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Distributions of hydrothermal activity along the Mid-Atlantic Ridge: interplay of magmatic and tectonic controls

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Abstract

Hydrothermal activity has been investigated along three different sections of the slow-spreading Mid-Atlantic Ridge (MAR): 11º20′–30ºN, 36–38ºN and the Reykjanes Ridge, 57º45′–63º06′N. When considered in total, the incidence of venting along these three sections of the MAR compares well with the predictions of a model in which frequency of venting is linearly related to ridge-crest spreading-rate. At the scale of individual study areas, however, departure from the model is observed by up to an order of magnitude. Venting is anomalously rare along the Reykjanes Ridge but anomalously abundant along the MAR 36–38ºN. Whilst such variability may be within the error of the linear spreading-rate model, we note that the interplay between magmatic and tectonic processes also differs between the three study areas. In the case of the Reykjanes Ridge we propose that the low incidence of venting reported may reflect a limitation of the sampling/investigative strategy because the style of venting which predominates may not give rise to conventional black-smoker hydrothermal plumes. Along the oblique and broadly segmented MAR 36–38ºN, we propose that vigorous hydrothermal venting in broad segment-end non-transform discontinuities may be focussed along deeply penetrating active faults with the requisite heat supply being supported through some combination of along-axis magmatic intrusions and thermal release associated with the serpentinisation of crustal peridotites.

Keywords: Mid-Atlantic Ridge; hydrothermal vents; Reykjanes Ridge

1. Introduction

Since the first discovery of ‘black smoker’ type hydrothermal activity on the East Pacific Rise [1], investigators have been striving to identify a unifying predictive theory on what controls the distribution of high-temperature venting around the global ridge crest (cf. [2]). To date, the most systematic studies of along-axis distributions of venting have been focussed along the East Pacific Rise and Juan de Fuca Ridge. In some cases (e.g. [3]) deep-tow photographic surveys have been used to locate new sites of hydrothermal venting. To obtain such extensive photographic coverage of the seafloor is expensive and time-consuming, however, and not practical for more widespread surveys. Instead, researchers have exploited the dispersed signals from hydrothermal plumes to prospect for high-temperature hydrothermal venting on the seabed (e.g. [4,5])?. When they first erupt, hydrothermal vent-fluids are buoyant and are carried upward from the seabed, mixing pro-

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gressively with the surrounding water column until some level of neutral buoyancy is attained [6]. These chemically enriched and particle-laden plumes are then dispersed over wide areas of the deep-ocean water column, where they can be detected using both chemical and optical methods. Use of optical sensors provides the added advantage that real time in-situ information concerning the location and lateral extent of deep-sea hydrothermal plumes can be obtained (e.g. [7]). Following this approach, systematic surveys of the occurrence of hydrothermal plumes have been conducted using CTD+transmissometer tow-yos along the intermediate spreading Juan de Fuca Ridge [8] and the fast to very-fast spreading northern and southern East Pacific Rise [9,10]. In a synthesis of these data, Baker et al. [11] have predicted that the incidence of on-axis hydrothermal venting along any section of ridge crest should be a simple linear function of that ridge-crest's spreading rate. Here, we examine the applicability of this model to the slow-spreading Mid-Atlantic Ridge. We demonstrate that, within the constraints of this model, additional variability in plume incidence can occur by up to an order of magnitude. We then explore the possibility that this variability is not purely statistical but may be directly linked to differing styles of second-order ridge segmentation along the slow-spreading Mid-Atlantic Ridge.

2. Distribution of hydrothermal activity along the Mid-Atlantic Ridge

In this section we present a synthesis of data collected along three different sections of the Mid-Atlantic Ridge: from the 11º20′N fracture zone to the Atlantis Fracture Zone at 30ºN; along the Reykjanes Ridge from 58 to 63ºN; and along the MAR southwest from the Azores Triple Junction, from 36 to 38ºN (Fig. 1).

