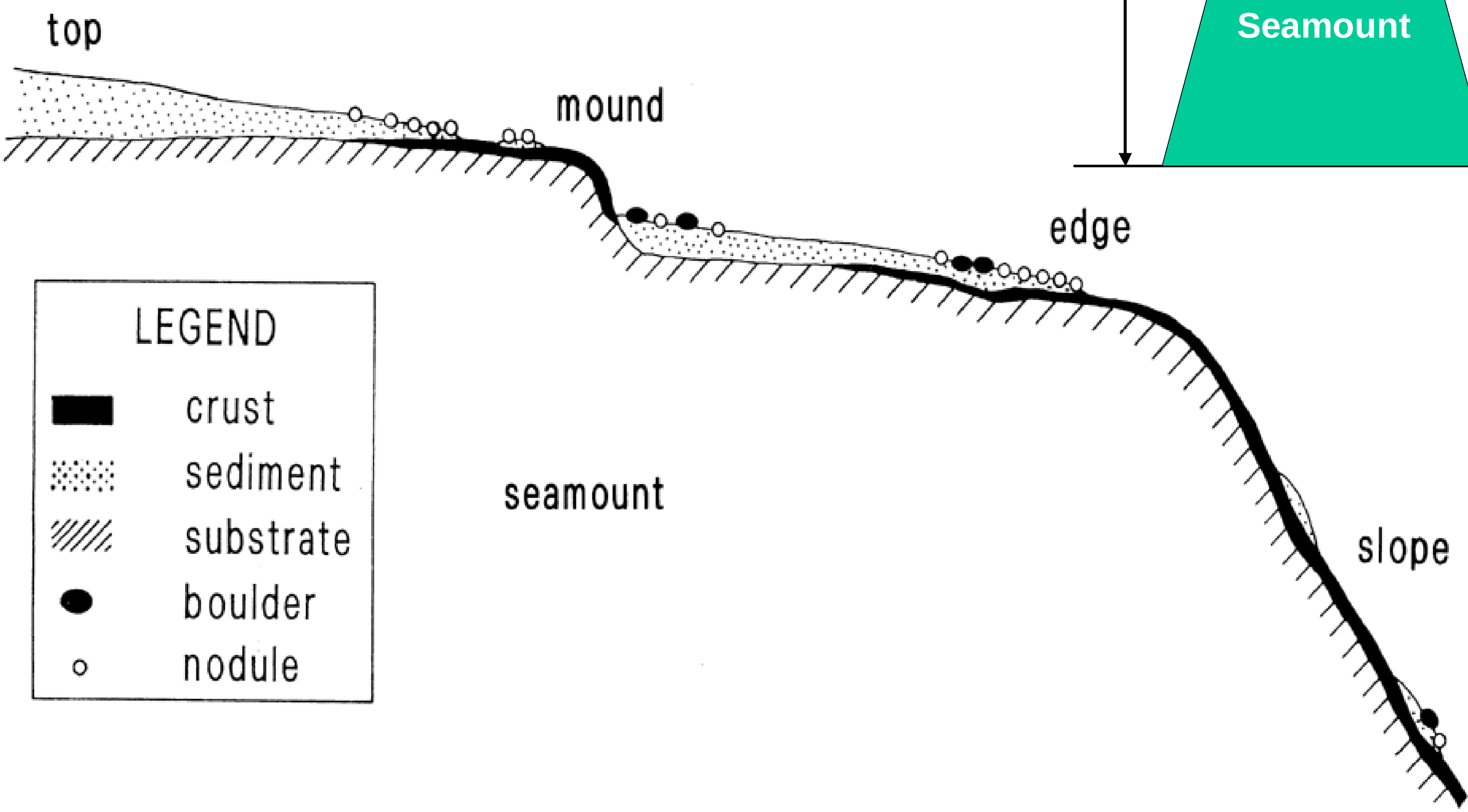
- Economic evaluation method and mining models, that were for examining and comparing the economic potentials of nodules and crusts, were developed by the author on the basis of some previous feasibility reports (Yamazaki et al., 2002). Big differences of the models are towed collector for nodules and self-propelled miner for crusts, and ore dressing subsystem only for crusts.

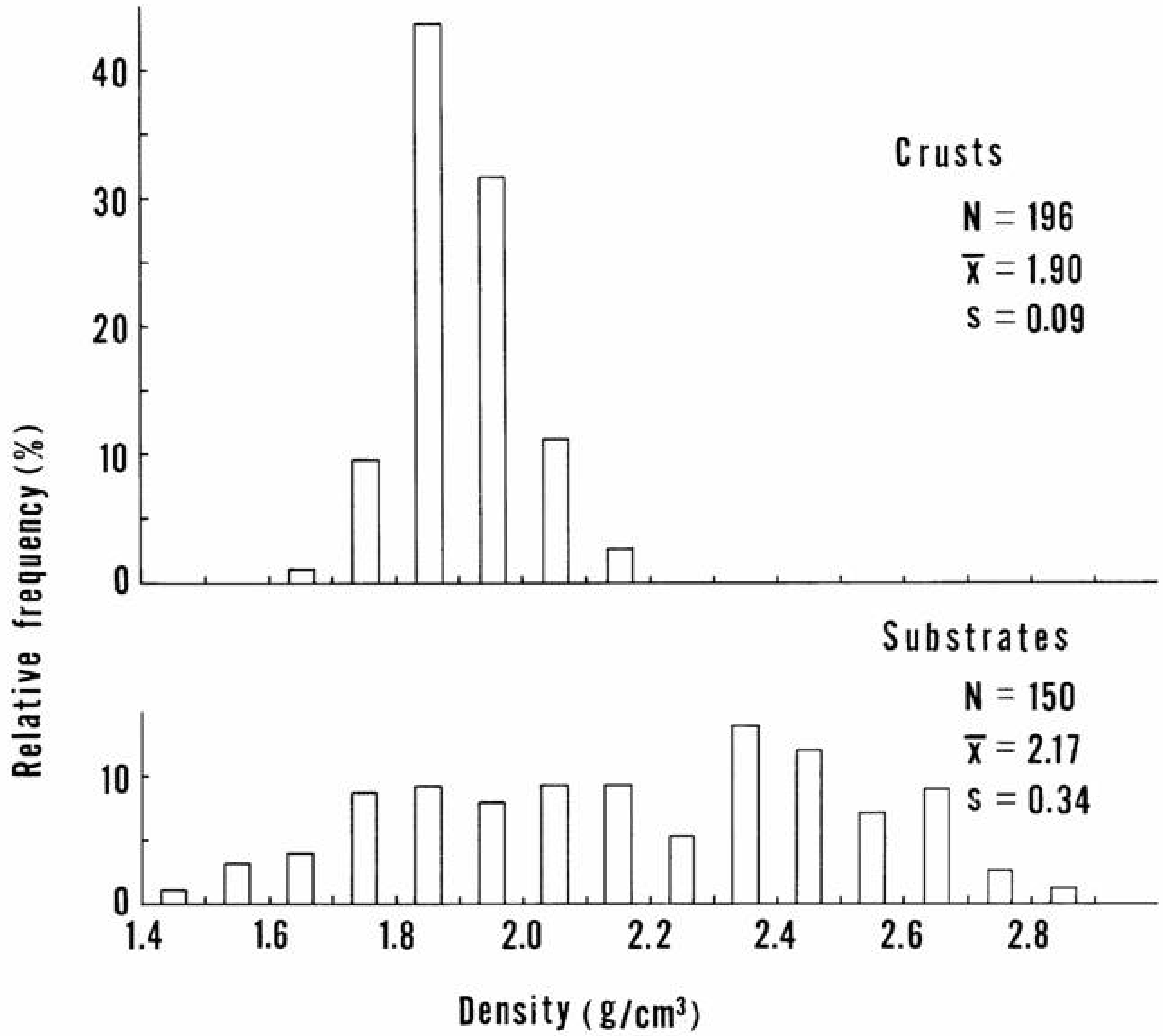
- Using the method and model, series of sensitivity analyses to clarify advantages and disadvantages of the crust mining are conducted.

- Less technical information is available for crusts. The definite economic evaluation is impossible.

