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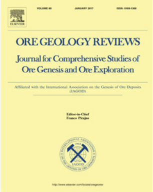

An integrated method for the quantitative evaluation of mineral resources of cobalt-rich crusts on seamounts

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ABSTRACT

Cobalt-rich crusts on seamounts potentially have the economic value of multiple metals. In the field of exploration, it is important to perform quantitative evaluations of mineral resources and delineate promising areas in survey regions for future mining. Accordingly, this study, based on prior knowledge, develops an integrated method to quantitatively evaluate mineral resources of cobalt-rich crusts on seamounts and gives an application example to demonstrate this method. The method includes four steps: first, defining units with certain areas and shapes on the target seamount (a 20 km^2 square block in the application example) and estimating characteristic values of the cobalt-rich crust for each unit with known geological survey data using a space interpolation method such as Kriging; second, presenting several model algorithms, i.e. Regional Coverage of Crusts, Suitable Slope Percentage for Mining and Fitting Area on Slopes, to extract the corresponding regional metallogenic factors for each unit by inputting regional surveying data (such as bathymetry data) into these models; third, considering both the features and regional metallogenic factors of cobalt-rich crusts in each unit to estimate their distribution of mineral resources on the entire seamount; and last, according to the distribution of the mineral resources and international social and economic requirements (such as the regulations of the International Seabed Authority), delineating a promising area for future mining.

1. Introduction

Cobalt-rich crusts occur on sediment-free surfaces of seamount slopes and summits and attract economic interest owing to their potential for manganese, cobalt, nickel, rare earth elements, tellurium and platinum resources (Hein et al., 2000; Hein, 2000; Verlaan et al., 2004). Therefore, explorations and evaluations of the mineral resources on seamounts have been performed by many countries since the 1980s. To delineate a promising area for future mining according to the regulations of the International Seabed Authority is an important task. Accordingly, many scientists are conducting studies to quantitatively evaluate mineral resources of cobalt-rich crusts on seamounts.

Yamazaki and Sharma (1998), based on data from camera photos and television video, have analysed the relationship between the coverage of cobalt-rich crusts/nodules and slope gradients on the Maloney Guyot in the Marcus-Wake Seamounts and have concluded that cobalt-rich crusts are enriched in areas where the gradients of the slopes are greater than 15°; when the slope is between 0°and 3°, they observed exposed sediment with some cobalt-rich nodules; when the gradients are between 4° and 15°, cobalt-rich crusts and nodules coexist with sediment. Chu et al. (2006) compared the coverage of the cobalt-rich crusts on spire seamounts with that on guyots and revealed that spire seamounts have higher crust abundances and coverage than guyots. Wu et al. (2000) presented the method of nearest domain and geological block to evaluate mineral resources of cobalt-rich crusts on a seamount in the eastern Pacific. He (2001) and Zhang et al. (2007) found that the distribution of cobalt-rich crusts on 12 seamounts in the western Pacific followed multidimensional fractal relationships with the slope gradient and water depth, and they believe that these relationships can be used with the method of nearest domain and geological block to delineate promising areas for future mining. Ma et al. (2007) proposed two parameters, the arisen frequency of mine and the ore-forming coefficient, to evaluate cobalt-rich crusts. Thickness, water depth, slope, coverage, metal concentration, abundance, area for exploration and area for future mining are emphasized as important factors in the

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evaluation of cobalt-rich crusts (Zhang et al., 2008; Hein et al., 2009). Kim et al. (2013) analysed the correlation between photos and videos and geological sampling data with acoustic backscatter data and concluded that acoustic backscatter data can be used to determine the regional spatial distribution of the cobalt-rich crust. Russian scientists on the ice breaker ship Yuzhmorgeologiya are investigating mineral resources on Pacific seamounts and attempting to delineate the most promising seamount areas for future mining (Novikov et al., 2014).

These studies show that (1) slope gradients, the depth of the water, terrain conditions and other parameters are integrated factors that control the distribution of mineral resources on seamounts; (2) international scientists are examining the problem from different angles to find a better method to identify areas that are rich in mineral resources on seamounts; (3) synthesizing geological sampling data with geophysical regional surveying data maybe an effective way to improve evaluations to determine regions that are best for future mining and (4) a synthesized and quantitative method to evaluate cobalt-rich crusts is currently absent.

Based on prior knowledge and our own studies, a comprehensive method is proposed here to quantitatively evaluate mineral resources in cobalt-rich crusts on seamounts by synthesizing geological sampling data with geophysical regional surveying data and using multiple methods and parameters to delineate promising areas for future mining. This method is demonstrated on the Magellan Seamounts in this paper.

2. Location and data

2.1. Location

The Magellan Seamounts, which are composed of a dozen guyots, are located to the east of the Mariana Trench in the northwest Pacific. Several guyots from the Magellan Seamounts, named Guyots MK, ME, Caiwei and Jiaxie, were selected as examples to demonstrate the evaluation of mineral resources of cobalt-rich crusts, as shown in Fig. 1. In particular, Guyot MK, located at 150°E, 17°N was evaluated.

Investigations and studies of cobalt-rich crusts on the Magellan Seamounts are abundant and comprehensive. Crust distribution, metallogenic conditions, geological chronology, layer structure, mineral and chemical composition, topography and substrate rock have all been evaluated and studied (Usui and Someya, 1997; Melinikov and Pulyaeva, 1994; Melinikov, 2005; Melinikov et al., 2006, 2007; Melinikov and Pletnev, 2009; Melinikov et al., 2009, 2012a,b; Melnikov and Pletnevb, 2013; Ren et al., 2011; Glasby et al., 2007; Bogdanov et al., 1998; Novikov et al., 2014; Hein et al., 2000; Okamoto and Usui, 2014). Previous studies of seamounts and their cobalt-rich crusts provide prior knowledge when evaluating mineral resources.

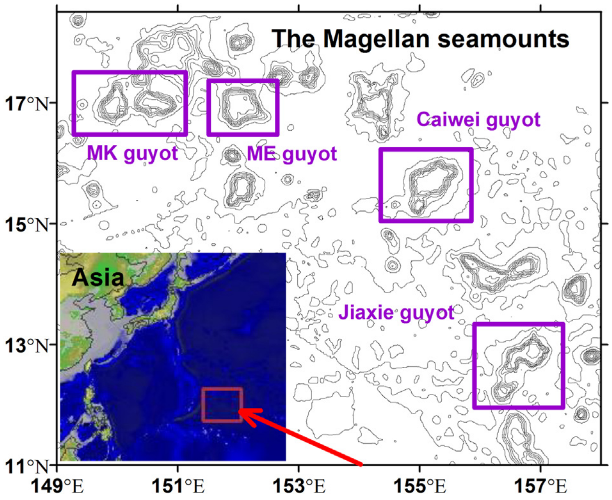

Fig. 1. The location of the guyots. (Guyot MK is the target seamount to be evaluated for its mineral resources. Guyots ME, Caiwei and Jiaxie were included in the evaluation in the following demonstration example.)

2.2. Geological sampling data and cobalt-rich crust features

Since the 1990s, the Magellan Seamounts in the western Pacific (shown in Fig. 1) have been investigated as promising regions for cobalt-rich crust deposits by geologists from the China Ocean Mineral Resources R&D Association (COMRA), and the guyots ME, MK, Caiwei and Jiaxie were chosen as examples to demonstrate our integrated method. On the seamounts, many types of data have been obtained, including bathymetric data by the Simrad EM120 multibeam echo sonar, camera and television video images and geological sampling data.

