Global Exploration Models for Polymetallic Sulphide Deposits in the Area: Possible Criteria for Lease Block Selection under the Draft Regulations on Prospecting and Exploration for Polymetallic Sulphides

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June 21, 2006

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Appendices

1. Introduction

More than 300 sites of submarine hydrothermal venting and associated mineralization are known on the ocean floor. About 100 of these are host to polymetallic sulphides (Figure 1 and Table 1). High-temperature, ~350^{o}C, black smoker vents are the most recognizable features of these sites, but a wide range of different styles of mineralization also has been found. Approximately 40% of the known sites are located in "the Area". For a number of reasons, including both legal and technical, recent commercial exploration of seabed polymetallic sulphides has been restricted to occurrences within established Exclusive Economic Zones or EEZs (Figure 2). This paper considers criteria and possible models for allocation of lease blocks for exploration in "the Area". It provides the scientific rationale for the selection of areas for prospecting and for a schedule of relinquishing lease blocks during the exploration phase.

Practical illustrations are provided for the allocation of lease blocks in areas of known sulphide occurrences using both "contiguous blocks" and "clusters of contiguous blocks". From a range of possible selection criteria and procedures, we compare two models for the allocation of exploration licenses in 32 different areas in which at least one occurrence of polymetallic sulphides is known, including 12 in "the Area" (Figure 3). The performance of the exploration models, in terms of their efficiency in selecting known areas of polymetallic sulphides (and relinquishing areas that do not contain polymetallic sulphides) is examined at the global, regional, and site-specific scales, beginning at the prospecting stage and ending with the selection of the most favourable blocks to be retained at the end of exploration. The models take into account (i) geological limitations on prospective areas, (ii) the known distribution of polymetallic sulphides, and (iii) the characteristics of individual sulphide occurrences. Other models that may be more appropriate also can be tested using the data presented in this paper.

Polymetallic sulphides have a number of important attributes that are dramatically different from crusts and nodules, in terms of their geological settings, distribution, and continuity that must be considered in area selection. Individual occurrences may have dimensions of no more than a few 10s of meters up to 100s of meters, whereas crusts cover larger areas of the seabed with greater physical continuity (e.g., kilometer scales: Hein et al., 1999). These differences require fundamentally different approaches to exploration.

The analysis given in this paper is based on the present state of knowledge of the sizes and distribution of polymetallic sulphide occurrences. No assumptions are made about possible economic or technical limitations on exploration for polymetallic sulphides at the locations discussed. The models proposed here consider only the exploration phase and do not consider actual mining, beyond estimating the minimum sizes of blocks that may be required for multi-year exploitation. Examples of possible lease blocks used in this paper do not represent an economic evaluation of specific occurrences or areas of the seabed. Sulphide occurrences that meet possible commercial criteria may be mentioned, but no economic valuations are considered or inferred. All cited examples are strictly for illustration purposes and in no way imply that resources suitable for commercial exploitation may actually be present in any given area. Information provided in this paper, including area x thickness of contiguous sulphide bodies, bulk density, grade of metals, or other mineralogical and metallurgical characteristics cannot be used to infer a resource and no such resources are implied, except as hypothetical examples and only insofar as information may be available to justify such examples. Any references to commercial enterprises involved in exploration for seabed polymetallic sulphides are also for illustration purposes only and are not meant to endorse the activities or programs of these companies or to recommend them as possible models for implementation in "the Area". Consistency with the Convention or the proposed Draft Regulations is not addressed, except in the design of the exploration models. Relevant paragraphs from the Draft Regulations used in the design of the models are provided in Appendix 1.

2. Terminology

For the purposes of this paper and in the models presented below, the following terminology is used:

Prospecting Area - A preliminary area that may contain seabed polymetallic sulphides or an area permissive for the occurrence of sulphides, a portion of which may be allocated for exploration as defined in the Draft Regulations. In the 32 examples discussed in this paper, a prospecting area is arbitrarily defined as an area of less than five degrees by five degrees and containing at least one known sulphide occurrence or other positive indication of mineralization. In reality, a prospecting area may be identified solely on the basis of permissive geology, in the absence of any indication of mineralization.

Exploration Area - A "license" or tenement within a prospecting area and comprising multiple contiguous or non-contiguous blocks reserved for advanced exploration. This is typically an area of not more than one degree of longitude by one degree of latitude and containing at least one known sulphide occurrence or other positive indication of mineralization. In the models presented herein, the size of an exploration area corresponds to 100 blocks of 10 km x 10 km each, as specified in the Draft Regulations.

Lease Block - A portion of an exploration area, measuring approximately 10 km x 10 km and no greater than 100 km^2, as defined in the Draft Regulations.

Permissive Area - A portion of a prospecting area having a number of geological attributes that are considered to be essential for the formation of polymetallic sulphides. In defining the limits of a permissive area, two key indicators that are commonly used are evidence for tectonic activity and seafloor volcanism. Typically, these are required to drive hydrothermal circulation and to focus hydrothermal fluids to the seafloor where metals may be deposited. A permissive area may include occurrences of polymetallic sulphides or other positive indications of mineralization, but this is not a requirement.

Most Prospective Area - An area chosen for advanced exploration and usually containing at least one sulphide occurrence. In the models presented here, the most prospective areas are generally those blocks that contain more than one sulphide occurrence.

Sulphide Occurrence - A discrete body of polymetallic massive sulphide (e.g., chimney or mound) or a cluster of such bodies within a defined area (e.g., a chimney field), commonly but not necessarily associated with active hydrothermal venting. Where an occurrence consists of more than one sulphide body, some degree of continuity or clustering is implied (e.g., a collection of chimneys or mounds within an area that is smaller than the distance to the next nearest cluster). The most prospective areas in an exploration license contain at least one such occurrence.

This paper makes no legal or technical distinction between "prospecting", which typically does not entail exclusive rights as defined in the Draft Regulations, versus "exploration" with exclusive rights. Prospecting might be carried out in multiple areas, a subset of which could be allocated under a plan of work for exploration, as illustrated in the models below. The term "deposit" is not used this paper, except in reference to massive sulphide deposits that have been mined economically on land. This is to avoid confusion about what constitutes a deposit on the seabed. In the scientific literature, the term "deposit" has been variably applied to a variety of entities, including individual sulphide mounds, entire vent fields, or whole geographical regions.

Other terms used in this paper are as defined in the Draft Regulations on Prospecting and Exploration for Polymetallic Sulphides and Cobalt-rich Ferromanganese Crusts in the Area.

3. Database

The areas chosen for analysis in this paper were selected from a global database of seafloor polymetallic sulphides and associated hydrothermal systems (Hannington et al., 2002, 2004). The database is available in two parts that were prepared separately for the Central Data Repository of the International Seabed Authority in 2002 and 2004. The first is a digital database of locations and descriptive information on more than 300 occurrences of seafloor polymetallic sulphides and related hydrothermal activity. The second is a compilation of published geochemical analyses of more than 2600 samples of seafloor polymetallic sulphides (61,000 records). From these data, 32 permissive areas were selected to test models for the allocation of exploration licenses, including 12 in "the Area".

Bathymetric data used to define initial prospecting areas were derived from the GEBCO 1-minute gridded digital atlas of the seafloor (General Bathymetric Charts of the Oceans, British Oceanographic Data Center, 2003). Although the standard GEBCO contour interval is 500 m, a contour interval of 1000 m was used here for ease of plotting. Similar regional maps also can be created from the global predicted bathymetric data of Smith and Sandwell (1997). This 2-minute gridded data, based on satellite gravity measurement, has the advantage of coverage over more remote and inaccessible regions of seafloor.

Areas permissive for polymetallic sulphides were selected from 5 deg. x 5 deg. maps. These maps are provided in Appendix 3. Maps illustrating the application of exploration models at this scale are shown in Appendix 4. A grid with a spacing of 0.1 degree is overlain on each map in the areas considered to be permissive for polymetallic sulphide occurrences and where prospecting might be carried out. This grid corresponds to block sizes of approximately 10 km x 10 km each (0.1 x 60 nm x 1.852 km = 11.11 km grid spacing). Decimal-degrees are used for ease of plotting sulphide locations. In each case, the placement of the grid is based on a number of different criteria discussed in Appendix 2.

Several examples of 30 min x 30 min maps (100 m contour interval) illustrate the distribution of sulfide occurrences in selected areas where more detailed bathymetric information may be available. These maps are provided in Appendix 5. This more detailed bathymetry can be used to significantly reduce the initial size of a permissive area, but the data are not available for all parts of oceans.

4. Models for Lease Block Selection

Permissive areas for the occurrence of polymetallic sulphides were selected in 32 map areas of 5 deg. by 5 deg., based on the broad geological attributes of each area as outlined in Appendix 2 (e.g., areas encompassing ridge crests, off-axis seamounts, volcanic arcs, back-arc basins, etc.). A range of physical characteristics of seafloor polymetallic sulphides were considered, including the spacing between deposits and the sizes of likely discoveries. For more information, the reader is referred to Appendix 2 and to overview papers on this topic by

Hannington et al. (1995, 2005) and Herzig and Hannington (1995, 1999, 2000). Additional information also can be obtained from Technical Study No. 2 on *Polymetallic Massive Sulphides and Cobalt-rich Ferromanganese Crusts – Status and Prospects*, published by the International Seabed Authority. The selection process is limited, to some extent, by the bathymetric detail in the plotted maps. In the 1000-m contour data from GEBCO, large areas at the edges of prospective geological features (e.g., flanks of ridges) are included in the initial area selection, owing to uncertainty in the seafloor geology. Higher-resolution bathymetry can be used to help reduce the selection of permissive areas, as discussed further below (see Results).

In Appendix 4, a number of models are presented that illustrate how these areas might be reduced to the minimum number of exploration lease blocks according to the schedule of relinquishment proposed in the Draft Regulations (50% of the allocated area after year five, 75% after year 10, and a maximum of 25 blocks after year 15). In a successful exploration exercise, the final allocation of 25 blocks is expected to contain enough polymetallic sulphide to sustain multi-year exploitation, herein defined as exploitation at commercially reasonable rates for a period of more than one year. Various models have been proposed for multi-year exploitation (e.g., ranging from 1 to 2 million tones per year), although grades, production rates, and other technical aspects have not been specified. The proposed exploitation models are based on comparisons with commercial mining operations on land. This is a reasonable approach, as it must be assumed that any future seabed exploitation would have to compete with land-based mining.

Accumulations in excess of 1 million tonnes might be contained in one large occurrence (e.g., TAG, Middle Valley) or, more likely, in multiple occurrences within a larger area. The size of an area likely to contain this amount of massive sulphide is not known. It might correspond to 20 blocks containing 50,000 tonnes each, 2 blocks containing 500,000 tonnes each, or 1 block containing more than 1 million tonnes. However, based on comparisons with fossil deposits, we estimate that the median tonnage in the most prospective block of 10 km x 10 km will be no more than 500,000 tonnes (Appendix 2). Few blocks of this size would be expected to contain more than 1 million tonnes, and the majority would be expected to contain no more than 50,000 tonnes. Of the 100 occurrences considered in this study, excluding the Atlantis II Deep, only two have been shown by drilling to contain more than 1 million tonnes of massive sulphide. Fewer than five others have dimensions that could be consistent with tonnages exceeding 1 million tonnes. Of these, only two are located in "the Area" (TAG and 13^{o}N EPR).

Mapping of sulphide occurrences on the seabed has shown that, individually, they cover areas of no more than 1 km in diameter, and exploitation of any given sulphide occurrence would not be expected to extend beyond an area of these dimensions. In no cases are the expected dimensions of a single occurrence larger than the minimum 10 km x 10 km block. In the majority of cases, blocks where exploitation might take place would not be arranged contiguously and may not be a subset from a single original exploration area. Blocks considered for exploitation may need to be selected from several non-contiguous exploration areas and split between two or more tenements. The following examples illustrate how contiguous and non-contiguous blocks might be allocated at the exploration stage.

4.1 Exploration Model 1 (contiguous blocks)

In this model, areas of permissive geology, physically bounded by ridge segments or other geological features of similar scale and containing at least one occurrence of polymetallic sulphide or other positive indication of mineralization, were selected in each 5 deg. by 5 deg. area (Appendix 3). Each permissive area corresponds to approximately 500 contiguous blocks of 10 km x 10 km each (50,000 km^2). This is approximately 20 times the size of the final allocation for exploitation as defined in the Draft Regulations (20 x 25 blocks = 500 blocks).

A single exploration area comprising 100 contiguous blocks of 10 km x 10 km each (10,000 km^2) was selected for advanced exploration, such as might be defined in a work plan. In this model, an exploration area was chosen that contains at least one of the known sulphide occurrences in the 5 deg. by 5 deg. area (e.g., Figure 4) and represents no more than 20% of the original prospecting area. In each case, 100 of the most prospective blocks (arranged in square blocks of 25) were selected to include as many of the known sulphide occurrences as possible. This mimics the selection process that would be expected in a permissive area during the first phase of exploration. This area is reduced to 50 contiguous blocks after year five and 25 contiguous blocks after year ten (Figure 4).

A single area of 25 contiguous blocks of 10 km x 10 km each (2,500 km^2) and containing at least one known sulphide occurrence was selected as the final lease within the exploration area. In this model, the final lease blocks were selected to contain the maximum number of known sulphide occurrences in an area representing no more than 25% of the original exploration area (Figure 4).

4.2 Exploration Model 2 (non-contiguous blocks)

In this second model, the exploration area is split into 4 clusters of 25 blocks each, with each cluster containing a known sulphide occurrence or other positive indicator of hydrothermal activity in a total combined area of 10,000 km^2 (e.g., Figure 5). During the exploration phase, portions of each cluster of contiguous blocks would be relinquished in multiple stages, eventually leaving 25 non-contiguous blocks of 10 km x 10 km each that contain all of the known sulphide occurrences in the original 10,000 km^2. Although not considered here, the optimum lease blocks in some areas would need to be chosen from more than one exploration area of 10,000 km^2. There is no guarantee that the most prospective blocks would be correctly identified in the exploration phase, but it is a reasonable expectation that explorers will be able to apply appropriate criteria to maximize the selection of clusters of blocks that contain sulphides.

5. Results

5.1 Selection of Permissive Areas and Areas for Exploration

Of the 32 areas of 5 deg. by 5 deg. considered in this study, the average area with permissive geology for the occurrence of polymetallic sulphides is 55,000 km^2 (Table 2). Areas of roughly equal size were selected in the 20 examples of national EEZs and in the 12 examples from "the Area". The permissive areas in some EEZs are smaller, owing to the proximity to land and large numbers of islands. In other EEZs the permissive areas are larger, owing to the selection of both back-arc areas and arc-front volcanoes. The variance in the size of permissive areas selected in examples from "the Area" is lower than in many EEZs, as the mid-ocean ridge spreading centers in "the Area" tend to be geologically less complex. In all cases, the areas chosen as being permissive for polymetallic sulphides are significantly larger than the 10,000 km^2 that would be encompassed by a single exploration area of only 100 blocks of 10 km x 10 km each.

Interpolation and gridding of the GEBCO data at 500-m contour intervals and a 1-minute spacing can recover additional seafloor details that may be useful in selecting smaller permissive areas, potentially reducing the areas selected in the first pass by as much as 50%. This is illustrated by the example of the N.E. Pacific, in which the permissive area selected from the GEBCO data is 55,000 km^2, whereas a permissive area of about 25,000 km^2 might have been chosen at a contour interval of 100 m (Appendix 5). Even with the higher resolution bathymetry, it is not always recommended to exclude deep or flat areas flanking the ridges. An example of this problem is the Middle Valley occurrence, which, owing to its location off-axis from the spreading center, might not have been included in an initial selection of permissive areas even at a 100-m contour interval. Thus, a 10-fold increase in the resolution of the bathymetry at the scale of 5 deg. by 5 deg. does not necessarily result in a 10-fold decrease in the area selected as being permissive for polymetallic sulphides. Restricting exploration to shallow water depths (e.g., <2,500 m), for as yet unspecified technological reasons, also would exclude many areas that are highly prospective for polymetallic sulphides, including most of "the Area". Whereas a high proportion of the known polymetallic sulphides in national EEZs occur at water depths of less than 2,500 m, many in "the Area" are as deep as 4,000 m (Figure 6 and Table 1).

The average number of sulphide occurrences in each of the ca. 55,000 km^2 permissive areas is 3.4 (Table 2). A slightly higher average number (3.7) was found in the examples from "the Area", reflecting the number small sulphide occurrences that characterize fast-spreading ridges. From an analysis of all106 sulphide occurrences in Appendix 3, the average spacing between occurrences in each five deg. by five deg. area is 98 km (Table 2). In "the Area", the average spacing is 95 km (n = 43). Although the spacing is greater on the slow-spreading ridges (167 km) than on the fast-spreading ridges (46 km), the individual sulphide occurrences on the slow-spreading ridges are larger on average. These data suggest that an exploration license of only 10,000 km^2 will likely include only a fraction of the known occurrences in an area. Given the wide distribution of vents, lease blocks may be required at a number of separate locations within discrete and possibly separate permissive areas. Although unfavourable areas could be systematically relinquished in such a way as to preserve a contiguous arrangement of retained blocks, it is more likely that explorers will rapidly identify the most favourable sites and that a number of non-contiguous prospective blocks would be established.

5.2 Comparison of Model 1 and Model 2

In Model 1, the average number of sulphide occurrences in 100 of the most prospective blocks, or 10,000 km^2, is 2.5. A slightly higher average number of occurrences (2.7) was found in the examples chosen from "the Area". On average, an exploration area that comprises 100 contiguous blocks encompasses 73% of the known sulphide occurrences in the permissive area. In the example shown in Figure 4, two occurrences were left outside the initial exploration area and a third occurrence had to be relinquished in order to retain a contiguous arrangement of blocks in the final selection. In this example, the final 25 contiguous blocks contain only 2 of the 4 sulphide occurrences in the original permissive area. On average only 53% of the known sulphide occurrences in a permissive area are contained in the final 25 blocks (Table 2).

In Model 2, the exploration areas were split into 4 sub-areas, each comprising 25 of the most prospective blocks (for the same total area of 10,000 km^2). In this case, it was possible to capture 97% of the known sulphide occurrences within the 100 most prospective blocks. In the few cases where sulphide occurrences were left outside the 100 most prospective blocks, the total number of occurrences was larger than could be contained in the 4 sub-areas. In the majority of the 5 deg. by 5 deg. areas, non-contiguous blocks would be required to encompass all of the known sulphide occurrences in the permissive area.

6. Conclusions and Recommendations

The draft regulations for prospecting and exploration likely could not be applied equally to crusts and polymetallic sulphides. Selection of exploration leases, rates of relinquishment of lease blocks, and legal and technical guidelines for management of these leases must be tailored to the specific attributes of crust and sulphides. The permissive areas for polymetallic sulphides are large, but the occurrences are more localized and the areas likely to be considered for exploitation are smaller than for crusts. Unlike crusts, which are mainly restricted to seamounts that can be readily identified in bathymetric surveys, large areas may be selected for initial stages of prospecting for polymetallic sulphides. Such areas can be rapidly reduced to the most highly prospective sites within the first 5 to 10 years, but more areas may need to be explored to ensure that sufficient exploitable resources are eventually identified. In the majority of cases, a single exploration area of 10,000 km^2 is too small to encompass all of the polymetallic sulphides that may occur within a prospective area of 5 deg. by 5 deg. For larger areas, the proposed schedule of relinquishment may not allow adequate assessment of all areas in enough detail to ensure that prospective blocks are not abandoned prematurely.

Given the known distribution of polymetallic sulphides in "the Area", it is likely that separate clusters of contiguous blocks would be needed to encompass all of the known sulphide occurrences in an exploration license. The use of contiguous blocks, as defined in the Draft Regulations, likely would not allow a contractor to secure adequate opportunities for multi-year exploitation, and applications for multiple 100-block licenses would almost certainly be required to cover the permissive geology. Because of the spacing between occurrences in a given area, 100 contiguous blocks in a plan of work for exploration is unlikely to be sufficient for the discovery of multi-year resources. Splitting the exploration areas into clusters of non-contiguous blocks would be required to ensure that the final clusters can be spread over a large enough area to contain such resources. The final 25 blocks selected for exploitation may not originate from the same initial allocation of 100 blocks in a single exploration license. In most applications of Model 1, at least one occurrence was left outside the initial exploration area and a second occurrence had to be relinquished in order to preserve a contiguous arrangement of the final 25 blocks. The regulations should allow licensing of areas for exploration that are large enough to contain a reasonable number of occurrences, or provide other rights at the prospecting stage to secure enough prospective areas that might contain exploitable resources. Applications for licenses comprising non-contiguous blocks should be permitted throughout the exploration and exploitation stages.

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Tables

Table 1. High-temperature hydrothermal vents and occurrences of seafloor polymetallic sulfides (Hannington et al., 2005)

Table 2. Analysis of permissive areas, numbers of sulfide occurrences, and spacing between occurrences in 32 areas (5 deg. by 5 deg.).

Figures

Figure 1. Distribution of seafloor hydrothermal vents and occurrences of seafloor polymetallic sulfides (Hannington et al., 2005). Numbers refer to occurrences listed in Table 1. Other low-temperature hydrothermal vents and Fe-Mn crusts or metalliferous sediments are indicated by open circles. Major spreading ridges and subduction zones (volcanic arcs and back-arcs) are indicated.

Figure 2. Locations of national EEZs (shaded areas correspond approximately to the 200 nm limit). The distribution of mid-ocean ridges in "the Area" is also shown.

Figure 3. Locations of 32 of the five degree by five degree areas considered in this paper.

Figure 4. An application of Model 1 in the Central Indian Ridge, showing 100 contiguous blocks of 10 km x 10 km each that were leased for exploration and contain at least one known sulphide occurrence or other positive indication of mineralization in the 10,000 km^2 area. 50% of the exploration area is relinquished in the first exploration stage (5 years), leaving 50 contiguous blocks of 10 km x 10 km each, containing three of the 5 known sulphide occurrences in a 5,000 km^2 area. In the final stage of exploration, 25 contiguous blocks of 10 km x 10 km each are retained, containing two of the known sulphide occurrences in a 2,500 km^2 area. In this model, two occurrences were left outside the initial exploration area and a third occurrence had to be relinquished in order to retain only contiguous blocks in the final selection of 25.

Figure 5. An application of Model 2 in the same areas as Figure 4, showing 100 non-contiguous blocks of 10 km x 10 km each, split between 4 clusters of 25 contiguous blocks of 2,500 km^2 each, containing all of the known sulphide occurrences in a total combined area of 10,000 km^2. There is no guarantee that the most prospective blocks would be correctly identified in the exploration phase, but it is a reasonable expectation that explorers will be able to apply appropriate criteria to maximize the selection of clusters of blocks that contain sulphides. The initial area for exploration may need to be significantly larger than 10,000 km^2 in order to secure all of the sulfide occurrences in the final stage of exploration.

Figure 6. Depth distribution of seafloor hydrothermal vents in different volcanic and tectonic settings (from Hannington et al., 2005, modified after Massoth et al., 2003).

Table 1. High-Temperature Hydrothermal Vents and Related Sea-floor Sulfide Deposits (1965-2005).

No.[1]	Deposit	Regional Setting	Spreading Rate (cm/yr)[2]	Volcanic Setting	Host Rocks[3]	Depth[4] (m)	Temp.[5] (°C)
A. Oceanic Spreading Centers and Related Rifts							
Intracontinental rifts:							
1.	Atlantis II Deep (21°22'N)	Red Sea	1.5	rift graben, brine pool	E-MORB, evaporites, sediments	2,200	66
2.	Thetis, Nereus, Gypsum (22°30'-24°30'N)	Red Sea	1.0-1.5	rift graben, brine pool	E-MORB, evaporites, sediments	1,700	low-T
3.	Kebrit Deep (24°43'N)	Red Sea	0.9	rift graben, brine pool	E-MORB, evaporites, sediments	1,600	low-T
4.	Shaban Deep (26°14'N)	Red Sea	<0.8	rift graben, brine pool	E-MORB, evaporites, sediments	1,600	low-T
Slow-spreading mid-ocean ridges:							
5.	Broken Spur (29°10'N)	Mid-Atlantic Ridge	2.3	rift valley floor	MORB	3,090	364
6.	TAG Mound (26°08'N)	Mid-Atlantic Ridge	2.4	rift valley floor	MORB	3,650	366
7.	MIR Zone (26°09'N)	Mid-Atlantic Ridge	2.4	rift valley wall	MORB	3,500	na
8.	Alvin Zone (26°10'N)	Mid-Atlantic Ridge	2.4	rift valley wall	MORB	3,500	na
9.	24°30'N, Mid-Atlantic Ridge	Mid-Atlantic Ridge	2.4	rift valley floor	MORB	3,900	na
10.	Snakepit Hydrothermal Field (23°22'N)	Mid-Atlantic Ridge	2.4	rift valley floor	MORB	3,480	366
11.	15°N, Mid-Atlantic Ridge	Mid-Atlantic Ridge	2.6	rift valley floor	MORB	3,500	na
12.	14°43'N, Logatchev Field	Mid-Altantic Ridge	2.6	rift valley wall	MORB, serpentinite, gabbro	2,950	>300
13.	36°14'N, Rainbow Field	Mid-Atlantic Ridge	2.1	rift valley wall	MORB, serpentinite, gabbro	2,300	362
14.	Mt. Jourdanne (27°51'S)	Southwest Indian Ridge	1.4	rift valley floor	MORB, E-MORB, ±ultramafic	2,960	na
15.	Gakkel Ridge, 86°N	Gakkel Ridge, Arctic Ocean	1.1	rift valley floor	MORB, E-MORB, ±ultramafic	>4,000	na
16.	Aurora Field (82°54'N)	Gakkel Ridge, Arctic Ocean	1.3	rift valley floor	MORB, E-MORB, ±ultramafic	>4,000	na
17.	Lena Trough (81°22'N)	Northern Mid-Atlantic Ridge	1.3	rift valley floor	MORB, E-MORB, ±ultramafic	>4,000	na
18.	69°N, Kolbeinsey Ridge	Northern Mid-Atlantic Ridge	1.7	rift valley floor	MORB	<1,200	na
19.	67°N, Kolbeinsey Ridge	Northern Mid-Atlantic Ridge	1.7	rift valley floor	MORB	100	<185
20.	63°06'N, Reykjanes Ridge	Northern Mid-Atlantic Ridge	1.7	rift valley floor	MORB	300	low-T
Intermediate-rate mid-ocean ridges:							
21.	JX/MESO Zone (23°24'S)	Central Indian Ridge	4.5	rift valley floor	MORB, minor E-MORB	3,300	na
22.	EX/FX Zone (21°15'S)	Central Indian Ridge	4.4	rift valley floor	MORB, minor E-MORB	3,000	plume
23.	Kairei Field (25°19'S)	Central Indian Ridge	4.8	off-axis, rift valley wall	MORB, minor E-MORB	2,460	365
24.	Edmond Field (23°53'S)	Central Indian Ridge	4.6	off-axis, rift valley wall	MORB, minor E-MORB	3,390	382
25.	Galapagos Rift, 86°W	Galapagos Spreading Center	6.3	axial volcanic high	MORB, low-K oceanic andesite	2,550	na
26.	Southern Explorer Ridge (49°45'N)	Northern Juan de Fuca	5.7	axial zone, central high	MORB, minor E-MORB	1,850	306
27.	High-Rise, Endeavour Ridge (47°58'N)	Juan de Fuca Ridge	5.7	axial volcanic high	E-MORB	2,170	342
28.	Main Field, Endeavour Ridge (47°57'N)	Juan de Fuca Ridge	5.7	axial volcanic high	E-MORB	2,200	380
29.	CoAxial Segement (46°10'N)	Juan de Fuca Ridge	5.6	axial volcanic high	MORB, E-MORB	2,060	294
30.	North Cleft, Monolith (44°59'N)	Juan de Fuca Ridge	5.6	axial volcanic high	MORB	2,300	330
31.	South Cleft, Plume (44°39'N)	Juan de Fuca Ridge	5.6	axial volcanic high	MORB	2,300	342
32.	North Gorda (42°45'N)	Northern Gorda Ridge	5.6	off-axis, rift valley wall	MORB	2,700	304
Fast-spreading mid-ocean ridges:							
33.	21°N, Northern EPR	East Pacific Rise	9.2	axial rift zone	MORB	2,600	355
34.	12°50'N, Northern EPR	East Pacific Rise	10.5	axial rift zone	MORB	2,600	380
35.	11°32'N, EPR 87D1 Seamount	East Pacific Rise	10.7	near-axis seamount	MORB	2,090	na
36.	11°N, Northern EPR	East Pacific Rise	10.9	axial rift zone	MORB	2,500	347
37.	9-10°N, Northern EPR	East Pacific Rise	11.1	axial rift zone	MORB	2,550	403
38.	3°55'N, Northern EPR	East Pacific Rise	12.0	axial rift zone	MORB	2,600	plume
39.	1°44'N, AHA Field, EPR	East Pacific Rise	12.3	axial rift zone	MORB	2,850	active
40.	7°00'S, Southern EPR	East Pacific Rise	13.6	axial rift zone	MORB	2,600	active
41.	7°30'S, Southern EPR	East Pacific Rise	13.7	axial rift zone	MORB	2,750	340
42.	14°00'S, Southern EPR	East Pacific Rise	14.4	axial rift zone	MORB	2,630	374
43.	15°00'S, Southern EPR	East Pacific Rise	14.5	axial rift zone	MORB	2,600	plume
44.	16°40'S, Southern EPR	East Pacific Rise	14.6	axial rift zone	MORB	2,600	active
45.	17°27'S, Southern EPR	East Pacific Rise	14.6	axial rift zone	MORB	2,600	active

46.	17°30'S, Southern EPR	East Pacific Rise	14.6	axial rift zone	MORB	2,600	active
47.	18°10'S, Southern EPR	East Pacific Rise	14.7	axial rift zone	MORB	2,670	305
48.	18°26'S, Southern EPR	East Pacific Rise	14.7	axial rift zone	MORB	2,635	374
49.	20°00'S, Southern EPR	East Pacific Rise	14.6	axial rift zone	MORB	3,000	active
50.	20°50'S, Southern EPR	East Pacific Rise	14.8	axial rift zone	MORB	2,600	plume
51.	21°30'S, Southern EPR	East Pacific Rise	14.9	axial rift zone	MORB	2,835	402
52.	21°50'S, Southern EPR	East Pacific Rise	14.9	axial rift zone	MORB	2,600	active
53.	22°30'S, Southern EPR	East Pacific Rise	14.9	axial rift zone	MORB	2,600	plume
54.	22°58'S, Southern EPR	East Pacific Rise	14.9	axial rift zone	MORB	2,600	active
55.	23°30'S, Southern EPR	East Pacific Rise	15.0	axial rift zone	MORB	2,600	active
56.	26°10'S, Southern EPR	East Pacific Rise	15.0	axial rift zone	MORB	2,600	active
57	31°51'S, Southern EPR	East Pacific Rise	9.4	axial rift zone	MORB	2,300	370
58.	37°40'S, Southern EPR	Pacific-Antarctic Ridge	9.4	axial rift zone	MORB	2,200	active
59.	37°48'S, Southern EPR	Pacific-Antarctic Ridge	9.4	axial rift zone	MORB, andesite, dacite	2,200	active
Off-axis volcanoes:							
60.	Green Seamount (20°48'N)	Larson Seamounts, N. EPR	(9.2)	small, off-axis seamount	MORB, E-MORB	2,000	na
61.	14°N, Northern EPR	East Pacific Rise	(10.3)	small, off-axis seamount	MORB, E-MORB	2,600	na
62.	13°N, Northern EPR	East Pacific Rise	(10.5)	large, off-axis seamount	MORB, E-MORB	2,650	na
63.	23°19'S, Southern EPR	Easter Microplate, S. EPR	(14.9)	small, off-axis seamount	MORB, E-MORB	2,200	--
64.	Pito Seamount (23°19'S)	Easter Microplate, S. EPR	(14.9)	small, off-axis seamount	MORB, E-MORB	<2,000	--
Sedimented ridges and related rifts:							
65.	Middle Valley (48°27'N)	Juan de Fuca Ridge	5.4	sediment-covered rift valley	MORB, minor E-MORB, sediment	2,425	276
66.	Escanaba Trough (41°00'N)	Southern Gorda Ridge	2.4	sediment-covered rift valley	MORB, sediment	3,200	217
67.	Grimsey Hydrothermal Field (66°36'N)	Mid-Altantic Ridge, Iceland	1.8	sediment-filled pull-apart basin	MORB, E-MORB, sediment	400	250
68.	Guaymas Basin (27°18'N)	Gulf of California	3.8	sediment-filled pull-apart basin	MORB, sediment	2,000	315
Ridge-hotspot intersections:							
69.	Axial Seamount (45°56'N)	Juan de Fuca Ridge	5.6	axial volcano, caldera	MORB, E-MORB	1,540	348
70.	Lucky Strike (37°17'N)	Mid-Atlantic Ridge, Azores	2.2	axial volcano, rift zone	E-MORB	1,670	333
71.	Menez Gwen (37°50'N)	Mid-Atlantic Ridge, Azores	2.0	axial volcano	E-MORB	850	284
Intraplate volcano:							
72.	Loihi Seamount	Hawaiian Hotspot	na	hotspot volcano	OIB	980	<200
B. Volcanic Arcs and Bac-arc Basins							
Intraoceanic arcs:							
73.	Myojin Knoll, Kita Bayonnaise (32°06'N)	Izu-Bonin Arc	na	arc front volcano, caldera	IAB, low-K andesite, dacite, rhyolite	1,300	278
74.	Myonjinsho (31°53'N)	Izu-Bonin Arc	na	arc front volcano, caldera	IAB, low-K andesite, dacite, rhyolite	900	na
75.	Suiyo Seamount (28°35'N)	Izu-Bonin Arc	na	arc front volcano, caldera	IAB, low-K andesite, dacite	1,300	317
76.	Kaikata Seamount (26°42'N)	Izu-Bonin Arc	na	arc front volcano, caldera	IAB, low-K andesite	900	na
77.	East Diamante (15°56'N)	Mariana Arc	na	arc front volcano	IAB, low-K andesite(?)	345	240
78.	Forecast Field (13°26'N)	Mariana Arc	na	arc-backarc volcano	IAB, BABB, low-K andesite	1,470	202
79.	Clark Seamount (36°27'S)	Kermadec Arc	na	arc front volcano, summit	IAB, minor BABB, med-K andesite	950	na
80.	Rumble II West (35°21'S)	Kermadec Arc	na	arc front volcano, caldera	IAB, minor BABB, med-K andesite	1,300	active
81.	Brothers Seamount (34°52'S)	Kermadec Arc	na	arc front volcano, caldera	IAB, minor BABB, med-K andesite	1,600	active
Intraoceanic back-arc basins:							
82	31°06'N, Sumisu Rift	Izu-Bonin	na	nascent back-arc rift	BABB, minor rhyolite	1,600	<150
83.	18°13'N, Alice Springs Field	Mariana Trough	2.6	back-arc basin, rift valley floor	MORB, minor BABB	3,650	287
84.	18°02'N, Central Mariana Trough	Mariana Trough	2.6	back-arc basin, rift valley floor	MORB, minor BABB	3,675	active
85.	13°24'N, Southern Mariana Trough	Mariana Trough	3.5	back-arc basin, rift valley floor	MORB, minor BABB	3,000	--
86.	16°59'S, White Lady and Kaiyo	North Fiji Basin	7.0	back-arc basin, rift valley floor	MORB, E-MORB, minor BABB	1,960	290
87.	16°57'S, Sonne99 and Père Lachaise	North Fiji Basin	7.0	back-arc basin, rift valley floor	MORB, E-MORB, minor BABB	1,980	active
88.	15°17'S, Papatua Site	Northern Lau Basin	8.5	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	2,100	--
89.	15°20'S, Kings Triple Junction	Northern Lau Basin	8.5	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	2,000	--
90.	21°58'S, White Church Field	Southern Lau Basin	6.0	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	1,850	na

91. 22°19'S, Vai Lili Field	Southern Lau Basin	6.0	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	1,750	342
92. 22°35'S, Hine Hina Field	Southern Lau Basin	6.0	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	1,850	40
93. 18°36'S, Central Lau Basin	Central Lau Basin	4.0	back-arc basin, rift valley floor	BABB, MORB, low-K andesite	2,000	--
94. Central Manus Basin (150°10'E)	Central Manus Basin	>5.0	back-arc basin	MORB, minor BABB	2,500	--
95. Vienna Woods (150°17'E)	Central Manus Basin	>5.0	back-arc basin	MORB, minor BABB	2,500	302
96. Western Ridge (147°20'E)	Western Manus Basin	>5.0	Back-arc basin	MORB, minor BABB	<1,000	--
Transitional island arcs and related back-arc rifts:						
97. Pacmanus (151°43'E)	Eastern Manus Basin	1.4	back-arc volcanic ridge	BABB, MORB, med-K andesite, dacite	1,650	276
98. SuSu Knolls (152°08'E)	Eastern Manus Basin	1.4	back-arc volcanic ridge	BABB, MORB, med-K andesite, dacite	1,460	220
99. Desmos Cauldron (151°52'E)	Eastern Manus Basin	1.4	back-arc caldera	BABB, MORB, med-K andesite	1,925	120
100. Palinuro Seamount (14°42'W, 39°32'N)	Aeolian Arc, Tyrrhenian Sea	na	arc volcano, summit	CA basalt, high-K andesite	600	na
101. Panarea Seamount (15°06'W, 38°38'N)	Aeolian Arc, Tyrrhenian Sea	na	arc volcano, summit	CA basalt, high-K andesite, rhyolite	80	low-T
102. Calypso Vents (37°41'S)	Taupo Zone, White Island	na	arc volcano, flanking rift	Med-K andesite, dacite, rhyolite	170	200
Intracontinental back-arc rifts:						
103. Minami-Ensei Knolls (28°23'N)	Central Okinawa Trough	2.0	back-arc volcano	basalt, high-K andesite, dacite, sediment	700	278
104. North Iheya Ridge (27°47'N)	Central Okinawa Trough	2.0	back-arc volcanic ridge	basalt, high-K andesite, dacite	970	311
105. Iheya Ridge, Clam Site (27°33'N)	Central Okinawa Trough	2.0	back-arc volcanic ridge	basalt, high-K andesite, dacite, sediment	1,390	220
106. Jade Site, Izena Cauldron (27°16'N)	Central Okinawa Trough	2.0	back-arc caldera	basalt, high-K andesite, dacite, rhyolite	1,400	320
107. Hatoma Knoll (24°51'N, 123°50'E)	Southern Okinanwa Trough	4.0	back-arc volcano	basalt, high-K andesite, dacite, sediment	1,460	310
108. Yonaguni Knoll (24°51'N, 122°42'E)	Southern Okinanwa Trough	4.0	back-arc volcanic ridge	basalt, high-K andesite, dacite, sediment	1,350	195
Volcanic rifted margins:						
109. Franklin Seamount (151°50'W, 9°54'S)	Western Woodlark Basin	2.7	rift volcano	MORB, andesite	2,275	30
110. Bransfield Strait (62°11'S)	Western Antarctic Peninsula	<1.0	rift volcanoes	basalt, high-K andesite, rhyolite, sediment	1,070	na

1. Data summarized from Hannington et al. (2004) and references therein, including Butterfield et al. (2000) and Ishibashi and Urabe (1995).
2. Spreading rates for oceanic spreading centers are full spreading rates from NUVEL-1A plate motion calculations of DeMets et al. (1994). Numbers in brackets refer to spreading rates of adjacent ridge segments.
3. MORB = mid-ocean ridge basalt, E-MORB – enriched MORB, BABB = back-arc basin basalt, IAB = island-arc tholeiite, OIB = ocean island basalt, CA = calc-alkaline
4. Depths are not precisely known for some locations where samples were collected by dredging.
5. Reported temperature is maximum measured temperature. na = inactive, plume = evidence of high-temperature plume, active = black smokers of unknown temperature, low-T = low-temperature vents, -- = unknown

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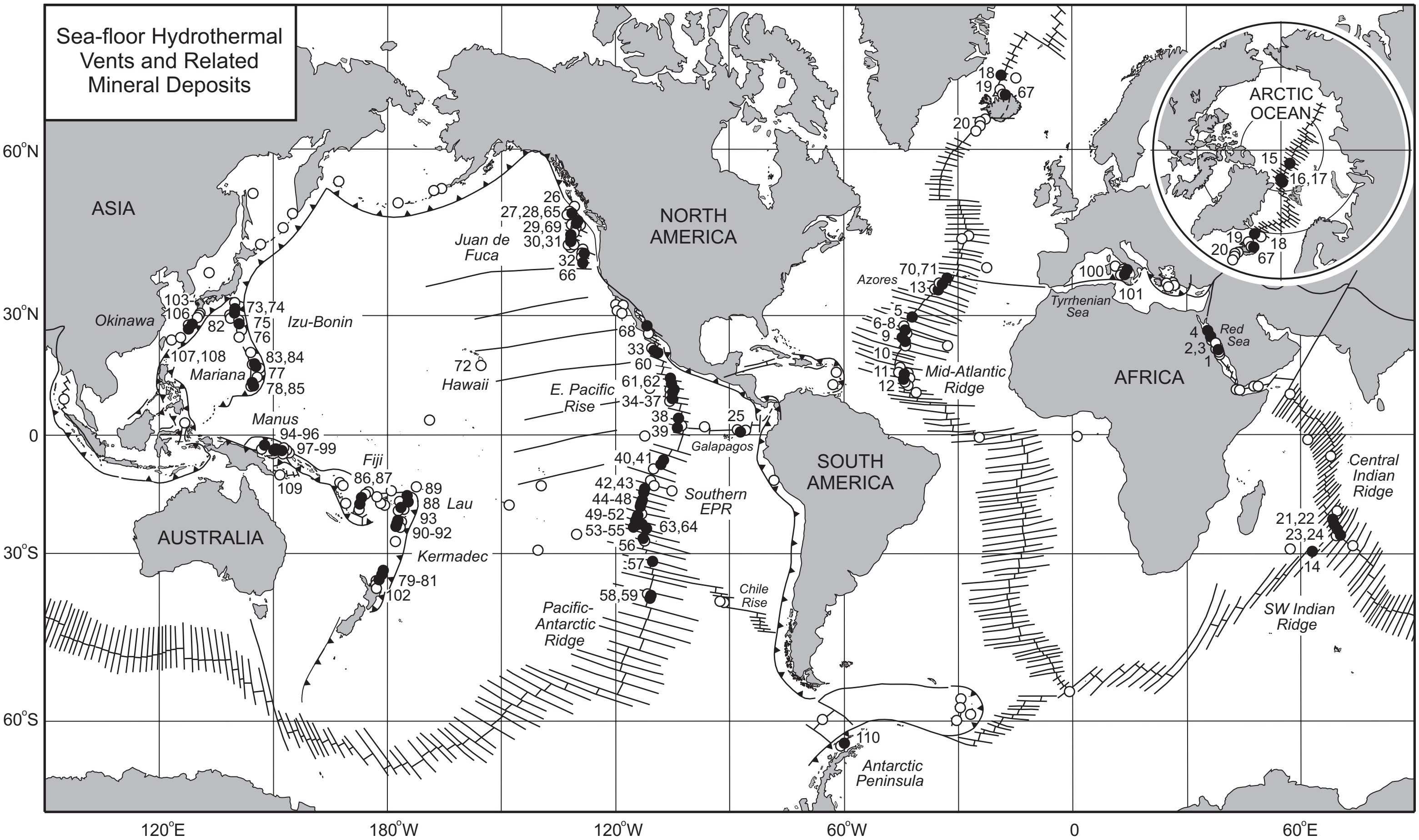
Table 2. Analysis of permissive areas, numbers of known sulfide occurrences, and spacing between occurrences in 32 areas (5 deg. by 5 deg.).