Schematic distribution aspect of cobalt-rich manganese crusts

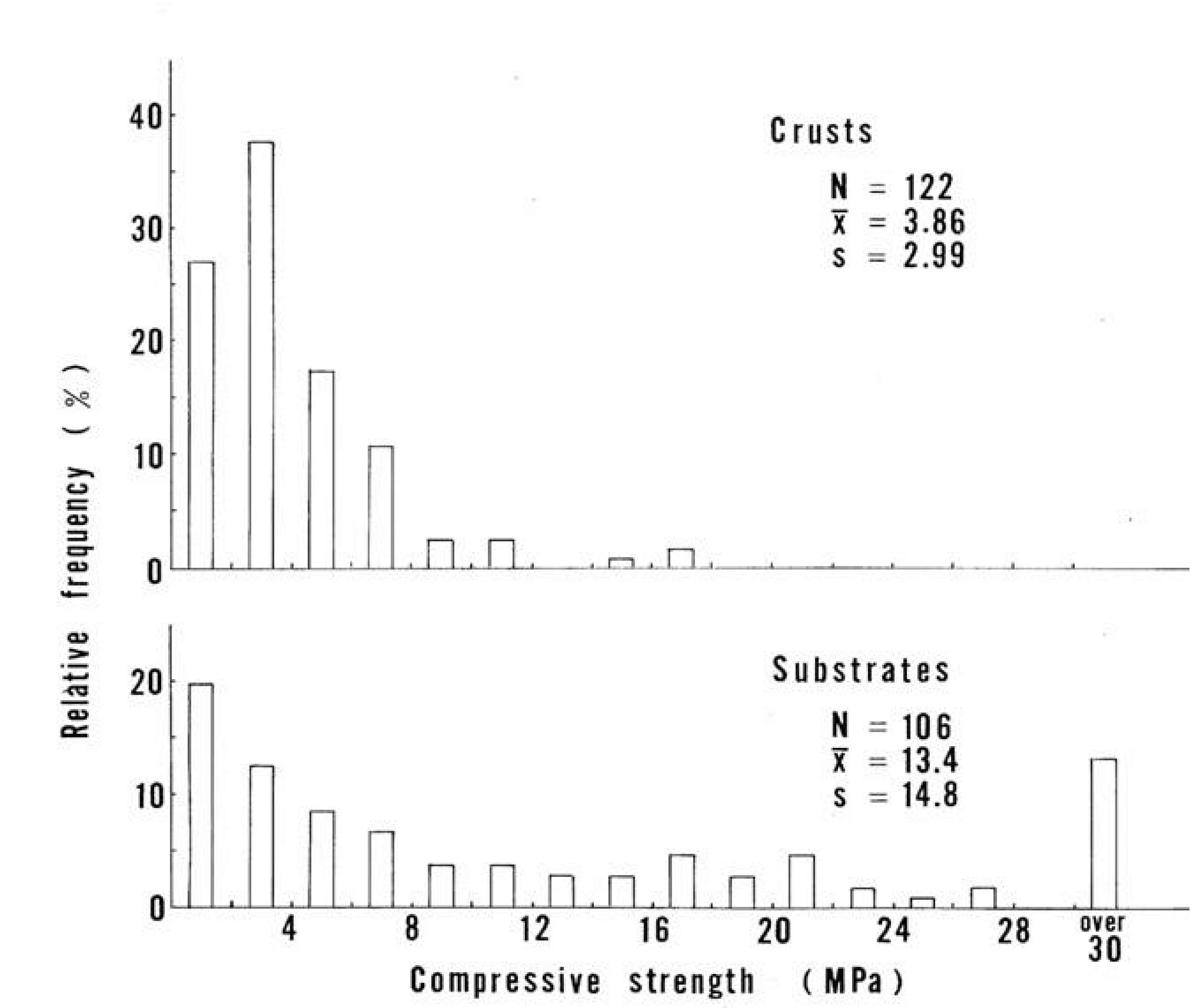




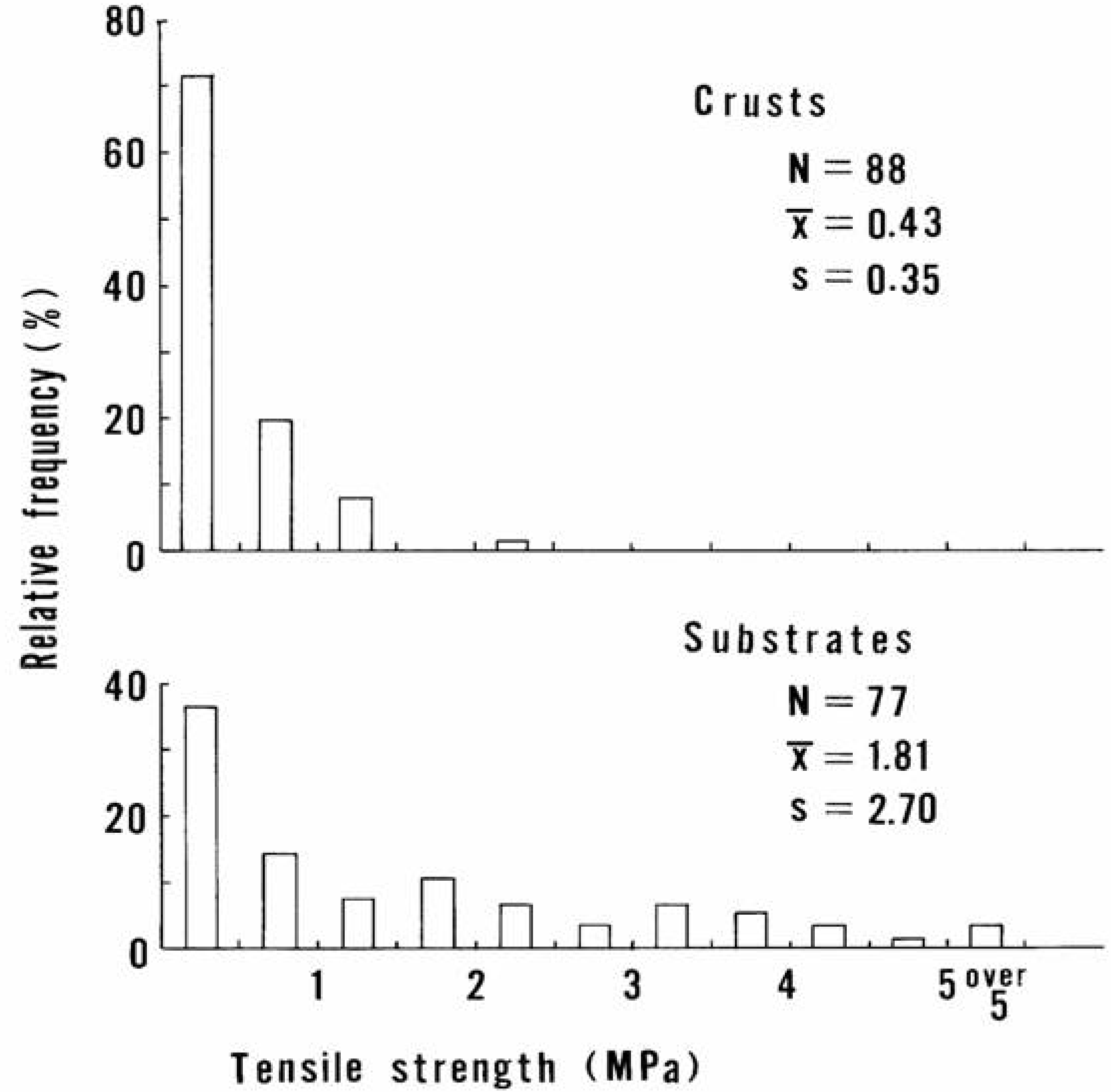


Frequency distribution of density of crusts and substrates

Fundamentals



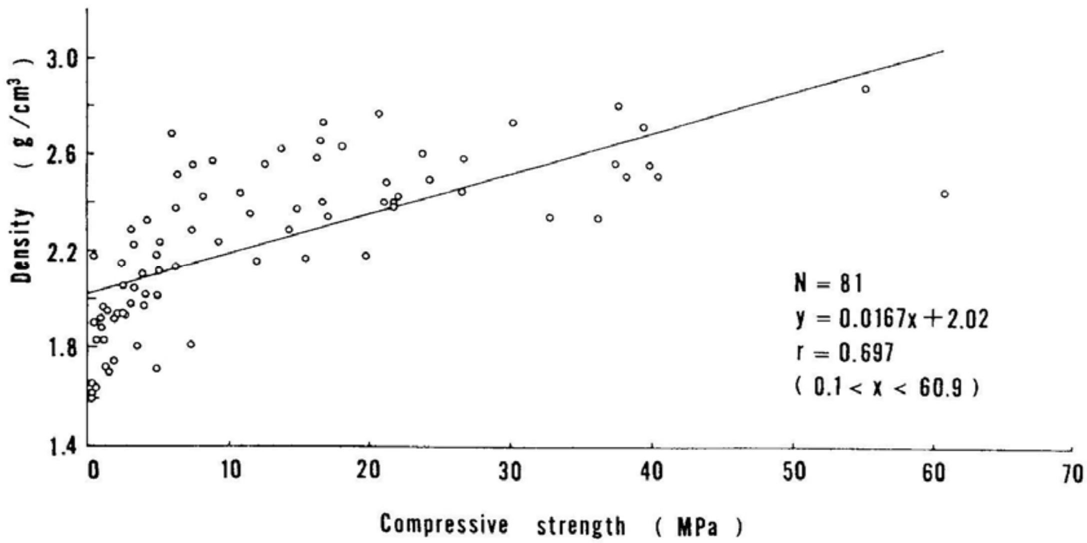
Frequency distribution of compressive strength of crusts and substrates



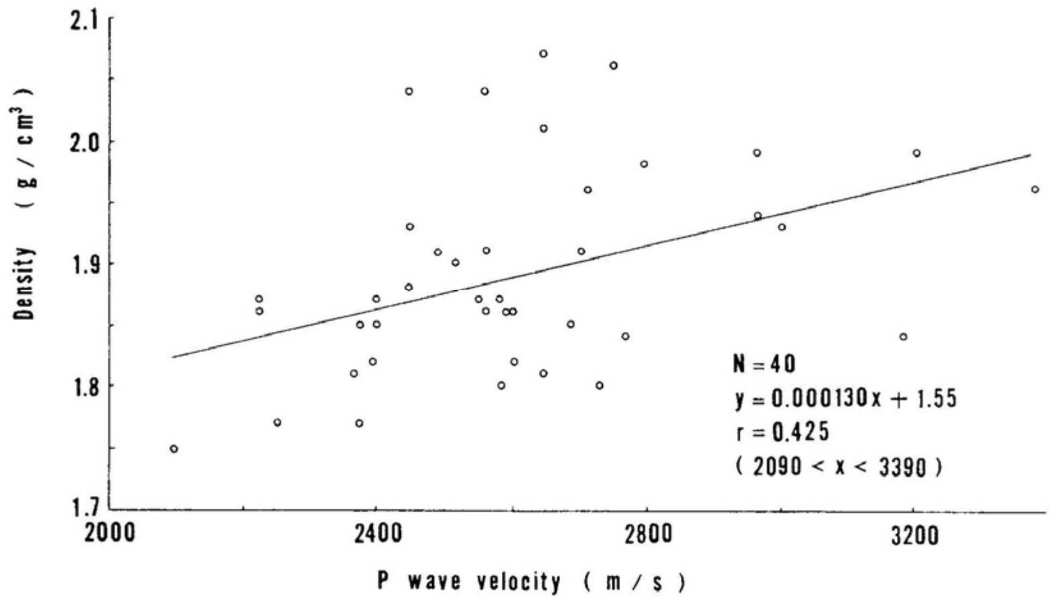
Frequency distribution of tensile strength of crusts and substrates

