The use of GIS technologies for the classification of underwater topography and estimation of their ore production (on the example of the Magellan seamounts, the Pacific Ocean)

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There are more than 100 thousands seamounts, atolls and islands in the World Ocean. Investigation of its relief gives scientists big opportunities in exploration of ocean volcanism and underwater ore deposits. Known seamount catalogs do not give enough information for mathematical analysis of spatial-time regularities in seamount distribution. In order to solve this problem we have developed the algorithm of seamount recognition from bathymetric data and calculation of their morphometric characteristics. GIS-technology and bathymetric data GEBCO_2020 (http://www.gebco.net) has been used for this calculation. The study of seamounts morphometric characteristics also has applied relevance. More than half century has passed after the discovery of iron-manganese ores on the surface of underwater mountains. GIS tools have been used to analyze spatial correlation of ore-crust distribution with different morphometric characteristics of seamounts. *KEYWORDS:* Geoinformatic; GIS-technology; oceanic volcanism; seamount; underwater ore deposits.

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Introduction

At present, there are more than 100,000 volcanic seamounts, atolls and islands on the bottom of the global ocean [*Wessel et al.,* 2010]. The study of the reliefs of the seamounts leads to a better understanding of the process of oceanic magmatism and for the study of the distribution of ore deposits throughout the ocean.

The most precise catalogue of seamount s available today was created on the basis of altimetric analysis and contains information about approximately 150,000 seamounts [*Wessel,* 2001]. Unfortunately, this database only indicates the coordinates of the summit, the height and the radius of the mount. It does not provide any information about the cartographic or vector model of the base of the mountain, or the area of the base of the seamounts or other morphometric data. Another popular catalogue – the Seamount Biogeoscience Network (SBN) (https://earthref.org/SC/) – contains raster images of the seamounts, which make mathematic analysis difficult. In the descriptive part of the catalogue, we can find morphometric data only for a very small number of mounts. A fuller description of seamount reliefs would make a catalogue more valuable for the study of the spatiotemporal characteristics of submarine volcanism.

To solve this problem, the author took bathymetric data from the GEBCO_2020 (http://www.gebco.net) global bathymetric grid at 15 arc-second intervals and developed an algorithm for identifying volcanic structures – their outlines (contours), for

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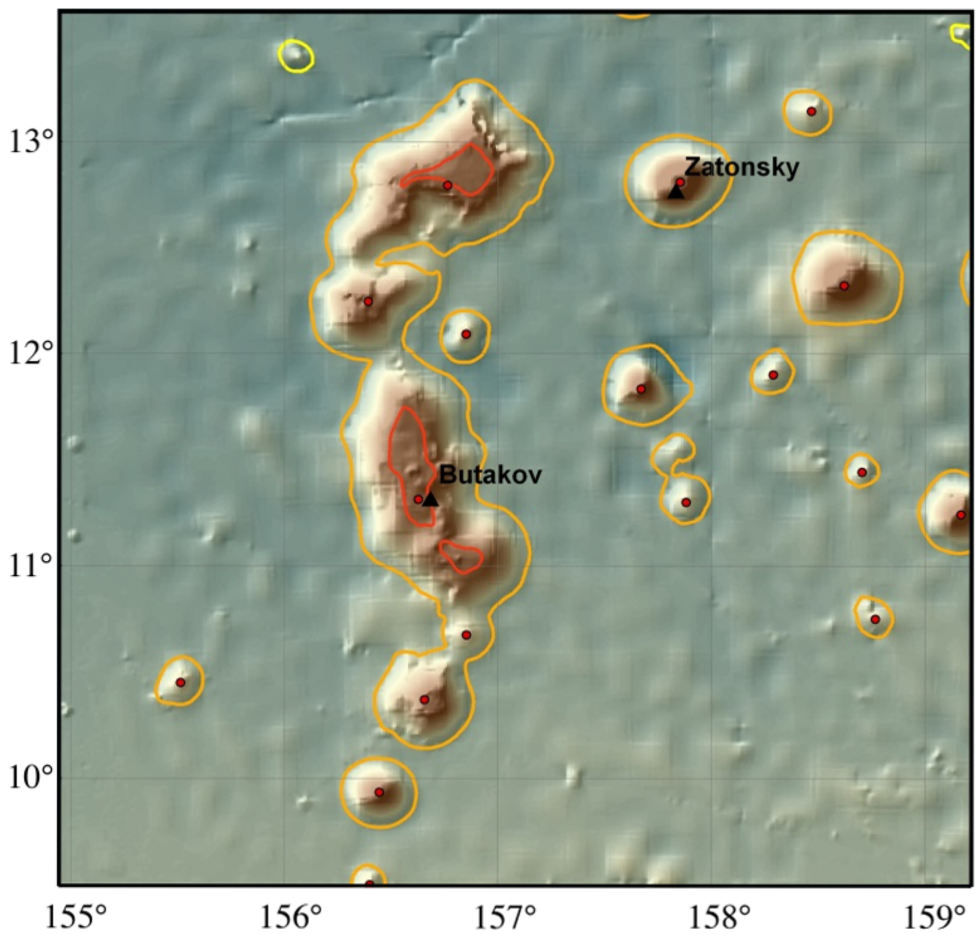