2.1. The Mid-Atlantic Ridge, 11º20′–30ºN

This section of the MAR extends between the Vema and Atlantis Fracture Zones, and comprises three first-order ridge segments, increasing in length from south to north from 220 km through 470 km to 820 km (Fig. 2). A combination of multibeam swath bathymetry and satellite altimetry data indicates a partitioning into a further 31 second-order segments with an average length of approximately 48 km. Relative plate motion is orthogonal to, or at a high angle to the plate boundary and the non-transform discontinuities separating the segments are narrow and have relatively short-offsets (on average $<$15 km) [12,13]. Klinkhammer et al. [14] performed the first detailed along-axis study of the water column overlying the Mid-Atlantic Ridge using a CTD-rosette to collect vertical profiles from ten stations, 11–26ºN, for total dissolvable Mn (TDM) analysis —a diagnostic tracer of hydrothermal plume discharge. TDM anomalies were identified in at least one profile collected from each of nine different offset segments (Fig. 2) indicating that at least one discrete source of high-temperature hydrothermal venting should occur within each segment, yielding an along-axis frequency of at least one vent-site every 150–175 km. Subsequent work by Charlou and Donval [15] used the same vertical profiling technique, coupled with dissolved CH_4 analyses to confirm a frequency of at least one vent-site every $\sim$110 km along twelve segments of the MAR between 12 and 26ºN (Fig. 2).

A common aspect to both the above surveys was that they focused their search for plume signals close to segment centres where fresh magmatic activity, it was considered, should be most likely to occur (cf. [2]). In 1993, Murton et al. [16] conducted an along-axis survey of the MAR, 27–30ºN, using the SOC deep-tow sidescan sonar instrument TOBI (Towed Ocean Bottom Instrument). Instead of occupying a series of vertical profile stations, however, continuous transmissometer data were collected from the TOBI platform as it was towed sub-horizontally throughout the deep portion of the water column. During the survey, transmissometer anomalies indicative of neutrally buoyant hydrothermal plumes were detected at three different locations along the ridge-axis, at 27º00′N, at 29º10′N and at 30º02′N (Fig. 2). Despite the different sampling strategies employed in this work, compared to previous profiling studies, the same basic frequency was reported of at least one vent-site every $\sim$110 km. Synthesising all three data sets, 11º20′–30ºN yields an average spacing between vent-sites of $\sim$130 km which is in reasonable agreement with the estimations of Baker et al. [11].

