

Seamount Characteristics and Mine-Site Model Applied to Exploration- and Mining-Lease-Block Selection for Cobalt-Rich Ferromanganese Crusts

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Regulations are being developed through the International Seabed Authority (ISBA) for the exploration and mining of cobalt-rich ferromanganese crusts. This paper lays out geologic and geomorphologic criteria that can be used to determine the size and number of exploration and mine-site blocks that will be the focus of much discussion within the ISBA Council deliberations. The surface areas of 155 volcanic edifices in the central equatorial Pacific were measured and used to develop a mine-site model. The mine-site model considers areas above 2,500 m water depth as permissive, and narrows the general area available for exploration and mining to 20% of that permissive area. It is calculated that about eighteen 100 km² exploration blocks, each composed of five 20 km² contiguous sub-blocks, would be adequate to identify a 260 km² 20-year-mine site; the mine site would be composed of thirteen of the 20 km² sub-blocks. In this hypothetical example, the 260 km² mine site would be spread over four volcanic edifices and comprise 3.7% of the permissive area of the four edifices and 0.01% of the total area of those four edifices. The eighteen 100 km² exploration blocks would be selected from a limited geographic area. That confinement area is defined as having a long dimension of not more than 1,000 km and an area of not more than 300,000 km².

Keywords ferromanganese crusts, lease-block sizes, mine-site model, permissive areas, seamount characteristics

Introduction

Draft regulations for cobalt-rich ferromanganese crusts (Fe-Mn crusts) have been prepared by the Legal and Technical Commission (LTC) of the International Seabed Authority (ISBA) based on information provided by scientists and engineers from a variety of disciplines during four workshops. Those draft regulations will most

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certainly be modified after discussion by the Council of Nations during their 16th session in 2010 and 17th session in 2011. Some of that discussion will focus on the size of the areas needed for exploration and a viable mine site for Fe-Mn crusts. Once adopted, the ISBA will regulate the exploration and exploitation of Fe-Mn crusts in areas beyond national jurisdictions (the Area).

This paper provides background information on the characteristics of seamounts and Fe-Mn crusts that can be used to estimate the size of viable exploration and mine-site areas, which will ultimately become part of the final set of regulations. This paper is significantly modified from that of Hein (2008, submitted in 2006) by the addition of new data, a nearly five-fold increase in seamount surface-area measurements, and a re-evaluation of all available data.

Fe-Mn crusts occur on nearly all rock surfaces in the global ocean that have been swept clean of sediment for millions of years. Fe-Mn crusts range in thickness from a patina to over 20 cm and occur as pavements on volcanic edifices or coat talus debris. Although Fe-Mn crusts have been considered as a potential Co-Ni ore, many rare elements occur in high concentrations in crusts that offer added incentive for developing mining technologies for their recovery. Elements of special interest for high technology applications that are abundant in Fe-Mn crusts include the rare-earth elements (REEs), Te, Ti, Mo, platinum-group elements (PGEs), Zr, Bi, W, and Mn (Hein et al. 2000; Hein 2004). With the dramatic increase in the price of each of these commodities, one or more of them may approach Co in the near future as the most valuable contained element.

The geologic, geochemical, and oceanographic parameters and global economic conditions that will ultimately determine a Fe-Mn crust mine site cannot be fully determined. However, reasonable assumptions can be made that will bracket the likely characteristics of a mine site (Tables 1, 2). From that range of possibilities, we selected a set of conditions that illustrate the selection process of lease blocks on seamounts for the exploration phase and mining operations for Fe-Mn crusts. The analysis is based on the present state-of-knowledge of the morphology and size of seamounts and the distribution and characteristics of Fe-Mn crusts on seamounts.

Table 1. Expected seamount exploration and mine-site parameters

Parameter	Range	Model site
Seamount area (km ²) ¹	>400	>500
Seamount slope (°)	0–20	0–10
Water depth (m)	<2,500	<2,500
Mean net crust thickness (cm)	3–10 cm	4 cm
Sediment cover (%)	0–70	60
Annual production (tonnes) ²	1.0–2.0	1.0
Area mined in 15 years (km ²)	130–510	192
Area mined in 20 years (km ²)	170–680	260
Mine-site sub-block size (km ²) ³	10–40	20
Exploration block size (km ²) ³	100–200	100

¹Above 2,500 m water depth.

²Millions of wet metric tonnes based on density of 1.95 g/cm³.

³Suggested possible range of block sizes for leasing.

Table 2. Area of seabed mined based on annual production and mean crust thickness (wet bulk density of 1.95 g/cm³)

	Cut-off case ¹	Model site	Good case
Mean net crust thickness (cm)	3.0	4.0	6.0
Wet tonnage (kg/m ²)	58.5	78	117
Annual production (million tonnes) ²	2	1	1
Area mined/year (km ²)	34.2	12.8	8.55
Area mined in 15 years (km ²)	513	192	128
Area mined in 20 years (km ²)	684	260	171
Area for exploration (km ²) ³	4,788	1,820	1,197
Rounded no. of 100 km ² explor. blocks	48	18	12
Rounded no. of 20 km ² mining sub-blocks	34	13	9

¹Minimum crust-thickness, maximum annual-production scenario.

²Wet metric tonnes based on density of 1.95 g/cm³.

³License area arbitrarily set at 7 times the area mined during 20-year operation.