	Five Degree Map Area	Estimated Permissive Area (km^2)	Number of Occurrences In the Area (N=106)	Max. Number of Occurrences in 100 Contiguous Blocks*	Max. Number of Occurrences in a Final 25 Blocks	Average Spacing (km) Between Occurrences
	In "the Area"					
1.	EPR, 13°N	80,000	8	6	3	54
2.	EPR, 9°N	50,000	4	4	3	23
3.	EPR, AHA Field	50,000	1	1	1	--
4.	EPR, 7°S	40,000	2	2	2	10
5.	EPR, 17°S	60,000	4	3	2	120
6.	EPR, 18°S	60,000	9	6	3	55
7.	EPR, 37°S	50,000	2	2	2	15
8.	MAR, TAG and Broken Spur	50,000	2	1	1	300
9.	MAR, 24°N and Snakepit	45,000	2	1	1	175
10.	MAR, 14°N and Logatchev	60,000	3	2	2	87
11.	MAR, 5°S	60,000	2	2	2	--
12.	Central Indian Ridge	50,000	5	3	2	108
	National EEZs					
1.	N. Juan de Fuca Ridge	56,000	3	2	1	86
2.	S. Juan de Fuca Ridge	40,000	4	4	3	40
3.	Gorda Ridge	50,000	4	3	3	67
4.	Guaymas Basin	40,000	1	1	1	--
5.	Galapagos Rift	50,000	1	1	1	--
6.	EPR, 21°N	50,000	3	3	3	10
7.	EPR, 23°S	110,000	4	2	2	250
8.	MAR, Lucky Strike, Menez	75,000	4	3	1	100
9.	Tyrrhenian Sea	35,000	3	3	1	70
10.	N. Red Sea	50,000	3	2	1	180
11.	S. Red Sea	52,000	1	1	1	--
12.	N. Okinawa Trough	60,000	4	4	2	53
13.	S. Okinawa Trough	45,000	3	2	1	75
14.	Izu-Bonin Arc	65,000	4	3	2	123
15.	Mariana Trough and Arc	75,000	3	2	1	165
16.	Eastern Manus Basin	25,000	6	3	3	48
17.	Woodlark Basin	40,000	1	1	1	--
18.	N. Fiji Basin	40,000	3	2	2	95
19.	S. Lau Basin	50,000	4	3	2	133
20.	Southern Kermadec Arc	70,000	4	2	1	110
	Average	55,000	3.4	2.5	1.8	98

*10,000 km^2 arranged in square blocks of 25



<u>Intracontinental rifts</u>
1. Atlantis II Deep, Red Sea
2. Thetis, Nereus, Gypsum Deeps
3. Kebrit Deep, Red Sea
4. Shaban Deep, Red Sea

<u>Slow-spreading mid-ocean ridges</u>
5. Broken Spur, Mid-Atlantic Ridge
6. TAG Mound, Mid-Atlantic Ridge
7. MIR Zone, Mid-Atlantic Ridge
8. Alvin Zone, Mid-Atlantic Ridge
9. 24°30'N, Mid-Atlantic Ridge
10. Snakepit Field, Mid-Atlantic Ridge
11. 15°N, Mid-Atlantic Ridge
12. Logatchev Field, Mid-Atlantic Ridge
13. Rainbow Field, Mid-Atlantic Ridge
14. Mt. Jourdanne, Southwest Indian Ridge
15. Gakkel Ridge, Arctic Ocean
16. Aurora Field, Arctic Ocean
17. Lena Trough, N. Mid-Atlantic Ridge
18. N. Kolbeinsey Ridge
19. Kolbeinsey Ridge
20. Reykjanes Ridge

<u>Intermediate-rate mid-ocean ridges</u>
21. JX/MESO Zone, Central Indian Ridge
22. EX/FX Zone, Central Indian Ridge
23. Kairei Field, Central Indian Ridge
24. Edmond Field, Central Indian Ridge
25. Galapagos Rift
26. S. Explorer Ridge
27. High-Rise, Endeavour Ridge
28. Main Field, Endeavour Ridge
29. CoAxial Site, Juan de Fuca Ridge
30. North Cleft, Juan de Fuca Ridge
31. South Cleft, Juan de Fuca Ridge
32. North Gorda Ridge

<u>Fast-spreading mid-ocean ridges</u>
33. 21°N, Northern EPR
34. 12°50'N, Northern EPR
35. 11°32'N, EPR Seamount
36. 11°N, Northern EPR
37. 9-10°N, Northern EPR
38. 3°55'N, Northern EPR
39. 1°44'N, AHA Field, EPR
40. 7°00'S, Southern EPR
41. 7°30'S, Southern EPR
42. 14°00'S, Southern EPR
43. 15°00'S, Southern EPR
44. 16°40'S, Southern EPR
45. 17°27'S, Southern EPR
46. 17°30'S, Southern EPR
47. 18°10'S, Southern EPR
48. 18°26'S, Southern EPR
49. 20°00'S, Southern EPR
50. 20°50'S, Southern EPR
51. 21°30'S, Southern EPR
52. 21°50'S, Southern EPR
53. 22°30'S, Southern EPR
54. 22°58'S, Southern EPR
55. 23°30'S, Southern EPR
56. 26°10'S, Southern EPR
57 31°51'S, Southern EPR
58. 37°40'S, Pacific-Antarctic Ridge
59. 37°48'S, Pacific-Antarctic Ridge

<u>Off-axis volcanoes</u>
60. Green Seamount
61. 14°N, Northern EPR
62. 13°N, Northern EPR
63. 23°19'S, Southern EPR
64. Pito Seamount

<u>Sedimented ridges and related rifts</u>
65. Middle Valley
66. Escanaba Trough
67. Grimsey Field
68. Guaymas Basin

<u>Ridge-hotspot intersections</u>
69. Axial Seamount, Juan de Fuca Ridge
70. Lucky Strike, Azores
71. Menez Gwen, Azores

<u>Intraplate volcano</u>
72. Loihi Seamount, Hawaii

<u>Intraoceanic arcs</u>
73. Kita Bayonnaise, Izu-Bonin Arc
74. Myonjinsho, Izu-Bonin Arc
75. Suiyo Seamount, Izu-Bonin Arc
76. Kaikata Seamount, Izu-Bonin Arc
77. East Diamante, Mariana Arc
78. Forecast Field, Mariana Arc
79. Clark Seamount, Kermadec Arc
80. Rumble II West, Kermadec Arc
81. Brothers, Kermadec Arc

<u>Intraoceanic back-arc basins</u>
82 Sumisu Rift, Izu-Bonin Arc
83. Alice Springs, Mariana Trough
84. Central Mariana Trough
85. Southern Mariana Trough
86. White Lady, North Fiji Basin
87. Pere Lachaise, North Fiji Basin
88. Papatua Site, Northern Lau Basin
89. Kings Triple Junction, Northern Lau
90. White Church, Southern Lau Basin
91. Vai Lili Field, Southern Lau Basin
92. Hine Hina, Southern Lau Basin
93. Central Lau Basin
94. Central Manus Basin
95. Vienna Woods, Manus Basin
96. Western Ridge, Manus Basin

<u>Transitional island arcs and back-arc rifts</u>
97. Pacmanus, E. Manus Basin
98. SuSu Knolls, E. Manus Basin
99. Desmos Cauldron, E. Manus Basin
100. Palinuro Seamount, Tyrrhenian Sea
101. Panarea Seamount, Tyrrhenian Sea
102. Calypso Vents, Taupo Zone

<u>Intracontinental back-arc rifts</u>
103. Minami-Ensei, Okinawa Trough
104. North Iheya, Okinawa Trough
105. Clam Site, Okinawa Trough
106. Izena Cauldron, Okinawa Trough
107. Hatoma Knoll, S. Okinawa Trough
108. Yonaguni Knoll, S. Okinawa Trough

<u>Volcanic rifted margins</u>
109. Franklin Seamount, Woodlark Basin
110. Bransfield Strait, Antarctica

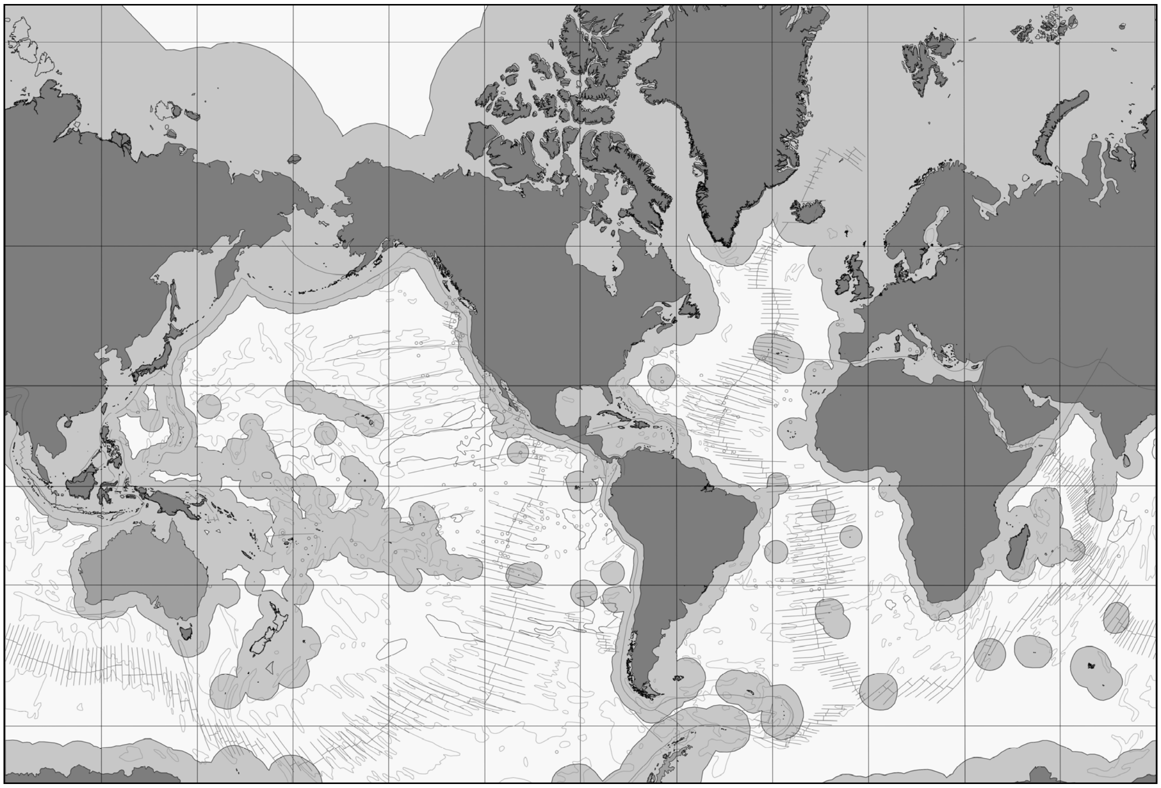


Figure 2. Distribution of seafloor hydrothermal vents and occurrences of seafloor polymetallic sulfides (Hannington et al., 2005). Numbers refer to occurrences listed in Table 1. Other low-temperature hydrothermal vents and Fe-Mn crusts or metalliferous sediments are indicated by open circles. Major spreading ridges and subduction zones (volcanic arcs and back-arcs) are indicated.

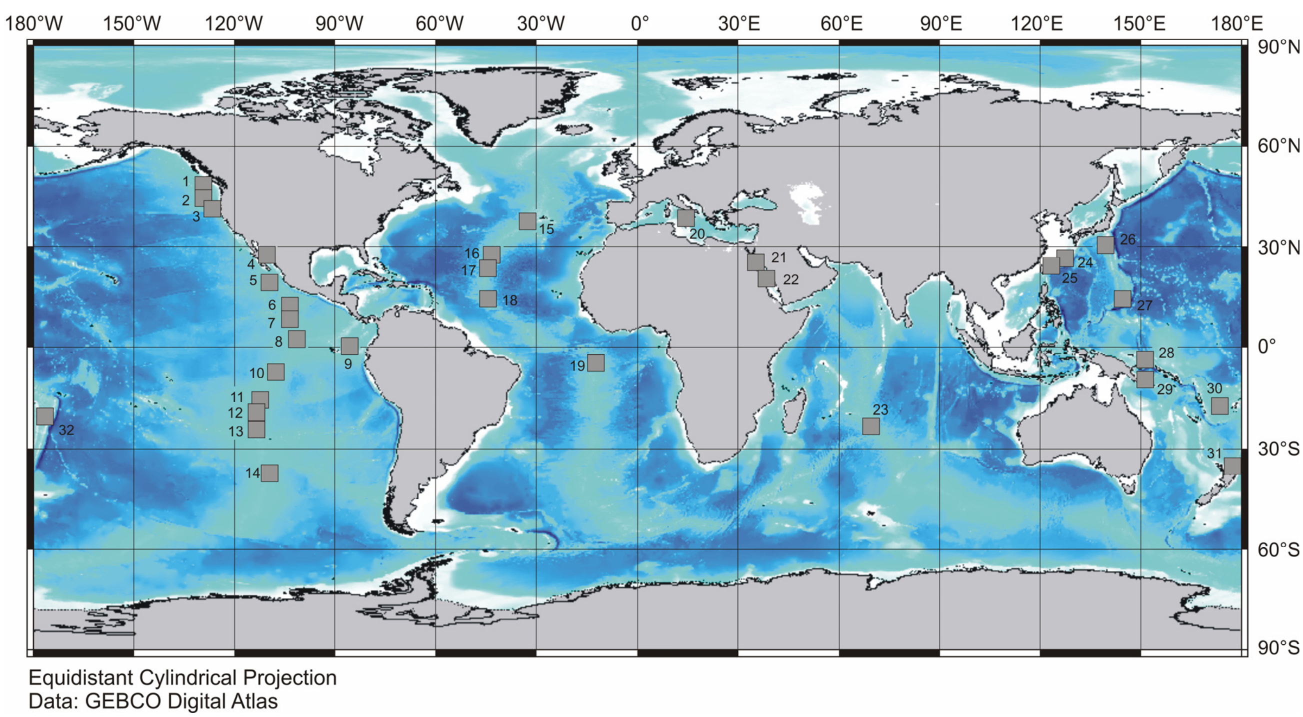
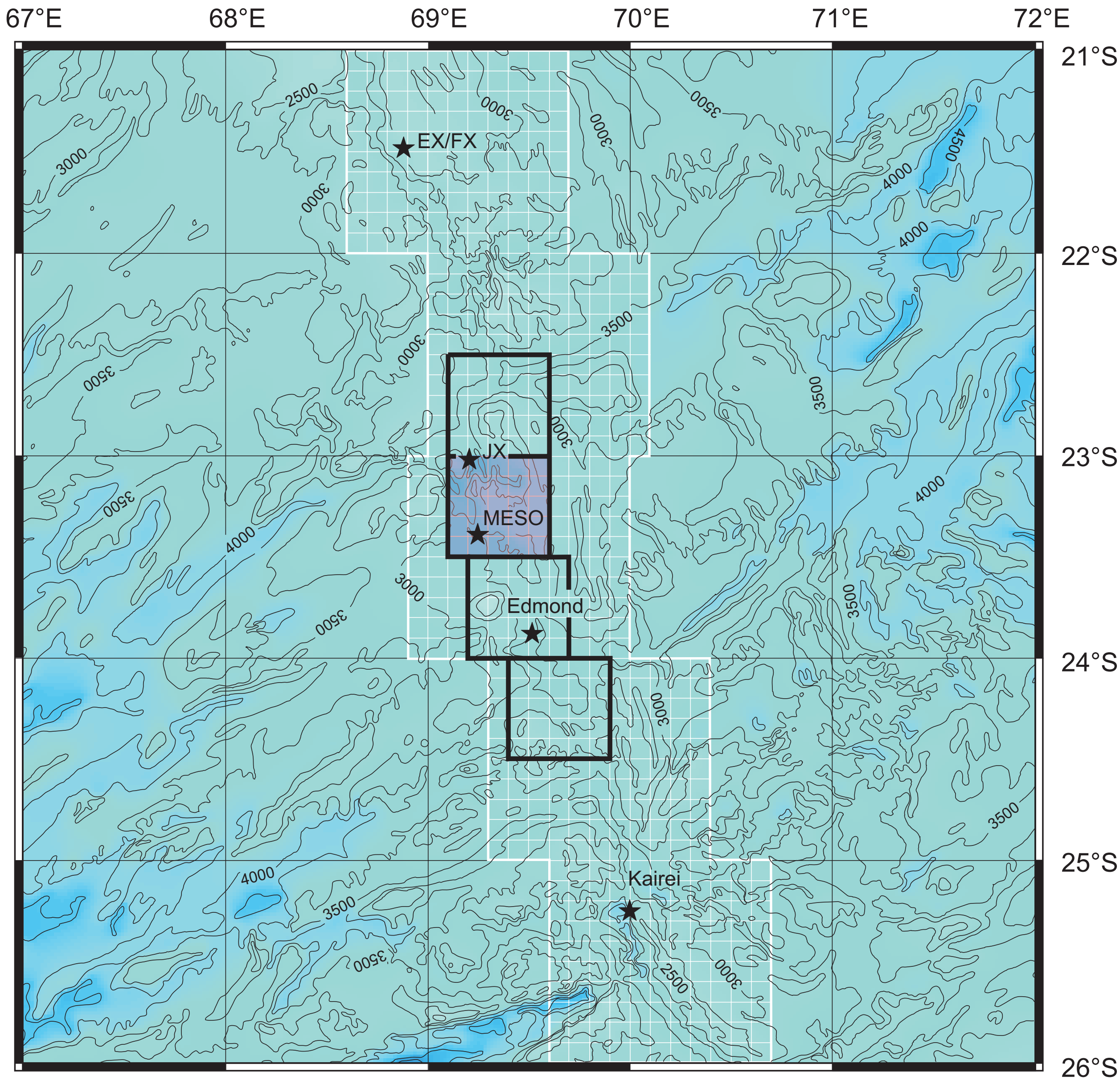


Figure 3. Locations of national EEZs (shaded areas correspond approximately to the 200 nm limit). The distribution of mid-ocean ridges in "the Area" is also shown.

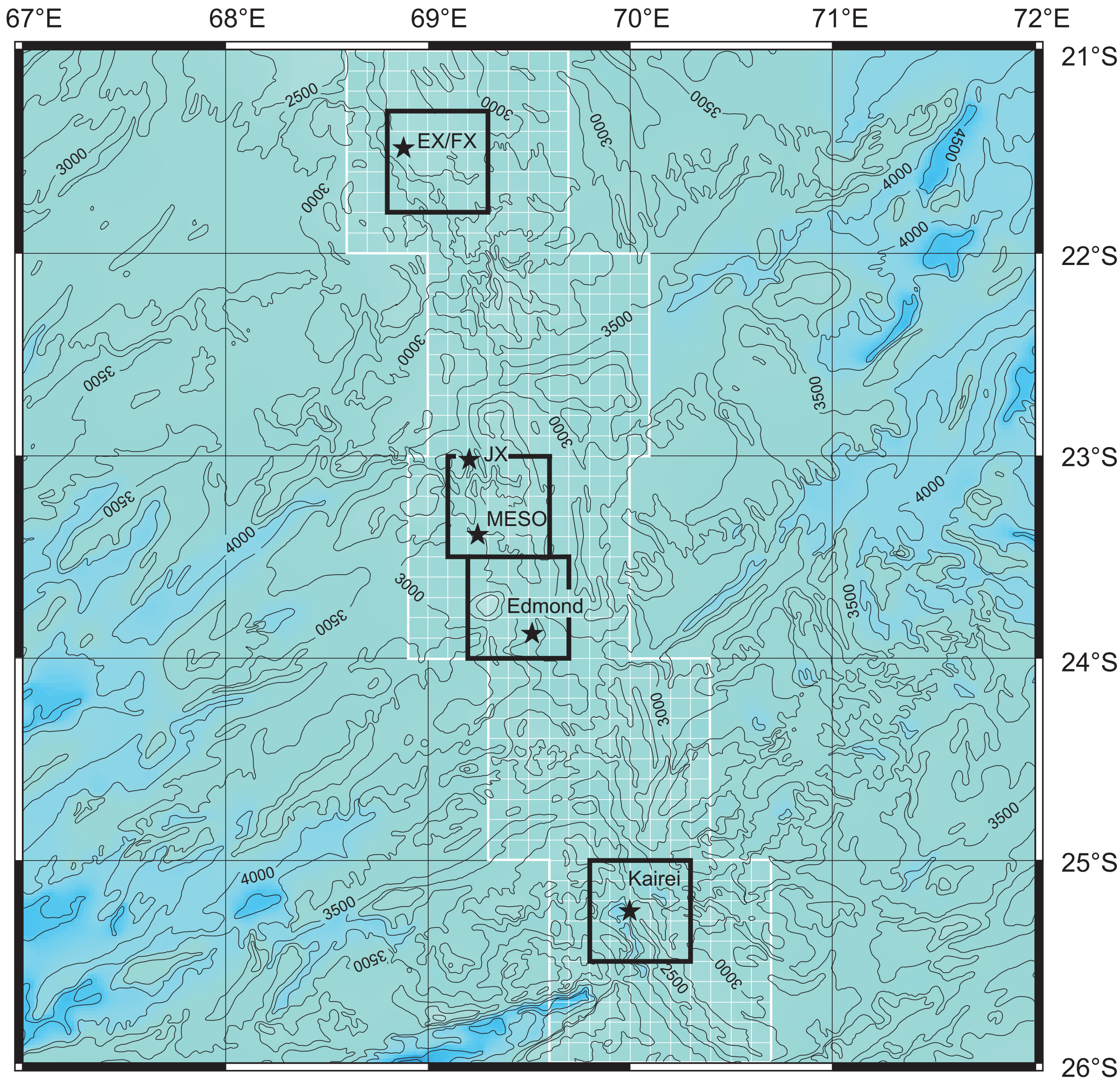
Location of the MESO Zone sulfide occurrence



Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Figure 4. An application of Model 1 in the Central Indian Ridge, showing 100 contiguous blocks of 10 km x 10 km each that were leased for exploration and contain at least one known sulphide occurrence or other positive indication of mineralization in the 10,000 km sq. area. 50% of the exploration area is relinquished in the first exploration stage (5 years), leaving 50 contiguous blocks of 10 km x 10 km each, containing three of the 5 known sulphide occurrences in a 5,000 km sq. area. In the final stage of exploration, 25 contiguous blocks of 10 km x 10 km each are retained, containing two of the known sulphide occurrences in a 2,500 km sq. area. In this model, two occurrences were left outside the initial exploration area and a third occurrence had to be relinquished in order to retain only contiguous blocks in the final selection of 25.

Location of the MESO Zone sulfide occurrence



Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Figure 5. An application of Model 2 in the same areas as Figure 4, showing 100 non-contiguous blocks of 10 km x 10 km each, split between 4 clusters of 25 contiguous blocks of 2,500 km2 each, containing all of the known sulphide occurrences in a total combined area of 10,000 km2. There is no guarantee that the most prospective blocks would be correctly identified in the exploration phase, but it is a reasonable expectation that explorers will be able to apply appropriate criteria to maximize the selection of clusters of blocks that contain sulphides. The initial area for exploration may need to be significantly larger than 10,000 km2 in order to secure all of the sulfide occurrences in the final stage of exploration.

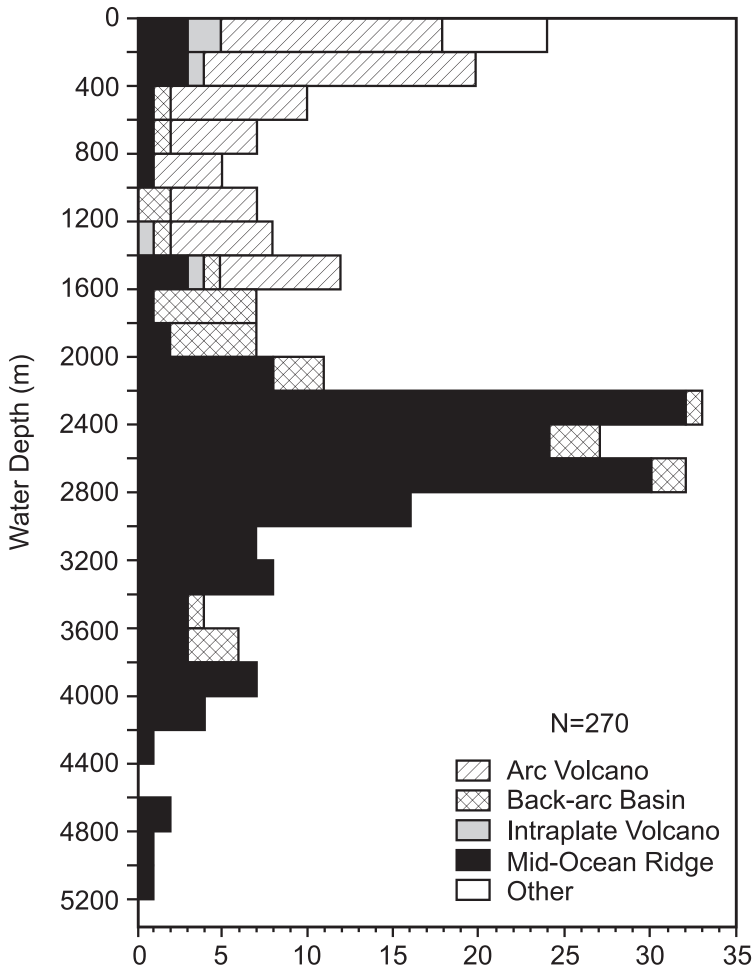


Figure 6. Depth distribution of seafloor hydrothermal vents in different volcanic and tectonic settings (from Hannington et al., 2005, modified after Massoth et al., 2003).

MARK HANNINGTON received a PhD. from the University of Toronto in 1989 and spent 15 years as a Research Scientist at the Geological Survey of Canada before moving the University of Ottawa in 2005. His research combines the study of active volcanoes on the ocean floor, and associated metal-depositing hot springs ("black smoker vents"), with research on ancient volcanic environments that host many of the world's largest and most valuable mineral deposits on land. During the last 20 years, Dr. Hannington has participated on 20 research cruises, exploring for seafloor polymetallic sulphides at submarine volcanoes on the East Pacific Rise, the Juan de Fuca Ridge, the Mid-Atlantic Ridge, Iceland, New Zealand, Antarctica, and Papua New Guinea. This work has focused on understanding the origins of base and precious metal deposits at submarine volcanoes and has led to the discovery of numerous previously unknown mineral deposits on the seafloor. His comparisons between modern volcanoes and ancient volcanic environments have also led to new and improved models for land-based mineral exploration.

Appendix 1. Relevant Paragraphs of the Draft Regulations

Regulation 12
1. The area covered by each application for approval of a plan of work for exploration shall be comprised of not more than 100 blocks.
2. For polymetallic sulphides or cobalt crusts the exploration area shall consist of contiguous blocks. For the purposes of this regulation two blocks that touch at any point shall be considered to be contiguous.
3. Notwithstanding the provisions in paragraph 1 above, where a contractor has elected to contribute a reserved area to carry out activities pursuant to annex III, article 9, of the Convention, in accordance with regulation 17, the total area covered by an application shall not exceed 200 blocks.

Regulation 17
1. Where the applicant elects to contribute a reserved area, the area covered by the application shall be sufficiently large and of sufficient estimated commercial value to allow two mining operations. The applicant shall divide the blocks comprising the application into two groups of equal estimated commercial value and composed of contiguous blocks. The area to be allocated to the applicant shall be subject to the provisions of regulation 27.

Regulation 27
1. The contractor shall relinquish the blocks allocated to it in accordance with paragraphs 2, 3 and 4 of this regulation.
2. By the end of the fifth year from the date of the contract, the contractor shall have relinquished:
(a) At least 50 per cent of the number of blocks allocated to it; or
(b) If 50 per cent of that number of blocks is a whole number and a fraction, the next higher whole number of the blocks.
3. By the end of the tenth year from the date of the contract, the contractor shall have relinquished:
(a) At least 75 per cent of the number of blocks allocated to it; or
(b) If 75 per cent of that number of blocks is a whole number and a fraction, the next higher whole number of the blocks.
4. At the end of the fifteenth year from the date of the contract, or when the contractor applies for exploitation rights, whichever is the earlier, the contractor shall nominate up to 25 blocks from the remaining number of blocks allocated to it, which shall be retained by the contractor.
5. Relinquished blocks shall revert to the Area.
6. The Council may, at the request of the contractor, and on the recommendation of the Commission, in exceptional circumstances, defer the schedule of relinquishment. Such exceptional circumstances shall be determined by the Council and shall include, inter alia, consideration of prevailing economic circumstances or other unforeseen exceptional circumstances arising in connection with the operational activities of the Contractor.

Appendix 2. Model Parameters

A range of physical characteristics of seafloor polymetallic sulphides and the geological environments in which they are found are considered here as guides for the selection of prospecting areas. Following is a brief review of the main parameters used for mid-ocean ridges. A thorough review of other geological settings listed in Table 1 is beyond the scope of this paper but should be the subject of any further consideration of global exploration for seafloor polymetallic sulphides. For more information, the reader is referred to overview papers on this topic by Hannington et al. (1995, 2005) and Herzig and Hannington (1995, 1999, 2000). Additional information also can be obtained from Technical Study No. 2 on *Polymetallic Massive Sulphides and Cobalt-rich Ferromanganese Crusts – Status and Prospects*, published by the International Seabed Authority.

A2.1 Geological Considerations

Polymetallic massive sulphides are products of high-temperature (ca. 350^{o}C) black smoker vents that occur in areas of active or recently active volcanism on the seafloor, including deep-sea mid-ocean ridges, sedimented ridges, mid-plate seamounts, arc volcanoes, and back-arc rift environments. The hydrothermal precipitates consist of massive accumulations of metallic minerals, including mainly pyrite, pyrrhotite, chalcopyrite and sphalerite that occur at and below the seafloor around hydrothermal vents. Most sulphide accumulations are associated with ongoing hydrothermal venting, but about 20% of these sites are no longer active.

About 65% of known sulphide occurrences are located at mid-ocean ridges; the remainder are in back-arc basins (22%), on submarine volcanic arcs (12%), and on intraplate volcanoes (1%). The distribution of vents is roughly proportional to the lengths of the ridges and arcs; mid-ocean ridges have a combined length of 55,000 km, and island arcs and adjoining back-arc basins have a combined length of 22,000 km. The sulphides are found on a variety of different substrates, including mid-ocean ridge basalt, ultramafic intrusive rocks, and more evolved lavas associated with volcanic arcs, as well as within sediments overlying both oceanic and continental crust. Permissive areas for the occurrence of polymetallic sulphides include areas of intense faulting and seafloor eruptions, which commonly can be identified from regional bathymetry. Black smokers are most abundant on fast-spreading mid-ocean ridges, which reflects the high heat flow and voluminous seafloor volcanism in this environment. However, the most abundant sulphides are not always associated with the highest spreading rates; the largest sulphide occurrences are located at intermediate- and slow-spreading centers, at ridge-axis volcanoes, in deep back-arc basins, and in sedimented rifts adjacent to continental margins. The lack of known sulphide occurrences in some parts of the oceans (e.g., the polar regions and Southern Ocean) mainly reflects the difficulties of marine research at these latitudes. Recent discoveries of hydrothermal plumes and massive sulphides in the high Arctic and in Antarctica confirm that seafloor hydrothermal activity in remote parts of the oceans is little different from that observed elsewhere.

In "the Area", mid-ocean ridges and intraplate volcanoes are the dominant volcanic features that host polymetallic sulphides (e.g., southern East Pacific Rise or EPR, Mid-Atlantic Ridge or MAR, Central Indian Ridge or CIR: Figure 1). The different types of mid-ocean ridges are discriminated on the basis of spreading rate and morphology, which vary in response to regional tectonic stresses and rates of magma supply. Fast-spreading ridges (full spreading rates of 6-10 cm/yr) occur in relatively thin oceanic crust and are characterized by abundant volcanic eruptions; intermediate-rate (4-6 cm/yr) and slow-spreading (1-4 cm/yr) ridges occur in relatively thick crust and are characterized by only intermittent volcanism between long periods of essentially amagmatic, tectonic extension and/or intrusive activity. Fast-spreading ridges account for about 25 percent of the total length of the ridges, whereas 15 percent of the ridges are classified as intermediate-rate and 60 percent are slow-spreading. Superfast-spreading centers, such as the southern EPR (up to 17 cm/yr), and ultraslow-spreading centers, such as the Arctic and Southwest Indian ridges (<1 cm/yr), are also recognized. The rate of magma supply, the depth of the subaxial magma, and the extent of magmatic versus tectonic extension influence the size and vigor of hydrothermal convection on the ridges. There is a general correlation between the spreading rate and the incidence of hydrothermal venting; however, as noted above, the largest sulphide occurrences are commonly found where volcanic eruptions are episodic and alternate with long periods of intense tectonic activity.

Ridges (and back-arc basins) are physically segmented at scales of 10s to 100s of kilometers by a variety of discontinuities, including transform faults, overlapping spreading centers, and other nontransform offsets. These features affect the distribution of magmatic heat and convective hydrothermal circulation, providing natural boundaries on the areas that are likely to be selected for exploration of polymetallic sulphides. At the scale of major ridge segments, high-temperature venting commonly occurs along the shallowest portions of the ridge at the middle of the segments, whereas the ends of segments are typically starved of magma and heat.

On fast-spreading ridges, such as the southern EPR, lavas are extruded onto the seafloor faster than the rate of extension, so the flows accumulate as local volcanic highs up to 100 m above the surrounding seafloor. The eruptive fissures typically occupy a narrow axial graben (~1 km wide), and this is the most common location for hydrothermal vents. Venting correlates closely with the areas of most recent volcanic eruptions. However, frequent eruptions can disrupt the flow of hydrothermal fluids and bury sulphide occurrences that are localized along the eruptive fissures. As a result, the vent complexes at fast-spreading ridges tend to be small (less than a few thousand tonnes, dry weight) and the sulphide occurrences may be rapidly displaced from their heat source by the high spreading rates.

Slow and intermediate-rate spreading centers, such as the MAR and CIR, are characterized by lower rates of magma supply and greater structural control on hydrothermal upflow than at fast-spreading ridges. Slow-spreading ridges, in particular, are characterized by a wide (up to 15 km) and deep (up to 2 km), fault-bounded axial valley. Here, eruptions occur only very rarely or at intervals of 100s to 1,000s of years. At the slowest spreading rates, eruption intervals may be as long as tens of thousands of years. Until 1984, it was generally accepted that hydrothermal activity on slow-spreading ridges would be limited because of the lack of near-seafloor magmatic heat. Following the discovery of the TAG Hydrothermal Field on the Mid-Atlantic Ridge, it became apparent that slow-spreading ridges may host some of the largest hydrothermal systems on the seafloor. These may be located well off-axis, where the substrate is stable enough to have supported growth of sulphide mounds for many hundreds of years, in contrast to younger vent fields near the neovolcanic zone that have not had sufficient time to accumulate massive sulphides. Hydrothermal venting at slow-spreading ridges is commonly focused along the walls of the rift valley. Because of large buoyancy forces acting on the hydrothermal fluids, it is not uncommon for high-temperature venting to occur on top of structural highs many kilometers from the center of the rift. For this reason, exploration of slow-spreading ridges must include large areas adjacent to the rift.

Off-axis volcanoes also may be sites of hydrothermal activity. These volcanoes are typically located 5 to 10 km from the ridges. They range in size from a few kilometers across to larger edifices up to 10s of kilometers in diameter. A few large sulphide occurrences are known where these volcanoes are close to the ridge (e.g., at 13°N EPR). However, most off-axis volcanoes are characterized by only low-temperature, Fe-Mn oxide precipitates. This may reflect the small sizes of the associated magma bodies or the lack of deeply penetrating faults associated with the off-axis volcanism.

