Hydrothermal exploration of mid-ocean ridges: Where might the largest sulfide deposits be forming?

Christopher R German[1*], Sven Petersen[2] & Mark D. Hannington[2,3]

[1]Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

[2]GEOMAR Helmholtz Centre for Ocean Research, 24148 Kiel, Germany

[3]Earth & Environmental Sciences, University of Ottawa, K1N 6N5 Ottawa, Canada

*corresponding author: cgerman@whoi.edu
MS#22 WHOI, Woods Hole Road
Woods Hole MA 02543, USA
Tel: 508-289-2853
Fax: 508-457-2150

Abstract

Here, we review the relationship between the distribution of modern-day seafloor hydrothermal activity along the global mid-ocean ridge crest and the nature of the mineral deposits being formed at those sites. Since the first discovery of seafloor venting, a sustained body of exploration has now prospected for one form of hydrothermal activity in particular – high temperature “black smoker” venting - along >30% of the global mid ocean ridge crest. While that still leaves most of that ~60,000km continuous network to be explored, some important trends have already emerged. First, it is now known that submarine venting can occur along all mid-ocean ridges, regardless of spreading rate, and in all ocean basins. Further, to a first approximation, the abundance of currently active venting, as deduced from water column plume signals, can be scaled linearly with seafloor spreading rate (a simple proxy for magmatic heat-flux). What can also be recognized, however, is that there is an “excess” of high temperature venting along slow and ultra-slow spreading ridges when compared to what was originally predicted from seafloor spreading / magmatic heat-budget models. An examination of hydrothermal systems tracked to source on the slow spreading Mid Atlantic Ridge reveals that no more than half of the sites responsible for the “black smoker” plume signals observed in the overlying water column are associated with magmatic systems comparable to those known from fast-spreading ridges. The other half of all currently known active high-temperature submarine systems on the Mid-Atlantic Ridge are hosted under tectonic control. These systems appear both to be longer-lived than, and to give rise to much larger sulfide deposits than, their magmatic counterparts - presumably as a result of sustained fluid flow. A majority of these tectonic-hosted systems also involve water-rock interaction with ultramafic sources. Importantly, from a mineral resource perspective, this subset of tectonic-hosted vent-sites also represents the only actively-forming seafloor massive sulfide deposits on mid-ocean ridges that exhibit high concentrations of Cu and Au in their surface samples (>10wt.% average Cu content and >3ppm average Au). Along ultraslow-spreading ridges,

first detailed examinations of hydrothermally active sites suggest that sulfide deposit formation at those sites may depart even further from the spreading-rate model than slow-spreading ridges do. Hydrothermal plume distributions along ultraslow ridges follow the same (~50:50) distribution of "black smoker" plume signals between magmatic and tectonics settings as the slow spreading MAR. However, the first three "black smoker" sites tracked to source on any ultra-slow ridges have all revealed high temperature vent-sites that host large polymetallic sulfide deposits in both magmatic as well as tectonic settings. Further, deposits in both types of setting have now been revealed to exhibit moderate to high concentrations of Cu and Au, respectively. An important implication is that ultra-slow ridges may represent the strongest mineral resource potential for the global ridge crest, despite being host to the lowest magmatic heat budget.

Keywords

Hydrothermal Activity; Seafloor Massive Sulfides; Mid-Ocean Ridges; Exploration; Copper; Gold

Highlights

• On slow spreading ridges, a higher proportion of active "black smoker" systems host large seafloor massive sulfide deposits than they do on fast-spreading ridges.

• The largest seafloor massive sulfide deposits found on slow spreading ridges are associated, typically, with long-lived tectonic fracturing, presumably as a result of sustained fluid flow.

• Among active, tectonic-hosted vent-sites on the Mid-Atlantic Ridge, those that also involve water-rock interactions with ultramafic rocks yield the highest average Cu (>10wt.%) and Au (>3ppm) contents in surficial sulfide samples.

• Distributions of hydrothermal plume signals over ultra-slow spreading ridges (with the exception of the Gakkel Ridge) appear to show the same ~50:50 distributions between magmatic and tectonic control that is seen for the slow-spreading Mid-Atlantic Ridge.

• Along ultra-slow ridges preliminary observations from the first three "black smoker" vent-sites tracked to source indicate that both magmatic and tectonic systems can give rise to large seafloor massive sulfide deposits that are also anomalously enriched in Cu and/or Au.

1. Introduction

Nearly 40 years after the first discovery of seafloor hydrothermal venting and associated massive sulfide deposits at mid-ocean ridges (Corliss et al., 1979; Francheteau et al., 1979; Spiess et al., 1980), high temperature "black smoker" hydrothermal systems are now known to occur in all ocean basins and along mid-ocean ridges of all spreading rates (German & Seyfried, 2014). Close to 300 high-temperature "black smoker" hydrothermal fields are already known along the ~60,000km of the global Mid Ocean Ridge (MOR) system of which 113 have been visually confirmed and a further 159 have been inferred from systematic water column plume surveys (Beaulieu et al., 2013). Statistical interrogation of the global InterRidge vents data-base allows us to predict that a further ~800 MOR vent-sites remain to be discovered, predominantly along slow-spreading ridges (defined as < 55 mm/yr full spreading rate; Beaulieu et al., 2015).

Our current state of knowledge (Fig. 1) has been attained through a concerted effort to explore systematically along the global ridge crest, first to understand what geological processes might control the global distribution of such high-temperature venting (e.g. Baker et al., 1996; German et al., 1996) and later augmented with further questions concerning what controls the biogeography of endemic vent fauna (e.g. Van Dover et al., 2002; German et al., 2011). As a result, approximately decadal reviews of the current state of the art, as embedded in the global InterRidge vents database, have allowed us to progress from knowledge of vent-distributions along less than 10% of the global system to more than 30% of the ~60,000km mid-ocean ridge crest having been surveyed (Baker et al., 1995; Baker & German, 2004; Beaulieu et al., 2015).

An important consideration concerning how our understanding of the global distribution of ridge-crest venting has progressed over the past 3 decades is that we have explored, primarily, for one specific form of hydrothermal activity – the high temperature fluid flow that is emitted from "black smoker" vents and results in characteristic particle-laden plumes that can be detected readily from water column surveys using CTD-rosette systems or, increasingly, using purposefully designed MAPR instruments that have revolutionized the international community's ability to explore for hydrothermal activity in parallel with co-registered petrologic and geophysical investigations (Baker et al., 2010). In this paper we combine insights obtained from two sources: (a) our progressively expanding understanding of hydrothermal vent distributions as determined from hydrothermal plume surveys and (b) direct field observations of active high-temperature hydrothermal fields that have been tracked to source beneath such plumes, along slow- and ultraslow-spreading ridges.

An important goal, in conducting this review, has been to investigate to what extent future predictions could be made, from hydrothermal plume studies alone, about the nature of any underlying vent-sources and, specifically, about the size and characteristics of the seafloor massive sulfide deposits that they might form. Recognizing that styles of hydrothermal venting exhibit increasing geologic diversity (including the sizes of seafloor massive sulfide deposits) at decreasing spreading rate (e.g. Fouquet et al., 2010; German & Seyfried, 2014) we use the relatively well-studied slow-spreading central Mid-Atlantic Ridge (8°S-45°N) as a test case for these studies. A key motivation is to be able to predict what might await discovery based on hydrothermal plume investigations elsewhere along slow and ultra-slow spreading ridges. Each of these classes of spreading rate represent ~25% of the cumulative length of the global Mid-Ocean Ridge system and it is along these slow- or ultra-slow spreading ridges, recent studies have predicted, that the majority of both seafloor massive sulfide deposits and active hydrothermal fields remain to be discovered (Hannington et al., 2011; Beaulieu et al., 2015).

Before proceeding further with this review, however, it is important to point out what is *outside* the scope of our considerations. First, we only consider the inter-relationship between hydrothermal plume distributions and SMS-forming high-temperature vent-sites along the global mid-ocean ridge system. We do not consider arc or back-arc systems in this review even though back-arcs have also been explored for more than 30% of their cumulative length (de Ronde et al., 2007, 2012; Monecke et al., 2014). Those systems have received much exploration activity in the past decade, largely due to commercial interests, along sections of seafloor volcanism that lie within the national jurisdiction of various coastal nation states (Beaulieu et al., 2013). By contrast, this paper focuses upon the slow-spreading end of the global mid ocean ridge spectrum that lies extensively within The Area (i.e. within waters beyond national jurisdiction) and where it is predicted that the majority of seafloor massive sulfides and active hydrothermal systems remain to be discovered. Further, along those mid ocean ridge crests, we only consider those sites that currently host active high-temperature venting (Beaulieu et al., 2015) *and* for which information on seafloor massive sulfide deposits is available (Hannington et al., 2005; Petersen et al., *unpubl. data*). We do this because, while other forms of predictive modeling most certainly exist, the approach followed here can only be validated from a consideration of seafloor massive sulfide sites that generate a modern day plume signal that is detectable from water-column surveys. Consequently, our review does not consider extinct seafloor massive sulfide deposits. Nor does it include known low-temperature vent-sites, such as those found at Lost City, Saldanha or Von Damm because (a) there is no indication that those sites give rise to seafloor massive sulfide (SMS) deposits and/or (b) none of those sites give rise to particle laden hydrothermal plumes that can be detected using optical hydrothermal plume detection techniques (Kelley et al., 2001; Dias & Barriga, 2006; McDermott et al., 2015). A final consideration for the discussions that follow is that, in the near complete absence of volumetric data for the majority of vent-sites, we are forced to rely upon the mapped *areal* extents of all seafloor massive sulfide deposits for size inter-comparisons even though we recognize that vent-fields of similar areal extent may host very different volumes of SMS deposit.

2. Global distributions of venting based on hydrothermal plume surveys.

In a highly influential early paper, Baker et al. (1996) noted a close correlation, from surveys along the Juan de Fuca Ridge and the northern and southern East

Pacific Rise, between the incidence of hydrothermal plume detection along a given section of ridge-crest and the full spreading rate of the underlying seafloor. The same correlation, it was argued, could also be applied to preliminary investigations from the slow-spreading Mid-Atlantic Ridge with hydrothermal plume activity predicted to reduce to zero at zero spreading rate. Independently, however, German & Parson (1998) noted that the distributions of hydrothermal plume signals varied markedly along three separate sections of the northern Mid-Atlantic Ridge, all of which exhibited very similar spreading rates, apparently as a result of variations in geologic setting (magmatic vs tectonic dominated seafloor) along-axis. While averaging of all three systems to generate a single average value for plume activity at this spreading rate fit well to the original linear "spreading rate" model (Baker & German, 2004) what was also recognized was that the incidence of high-temperature hydrothermal activity tends to be suppressed in close proximity to ridge-hot-spot interactions, presumably due to increased plastic rather than brittle deformation in the over-thickened crust (Phipps Morgan & Chen, 1993; German et al., 1994; see also discussion in Baker & German, 2004). Further, continuing surveys along ultra-slow spreading ridges subsequently revealed that additional hydrothermal plume activity, beyond what would have been predicted from spreading rate alone (*sensu* Baker et al., 1996) was not only observed along some sections of slow-spreading mid-ocean ridges (German et al., 1996) but also along ultra-slow ridges as well (German et al., 1998; Bach et al., 2002; Edmonds et al., 2003; Baker et al., 2004).

This "excess" of venting at Earth's slow and ultra-slow spreading ridges remains readily apparent in the latest synthesis of global ridge-crest vent distributions (Beaulieu et al., 2015). In Fig.2, all the data from the InterRidge vents data base that has been collected away from any hot-spot influence have been binned into five categories: ultraslow (0-20mm/yr full spreading rate), slow (20-55mm/yr), intermediate (55-80mm/yr), fast (80-140mm/yr), and superfast, (>140mm/yr) spreading rates. The resulting linear fit to the data both resembles but also exhibits significant departure from the original "spreading rate" model of Baker et al., (1996): the slope of the best-fit correlation is now shallower and the trend no longer predicts a zero incidence of hydrothermal vent activity at zero spreading rate (i.e. sustained hydrothermal venting despite zero magmatic heat flux). Figure 3 shows a directly related plot for the slow- and ultraslow-spreading ridge survey data (full spreading rates <55mm/yr) that were used to generate the single average values for slow and ultra-slow mid ocean ridges shown (with corresponding ranges of uncertainty) in Fig.2. Here, we argue that these data *can* be fit to a single, global, linear trend but that an alternate representation would be to consider the same data as two separate classes: those for which the frequency of venting could already be predicted from magmatic heat budget alone, using the original model of Baker et al. (1996) and those for which an additional cause of seafloor hydrothermal venting is required. In the latter case, our interpretation of the data would be that magmatically-controlled venting would, indeed, decrease to zero at zero spreading rate (no magmatic heat budget) but that, at spreading rates of < 40mm/yr (which corresponds to ~50% of the cumulative length of all mid-ocean ridges: Sinha & Evans, 2004), there is also evidence for “excess” hydrothermal vent-activity beyond what would be predicted from “typical” seafloor spreading.