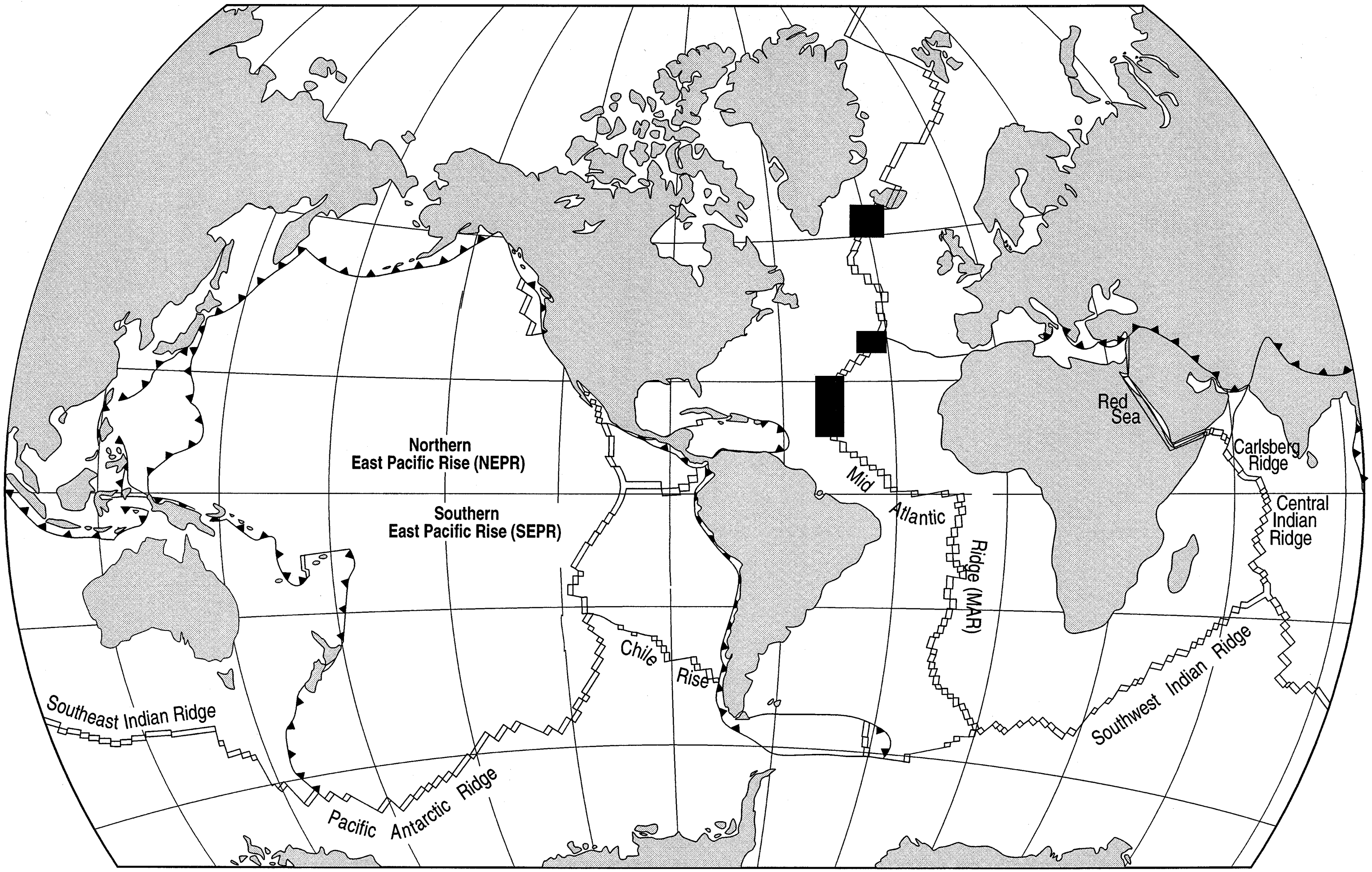

Fig. 1. Schematic illustration of the global mid-ocean ridge system showing the locations and relative sizes of the three study areas (solid rectangles) along the slow-spreading Mid-Atlantic Ridge (MAR).