Most mid-ocean ridge vents occur at water depths of between 2,000 and 3,000 m, but a large number are also known at water depths of as much as 4,000 m (Figure 6 and Table 1). The deepest vents occur on slow- or ultraslow-spreading centers that lack the crustal buoyancy associated with large volumes of subaxial magma. However, at a regional scale, most hydrothermal venting is focused at the summit regions of volcanic edifices (shallowest portions of mid-ocean ridge spreading centers; summits of off-axis seamounts). More locally, sulphide occurrences may be found in volcanic or tectonic depressions that are superimposed on the volcanic highs (e.g., rift grabens at the summit of a ridge segment; summit calderas of arc volcanoes). The deeper outer flanks of ridges or volcanoes are less prospective areas for hydrothermal activity and are less likely to host significant polymetallic sulphides, except where major structures may be present to focus hydrothermal upflow.

Unlike areas where crusts might be exploited, sediment cover should not discourage exploration for polymetallic sulphides unless the cover is so thick as to prevent hydrothermal fluids from reaching the seafloor. However, some heavily sedimented environments, such as sedimented ridges and rifted margins, may be specifically targeted for sediment-hosted polymetallic sulphides, especially where other indicators of mineralization are present (e.g., high heat flow, evidence of subseafloor hydrothermal activity or alteration of the sediment). One of the largest known occurrences of polymetallic sulphides (Middle Valley on the Juan de Fuca Ridge) is in an area of almost 100% sediment cover, although hydrothermal manifestations are evident and indicate near-subseafloor mineralization. In the models presented in this paper, sediment cover is not considered in the selection of permissive geological environments, but this criterion, together with the presence or absence of hydrothermal indicators, will likely be used by explorers in the selection of blocks with limited volcanic activity to be released from tenements following an initial phase of exploration.

Prohibitive bathymetric relief can be expected in many areas of recent volcanic and tectonic activity. This may be a positive indicator of magmatic and hydrothermal processes that can lead to concentrations of polymetallic sulphides, but extremes of relief or poor ground stability which may be an impediment to any future exploitation. The walls of rift grabens or summit calderas of recently active volcanic edifices are inherently unstable and rugged, although the bottoms of rifts and calderas may include locally flat areas where polymetallic sulphides may accumulate. Typical relief at fast-spreading centers is 10s to 100s of meters over distances of 1 km; relief at slow-spreading centers may be 100s of meters up to 1 km over horizontal distances of 1 km. In some places, ongoing volcanic eruptions may be an impediment to exploration or exploitation of sulphides. Some arc volcanoes are off-limits to navigation owing to volcanic hazards.

A2.2 Other Considerations

Biological communities associated with active hydrothermal venting are typically located at or near occurrences of polymetallic sulphides. Regulations may prohibit any disturbance of such communities so that a large proportion of the known sulphide occurrences may be excluded from any commercial exploration at an early stage. Inactive sulphide chimneys and mounds are typically not associated with living biological communities, and therefore are potential candidates for exploitation, but they commonly occur in close proximity to active vents (within 1-

2 km) and are almost always associated with the same geological features. The disturbance of inactive sulphide accumulations adjacent to active sites is likely to have an unknown impact on nearby active systems and their associated biological communities.

At some sites entanglement hazards may be presented by abandoned gear (cables, dredges, fishing gear, scientific instrumentation). For example, the TAG mound, which was drilled at 17 different locations within an area of less than 250 m, has numerous abandoned holes, including drill pipe.

A2.3 Sizes of Exploration Areas

The expected number and distribution of high-temperature hydrothermal vents on the mid-ocean ridges will limit the optimal size of an exploration area. Generally the spacing of vents is not known, but a variety of geophysical measurements provide an indication of the possible numbers of vents on the ridges. For example, heat loss from the axial zones of the global mid-ocean ridges is on the order of $1.8 \pm 0.3 \times 10^{12}$ W (Mottl, 2003). About 10 percent of this heat is discharged at black-smoker temperatures. Assuming a heat flux of 2 to 5 MW for a single black smoker vent (e.g., discharge rates of 1 to 2 kg/s: Converse et al., 1984), the estimated flux of high-temperature fluids to the seafloor (10% of $1.8 \pm 0.3 \times 10^{12}$ W) would be equivalent to about 50,000 to 100,000 black smokers (i.e., at least one black smoker for every 1 km of ridge). However, the number of known black smokers is extremely small by comparison, and their distribution is far from uniform. A single large vent field may contain as many as 100 black smoker vents having a total heat output of 200 to 500 MW (e.g., Becker and Von Herzen, 1996). Thus, one vent field every 50 to 100 km could potentially account for the estimated high-temperature discharge at mid-ocean ridges. Although this estimate does not consider large-scale variations in heat flux according to spreading rate and other factors, it is a useful first-order guide for choosing the size of an area to explore along a given segment of ridge crest.

Independent estimates based on the actual distribution of known vent sites suggests that the spacing of sulphide occurrences along segments of mid-ocean ridges might be quite regular at the regional scale. From an analysis of 100 known sulphide occurrences in 32 five deg. by five deg. areas considered in this study, the average spacing between occurrences is 98 km (Table 2). Among those in "the Area" (n = 43), the average spacing is 95 km. Although the spacing is greater on the slow-spreading ridges (167 km) than on the fast-spreading ridges (46 km), the individual sulphide occurrences on the slow-spreading ridges are larger on average.

Given the wide distribution of vents, lease blocks may be requested at a number of separate locations within discrete and possibly separate permissive areas requiring extensive assessment work. Although unfavourable blocks could be systematically relinquished over the 15-year time period specified in the Draft Regulations, it is more likely that explorers will rapidly identify the most favourable sites and that a minimum number of non-contiguous prospective blocks could be established quickly. This possibility is considered in the model of non-contiguous blocks.

A2.4 Sizes of Exploration Targets

The minimum size of an exploration area is determined by the size of the expected discovery and the geological features that control its location. Larger clusters of sulphide occurrences are mainly controlled by geological features that can be readily identified in bathymetric surveys (rift grabens or calderas with maximum dimensions of a few 10s of kilometers). More local controls may include faults, dike swarms, lava lakes, or other eruptive features with dimensions of a few

100s of meters up to several kilometers. Individual sulphide occurrences may consist of single mounds or groups of chimneys and mounds that cover areas of the seafloor ranging from 10s to 100s of meters in diameter. These may be separated by 100s of meters up to several kilometers, commonly with intervening areas of barren sediment or lava. On the Endeavour segment of the Juan de Fuca Ridge (Figure A1), 30 different sulphide complexes are distributed among 8 vent fields along a 10-km segment of the axial valley. The main vent fields are evenly spaced, 2 to 3 km apart (Figure A2). In the TAG Hydrothermal Field, the three main massive sulphide mounds (TAG, MIR, Alvin) are located within an area of about 25 km^2 (Figure A3). Based on these observations, areas of the seafloor that are likely to be considered for the most advanced exploration, which may include high-resolution bathymetric mapping, bottom photography or other seafloor observations and sampling, are not expected to exceed 100 km^2.

Of the more than 100 sites of high-temperature hydrothermal venting and polymetallic sulphide occurrences considered in this paper, only about 1/3 have accumulations of polymetallic sulphide on the order of 10s to 100s of meters in diameter (Hannington et al., 1995; Fouquet, 1997). Most are incompletely surveyed, and reported dimensions commonly include large areas of discontinuous sulphide outcrop or barren substrate between the chimneys and mounds. The continuity of sulphide bodies is difficult to assess, even with the most detailed surveys. A number of examples illustrate that preliminary estimates of the surface areas of such occurrences cannot be used to reliably determine the volume of sulphide on or near the seafloor. Only drilling can provide this information, although future developments in geophysical methods might provide additional tools for this purpose.

When polymetallic sulphides were first discovered at Explorer Ridge, in the N.E. Pacific (Figure A1), the largest sulphide mound was estimated to be 250 m x 200 m in size, based on submersible observations. Recent high-resolution surveys have shown that this area comprises mainly lava covered by discontinuous Fe-stained sediment, with only four 50-m diameter clusters of chimneys, covering less than 25% of the area originally considered to be massive sulphide (http://oceanexplorer.noaa.gov/explorations). In a similar survey of the Sunrise occurrence, on the Myojin Knoll submarine volcano, Izu-Bonin arc, an area of sulphide mineralization measuring 400 m x 400 m was reported (Figure A4). Based on a relief of 30 m and a bulk density of 1.9 gm/cm^3, a total accumulation of 9 million tonnes of massive sulphide was calculated (Iizasa et al., 1999). Three important assumptions are implicit in this calculation: (i) the sulphide outcrop was considered to cover 100% of the outlined area (i.e., including areas between sulphide ridges and mounds that are concealed by sediment); (ii) the observed relief is due entirely to the accumulation of massive sulphide on a flat seafloor and not due to faults or buried volcanic features (e.g., lava domes); (iii) the bulk density is uniform and represents the entire volume used in the calculation. In Figure A4, no more than 5 line-km of surveys cover the 400 m x 400 m outlined area, providing visual coverage of not more than 30% (e.g., surveys based on submersible observations or camera tows typically have a maximum field of view of not more than 10 m beyond the survey track). Visually identifiable sulphide outcrops, such as active or inactive sulphide chimneys, are shown to cover only about 25% of the area. Given the limitations of the visual surveys and the uncertainties inherent in the calculations, the value of such estimates of bulk tonnage is questionable.

Drilling provides the necessary confidence to extrapolate surface observations to depth and to judge the continuity of sulphide outcrop. Two examples of sediment-hosted sulphide occurrences illustrate the importance of drilling. At Middle Valley on the Juan de Fuca Ridge and Escanaba Trough on the Gorda Ridge, the seafloor is marked by numerous uplifted blocks of sediment, up to several 100 m in diameter and 50 m high. Drilling and other detailed surveys showed that most of these mounds are mainly buried volcanic sills. However, drilling of one mound at Middle Valley (Bent Hill, which has a surface expression of 90 m x 60 m) intersected 95 m of massive sulphide below the seafloor, and a second smaller sediment-covered mound 300 m away (ODP mound), also was shown to comprise mainly massive sulphide (Davis et al., 1992). In contrast, drilling of similar mound-like features at Escanaba Trough (270 m x 100 m) indicated that massive sulphide is restricted to a small area only 5 to 15 m deep (Zierenberg and Miller, 2000).

Reliable estimates of the sizes of sulphide accumulations have been possible in only a few cases where drilling information is available. At the TAG mound (200 m x 45 m) on the Mid-Atlantic Ridge, 17 holes drilled to a maximum depth of 125 m indicated a bulk tonnage of 2.7 million tonnes of massive sulphide averaging 2 wt. percent Cu and 1.2 million tonnes of stockwork mineralization at 1 wt. percent Cu (Hannington et al., 1998). At Bent Hill and ODP mound in Middle Valley, 4 deep drill holes indicated a combined bulk tonnage of between 10 and 15 million tonnes (Fouquet et al., 1998; Zierenberg et al., 1998). The next largest occurrences on the mid-ocean ridges, based on apparent surface areas, may be on the order of 100,000 up to 1 million tonnes, but no information is available from drilling. However, the great majority of known sulphide occurrences are much smaller. Individual sulphide structures and mounds rarely exceed a few 10s of meters m in diameter, with bulk tonnages of no more than a few 1,000s of tonnes each. At Endeavour Ridge, the 30 sulphide edifices along 10 km of the ridge total no more than about 50,000 tonnes. For the most part, sulphide occurrences in the back-arc rifts and on volcanic arcs of the western Pacific are similar in size to those on the mid-ocean ridges.

The accuracy of estimates of bulk tonnage is further subject to considerable uncertainty about the physical properties of the sulphide mounds and chimneys. Hannington et al. (1998) used a bulk density of between 3.5 and 4 for the tonnage calculation of the TAG mound, based on shipboard density measurements of drill core. However, the bulk dry densities of sulphide chimneys, crusts, and sediments from other occurrences are much lower. Sulphide chimneys from the East Pacific Rise have a dry density of only 1-2 gm/cm^3 and an in situ water content of 25-50 per cent (Crawford et al.). Higher densities due to compaction, open-space filling, and hydrothermal recrystallization of the sulphides might be expected in the interiors of mounds, but it is clear that these effects are not uniform.

A2.5 Comparisons with Land-based Mining

Although there are considerable uncertainties in estimates of the sizes of sulphide accumulations on the seafloor, the range is expected to be similar to that of certain types of fossil sulphide deposits that have been mined on land. There are two potentially relevant models. So-called "Cyprus-type" massive sulphide deposits have long been considered to be the best ancient analogs of polymetallic sulphides that occur on the mid-ocean ridges and in mature back-arc basin environments (e.g., Hannington et al., 1998, and references therein). The "kuroko" deposits of Japan are analogs of polymetallic sulphides that occur in volcanic arc environments. The use of ancient analogs for predictive purposes assumes that the conditions of ore formation have been uniform over geological time, since the fossil record includes deposits of all ages. Nevertheless, it is unlikely that anything will be found on the present-day seafloor that is dramatically different from what is already known from these land-based deposits. Therefore unique grade and tonnage models for modern seafloor polymetallic sulphides are probably not required.

The data for Cyprus-type deposits indicate a median size of 1.6 million tonnes (Figure A5). These data are skewed towards larger deposits because tonnages and grades are only known or reported for those deposits of sufficient size to have been mined economically. The vast majority of sulphide occurrences are either too small or of too low grade to be mined, and large numbers of small deposits are not included in the published reserves. Among the Cyprus-type deposits, this includes more than 90 undeveloped prospects containing <100,000 tonnes each, and probably many more much smaller occurrences that were never considered to be prospects (Hannington et al., 1998, and references therein). This situation is analogous to the many small isolated chimneys and mounds that are found on active segments of the mid-ocean ridges. When undeveloped prospects are included, the curves are shifted toward significantly lower tonnages (Figure A5). In the case of the Cyprus-type deposits, the median size including uneconomic occurrences is expected to be less than 500,000 tonnes.

During mining of the "kuroko" deposits of Japan, careful records were kept of the physical dimensions of the mined orebodies. Of the 44 mined deposits in the Hokuroku basin, the average surface area of the orebodies was about 200 m x 200 m (Tanimura et al., 1983). Ore clusters typically occupied less than 100 km^2 and contained up to 10 orebodies. Sangster (1980) showed a similar distribution of orebodies in massive sulphide mining districts in Canada, which have an average of 12 deposits in an area of 84 km^2. In these areas, the single largest deposit typically accounts for 60-70% of the total metal reserves; the second largest deposit may contain only 10-20%. The next nearest area with another large deposit may be located 10s to 100s of kilometers away. While these comparisons are potentially useful in defining target sizes for exploration of seafloor polymetallic sulphides, it is important to recall that the areas represented in ancient mining districts typically include deposits that are exposed at a number of different stratigraphic levels (i.e., many more deposits may be exposed on eroded surfaces on land than are likely to be exposed on a flat seabed).

The size distribution of sulphide occurrences in most areas of the seafloor suggests that rates of exploitation comparable to those employed at mining sites on land would exhaust the resource in 2,500 km^2 within one year. Except in very rare cases, additional resources to sustain multi-year exploitation would need to be sought in other areas.

A2.6 Comparison with Commercial Seabed Exploration in EEZs

Commercial exploration licenses that have been granted to two corporations (Nautilus Minerals in the Eastern Manus Basin of P.N.G. and Neptune Minerals in the Tonga-Kermadec arc region of New Zealand) provide cogent examples of the limitations of different models for exploration and lease block selection. The original prospecting licenses of Neptune Minerals in New Zealand were 33,000 km^2 in 1999 and were reduced to a tenement of 7,790 km^2 (24%) in 2003. Nautilus Minerals' exploration licenses in P.N.G totalled 15,000 km^2 in 1996. The two most prospective sites now being explored in the Eastern Manus Basin occur within an area of 2,500 km^2 (17%). In the tenements of both Neptune Minerals and Nautilus Minerals, the known sulphide occurrences could not have been captured in a single exploration license of 100 contiguous blocks (Figure A6).

Appendix 2. Figures

Figure A1. Example of a 5 degree by 5 degree area in the N.E. Pacific (1000 m contour interval), overlapping the Juan de Fuca Ridge and known occurrences of polymetallic sulfides at Southern Explorer Ridge, Middle Valley, and Endeavour Ridge.

Figure A1. 30 min by 30 min map of the Endeavour Ridge (100 m contour interval) showing the locations of discrete sulfide occurrences, located about 2-3 km apart.

Figure A3. Distribution of sulfide occurrences in the TAG Hydrothermal Field, Mid-Atlantic Ridge (Humphris et al., 1995). The three main massive sulphide mounds (TAG, MIR, Alvin) are located within an area of about 25 km^2.

Figure A4. Map showing the submersible survey of the Sunrise occurrence, on the Myojin Knoll submarine volcano, Izu-Bonin arc (Iizasa et al., 1999). The depicted area of sulphide mineralization measures 400 m x 400 m. Based on a relief of 30 m and a bulk density of 1.9 gm/cm3, a total accumulation of 9 million tonnes of massive sulphide was calculated. However, surveys based on submersible observations or camera tows typically have a maximum field of view of not more than 10 m beyond the survey track. In the map shown, no more than 5 line-km of surveys cover the 400 m x 400 m outlined area, providing a visual coverage of not more than 30%. Visually identifiable sulphide outcrop (i.e., active or inactive sulphide chimneys) are shown to cover only about 25% of the area. Given the limitations of the visual surveys, the lack of any drilling information, and the fact that the sulfides are not deposited on a flat seafloor, the calculated tonnage is uncertain.

Figure A5. Tonnage model for 49 "Cyprus-type" massive sulphide deposits, showing the range of sizes of deposits. The median tonnage (50th percentile) is indicated at 1.6 million tonnes. The plotted data are from Singer and Mosier (1986), and include only those deposits of sufficient size to have been mined economically or for which reserves have been reported. The vast majority of sulphide occurrences are either too small or of too low grade to be mined, and large numbers of small deposits are not included in the published reserves. This includes more than 90 undeveloped prospects containing <100,000 tonnes each (Hannington et al., 1998, and references therein), and probably many more much smaller occurrences that were never considered to be prospects. When undeveloped prospects are included, the curves are shifted toward significantly lower tonnages, as indicated. In the case of the Cyprus-type deposits, the median size including undeveloped prospects is expected to be less than 500,000 tonnes.

Figure A6. Examples of commercial exploration licenses in P.N.G and New Zealand. The original prospecting licenses of Neptune Minerals in New Zealand (A) were 33,000 km^2 in 1999 and were reduced to a tenement of 7,790 km^2 (24%) in 2003 (www.neptuneminerals.com). The licenses of Nautilus Minerals in P.N.G (B) totalled 15,000 km^2 in 1996, and 2,500 km^2 (17%) have now been identified that contain the two most prospective areas in the Eastern Manus Basin (www.nautilusminerals.com). In these examples, exploration licenses based on 100 contiguous blocks would not have permitted all of the known sulphide occurrences to be included in a single tenement (see also Appendix 3).

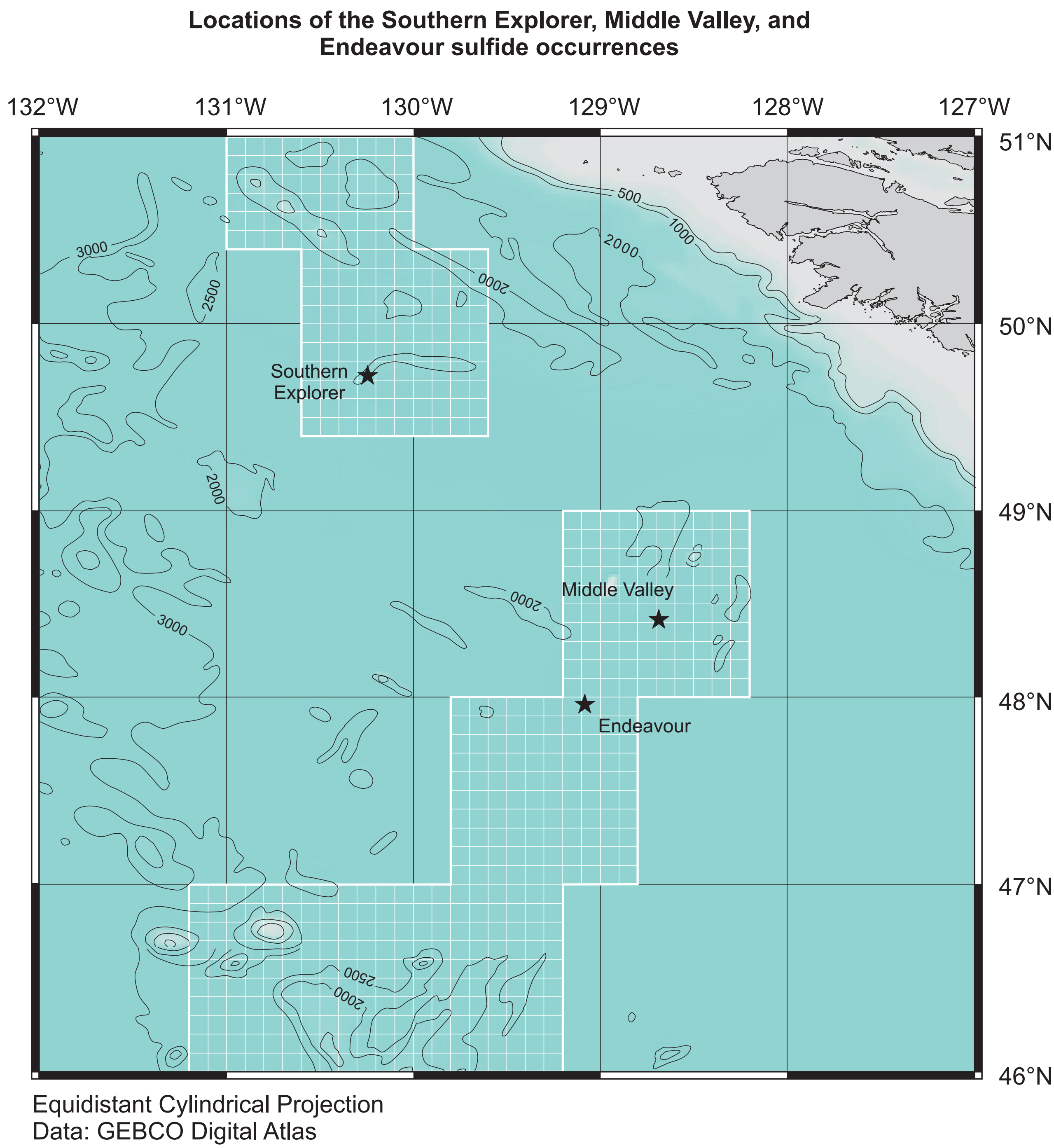
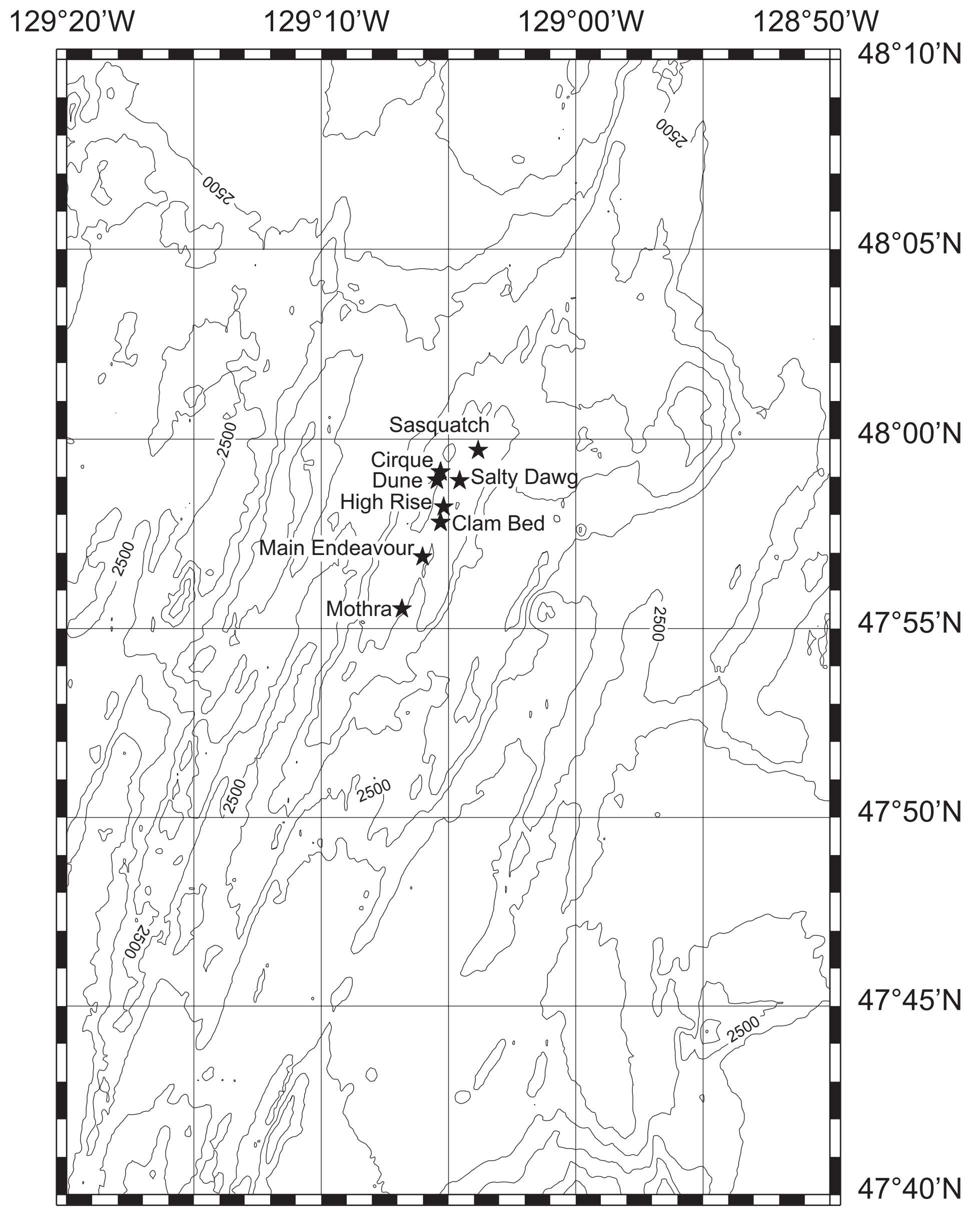


Figure A1. A. Example of a 5 degree by 5 degree area in the N.E. Pacific (1000 m contour interval), overlapping the Juan de Fuca Ridge and known occurrences of polymetallic sulfides at Southern Explorer Ridge, Middle Valley, and Endeavour Ridge.

Bathymetry of the Endeavour Field



Mercator Projection
Data: NOAA Multibeam Bathymetry Database
Endeavour Field at 47°55' to 48°00'N, 129°03' to 129°07'W
(Delaney et al., 1992)

Figure A2. 30 min by 30 min map of the Endeavour Ridge (100 m contour interval) showing the locations of discrete sulfide occurrences, located about 2-3 km apart.

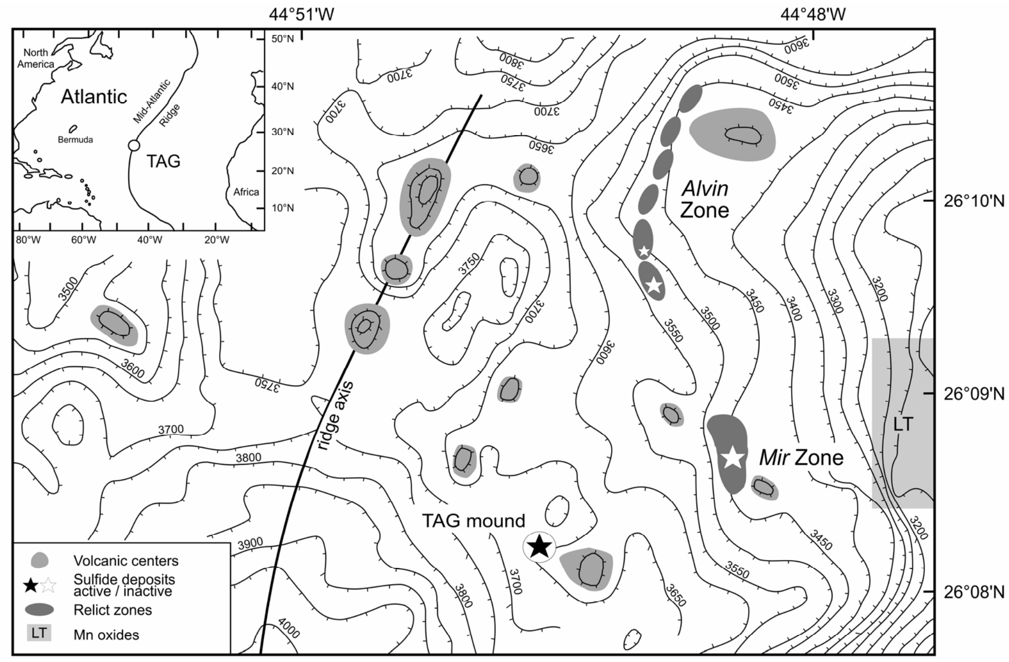
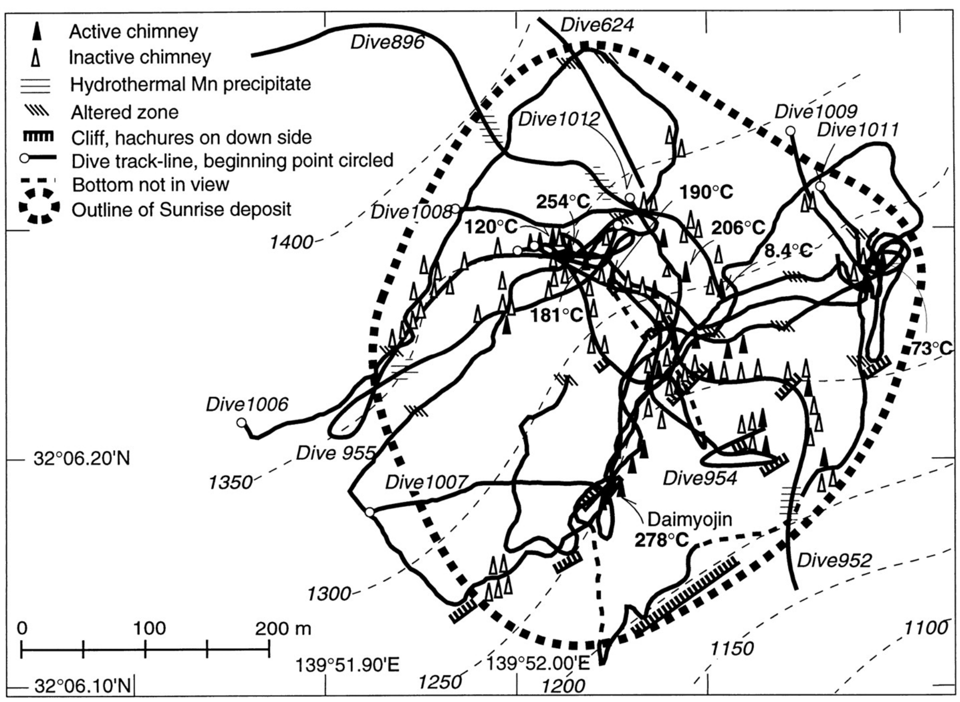


Figure A3. Distribution of sulfide occurrences in the TAG Hydrothermal Field, Mid-Atlantic Ridge (Humphris et al., 1995). The three main massive sulphide mounds (TAG, MIR, Alvin) are located within an area of about 25 km^2.



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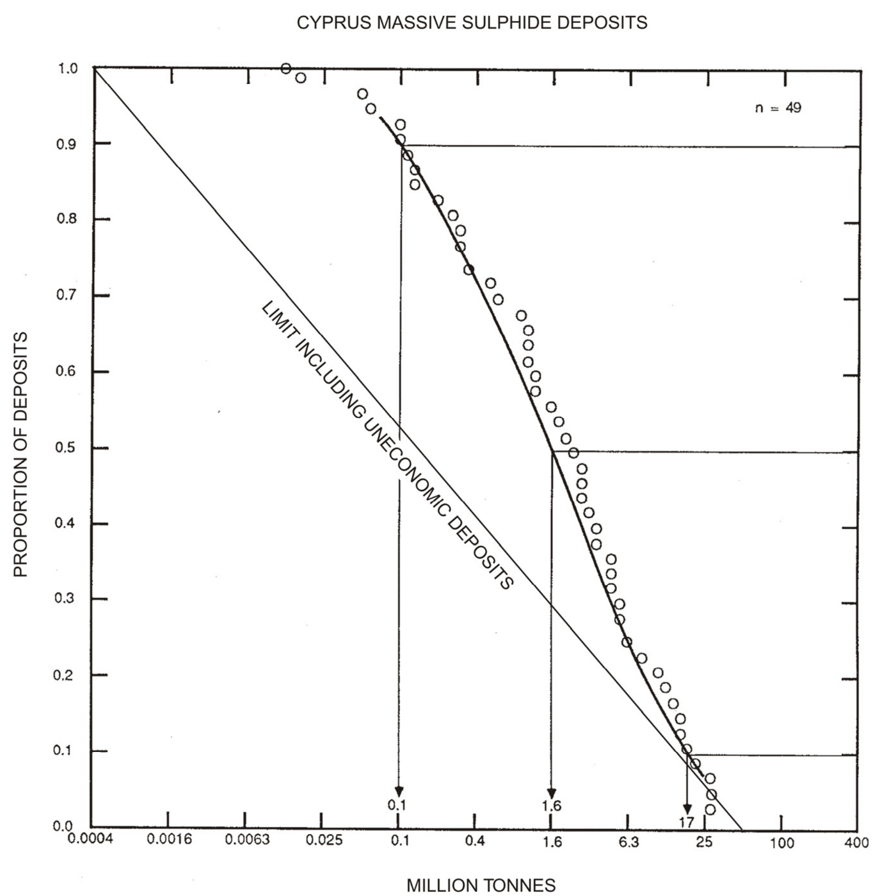


Figure A5. Tonnage model for 49 "Cyprus-type" massive sulphide deposits, showing the range of sizes of deposits. The median tonnage (50th percentile) is indicated at 1.6 million tonnes. The plotted data are from Singer and Mosier (1986), and include only those deposits of sufficient size to have been mined economically or for which reserves have been reported. The vast majority of sulphide occurrences are either too small or of too low grade to be mined, and large numbers of small deposits are not included in the published reserves. This includes more than 90 undeveloped prospects containing <100,000 tonnes each (Hannington et al., 1998, and references therein), and probably many more much smaller occurrences that were never considered to be prospects. When undeveloped prospects are included, the curves are shifted toward significantly lower tonnages, as indicated. In the case of the Cyprus-type deposits, the median size including undeveloped prospects is expected to be less than 500,000 tonnes.

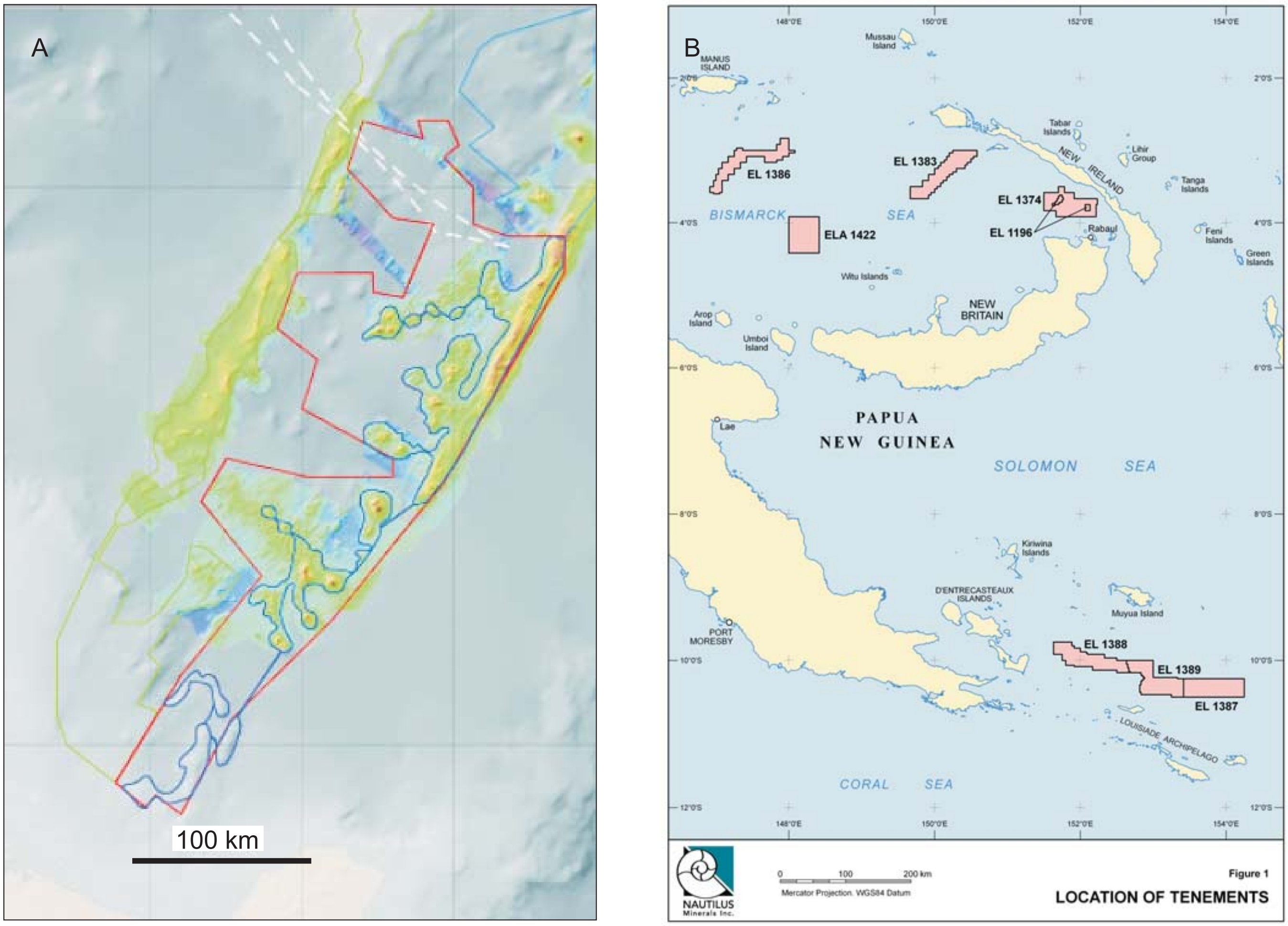
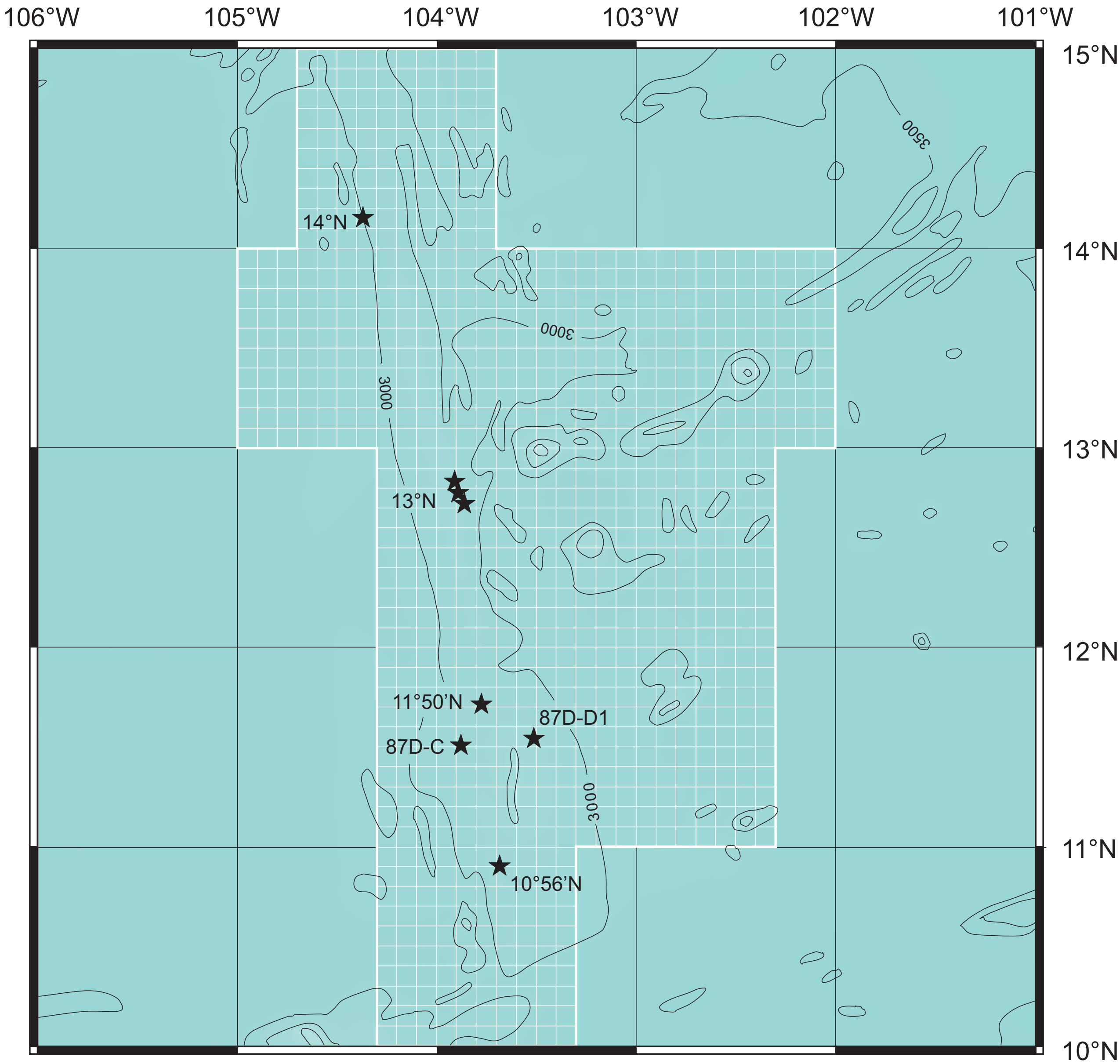


Figure A6. Examples of commercial exploration licenses in P.N.G and New Zealand. The original prospecting licenses of Neptune Minerals in New Zealand (A) were 33,000 km sq. in 1999 (red line) and were reduced to a tenement of 7,790 km sq. (24%) in 2003 (blue line) (www.neptuneminerals.com). The licenses of Nautilus Minerals in P.N.G (B) totalled 15,000 km sq. in 1996, and 2,500 km sq. (17%) have now been identified that contain the two most prospective areas in the Eastern Manus Basin (www.nautilusminerals.com). In these examples, exploration licenses based on 100 contiguous blocks would not have permitted all of the known sulphide occurrences to be included in a single tenement.