3. Hydrothermal Vent-Sites on the Mid-Atlantic Ridge, 8°S to 45°N.

To investigate the concepts discussed above in more detail, we have conducted a systematic review of what is known from the slow-spreading Mid-Atlantic Ridge (8°S-45°N) which includes a section of the northern MAR where surveys have revealed a broad range of plume incidences at near constant spreading rates: MAR 11-21°N, 27-30°N and 36-38°N (Fig.3). In this region, since the first direct observations of the TAG hydrothermal field in 1985 (Rona et al., 1986), a total of 19 high temperature hydrothermal fields are now known along > 5000km of slow spreading ridge axis (Table 1). A first important characteristic to consider is the extent to which each of these vent-sites is hosted in a magmatic- or tectonic-controlled setting.

Many of the vent-sites that have been located on the Mid-Atlantic Ridge are in settings which, at the scale of the individual vent-field, are not readily distinguishable from those hosted by recent neo-volcanic activity on a fast-spreading ridge such as the East Pacific Rise. For example, the Turtle Pits vent-site at 4°49'S on the Mid-Atlantic Ridge (Fig.4) is situated along an axial high toward the center of a second order ridge-segment and, further, is set within an area of ~18km^2 of fresh sheet flows directly comparable in extent to the most recent lava flows at 9°50'N on the East Pacific Rise (Soule et al., 2007; German et al., 2008). When mapped out in detail by ROV, the full extent of venting at Turtle Pits was found to occur in the form of just a few discrete high-temperature sulfide structures that extended over an area of no greater than ~1000m^2 (Haase et al., 2007). While not all magmatic-hosted MAR hydrothermal systems are hosted by such fresh, recent lava flows, the general pattern *does* recur further north within this study area where multiple other systems located toward the centers of second-order ridge-segments are also hosted in young volcanic rocks and, further, yield seafloor massive sulfide deposits of no greater than 3000m^2. Examples of magmatic-hosted high temperature vent-sites that fit to this general pattern are the Comfortless Cove and Red Lion sites on the southern MAR (Haase et al., 2007) and the SnakePit (Gente et al., 1991), Broken Spur (Murton et al., 1995), Bubbylon (Marcon et al., 2013) and Menez Gwen (Ondréas et al., 1997) vent systems on the northern MAR (Table 1).

In contrast to the magmatic vent sites described above, a second class of hydrothermal field has also been recognized along the slow-spreading Mid-Atlantic Ridge, illustrated here by the Rainbow system at 36°14'N (Fig.5). There, deep penetrating faults rather than recently emplaced volcanism represent the dominant geologically controlling feature observed from detailed seafloor investigations. In some cases, including at Rainbow, these faulted systems coincide with the non-transform discontinuities between adjacent second order ridge segments (Gracia et al., 2000). In other cases, tectonics-controlled systems can occur toward the centers of ridge segments, directly associated with the rift-valley walls, as seen at the TAG hydrothermal field (de Martin et al., 2007). Many tectonic systems, including both TAG and Rainbow, are also hosted by long-lived detachment faults which, in a subset of circumstances, can lead to core complex formation, the exhumation of ultramafic rocks and/or the involvement of serpentinization reactions within the hydrothermal circulation cell, beneath the seafloor (Fouquet et al., 2010). Vent sites within this category are often much larger than those found in magmatic settings (Table 1). At Rainbow, for example, a total of 10 discrete sites of high temperature venting and an even higher number of extinct chimneys have been observed aligned West to East (orthogonal to the trend of the plate boundary between the North American and Eurasian plates at this latitude) over more than 200m along strike, yielding a seafloor massive sulfide deposit that, in areal extent, is close to 30,000m^2 (Fig. 5).

In these tectonic "black smoker" systems, it is generally considered that the circulating hydrothermal cell must still be driven by a magmatic (gabbroic-composition) heat source at depth to account for the nature of the high-temperature vent fluids analyzed (Gallant & Von Damm, 2006; Seyfried et al., 2011). The key to providing access to that heat in tectonic settings, however, is through deep-penetrating faulting (e.g. Gracia et al., 2000) including, for at least a subset of all such sites, long-lived detachment faults (Cannat et al., 2010). Indeed, even in the most peridotite-rich oceanic core complexes studied to-date (e.g. Schoolmeesters et al., 2012), gabbroic rocks indicative of frozen basaltic melts, are also found to be present. In such settings, it has been proposed that the contact between shallow crust and deeper crust/mantle lithologies across the detachment surface may act as a conductive boundary layer (CBL) – directly akin to the role that the dike-gabbro transition plays along fast-spreading ridges – such that detachment faults can act as a conduit for extensive fluid flow (McCaig et al., 2007; McCaig & Harris, 2012). The mechanisms by which such high temperature fluid flow can be sustained along detachment faults, however, over the extended time-scales required to generate seafloor massive sulfide deposits, remains an area of active research. For example, recent seismic studies at the Logatchev hydrothermal field (Grevemeyer et al., 2013) have revealed the presence of an extensional fault underlying the tectonic-controlled Logatchev hydrothermal field that slopes toward the center of the ridge axis at depth, just as has been reported previously for the TAG hydrothermal field (de Martin et al., 2007). While this indicates that the required pathways for fluid circulation most certainly exist, however, subsequent modeling has shown that such fault systems can only support high temperature venting if a specific range of conditions are also met (Andersen et al., 2015). If fault “transmissivity” (a combination of fault width and permeability contrast) is too high then extensive mixing will occur subsurface and only low-temperature (metal-poor) hydrothermal fluids will exit the seafloor. Conversely, if the fault transmissivity is too low then the fault in question will fail to “capture” the hydrothermal circulation cell and deflect it off-axis such that sustained tectonic-controlled venting away from the neovolcanic ridge-axis (and associated formation of large tectonics-hosted seafloor massive sulfide deposits) will fail to arise.

To a first approximation, then, a general-case working model for the Mid-Atlantic Ridge is one in which magmatic systems – just like those found along fast-spreading ridges – give rise to relatively short-lived venting and small seafloor massive sulfide deposits. By contrast, tectonic-hosted systems have the potential to sustain long-lived fluid flow and correspondingly larger seafloor massive sulfide deposits. There is one important exception to the above rule that has been observed along the Mid-Atlantic Ridge: anomalously large segment-center volcanic systems such as the Lucky Strike vent-site at 37°17’N (Humphris et al., 2002) which, multi-beam bathymetry reveals, hosts a tall volcanic high with a summit that is almost as shallow as the adjacent rift-valley walls (Fig.6). Clearly, this volcanic construct must result from an anomalously extensive and sustained focussing of magma delivery toward the center of this 2nd order ridge-segment which, rarely for a slow-spreading Mid-Atlantic Ridge segment, has also been shown to be underlain by an active magma chamber (Crawford et al., 2010). Hydrothermal venting at this location comprises multiple vent-sites and associated sulfide deposition surrounding a central lava-lake where detailed mapping has revealed that the resulting seafloor massive sulfide deposit is at least 15,000m^2 in extent Humphris et al (2002). This is closer in area to the TAG and Rainbow hydrothermal fields than the more typical magmatic settings described above. With an estimated SMS deposit size closer to 30,000m^2, the Puy de Folles vent-field situated at 20°30'N represents a second areally extensive sulfide deposit associated with a large volcanic edifice (Cherkashov et al., 2010). Caution should be taken when considering the Puy de Folles site, however, for two reasons. First, detailed descriptions of the vent sites are lacking and therefore the size estimate is only an approximation. Second, while the Puy de Folles site is associated with a large volcanic edifice, comparable to Lucky Strike, it does not occur at the center of a 2nd order ridge segment but, instead, is associated with a non-transform offset (Cherkashov et al., 2010), a combination of features that is not observed anywhere else along the slow-spreading Mid-Atlantic Ridge between 8°S and 45°N (Table 1).

Plotting all of the known MAR vent-sites together, along the length of the ridge-axis, what is immediately apparent is that only approximately half of the vent-sites present are associated with magmatic settings while as many are hosted in tectonic settings (Fig.7). From the perspective of past and present syntheses of global vent distribution, we would argue that it is these tectonically-hosted vent sites along the Mid-Atlantic Ridge that may account for the “excess” in hydrothermal plume signals and, hence, inferred abundances of venting that are observed along slow spreading ridges when compared to what was originally predicted based on spreading rate alone. This is readily illustrated by referring back to the plume survey areas A, B and C highlighted in Fig.3. No tectonic hosted systems have been identified in Area B (MAR 27-30°N) where the overlying plume-survey data fit closely to the Baker et al (1996) spreading-rate model for magmatic-controlled venting, only. For Area C (11-21°N) detailed follow-on studies have revealed multiple tectonic-hosted vent-sites with the area

(Table 1) consistent with an excess abundance of hydrothermal plum signals in the overlying water column. For the MAR 36-38N area (Area A), the majority of the plume signals obtained were associated with non-transform discontinuities along this section of ridge-crest (German et al., 1996; Gracia et al., 2000). However, since only one of those plumes has ever been tracked to source, the Rainbow vent-site, the importance of tectonic-hosted venting may still be under-represented in Table 1. If so, this is important because our analysis of seafloor deposits underlying MAR plume-signals has revealed that not all “black smoker” hydrothermal systems are alike. Rather, it is the tectonic hydrothermal fields that host the largest SMS deposits, in terms of areal extent mapped at the seafloor (Fig.8a). Further, it is a subset of those tectonic-hosted systems, alone among all mid-ocean ridge SMS deposits worldwide, that exhibit high concentrations of copper and gold in seafloor sulfide samples with >10wt.% average Cu content and >3ppm average Au content (Fig.8b).

We hypothesize that both the size and content of a tectonic-hosted SMS deposit can be explained from their geologic setting. First, as discussed above, tectonic-hosted vent sites are closely associated with both deep-penetrating and long-lived faults that form the rift-valley walls and non-transform discontinuities of the slow-spreading Mid-Atlantic Ridge. As such, they have the potential to provide access to much larger reservoirs of heat associated with the emplacement of oceanic crust than is likely to be the case at a magmatic system where intrusion of a 1m-wide dike, fed from a shallow underlying magma-chamber might be considered the “quantum” event for seafloor spreading – a mechanism that also restricts fluid penetration to be much shallower (see, e.g., German & Lin, 2004; Lowell et al., 2013). Further, because the host faults are long lived, reactivation of those faults must also offer the potential for extensive (time-integrated) fluid flow along a near-constant pathway, over timescales of thousands of years (Lalou et al., 1995; Cave et al., 2002). Second, when considering the composition of polymetallic sulfides deposited at the seafloor, that subset of tectonic vent-sites that are associated with long-lived detachment faults also have the potential to bring the circulating vent-fluids into contact with ultramafic rocks, at or below the seafloor. These rocks may be an enriched source of Cu and Au that are then released into the hot vent-fluids and, subsequently, deposited in chimneys and surface samples of SMS deposits at the seafloor – a process that could not arise at any intermediate or faster-spreading ridge crest where only basaltic/gabbroic bulk-composition lithologies interact with the circulating seawater (Fouquet et al., 2010). Of course, it is important to remember that high average Cu and Au concentrations are, in most cases, reported for surface samples only and may not be representative for the entire deposit since zone refining processes are known to enrich these metals at the surface. Only a few deposits have been sampled at depth and, as the lone example for a slow-spreading mid-ocean ridge, drilling at the TAG active hydrothermal mound revealed that the interior of the deposit contains considerably less Cu and Au (2.3wt.% Cu and 0.2ppm Au; Hannington et al., 1998) when compared to the surface sample values reported here (Table 1). On the other hand, it is unlikely that the Au enrichment we see at tectonically-controlled sites is solely related to a sampling bias, since no magmatic-controlled site shows an Au-enrichment along the Mid-Atlantic Ridge despite the fact that preferred sampling of chimneys is apparent at all sites included in Table 1.