The illustrations presented here are not meant to be an economic evaluation, so the crust grade (contents of Co, Ni, REEs, etc.) is not considered. Only those characteristics that apply directly to evaluating lease-block sizes and the allocation and relinquishment of blocks during the exploration phase are considered. The geologic rationale for those determinations is discussed. Many seamounts, with a range of appropriate metal grades, do occur within the bounds of the examples illustrated here. This paper provides a geologic basis for the selection and quantification of parameters that can be used to define a seamount mine site for Fe-Mn crusts, and the geologic framework for legal and technical documents that apply to that selection process. The goal is to balance the needs of the contractor in leasing the appropriate amount of territory needed during the exploration phase to identify a viable mine site with the needs of the ISBA to not have unnecessarily large tracts of land in the Area sequestered. The Area is considered the common heritage for all the people.

Surface Area of Seamounts

The surface areas of 155 typical north-equatorial Pacific (from 160° W to 145° E longitudes) volcanic edifices were measured, including conical seamounts, guyots (flat-topped seamounts), ridges (defined as having a length three times greater than the width), and plateaus (Figure 1; Table 3). Some volcanic edifices have one or more peaks or consist of two or more overlapping cones; these are included where they fit best in one of the four categories above. If the water depth between peaks or cones is greater than 3,400 m, then the edifice is divided into separate structures for measurement of surface area; otherwise the edifice is measured as a single structure regardless of the complexity of the structure. The 3,400 m depth is somewhat arbitrary; however, without this constraint some very large raised areas of seabed would compose enormous deep-water plateaus. Edifice baseline depths vary between about 3,800 to 4,400 m.

Surface areas were determined using ArcMap's 3-D analyst, which is a component of ArcGIS. The surface areas of the 81 conical seamounts, 52 guyots, 14 ridges,

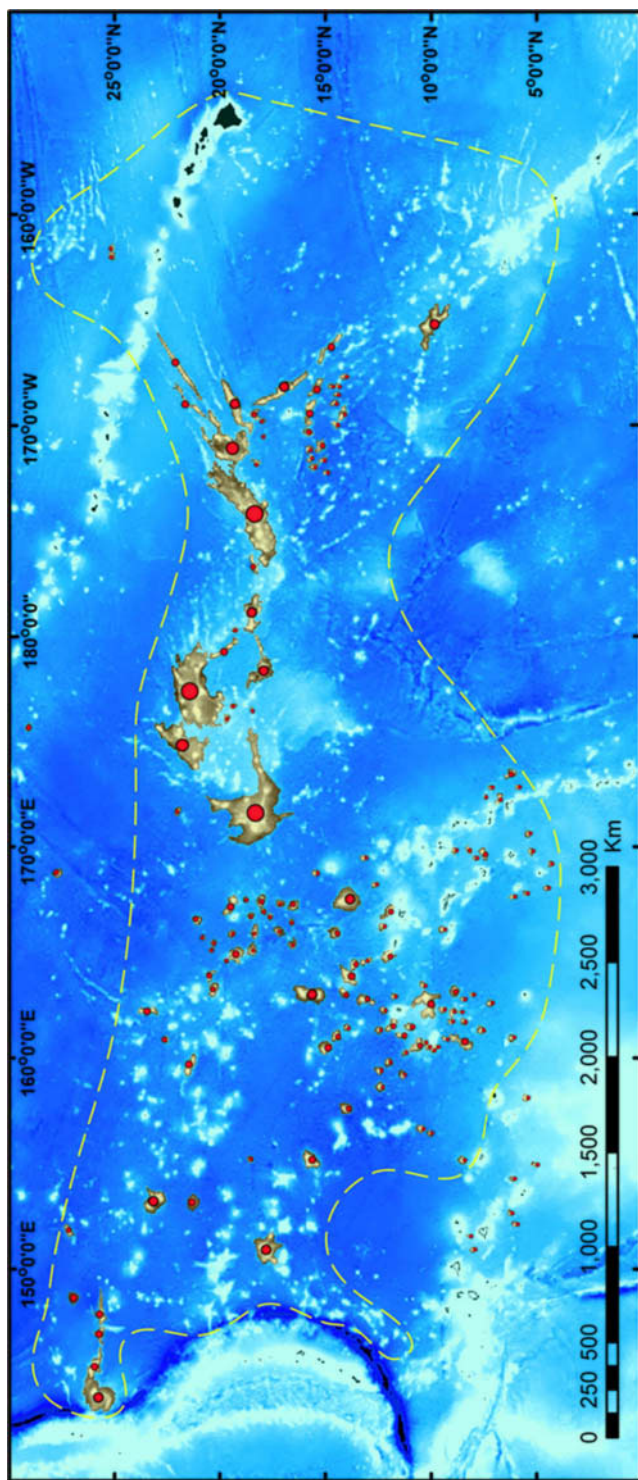


Figure 1. Location of seamounts, guyots, ridges, and plateaus used for surface area measurements (see Table 3). Brown areas were measured and are marked also by red filled circles of five sizes, indicating relative sizes of the measured edifices. Shades of brown indicate bathymetry with paler shades being shallower water. The dashed line encloses the largest region in the global ocean that has permissive conditions for development of thick, cobalt-rich crusts.

Table 3. Surface area (in square kilometers) of representative volcanic edifices within the north-equatorial Pacific region (see Figure 1)

	n	Mean	Median	SD	Min	Max
All data						
Total surface area	155	3,389	1,553	5,354	233	35,519
Surface area above 2,500 m	155	1,039	355	1943	0	13,443
Surface area above 1,500 m	155	117	0.8	266	0	1,798
Conical seamounts						
Total surface area	81	1,154	968	653	233	2,841
Surface area above 2,500 m	81	193	138	233	0	1,281
Surface area above 1,500 m	81	18	0	65	0	468
Guyots						
Total surface area	52	3,495	2,905	2,628	590	11,761
Surface area above 2,500 m	52	1,152	832	938	0	4,088
Surface area above 1,500 m	52	164	105	189	0	861
Ridges						
Total surface area	14	6,249	5,184	4,502	1,306	14,728
Surface area above 2,500 m	14	1,852	1,658	1,528	48	4,782
Surface area above 1,500 m	14	93	9	211	0	716
Plateaus						
Total surface area	8	20,720	18,100	11,054	8,076	35,519
Surface area above 2,500 m	8	7,437	6,966	3,903	2,213	13,443
Surface area above 1,500 m	8	862	839	630	87	1,798
Mid-pacific mountains¹						
Total surface area	15	10,854	4,754	12,719	719	35,519
Surface area above 2,500 m	15	3,785	1,606	4,499	48	13,443
Surface area above 1,500 m	15	373	74	558	0	1,798