Appendix 3. Maps of 32 Areas Permissive for the Occurrence of Polymetallic Sulphides

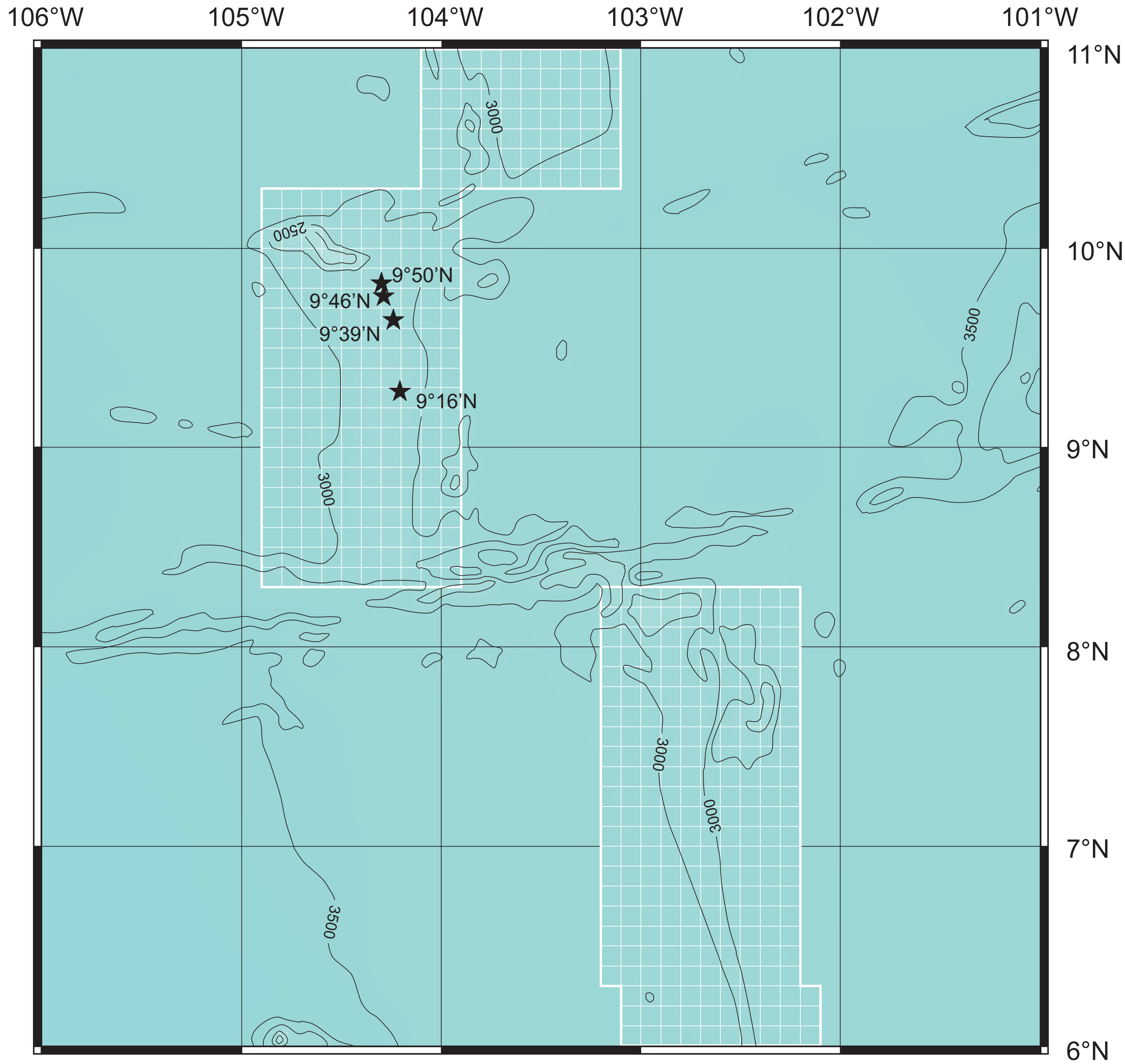
Areas that are considered permissive for polymetallic sulphides were selected in 32 map areas of 5 deg. by 5 deg. The prospecting area was arbitrarily defined as less than five degrees by five degrees and containing at least one known sulphide occurrence or other positive indication of mineralization. A 0.1 degree grid was overlain on each map in the areas considered to be permissive for polymetallic sulphides and where exploration might be carried out. This grid corresponds approximately to block sizes of 10 km x 10 km each (0.1 x 60 nm x 1.852 km = 11.11 km grid spacing). Decimal-degrees are used for ease of plotting sulphide locations. In each case, the placement of the grid is intended to cover all permissive areas, based on the broad geological attributes of each map area as discussed in this paper. In the models presented herein, the size of the permissive areas correspond approximately to 20 times the size of the final allocation of blocks at the end of a 15-year exploration cycle (20 x 25 blocks).

Locations of the sulfide occurrences near 14°N, 13°N, 11°50'N, 10°56'N, and at the 87D-D1 and 87D-C Seamounts



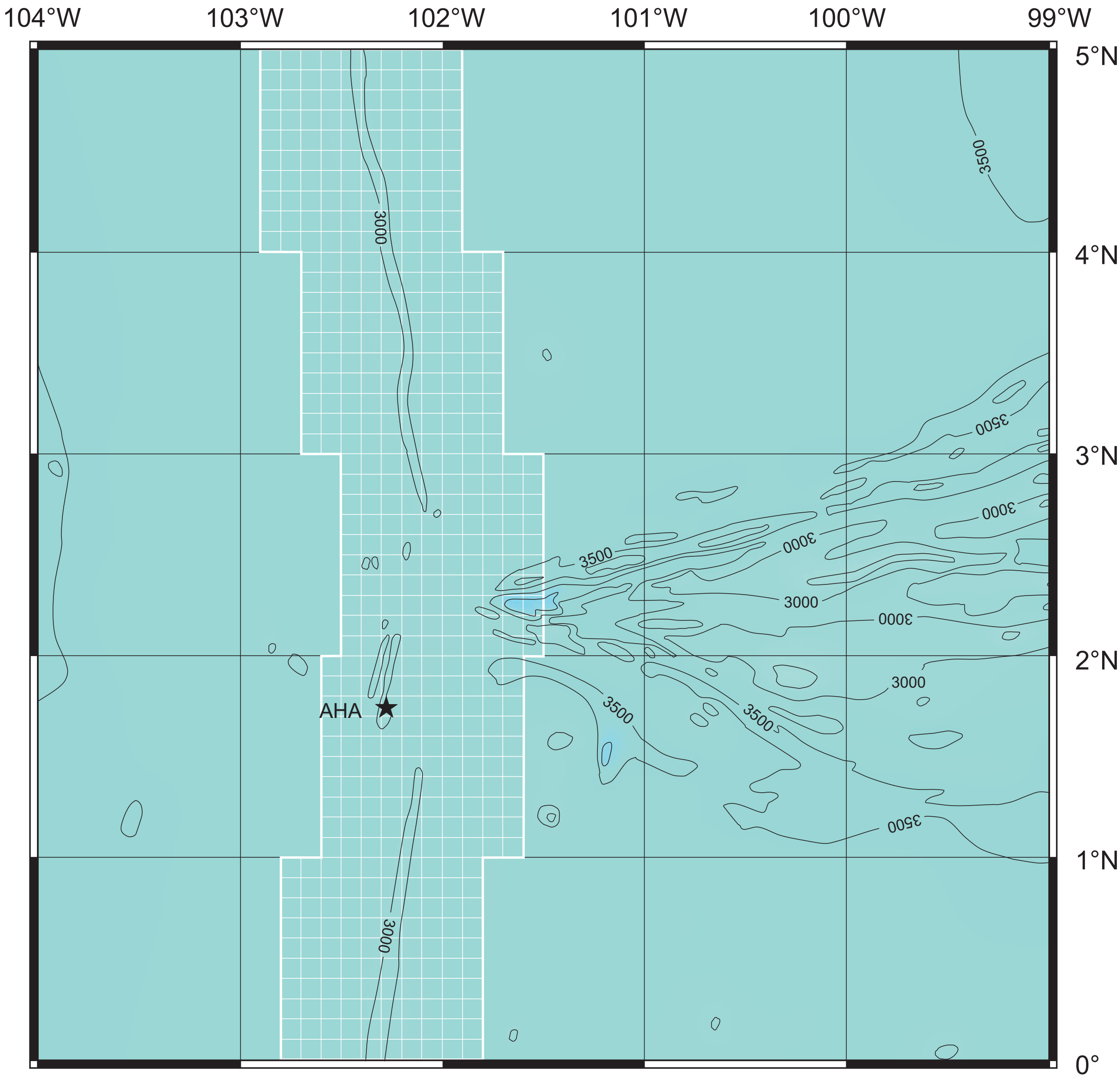
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 9°50'N, 9°46'N, 9°39°N, and 9°16°N



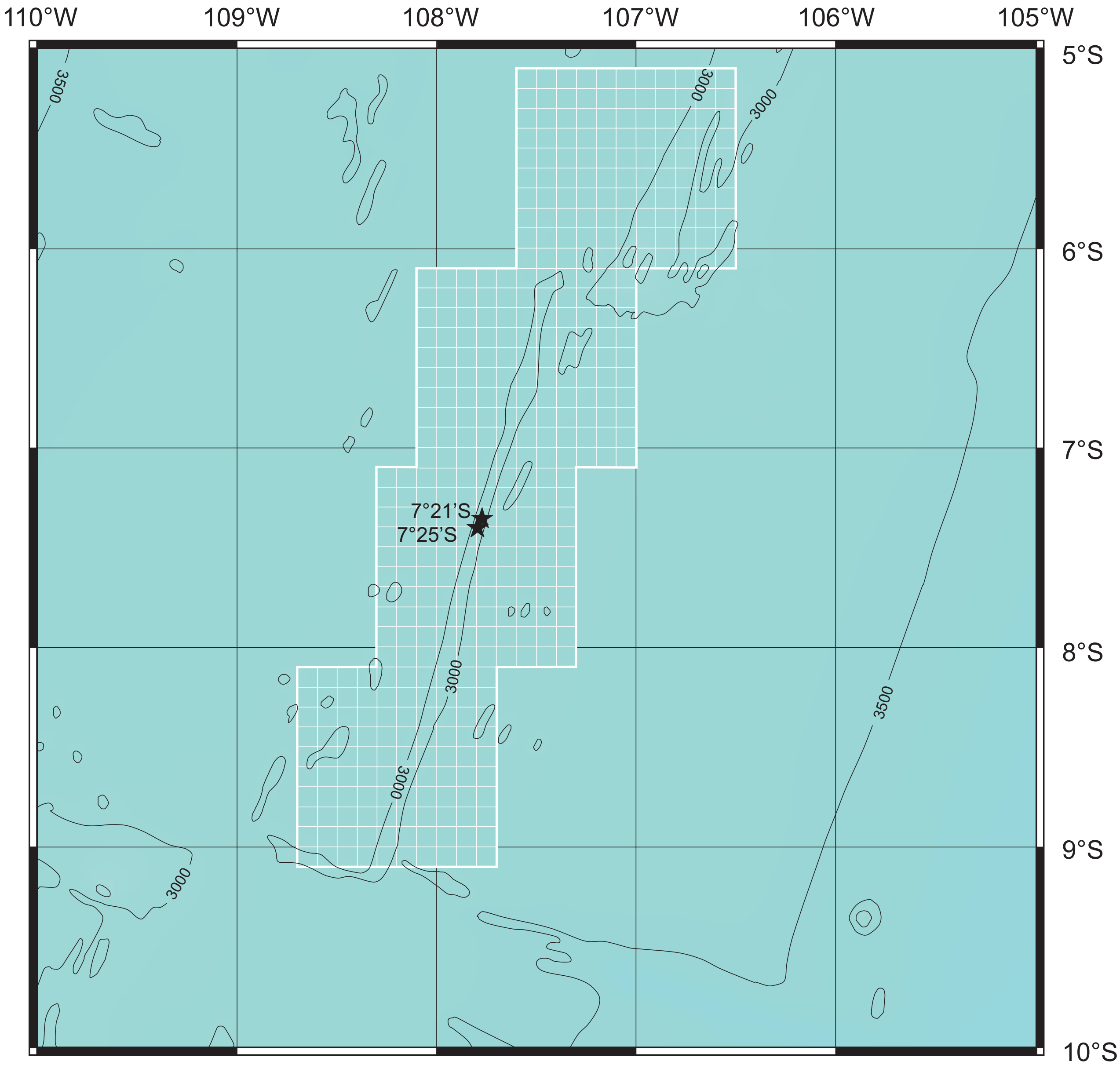
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the AHA Vent Field



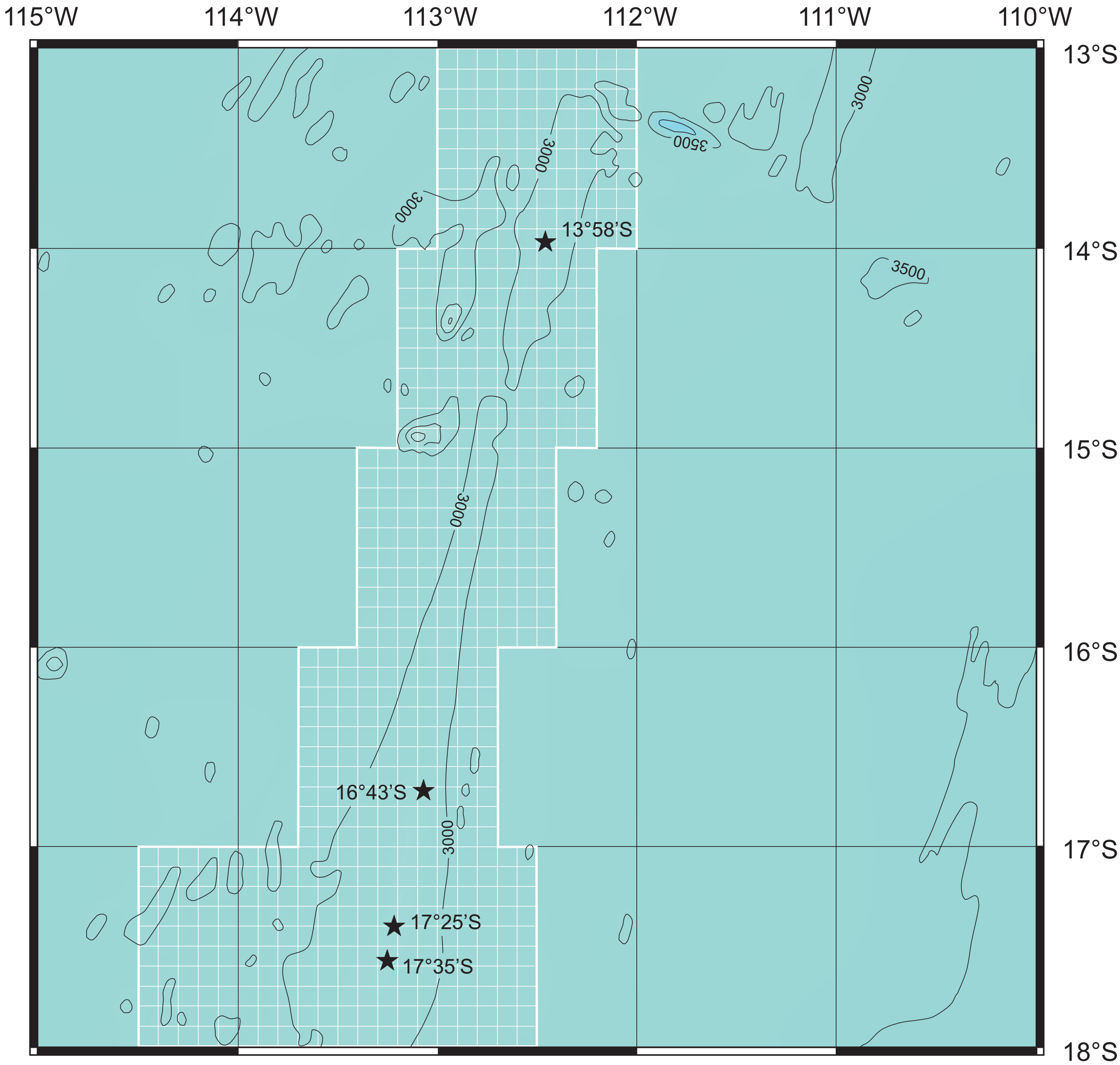
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 7°21'S and 7°25'S



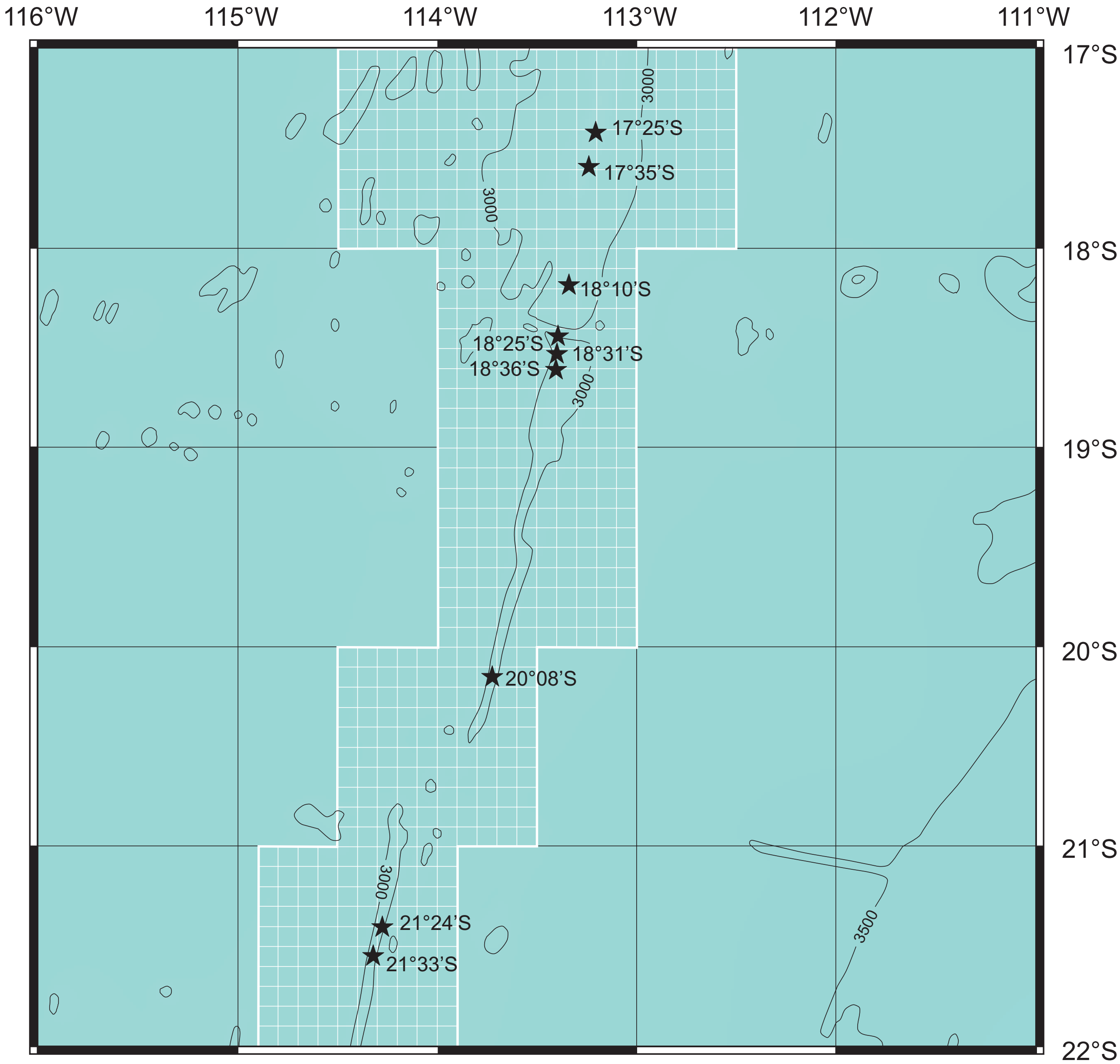
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 13°58'S, 17°25'S, and 7°35'S



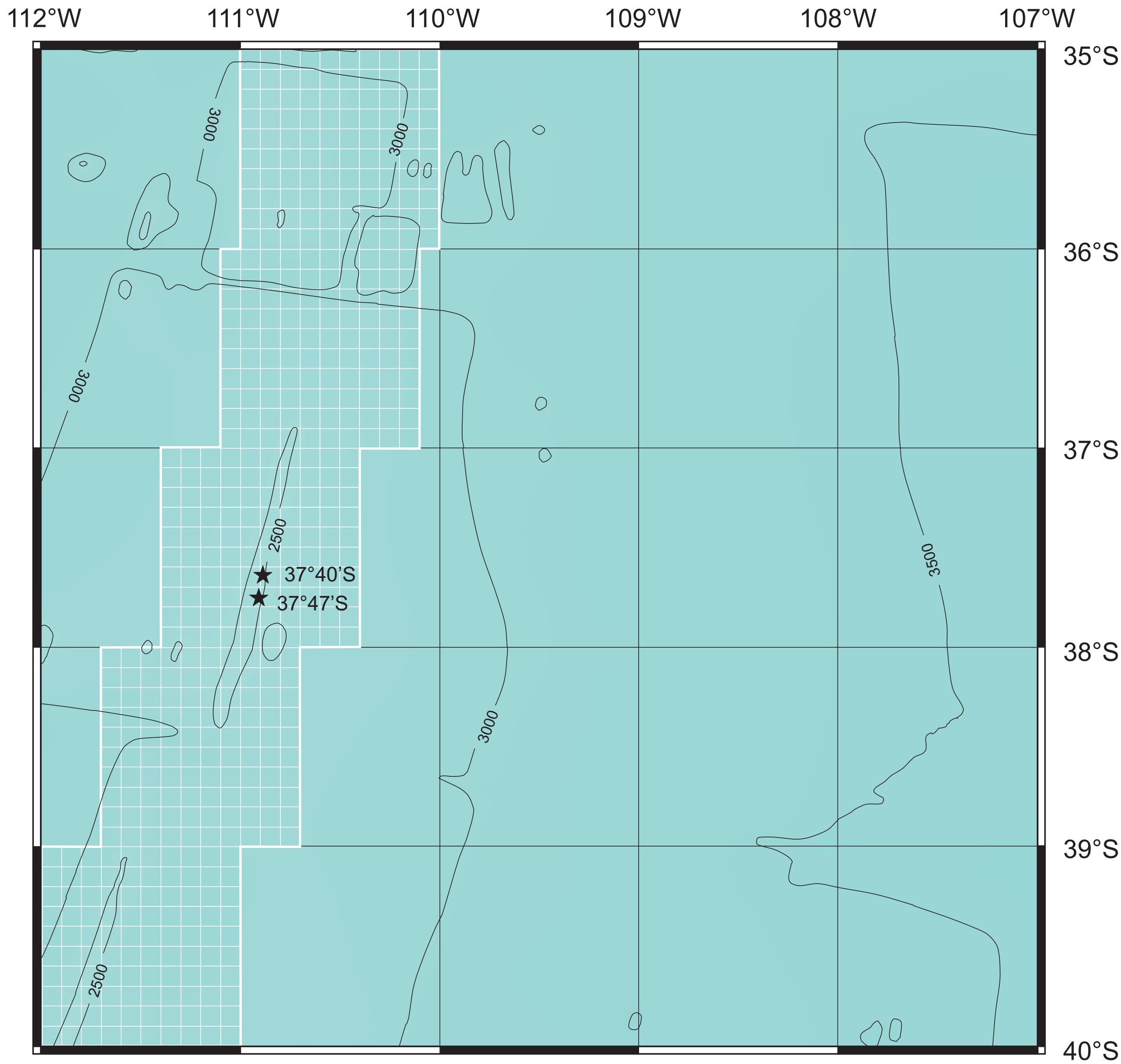
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 17°25'S, 17°35'S, 18°10'S, 18°25'S, 18°31'S, 18°36'S, 20°08'S, 21°24'S, and 21°33'S



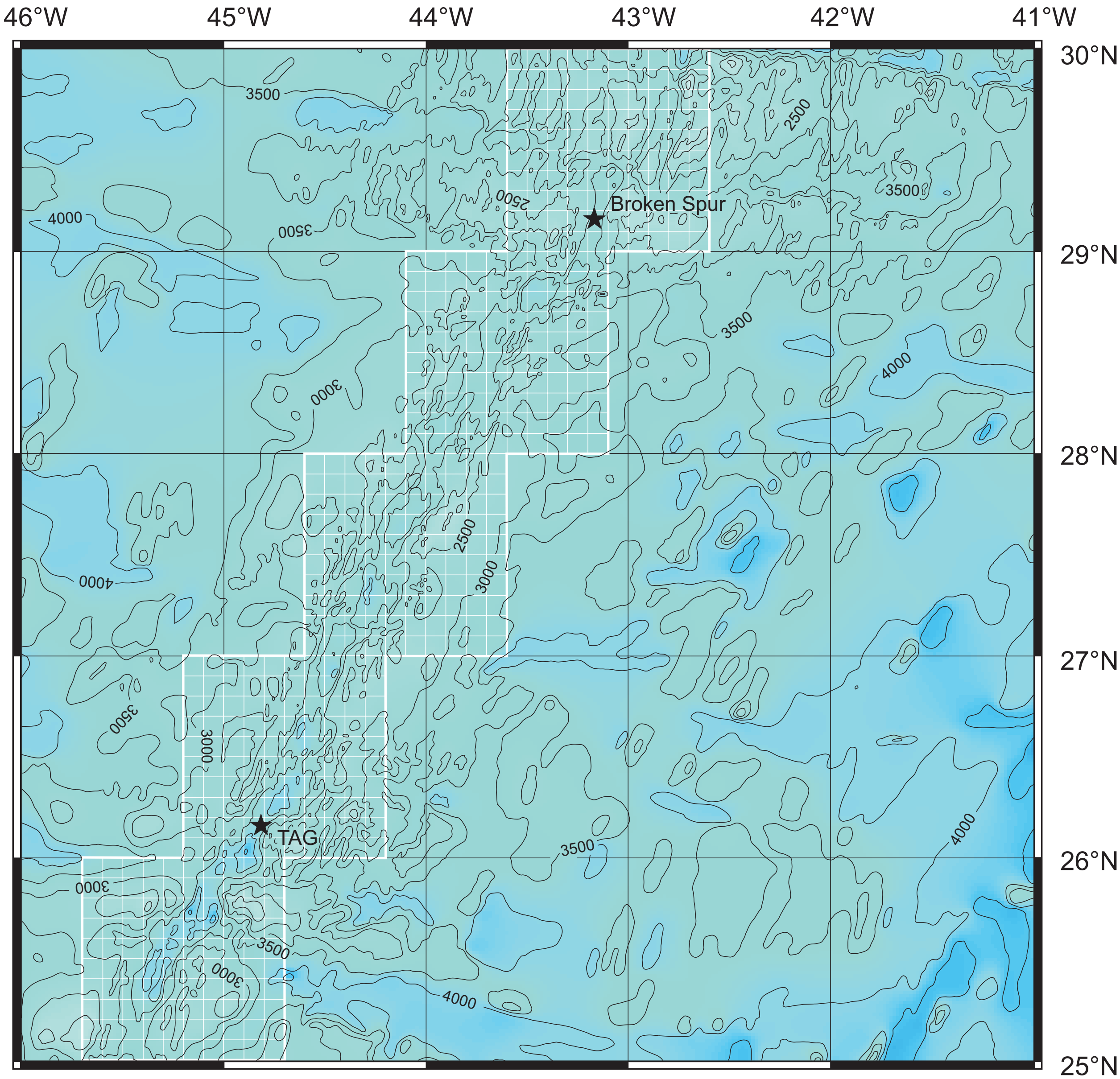
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 37°40'S and 37°47'S



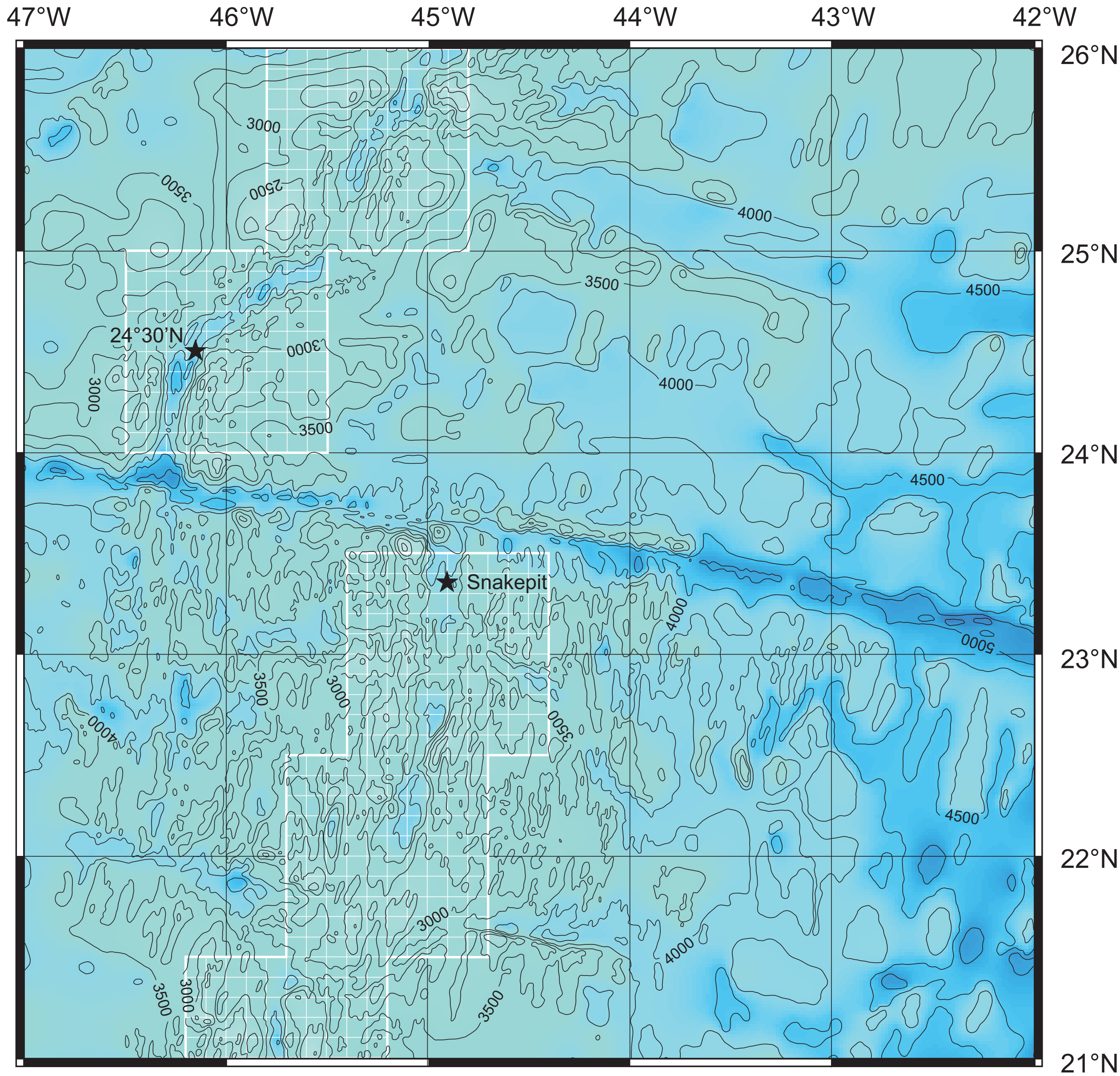
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Broken Spur and TAG sulfide occurrences



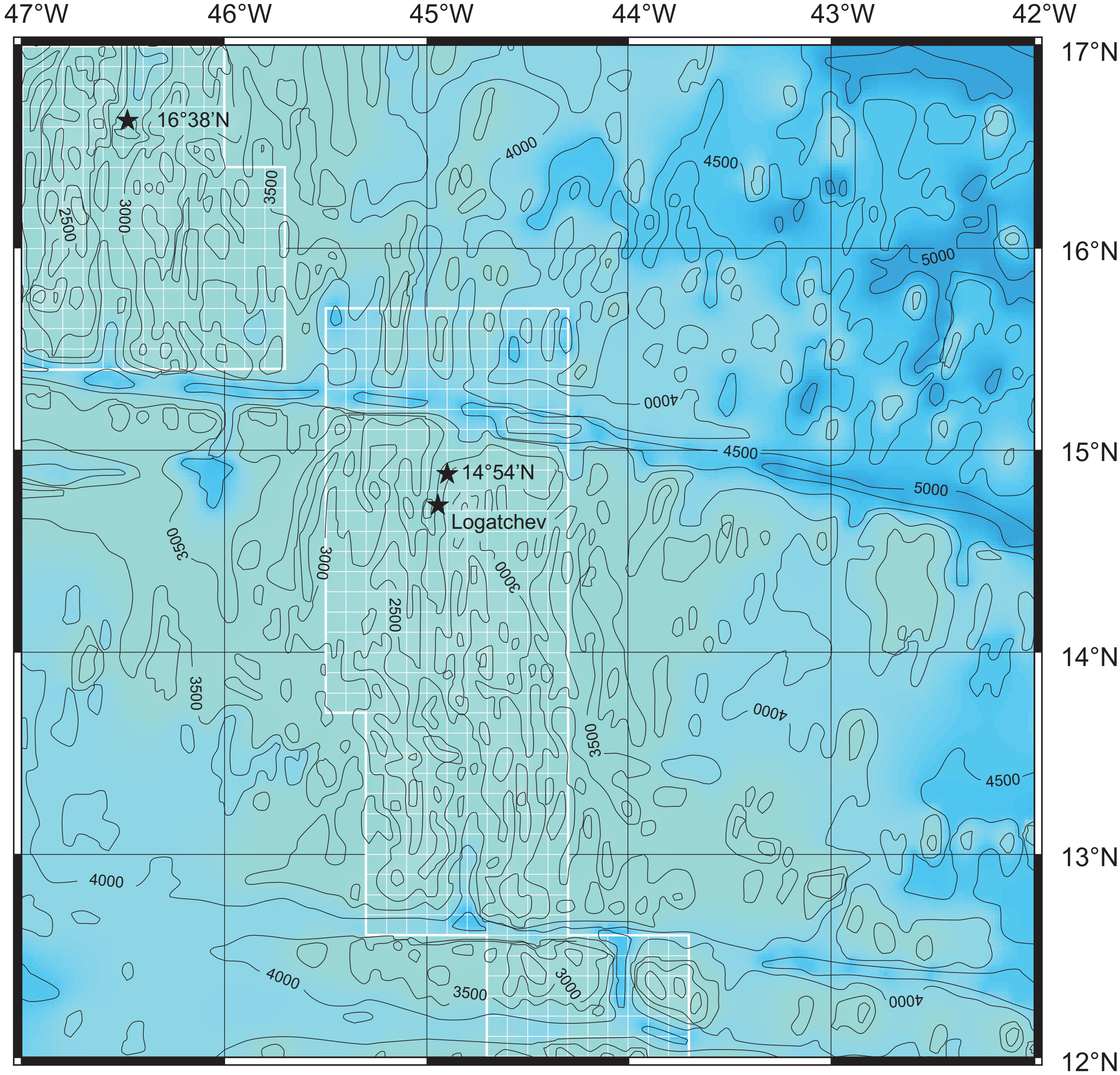
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the 24°30'N and Snakepit sulfide occurrence