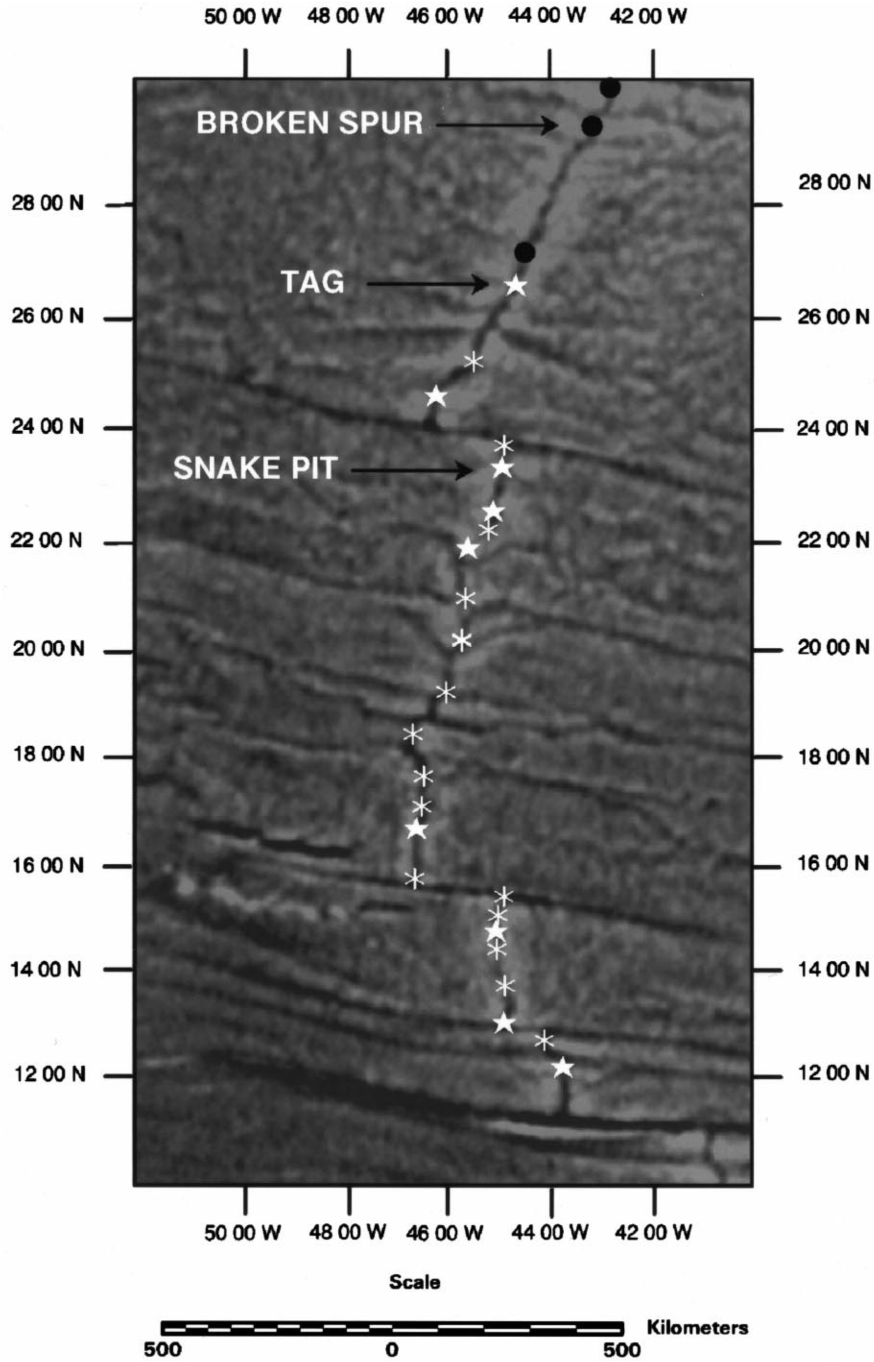

Fig. 2. Gridded estimate of Atlantic seafloor topography (10–30ºN), including the segmented Mid-Atlantic Ridge, showing the locations at which evidence for hydrothermal activity has been observed from vertical profile TDM anomalies (stars), vertical profile dissolved CH_4 anomalies (asterisks) and deep-towed transmissometer anomalies (solid circles). Hydrothermal plume data from Refs. [14–16] are superposed upon the estimated topography from Ref. [61]. Note: apparent increase in frequency of venting, south of 24ºN, is due to duplicate surveys in this area [14,15], not true variations.

2.2. Reykjanes Ridge, 58–63°N

The 900 km long, obliquely spreading Reykjanes Ridge has no first- or second-order ridge offsets (Fig. 3), although it is characterised by an en-echelon series of axial volcanic ridges which define a bathymetric segmentation pattern [17]. The ridges are oriented approximately orthogonally to the spreading direction, range in length from 15 to 40 km, and are offset from each other in general by less than 10 km [18]. Using CTD profiling techniques, German et al. [19] occupied 175 stations between 57°44′N and 63°09′N, at much higher frequencies than had been employed previously along the Mid-Atlantic Ridge, 11–30°N. Despite this intense sampling, however, hydrothermal activity was only detected at one site along 600 km of ridge axis, the Steinahóll vent-field at 63°06′N [20].