2.2.1. Thickness of the crusts

Sampling methods included submarine drilling and dredging. Crust samples were measured to obtain their thickness using a steel rule on the deck of a surveying vessel. There are a total of 264 crust thickness data from the four guyots.

2.2.2. Water content

The wet crust weight was measured using a balance. Then, the sample was put into a vacuum dryer to be dried, and the dry crust weight was measured to obtain the final rate of water content.

2.2.3. Wet density of the crusts

The wet weight (g) and volume (ml) of the crust samples were measured on the deck of the vessel. The wet density of the crust (g/cm^3) is the quotient of the wet weight (g) divided by the volume (ml).

2.2.4. Coverage of crusts

The coverage of crusts is the exposure percentage of the crusts in a local area, which can be observed and estimated using a near-seabed visual observation system. At our surveying stations, the coverage of crusts was approximately 40–80%.

2.2.5. Metal concentration

Samples were ground into a uniform powder, and four ore elements (Cu, Co, Ni and Mn) were analysed using the AAS method. A total of 50 data sets of the ore element concentration were obtained from the crusts on Guyot MK.

2.2.6. Cobalt-rich crust features

The cobalt-rich crust features include five parameters: thickness, wet density, water content rate, coverage and metal concentration. These parameters were all obtained at the geological survey stations primarily by sampling and provide direct and effective information for the evaluation of mineral resources, especially in local areas.

2.3. Regional survey data and regional metallogenic factors

2.3.1. Regional survey data

There are remarkable distinctions between the regional survey data and the geological sampling data. Regional survey data are primarily obtained using geophysical surveying methods, such as bathymetry, sonar image mapping, gravity and magnetic surveying, and they have multiple advantages, such as denser survey data points, smaller costs and wider coverage. They provide indirect information for evaluating mineral resources; therefore, by analysing the relationships between regional survey data and geological sampling data, we can extract regional metallogenic factors for the quantitative evaluation of mineral resources. Combining regional survey data with geological sampling data, we can not only improve precision mineral resource estimation but also reduce the cost of the survey.

The bathymetry data from the EM120 multibeam echo sonar are applied in the demonstration example and were interpolated to a 100 m × 100 m grid data using ArcGIS.

Additional regional survey data, such as side scan sonar images, can be used with this method too.

2.3.2. Regional metallogenic factors

The information extracted from regional geophysical surveying data that can be used to evaluate mineral resources of cobalt-rich crusts on seamounts are defined as regional metallogenic factors, such as the Regional Coverage of Crusts, the Suitable Slope Percentage and the Fitting Area on Slopes, which will be incorporated in the following section.

3. Methodology and demonstration

The methodology includes the following steps:

(1) Defining units on a seamount

First, certain areas and shapes on the target seamount are defined as units (20 km^2 square blocks in this demonstration). All operations, such as estimating cobalt-rich crust features, extracting regional metallogenic factors and estimating the distribution of mineral resources, are executed for each unit.

(2) Estimating cobalt-rich crust features in each unit

The features of the cobalt-rich crust in each unit are estimated based on the known geological survey data via a spatial interpolation method, such as Kriging or another feasible method.

(3) Extracting regional metallogenic factors

Several model algorithms, such as the Regional Coverage of Crusts, the Suitable Slope Percentage for Mining and the Fitting Area on Slopes, are used with the input regional survey data (e.g. the bathymetry data), and the corresponding regional metallogenic factors for each unit are extracted.

(4) Estimating the distribution of mineral resources

Considering both the cobalt-rich crust features and the regional metallogenic factors of the cobalt-rich crusts in each unit, the distribution of mineral resources on the entire seamount is estimated.

(5) Delineating a promising area for future mining

According to the distribution of mineral resources on the seamount and the international social and economic requirements (such as the regulations of the International Seabed Authority), promising areas for future mining are delineated. A flow diagram of the method is shown in Fig. 2, and detailed steps are described in the following sections.

3.1. Dividing units

The divided units have the same area and shape, and each unit has a specific location on one or several seamounts. The units are the targets, and all operations, such as estimating the cobalt-rich crust features, extracting regional mineral factors and estimating the mineral resources, are aimed at the units. Once the mineral resources on some of the units are estimated, their distribution on one or several seamounts is estimated. In the demonstration, 20km^2 square grid cells are used as units.

Units on seamount slopes are divided according to multiple factors, such as the aim of the mineral resource evaluation, distribution characteristics of the crusts, the form and scale of the seamount and the precision of the survey data.

The regulations of the International Seabed Authority(ISBA/13/LTC/3) specify that the area of the basic unit for cobalt-rich crust exploration and application on seamounts is 20 km^2; therefore, the unit area of mineral resource evaluations for this purpose should not be greater than 20 km^2 (Hein et al., 2009).

In our demonstration, the area on Guyot MK shallower than 1500 m is a flattop covered by unconsolidated sediment; on its slope deeper than 4000 m, the crusts are thin and sparse. The geological survey station for this study is located in the depth range of 1500–4000 m. If the area of each unit is 20 km^2, the number of grid cells in the bathymetry data is approximately 2000; therefore, there are enough bathymetry data to analyse the terrain characteristics and extract regional metallogenic factors. According to the comprehensive factors above, in the range of 1500–4000 m depth, the slope of Guyot Mk was divided into units using horizontal projection areas of 20 km^2 square grid cells.

3.2. Cobalt-rich crust features

Each unit has sufficient bathymetry data for a terrain characteristics analysis; however, not all units include a geological sampling station. To assign a value to the cobalt-rich crust features for each unit, space interpolation methods (such as Kriging, simple average value and distance inverse weighting) are used.

3.2.1. Estimating the thicknesses of the crusts

Of all the cobalt-rich crust features, the crust thickness has the largest variation coefficient (shown in Table 1) and contributes much more to spatial changes in mineral resources. Finding a suitable spatial interpolation method to improve the estimating precision is an important component of mineral resource evaluations.

Kriging is a widely used and effective method for mineral resource estimations and reserve calculations (David, 1977; Journel et al., 1978); however, Kriging faces two problems when evaluating mineral resources on seamounts. First, conventional distance–orientation-based, or simply distance-based, variogram functions do not express the spatial self-correlation or spatial continuity of cobalt-rich crust thicknesses on seamounts (Du et al., 2017); Second, sampling stations on a single seamount are very sparse for conducting an experiment and fitting a variogram. In this paper, we used the distance-gradient-based variogram method (Du et al., 2017) based on united data from Guyots MK, ME, Caiwei and Jiaxie for the experiment and fitted a variogram; we then used Kriging to interpolate for the thickness of the cobalt-rich crusts on Guyot MK.

To evaluate how well the interpolation actually predicts thicknesses of cobalt-rich crusts on surveying stations, we used subsets of surveying data that could demonstrate how kriging improved the interpolation precision of estimating the thicknesses of cobalt-rich crust on seamounts. In addition to the kriging, we also considered the window averaging and the inverse distance weighting method. Here we set the same interpolation parameters, i.e. the same search radius and information point number, for each of these three methods.