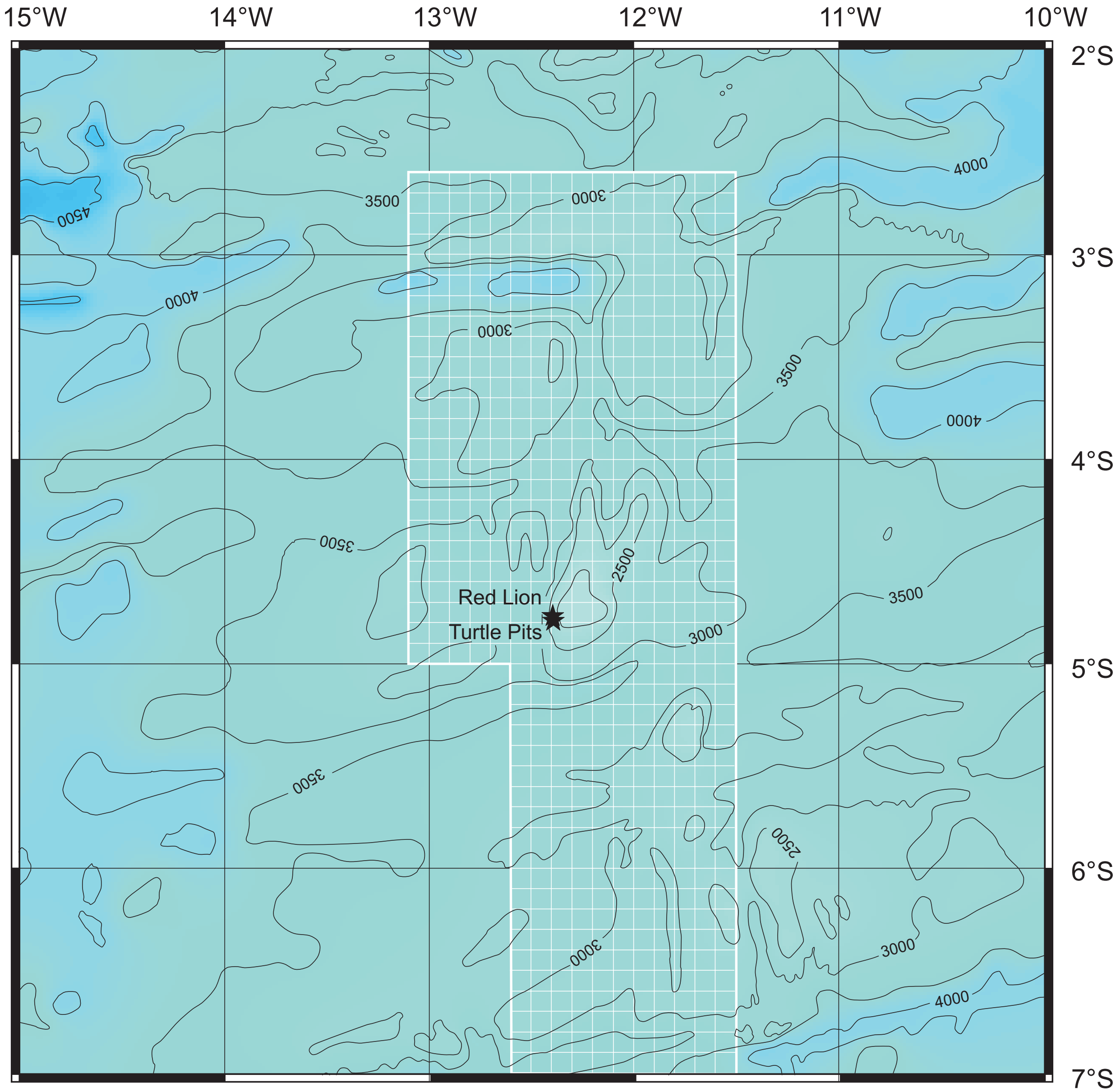
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the sulfide occurrences at 16°38'N, 14°54'N, and the Logatchev Field



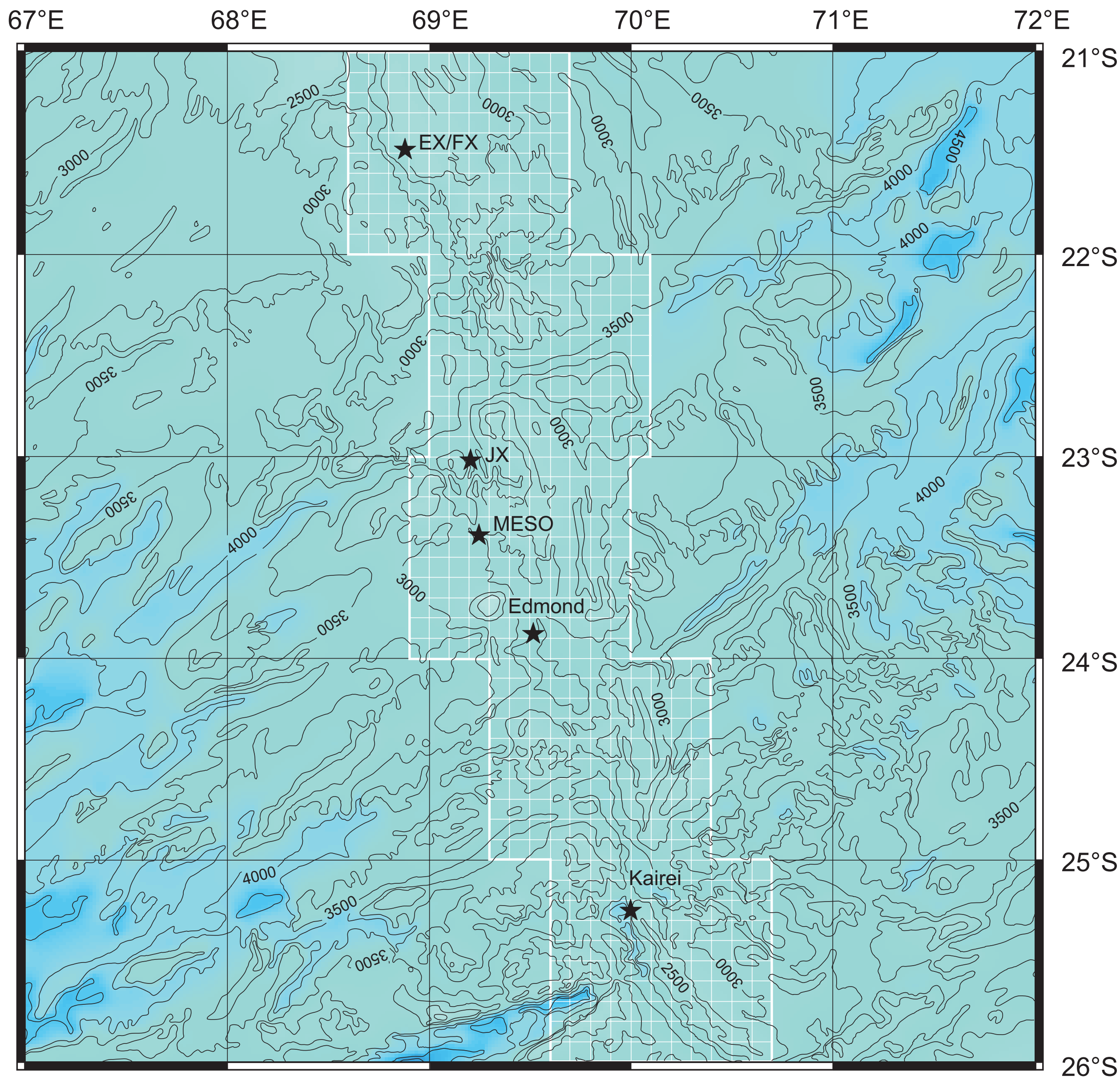
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Turtle Pits and Red Lion sulfide occurrences



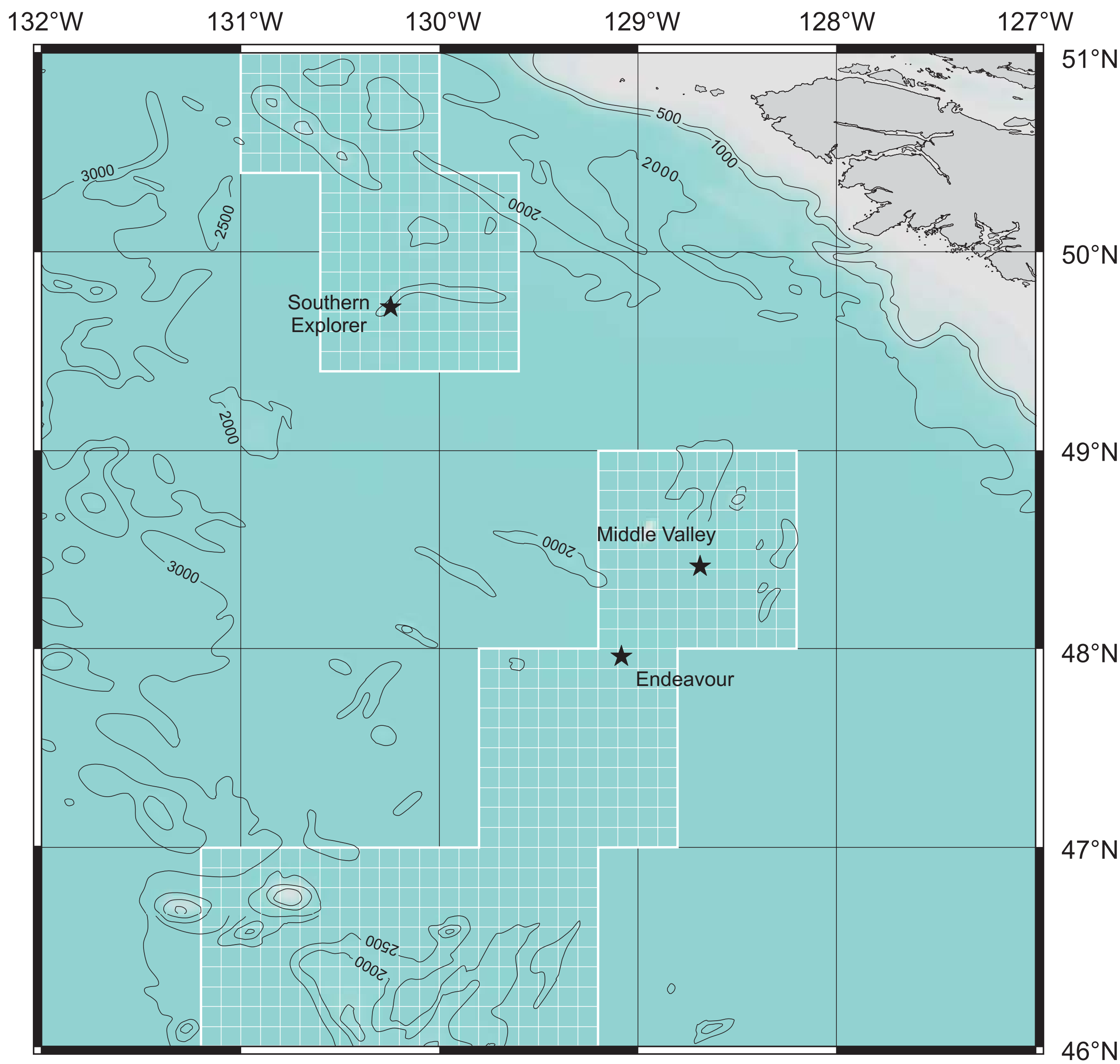
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the MESO Zone sulfide occurrence



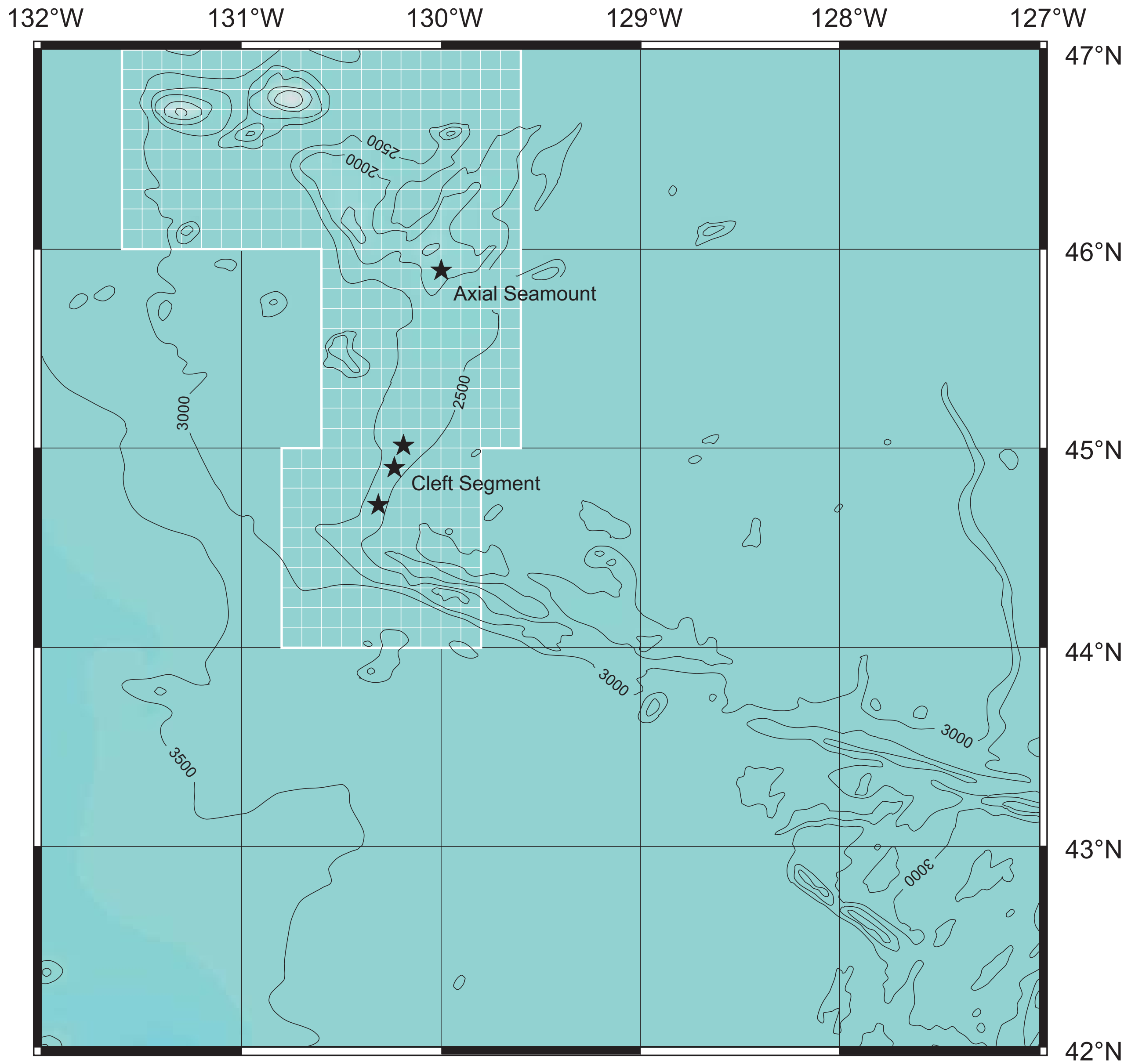
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Southern Explorer, Middle Valley, and Endeavour sulfide occurrences



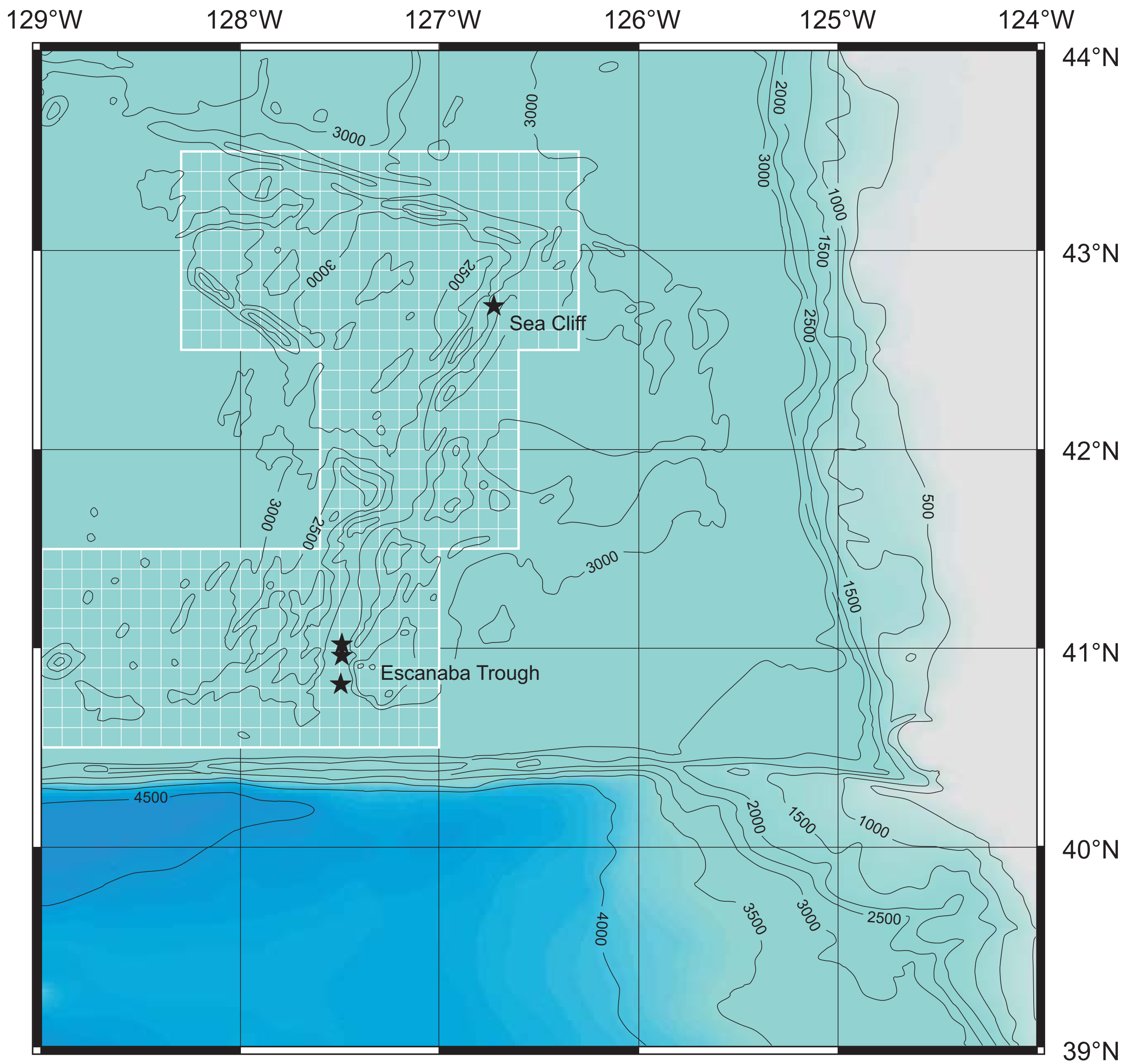
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Axial Seamount and Cleft Segment sulfide occurrences



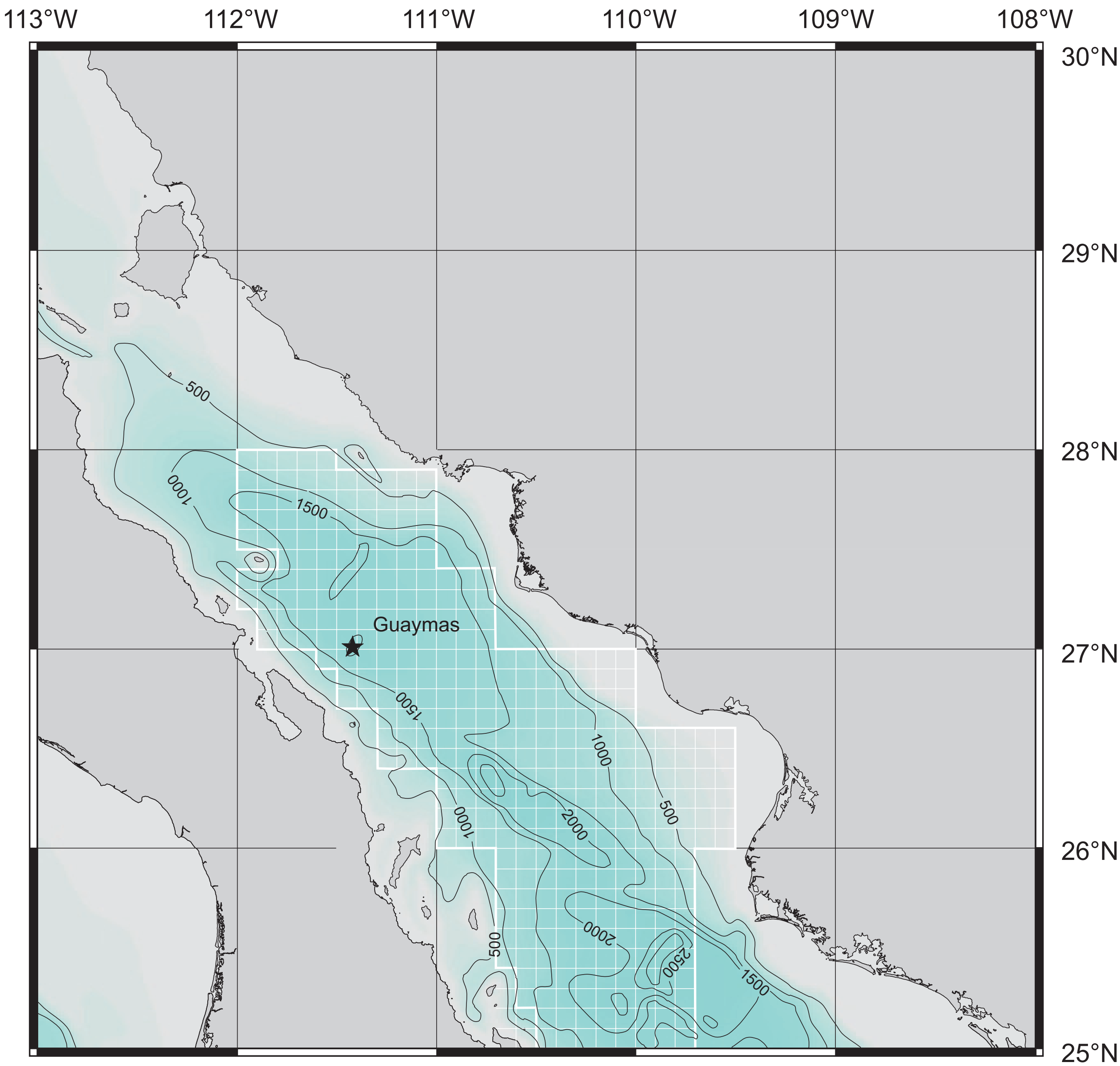
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the Escanaba Trough and Sea Cliff sulfide occurrences



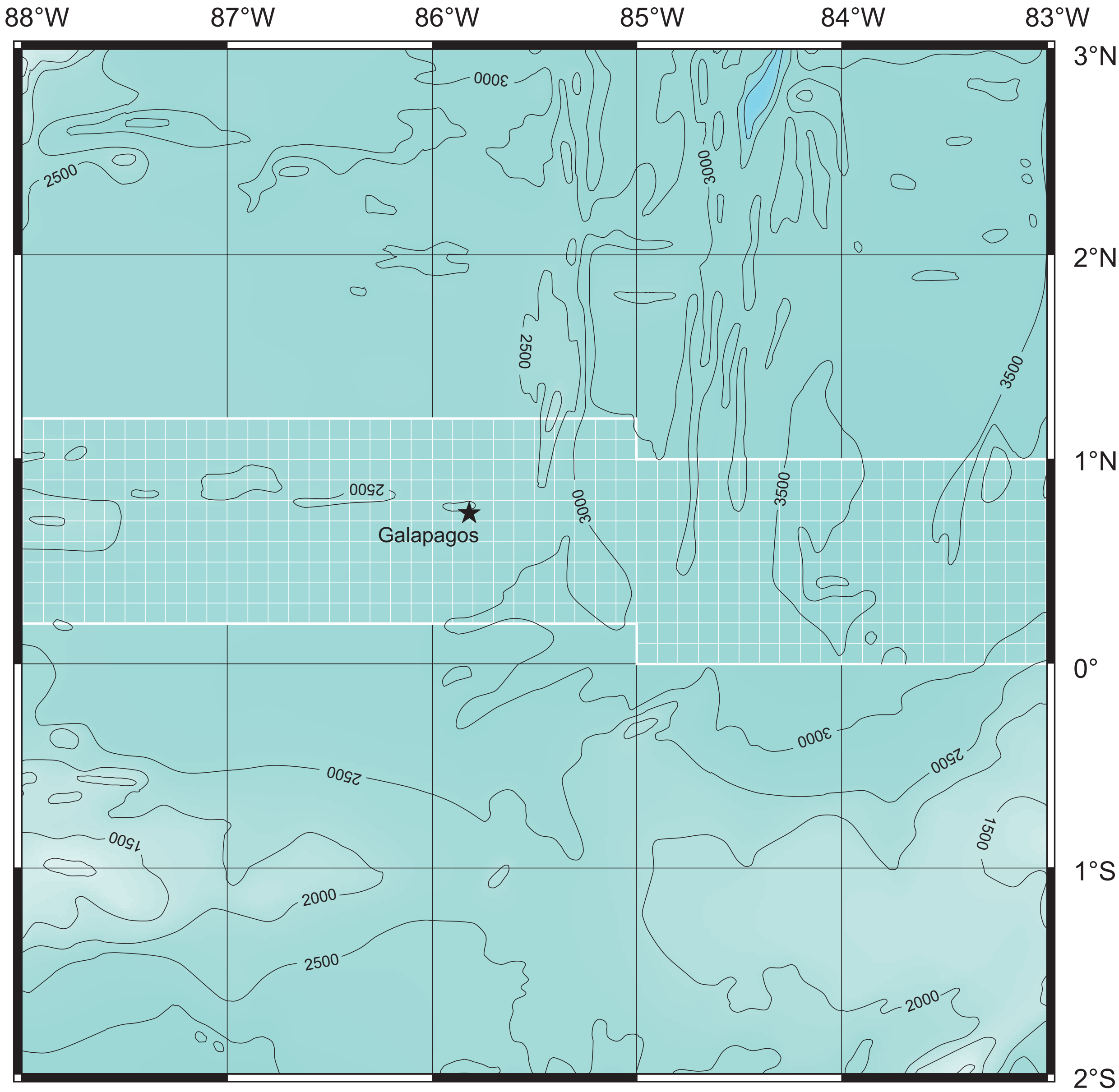
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the Guaymas Basin sulfide occurrences



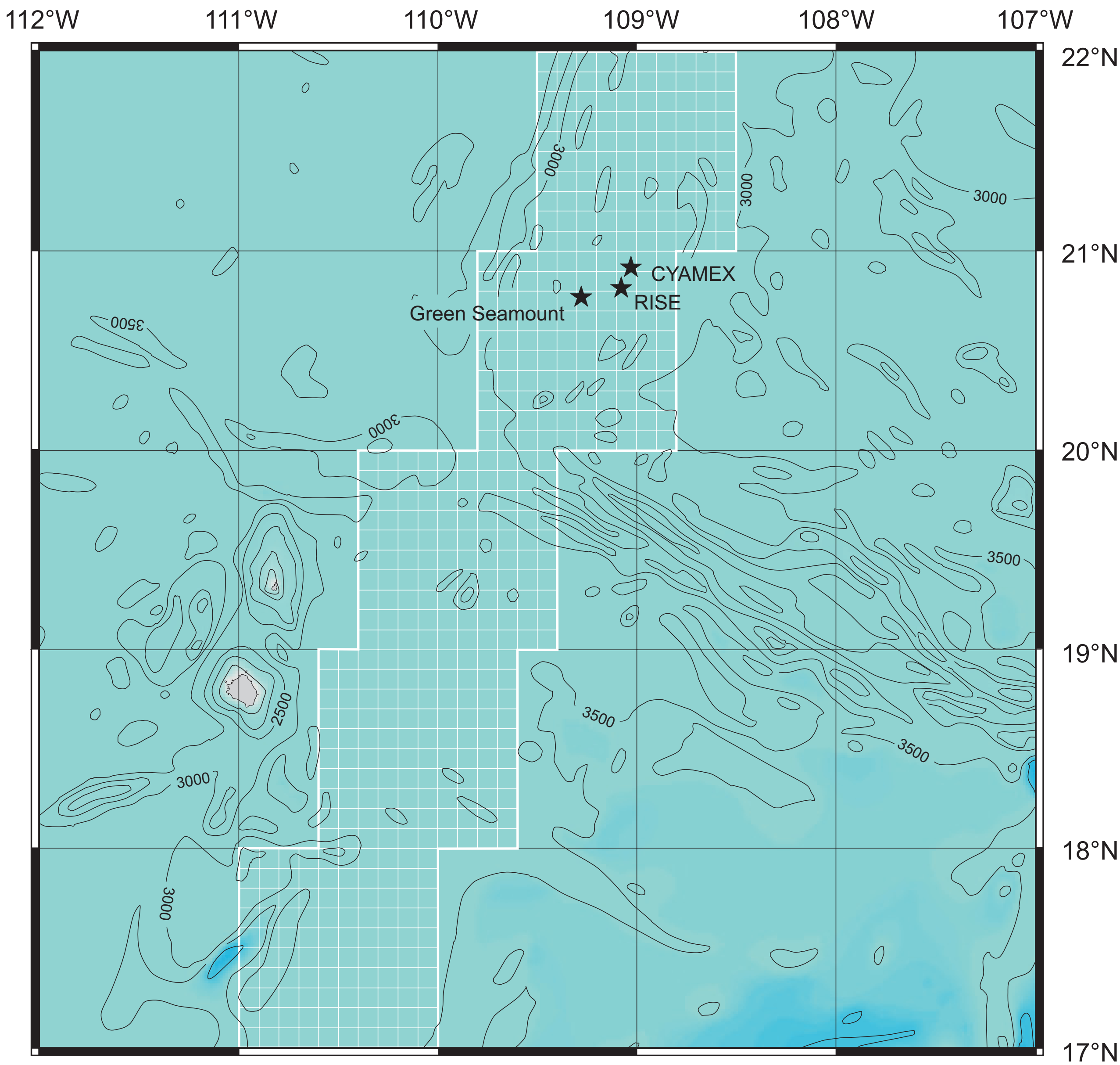
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the Galapaos Rift sulfide occurrence



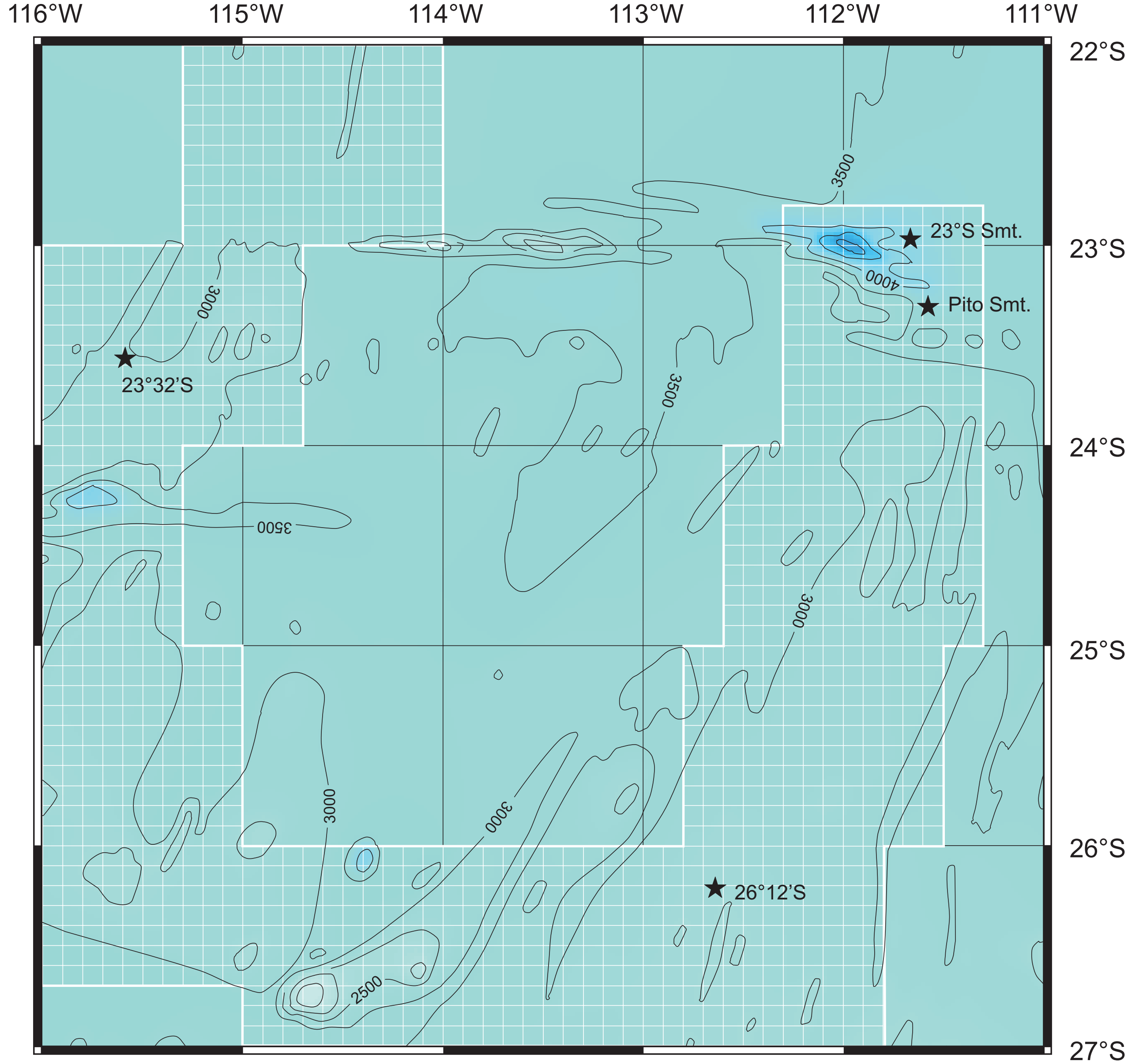
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the CYAMEX and RISE Fields and the sulfide occurrence at Green Seamount



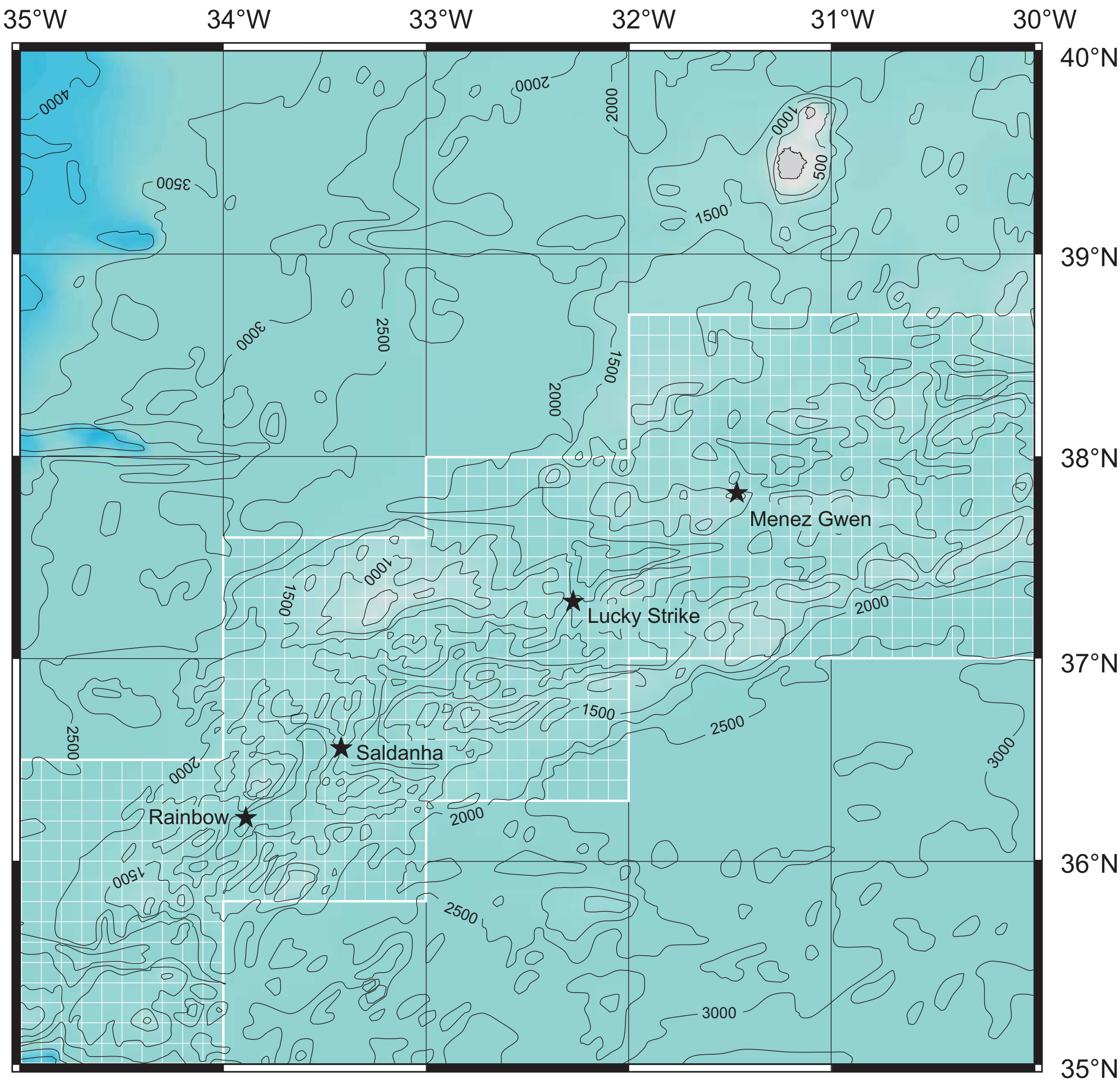
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at the 23°S and Pito Seamounts as well as at 23°32'S and 26°12'S



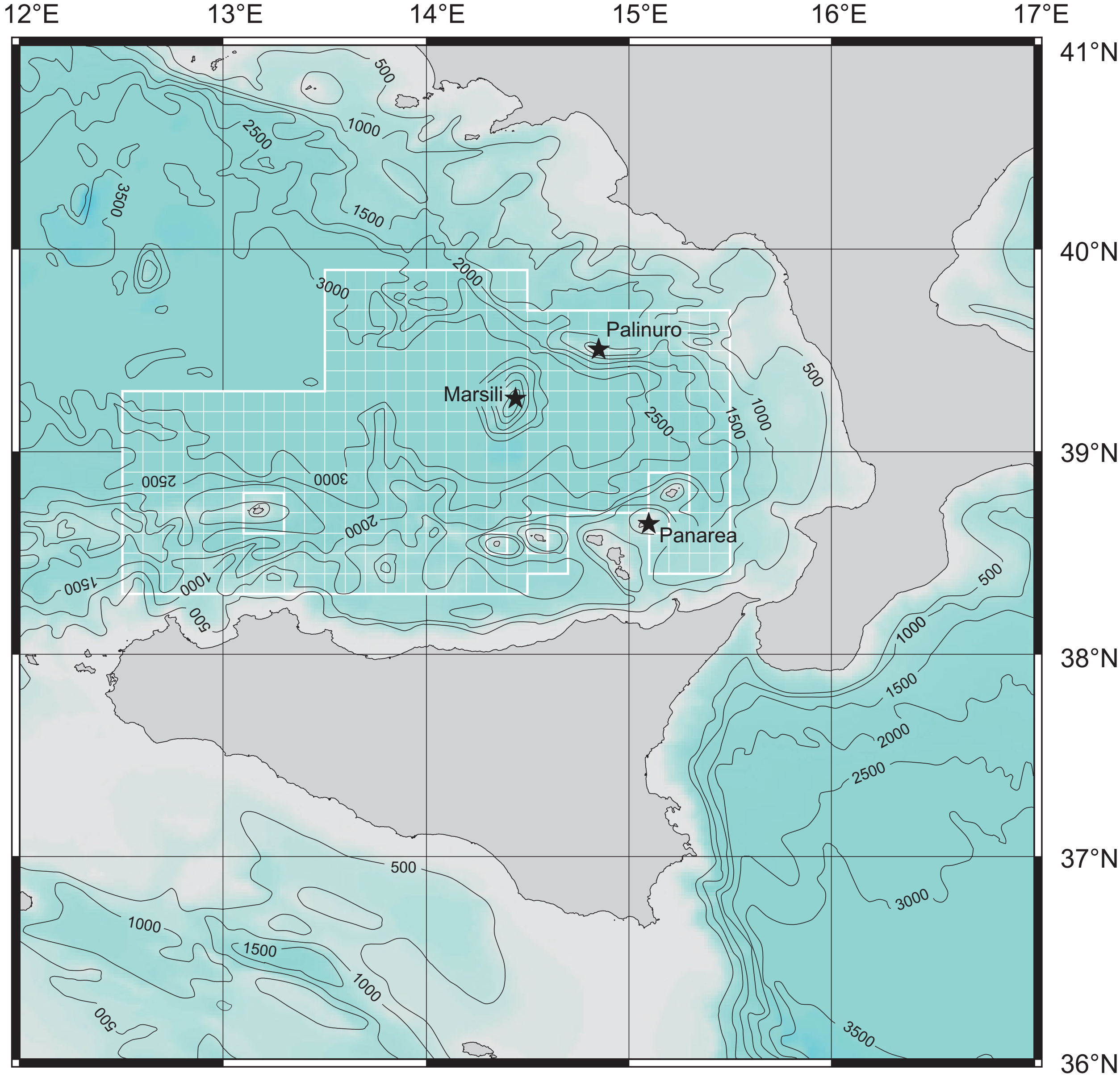
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Menez Gwen, Lucky Strike, and Rainbow sulfide occurrences