Figure 1. Identified outlines (contours) of seamounts. Yellow lines – bases; red lines – flat tops; black dots – summits.

which we used the tools provided by ArcGIS Spatial Analyst. As a result, a catalogue is generated automatically, and no mountain structure shown on the bathymetric grid is excluded from consideration. The north-western part of the Pacific Ocean was chosen to test the algorithm.

Methodology of the Catalogue

The algorithm is based on the calculation of gradients (tilt angles) of the surface of the ocean's bottom. In order to determine the outlines (contours) of a mount, areas with positive gradients exceeding 5° (five degrees) were considered within the limits of closed contours (a mount is a closed type of a relief) (Figure 1). Averaging in a "sliding window" was done in order to exclude large relief forms (a low-frequency component). The width of the Pacific seamount ridges and rises varies from 200 km to 1000 km (the measurements were taken from the same bathymetric grid); therefore, the area of the sliding window was set at 200×200 km. The background component was deducted from the analysis.

The background component was subsequently used to identify large structures (rises, trenches). Each mount was attributed to a certain structure in the catalogue (Figure 2).

Once the contour of a seamount was determined, also using built-in Spatial Analyst ArcGIS 10.1 tools, the coordinates of the summit, the depth of the base and the summit, the relative height of the structure, the trend azimuth, the degree of isomerization, existence of terraces, the degree of articula-

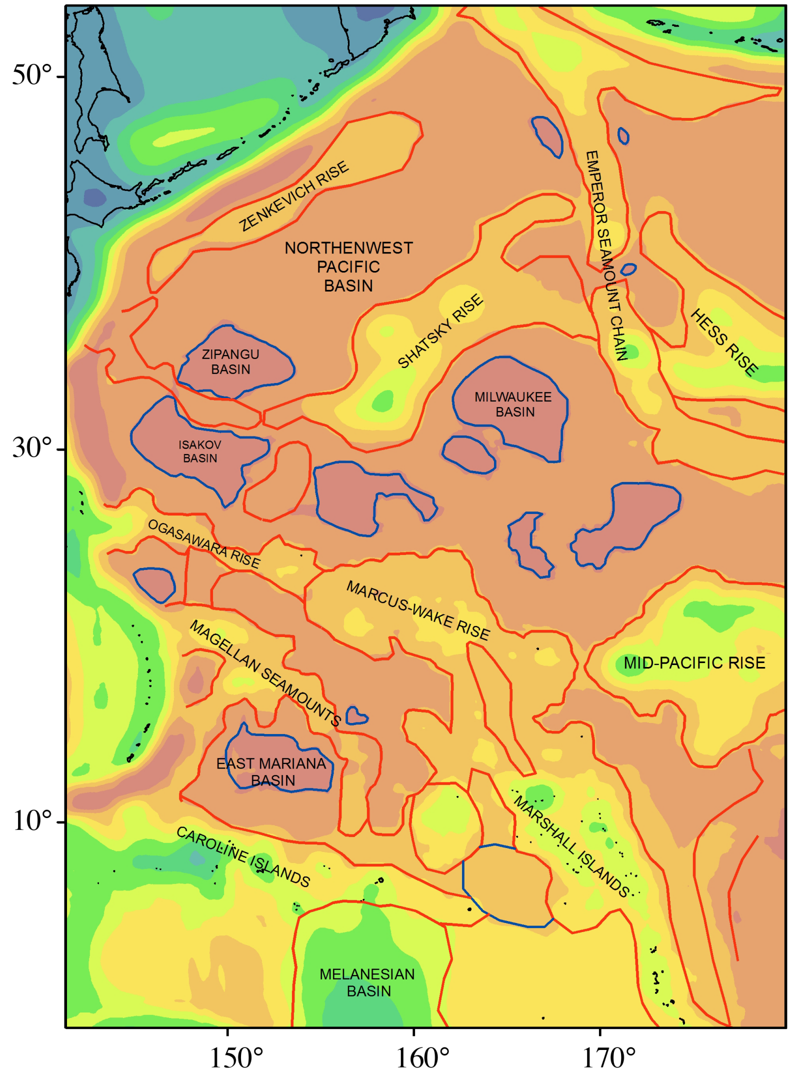

Figure 2. Background component of bathymetric data. Main structural elements of the research region.

tion, area, volume etc. were calculated on the basis of the bathymetric grid and its various transformations (gradient charts, curvature charts and the chart of isolated points). These parameters were then input into the attribute table of the shape file.