Relationships among geotechnical properties of crusts and the substrates

Fundamentals

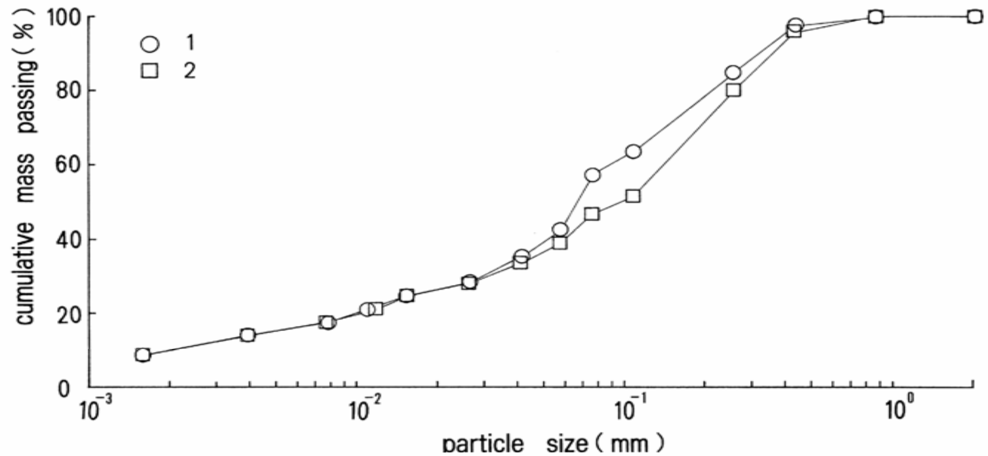


Relationship between bulk wet density and compressive strength of substrates

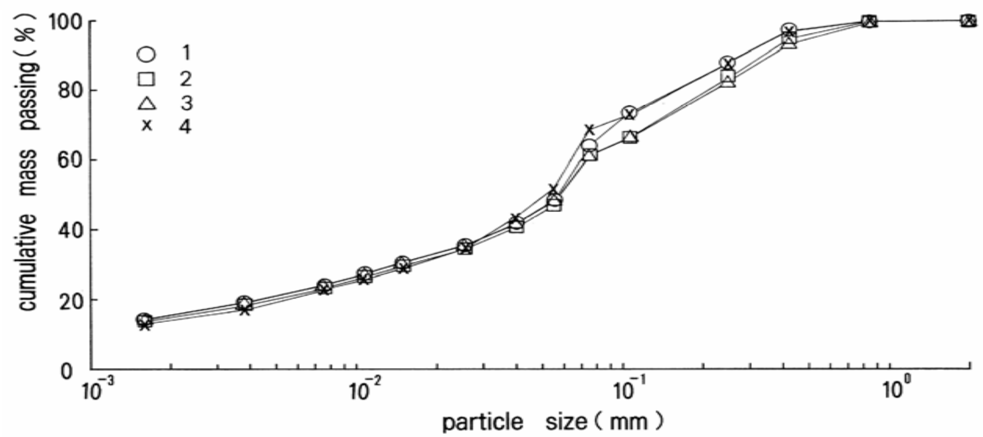


Relationship between bulk wet density and P-wave velocity of crusts

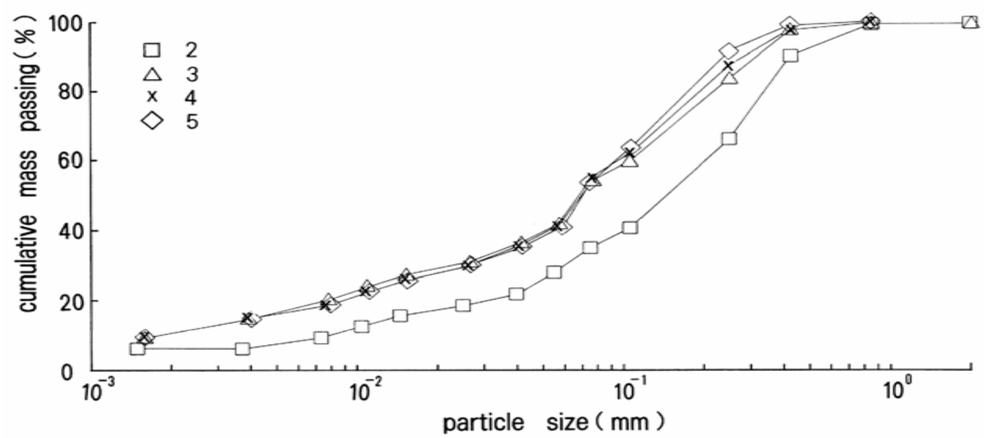
Fundamentals



E-LC10



E-LC24



E-LC11

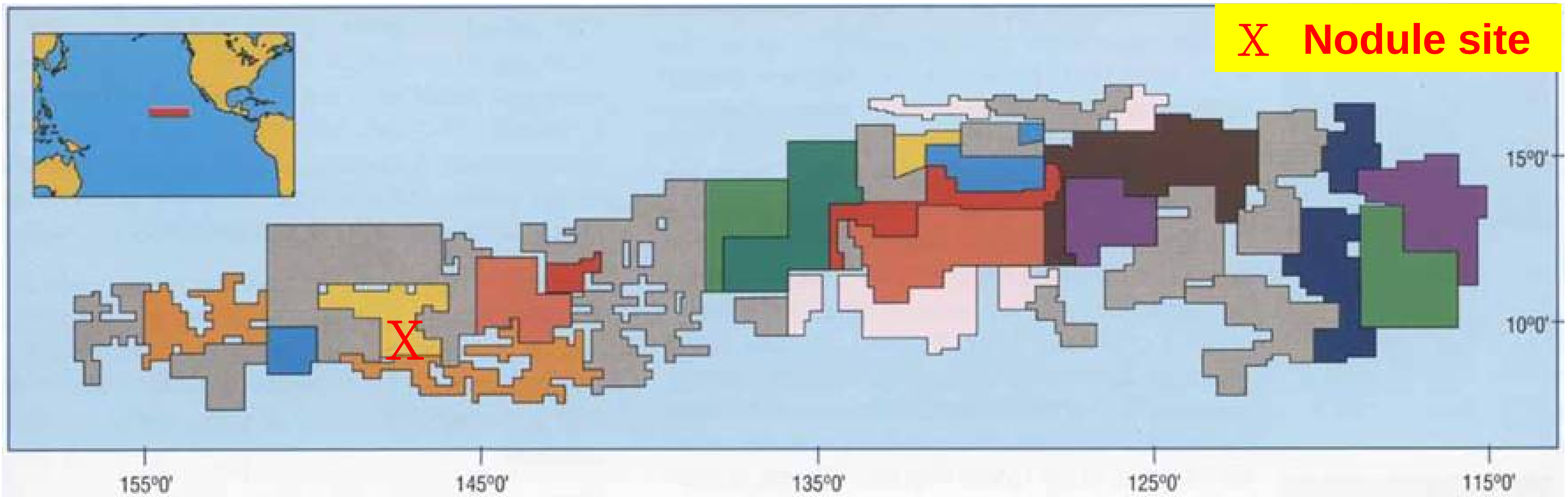
Example size distribution of seamount sediments

Cohesion and internal friction angle of seamount sediments

Fundamentals

Sample name (depth)	Cohesion (kPa)	Internal friction angle (degree)
A-LC31-b (60cm)	16	18.5
A-LC32-a (20cm)	32	5.7
C-LC27-c (100cm)	40	3.1
D-LC13-a (20cm)	20	4.6
D-LC13-c (130cm)	14	5.8
E-LC09-a (20cm)	35	13.9
E-LC09-c (110cm)	34	7.1
E-LC11-b (40cm)	17	6.3
E-LC11-e (190cm)	27	4.4

Location of nodule mining site assumed in FS



DISPOSITION OF SECTORS OF REGISTERED PIONEER AREAS IN THE CLARION-CLIPPERTON FRACTURE ZONE IN THE PACIFIC OCEAN

PIONEER AREAS OF THE INTERNATIONAL SEA-BED AUTHORITY

PIONEER AREAS OF THE REGISTERED PIONEER INVESTORS

- RUSSIA (YUZHMORGEOLOGIYA)
- JAPAN (DORD)
- FRANCE (IFREMER/AFERNOD)
- CHINA (COMRA)
- INTEROCEANMETAL JOINT ORGANIZATION (IOM)
- KOREA (KORDI)

AREAS CLAIMED BY CONSORTIA

- OMA (Ocean Mining Associates Consortium)
- OMCO (Ocean Minerals Co. Consortium)
- OMI-I (Ocean Management Inc. Consortium)
- OMI-II (Ocean Management Inc. Consortium)
- KCon (Kennecott Consortium)