From our studies of the slow-spreading Mid-Atlantic Ridge, then, two important inferences can be drawn:
i) one should expect a higher incidence of hydrothermal plume signals derived from high-temperature “black smoker“ venting along the ~25% of the global ridge crest that is slow-spreading (20-40mm/yr) than would be predicted from magmatic heat flux alone.
ii) wherever a hydrothermal plume signal on a slow-spreading ridge overlies a tectonic rather than a neo-volcanic seafloor domain, one should expect the SMS deposit at its source to be larger than typical (≥10,000m^2), or exhibit unusually Cu-rich (≥10wt%) and Au-rich (≥3ppm) surficial sulfide samples, or both (Fig.8).

Cumulatively, these inferences – drawn from a consideration of nearly 20 vent-sites along more than 5000km of the Mid-Atlantic Ridge - indicate that slow-spreading ridges might offer significantly greater resource potential, per unit length of ridge axis, than any intermediate or faster spreading sections of mid-ocean ridge. An immediate question that arises, therefore, is: To what extent can the same expectations be applied to the much less extensively explored ultraslow-spreading ridges (0-20mm/yr full spreading rate) which represent a further ~25%, by length, of the global ridge crest?

4. Hydrothermal Vent-Sites on Ultraslow-Spreading Ridges.

Hydrothermal plume distributions along ultraslow ridges were reviewed previously by Baker et al. (2004) and concluded to exhibit much higher efficiency than faster spreading ridges in sustaining high-temperature venting, per unit ridge-length, when normalized to basaltic magma supply rates. Along the South West Indian Ridge (SWIR) between 58-66°E, German et al. (1998) noted that half of all plume signals identified from hydrothermal plume surveys co-registered with deep-tow side-scan characterization of the underlying seafloor were associated with magmatic domains and an equal amount were hosted in tectonically dominated settings. This reflected the same distribution as identified, on a like-for-like basis, for the slow-spreading Mid-Atlantic Ridge at 36-38°N (German et al., 1996). Elsewhere, along the SWIR at 10-23°E, Bach et al (2002) used a different approach, conducting hydrothermal plume surveys in concert with seafloor petrologic sampling. In that study, which collected plume survey data through a series of near-vertical rock sampling casts rather than a continuous along-axis survey, it was routinely possible to identify the host-rock lithology at each station as well as the absence or presence of active "black smoker" hydrothermal plumes. While plume signals coincident with ultramafic lithologies were twice as abundant as those that coincided with basaltic lithologies in that study (Bach et al., 2002), a more conservative approach is to consider the proportions of plume signals that coincided with both host-rock identification *and* the identification of polymetallic sulfide deposits in the seafloor samples. We prefer this approach because the latter can be interpreted as evidence of proximity to the “black smoker” source and, hence, precludes the possibility of aliaising the data by “double counting” interception of the same dispersing plume at multiple adjacent rock-sampling stations. If we re-analyze the Bach et al. (2002) data-set using those criteria, we calculate that distributions become closer to the 50:50 partitioning between tectonic and magmatic control reported from the Mid-Atlantic Ridge (Section 3). Unlike the SW Indian Ridge, survey work conducted along the Gakkel Ridge (Edmonds et al., 2003) revealed a quite different pattern. There, hydrothermal plume signals were pervasive along ~1100km of ridge-axis but, when multiple interceptions of the same plume were accounted for, the same data resolved down to compelling evidence for no more than 9 discrete vent-sources. Of these, three sources in the Western Volcanic Zone and four sources in the Eastern Volcanic Zone were attributed to being hosted by basaltic mounds or crusts while the remaining two sites were situated in the central Sparsely Magmatic Zone where the spatial resolution possible from hydrothermal plume surveys in the ice-covered Arctic ocean meant that the precise geologic setting for venting at the seafloor remains unclear (Baker et al., 2004).

Hydrothermal plume surveys had proven, before the end of the last century, that ultra-slow ridges could host high-temperature venting. But it is only now that the first detailed seafloor investigations of any source “black smoker” vent-sites have been conducted (Table 2). To-date, three such discoveries have been reported: at 49°39’E on the SWIR (Tao et al., 2012), at 73°33’N, 08°09’E on the Mohns Ridge (Pedersen et al., 2010) and at 18°33’N on the Mid Cayman Rise (Kinsey & German, 2013). At the 49°39’E SWIR site, active venting is situated close to the non-transform discontinuity between two adjacent second order ridge segments exhibiting high topography and relatively thin crust – a typical example of what, on the MAR, would be assigned to a tectonically-hosted vent-site. Consistent with that, a detailed 5m-altitude photo-mosaic survey of the active hydrothermal field using the ABE autonomous underwater vehicle has allowed us to map an extensive area of ~10,000m^2 in which seafloor massive sulfides have been imaged continuously and which also hosts multiple point sources of active "black smoker" venting (Fig.9). This deposit is directly similar, in size, to the large tectonically hosted systems reported previously from the Mid-Atlantic Ridge (Table 1).

The Loki's castle hydrothermal field (73°33'N, 08°09'E) is located in the easternmost segment of the Mohns Ridge, immediately adjacent to the southern limit of the Knipovich Ridge, which is also ultraslow-spreading (Pedersen et al., 2010). There, high temperature venting issues from four active black smoker systems all located along, and close to the summit of, an axial volcanic ridge that extends for ~30km along axis (Fig. 10). When compared to previously investigated sites along the Mid-Atlantic Ridge, the geologic setting for this site corresponds most closely to the Snake Pit and Broken Spur hydrothermal fields (Table 1). What is particularly unusual about this site, therefore, is the recognition that seafloor massive sulfides associated with the venting extend across a much wider area than has been identified at other, similar, magmatic-hosted vent settings (Pedersen et al., 2010). At Loki's Castle, venting occurs in two adjacent clusters each hosted in mounds that are ≥150m in diameter, yielding an estimated area of deposit of ~35,000m^2 , i.e. greater than both the tectonically hosted 49°39'E site on the SWIR (Table 2) and, indeed, any of the SMS deposits associated with active hydrothermal venting on the MAR (Table 1).

Intriguingly, directly comparable discoveries have also now been made on the ultraslow spreading Mid-Cayman Rise (Table 2, Fig.11). At the Piccard hydrothermal field, Kinsey & German (2013) have mapped out a series of seven conical mounds of seafloor massive sulfide deposit, three of which continue to host active venting (the Beebe Vents, Beebe Woods and Beebe Sea mounds). As at Loki's castle, high temperature venting at the Piccard Hydrothermal Field is situated along the crest of a spur of pillow-basaltic material which buds out from an ~15km long axial volcanic ridge (Kinsey & German, 2013). The two high-temperature “black smoker” vents (Beebe Vents, Beebe Woods) are each associated with mounds that are ~60m across while diffuse flow is all that continues to exit the much larger (~100m across) Beebe Sea mound. Cumulatively, including the immediately adjacent extinct mounds, seafloor massive sulfides at this location have been mapped to cover an area of ~15,000m^2 which, again, is in excess of the size of the 49° 39’E tectonically-hosted system on the SWIR. In terms of other active magmatic-hosted vent-sites, the SMS desposits reported here are comparable in extent to those from the Lucky Strike and Puy de Folles vent-sites even though the geologic setting, as at Loki’s Castle, appears more directly comparable to the axial volcanic ridge settings of both Snake Pit (Gente et al., 1991) and Broken Spur (Murton et al., 1995).

5. Discussion

In a recent paper, Beaulieu et al (2015) predicted that nearly 800 vent-sites still remain to be discovered along Earth’s mid-ocean ridges (compared to the just over ~300 sites that are already known, Beaulieu et al., 2013). Of these, it is predicted that up to 200 sites remain to be discovered along intermediate-spreading (55-80mm/yr) ridges, together with perhaps 200 more, cumulatively, still to be found along fast and superfast ridge crests (spreading at >80mm/yr). Most important for this study, however, is the complementary prediction that a further ~400 vent-sites remain to be discovered (i.e. significantly more than have ever been discovered to-date, worldwide) along mid-ocean ridges spreading at <55 mm/yr full spreading rate (Beaulieu et al., 2015). Of these, the vast majority (>300) are predicted to occur along the ~50% of the mid-ocean ridge crest that spreads at 0-20 mm/yr or 20-40 mm/yr (Fig.12). This provides an interesting convergence with an independent approach pursued by Hannington et al. (2011) who analyzed a comprehensive data base for seafloor massive sulfide deposits (active and inactive) and predicted that mid ocean ridges spreading at <40mm/yr should host 86% of the cumulative tonnage of seafloor massive sulfides along the global mid-ocean ridge crest (Fig.13).

If we assume a pattern for slow- and ultraslow-spreading ridge-crests that follows that for the central Mid-Atlantic Ridge we would predict that about half of the >300 active vent-sites predicted to await discovery along ridges spreading at <40mm/yr will occur under tectonic control – similar to the ten tectonic-hosted active sites already identified between 8°S and 45°N on the MAR (Fig.7, Table 1). Further, all >150 of these tectonic sites would have the potential to host large (>10,000m^2 area) seafloor massive sulfide deposits and, equally, all >150 such sites would also have the potential to contain polymetallic sulfides enriched in Cu and Au. Even this may represent a conservative estimate of the resource potential for Earth's slowest-spreading ridges, however, when one considers the most recent discoveries in the field.

First, along the slow-spreading Mid-Atlantic Ridge, two magmatic sites – Lucky Strike and Puy de Folles - have now been shown to exhibit anomalously large SMS deposits (Fig.8a). Further, there is preliminary evidence (but the size of the sample set is small) to suggest that the Puy de Folles system can also give rise to high Cu grades in surficial sulfides at the seafloor (Table 1). Since there have also been predictions that large volcanic constructs may recur more frequently on the southern Mid-Atlantic Ridge (Devey et al., 2010), where spreading rates are slightly elevated (30-40mm/yr) compared to the northern MAR, we recommend continuing exploration along slow spreading (20-40 mm/yr) ridges as a potentially highly rewarding area for future hydrothermal research.

Even more intriguing, however, is the case for ultraslow-spreading ridges. Based on our (admittedly sparse) data-set for just three vent-sites, we have observed that large seafloor massive sulfide deposits can occur on ultraslow ridges in magmatic as well as tectonic settings. Further, the axial volcanic ridge settings reported for the Loki's Castle and Piccard sites do not resemble the large volcanic constructs observed at Lucky Strike or Puy de Folles. Instead, they are more similar to the geologic settings of the small-scale hydrothermal fields at

Snake Pit and Broken Spur on the Mid-Atlantic Ridge which, in turn, are the most closely comparable of all MAR sites to vent-sites on the fast-spreading East Pacific Rise. An important question that arises, therefore, is: Can large seafloor massive sulfide deposits be formed at magmatic as well as tectonic hydrothermal fields along the ~25% of the global ridge-crest that is classified as ultraslow-spreading? If so, the possibility exists that *all* hydrothermal fields along the Arctic Mid Ocean Ridge (AMOR) system, as well as along the entire SWIR, could host large seafloor massive sulfide deposits.

There is a further reason why the resource potential of ultraslow ridge hydrothermal systems may have been underestimated until now. As discussed previously (Section 3), on the slow-spreading Mid-Atlantic Ridge it is only at that subset of tectonic hosted “black smoker” vent-sites where long-lived detachment faults cause uplift of underlying mantle rocks to sufficiently shallow depths that resultant vent-fluid chemistries give rise to anomalously copper- and gold-rich surficial seafloor massive sulfides (Table 1). By contrast, ocean crust is anomalously thin along all forms of ultraslow spreading ridge (John & Cheadle, 2010), whether they are normal, magma poor (with 30-50% of crustal extension achieved through assymetric spreading along long-lived detachment faults), or magma starved (in which case smooth seafloor terrain dominates). On the Mid Cayman Rise, Kinsey & German (2013) have calculated that the entire Piccard Hydrothermal Field could be deposited over a period of ~10ky if fluid circulation were able to access and extract all of the heat available from just ~3.5-5.5km along axis, at steady state. This calculation does not appear to be particularly remarkable when, on a like-for-like basis, it has been estimated that emplacement of the Rainbow hydrothermal field would require comparable levels of heat extraction for >20km along-axis (German & Lin, 2004). What *is* intriguing to consider in the context of this study, however, is that while the minimum length-scales of fluid circulation required *along-axis* to sustain development of large SMS deposits in magmatic settings at an ultraslow-spreading ridge-crest may only be on the order of a few kilometers, the anomalously thin ocean crust observed at ultraslow ridges means that fluid circulation may, nevertheless, circulate to sufficient depth to interact with, and be influenced by, ultramafic rocks.