Based on the new algorithm, approximately 2000 seamounts were identified in the analyzed region. To compare, the catalogue [*Wessel,* 2001] indicates more than 6000 mounts in this area. Refer to Figure 3 for a comparison of the catalogues.

The much smaller number of mounts identified using the proposed method is explained by the fact that we have identified a single multi-summit structure united by a common base, which could possibly mean that they came from the same magma chamber. The number of the summits of the structure is provided in the catalogue. At the same time, it is clear that not all mounts are presented in the catalogue [*Wessel et al.,* 2010], even large ones.

This number of distinguished seamounts is sufficient for a statistical analysis. An important characteristic of objects helping to understand the mechanism of their development is a function of distribution of the number of objects depending on their sizes. When studying the type of distribution, we can obtain indirect data about the interrelation of parameters, and, accordingly, get to seamount formation mechanisms.

The bar chart above is visually divided into several segments (Figure 4).

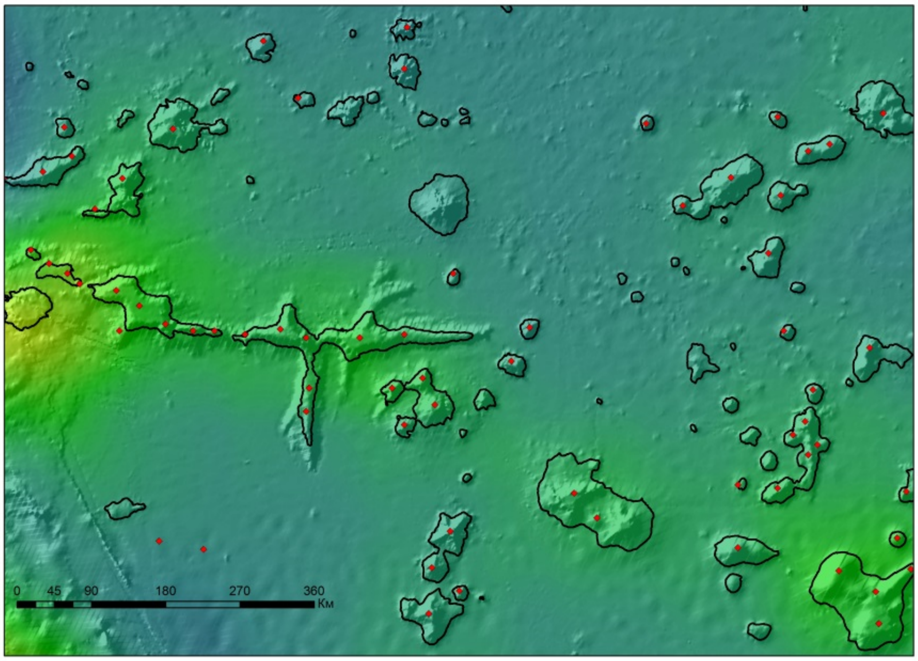

Figure 3. Comparison of catalogues. Red dots – the Wessel catalogue; black lines – contours of identified mounts using the proposed methodology.

In order to clarify the borders of the segments an analysis of the grouping was conducted (ArcGIS spatial statistics tools were used), which involved determining several most differing subsamples (by given parameter) and making sure that the variance inside each group is as limited as possible. A total of 5 areas were identified (shown in different colors above). It is possible, that the varying sizes of these groups reflect certain characteristic features of the process which is responsible for the formation of seamounts. In particular, the reason for these differences may lie in various heat capacities or various depths which lead to the volcanism of magma chambers.

From a physical point of view, the most interesting parameter of a seamount in terms of the distribution of the energy of the process which produces seamounts is not its base, but its volume.

The obtained logarithmic distribution of the volumes of seamounts is shown in Figure 5.

The segmentation of the distribution function is also shown in Figure 5. These segments can be described by the power law. Note that the method when the intrinsic distribution law is replaced by several simple power laws, is often used when describing the graph of the frequency of earthquakes which is described by the Gutenberg-Richter Law ($\ln N = bA$, where N is the number of events having a magnitude, A is the size of the event's parameter and b is the power coefficient).

According to this law, this segmentation can reflect the independence of the process of mount formation in the identified groups.

If we recalculate the volume as an equivalent radius of the base of the mount, we receive the value of radiuses of the points of the borders of the segmentation ranges (the borders are marked by green lines on the figure) – 10, 30, 50–60 km. Figure 5 features a straight inclining red line. It touches the empiric distribution of mounts with the size of 30,000 km^3. For a regular cone, this equals a base radius of approximately 40 km.