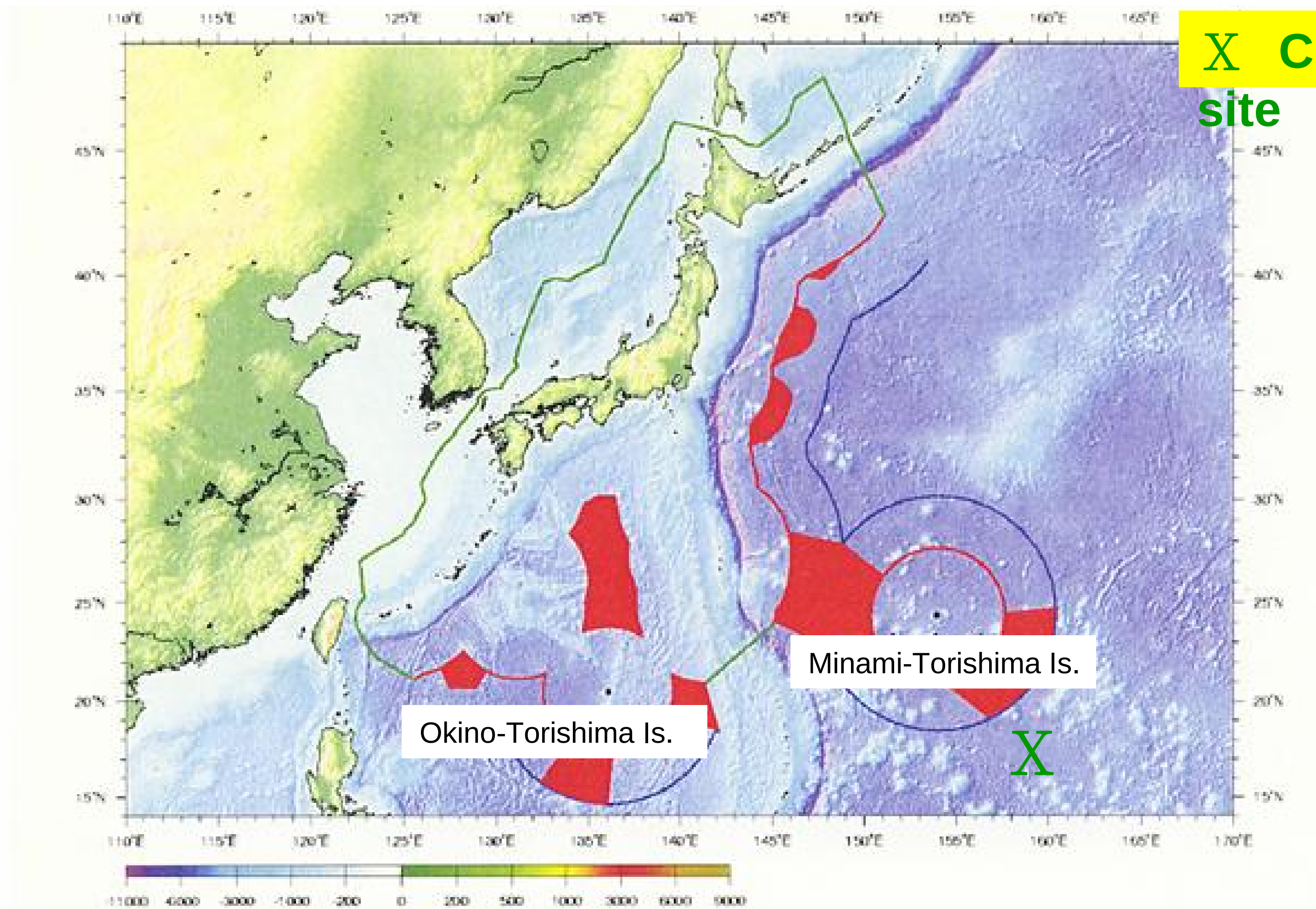
Evaluation

Geophysical and geological factors for nodule mining model

Site location: N10º, W147º
Site depth: 5,000 m
Nodule population: 10 kg/m^2 in wet weight
Metal content in nodule: 0.20 % in Co, 1.44 % in Ni, and 1.12 % in Cu in dry weight
Nodule density: 2.0 in wet bulk
Nodule water content: 0.35 in weight.

Evaluation

Location of cobalt-rich manganese crust mining site assumed in FS



Red colored areas have possibilities of extension of continental shelf.

Evaluation

Geophysical, geological, and engineering factors for crust mining model

Seamount location: N17º, E157º
Seamount depth: 2,000 m
Crust abundance: 100 kg/m^2 in wet weight
Crust thickness: 50 mm
Metal content in crust: 0.64 % in Co, 0.50 % in Ni, and 0.13 % in Cu in dry weight
Crust density: 2.0 in wet bulk
Crust water content: 0.35 in weight
Substrate density: 2.5 in wet bulk
Substrate water content: 0.1 in weight
Substrate weight ratio in excavated wet ore: 0.194
Content in substrate: 0.6 limestone vs. 0.4 basalt

Images of nodule and crust mining systems assumed

Evaluation

Image of nodule mining system with towed collector

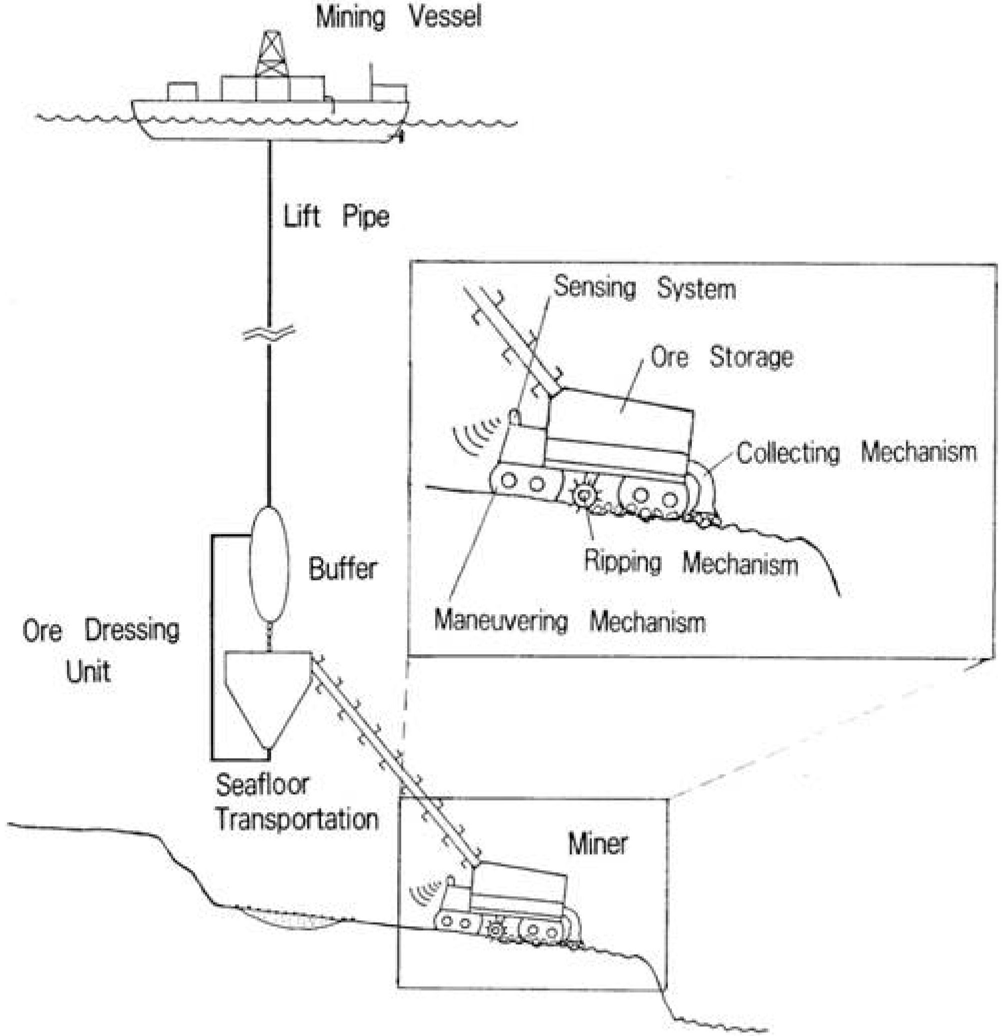


Image of crust mining system with self-propelled miner

Evaluation

Description of mining system

- The mining subsystem is composed of a seafloor collector or a miner, a pipe string with submersible hydraulic pumps, and a mining vessel.

- A towed collector with a hydraulic nodule pick-up device developed in Japan's R&D project is assumed for nodules.

- A self-propelled miner with mechanical slicing and crushing, along with hydraulic pick-up devices, is assumed for crusts. The miner weight is heavier than the collector, the power consumption more, and the structure and control more complicated.

- Sediment separators and buffers with size- and feed rate-regulating devices on collector and miner are similar.

- A pipe string composed of steel pipe and flexible hose, and pumps are similar. Their dimensions, strengths, numbers, and capacities are different.

Fundamental nodule and crust mining models assumed in FS

Evaluation

Nodule

Co=0.20 wt%, Ni=1.44 wt%, Cu=1.12 wt%

Collector	Lift	Vessel	Transport	Metallurgy
Collect →	Hydraulic 5,000m →	Dewatering Drying →	8,320km →	Leaching Smelting

0.70x0.87
2,180,000t/y(wet)

0.98x0.65
1,390,000t/y(dry)

0.90
Co: 2,500t/y

Crust

Co=0.64 wt%, Ni=0.50 wt%, Cu=0.13 wt%

Miner	Lift	Vessel	Transport	Metallurgy
Cut or Slice Fracture Collect →	Hydraulic 2,000m →	Dewatering Drying Ore dressing →	2,530km →	Leaching Smelting

0.70x0.87
914,000t/y(wet)

0.98x0.65x0.87
496,000t/y(dry)

0.90
Co: 2,500t/y

Evaluation

Description of mining models

- The smelting and chlorine leach method (SCL) for 3-metal recovery is selected as metallurgical processing method.

- The location of metallurgical plant is set near Tokyo.