¹This is a subset of all data and is separated out because it represents a large region of anomalously shallow water, including guyots, conical seamounts, ridges, and plateaus.

and 8 plateaus vary from 233 to 35,519 square kilometers (km^2) and average 1,154, 3,495, 6,249, and 20,720 km^2 , respectively (Table 3). The amount of surface area above 2,500 m water depth, where mining is likely to occur (see below), is very small for conical seamounts (average 193 km^2), but large for guyots, ridges, and plateaus (Table 3). Guyots are much larger than conical seamounts because guyots at one time grew large enough to be islands before subsidence and erosion took place. The conical seamounts never grew large enough to breach the sea surface. Some have considered that mining will take place only at shallow water depths, above 1,500 m; however, the amount of area above 1,500 m is quite small on most measured edifices, except plateaus (Table 3).

Rationale for Seamount Selection Parameters and Permissive Areas

The characteristics of seamounts and Fe-Mn crusts that are most conducive to mining can be broadly defined as follows.

Geomorphology

Mining operations will probably take place around the summit region of guyots, ridges, and plateaus on flat or shallowly inclined surfaces, such as summit terraces, platforms, and saddles, which have relatively smooth small-scale topography. These are the areas with the thickest and most metal-rich crusts (Hein et al. 2000; Hein 2004). In contrast, conical seamounts are smaller in area overall, and most importantly have much smaller surface areas above 2,500 m water depth. Most conical seamounts have much more rugged summit topography than do guyots. Much thinner crusts occur on the steep flanks of both guyots and conical seamounts (Manheim 1986; Hein et al. 2000, Zhang et al. 2008). The flanks of atolls and islands will not be considered for mining because crusts are generally very thin on those edifices (De Carlo et al. 1987; Hein et al. 1988).

Water Depth

The summit of guyots that are most likely to be leased will not be deeper than about 2,200 m and the associated terraces not deeper than about 2,500 m. The 2,500 m cut-off depth is important for several reasons. Edifice slopes are more rugged at depths

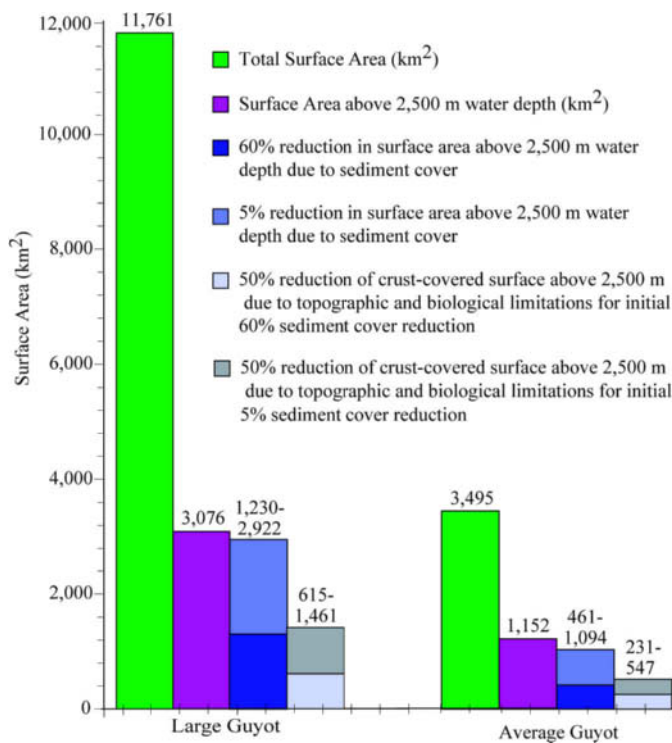


Figure 2. Histogram of total surface area and surface area above 2,500 m water depth of the largest guyot measured and the average for all the guyots measured. The other bars indicate reductions in surface area available for mining based on 60% and 5% sediment cover and further reductions to those reductions for biological and topographic limitations.

greater than 2,500 m, crusts are generally thinner, and contents of Co, Ni, and other metals are generally lower (Usui and Someya 1997; Hein et al. 2000; Zhang et al. 2008). There are also technological reasons for mining at water depths as shallow as possible. A 2,500 m cut-off depth and 400 km² cut-off summit area (see below) permits a large number of edifices to be included as possible exploration targets, including 100% of the plateaus, 88% of the ridges, and 85% of the guyots, but only 12% of the conical seamounts.

Other water depth limits have been proposed in the literature, the most common one being 2,400 m (e.g., Morgan 2008). That is a valid depth to use, but would eliminate some areas of potentially thick crusts on volcanic edifices. Another water depth limit that has been used is 1,500 m because of the high metal contents that characterize crusts formed at depths from about 800–1,500 m (e.g., Pichocki and Hoffert 1987; De Carlo and Fraley 1992). Because the flanks of atolls and islands will not be considered for mining, this leaves only a few very large edifices with enough summit surface area above 1,500 m to be considered for mining. Of the 155 volcanic edifice surface areas measured here, only one of the 81 conical seamounts has a summit area of greater than 400 km² above 1,500 m water depth; 13–14% of the guyots (7 of 52) and ridges (2 of 14) and 33% of the plateaus (5 of 15) have summit areas of greater than 400 km² above 1,500 m water depth. If 1,500 m is used as a cut-off water depth, then a large number of seamounts would have to be mined to support a single 15–20-year mining operation. In general, the technological requirements needed to operate at 1,500 m will not be much different from those needed to operate at 2,500 m, but the environmental impact of mining a greater number of edifices might be a disadvantage.