Continuing work at all three of the ultra-slow spreading ridge vent-sites that have been investigated to-date suggest that this may, indeed, be the case. At Loki's castle, for example, it has been suggested that the longevity of venting suggested by the sheer size of the seafloor massive sulfides observed may be indicative of some long-lasting conduit beneath the axial volcanic ridge (Pedersen et al., 2010). Similarly, studies at the Mid Cayman Rise have determined that the Si contents of the vent-fluids from the Beebe Vents site are most consistent with fluid circulation to a depth of 1.8km sub-surface which is deeper than the anticipated thickness of basaltic/gabbroic ocean crust (Webber et al., 2015). Consequently, hydrothermal systems formed at ultra-slow spreading ridges may have the potential to host large seafloor massive sulfide deposits, whether they are hosted in a magmatic or a tectonic setting. Further, preliminary data from both the tectonic-hosted SWIR and the magmatic-hosted Mid Cayman Rise sites (Table 2) exhibit moderately enhanced Cu concentrations and extremely high concentrations of Au (Tao et al., 2011; Ye et al., 2012; Webber et al., 2015). We can predict, therefore, that many other ultra-slow ridge hydrothermal fields may have the potential to yield high Cu and Au concentrations in surficial sulfide samples in either case.

Only continuing exploration will allow the hypotheses outlined here to be tested. Of the 155 hydrothermal fields predicted to exist along ultra-slow ridges (Fig.12) only 55 have been located (of which >50 still await first detailed seafloor investigations) and another ~100 remain to be discovered. But while such a hypothesis may be considered highly speculative in the modern day, we do note that the past 20 years of exploration have helped to confirm what was once an equally speculative hypothesis, also based on preliminary data-sets: that tectonically controlled venting might be of importance along slow-spreading ridges (German et al., 1996). From that historic perspective we eagerly anticipate what the future exploration of Earth's slowest-spreading ridges might bring!

6. Summary

• Although the occurrence of hydrothermal activity along mid ocean ridges *can* be predicted from spreading rate alone, not all venting at slow and ultraslow-spreading ridges may be related, directly, to ridge-crest magma delivery rates.

• On the slow-spreading Mid-Atlantic Ridge, only half of the ~20 active sites that have been investigated in detail are located at the centers of second order ridge segments, in magmatic-hosted settings comparable to hydrothermal systems on fast-spreading Mid Ocean Ridges. An approximately equal number of MAR "black smoker" systems occur that are tectonic-controlled.

• Due to sustained fluid circulation along deep-penetrating and continuously reactivated fault systems, tectonic-hosted vent-sites on slow spreading ridges have the potential to host much larger seafloor massive sulfide deposits than are formed in magmatic-hosted settings.

• In an important subset of tectonically hosted MAR systems where fluids interact with ultramafic rocks, surface samples from the resulting SMS deposits are particularly enriched in both copper (>10wt.%) and gold (>3ppm).

• Along ultraslow-spreading ridges, formation of large SMS deposits is also predicted to occur in tectonic-hosted settings but formation of large SMS deposits in magmatic-hosted settings may also be common.

• Because of the anomalously thin ocean crust typical along ultraslow-spreading ridges, SMS deposits formed in both tectonic and volcanic settings on these ridges may also be anomalously Cu- and Au-rich.

• It is predicted that more high temperature vent-sites remain to be discovered along Earth's slow and ultra-slow spreading ridges than have ever been discovered worldwide, to date. The potential for future resource discovery along Earth's slowest spreading ridges is higher now than ever previously predicted.

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Figure Captions

Fig. 1. Distribution of confirmed and inferred active submarine hydrothermal fields, worldwide, along the global mid-ocean ridge system. Ridge segments that have not yet been surveyed for hydrothermal activity are color-coded according to five spreading-rate categories: ultraslow (0-20mm/yr full spreading rate); slow (20-55mm/yr); intermediate (55-80mm/yr); fast (80-140mm/yr) and superfast (>140mm/yr). The focus of this review falls primarily upon high-temperature "black smoker" venting along the slow and ultra-slow ridges that constitute ~50% of the cumulative length of the 60,000km global mid-ocean ridge axis, including a continuous sequence from the Gakkel Ridge in the Arctic, via the Mid-Atlantic Ridge and SW Indian Ridge to the Rodriguez Triple Junction, Central Indian Ocean. Figure reproduced, with permission, from Beaulieu et al. (2015).

Fig. 2. Scatterplot of vent field frequencies (per 100 km strike length, F_s) versus full spreading rate (weighted average mm/yr, u_s). Colored diamonds represent cumulative data for 21 non-hotspot surveys of suitable length and type, binned into 5 spreading rate categories. See Table 1 in Beaulieu et al. (2015) for description of full data-set. Horizontal and vertical bars indicate ranges for values from separate field-surveys considered within each spreading-rate data-bin. Solid line shows modern, global, linear fit of vent field frequency to spreading rate; dashed lines show 95% CIs. Figure reproduced, with permission, from Beaulieu et al. (2015).

Fig. 3. Scatterplot of vent field frequencies (per 100 km strike length, F_s) versus full spreading rate (weighted average mm/yr, u_s) for a series of 15 surveys contributing to the global InterRidge vents-database at mid-ocean ridges with full spreading rates that are either ultraslow (0-20mm/yr) or slow (20-55mm/yr). See Table 1 in Beaulieu et al. (2015), for full data-set description. Dotted blue line shows modern, global, linear fit of vent field frequency to spreading rate *(cf* Fig.2). Dashed red line shows alternate trend corresponding to the original correlation (after Baker et al., 1996) in which hydrothermal activity was predicted

to fall to zero at zero spreading rate (i.e. at zero axial magma budget). Shaded area shows plume survey data for three separate sections of the northern Mid Atlantic Ridge [(A) 36-38°N; (B) 27-30°N; (C) 11-21°N] that either converge with or depart positively away from the Baker et al. (1996) spreading rate model, all at a near-constant spreading rate.

Fig. 4. *a)* Shipboard multibeam and *b)* TOBI deep-tow sidescan sonar data from the axial valley high at the center of the second order ridge segment, 5°S Mid-Atlantic Ridge that hosts the Turtle Pits hydrothermal field which is situated within an ~18km^2 area of unfaulted and sheet-flow dominated lava flows (Reproduced, with permission, from German et al., 2008). *c)* detailed ROV-based geologic map of the Turtle Pits Hydrothermal field, showing high-temperature "black smoker" venting and associated deposits directly associated with the extensive young, un-sedimented and largely un-fractured lava flows that characterize the summit of this ridge segment's axial volcanic high (Reproduced, with permission, from Haase et al., 2007).

Fig. 5. *a)* Cross sectional interpretation and *b)* 3D perspective view (from shipboard multibeam bathymetry) to illustrate the location of the Rainbow hydrothermal field within the non-transform discontinuity between two adjacent second-order ridge segments of the Mid-Atlantic Ridge near 36°14'N. Black line in 3D perspective view (*b*) represents location of cross-section shown in (*a*). Fluid flow along the normal fault that defines the rift-valley wall at this location is envisaged to represent the primary source for fluids exiting the Rainbow hydrothermal field, which show evidence for water-rock interaction with both gabbroic and ultramafic lithologies at depth (Reproduced, with permission, from Cannat et al., 2010). *c)* detailed ROV-based high-resolution bathymetry of the Rainbow site showing ten active "black smoker" vents aligned W-E, i.e. orthogonal to the strike of the ridge-axis but sub-parallel to the trend of the cross-cutting non-transform discontinuity. (Reproduced, with permission, from Seyfried et al., 2011).

Fig. 6. *a)* multibeam bathymetric map of the Lucky Strike segment, 37°N Mid-Atlantic Ridge showing the extensive volcanic construct at the center of the segment with elevations that are so anomalously high as to be directly comparable in depth to the bounding rift-valley walls. *b)* detailed ROV-based geologic map of the Lucky Strike hydrothermal field showing the location of active vents and associated deposits arranged around the perimeter of a lava lake situated at the center of the axial volcanic high. (Reproduced, with permission, from Humphris et al., 2002).

Fig. 7. Map showing the locations of 19 active high-temperature hydrothermal fields along the Mid-Atlantic Ridge, 8°S-45°N that have been investigated, visually, at the seafloor to determine their detailed geologic settings (Table 1). Yellow circles indicate tectonic settings and red circles indicate magmatic settings. Tectonic systems represent approximately half of all known high-temperature vent-sites identified to-date along the slow-spreading Mid-Atlantic Ridge.

Fig. 8. Histograms for 19 active high-temperature hydrothermal fields along the Mid-Atlantic Ridge, 8°S-45°N, showing: (*a*) estimated areal extent of seafloor massive sulfides at each site and (*b, c*) average surficial sulfide sample Cu and Au concentrations (where determined). Vertical dashed line in *(b)* denotes 10 wt.% Cu; vertical dashed line in *(c)* denotes 3ppm Au. Data values are plotted from Table 1.

Fig. 9. Detailed *ABE* AUV-based map showing the locations of active venting and inactive sulfide deposits at the first vent-site to be located anywhere along an ultra-slow spreading ridge crest near 49°39'E on the SW Indian Ridge. Black lines show track lines of ABE dive #202; colored ellipsoids show seafloor areal coverage for active and inactive hydrothermal features detected from photographs ± *in situ* sensors. Redrawn after Tao et al., 2012.

Fig. 10. *a)* Perspective view (from SE) of shipboard multibeam bathymetry at the eastern-most Mohns Ridge , Norwegian-Greenland Sea, showing the location of the Loki's Castle hydrothermal field (73°33'N, 08°09'E) at the rifted summit of an ~30km long axial volcanic ridge. Reproduced, with permission, from Pedersen et al., 2010; *b)* High resolution multibeam bathymetry of the Loki's Castle hydrothermal field showing the two roughly circular and ≥150m diameter hydrothermal mounds that coalesce to form the full extent of the seafloor massive sulfide deposits at this site (R.Pedersen, unpubl. data).

Fig. 11. *a)* High resolution bathymetry and *b)* detailed ROV-based geologic map of the Piccard Hydrothermal Field, Mid Cayman Rise, showing the areal extent of three actively venting hydrothermal mounds and four adjacent extinct seafloor massive sulfide mounds (dark and light grey shading in right panel), all aligned along a spur budding out from an ~15km long Axial Volcanic Ridge. Reproduced, with permission, from Kinsey & German (2013).

Fig. 12. Plot showing number of active hydrothermal vent fields both known and, as predicted by Beaulieu et al. (2015), that are yet to be discovered along Earth's mid-ocean ridges as a function of spreading rate. Stacked histogram represents (blue) vent sites known prior to 2000, (red) vent sites discovered since 2000 and (black) vent sites remaining to be discovered. Note that significantly more vents remain to be discovered along slow and ultra-slow ridges spreading at <40mm/yr full spreading rate, than are predicted to await discovery along fast and superfast ridges combined (>80 mm/yr). Redrawn from Beaulieu et al. (2015).

Fig. 13. Expected distribution of seafloor massive sulfide deposits along the mid-ocean ridges as a function of spreading rate. The proportion of massive sulfide at different spreading rates is estimated from the lengths of ridge segments, deposit density as a function of spreading rate, and expected sizes of the deposits (Hannington et al. 2011). The large proportion of massive sulfide expected on

slow- and ultra-slow spreading ridges reflects the cumulative length of the slow ridges plus the large sizes of the known deposits that occur there.