- The production rate is defined from the final cobalt recovery, 2,500t/y, because the market size is the smallest and the amount is set less than the 10% of the demand in late 1990s.

- The froth floatation method on board mining vessel is assumed in the crust ore dressing, but the gravity and magnetic separations are also examined.

-Dumping the tailing waste from the ore dressing directly to the ocean is assumed.

- Sweep efficiency is not included. Excavation efficiency, pick-up efficiency, dewatering efficiency, ore dressing efficiencies, and leaching efficiencies are considered.

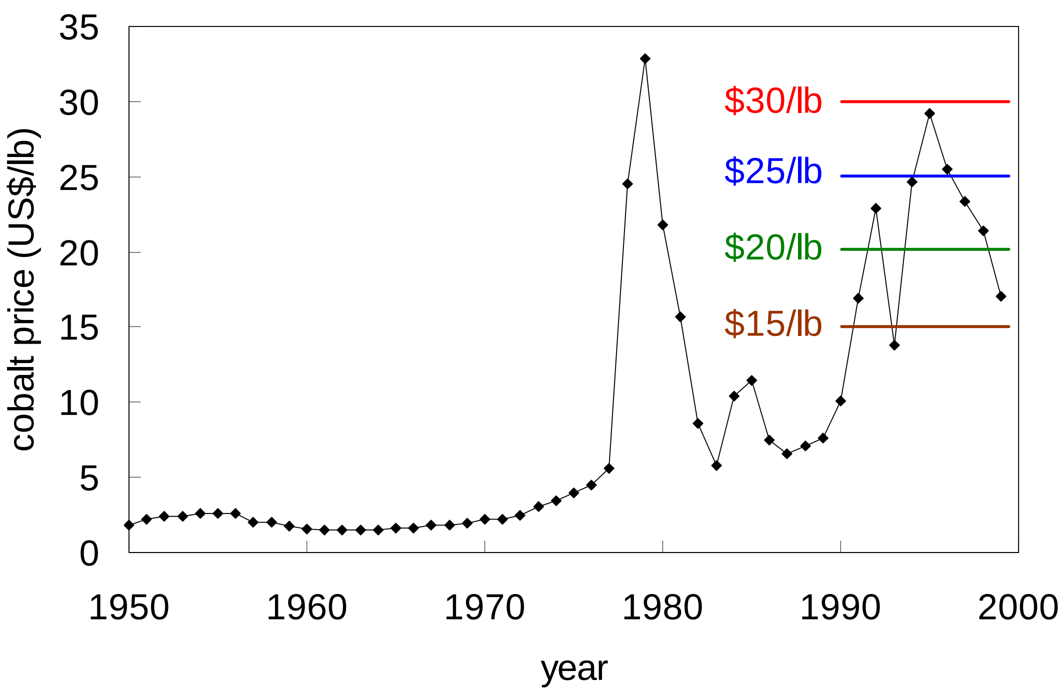
Total investments required for nodule and crust mining ventures

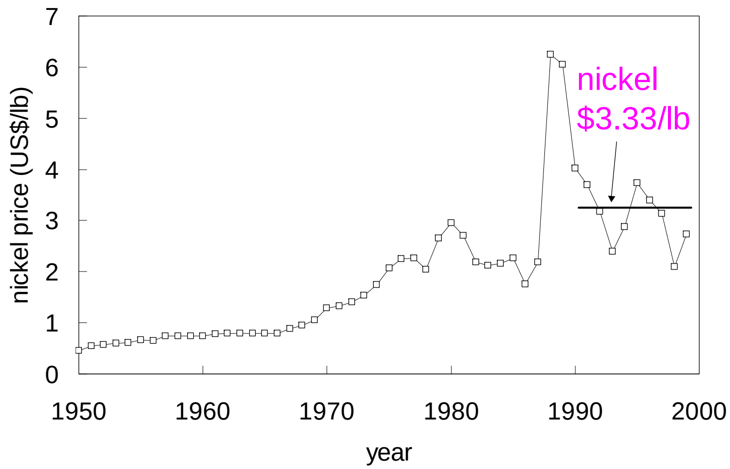
Evaluation

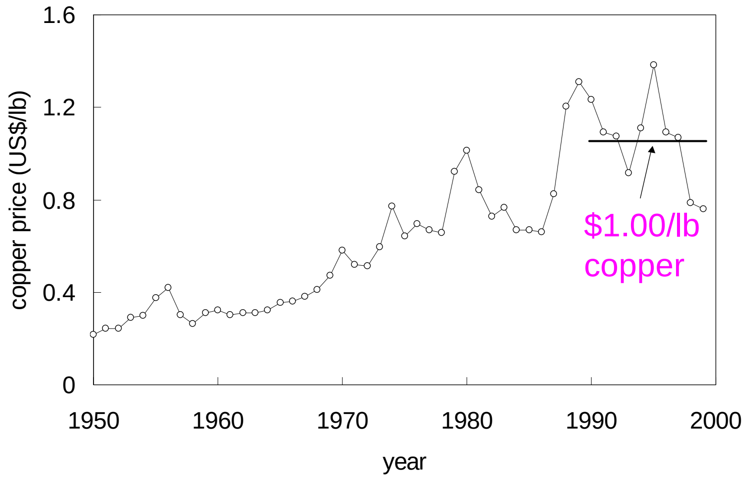
Subsystem	Cobalt-rich crust		Manganese nodule	
	Capital costs	Operating costs	Capital costs	Operating costs
Mining system Ore dressing Transportation Metallurgical processing	107.1 28.1 48.9 239.4	16.8 4.3 10.3 21.5	202 142.7 417	45.0 27.1 53.5
Sub-total	423.5 M$	52.9 M$	761.7 M$	125.6 M$
Continuing expenses Working capital	129.8 92.5		177.1 219.8	
Total investments	645.8 M$		1158.6 M$	

Calculated on the bases of economic factors in 1999

Metal prices used in FS



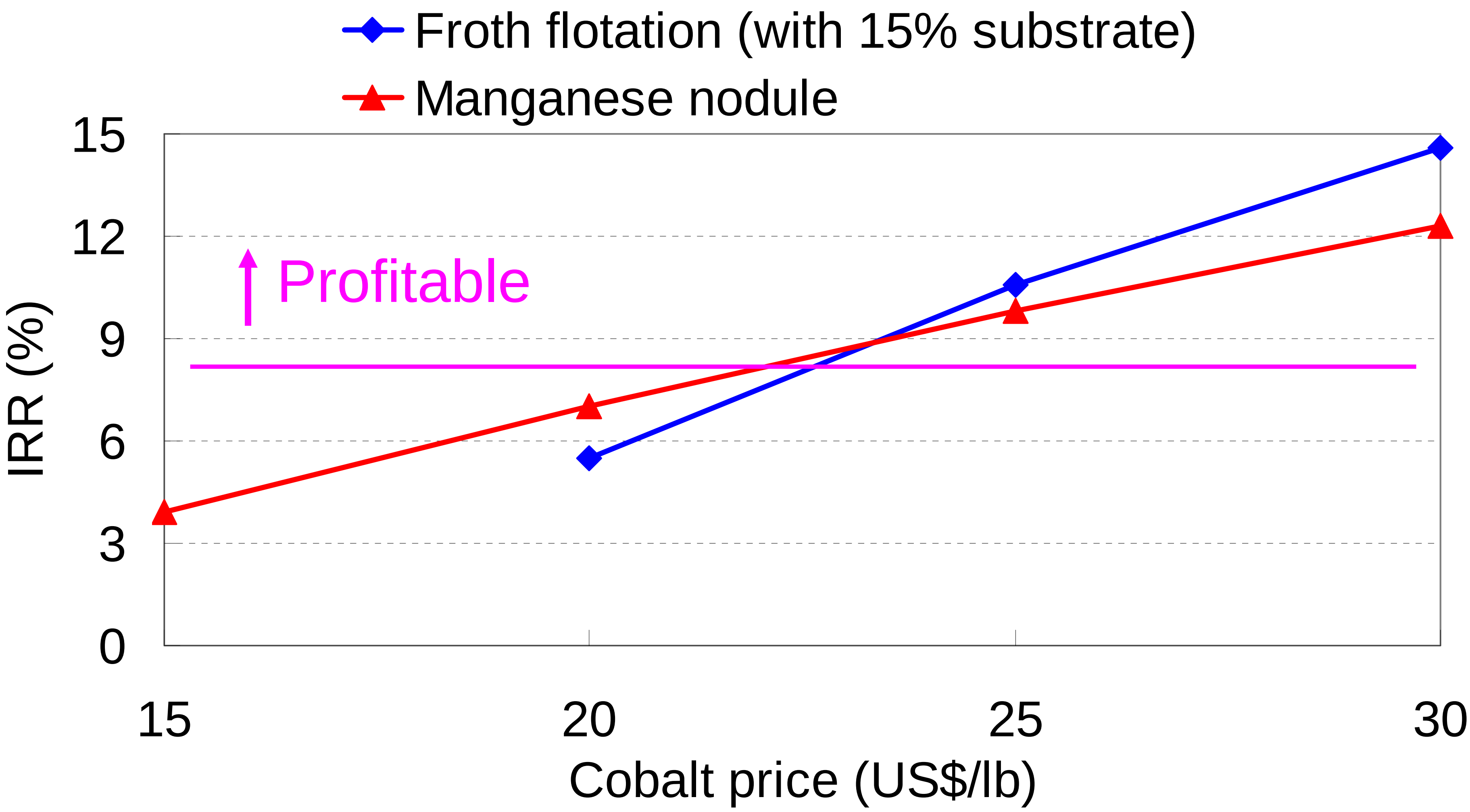




Cobalt is expensive but unstable to set the price.