Size of Summit Area

The summit region above 2,500 m water depth will be large, probably greater than about 400 km². This estimate is based on the size of equatorial Pacific guyot summits shallower than 2,500 m water depth (Table 3) and the range of percentages of the summit areas that are likely to be available for mining (Figure 2). This minimum area for the summit yields the fewest number of seamounts that would be needed to support a 15–20-year mining operation. The mining of many seamounts for a single 15–20-year operation will likely be technological and economically feasible, but could potentially have both positive and negative environmental consequences. For example, endemic species may characterize many seamounts, in which case fewer seamounts would be better; on the other hand, species recruitment of mined-out areas would be facilitated by smaller areas mined and therefore more seamounts would be needed.

Sediment Cover

The amount of sediment versus hard-rock (crust-covered) areas were calculated from bottom-photo mosaics, video transects, side-scan sonar back-scatter images, and estimated from seismic-reflection data. Sediment cover on the summits of the volcanic edifices ranges from nearly completely sediment covered to nearly sediment free. Seamounts will be chosen for exploration that have little sediment on the summit region, which implies strong and persistent bottom currents. Guyots with more than about 70% sediment cover will likely be passed over in favor of guyots with more promising crust distributions. However, this area limit will depend in part on the

overall size of the edifice, with a greater tolerance for more sediment cover on the larger edifices. In addition, Yamazaki et al. (1993, 1996) showed that Fe-Mn crusts are commonly found buried under centimeters to meters of calcareous sediment that could be removed during the mining process.

Limestone Outcrops

Reefal limestones cap some guyots or occur around the summit margins. While Fe-Mn crusts grow on these hard substrates, they are generally thinner than they are on volcanogenic and phosphorite substrates because the limestones are younger than the other rocks (Hein et al. 1988). In addition, Fe-Mn crusts are usually more strongly attached to the limestone substrates because of partial replacement of carbonate by Mn-Fe oxides and precipitation of the oxides in fractures, pores, and vugs in the limestone (Halbach and Manheim 1984; Benninger and Hein 2000). The presence of limestone will therefore limit the area where the thick Fe-Mn crusts targeted during exploration will be found.

Volcanic Edifice Age

The most promising guyots will be Cretaceous in age because younger volcanic edifices will not have had sufficient time to accrete thick crusts (Usui and Someya 1997; Hein 2004; Zhang et al. 2008). These older seamounts are the only ones that form large guyots with extensive summit areas that have remained stable enough (from gravity processes) to support continuous crust growth for tens of millions of years. Crusts on Cretaceous guyots can be up to 25 cm thick.

Proximity

Areas with clusters of large guyots will be favored because more than one guyot may be needed to fulfil the tonnage requirements for a 15–20-year mine site and ISBA regulations will probably include a confinement area within which exploration blocks can be chosen (see below).

Mining Efficiency

The recovery of crust deposits during mining operations will depend on the small-scale topography, crust thickness, and the extraction technique used, which is presently unknown. Estimates of efficiency have varied from 30% to 80% (Hein 2008; Morgan 2008; Yang 2008). Efficiency will increase significantly with increasing crust thickness and decreasing topographic roughness (Morgan 2008), which is why these two parameters will play central roles during exploration for potential mine sites. Because the efficiency of the mining tool for removing Fe-Mn crust is not known, the issue of mining efficiency may best be addressed here by using recoverable crust thickness (net crust thicknesses) in place of *in situ* crust thickness (gross crust thickness). For example, if the contractor requires 60 kg of crust/m² of seabed (about 3 cm thick crust) for a viable mine site and the efficiency of the mining equipment is 50%, then areas with mean crust thicknesses of ≥ 6 cm would be required and selected for mining; if only 30% efficiency can be obtained, then areas with even thicker crusts would be selected. Net crust thickness will be used here instead of mining efficiency.

Crust Thickness

Guyots with thick crusts will be chosen. The detailed distribution of crust thicknesses is not known for any guyot, nor even for broad areas of a single guyot. Thicknesses vary from less than 1 to more than 20 cm. Sites with crusts of less than 2 to 3 net cm thick will not be considered for mining and it is likely that large areas will be found with mean net crust thicknesses in the range of 3–6 cm (Table 2). The minimum thickness will depend on the method ultimately used for mining crusts, which is yet to be established. We use a mean net crust thickness of 4 cm for our model mine site (Tables 1, 2). Development of a deep-towed instrument to measure crust thicknesses *in situ* will be essential for carrying out a successful exploration program.

Grade

Summit areas with high grades (Co, Ni, Ti, REEs, Mn, Pt, etc.) will be chosen. Grade will depend partly on whether substrate rock is recovered with the Fe-Mn crust, which would dilute the ore grade. This is another reason why thick crusts will be targeted during exploration even though the grades for some of the metals are somewhat lower in thick crusts compared to thin crusts (e.g., Halbach et al. 1982; Hein et al. 1988). The grades of bulk thick crusts do not vary greatly throughout the central equatorial Pacific region.