Figure

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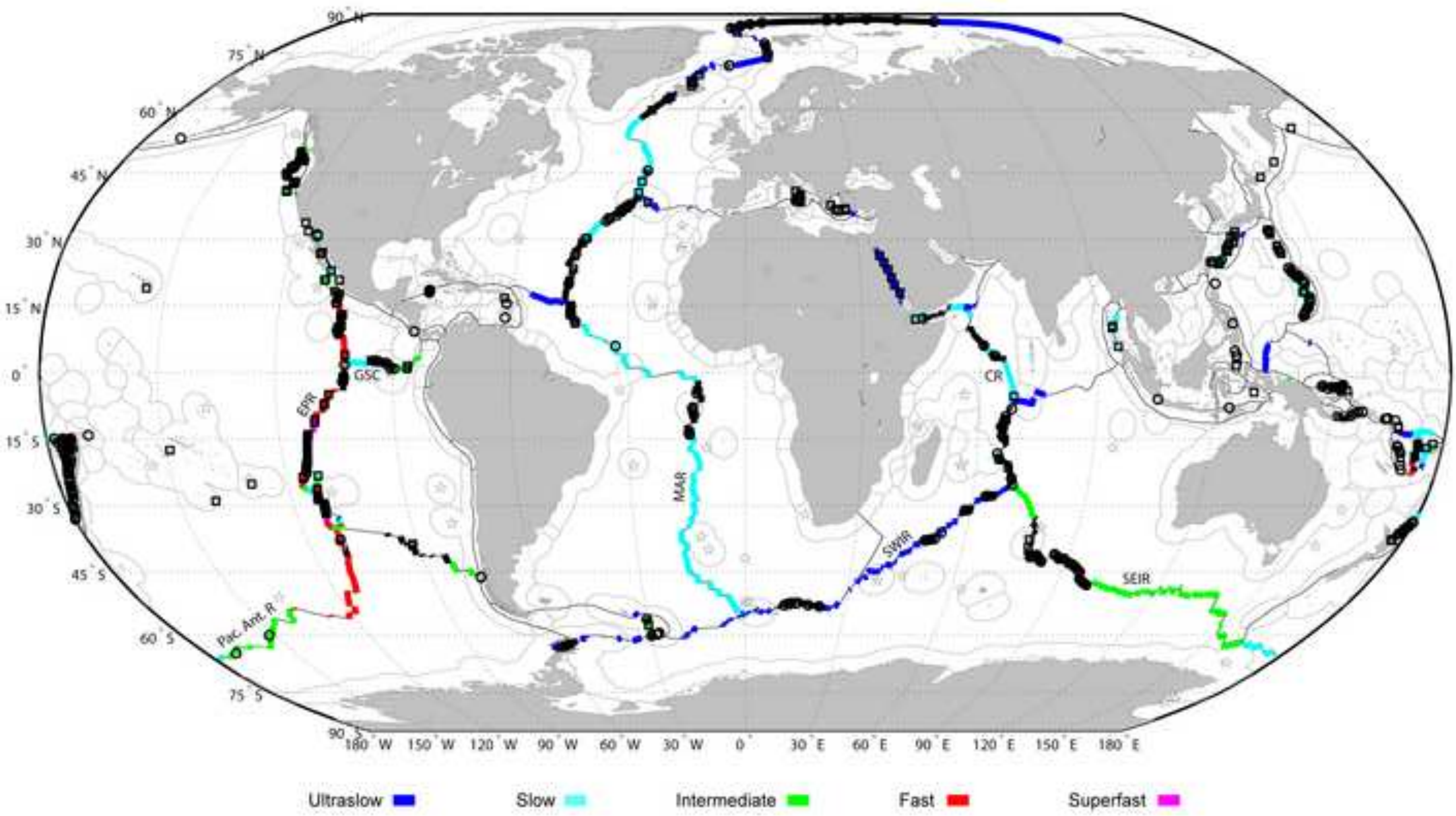

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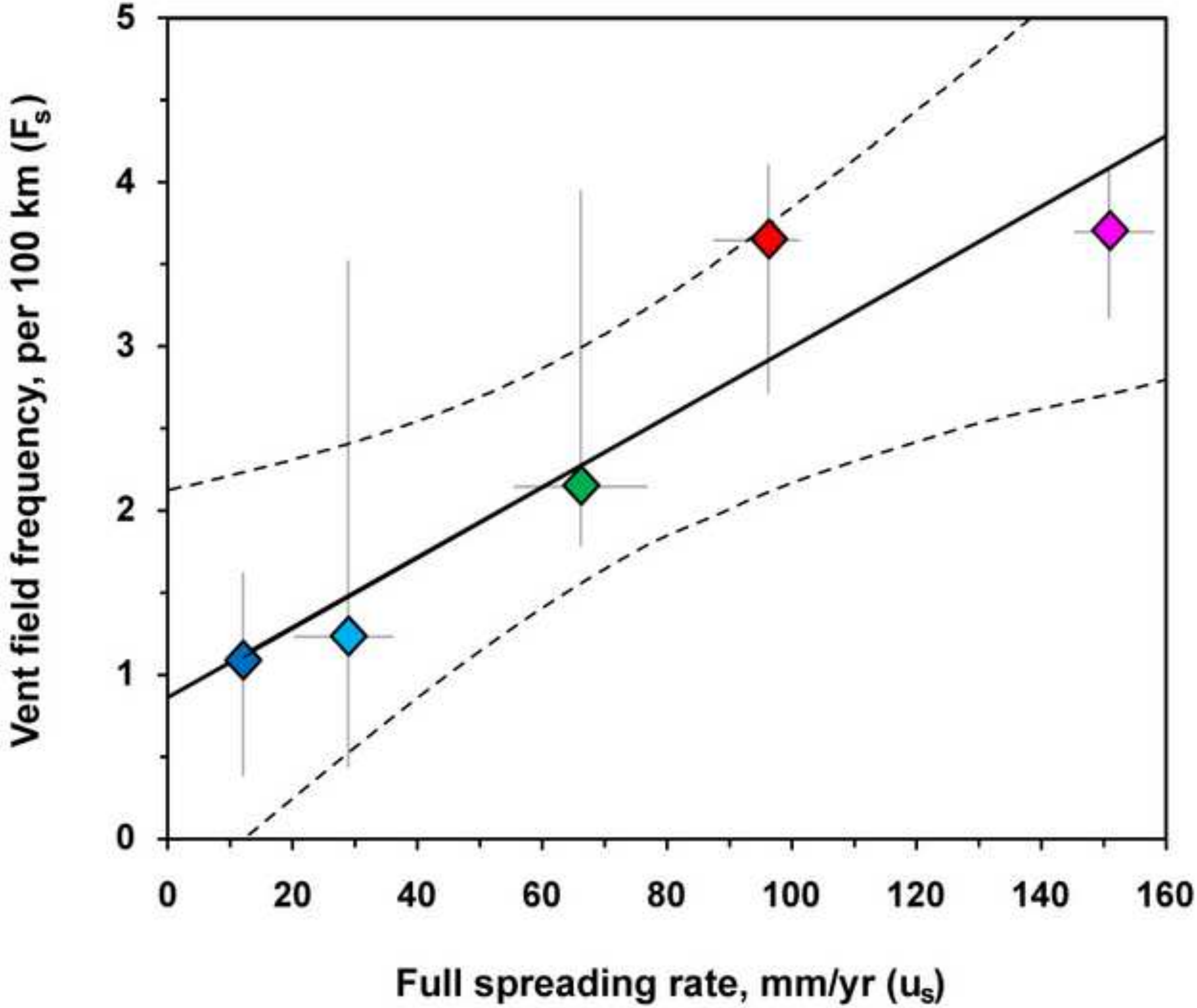

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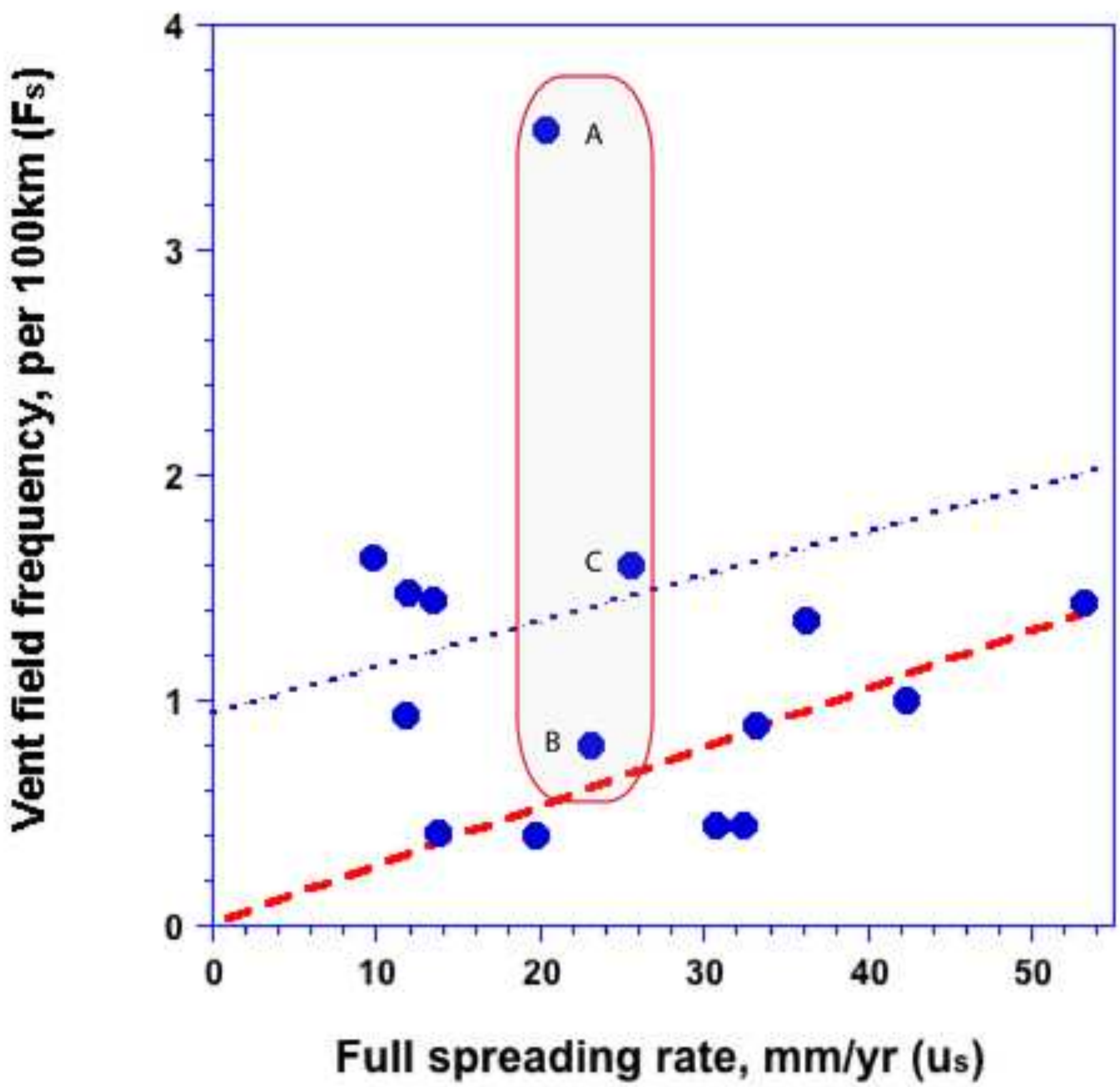