Example result of economic comparison

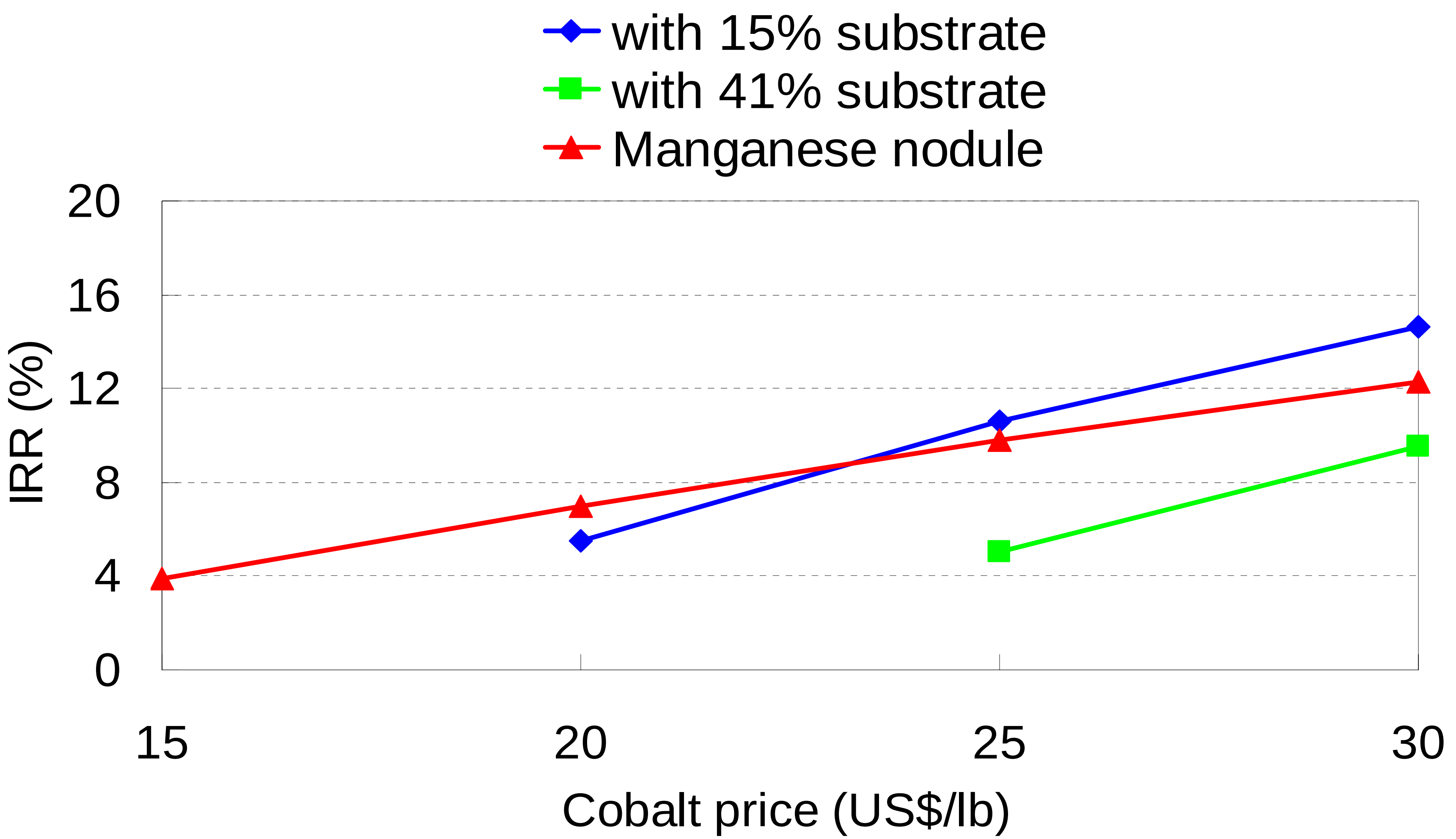
Evaluation



IRR: internal rate of return

Effect of degradation with increase of substrate rock in excavated ore

Evaluation



IRR: internal rate of return

Examination of necessity of ore dressing

Evaluation

Crust without ore dressing

Miner	Lift	Vessel	Transport	Metallurgy
Cut Slice Fracture Collect	Hydraulic 2,000m	Dewatering Drying ~~Ore dressing~~	2,530km	Leaching Smelting

→ Miner → Lift → Vessel → Transport → Metallurgy

0.70x0.87
911,000t/y(wet)

0.98x0.65~~x0.93~~
~~554,000t/y(dry)~~
624,000t/y(dry)

0.90
Co: 2,500t/y

Reductions

-Capital and operating costs for ore dressing

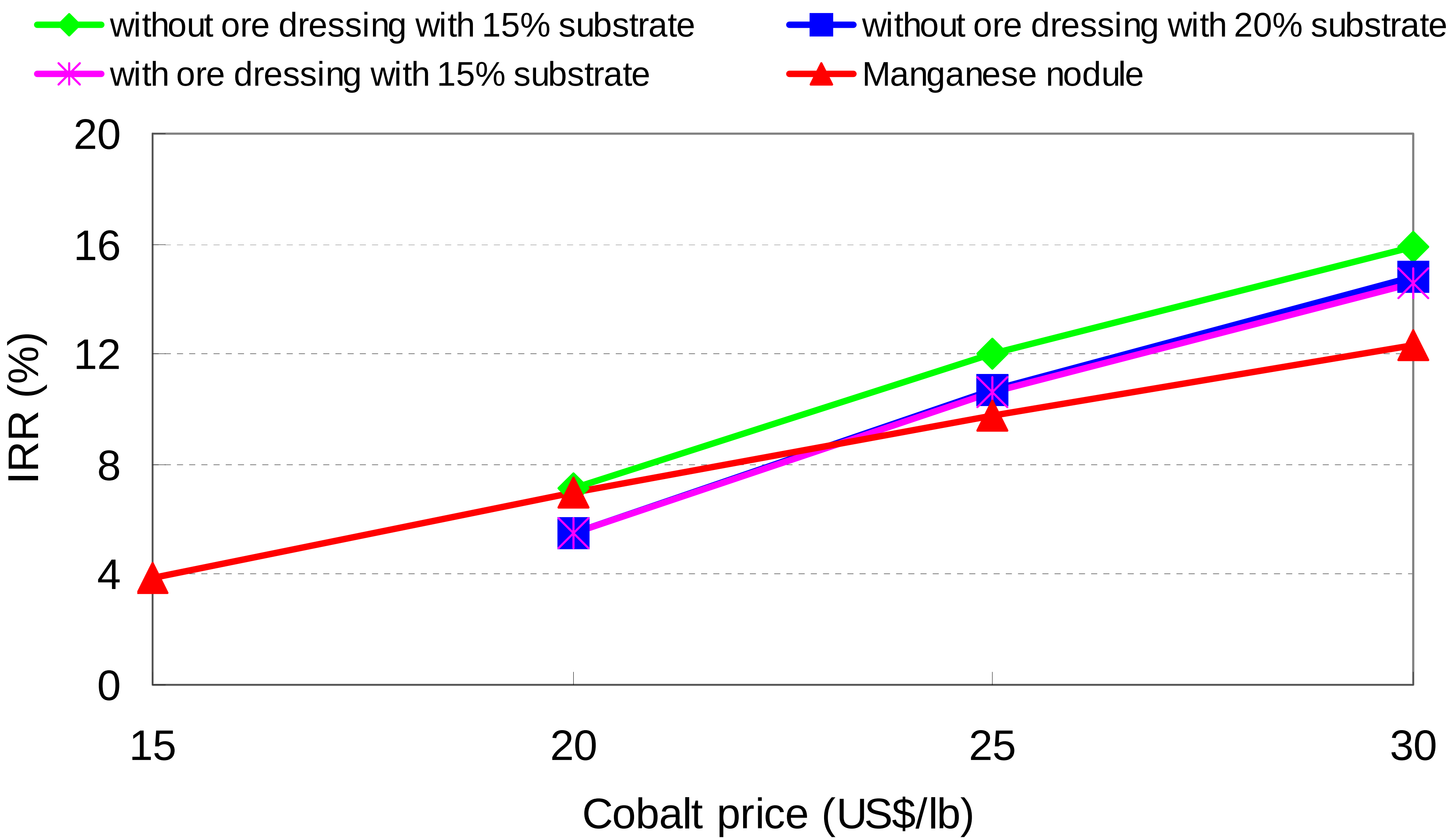
Increases

-Capital and operating costs for transportation

-Capital and operating costs for metallurgical processing

Evaluation

Improved economy in “without” ore dressing



IRR: internal rate of return

Comparison of economic factors and metal prices used in validation analyses

Evaluation

Prices of main cost elements in 1999 and 2004

Items	1999	2004	Changing ratio	Application
Heavy oil (3%C)	113 US$/kl	238 US$/kl	▲2.11	Whole system
Coal	30.0 US$/t	35.9 US$/t	▲1.20	Processing
Electricity	0.086 US$/kWh	0.11 US$/kWh	▲1.28	Whole system
Calcined lime	66.6 US$/t	85.5 US$/t	▲1.28	Processing
Material (Others)			▲avg. 1.25	Processing
Foreign exchange	1 US$= 121 Yen	1 US$= 112Yen	▼0.93	
Labor	2,350 US$/month	2,327 US$/month	▼0.99	
Interest	8%	3%	▼0.38	

Prices of metals in 1995-1999 and 2004

Metal	in 1995-1999	2004	Changing ratio
Cobalt	US$ 15/lb, US$ 20/lb, US$ 25/lb, US$ 30/lb	US$ 26.8/lb	
Nickel	US$ 3.3/lb	US$ 6.28/lb	▲1.90
Copper	US$ 1/lb	US$ 1.26/lb	▲1.26
Lead	US$ 0.45/lb	US$ 0.37/lb	▼0.82
Zinc	US$ 0.55/lb	US$ 0.47/lb	▼0.85
Gold	US$ 336.4/oz	US$ 407.5/oz	▲1.21
Silver	US$ 5.2/oz	US$ 6.76/oz	▲1.30

Evaluation

Comparison of total investment costs for nodule mining

Subsystem	Manganese nodule with the operating costs in 1999 and metal prices in 1995-1999		Manganese nodule with the operating costs in 2004 and metal prices in 2004	
	Capital costs	Operating costs	Capital costs	Operating costs
Mining system Mineral processing Transportation Metallurgy	202.6 - 142.7 417.0	45.4 - 27.1 53.5	202.6 - 142.7 417.0	56.3 - 39.5 61.6
Sub-total	**762.3 M$**	**126.0 M$**	**762.3 M$**	**157.4 M$**
Continuing expenses Working capital	177.1 219.8		133.2 275.5	
Total investment	**1159.2 M$**		**1171.0 M$**	

Note: Capital costs for subsystem construction are assumed the same. No mineral processing is applied for manganese nodule.