Permissive Areas

Applying these criteria will delineate areas permissive for Fe-Mn crust exploration and mining. Permissive area is used to define those geographic regions where geologic, geochemical, and oceanographic conditions are appropriate to allow for the formation of thick (high tonnage) and high grade Fe-Mn crusts. We identify both regional and local permissive areas. The most permissive area from a global perspective is the north-central equatorial Pacific (Figure 1). Within that region, a great many volcanic edifices occur both within national jurisdictions and within the Area that would be appropriate targets for exploration. Much smaller regional permissive areas exist in the South Pacific, Atlantic, and Indian Oceans. On a local scale, permissive area refers to those areas on volcanic edifices above 2,500 m water depth.

Assumptions and Calculations Used for the Model Mine Site

For most guyots and seamounts, the surface area that is likely to be mined is less than the area that exists above 2,500 m water depth due to sediment cover, limestone outcrops, rough or steep topography, biological corridor set-asides as refuges and reference sites, and other factors (Figure 2). The amount of surface area lost by each of these can be estimated from side-scan-sonar images, swath bathymetry, bottom-photo surveys, seismic-reflection profiles, and ROV observations.

It should be strongly emphasized that commercial mine sites identified from exploration programs will not be representative of typical or general conditions found on volcanic edifices, but rather will be those rare places where the best conditions for thick and high-grade crusts come together. The following paragraphs outline the conditions that we use as an example exploration/mine-site model that can be applied to determining the size of areas needed by contractors for both the exploration and

mining phases. The average guyot (Table 3) and the largest guyot measured, the composite volcanic structure called Wod-En Ion/Rok located in the Area, are used for model calculations (Tables 1, 2). The largest guyot measured is by no means the largest that exists. Mine-site operations of 15–20 years are considered here.

Crust Exposure/Sediment Cover

Volcanic edifices with more than about 70% sediment cover are unlikely to be considered for mining in favor of more promising edifices as mentioned above. We made calculations based on a range of 5% to 70% sediment cover, and use 60% sediment cover in calculations for our mine-site model (Figure 2). A 60% reduction of the average guyot surface area above 2,500 m ($1,152 \text{ km}^2$) leaves an area remaining of 461 km^2 (or $1,094 \text{ km}^2$ for 5% sediment cover) that could potentially be available for mining; and an area of about $1,230 \text{ km}^2$ for the largest guyot measured (or $2,922 \text{ km}^2$ for 5% sediment cover) (Figure 2).

Area Loss Due to Impediments to Mining

The area not covered by sediment will be further reduced because of prohibitive small-scale topography, un-mined biological corridors, and other impediments to mining; we consider a further approximately 50% reduction to the non-sediment-covered area as a reasonable estimate for these limitations. Consequently, the average guyot would yield 231 km^2 (or 547 km^2 for 5% sediment cover) available for mining; and the largest guyot measured would yield 615 km^2 (or $1,461 \text{ km}^2$ for 5% sediment cover).

With this approximately 80% (60% + 50% of remaining 40%) total reduction in surface area, one average-size guyot could possibly provide the 260 km^2 area above 2,500 m water depth needed for a viable 20-year mine site (Figure 2; Tables 1, 2).

Annual Production

The annual tonnage required to support a viable mining operation is unknown and will depend in part on the global market for metals at the time of mine development. It has been generally accepted that an incursion into the global cobalt market of more than 10% would initiate a slide in market prices (Morgan 2008; Yamazaki 2008). This means that only one or two seamount mine sites could be in operation at any time. Estimates for annual tonnage production have thus varied widely because of the variable annual production of cobalt. Many recommendations in the literature cannot be evaluated because it was not specified whether dry weight or wet weight was being considered. The most common suggestions for production range from about 0.70 to 2 million wet tonnes per year. We base our model mine site on 1 million wet tonnes per year and use a wet bulk density for crusts of 1.95 g/cm^3 (Tables 1, 2).

Crust Thickness and Square-Meter Tonnage

We consider that a mean net crust thickness of 3 cm will be a lower limit (58.5 kg of crust per m^2 of seabed wet weight) and that 2 million wet tonnes per year will be a maximum production. Those thickness and tonnage limitations would require the mining of 684 km^2 of seabed to satisfy a 20-year mining operation (or 342 km^2 for 20 years of 1 million wet tonnes annual production; Tables 1 and 2).

As a good-case scenario, we use a mean net crust thickness of 6 cm (117 kg of crust/m² of seabed wet weight) and 1 million wet tonnes per year production, which would require the mining of 171 km² of seabed during 20 years of operation (342 km² for 2 million wet tonnes annual production).

For the model mine site, a mean net crust thickness of 4.0 cm (78 kg of crust wet weight/m² of seabed) and 1 million wet tonnes annual production would require the mining of 256 km² (rounded to 260 km² hereafter) of seabed during 20 years of operation (Tables 2 and 3).

Scientific exploration has shown that there exist hundreds of square-meter areas on seamounts with mean crust thicknesses of approximately 14 cm, but their extent is unknown. A mean crust thickness of 14 cm would yield an incredible 273 kg wet weight of Co-rich crusts/m² of seabed.

Number of Seamounts

From the data on volcanic edifice sizes and the areas that will likely be available for mining presented in Figure 2, it can be concluded that 2.4 to 5.6 mine sites could be accommodated on a large guyot given the parameters for our model 20-year mining operation; 0.9 to 2.1 mine sites on an average guyot. Larger guyots exist than the largest one measured here and most of the ridges and plateaus measured are larger than the largest guyot measured. Under favorable conditions, a single edifice could accommodate a 20-year mining operation. Large guyot summits with little sediment cover, relatively subdued topography, and thick crusts will be targets for exploration and the likely location of future mine sites.