Finally, we obtained interpolated values for 28 of the surveying stations (i.e. a subset of surveying stations). Therefore, we obtained

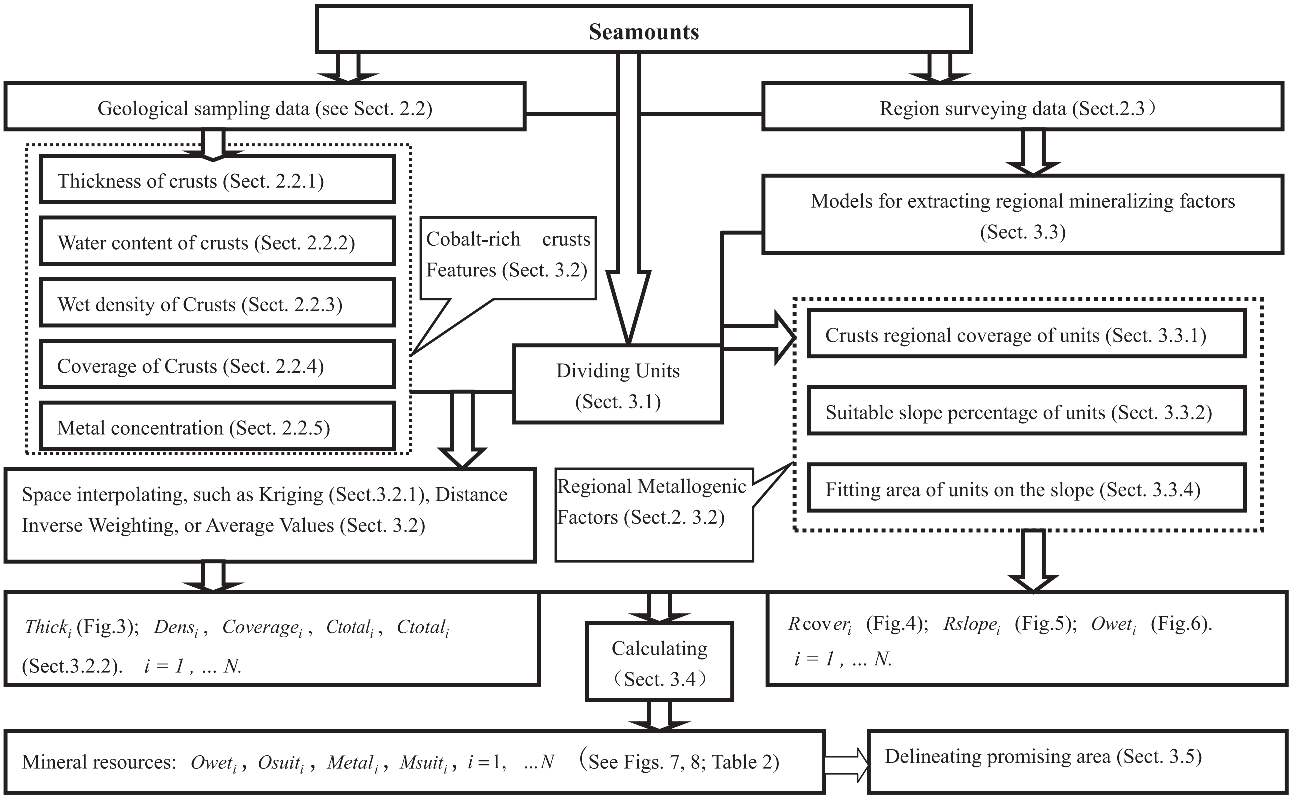

Fig. 2. Flow diagram of the method for evaluating mineral resources on a seamount.

Table 1
Statistical features of the crust variables on Guyot MK.

Feature	Variable							
	Concentration (%) (Cu + Ni + Co + Mn)	Cu (%)	Ni (%)	Co (%)	Mn (%)	Water (%)	Density (g/cm^3)	Thickness (mm)
Mean	21.45	0.13	0.40	0.50	20.42	26.52	1.86	58.0
Standard deviation	2.36	0.03	0.08	0.10	2.22	2.54	0.10	33.7
Relative deviation (%)	11.0	18.9	21.2	19.9	10.9	9.6	5.6	56.9

The statistical features of the metal concentration were calculated with 49 samples, the water content or density was calculated with 50 samples and the thickness was calculated with 77 samples.

two sets of values regarding cobalt-rich crust thicknesses, i.e. known data obtained via surveying and forecast values estimated by window averaging, inverse distance weighting or Kriging methods. The relative errors between the two sets of values for the three methods were 28.2%, 21.0% and 17.1% respectively. Moreover, the average errors for the three methods were 19.2 mm, 14.3 mm, 11.6 mm respectively. Furthermore, the correlation coefficients were 0.36, 0.75 and 0.84 respectively. The forecasting effects of the three methods were obviously different. Of the three, the Kriging interpolation method had the smallest average and relative errors, as well as the largest correlation coefficient.

Given the above, we give preference to the Kriging as a spatial interpolation method for estimating the thicknesses of the crusts. The distribution of cobalt-rich crust on guyot MK estimated by the Kriging method is shown in Fig. 3.

3.2.2. Estimating other features

In addition to the thickness of the crust, there are other cobalt-rich crust features that need to be interpolated for the units on the slope of the seamount. As with the crust thickness, the average values, distance inverse weighting and Kriging can also be used to interpolate these features.

(1) Coverage of Crusts

The Coverage of Crusts is expressed as the exposure percentage of the crusts in a local area that can be observed and estimated via a seabed visual observation system at geological sampling stations (Yamazaki, 1993; Yamazaki and Sharma, 1998; Chu et al., 2006; Zhang et al., 2007). This variable is similar to thickness in that it has values only at the observation stations. It is difficult to interpolate the coverage for the units due to the scarcity of the observation stations.

On the slope of Guyot MK, according to TV observation data from COMRA, the Coverage of Crusts has values ranging from 40% to 80% on the sediment-free slopes. The value of each unit is $Coverage_i = 60$, $i = 1, \dots N$ ($N = 228$). This homogenization value is useful for estimating the mineral resources but useless for locating ore-rich units.

(2) Metal concentration

The metal concentration (Cu + Co + Ni + Mn) has the smallest variation coefficient, as shown in Table 1, of all the cobalt-rich crust features, approximately 11%, which is one fifth that of the