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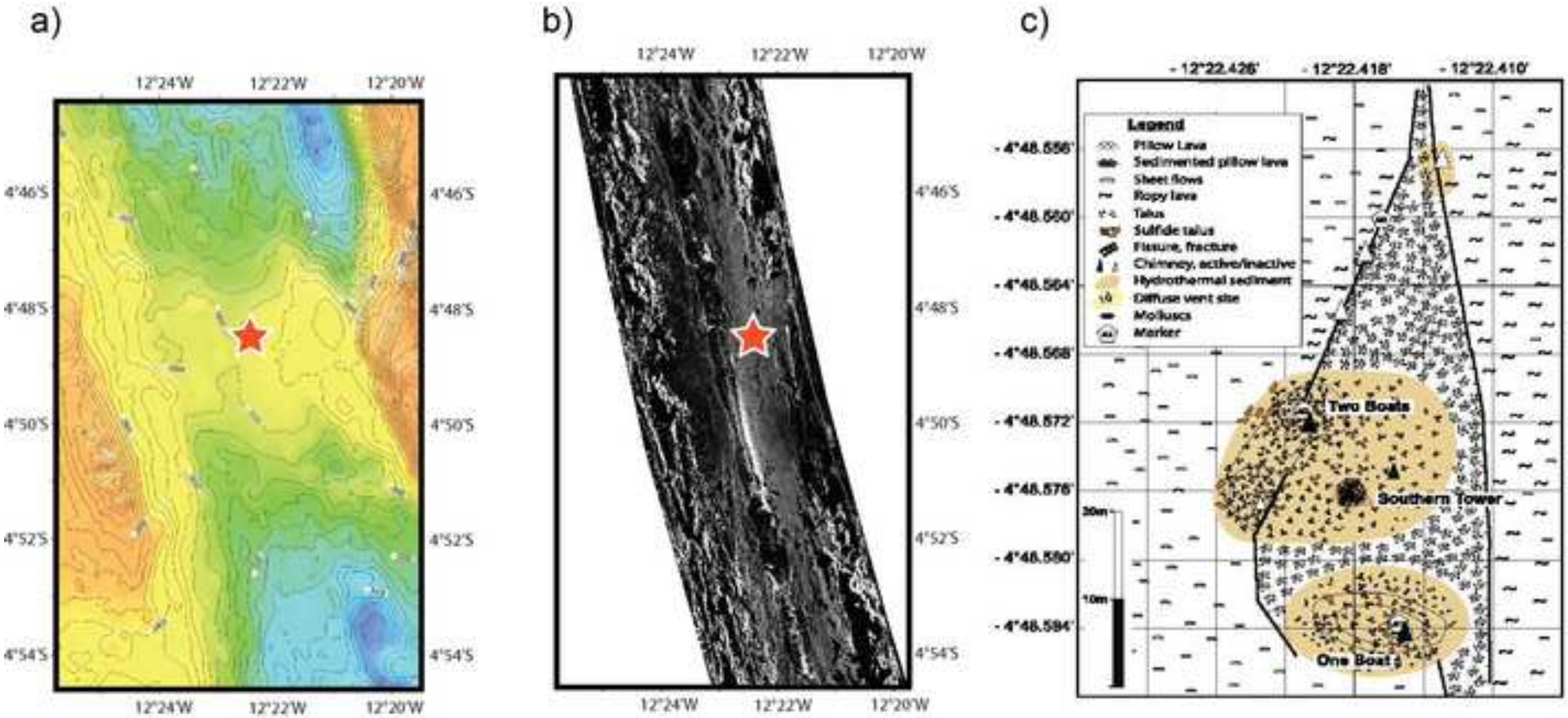

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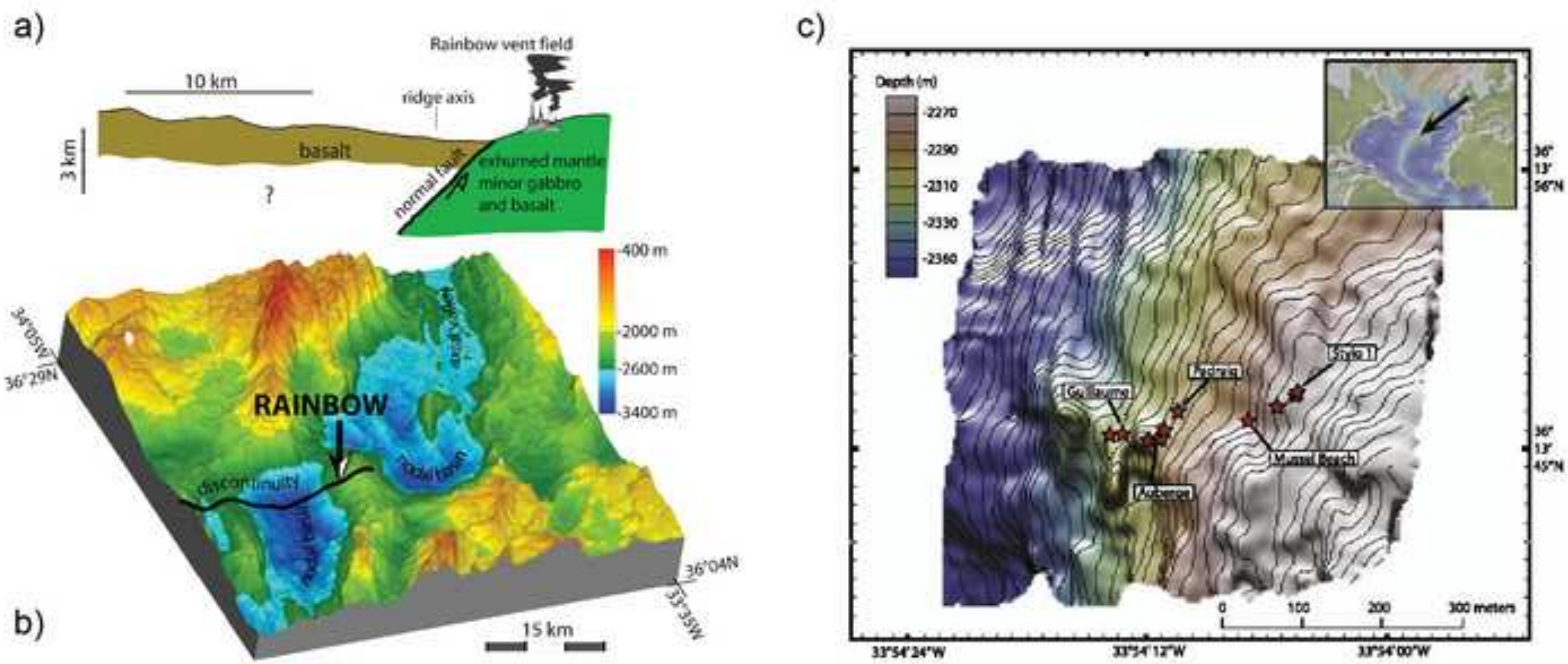

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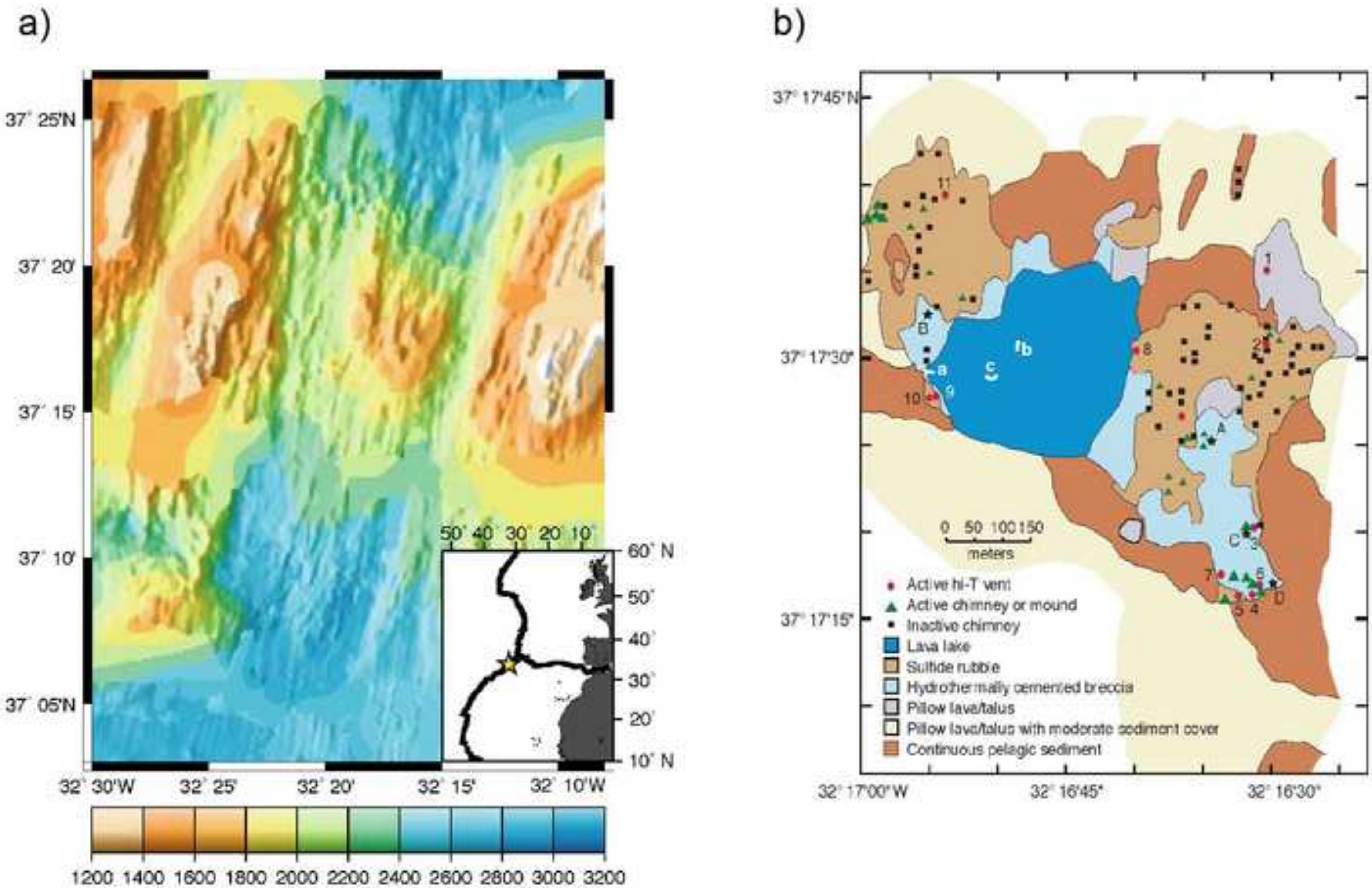

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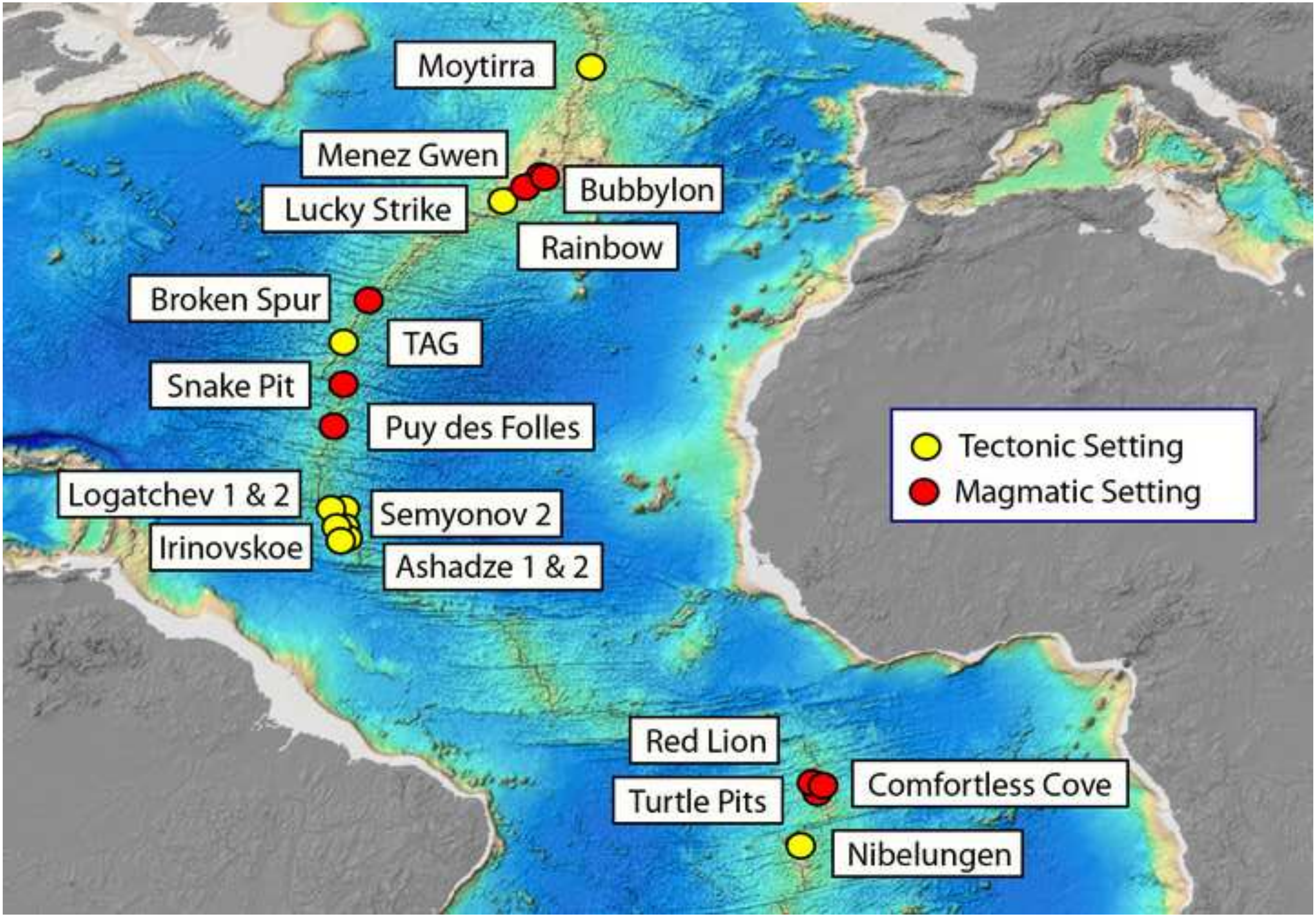