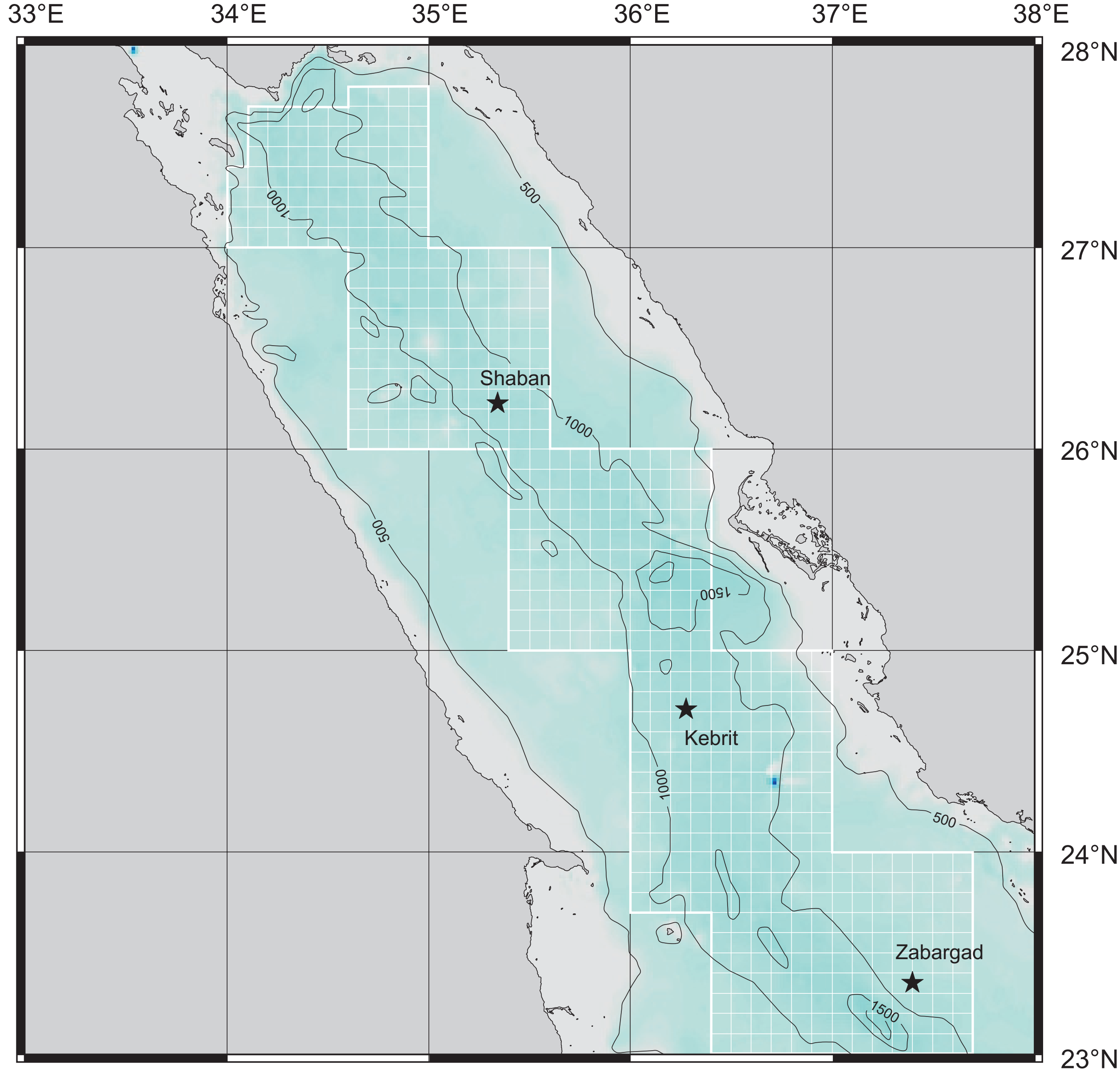
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at Palinuro Seamount, Marsili Seamount, and offshore Panarea Island



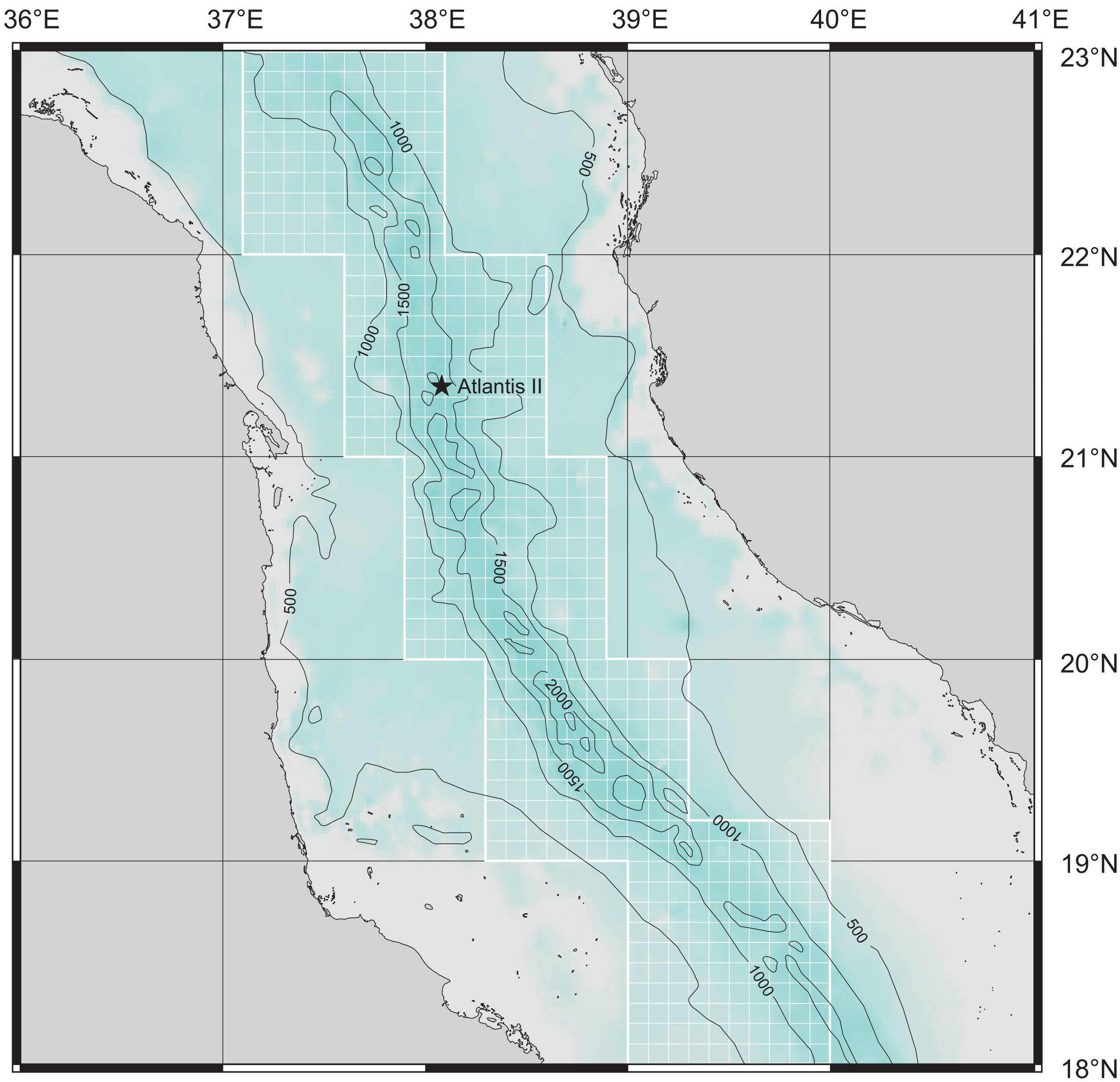
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences in the Shaban, Kebrit, and Zabargad Deeps



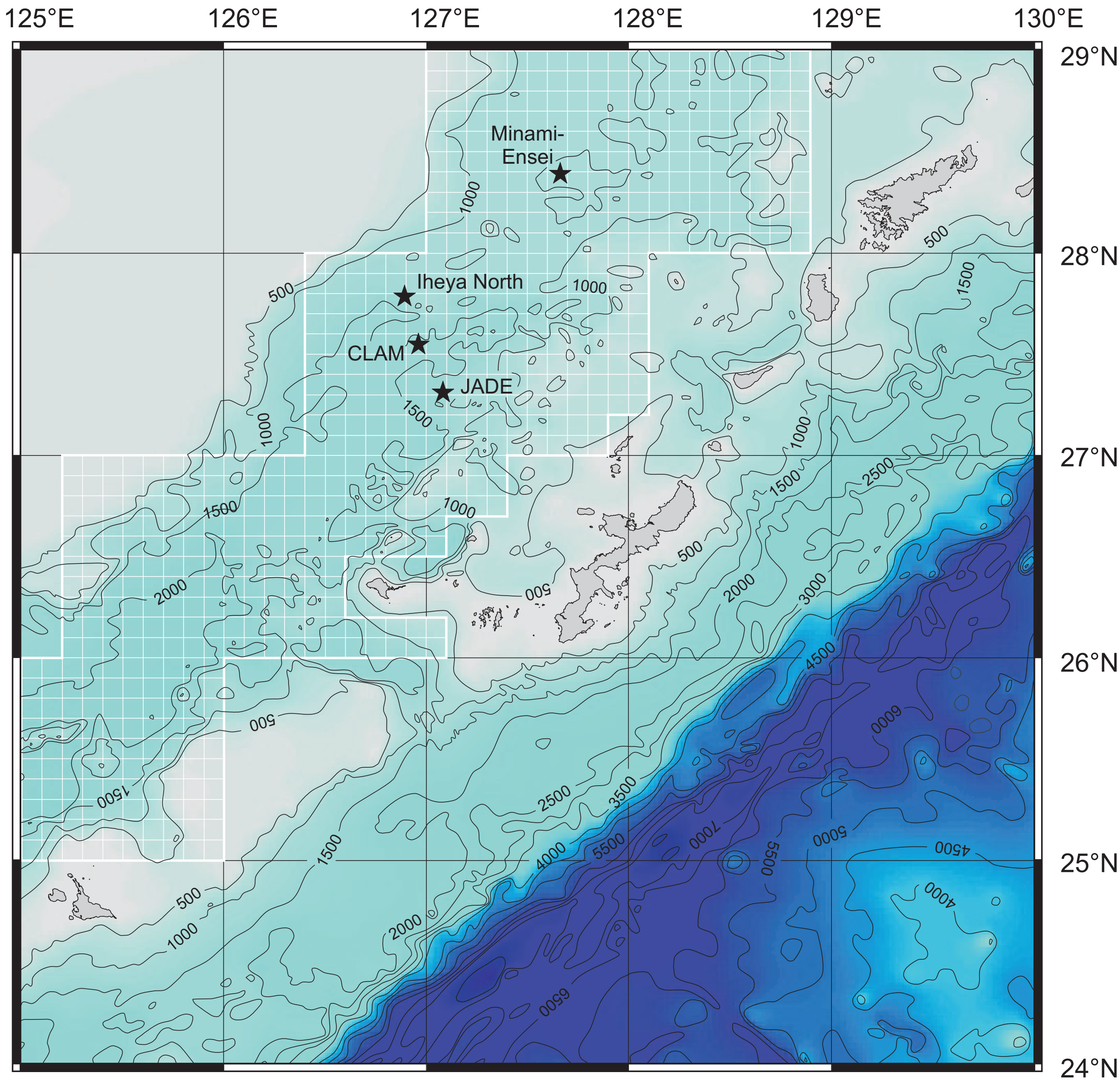
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the sulfide occurrence in the Atlantis II Deep



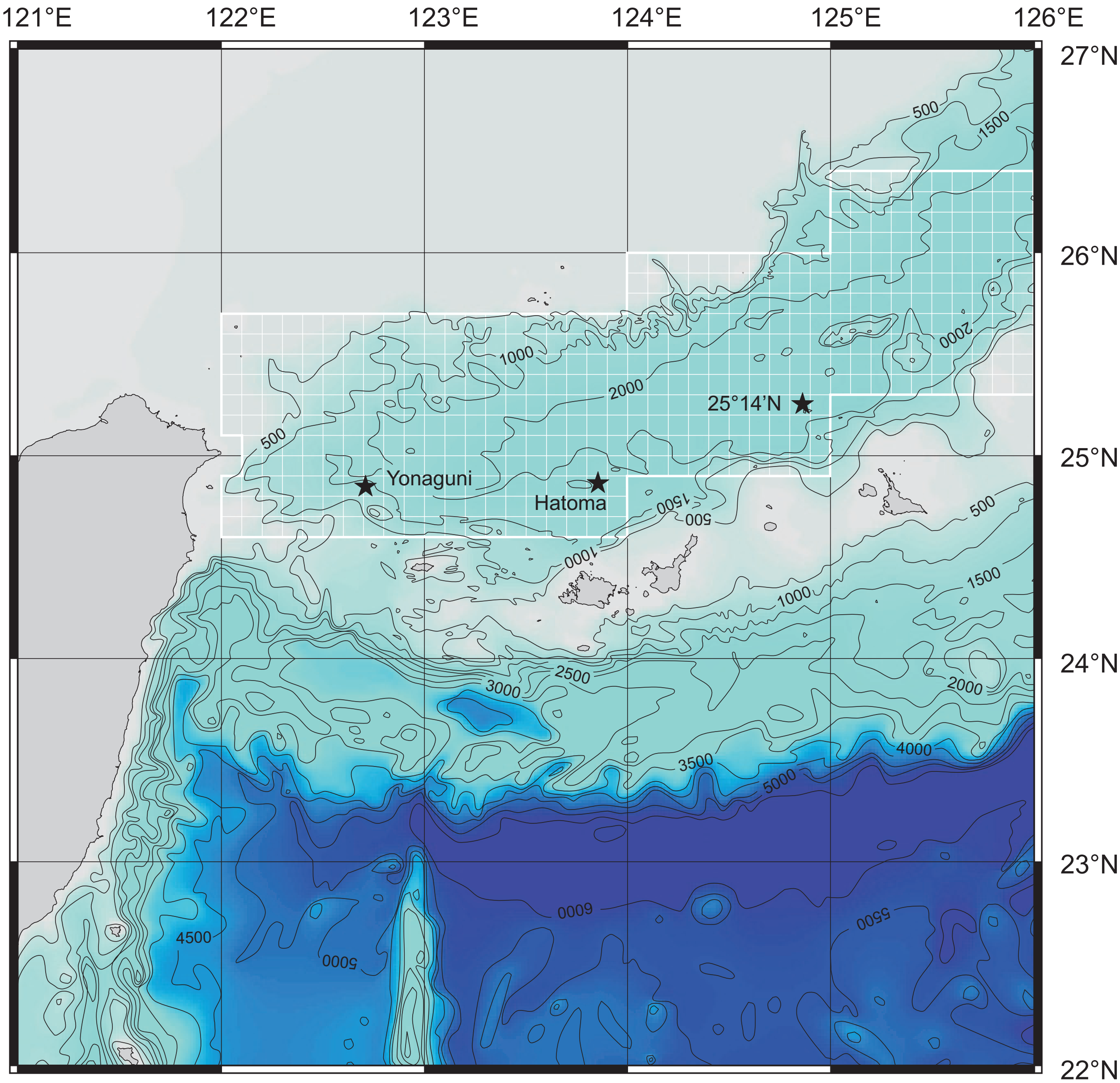
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at the JADE and CLAM Sites, as well as at the Minami-Ensei and Iheya North Knolls



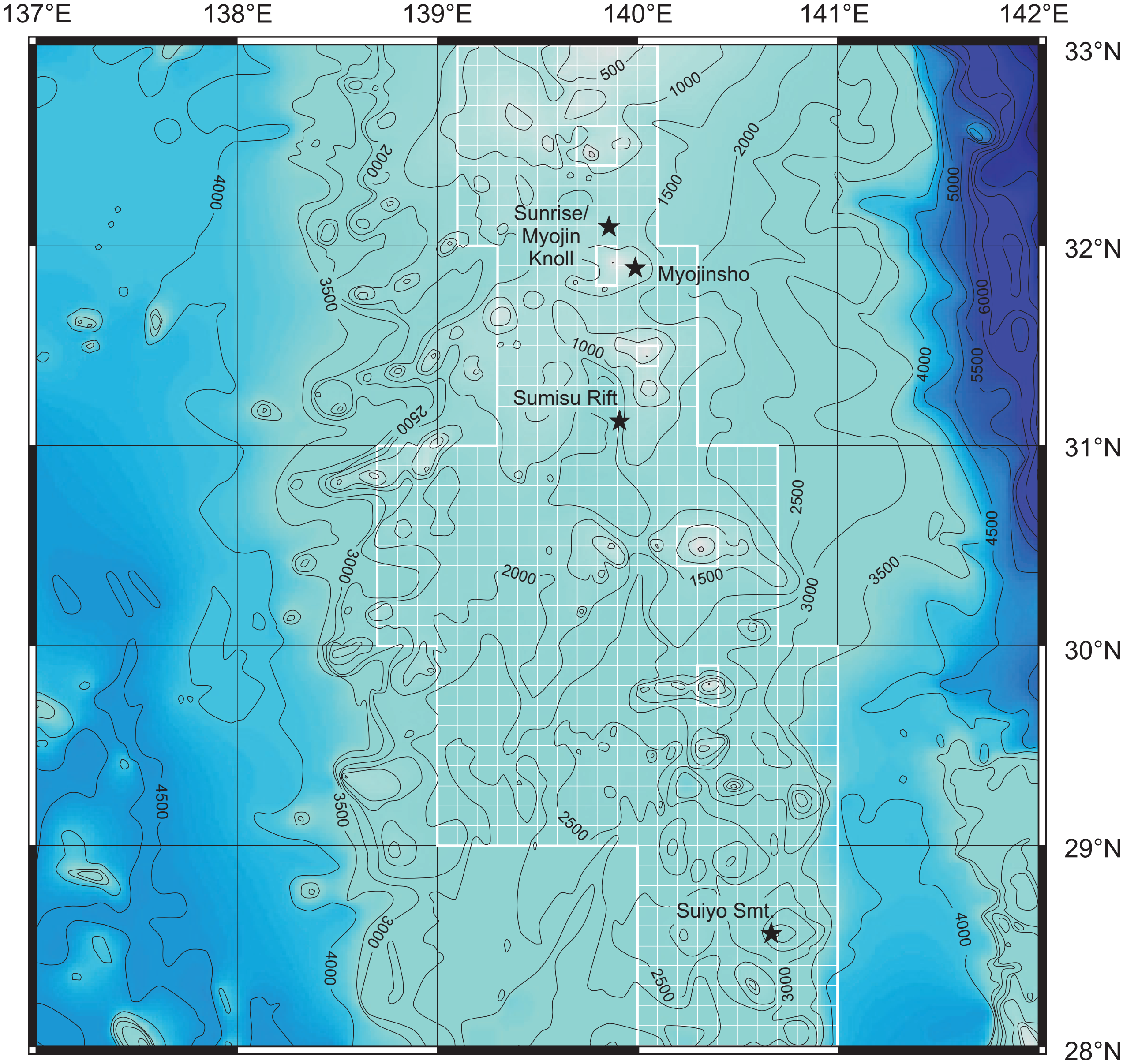
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at Yonaguni Knoll, Hatoma Knoll, and at 25°14'N



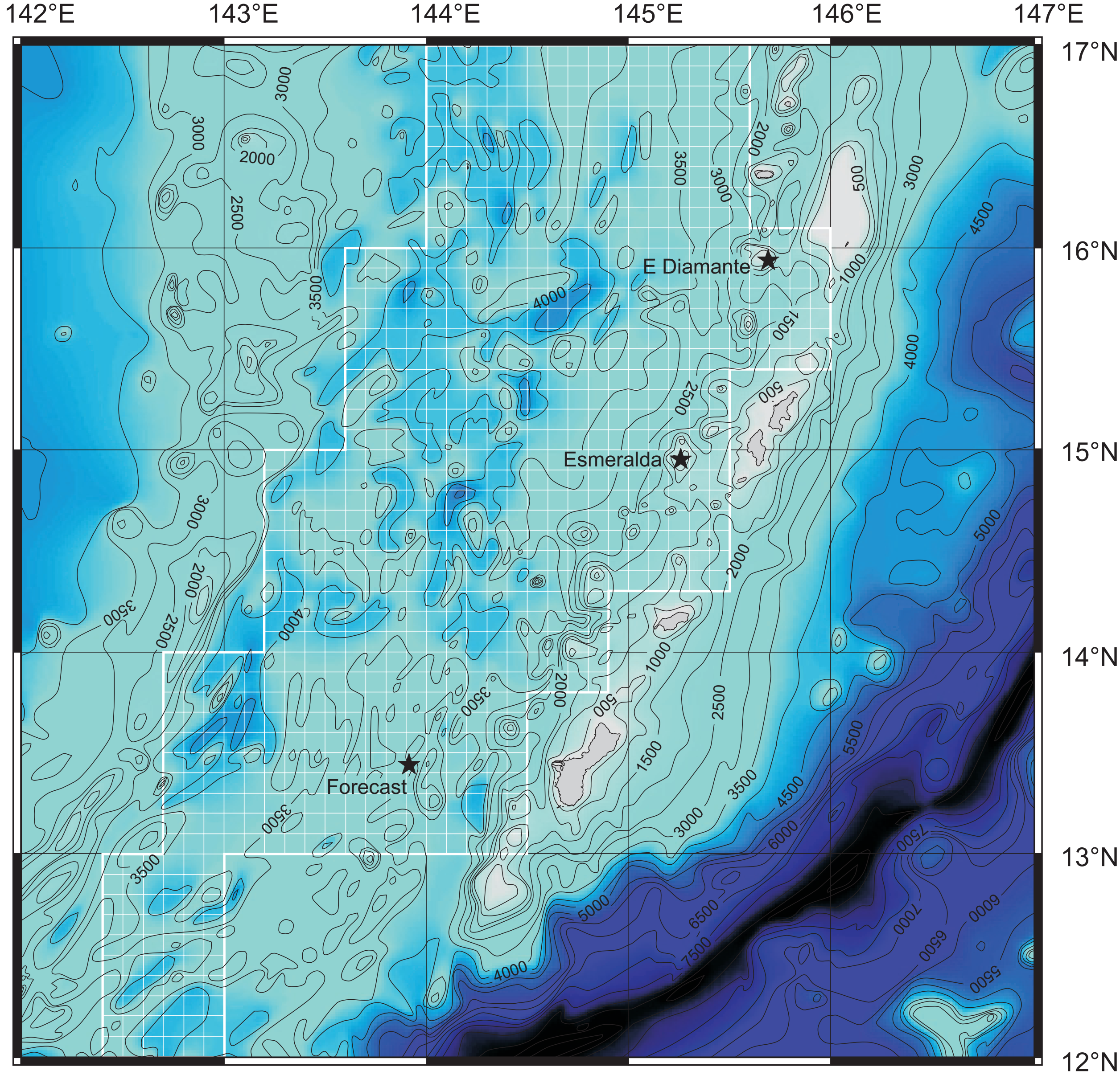
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at Myojin Knoll, Myojinsho Knoll, and at Suiyo Seamount



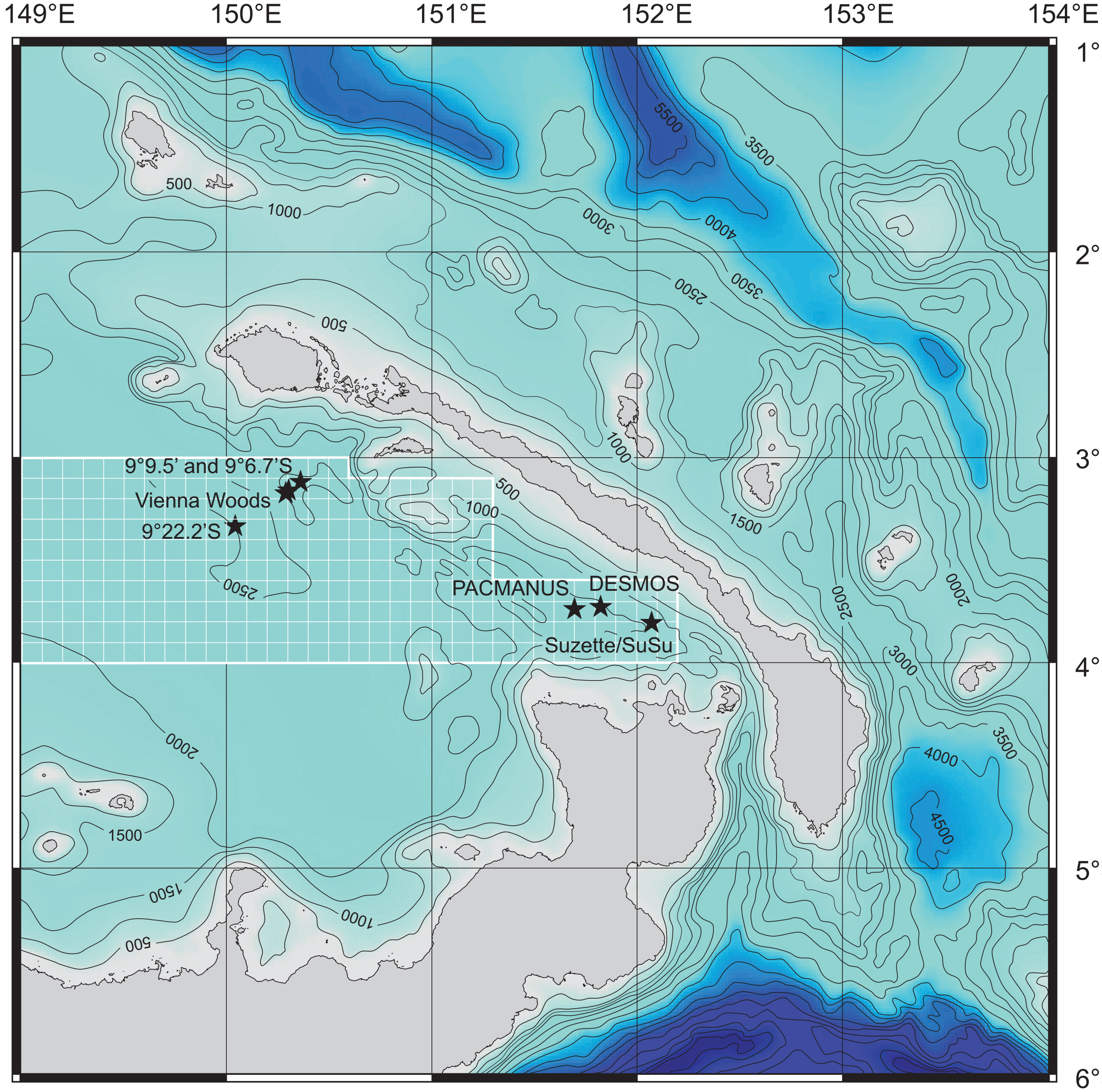
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at East Diamante, Esmeralda Bank, and the Forecast Vent Field



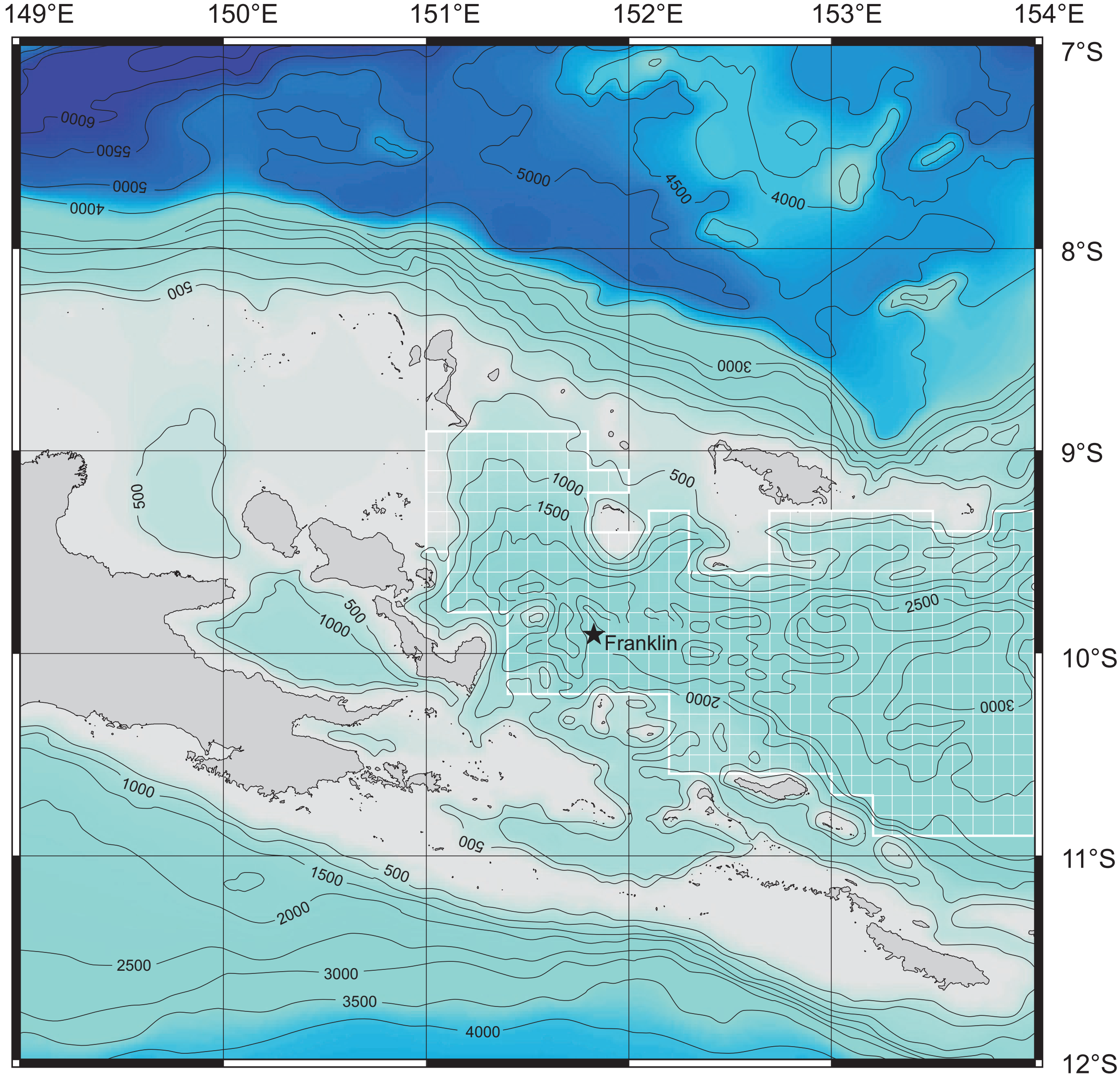
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at PACMANUS, DESMOS, Suzette/SuSu, Vienna Woods, and the fields near 9°9.5'S, 9°6.7'S, and 9°22.2'S



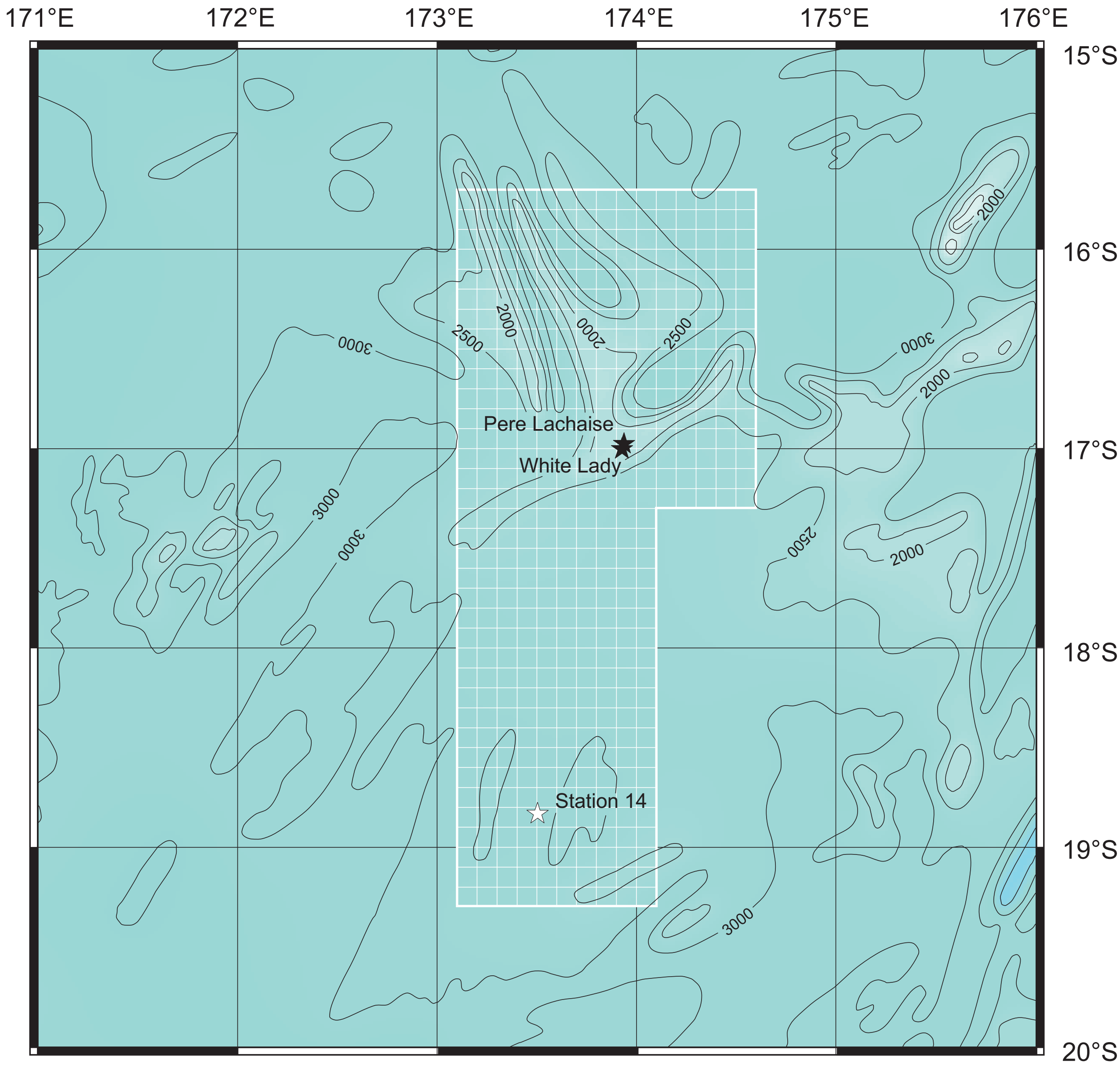
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrence at Franklin Seamount



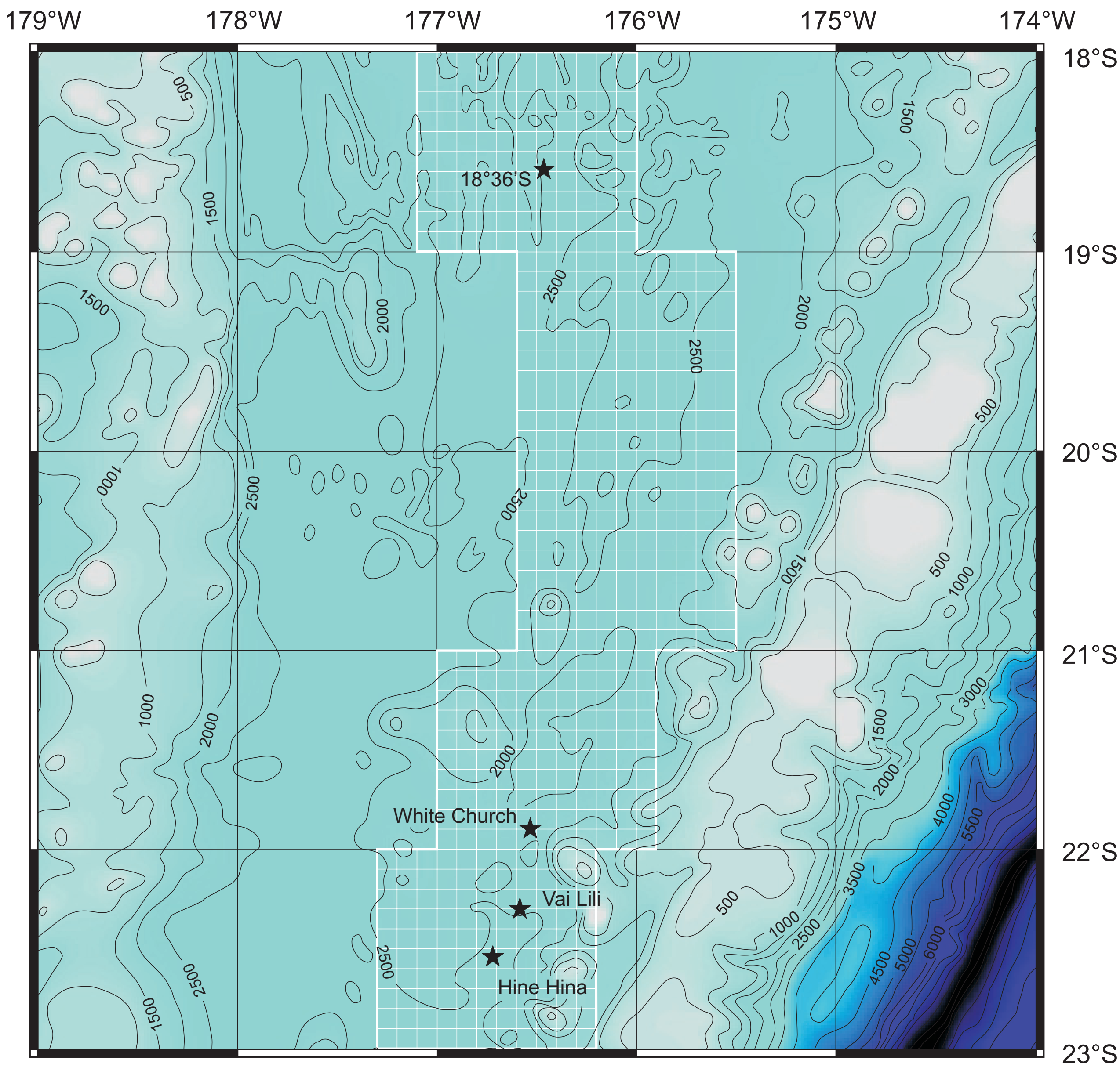
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Pere Lachaise and White Lady sulfide occurrences