Selection of Exploration- and Mine-Site-Block Sizes

The block size best suited for exploration and that for a mine site are different. The term blocks will be used for exploration units and sub-blocks for mine-site units. The choice of a sub-block size to define a mine site is somewhat arbitrary; however, the size should be small enough so that areas with continuous coverage by crusts can be enclosed within a single sub-block. Based on the range of seamount parameters discussed above (Tables 1–3), sub-block sizes of 10–40 km² (3.16 to 6.32 km on a side) would be reasonable for defining a mine site. Based on the senior author's experience studying seamounts in the field and a literature survey concerning the distribution of crusts on guyot summits, a sub-block size of about 20 km² (4.47 km on a side; or 4 by 5 km) is reasonable that in aggregate can successfully define a mine site (Figures 3–6). It is likely that those 20 km² sub-blocks will be strung together in a pattern that follows summit terrace, platform, and saddle topography. About 13 such sub-blocks strung together or clustered would comprise our model 20-year mine site consisting of about 260 km². The 13 sub-blocks may be on the summit of one guyot, or perhaps split between two or more guyots (Figures 3–6). For our minimum crust-thickness scenario (Table 2), about 34 sub-blocks would be needed to cover the 684 km² 20-year mining operation.

The choice of a lease-block size for exploration is also somewhat arbitrary; however, the size should be large enough so that a limited number of seamounts will be included in a single license. A reasonable block size would be 100 km², or five times the sub-block size used to define a mine site; this 100 km² need not form a square, but must consist of contiguous 20 km² sub-blocks (see examples below in Figures 4, 5). The size

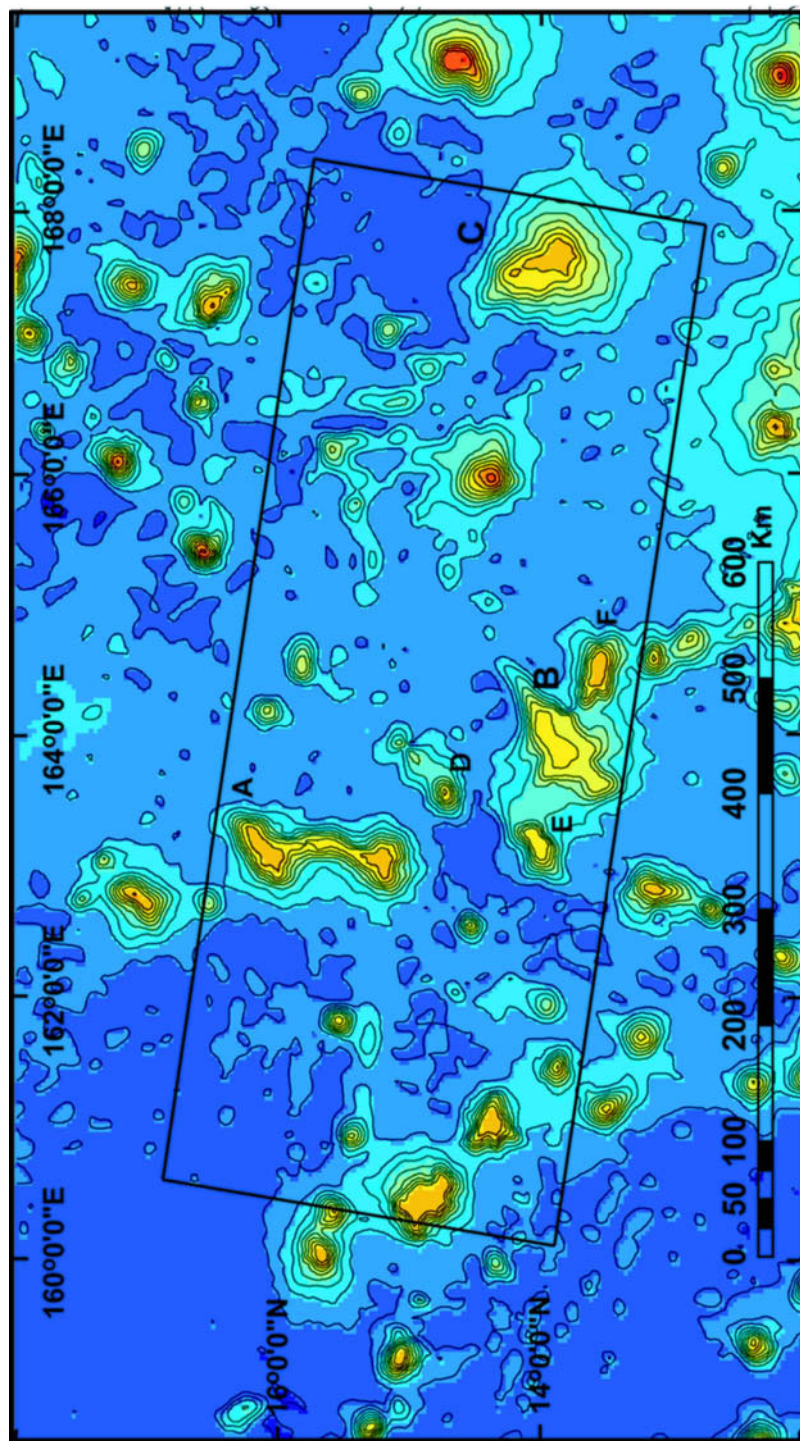


Figure 3. Area used to illustrate a hypothetical mine-site model. Parts of the seamounts labelled A through F are considered for applications for exploration and mining licenses in this illustrative model (see Figures 4–6). The rectangle is a 300,000 km² confinement area within which the exploration blocks can be identified.