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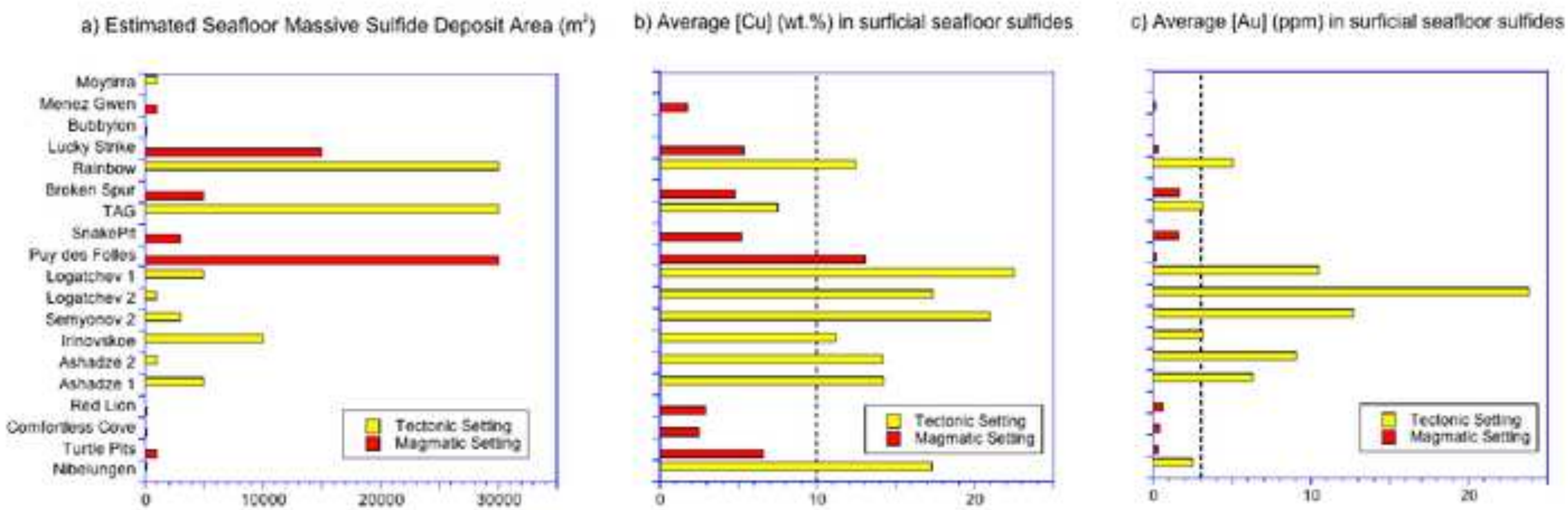

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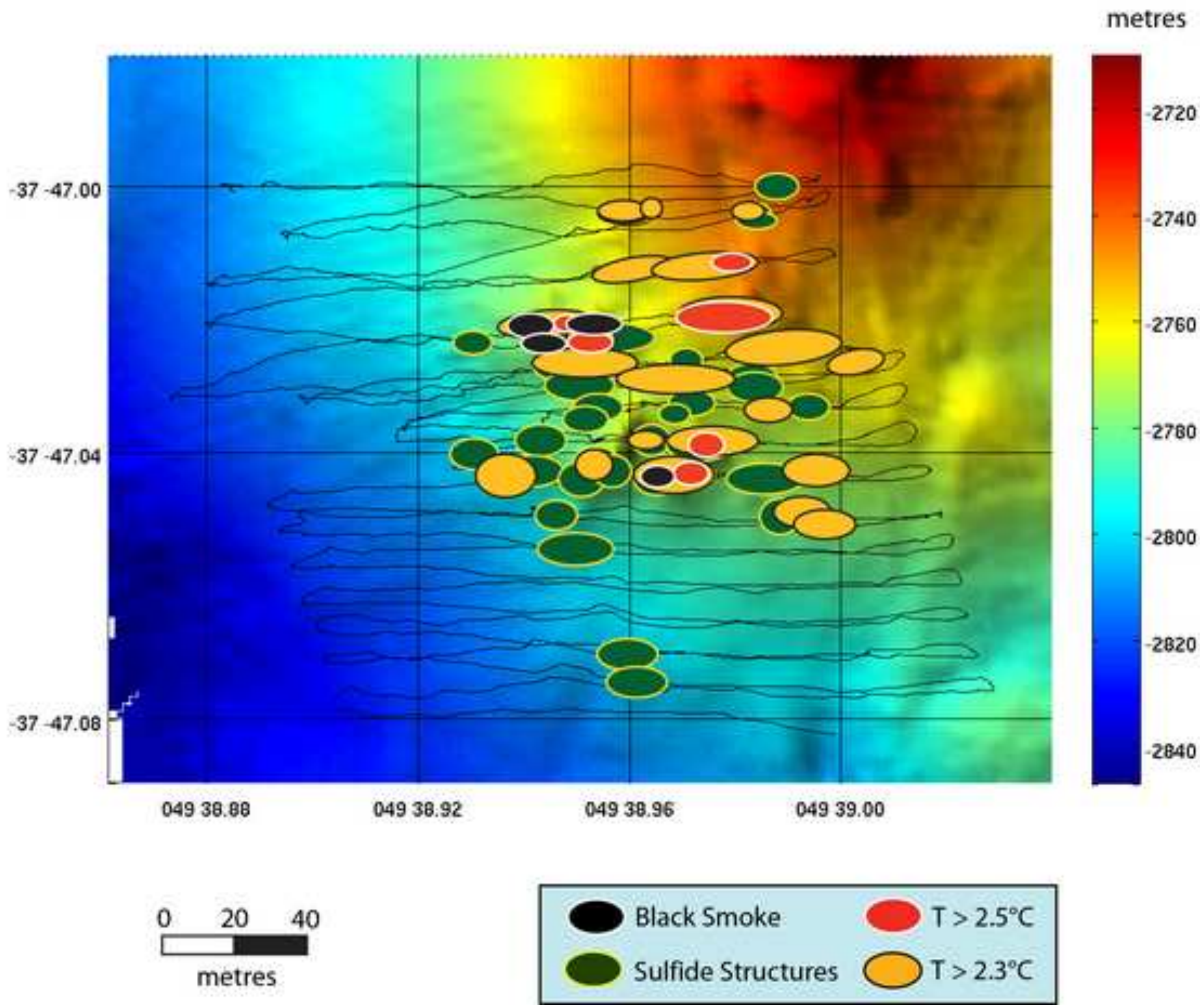

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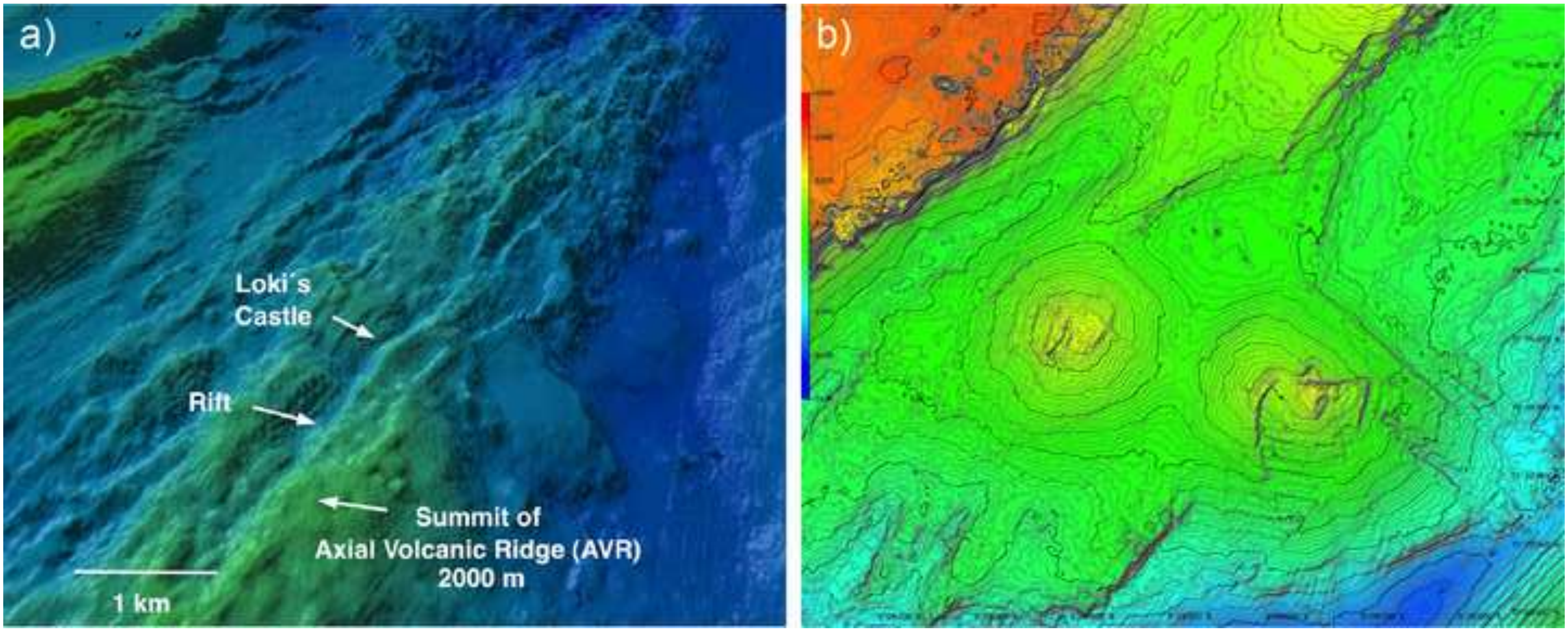

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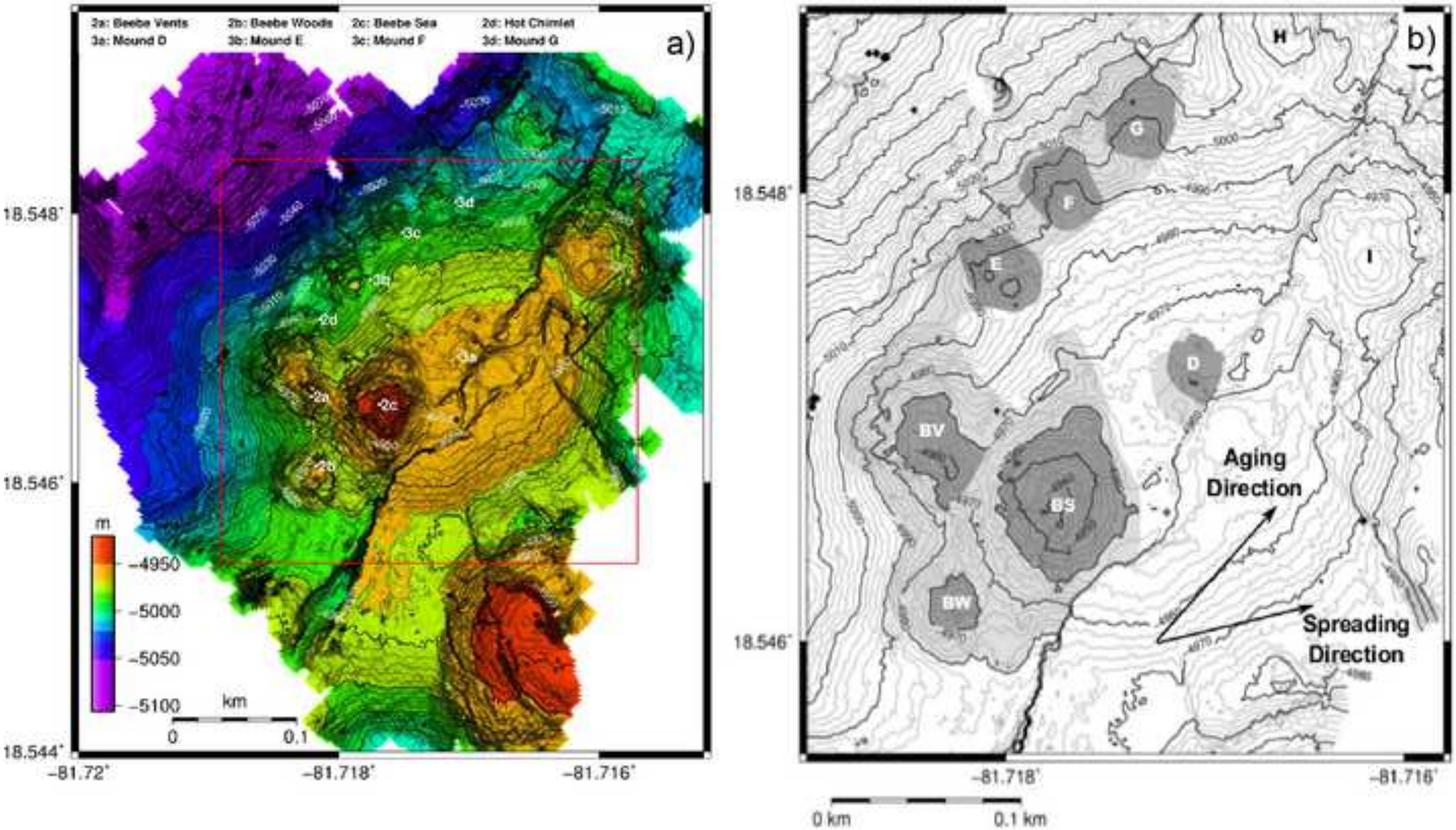