Similarly to the earthquake frequency graph [*Pisarenko and Rodkin,* 2007], we can show that mountains of this size will account for the maximum volume on the bar chart (size-dependent).

Accordingly (based on a simple analogy: volume of a volcanic mount – energy of eruption), we can suppose that mountains of this size will account for maximum eruptions (in terms of volume and energy).

A ranging of seamounts was made on the basis of key morphometric features (area, height, volume).

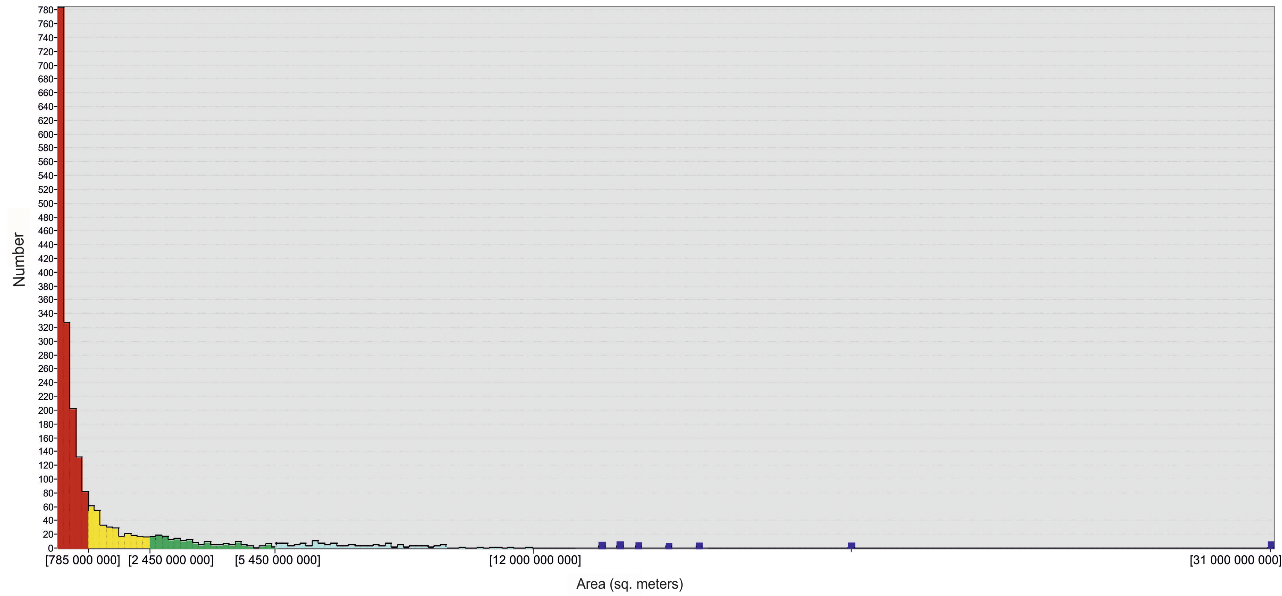

Figure 4. Histogram of the distribution of the number of mountains depending on the area of their base (values are shown in meters).

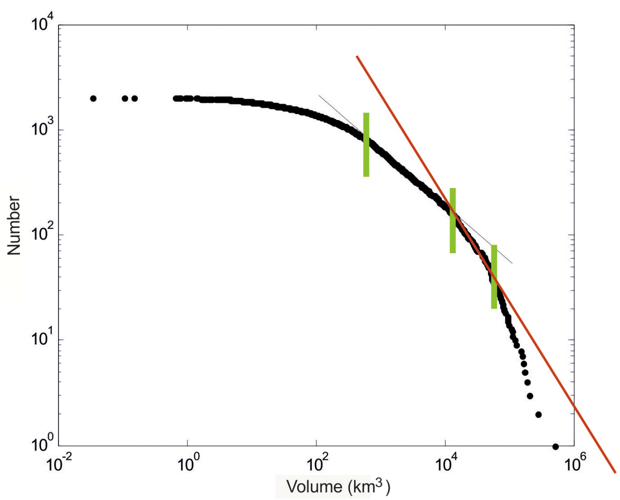

Figure 5. Function of the distribution of the mounts depending on their volume.

"Gigantic", "large", "medium", "lesser" and "small" mounts were identified as provisional name.