2.3. Mid-Atlantic Ridge, 36–38°N

For 300 km south of the Azores Triple Junction, the MAR is defined by a series of short second-order ridge segments ranging between 16 and 54 km long, separated by broad non-transform discontinuities with a similar range of offset length between 16 and 48 km. The obliquity of the spreading direction (approximately 045° to the plate boundary) controls the characteristic 'staircase' geometry of the ridge [21]. This area was surveyed by TOBI coupled with a transmissometer, followed by vertical CTD profiles in those areas where transmissometer anomalies were detected [22]. A double-swath of sidescan sonar and transmissometer data were collected along this 200-km section of ridge axis and anomalies representative of different vent-sources were located at seven different sites along-axis (Fig. 4). Whilst three of these sources were in segment centres, in addition to the previously reported Lucky Strike and Menez Gwen vent-sites [23,24], a further four sites occurred within non-transform discontinuities (NTDs) [22], including the Rainbow hydrothermal field at 36°14′N [25,26]. In combination, hydrothermal surveys of the MAR 36–38°N have yielded evidence for an average spacing between adjacent vent-sites of just 25–30 km along-axis.

3. Discussion: magmatic vs. tectonic controls of venting on the MAR

3.1. Model predictions and the comparability of different data sets

According to the model of Baker et al. [11] the fraction of MAR ridge-crest length which would be predicted to be overlain by hydrothermal plumes, p_h, is given by the equation:

$$p_h = \alpha u_s \tag{1}$$

in which u_s is the full spreading rate and $\alpha = 0.004$ Ma/km. For full-spreading rates between 20 and 26 km/Ma [27] this model would predict values for plume incidence in the range, $p_h = 0.080$–0.104. Experience from hydrothermal plume surveys at TAG (26°N), Broken Spur (29°N), Lucky Strike (37°N) and Steinahóll (63°N) indicates that the full extent of a MAR neutrally buoyant plume typically falls in the range 5–8 km [19,28–30] although in extreme cases a plume can extend beyond 50 km from its source [31]. For a plume of 5–8 km extent, however, the Baker et al. model [11] would predict vent frequencies for the Mid-Atlantic Ridge which would range from 50 to 75 km spacing between the 11°20′N and Atlantis Fracture Zones and from 36 to 38°N, increasing to one site every 60–100 km along-axis along the Reykjanes Ridge. As described previously, therefore, the data from the Mid-Atlantic Ridge, 36–38°N, show a 2- to 3-fold increase over the maximum incidence of venting predicted, whilst the data from the Reykjanes Ridge exhibit a 6- to 10-fold decrease in plume incidence with respect to the model average values [11].

It should be noted that the biggest extremes in these data come from the shorter study areas reported and it is certainly the case that volcanic/magmatic cycles must become increasingly decoupled, temporally, from hydrothermal cooling processes at slower spreading ridge axes [32]. In considering slowly and very slowly spreading ridges, therefore, it is clear that the model of Baker et al. [11] should most appropriately be applied over increasing length scales when compared to the previous studies of intermediate, fast and very-fast spreading ridges. Another important consideration, at this stage, is the internal consistency between the three North Atlantic