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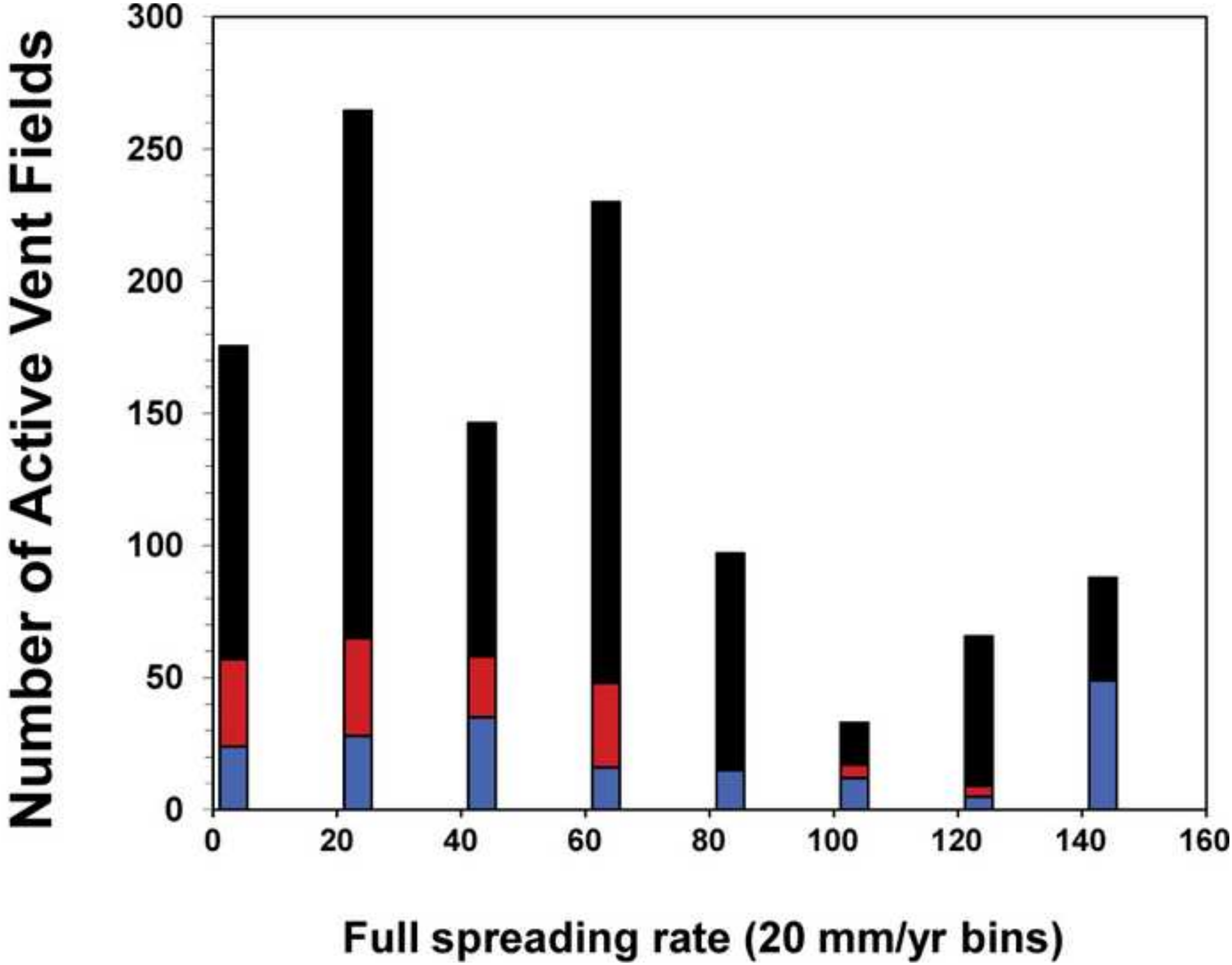

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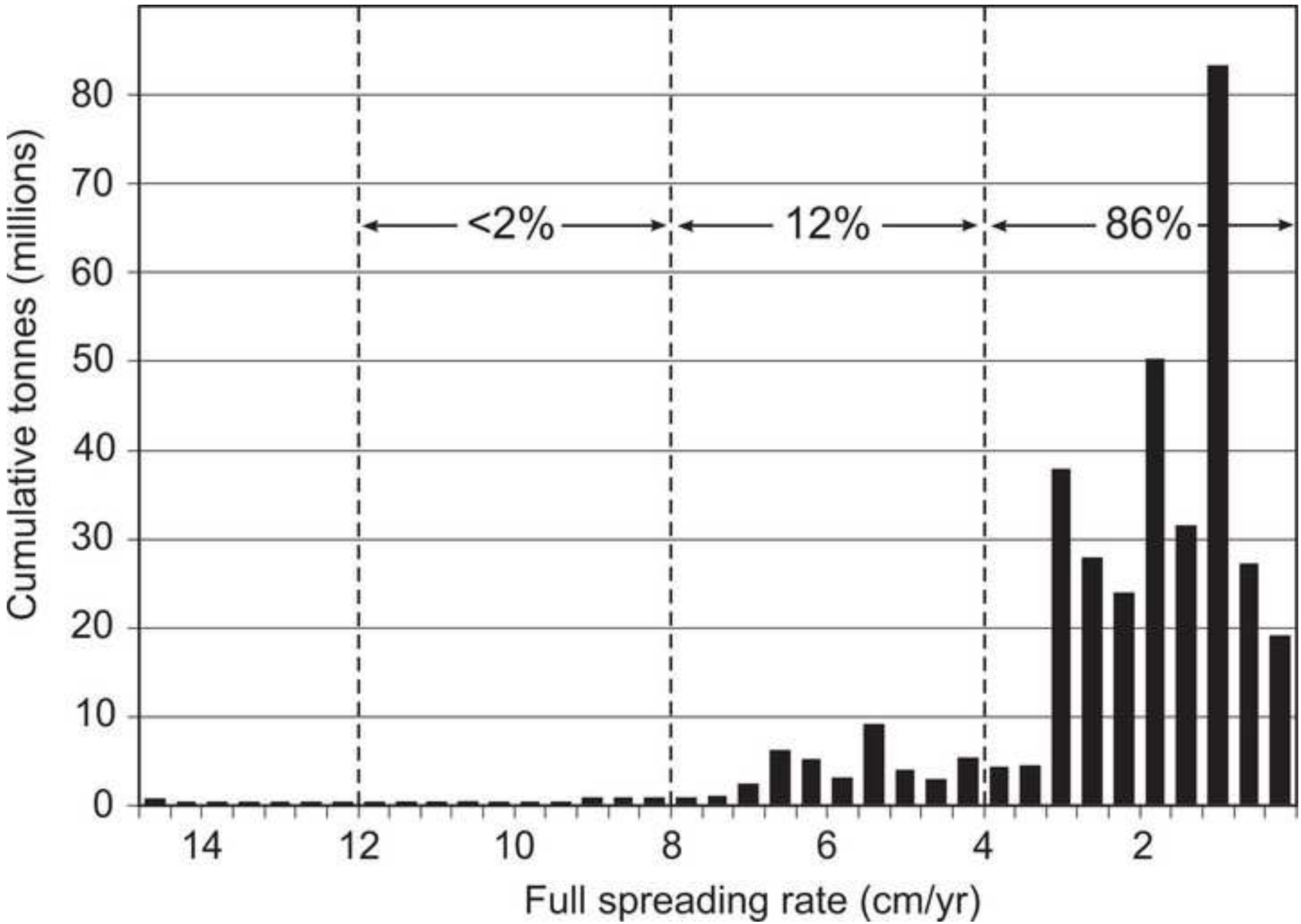

Table
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Table 1: Active High Temperature Vent Sites on the MAR (8°S-45°N)

Site	Latitude	Longitude	Depth (m)	Setting	Area (m2)	[Cu]* (wt.%)	[Au]* (ppm)
Moytirra	45° 29'N	27° 51'W	3000	Tectonic	<1000	tbd	tbd
Menez Gwen	37° 50'N	31° 31'W	830	Magmatic	<1000	1.75	0.13
Bubbylon	37° 48'N	31° 32'W	1000	Magmatic	<100	tbd	tbd
Lucky Strike	37° 17'N	32° 16'W	1700	Magmatic	≥15000	5.37	0.30
Rainbow	36° 14'N	33° 54'W	2300	Tectonic	**30000**	**12.43**	**5.10**
Broken Spur	29° 10'N	43° 10'W	3100	Magmatic	5000	4.78	1.64
TAG	26° 08'N	44° 49'W	3670	Tectonic	**30000**	7.51	**3.15**
Snakepit	23° 22'N	44° 57'W	3490	Magmatic	3000	5.18	1.58
Puy des Folles	20° 30'N	45° 39'W	1960	Magmatic	30000	**13.07**	0.23
Logatchev 1	14° 45'N	44° 58'W	2990	Tectonic	5000	**22.51**	**10.47**
Logatchev 2	14° 43'N	44° 56'W	2700	Tectonic	1000	**17.39**	**23.80**
Semyonov 2	13° 31'N	44° 58'W	2420	Tectonic	3000	**21.00**	**12.71**
Irinovskoe	13° 20'N	44° 54'W	2770	Tectonic	**10000**	**11.20**	**3.14**
Ashadze 2	12° 59'N	44° 54'W	3260	Tectonic	1000	**14.14**	**9.10**
Ashadze 1	12 °58'N	44° 52'W	4088	Tectonic	5000	**14.21**	**6.30**
Red Lion	04° 48'S	12° 23'W	3050	Magmatic	<100	2.90	0.64
Comfortless Cove	04°48'S	12° 22'W	2996	Magmatic	<100	2.50	0.42
Turtle Pits	04° 49'S	12° 22'W	2990	Magmatic	1000	6.60	0.25
Nibelungen	08° 18'S	13° 30'W	2905	Tectonic	<100	**17.30**	2.52

* Average concentrations in surficial seafloor sulfides, only.

Table
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Table 2: Active High Temperature Vent Sites on Ultraslow-Spreading Ridges

Site	Latitude	Longitude	Depth (m)	Setting	Area (m2)	[Cu]* (wt.%)	[Au]* (ppm)
49°39'E, SWIR	37° 47'S	49° 39'E	2770	Tectonic	10000	*1.90*	***4.00***
Loki's Castle, MR	73° 33'N	08° 09'E	2400	Volcanic	35000	*tbd*	*tbd*
Piccard, MCR	18° 33'N	81° 43'W	4960	Volcanic	15000	*6.90*	***17.10***

* Average concentrations in surficial seafloor sulfides, only.