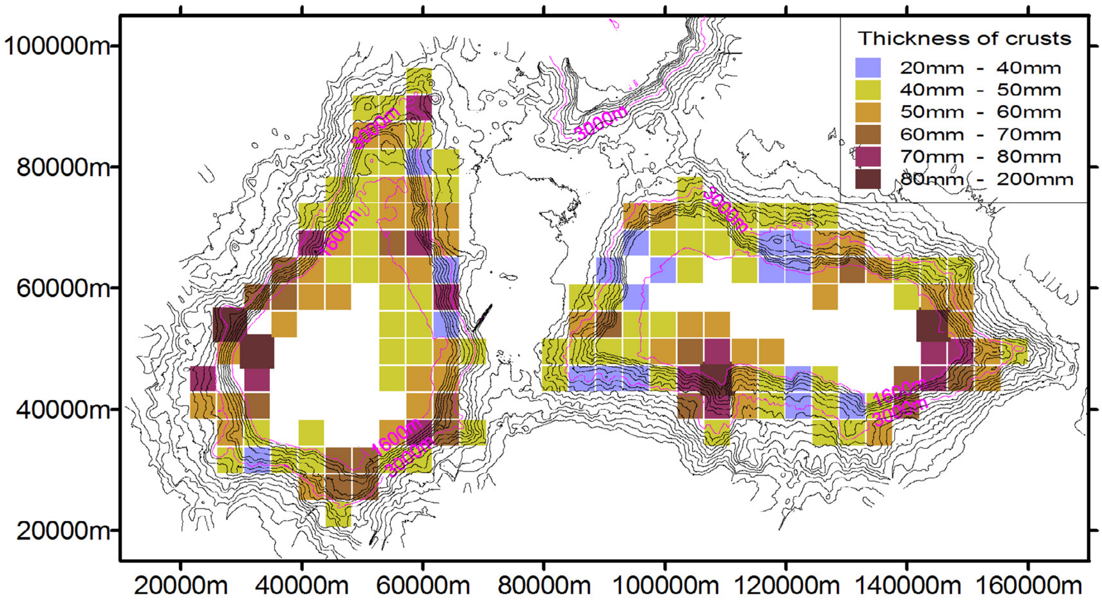

Fig. 3. Cobalt-rich crust thicknesses of units on Guyot MK estimated via Kriging The starting coordinate is 149° 30′ E and16° 30′ N, and the area of the units is 20 km^2 in the horizontal projection. *Thick* indicates the estimated values of the crust thickness in each unit: $Thick_i$, $i = 1, \ldots N$, where i is the serial number and $N = 228$ is the total number of effective units on Guyot MK.

crust thickness, and contributes little to the spatial change of mineral resources. Therefore, we use the average value, 21.45%, of 50 stations as the values for the units. The total metal concentration is written as $Ctotal_i$, $i = 1, \ldots N$, where i is the unit number and N is the total number of effective units on the guyot, $Ctotal_i = 21.45\%$, $i = 1, \ldots N$ ($N = 228$). Conversely, if there are enough data, the Kriging method can be used to interpolate for this value.

(3) Water content and the density of the wet crusts

For the same reason, the average values of the water content, 26.52%, and the density of the wet crusts, 1.86 g/cm^3, are assigned for the units, where the values of the water content and the density of the wet crusts of each unit are $Water_i = 26.52\%$, $i = 1, \ldots N$ and $Dens_i = 1.86$ g/cm^3, $i = 1, \ldots N$, respectively ($N = 228$).

3.3. Models for extracting regional mineral factors

Several models or methods can be set up and used to extract regional mineral factors from regional survey data to evaluate mineral resources on seamounts. In this demonstration, three models are presented to extract regional mineral factors, and only the bathymetry data are used. In the near future, additional methods maybe used, and other geophysical survey data may be included.

3.3.1. Regional coverage of crusts

In general, some slopes on seamounts are covered by loose sediment and other slopes consist of substrate rocks covered by cobalt-rich crusts (there maybe additional situations, such as cobalt-rich nodes with sediments on slight gradient slopes, which will be discussed in Section 4). It is always interesting to determine the difference between the two types of slopes.

The Coverage of Crusts is usually used to describe the percentage of substrate rocks covered by cobalt-rich crusts on slopes that are observed and estimated via geological sampling and the video system on geological survey stations (Yamazaki et al., 1995; Xu et al., 2011). These methods are effective but expensive and are limited to a local area due to the sparse station network; the concept of the Coverage of Crusts is seemingly used to describe the local character of the proportion and is difficult to deduce for regional areas. Therefore, the concept of Regional Coverage of Crusts is proposed in this study to describe the regional character of the percentage of substrate rocks covered by cobalt-rich crusts on slopes. It is defined as the percentage of sediment-free slopes that are favourable to the growth of crusts in the regional area.

Yamazaki et al. (1995) and Yamazaki and Sharma (1998) found that slopes with gradients between 0°and 4° are covered by sediment and crusts there are sparse; meanwhile, from 0°to 3°, there are no crusts, only some nodules. Xu et al. (2011) found that slopes are entirely covered with sediments when their gradients are smaller than 2°. In our study on Guyot MK, the slopes gradients of 29 shallow drilling stations on which cobalt-rich crusts were obtained were all greater than 4°, and the 7 stations on which sediments were obtained all had slopes smaller than 4°.

These observations have been confirmed by geotechnical studies in hydrodynamic environments (Huhnerbach and Masson, 2004; Kvalstad et al., 2005; Urlaub et al., 2015; Hornbach et al., 2007; Sultan et al., 2004; Masson et al., 2010). When the gradient of the slopes exceeds a certain threshold value, unconsolidated sediments on the slope move down to the bottom of the seamount because of gravity. Moreover, consolidated rocks are exposed as a substrate for cobalt-rich crusts to grow stably on it. Conversely, when the gradient of the slopes is under a certain threshold value, the slope on the seamount becomes a sediment field, which is not favourable to crust growth. Based on this knowledge, we present a model to estimate the Regional Coverage of Crusts.

Models to estimate the Regional Coverage of Crusts are the following:

The gradient of the slope is denoted by g, and there exists a certain threshold value, $g_{\min}$ (degree).

When $g \leqslant g_{\min}$, slopes are covered by sediments or have poor crusts; when $g > g_{\min}$, slopes are covered by substrate rocks with crusts. The percentage of the slope area with $g > g_{\min}$ is defined as the Regional Coverage of Crusts.

Assume that there are N grid nodes of bathymetry data in a unit. A gradient is calculated for each node via a 3 × 3 difference operator (Shi et al., 2007). $N(g > g_{\min})$ denotes the total number of nodes with gradients greater than $g_{\min}$. Then, the Regional Coverage of Crusts ($Rcover$) is estimated as

$$Rcover \approx \frac{N(g > g_{\min})}{N} \times 100\% \tag{1}$$

When using bathymetry data to estimate the Regional Coverage of Crusts, the key is to confirm the threshold value $g_{\min}$, which is a physical parameter subject to the hydrodynamic environment and engineering mechanical parameters of the sediments (Urlaub et al., 2015). According to previous study results (Huhnerbach and Masson, 2004; Kvalstad et al., 2005; Hornbach et al., 2007; Sultan et al., 2004; Masson et al., 2010) and our study on Guyot MK, a value of 4° was assigned to $g_{\min}$; the Regional Coverage of Crusts was estimated in each unit and its distribution is shown in Fig. 4.

3.3.1. Suitable slope percentage

Even though slopes with larger gradients are favourable for crust growth, slopes with too high a gradient are either prone to landslides with thin crusts or are not favourable to the operation of mining machinery. Assume that there is certain threshold value, $g_{\max}$, where, when $g \geqslant g_{\max}$, slopes with a gradient of g are not favourable to mining.

Taking Sections 3.3.1 and 3.3.2 into account, the Suitable Slope Percentage is defined by the following.

When $g_{\min} < g < g_{\max}$, slopes on a seamount with gradient g are suitable slopes for crusts to grow and for mining in the future. Therefore, the percentage of slope area with $g_{\min} < g < g_{\max}$ is defined as the Suitable Slope Percentage (*Rsuitable*).

The estimated value of the Suitable Slope Percentage (*Rslope*) is given by Eq. (2)

$$Rslope \approx \frac{N(g_{\min} < g < g_{\max})}{N} \times 100\% \tag{2}$$

The calculation method for the gradient is the same as that used in Eq. (1)

In this example, $g_{\min} \approx 4^o$ and $g_{\max} \approx 15^o$, and *Rslope* in each unit is found via Eq. (2), such that $Rslope_i$, $i = 1, \ldots N$ $(N = 228)$, as shown in Fig. 5.