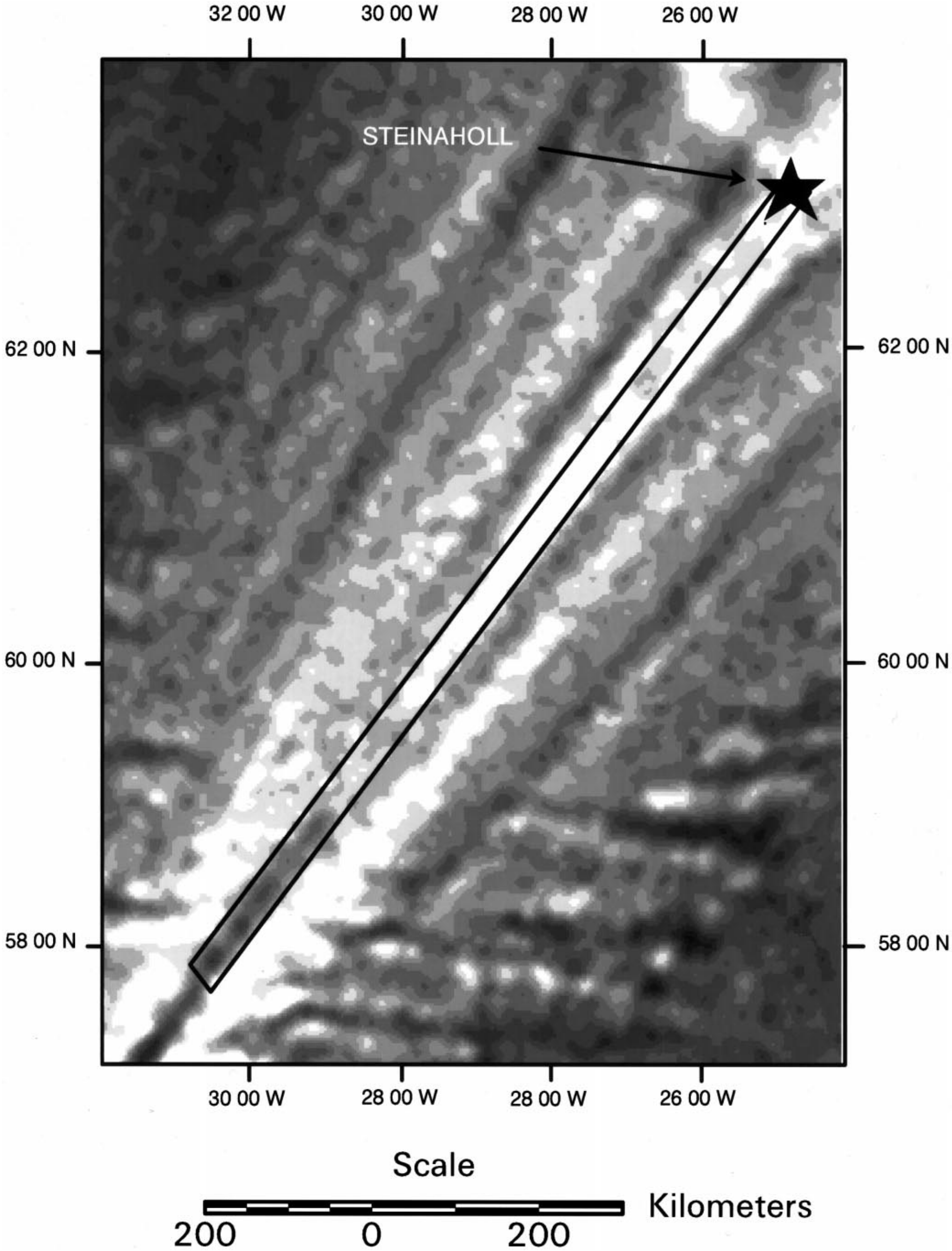

Fig. 3. Gridded estimate of Atlantic seafloor topography (57–63.5ºN) including the Reykjanes Ridge, indicating the area within which 175 closely spaced CTD stations were occupied. The location of the only hydrothermal plume detected, at Steinahóll near 63º06′N, is located by the solid star. CTD survey area and Steinahóll location from Ref. [19], estimated topography from Ref. [61].

hydrothermal plume data-sets considered —i.e. are we comparing like with like? For the central MAR between 11º20′N and the Atlantis Fracture Zone we have seen that directly comparable results are obtained from both CTD profiling techniques [14,15] and the along-axis TOBI/transmissometer survey