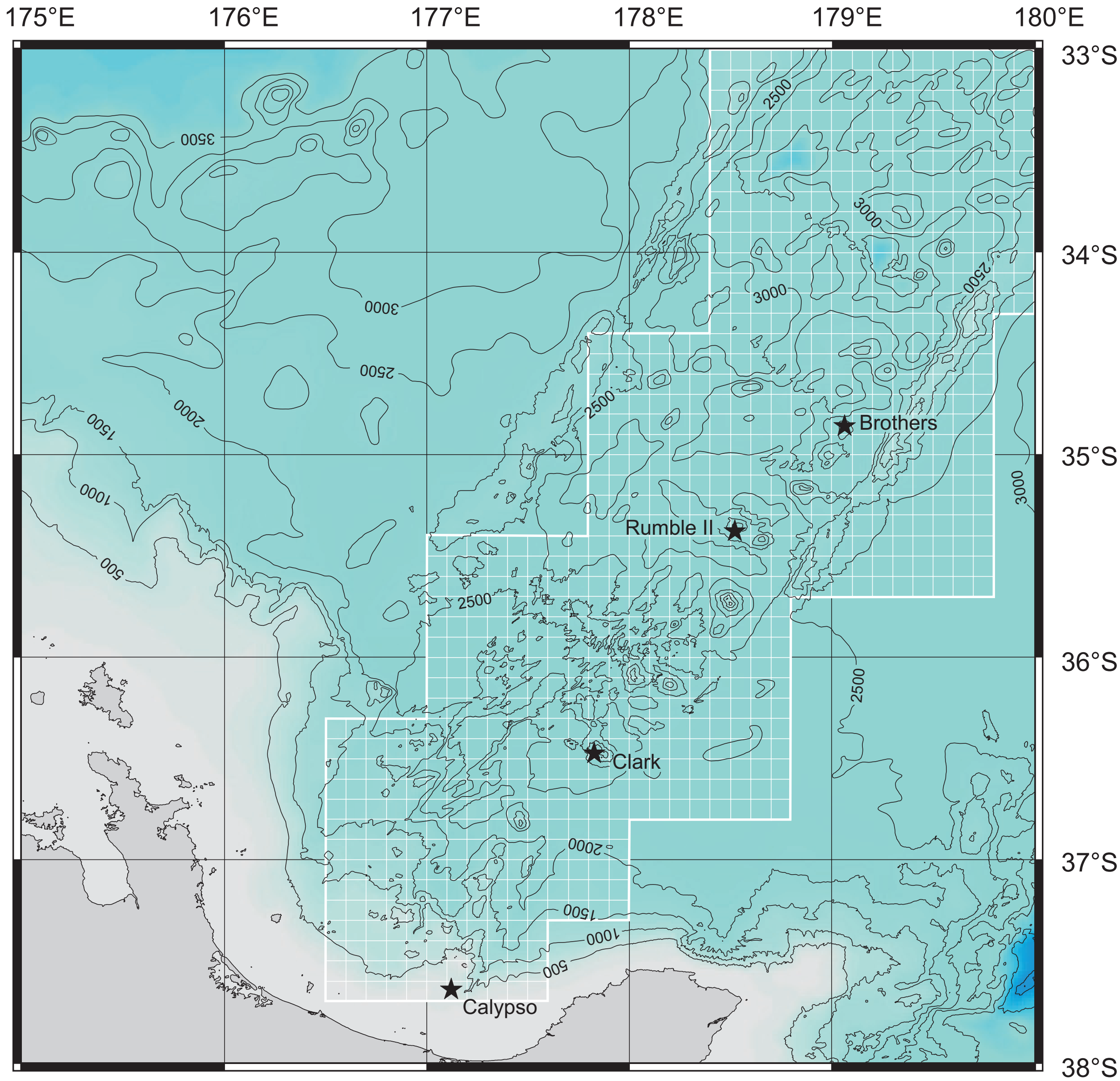
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at 18°36'S, White Church, Vai Lili, and Hine Hina



Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences at Brothers Seamount, Rumble II Seamount, Clark Seamount, and at the Calypso Vents

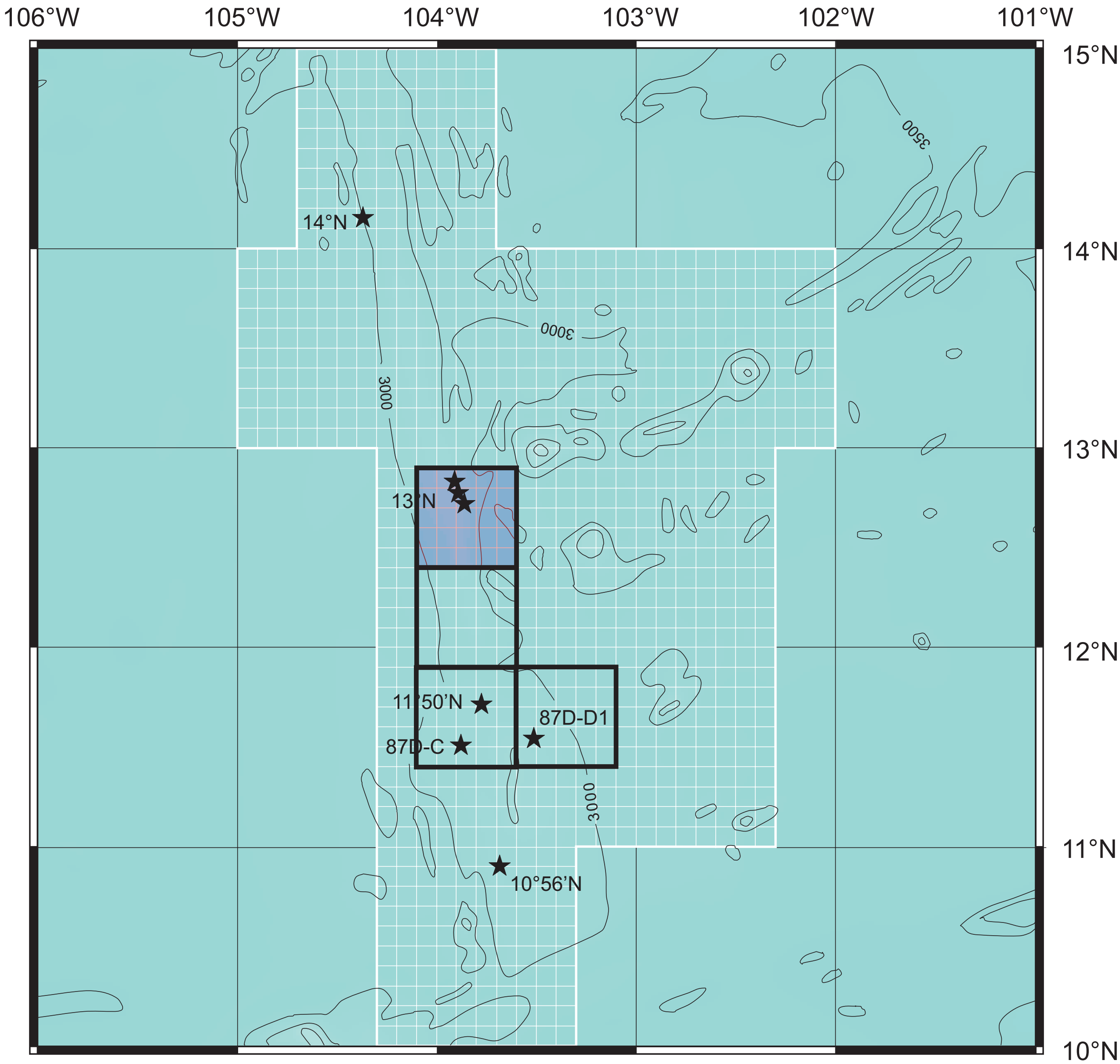


Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Appendix 4. Maps of 12 Model Exploration Areas

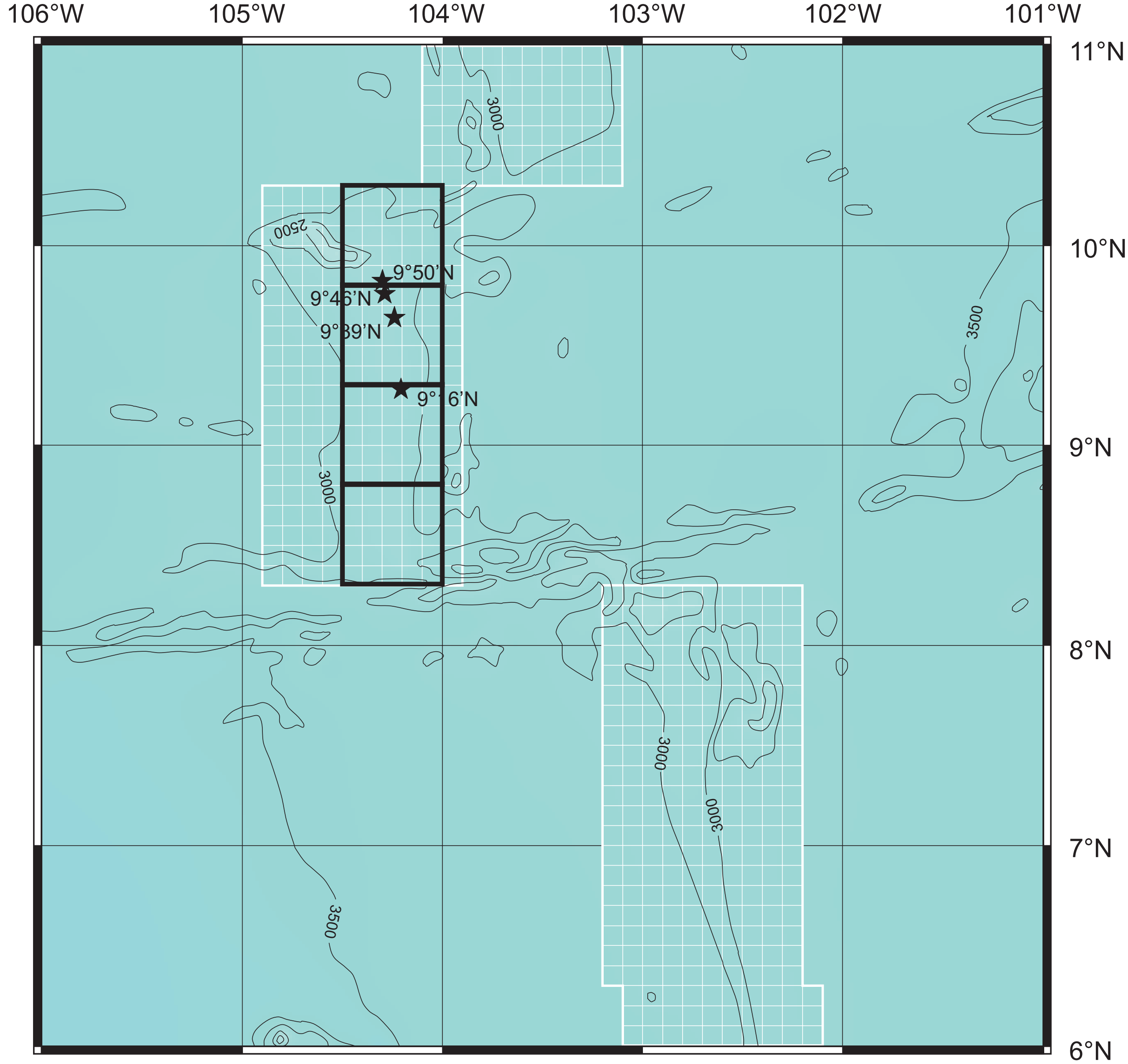
Model exploration areas using 5 deg. by 5 deg. maps and 1000-m contour intervals were measured for 12 case studies in "the Area". Models are presented that illustrate how these areas might be reduced to the minimum number of exploration lease blocks according to the schedule of relinquishment proposed in the Draft Regulations (50% of the allocated area after year five, 75% after year 10, and a maximum of 25 blocks after year 15).

Locations of the sulfide occurrences near 14°N, 13°N, 11°50'N, 10°56'N, and at the 87D-D1 and 87D-C Seamounts



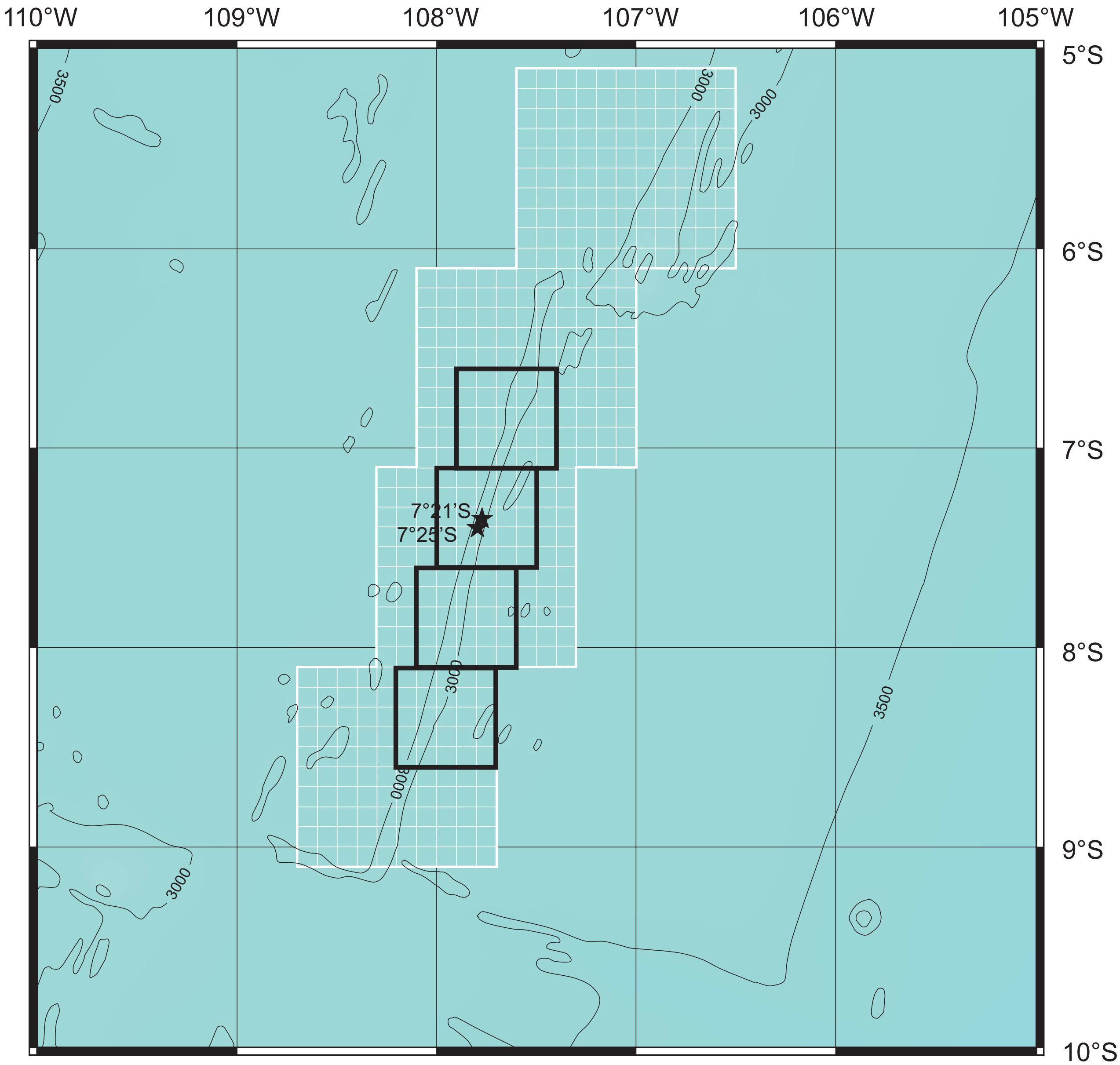
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 9°50’N, 9°46’N, 9°39°N, and 9°16°N



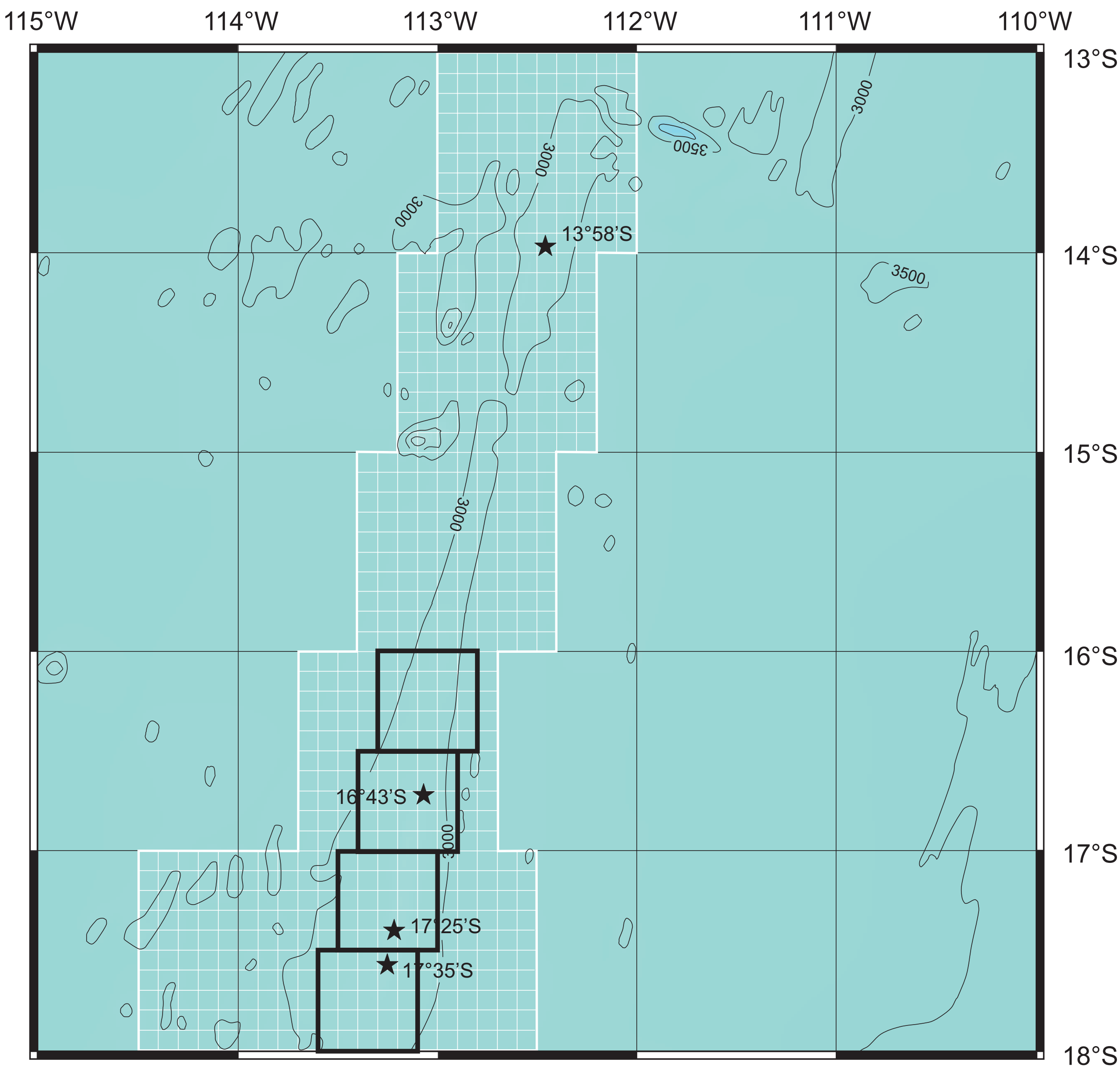
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 7°21’S and 7°25’S



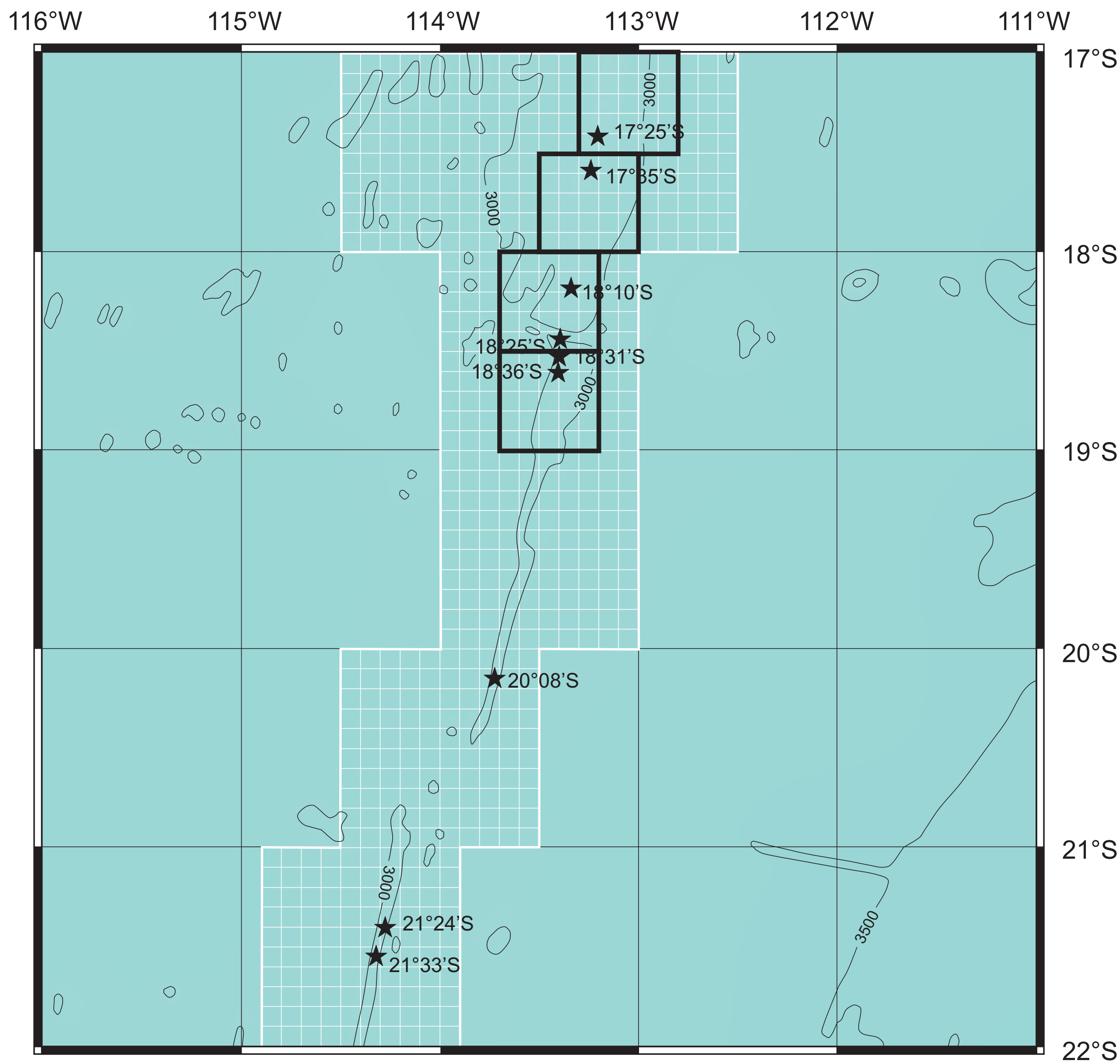
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 13°58'S, 17°25'S, and 7°35'S



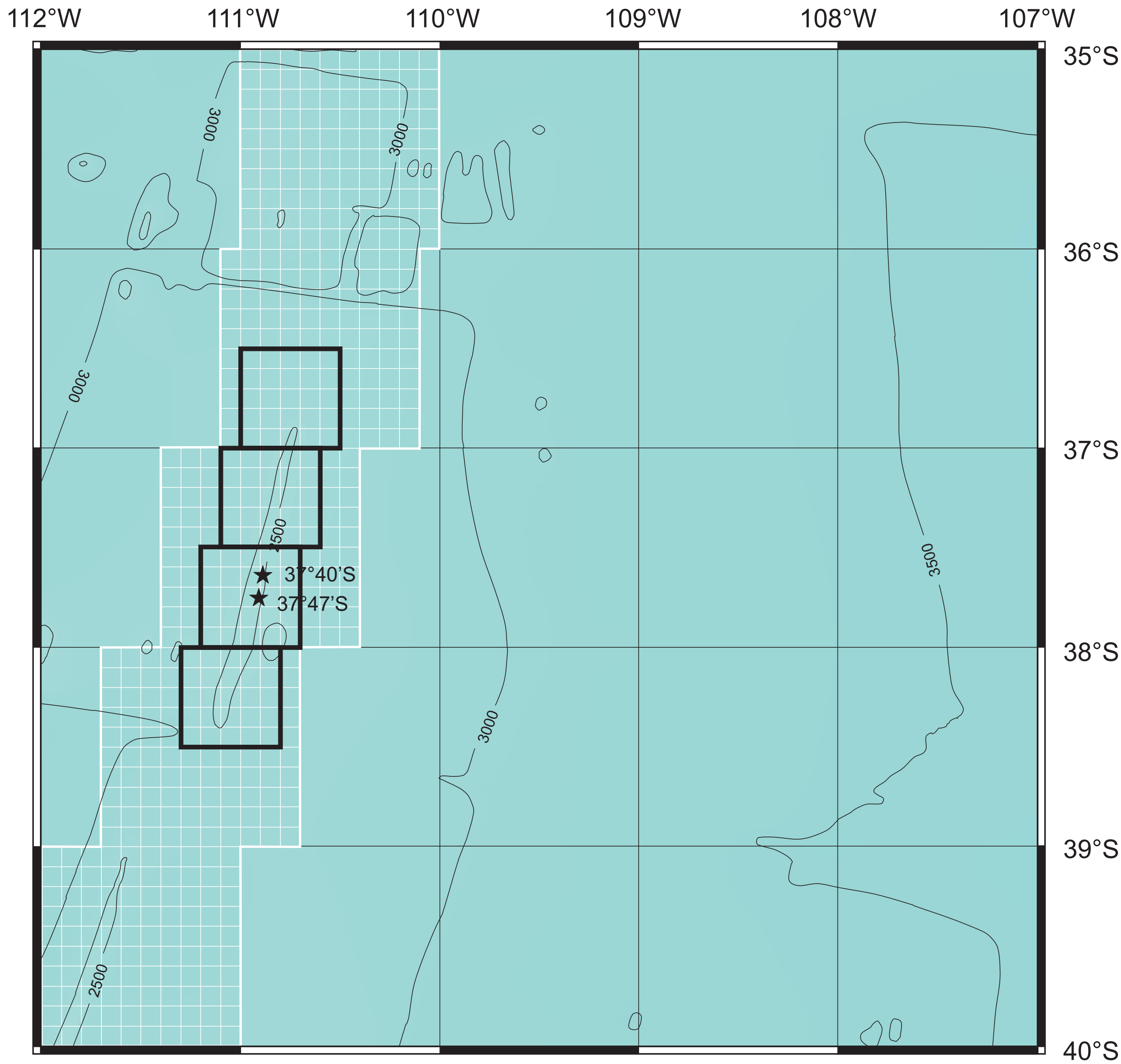
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 17°25'S, 17°35'S, 18°10'S, 18°25'S, 18°31'S, 18°36'S, 20°08'S, 21°24'S, and 21°33'S



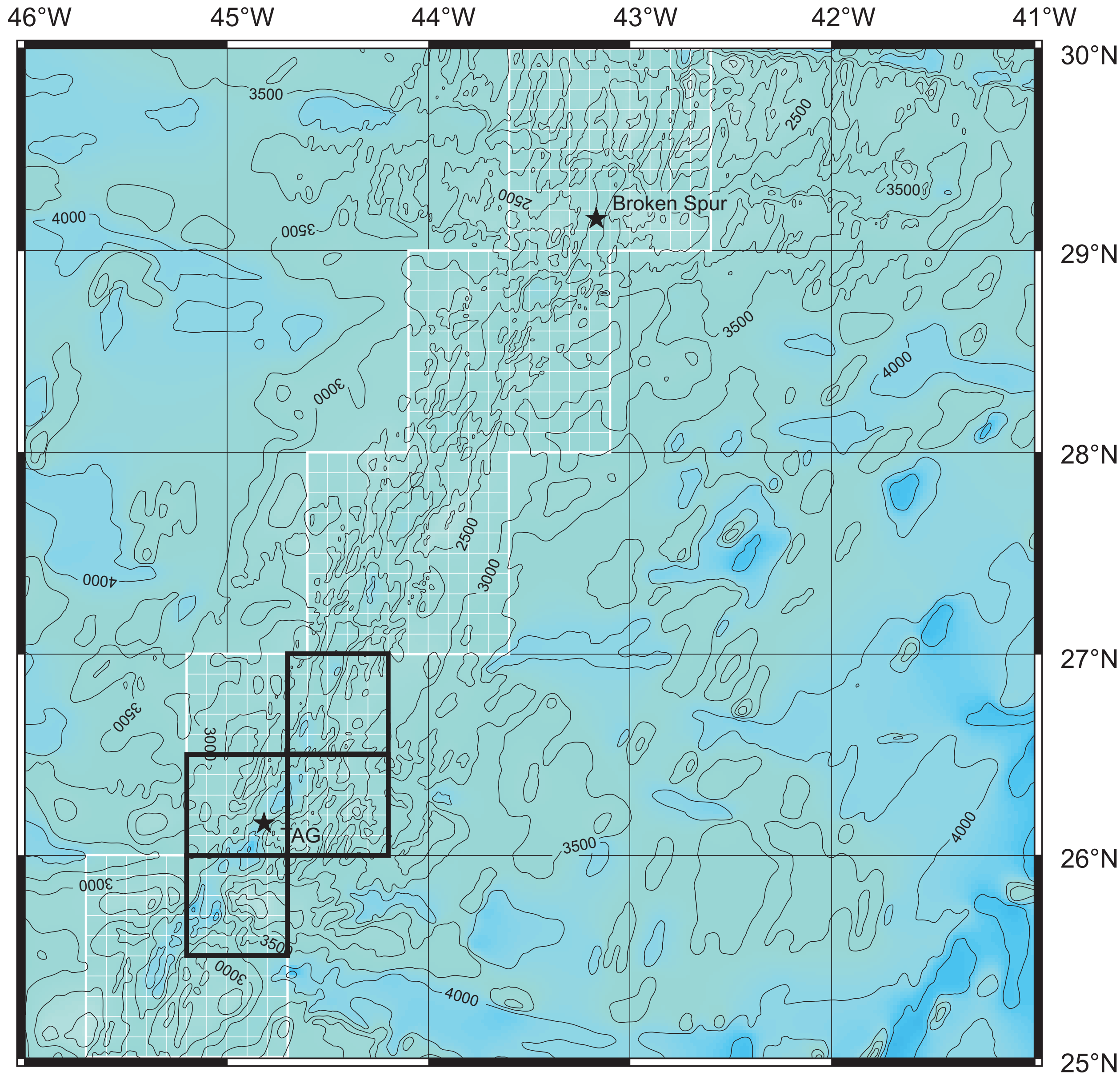
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the sulfide occurrences near 37°40'S and 37°47'S



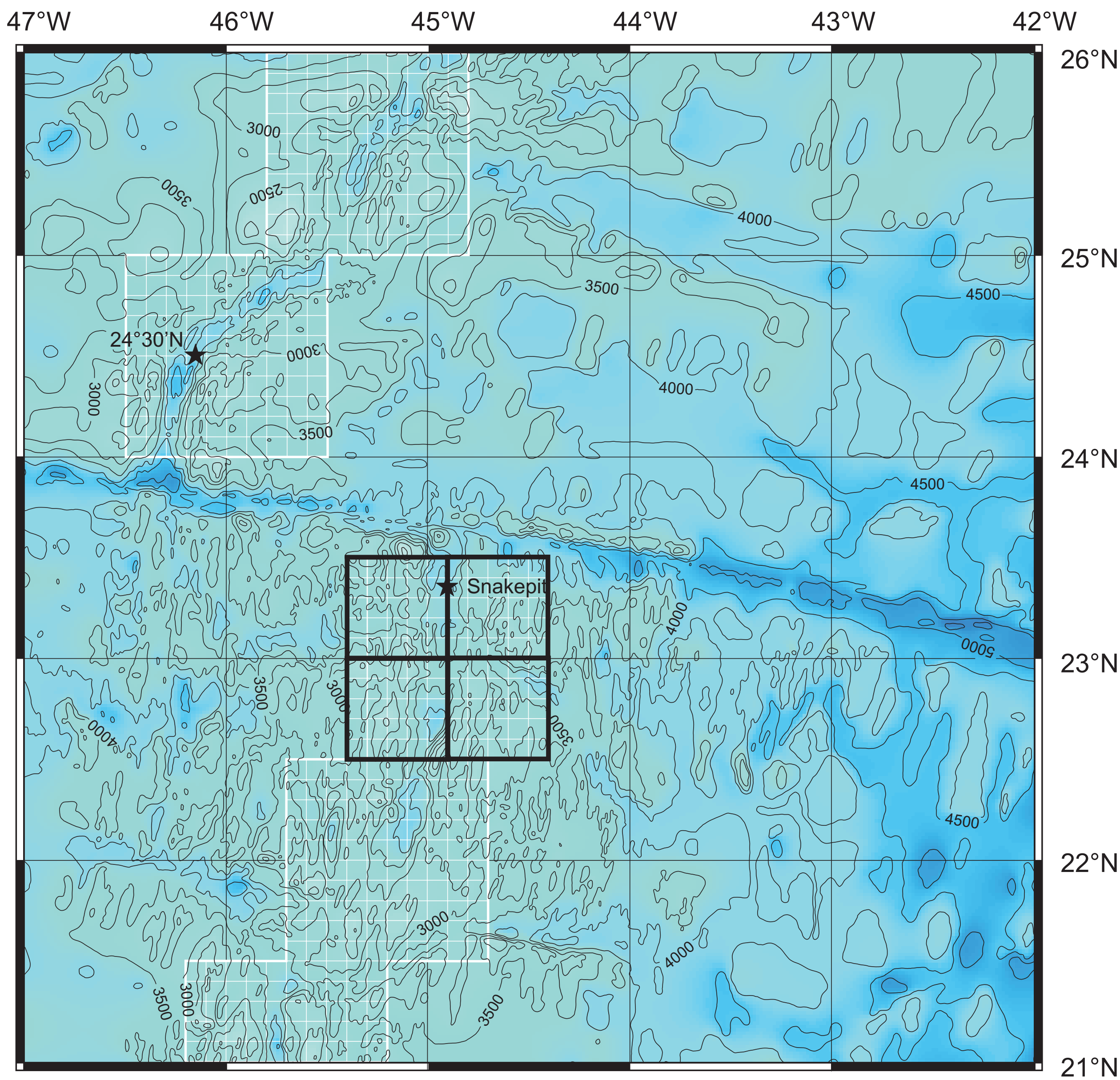
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Locations of the Broken Spur and TAG sulfide occurrences



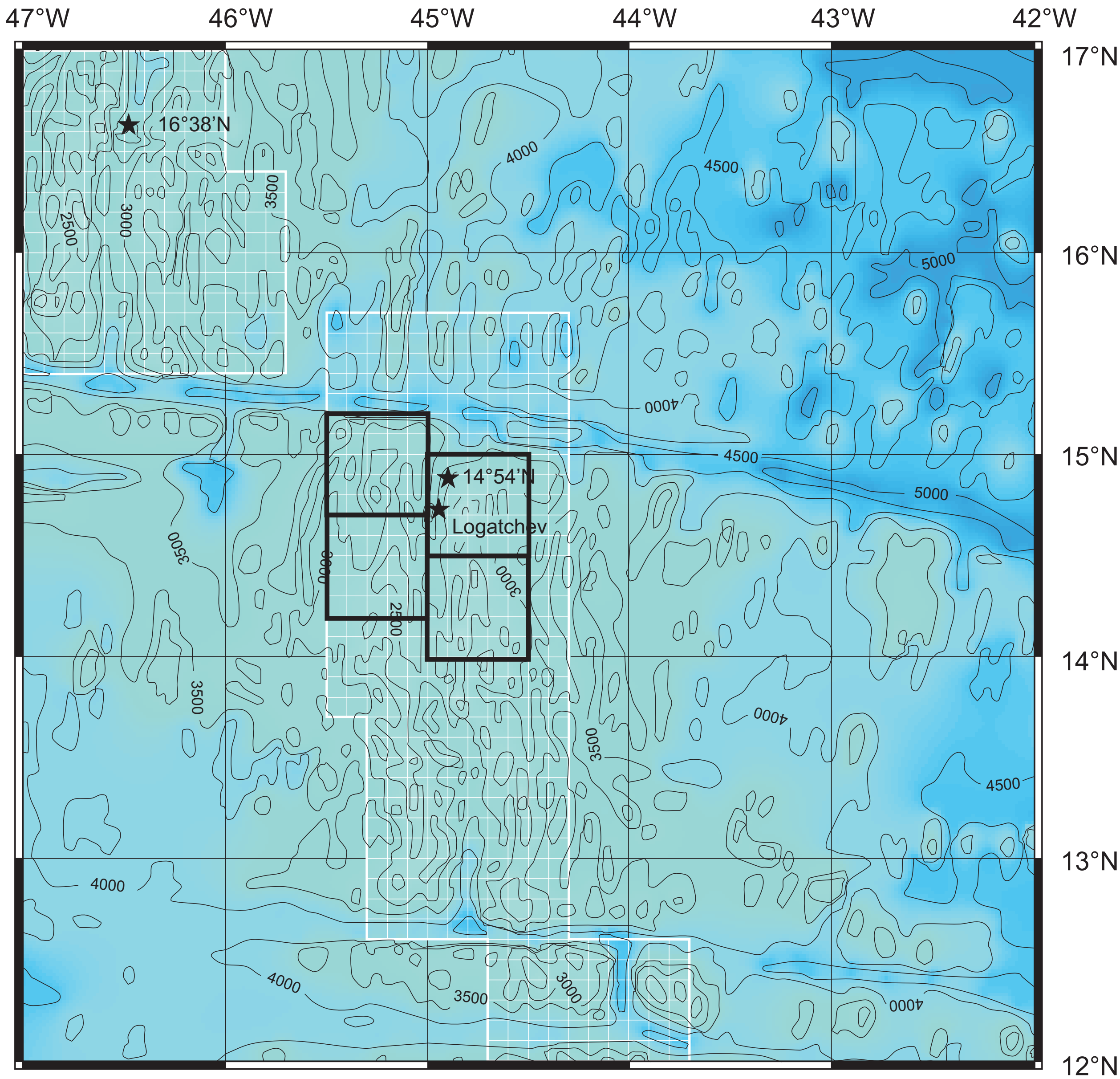
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the 24°30'N and Snakepit sulfide occurrence