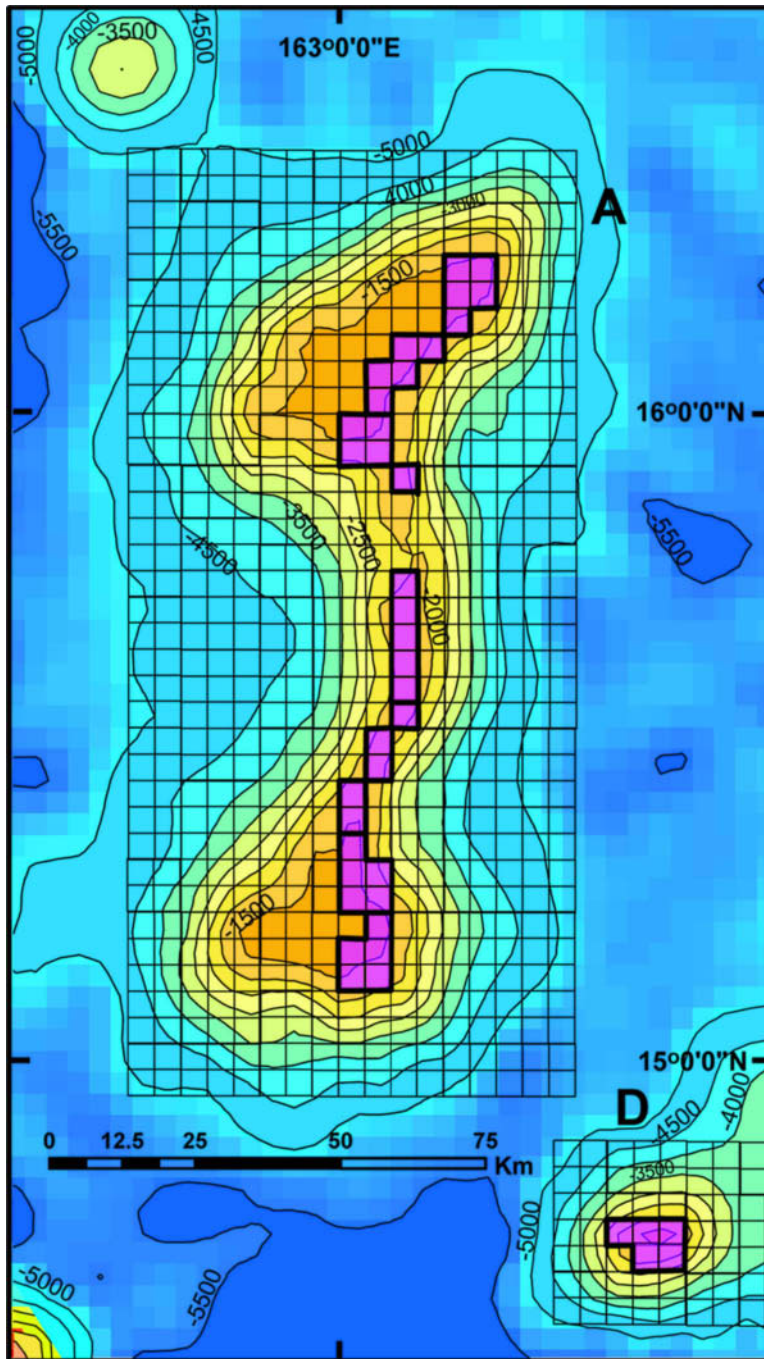


Figure 4. Seamounts A and D from Figure 3 overlain by a 20 km^2 grid. Seven 100 km^2 exploration blocks on seamount A and one on seamount D were chosen, each exploration block composed of five 20 km^2 sub-blocks.

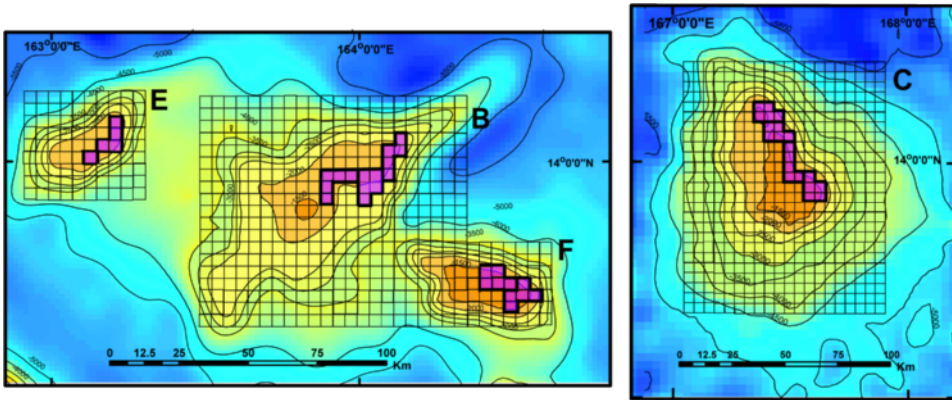


Figure 5. Seamounts B, C, E, and F from Figure 3 overlain by a 20 km² grid. Three 100 km² exploration blocks on seamount B, four on seamount C, one on seamount E, and two on seamount F were chosen, each exploration block composed of five 20 km² sub-blocks.