1. The first group is comprised of unique mountain structures. It can be divided into two sub-groups. This a series of complex flat-top mountains united by the same base, i.e. guyots (Emperor Seamount Chain, Gilbert Seamount, Marshall Islands), and gigantic shield volcanoes (Shatsky Rise, Mid-Pacific Seamounts, Hess Rise). Guyots are different from shield volcanoes – they are much higher. Guyots usually have the height of 2000–4000 m, while shield volcanoes – approximately 1000 m.
2. The second group of large mounts is also divided into two sub-groups – high and low-rise (Figure 6). High mountains are slow-evolving complex structures with several summits on a single base (Magellan Seamounts, Marcus-Wake Seamount Group, Caroline Islands) – green, orange and red squares on the chart. Large and low-rise mounts are shield volcanoes or structures located on swells in front of deep-sea trenches, and also seamounts related to faults – blue and purpose squares). Fault-zone mounts differ from all others by a greater degree of extension (elongation). The graph also shows that it is typical for large-area mountains (gigantic) to be smaller in height.
3. Medium and high structures are mostly ideally-shaped formations – isometric, with very little angulations, single-standing mounts or mounts that are parts of ranges. There are guyots among them, but unlike large mountains, they do not form complex structures on a single base (Geisha Rises, Mid-Pacific, etc). Medium flat mounts are seamounts located on neotectonic rises, either isometric or elongated

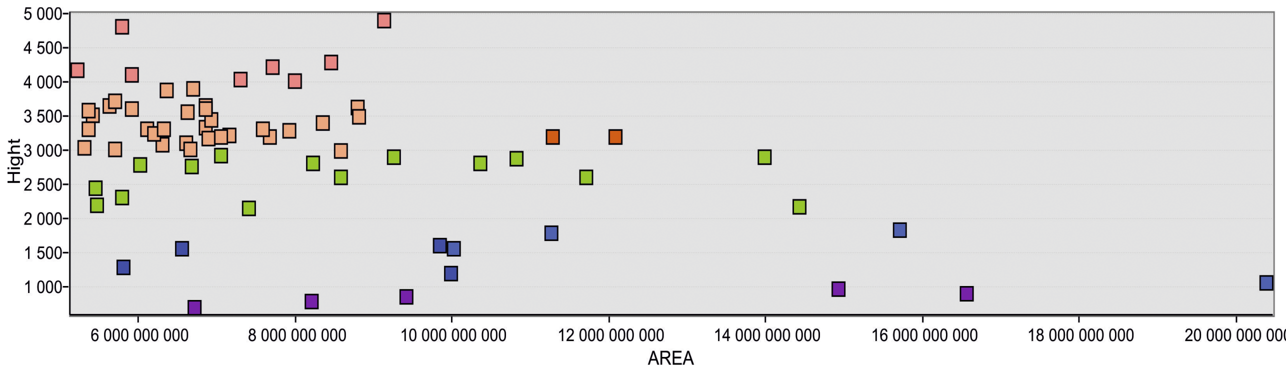

Figure 6. Distribution of large and gigantic mounts by area of base and height.

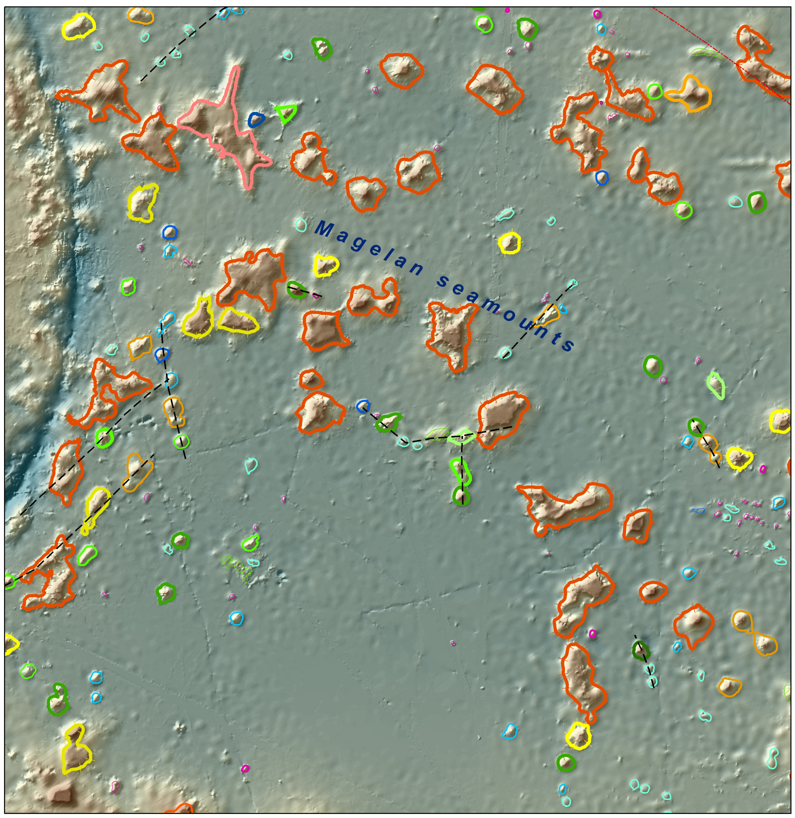

Figure 7. Example of ranging of seamounts on the example of the Magellan Seamounts.

along neo-faults. I.e. medium mounts mostly related to recent tectonic geology.