3.3.2. Fitting area on slopes

The slope area is one of the most important parameters for estimating the mineral resources, and precisely fitting the area on the slopes is one of the most important premises to accurately estimate the mineral resources. The quotient of the horizontal projection area of a unit divided by the cosine of the average gradient of the slopes is usually used to estimate the slope area (Hein et al., 2009). In this paper, the following method is used: based on the grid data of bathymetry, the areas of two triangle slopes in each grid cell are calculated accurately in a 3D coordinate system, and then, the areas of the triangle slopes in each unit are accumulated to obtain the Fitting Area on Slopes. The distribution of fitting areas is shown in Fig. 6. Differences of slope area between units are large, and the maximum is 27.5 km^2. The mineral resources calculated from the Fitting Area on Slopes will increase by approximately 30% compared with those calculated from areas provided by previous methods. The Fitting Area on Slopes is denoted by $Area_i$, $i = 1, \ldots N$ $(N = 228)$.

3.4. Calculating for the mineral resources

Four indexes of the mineral resources are used here, the million tonnage of wet ore (*Owet*), the million tonnage of wet ore on suitable slopes (*Osuit*), the million tonnage of metal (*Metal*) and the million tonnage of metal on suitable slopes (*Msuit*). For all of the above, $i = 1, \ldots N$, where N is the total number of effective units on Guyot MK $(N = 228)$.

3.4.1. The tonnage of wet ore (in millions of tonnes)

$$\begin{aligned} \mathrm{Owet}_i = {} & Area_i(\mathrm{km}^2) \times Thick_i(\mathrm{mm}) \times Rcover_i \times Coverge_i \\ & \times Dens_i \times 10^{-7} \end{aligned} \tag{3}$$

The distribution of Owet$_i$ is shown in Fig. 7 and Table 2.

3.4.2. The tonnage of wet ore on a suitable slope (in millions of tonnes)

$$\begin{aligned} \mathrm{Osuit}_i = {} & Area_i(\mathrm{km}^2) \times Thick_i(\mathrm{mm}) \times Rslope_i \times Coverage_i \\ & \times Dens_i \times 10^{-7} \end{aligned} \tag{4}$$

The distribution of Osuit $_i$ is shown in Fig. 8 and Table 2.

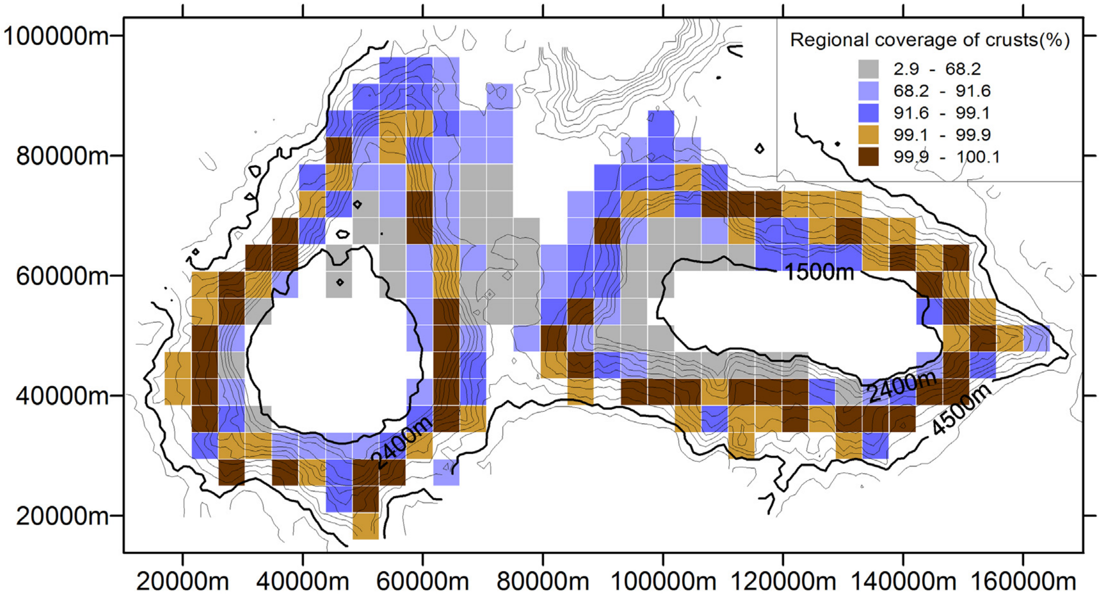

Fig. 4. Distribution of the Regional Coverage of Crusts, $Rcover_i$, $i = 1, \ldots 228$. $g_{\min} \approx 4^o$, percentage calculated from Eq. (1).

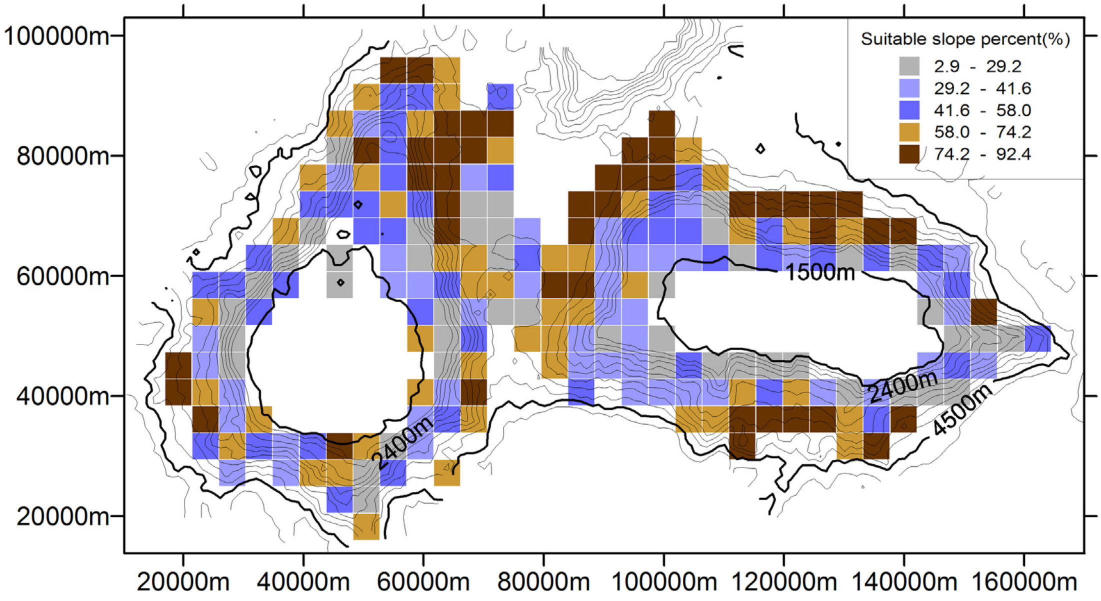

Fig. 5. The Suitable Slope Percentage, $Rslope_i$, $i = 1, \ldots 228$. $4^o < g < 15^o$, percentage calculated by Eq. (2).