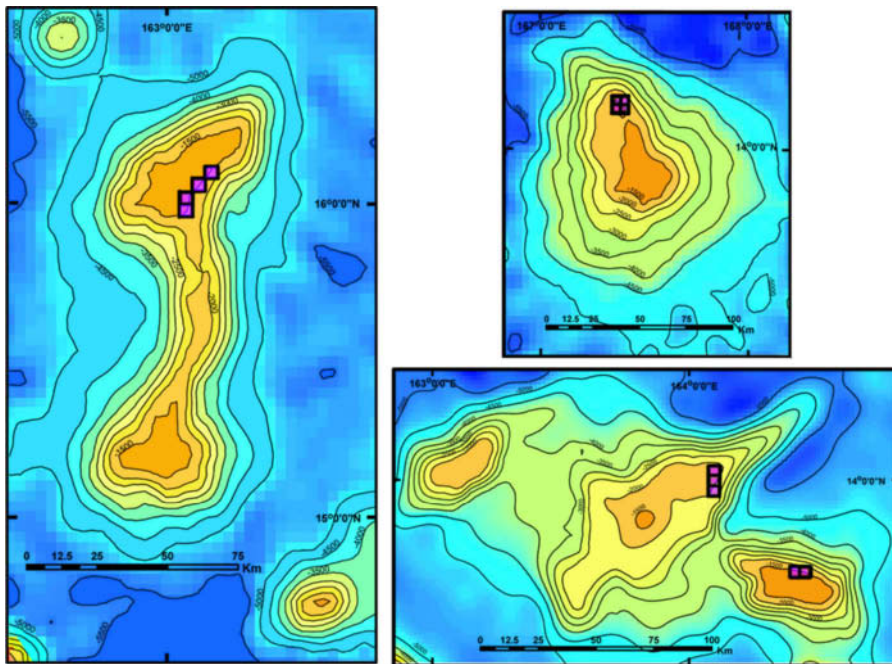


Figure 6. Thirteen of the 90 sub-blocks that compose the 18 exploration blocks were chosen for the final mine site. Four of the six seamounts in this hypothetical case were found to contain Fe-Mn crust resources adequate for a 20-year mine site. The total surface area of the mine site is 3.7% of the total surface area above 2,500 m water depth for the four seamounts or 0.01% of the total surface area of the four seamounts.

of the area allotted for exploration is again somewhat arbitrary and has generally been considered by the LTC to be about five times the area needed for a 20-year mine site. This factor might be a little too conservative and using perhaps seven times the 20-year mine-site area would provide sufficient area for exploration. Using that number, the area of exploration would be 1,820 km² for our model mining operation (Table 2). Thus, for our model mine site, about eighteen 100 km² exploration blocks would be allocated. For the minimum crust-thickness and good-case scenarios, about forty-eight and twelve 100 km² blocks, respectively, would be needed (Table 2).

It may be considered that exploration licenses cover portions of the summit area of guyots above 2,500 m water depth and that sub-blocks will be relinquished as unfavorable areas are identified along a given summit. In reality, the contractors will likely have a good idea prior to applying for exploration licenses where the most promising Fe-Mn crust blocks are located on a volcanic edifice and may request blocks on numerous seamounts located throughout a large region. If that is not a desirable outcome, then the dual lease-block size discussed here, combined with a confinement area in which to place exploration blocks (see next paragraph), will produce a workable solution. The 20 km² sub-blocks should be the block size used for relinquishment of territory in addition to defining the final mine site.

A mechanism is required to confine the area in which a single exploration license can be given so that “cherry picking” across a large area of the oceans does not take place. It is important to emphasize that the confinement area would disappear once the exploration blocks are identified and a license allocated. Then, that same area, excluding the licensed blocks, would be available for part of another contractor’s confinement area if so needed. The most common proposal by the LTC for a confinement area has been a square of 5° latitude on a side. Since the area of that latitude-defined square would change with latitude, a numerical designation would be more equitable. Also, allowing for the flexibility of using a rectangle rather than a square would be preferable. A confinement rectangle could be defined by using two parameters: a long dimension of not greater than 1,000 km and an area of not greater than 300,000 km², which defines an area near that of a 5° latitude/longitude square at the equator (~308,000 km²). A similar confinement metric was proposed during the 14th Council session in 2008 for polymetallic sulfides (also see discussion by Hannington and Monecke 2009).

In summary, for our model mining operation, about eighteen 100 km² blocks would be leased for exploration and chosen from within a confinement rectangle of 300,000 km². About 1,820 km² would be provided for each initial exploration license. Within designated periods of time, groups of 20 km² sub-blocks would be relinquished until finally about 13 sub-blocks of 20 km² remain that will approximate the final 260 km² 20-year mine site used here as an example. If an adequate mine site is not found, then an application for a second exploration license could be made.

Illustration of the Model Mine Site

This is a hypothetical illustration and is not a recommendation nor indication of potential mine sites. The area considered includes the largest guyot measured here and several smaller nearby guyots that we use for our model exploration and mine site, which span the northwest border of the Republic of the Marshall Islands EEZ. The 300,000 km² confinement area includes guyots with a total surface area above 2,500 m water depth of 12,723 km², which includes many seamounts not used

in our illustration as potential exploration targets; total area excludes atolls. Based on previous prospecting, exploration blocks would be chosen (Figures 4, 5). Seamount A has a total surface area of 3,076 km² above 2,500 m water depth, of which 23% is chosen here to be included in the exploration license. If 59% or more of the permissive surface area of this single guyot was found to be appropriate for exploration, then this single edifice could accommodate the license for the confinement area. Figures 4 and 5 show the eighteen 100 km² blocks illustrated here for the model mine site to be licensed for exploration, each composed of five 20 km² sub-blocks. The area licensed for exploration covers 22.8% of the total area above 2,500 m for those six edifices and the mine site covers 3%, or 3.7% of the area above 2,500 m on the four edifices with identified mine-site sub-blocks. The final mine site would cover 0.01% of the total area of the four impacted edifices.

Some of the exploration territory would be relinquished during two or more stages during the lifespan of the license, finally ending up with thirteen 20 km² sub-blocks that would define the final 260 km² mine site (Figures 4–6). In this example, the eighteen 100 km² exploration blocks are not always contiguous and the final choice of thirteen 20 km² sub-blocks for mining operations are also not always contiguous, but both types of blocks commonly occur in clusters.

This same lease-block analysis can be made for a 15-year mine-site scenario in which case the areas needed for exploration and a mine-site would be significantly less (Tables 1, 2).

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