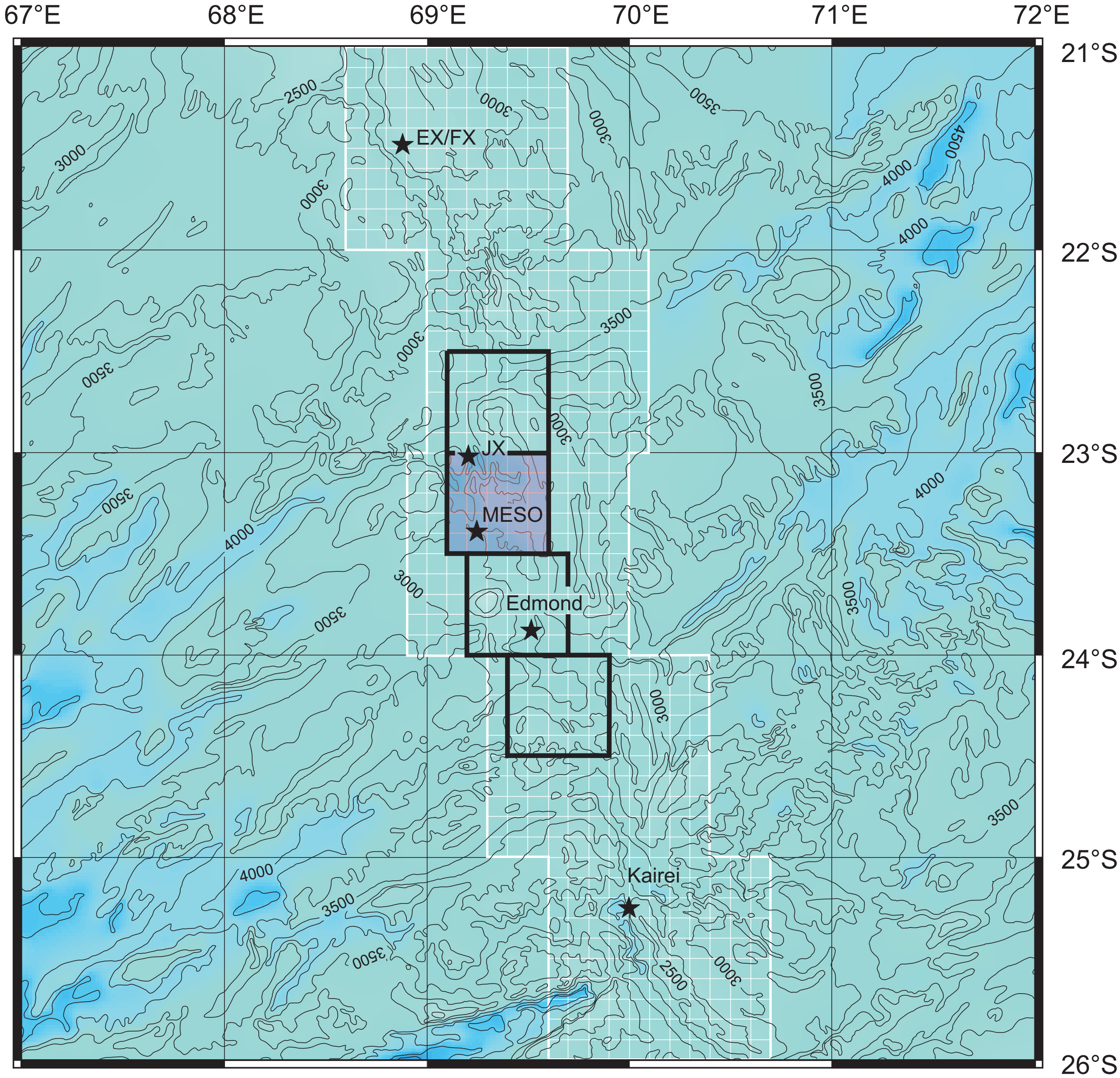
Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the sulfide occurrences at 16°38'N, 14°54'N, and the Logatchev Field



Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Location of the MESO Zone sulfide occurrence

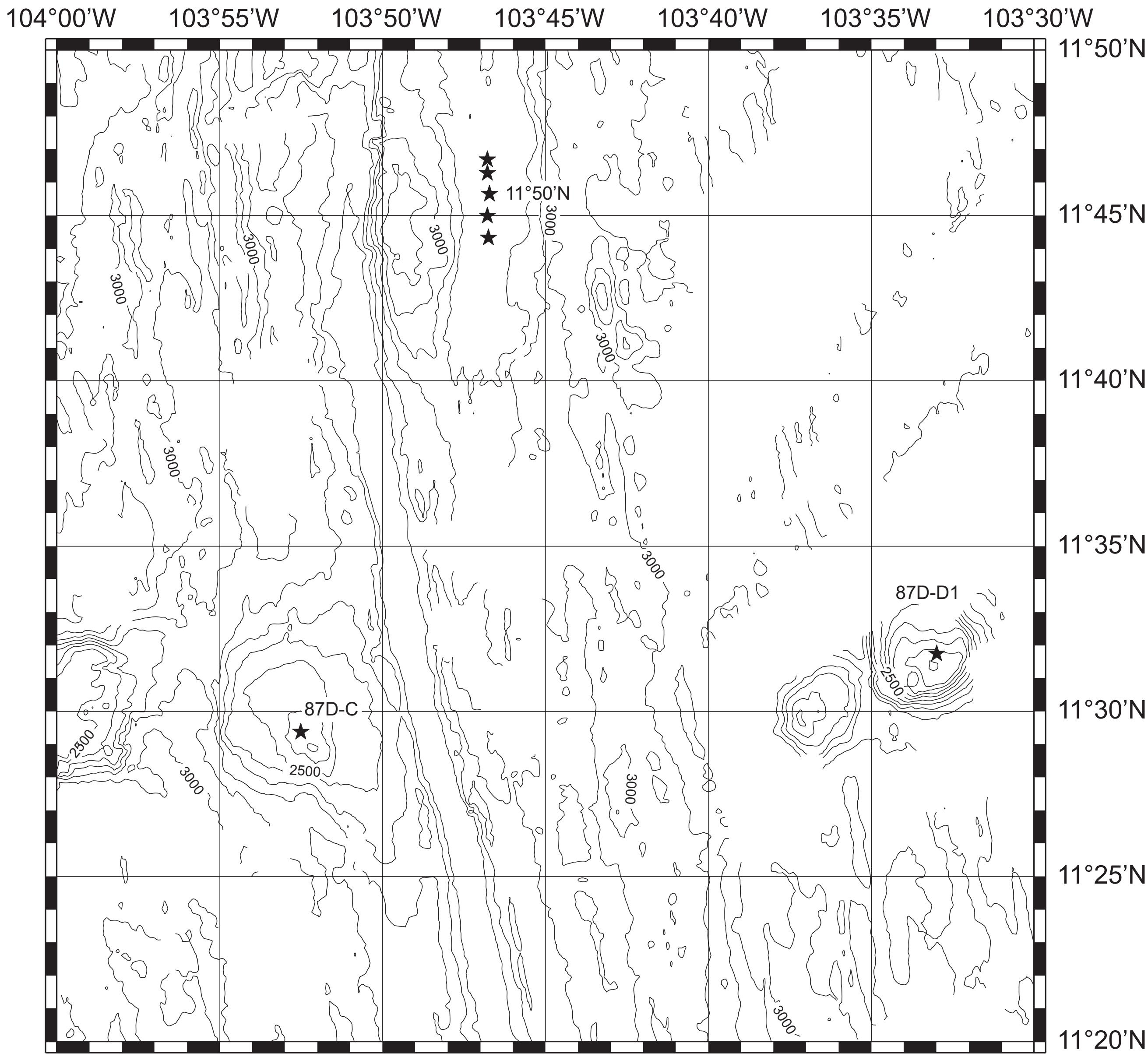


Equidistant Cylindrical Projection
Data: GEBCO Digital Atlas

Appendix 5. Examples of Detailed Maps of Selected Areas at 100-m Contour Intervals

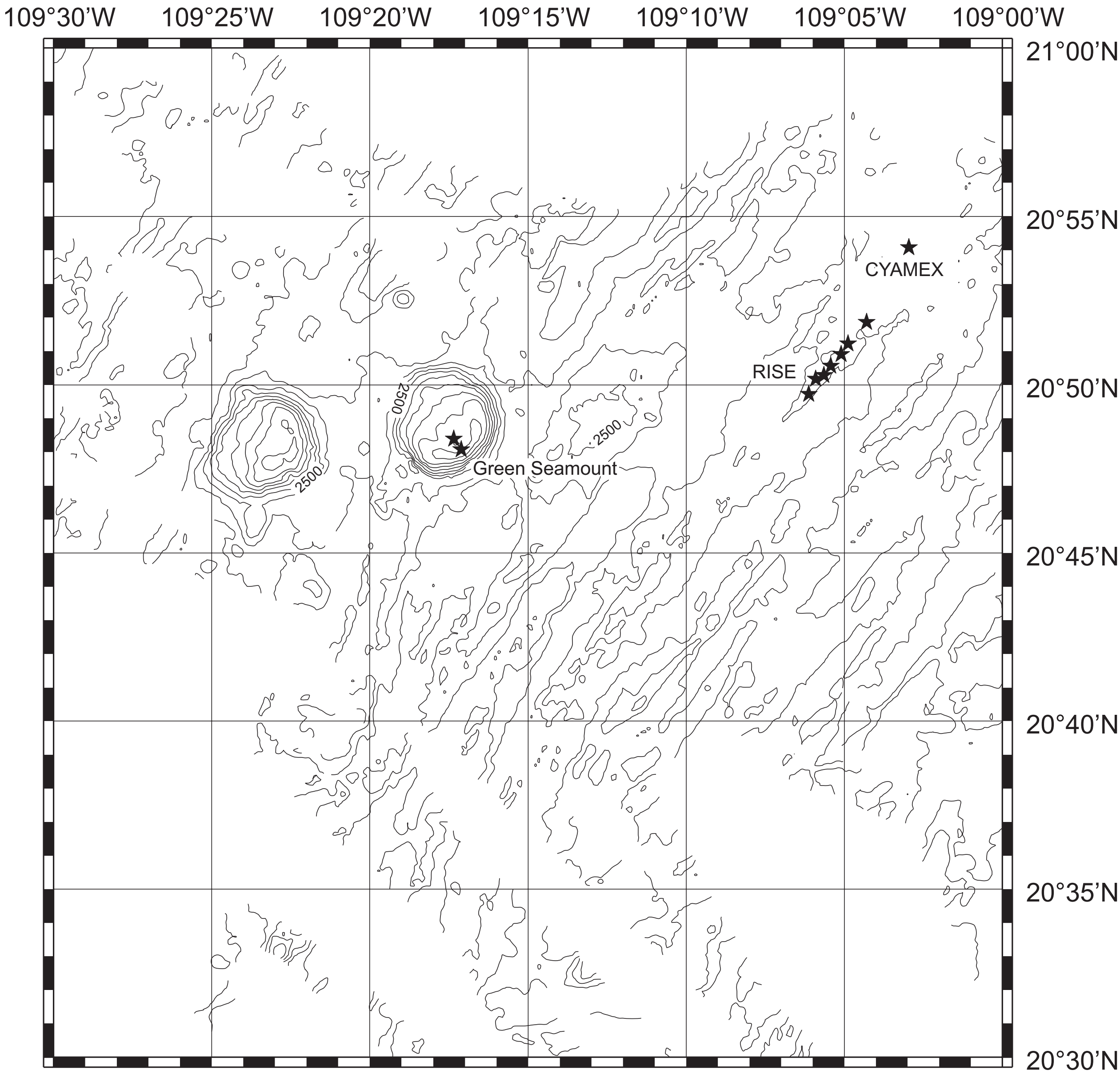
A series of 30 min x 30 min maps showing examples of 100 m contour intervals in selected areas where detailed bathymetric information is available. The data shown here are from the National Geophysical Data Center inventory of multibeam bathymetry (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html). These maps can be used to significantly reduce the initial size of a permissive area, but the data are not available for all parts of oceans.

Bathymetry of sulfide occurrences near 11°50’N and at the 87D-D1 and 87D-C Seamounts



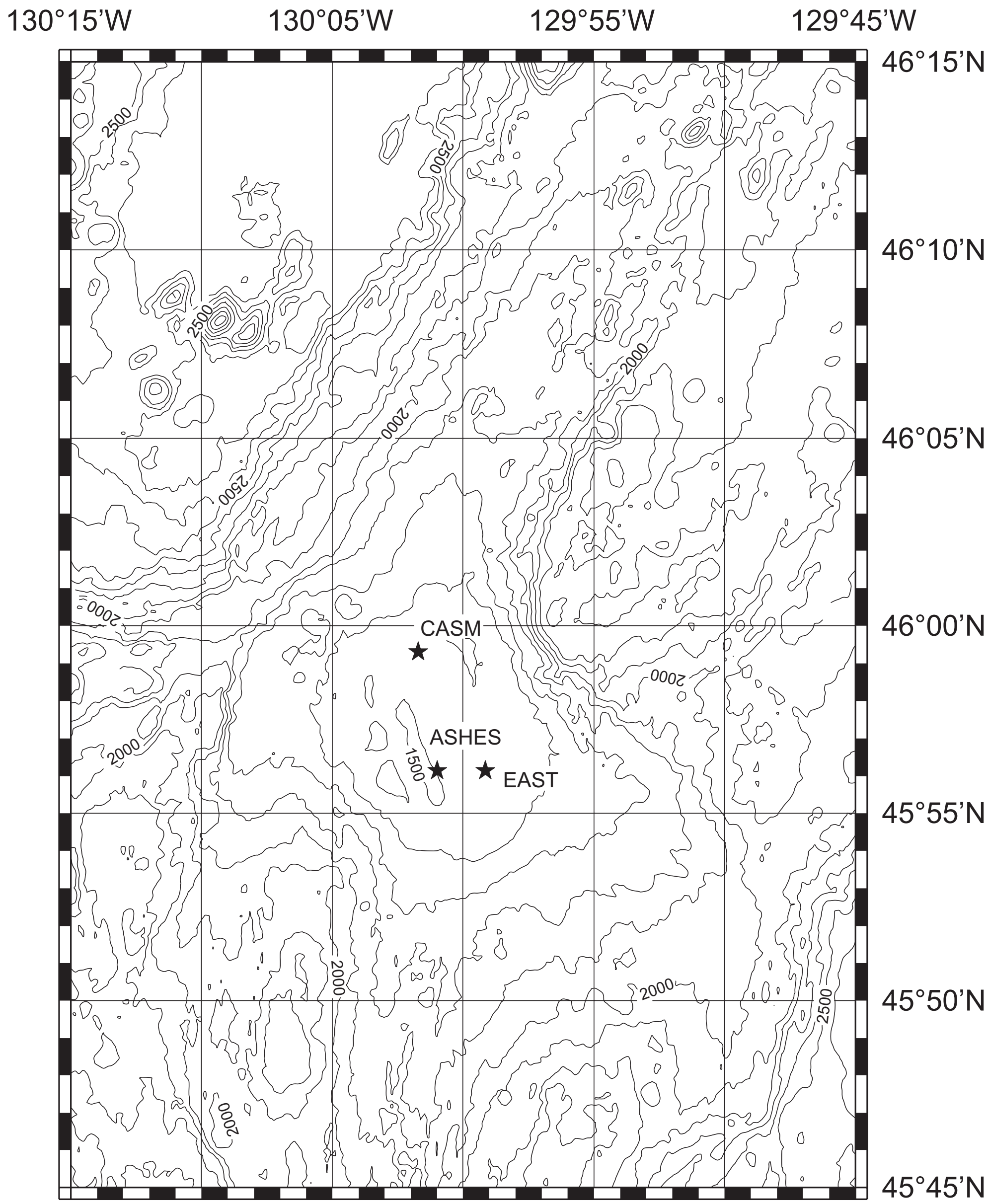
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
87D-D1 Seamount at 11°31.8’N, 103°33.0’W (Kuriyama et al., 1994)
87D-C Seamount at 11°29.5’N, 103°52.5’W (Kuriyama et al., 1994)
11°50’N Site between 11°44.5’ to 11°47’N, 103°47’W (Ballard et al., 1988)

Bathymetry of the CYAMEX and RISE Fields and the sulfide occurrences at Green Seamount



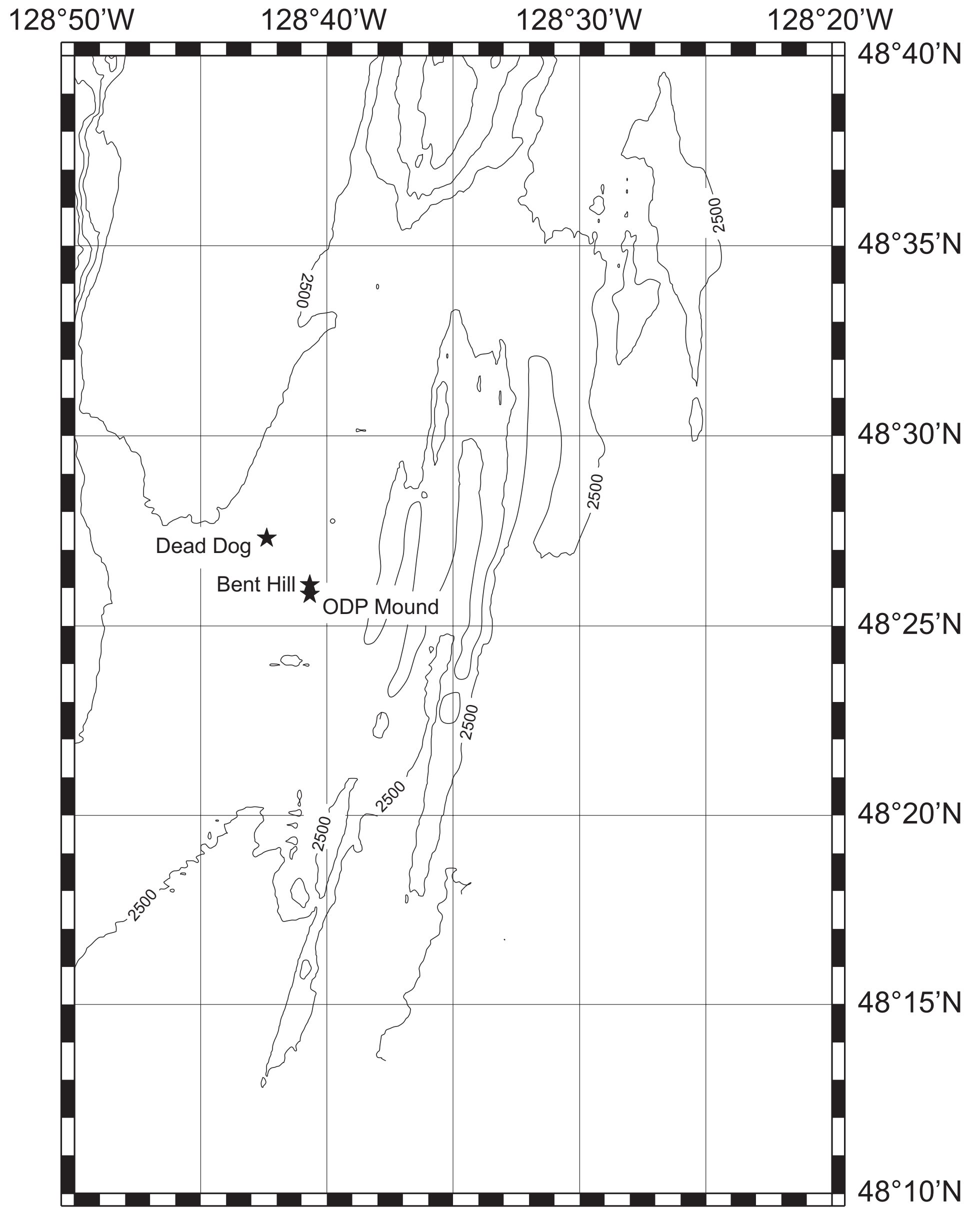
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
Green Seamount at 20°48'N, 109°17'W (Alt, 1988)
CYAMEX Field at 20°54'N, 109°03'W (Hekinian et al., 1980)
RISE Field at 20°49.5' to 20°52'N, 109°04.5' to 109°06'W (Spiess et al., 1980)

Bathymetry of sulfide occurrences at Axial Seamount



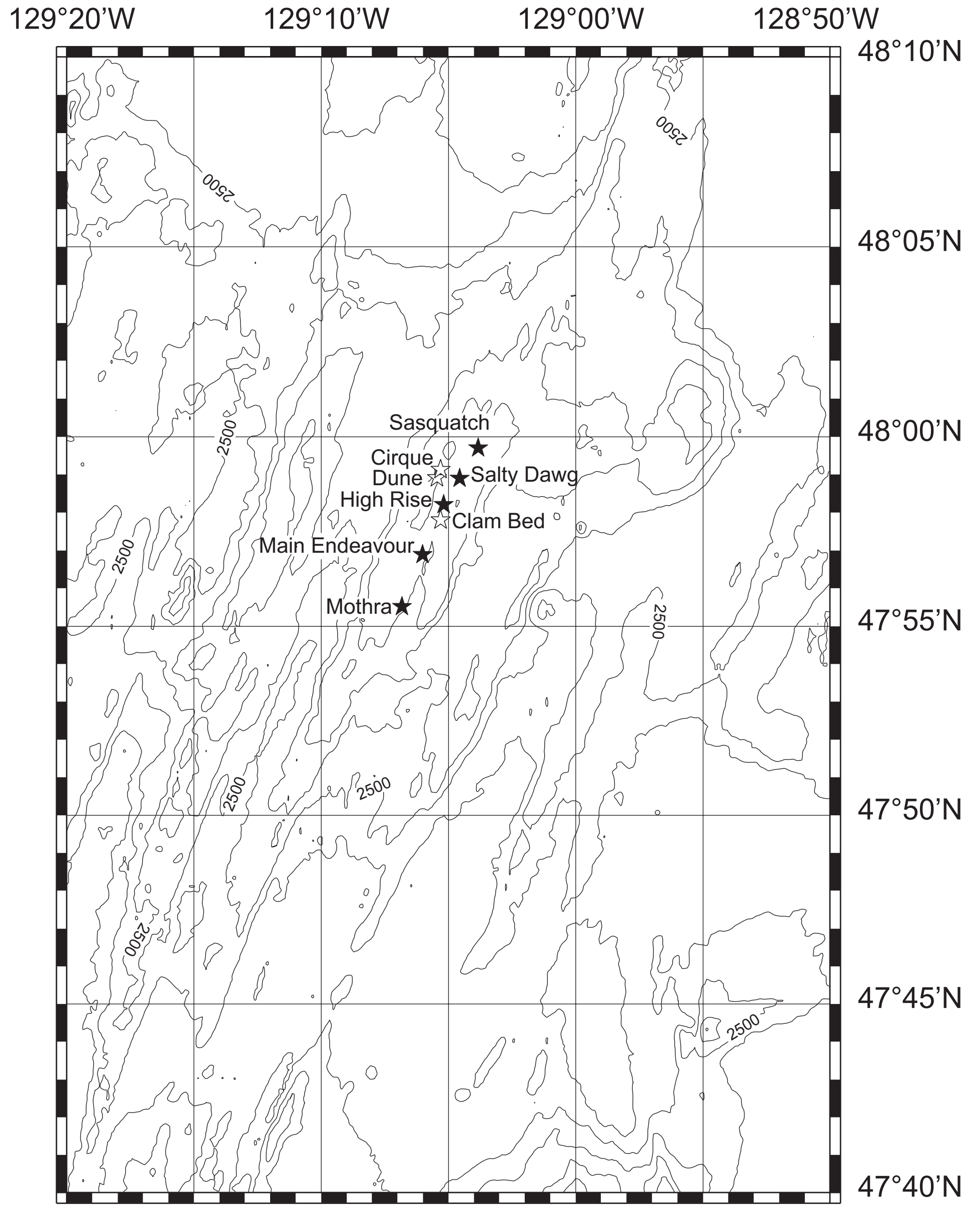
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
CASM Field at 54°59.4'N, 130°01.8'W (Embley et al., 1991)
ASHES Field at 45°56.0'N, 130°00.9'W (Embley et al., 1991)
EAST Field at 45°56'N, 129°59.0'W (Embley et al., 1991)

Bathymetry of the Middle Valley Field



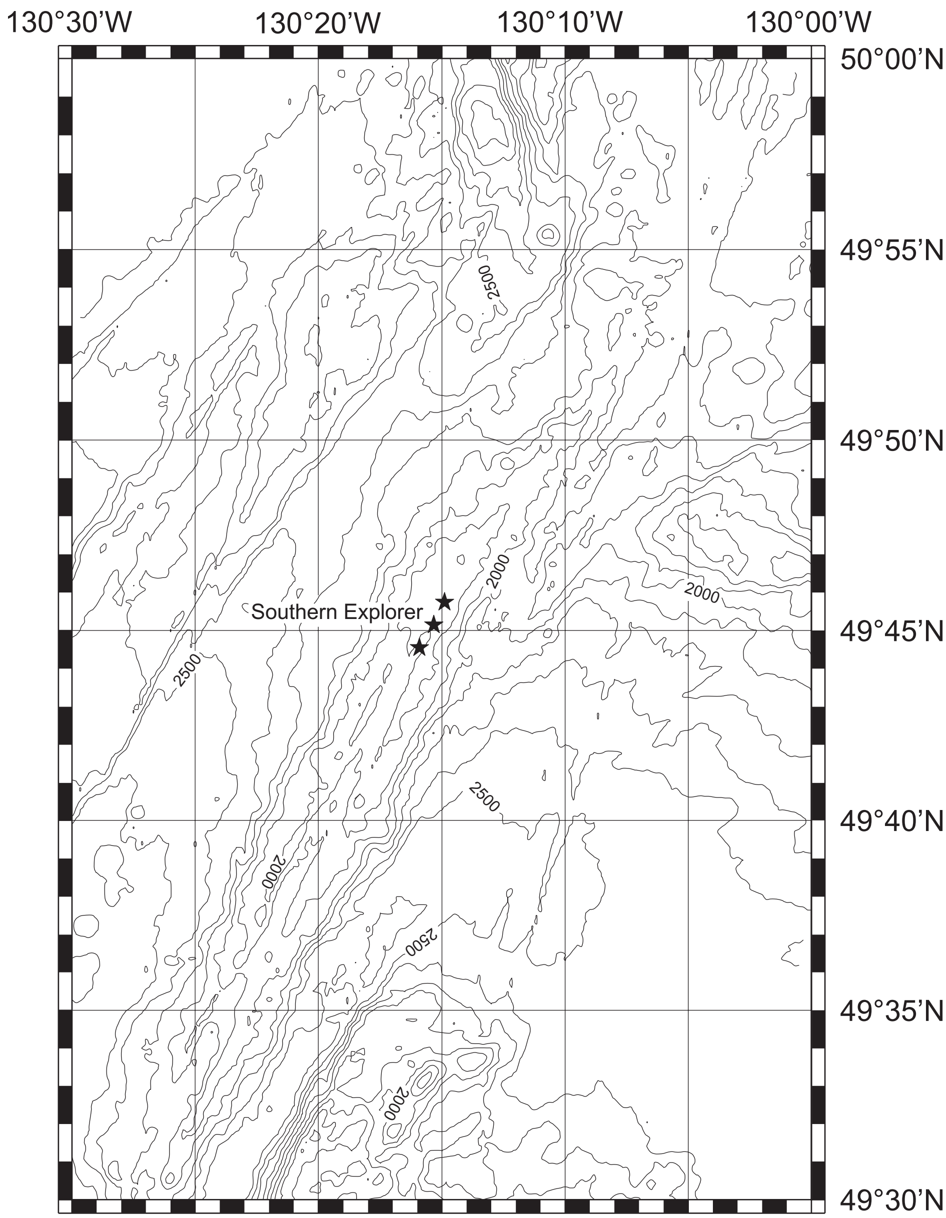
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
Dead Dog at 48°27.5'N, 128°42.5'W (Fouquet et al., 1998)
Bent Hill at 48°26.3'N, 128°40.8'W (Fouquet et al., 1998)
ODP Mound at 48°25.8'N, 128°40.9'W (Fouquet et al., 1998)

Bathymetry of the Endeavour Field



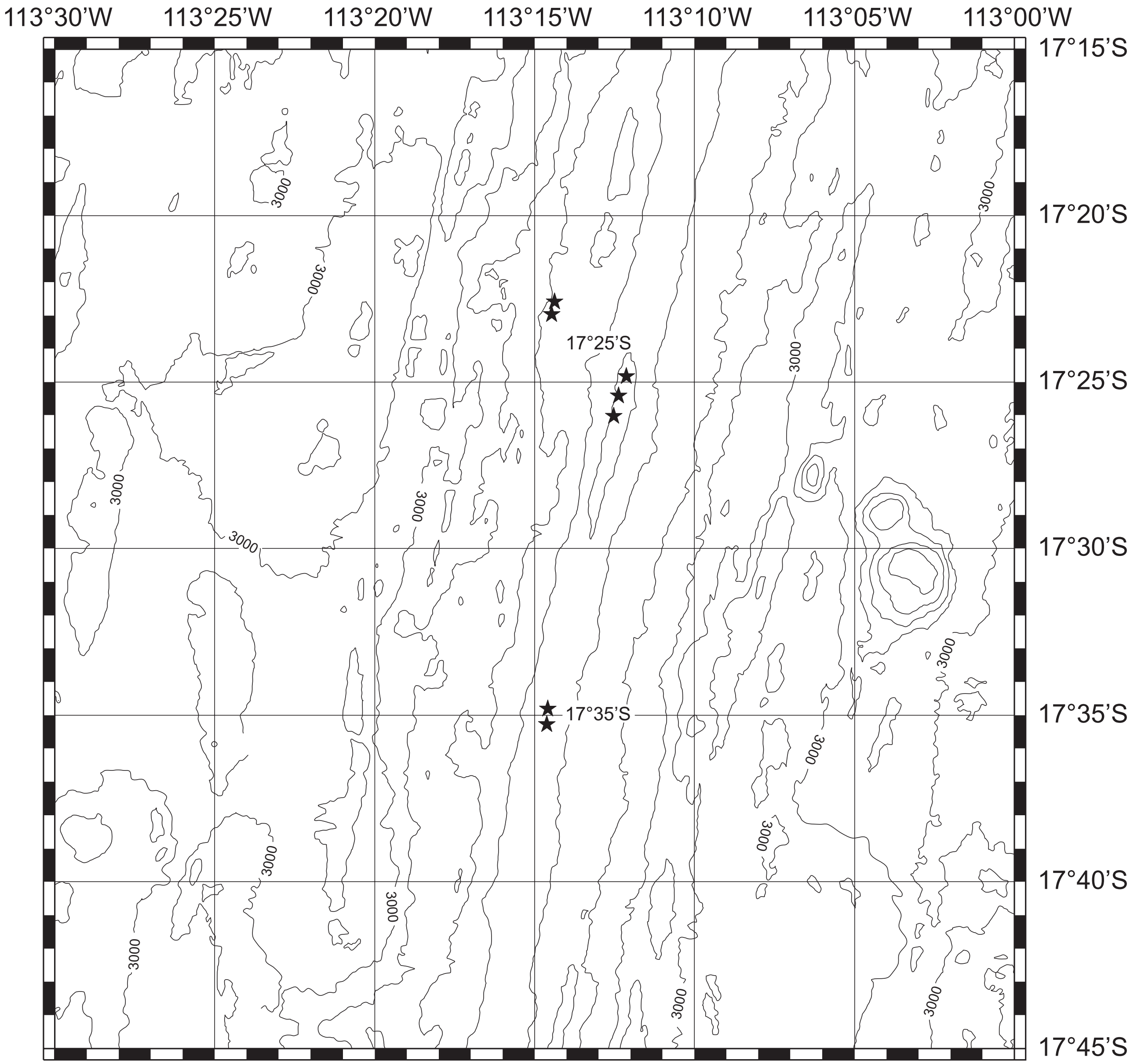
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
Endeavour Field at 47°55' to 48°00'N, 129°03' to 129°07'W
(Delaney et al., 1992)

Bathymetry of the Southern Explorer Field



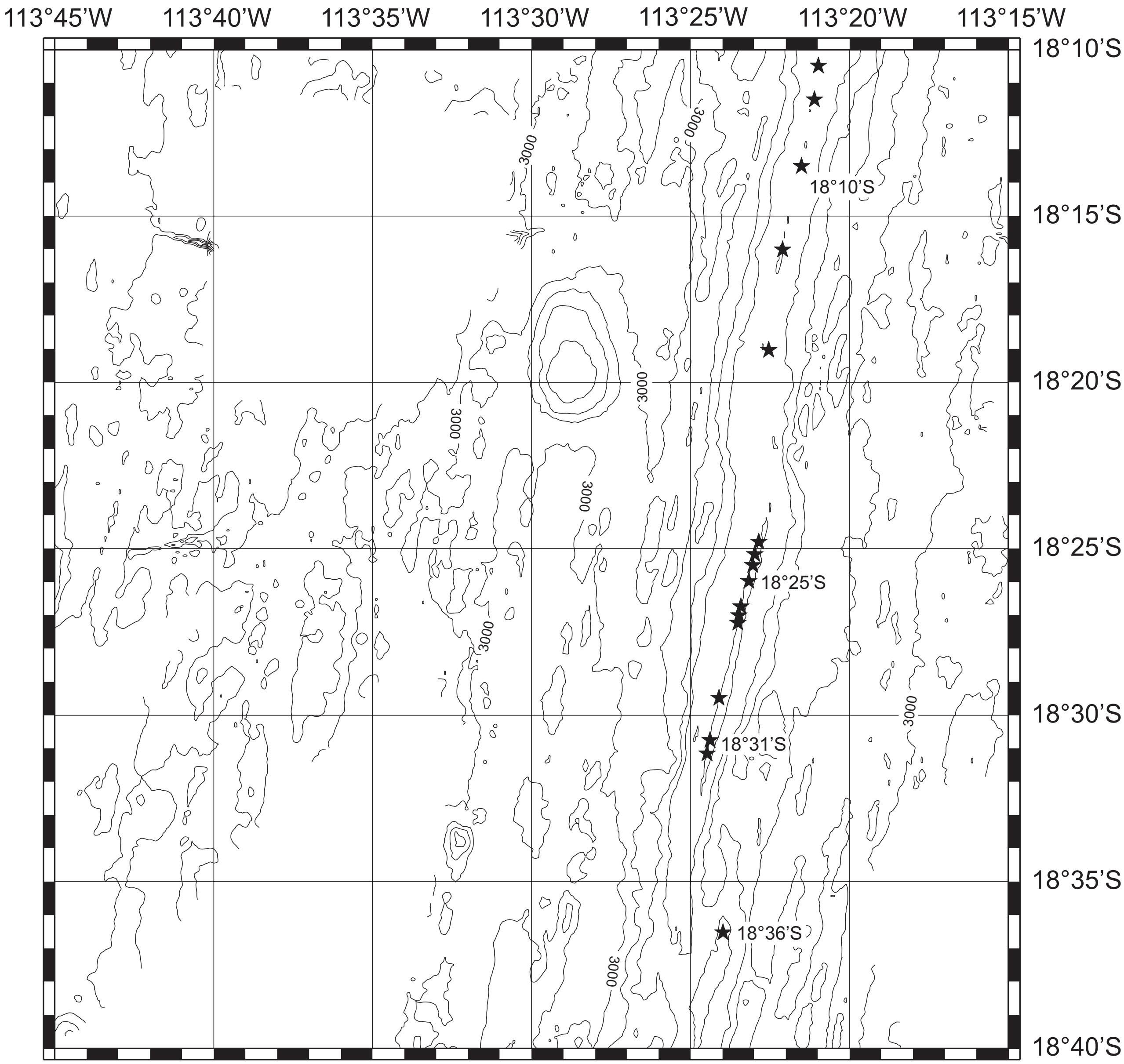
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
Southern Explorer Field at 49°44' to 49°46'N, 130°14' to 130°16'W
(Tunicliffe et al., 1986; Scott et al., 1990)

Bathymetry of the sulfide occurrences at 17°25'S and 17°35'S



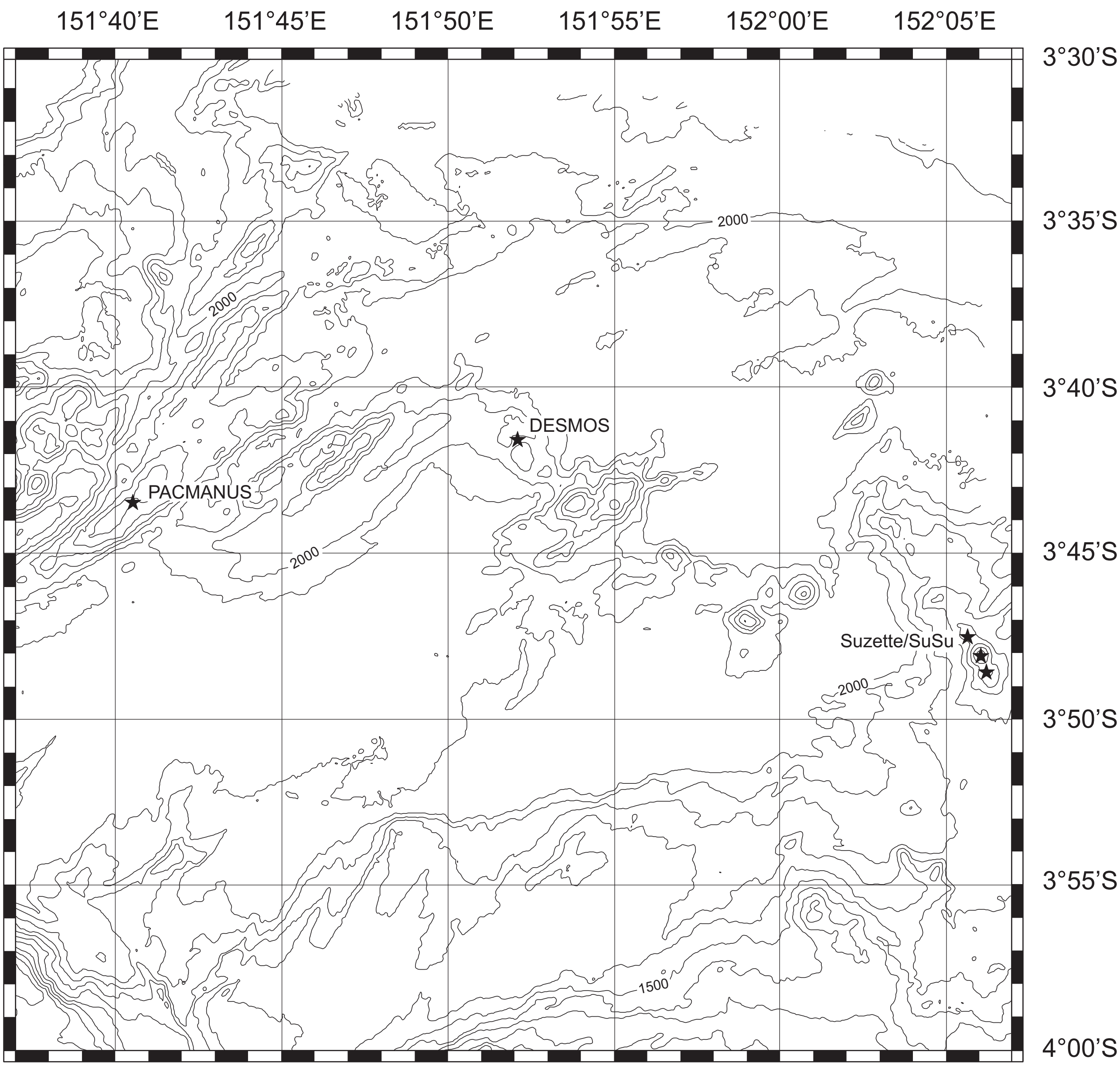
Mercator Projection
Data: NOAA Multibeam Bathymetry Database
17°25'S Zone at 17°22.5' to 17°26'S, 113°12.1' to 113°14.5'W (Renard et al., 1985; Auzende et al., 1994; Jollivet et al., 2004)
17°35'S Zone at 17°34.9' to 17°35.5'S, 113°14.7 to 113°14.8'W (Jollivet et al., 2004)

Bathymetry of the sulfide occurrences near 18°10’S, 18°25’S, 18°31’S, and 18°36’S



Mercator Projection
Data: NOAA Multibeam Bathymetry Database
18°10’S Zone at 18°10.5’ to 18°11.5’ S, 113°21’W, at 18°13.5’S, 113°21.5’W, at 18°16’S, 113°22’W, and at 18°19’S, 113°22.5’W (Auzende et al., 1994)
18°25’S Zone at 18°24.8’ to 18°27.6’S, 113°23.5’ to 113°24.0’W (Marchig et al., 1988; Auzende et al., 1994)
18°31’S Zone at 18°29.5’ to 18°31.3’S, 113°24.5’ to 113°25’W (Renard et al., 1985; Bäcker et al., 1985; Marchig et al., 1988; Auzende et al., 1994)
18°36’S Zone at 18°36.5’S, 113°24.0’W (Jollivet et al., 2004)

Bathymetry of the sulfide occurrences at PACMANUS, DESMOS, and Suzette/SuSu Knolls



Mercator Projection
Data: Multibeam Bathymetry from Auzende et al. (2002)
PACMANUS Field at 3°43.5'S, 151°40.3'E (Binns et al., 2002)
DESMOS at 3°41.5'S, 151°52'E (Gena et al., 2001)
Suzette/SuSu at 3°47' to 3°49'S, 152°05.5' to 152°06.5'E (Binns et al., 2004)