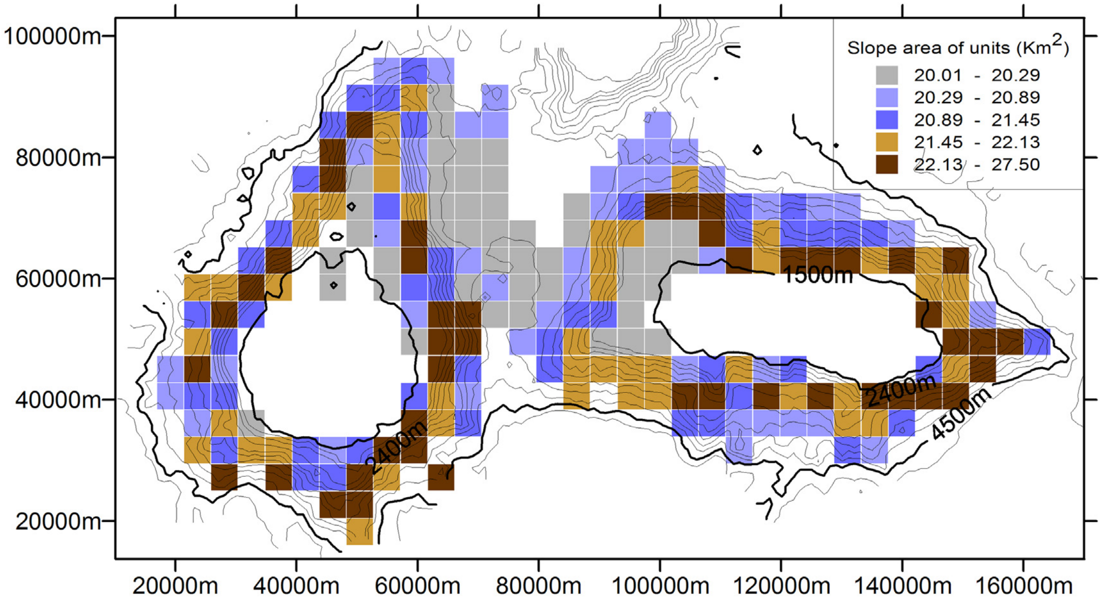

Fig. 6. Fitting Area on Slopes. $Area_i$, $i = 1, \ldots 228$. The total number of 100 m × 100 m grid cells in each unit is 2000.

3.4.3. The tonnage of metal (in millions of tonnes)

$$Metal_i = Owet_i \times (100 - Water_i) \times Ctotal_i \times 10^{-2} \qquad (5)$$

The distribution of Metal_i is shown in Fig. 9.

3.4.4. The tonnage of metal on a suitable slope (in millions of tonnes)

$$Msuit_i = Osuit_i \times (100 - Water_i) \times Ctotal_i \times 10^{-2} \qquad (6)$$

The distribution of Msuit_i is shown in Fig. 10.

3.5. Delineating promising areas

The units are ranked according to their tonnage of wet ore in Fig. 7 and tonnage of wet ore on a suitable slope in Fig. 8 from largest to smallest. The largest rank is 1, the smallest is 228, and every 25th rank is classified as one interval and shown as one colour. The rank distribution of the tonnage of wet ore is shown in Fig. 9 and the rank distribution of the tonnage of wet ore on a suitable slope is shown in Fig. 10.

If a 1000 km^2 area is to be reserved for future mining, in accordance with the regulations of the International Seabed Authority, 50 units can be chosen from the first rank that are adjacent to each other.

Comparing Figs. 9 and 10, the distinction between two types of ranks is obvious, and it depends on whether the Suitable Slope Rate is employed. This suggests that the Suitable Slope Rate is an important factor that must be taken into account when locating promising areas to be delineated for future mining.

In future exploration, $g_{\min}$ and $g_{\max}$ are two important parameters that need to be determined via surveying. Accurate values of $g_{\min}$ and $g_{\max}$ will help us precisely calculate the Suitable Slope Rate and locate promising areas.

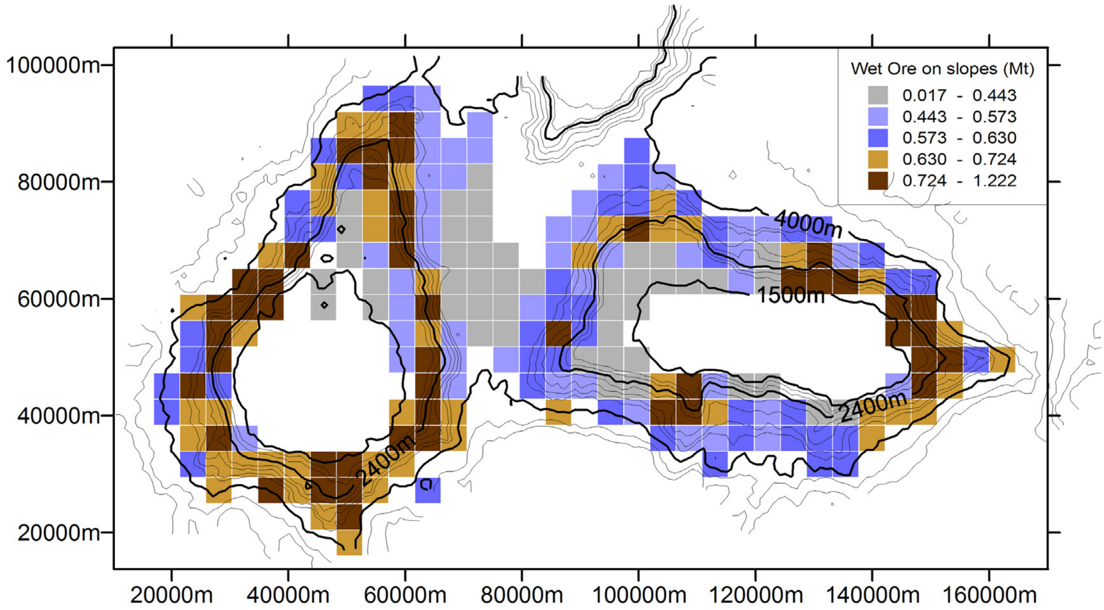

Fig. 7. Tonnage of wet ore ($Owet_i$, $i = 1, \ldots 228$).

Table 2
Estimated features and mineral resources of the units on the slope of Guyot MK (5 of 228 units).

$Unit_i$	Spatial position			Cobalt-rich crusts features					Regional mineral factors			Ore (Mt)		Units rank for mining	
i	X_i (m)	Y_i (m)	Depth (m)	$Thick_i$ (mm)	$Water_i$ (%)	$Dens_i$ (g/cm^3)	$Ctotal_i$	$Coverage_i$ (%)	$Area_i$ (km^2)	$Rcover_i$ (%)	$Rslope_i$ (%)	$Owet_i$	$Osuit_i$	$Rank_i(Owet)$	$Rank_i(Osuit)$
1	19144	45104	2945	36	27	1.86	0.21	60	20.65	100.0	87	0.829	0.722	110	19
2	54920	85352	2072	55	27	1.86	0.21	60	21.51	100.0	55	1.321	0.726	12	20
3	45976	31688	1609	61	27	1.86	0.21	60	20.47	84.0	79	1.170	1.101	23	1
4	50448	31688	1616	65	27	1.86	0.21	60	21.15	86.0	59	1.316	0.907	11	2
228	72808	54048	3950	36	27	1.86	0.21	60	20.00	29.0	29	0.023	0.023	228	228

$Unit_i$($i = 1, \ldots N$), here i is the number of units and $N = 228$ is the total number of units that have an estimated value of crust thickness; the horizontal area of each unit is 20 km^2; (X_i, Y_i) is the coordinate of a unit's centre; $Thick_i$ is the crust thickness estimated using the Kriging, its distribution is shown in Fig. 3; $Area_i$ is the Fitting Area on Slopes in the units, its distribution is shown in Fig. 6; $Rcover_i$ is the Regional Coverage of Crusts in each unit; $Rslope_i$ is the Suitable Slope Rate in each unit, its distribution is shown in Fig. 5; $Owet_i$ is the wet ore resources in millions of tonnes in each unit and $Osuit_i$ is the wet ore resources on a suitable slope in each unit, their distributions are shown in Figs. 7 and 8, respectively; and $Rank_i(Owet)$ and $Rank_i(Osuit)$ are the unit's rank of $Owet_i$ and $Osuit_i$, and their distributions are shown in Figs. 9 and10, respectively.