Evaluation

Comparison of total investment costs for crust mining

Subsystem	**Cobalt-rich manganese crusts** with the operating costs in 1999 and metal prices in 1995-1999		**Cobalt-rich manganese crusts** with the operating costs in 2004 and metal prices in 2004	
	Capital costs	Operating costs	Capital costs	Operating costs
Mining system	107.3	16.9	107.3	24.3
Mineral processing	28.5	4.3	28.5	6.7
Transportation	45.7	9.2	45.7	11.9
Metallurgy	224.0	19.3	224.0	25.4
Sub-total	**405.5 M$**	**49.7 M$**	**405.5 M$**	**68.3 M$**
Continuing expenses	127.3		114.6	
Working capital	86.9		119.4	
Total investment	**619.7 M$**		**639.9 M$**	

Note: Capital costs for subsystem construction are assumed the same.

Evaluation

Results of economic validation analyses for nodule and crust mining venture in 2004

Case	Manganese nodule			Cobalt-rich manganese crust (with 14.9% substrate)		
	Payback periods (year)	NPV ($)	IRR (%)	Payback periods (year)	NPV ($)	IRR (%)
Metal prices in 1995-1999 (Co: US$ 25/lb)	11.7	77M	9.8	11.1	62M	10.6
Metal prices in 2004	6.6	584 M	19.2	9.7	105 M	12.3

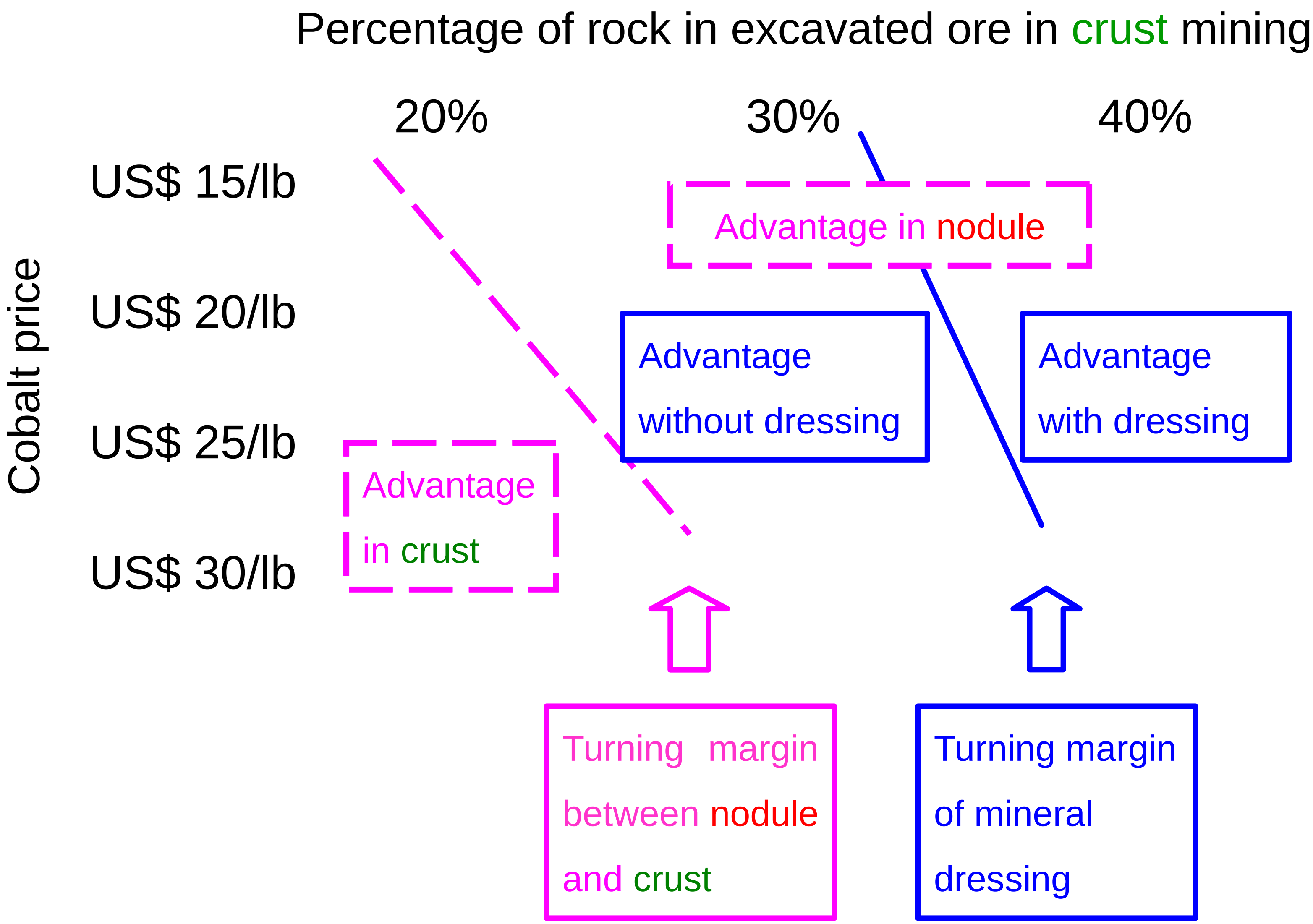
Other sensitivity analyses conducted

Evaluation

- The ammonium sulfite leaching method (ASL) was applied as metallurgical processing method.
- Possibility of silico-manganese (Si-Mn) recovery was examined.
- Locating the processing plant in Mexico is assumed.
- Effect of cobalt content in crusts is considered.
- Preliminary effect of platinum recovery is evaluated.
- Effects of production rates are calculated.

Concluding comparison of nodule and crust mining ventures

Problems



Reminder: Nodule and crust mining ventures are competitive.

Information necessary for an advanced validation analysis of crust mining

Problems

1. Microtopography of the targeted areas, and variation in thickness and metal contents of the manganese oxide layer

- Estimation of metal contents in the excavated ore (crust and rock mixture) is necessary.

Constant metal contents in manganese oxide only are used in the deposit evaluation. Crust and rock separation is possible, but very expensive if the rock percentage increases.

- Estimation of the economic reserve is necessary.

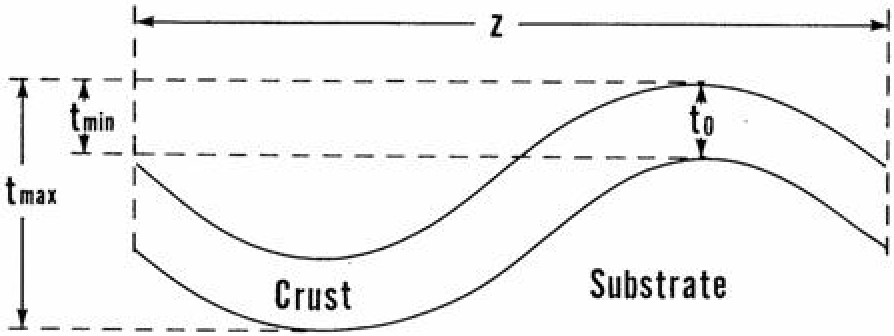
Geological reserve is calculated using the constant thickness and 100%-recovery base, but it is impossible to recover all the oxide for keeping the degradation in minimum.

2. Burial depths of crust beneath seamount sediments

- The burial depth affects the estimation of the economic reserve.

Detailed multi-narrow beam or bathymetric SSS and near-seafloor sub-bottom profiling surveys are the example solutions.