4. Lesser high mounts are isometric, ideally-shaped or angulated mounts. There are no elongated shapes in this group.

The identified group of medium and lesser mounts is often connected to active-fault systems. Fault-zone structures are small, regularly-shaped, or elongated mounts located in a chain with small distances in between the mounts. The distance between the centers of volcanism has never been evaluated before. However, this parameter can help to understand certain patterns of seamount formation. The parameter (distance to the nearest neighbor) was calculated as the distance between the geometric centers of the seamounts which are part of the same classification group.

Figure 7 shows the Magellan Seamounts. It is clear from the graph that large guyots are located at a great distance from each other, while small mountain chains are likely located along faults (black dotted lines).

We believe that great distances between mounts located along arches mean that the mount was formed at the point of exit of the rising hot mantle matter. An underwater volcano continues to grow because it is fed by the plume-related source in the mantle until the time when the magma channel is broken. The channel is broken once its trajectory by which the magma travels becomes too complicated due to the fact that the mount has moved far away from the plume area. In this case there is little chance that a new mountain will be formed in the vicinity, despite the fact that the volcanic process is highly active. A new volcanic mount can be formed once the earlier-formed mountain has moved away from the plume area.

The mechanism whereby the center of volcanism migrates to a different place and the formation of a new seamount is triggered is determined by the mechanisms of mantle melt draining into a certain point of volcanic activity. A "repulsion" scenario is typical for this point and its vicinity, i.e. it is impossible to form a new channel for the draining of mantle melt.

In contrast, during the formation of fissure-type volcanoes, the drainage area is formed immediately in the form of an outstretched linear fault formed during the lessening of the internal energy of an active geo-environment. In this case the "repulsion" scenario does not happen.

Accordingly, based on available geometric characteristics, it is possible to conduct ranging which would reflect the processes of seamount formation.

The created cartographic database of seamounts is published as a web service on the portal ArcGIS Online and has been updated for web-map users, which makes it possible not only to view it in the browser, but also in desktop applications.

Usage of Morphological Analysis to Assess the Ore-Bearing Capacity of Seamounts

In addition to the conclusions made from the analysis of small-scale seamount maps, very interesting results can be obtained from analyzing detailed large-scale maps. The study of the morphological characteristics of seamounts has great practical significance because cobalt-manganese crusts (CMC) are mostly attributed to underwater rises, most of which are volcanic in nature. In terms of their content, these crusts are polymineral formations rich in cobalt and manganese ore.

In this respect, the Magellan Seamounts are very interesting. Substantial accumulations of ferromanganese nodules and crusts [*Melnikov,* 2006] were discovered on the slopes and summits of the Magellan Seamounts. These mounts are an outstretched (up to 1500 km long) arch-shaped chain of seamounts, mainly guyots, framing the Mariana Trench at 10°N and 19°N and 148°E and 158°E. So far, a substantial number of geologic and geophysical studies have been conducted in the vicinity of the Magellan Seamounts, deep-water holes have been drilled, and underwater profiling has been done. Based on the results of acoustic depth sounding by the "Geledzhik" research team in 1999–2003 using Simrad EM12 S-120, and on the data obtained from deep-water drilling and dredging, detailed bathymetric charts (with bathymetric contours of 25–50 m) and detailed maps of the ferromanganese deposits of the seamounts (showing the distribution of the capacities of ore crusts containing metals) were developed [*Melnikov et al.,* 2009, 2012].

The patterns of the distribution of ferromanganese crusts depending on the morphometric characteristics of the guyots were identified and modeled using GIS tools. 3D models of the seamount reliefs were built using ArcGIS (Spatial Analyst) tools (Figure 8).

Secondary morphologic surfaces were built in relation to these surfaces: charts of slope angles, curvature, degree of angulations (articulation) of the relief, etc. In order to build a map of angulations, a number of interest points (bending points and spill points) had to be calculated using focal statistics.