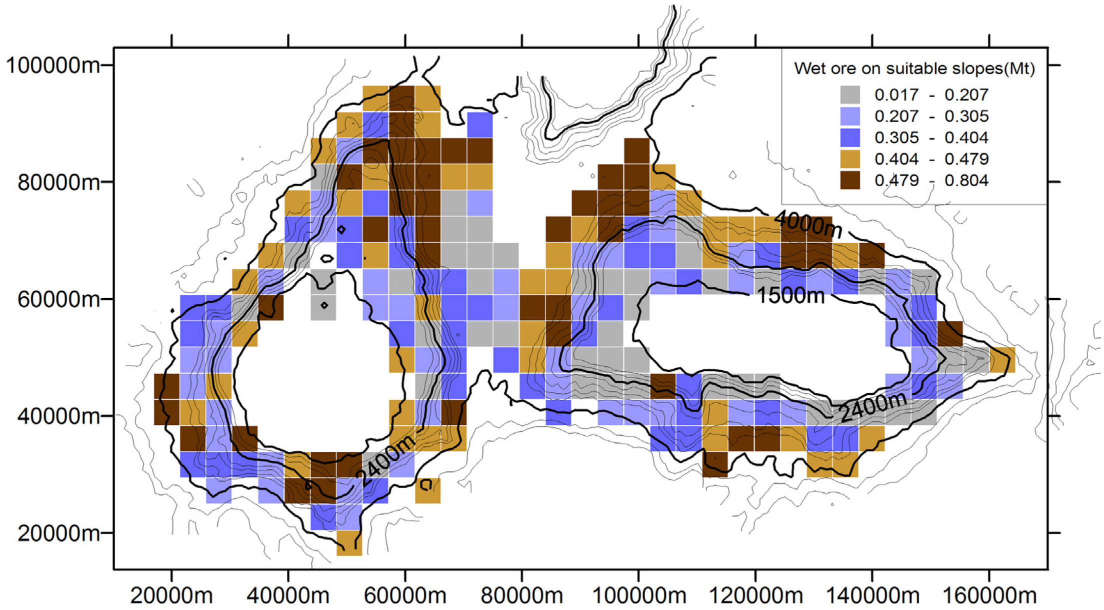

Fig. 8. The tonnage of wet ore on a suitable slope($Osuit_i$, $i = 1, \ldots 228$).

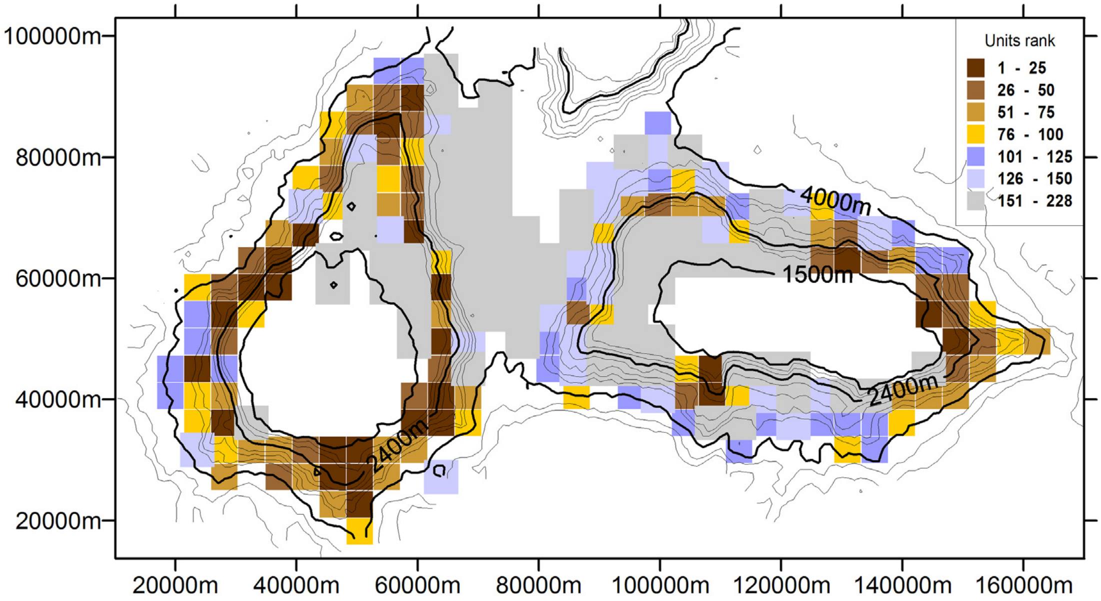

Fig. 9. Rank distribution of wet ore tonnage. $Rank_i(Owet)$, $i = 1, \ldots 228$.

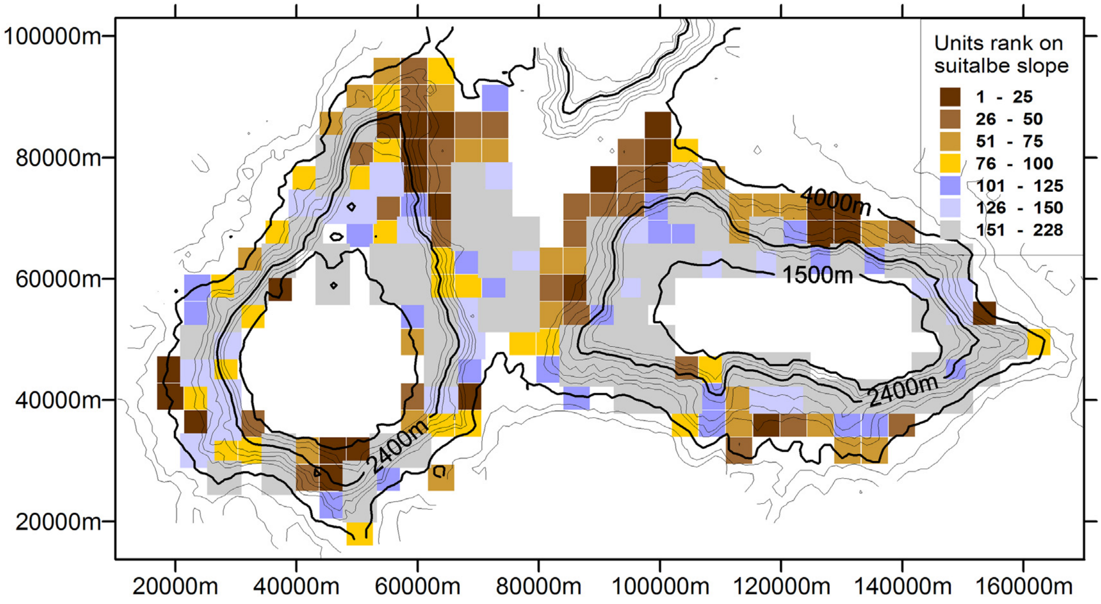

Fig. 10. Rank distribution of wet ore tonnage on suitable slopes. $Rank_i(Osuit)$, $i = 1, \ldots 228$.