Problems



Schematic image of ore degradation expected under microtopographic undulation

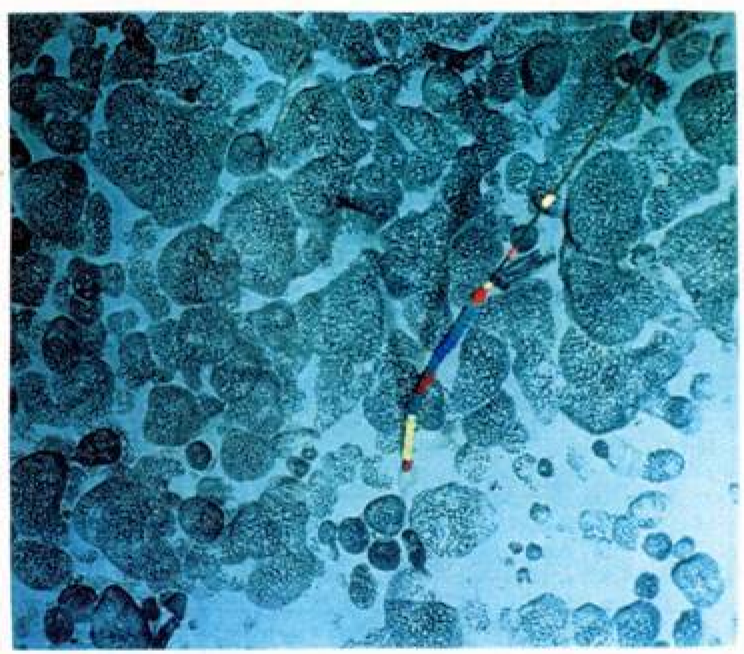
t_0 : Crust thickness

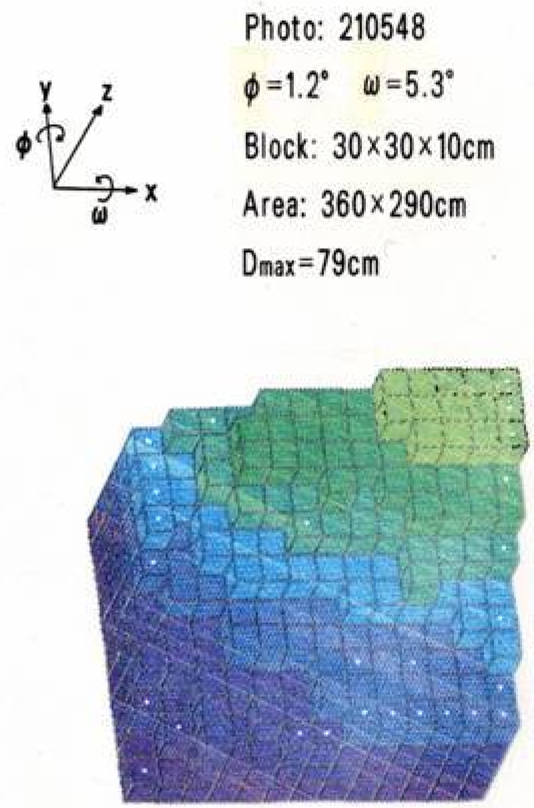
t_{min} : Minimum cut

t_{max} : Maximum cut

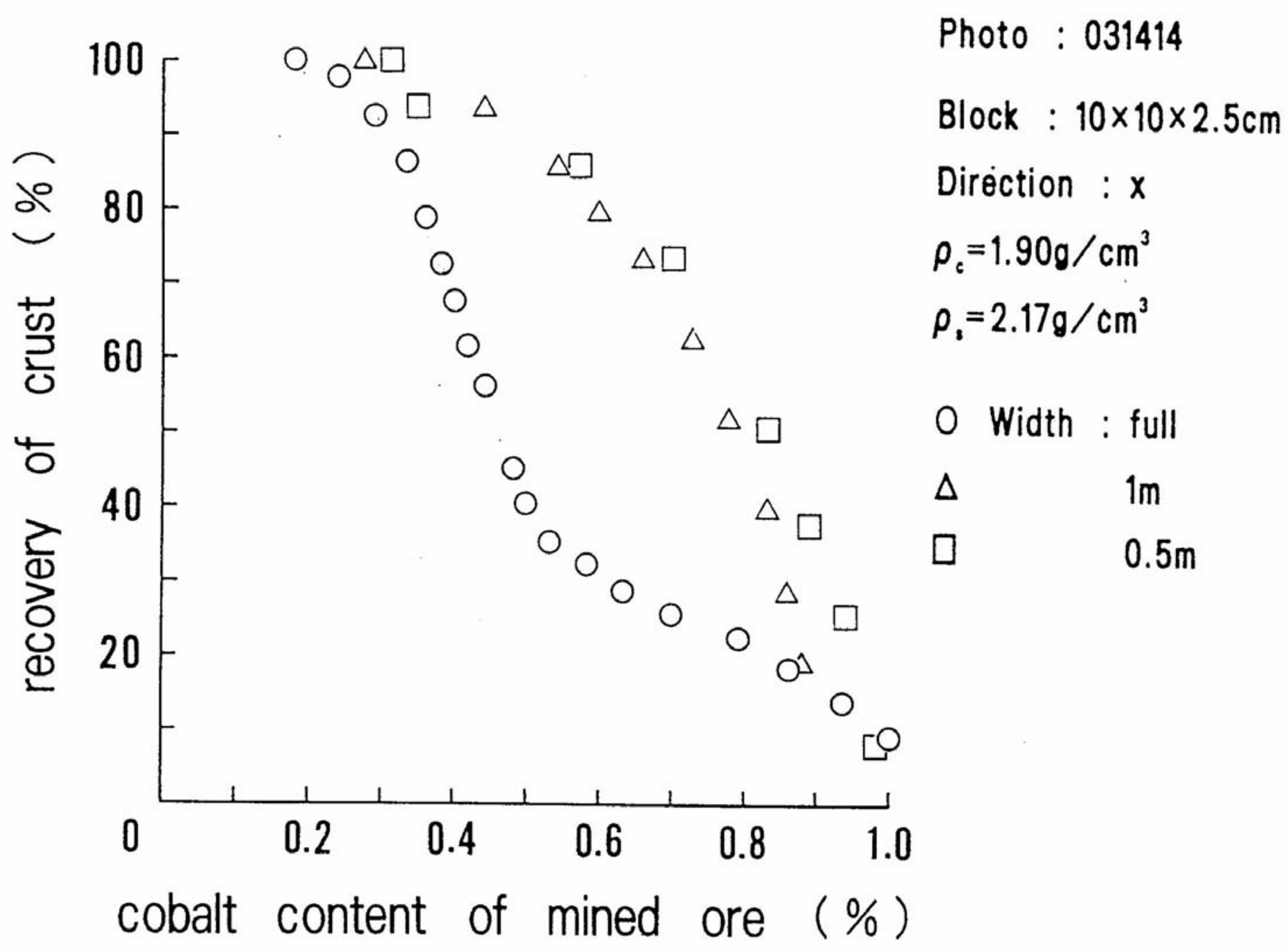
z : Cutoff width

An example result of seafloor microtopography analysis of crust distribution area





Problems



An example simulation result of crust excavation: Relationship between recovery and metal content (Widths of excavation head, 0.5 m, 1m, and about 2.5m are the parameter.)

Technical issues necessary for realizing crust mining

Problems

- Estimations of metal contents in excavated ore and economic reserve are required, to select potential mining sites for crust mining.

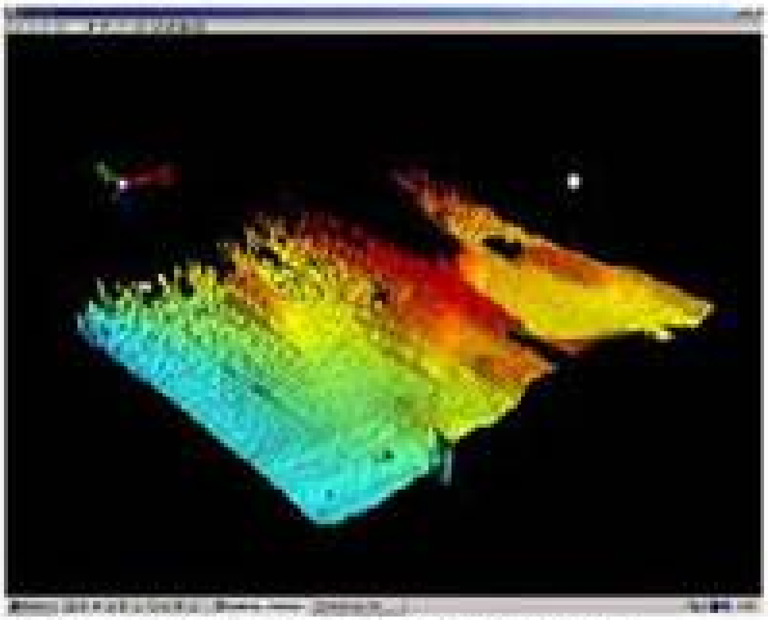
- Acoustic survey data for microtopography less than 1 m resolution is required for the estimations.

- Combination analysis of acoustic and photographic data will classify the microtopgraphic characteristics of the sites with a vertical resolution in crust thickness.

- Behavior of platinum in metallurgical processing must be clarified to estimate the effect of platinum recovery on the economy.

Problems

Survey for microtopography
-Deep-towed bathymetric side scan sonar-



Woods Hole, MA: 3D Profile Segment February 2002

Frequency: 200kHz (standard), 100kHz (option)
Maximum depth: 2,000m (standard), 6,000m (option)
Height: 25m-300m (200kHz), 25m-500m (100kHz)
Cover area: 10 times of height
Vertical resolution: 51.0cm（200kHz）
Horizontal resolution：5.5cm(200kHz), 7.5cm(100kHz)
Beam width: 1º (200kHz), 1º(100kHz)

Little chance of crust mining

Problems

- The typical size of potential mining sites on seamounts is very small. For example, when the surface area of seamount equals 1,500 km^2, the size of mining sites in the area is calculated as 60 km^2. This is introduced from the exposed crust coverage, 20 % of the area, and the portion, 20 %, that can be mined in the exposed crust.

- Among the mining sites, because of the microtopographic undulation, 70-80 % of them may be less profitable than nodule mining.

- A lower substrate ratio in excavated ore is required for an advantaged crust mining.

Concluding remarks

Problems

- Cobalt-rich but nickel and copper poor natures of cobalt-rich manganese crusts are the weak point of crust mining.

- A lower substrate ratio in excavated ore is required for the advantage of crust mining with nodule one.

- In addition to the microtopography, variation in thicknesses and metal contents of oxide layer, and burial depths of oxide layer beneath seamount sediments of the targeted area are the important data for improving the technical and economic evaluation of crust mining.

End of presentation

Thank you for your attention.

Japanese nodule collector for ocean test on a Pacific seamount in 1997