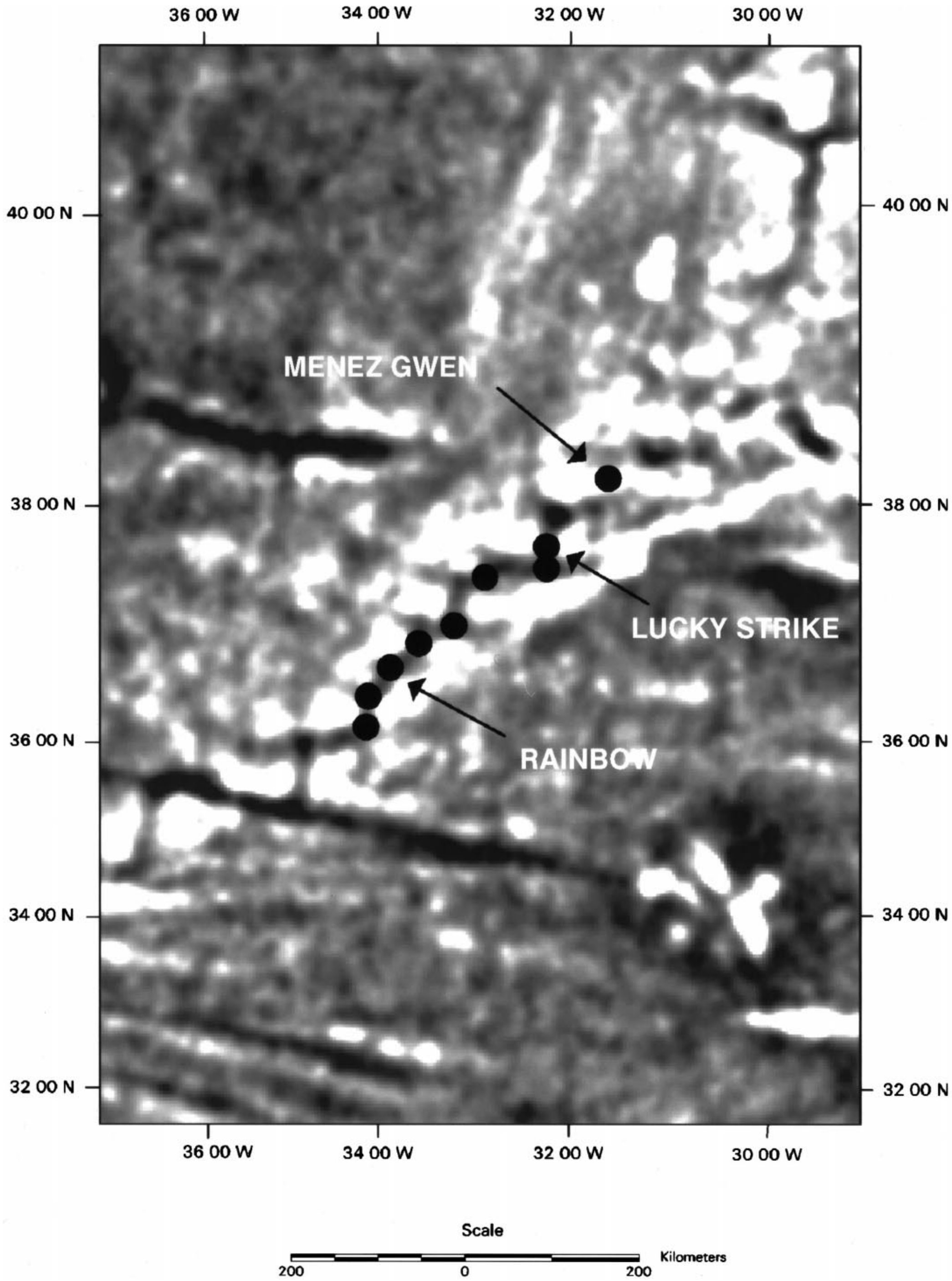

Fig. 4. Gridded estimate of Atlantic seafloor topography (32–42ºN), including the oblique and segmented section of the Mid-Atlantic Ridge (36–38ºN), southwest of the Azores, which hosts seven sites of hydrothermal activity as identified from TOBI-transmissometer anomalies (solid circles). Also labelled are the previously reported Lucky Strike and Menez Gwen vent-sites. Plume and vent locations are from Refs. [22–24], estimated topography is from Ref. [61].