4. Discussion

(1) Discrimination between the Regional Coverage of Crusts and the Coverage of Crusts

The Regional Coverage of Crusts is defined as the percentage of sediment-free slopes that are favourable to growing crusts in a regional area. This is easy to calculate using high precision bathymetry data, and it costs little to evaluate mineral resources on a seamount using the regional cover and effective parameters.

The Coverage of Crusts is the exposed percentage of crusts on slopes. It is a local characteristic, observed and estimated by seabed visual observation systems at geological sampling stations; therefore, it is expensive and data are sparse, and it is difficult to deduce in regional space. We suggest that it be called the Local Coverage of Crusts to distinguish it from the Regional Coverage of Crusts.

Some regions on seamounts are favourable to the growth of crusts and some are not; therefore, the Regional Coverage of Crusts is proposed to describe the distribution of the two types of slopes. The slopes on seamounts that are favourable to the growth of crusts are not 100% covered by crusts; therefore, to describe the distribution of crusts on the slope, Local Coverage of Crusts is used.

First, the Regional Coverage of Crusts is used to describe the percentage of favourable slopes on a seamount, and then the Local Coverage of Crusts is used to describe the percentage of crusts on favourable slopes. Distinguishing them and combining their use could result in a better evaluation of the mineral resources on a seamount.

(2) Cobalt-rich nodules and gravels in sediment regions

As opposed to sediment-free slopes, sediment covers discourage crust growth; however, some nodules and gravels do occur on such slopes. If cobalt-rich nodules and gravels are considered, Eqs. (3) and (4) should be modified.

The ore abundance (the quality of nodules and gravels per 1m^2 area, could been estimated by geological surveying) denoted as $Abundance_i$ (kg/m^2) in i units, and assuming that the sediment coverage in the i-th unit is $Scover_i$, then Eqs. (3) and (4) can be changed to Eqs. (7) and (8), respectively:

$$Owet_i = \{Area_i \times [Thick_i \times Rcover_i \times Coverage_i \times Dens_i + (Scover_i \times Abundence_i)]\} \times 10^{-7} \quad (7)$$

$$Osuit_i = \{Area_i \times [Thick_i \times Rslope_i \times Coverage_i \times Dens_i + (Scover_i \times Abundence_i)]\} \times 10^{-7} \quad (8)$$

Here, $Rcover_i + Scover_i \approx 100\%$

(3) Unfavourable slope regions for crusts

Not only sediment cover areas but also slopes with landslides are unfavourable to crust growth; in particular, landslides that occurred since the Pliocene Epoch lead to a poor distribution of crusts. Sediment cover regions can be recognized by their slope gradients, as mentioned above and included in the evaluation. Landslide regions on slopes can be identified by terrain classifications and geological surveys to form a blacklist to remove units from the promising areas.

(4) Gradient threshold values of the slope

To calculate the Suitable Slope Rate, two gradient threshold values of the slope, g_{min} and g_{max}, were assigned values in our example; according to survey data from Guyot MK and other adjacent seamounts, $g_{\min} \approx 4^0$, and according to the opinion of mining experts, $g_{max} \approx 15^0$. These are temporary values used for this demonstration. Obtaining accurate threshold values should be an important goal in future explorations and mechanical experiments on seamounts.

(5) Bathymetry data

The methodology in this article involves several factors, such as the Regional Coverage of Crusts, the Suitable Slope Rate and the Fitting Area on Slopes, which are all extracted from bathymetry data. It is obvious that the bathymetry data play an important role in many ways. Bathymetric surveys in the deep sea should be improved to provide more reliable evaluations of mineral resources on seamounts.

(6) Additional data and methods should be involved

The demonstration example involves only common data, including geological sampling data and bathymetry data. In practical applications, additional data can be included, such as backscatter data and sidescan sonar maps (Kim et al., 2013; Joo et al., 2016). Technical and economic factors for mining (Park and Yang, 2009) could also provide useful information.

5. Conclusions

(1) When the slope gradients exceed a certain threshold value of $g_{\min}$, unconsolidated sediments on the slope move down to the bottom of the seamount due to gravity and consolidated rocks are exposed as a stable substrate for cobalt-rich crusts to grow; conversely, when the slope gradient is smaller than a certain threshold value of $g_{\min}$, the slope on a seamount becomes a sediment field, which is not favourable to the growth of crusts. The Regional Coverage of Crusts is proposed to estimate the percentage of the two types of slopes; it can easily be calculated using high precision bathymetry data and is a cheap, regionally covered and effective parameter for mineral resource evaluations on seamounts. The threshold value $g_{\min}$ used to estimate the Regional Coverage of Crusts will be an important characteristic to be calculated in future geological surveys.

(2) In previous studies, the Regional Coverage of Crusts and the Coverage of Crusts were mixed as the Coverage of Crusts; however, the Regional Coverage of Crusts will be an important characteristic for mineral resource evaluations on seamounts in the future.

First, the Regional Coverage of Crusts is used to describe the percentage of favourable slopes on a seamount. Then, the Local Coverage of Crusts is used to describe the percentage of crusts on favourable slopes. Distinguishing them and combining their use could result in better evaluations of the mineral resources on a seamount.

That the Coverage of Crusts is known as the Local Coverage of Crusts to distinguish it from the Regional Coverage of Crusts.

(3) Slope area is one of the most important parameters for estimating the mineral resources. Based on the bathymetry data, the slope area of two triangles in each grid cell can be accurately calculated in a 3D coordinate system, and a unit area on the slopes can be fitted by accumulating the areas of the triangles. Using the Fitting Area on Slopes will improve the precision of ore reserve calculations.

(4) Slopes with small gradients are not favourable to the growth of crusts. Slopes with larger gradients are favourable to their growth; however, slopes with too large a gradient have either been subjected to landslides, resulting in thin crusts, or are not favourable to the operation mining machinery. Assuming that there are certain threshold values of $g_{\min}$ and $g_{\max}$, when $g_{\min} < g < g_{\max}$, slopes on seamount with a gradient g are suitable for crust growth and for mining in the future. The estimated the mineral resources depend greatly on the employment of the Suitable Slope Rate. It is suggested that the Suitable Slope Rate is an important factor that must be taken into account when delineating promising areas for future mining. In future exploration, g_{min} and g_{max} are two important parameters that need to be examined via surveys.

(5) Based on a correlation analysis between the geological survey data and the regional survey data and a combination of a variety of methods, a synthesized evaluation method to estimate cobalt-rich crust mineral resources on seamounts, which is concise, quantitative and can be run on computers, was proposed in this study. Even though this method had been demonstrated on the Magellan Seamounts, it needs to be improved in many ways. We hope to draw other scientists' attention so that we can improve it together.

(6) This method is suitable for all mineral resource evaluations on seamounts, including guyots and spire seamounts.

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