These characteristics were then compared to the distribution of the crusts of varying thickness. For this, the areas of overlapping of the bases with different morphometric parameters and bases of the distribution of the crusts of varying thickness were calculated using overlay operations. Graphs showing the distribution of various crusts depending on their morphometric characteristics were built using ArcGIS tools. Figure 9 shows how the areas of distribution of ore bodies depend on depth. It is clear from the graph that young crusts (with

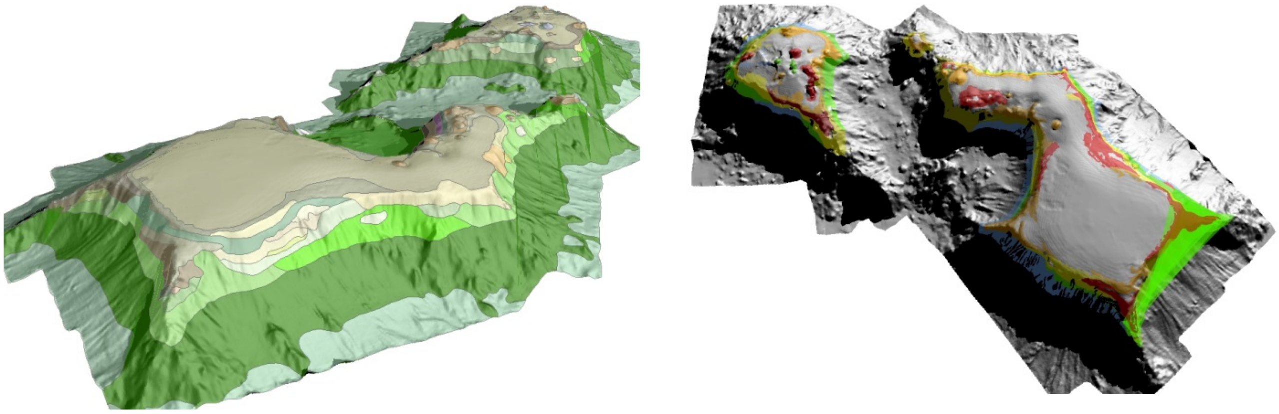

Figure 8. Magellan Seamounts. Ita Mai Tai Guyot. 3D model of the relief and mineralization.

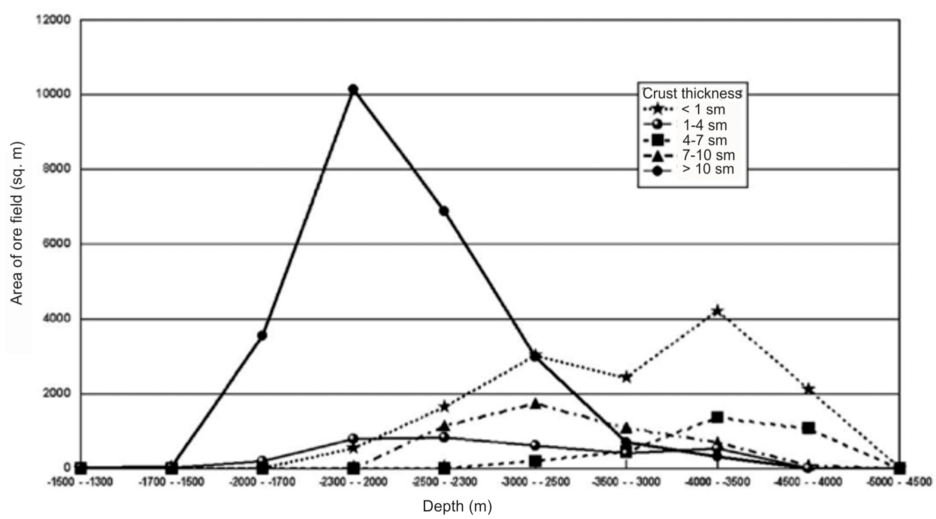

Figure 9. The thickness of ore crusts on the surface of the ITA-Mai-Tai Guyot depends on the depth of the ocean.

shallow thickness) are distributed at 3500–4000 m deep, while old ones (thickness $>$ 7 cm) – at 2000–2300 m.

Figure 10 shows that the distribution of the crusts depends on the angle of the relief. The number of crusts drops sharply at $>$ 25 angles and at angles of less than 3 degrees. However, crusts of varying thickness show different maximums. We also identified a direct positive dependence on the degree of angularity of a relief.

The curvature charts, where concave and convex surfaces are shown, evidence that the crusts are predominantly located on outstretched convex surfaces of seamounts (edges of flat tops, large troughs).

The charts of morphologic features were then rebuilt as derivative charts depending on what dependencies of each property and what type of distribution of ore deposits were found. When all parameters were summed up, a resulting projection map (Figure 11) was built. Figure 11 shows the projection map and a map of the actual distribution of CMC in Ita Mai Tai Guyot. The similarity of this map to the map of the real distribution of the crusts proves that we have been able to build a projection model for the formation of ore that is quite close to reality. Therefore, we can use the obtained results for predictive modeling of ore deposits and their assessment without detailed exploration work at other guyots.

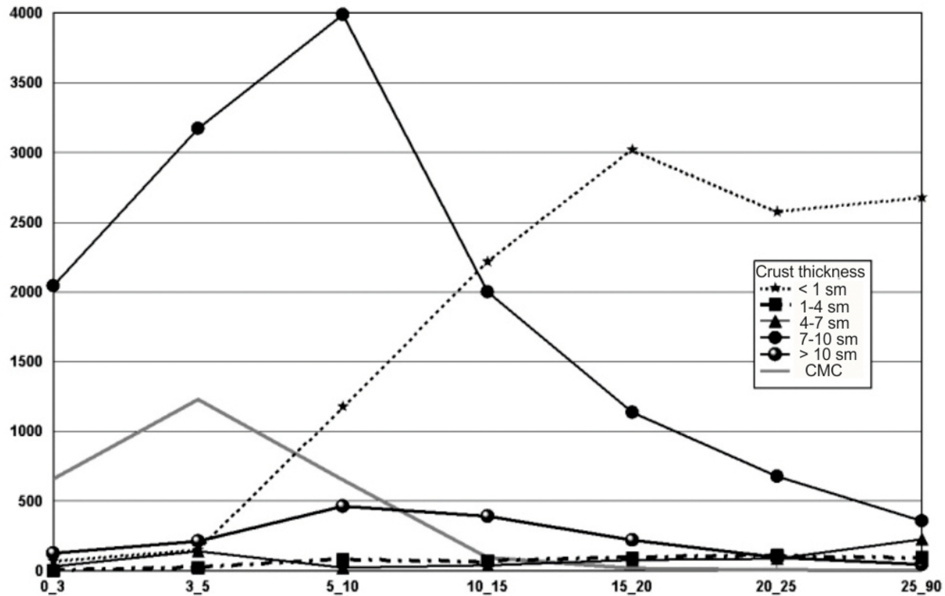

Figure 10. Thickness of ore crusts on the surface of the Guyot depending on the angles of its slopes.

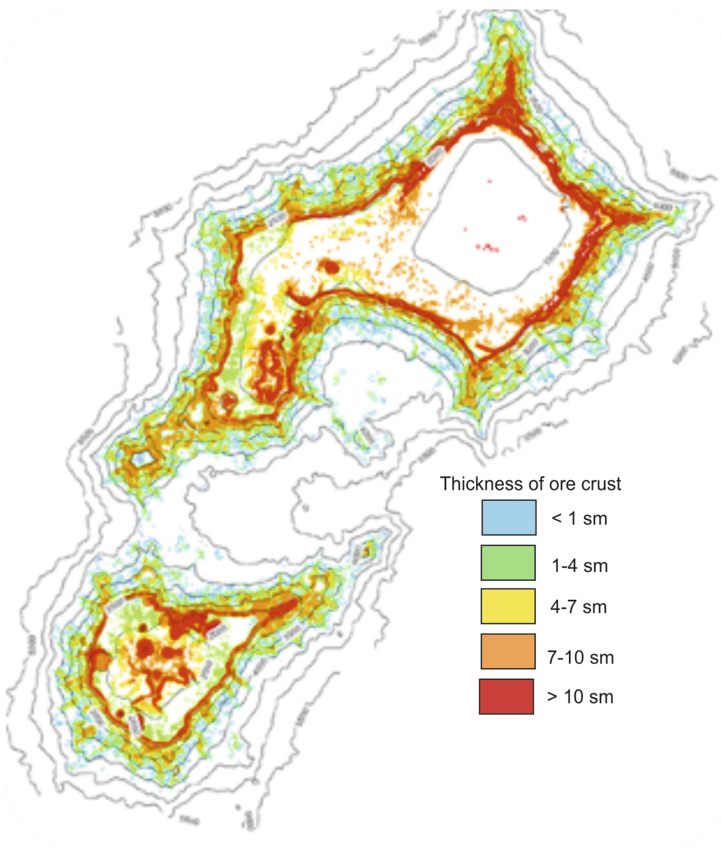

Figure 11. Resulting projection map (left) and map of the actual distribution of cobalt-manganese crusts (CMC) (right) in Ita Mai Tai Guyot.

Conclusions

We have conducted a study of geologic features called seamounts on the basis of bathymetric grids using various scales. The analysis was conducted using standard GIS surface processing tools.

We have proposed an automatic algorithm for the determination of the bases of seamounts on the map that were then ranged by height and volume. A new classification of seamounts on the basis of morphologic properties was proposed.

The analysis of large-scale bathymetric and geologic maps of the Magellan Seamounts resulted in our being able to connect the morphology of the surface and the location of ferromanganese deposits. This aspect has great practical value.

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