[16]. This provides further confirmation of the validity of combining profiling and tow-yo approaches, as discussed recently by Scheirer et al. [33]. Further, the survey technique employed along the MAR 36–38ºN [22] was directly comparable to that employed along the MAR 27–30ºN [16] ensuring compatibility between those two data-sets. Perhaps the most intriguing data set, therefore, is that for the Reykjanes Ridge, where only one site of hydrothermal venting was identified. As discussed previously [19] the plume at Steinahóll could be detected across 8 km of water column, despite its shallow setting in which the effects of cross-currents on plume dispersion should be most problematic [34]. All other CTD profiles, further south along the Reykjanes Ridge, were conducted in increasingly deeper water where plume dispersion effects would not be predicted to be any more pronounced than at Steinahóll. Because the Reykjanes Ridge CTD profiles were typically occupied at spacings of $\leq$8 km, therefore (the exception was between 58º30′–59º30′N where 15 km spacing was employed along the crests of the consecutive AVRs) we do not believe that additional sites of presently active high-temperature hydrothermal venting could have been missed unless the lateral extent of their plumes was significantly less than this mean separation. Even if this were the case, however, the increased sampling frequencies of the Reykjanes Ridge survey, when compared to previous work between 11º20′N and 30ºN [14,15], would still indicate an anomalously low incidence of venting, or completely different styles of venting along the Reykjanes Ridge (see later).

Of course, relying upon water column data alone, one could still argue that the variability described above was purely a statistical departure from the Baker et al. model [11], due to insufficient lengths of ridge crest being considered. Indeed, in total, the three study areas represent some 2700 km of ridge crest hosting an estimated 25 sites of venting at a mean spacing of ~110 km which is not dissimilar to the average spacings predicted by the model. Importantly, however, our water column data have been collected together with co-registered seafloor observations. In the discussion which follows, we argue that any reported variability in the incidence of venting between these three study areas may be intrinsically linked to the differing styles of second-order ridge segmentation which they exhibit.

3.2. The importance of axial magmatism

The only site of venting identified along the Reykjanes Ridge was the Steinahóll vent-field which is located on top of an axial volcanic ridge in a neovolcanic setting [19,20]. In this regard, the site can be considered to be similar to the setting of East Pacific Rise hydrothermal fields in that it sits atop a section of maximum along-axis ridge elevation and maximum axial cross-section (cf. [2,3,35]). As described previously, segmentation of the Reykjanes Ridge is principally defined by these spaced axial volcanic ridges (AVRs) which, it has been argued, may represent fundamental building blocks of the entire slow-spreading Mid-Atlantic Ridge [18].

Recently, Sinha et al. [36] have used a combination of geophysical techniques to image an axial magma chamber beneath one particular AVR centred at 57º45′N on the Reykjanes Ridge. Chen [37] has argued that to maintain a magma chamber *at steady state* at such a shallow level in the crust would require anomalously inefficient near-axis hydrothermal cooling, consistent with the low incidence of hydrothermal venting reported from along the entire length of the Reykjanes Ridge [19]. This is contradicted, however, by Sinha et al. [38] who argue that crustal magma chambers at slow-spreading ridges such as the Reykjanes Ridge can only be transient or ephemeral features, generated on an episodic or cyclic timescale. From modelling of both seismic and controlled source electromagnetic measurements, MacGregor et al. [39] and Sinha et al. [38] argue that the upper 500 m of the crust of the 57º45′N AVR should be heavily fractured and saturated with seawater at temperatures of 100–200ºC, intermediate between seawater temperatures and conventional ~360ºC high-temperature black-smoker fluids. This is important because fluid circulating at such intermediate temperatures might result from dilution between conventional black-smoker fluids and seawater with concomitant subsurface precipitation of the dissolved metals typically vented to the ocean in other settings. As such, the nature of emission of such fluids might be quite different from what has typically been observed previously elsewhere along the mid-ocean ridge. A good corollary might be the Menez Gwen vent-site at 38ºN, MAR. There, clear fluids rich in reduced gases such as CH_4 and H_2S are vented from the seafloor (800 m water depth) in an axial volcanic setting but no conventional strong hydrothermal plume signals are developed in the overlying water column [40]. The occurrence of similar styles of venting along the Reykjanes Ridge, whether due to phase separation at these relatively shallow depths or as a result of pervasive subsurface mixing within the unusually high porosity crust of this unique setting, would be consistent with both geophysical and oceanographic observations because, whilst Sinha et al. [36] have concluded that vigorous hydrothermal venting should be hosted by the 57º45′N axial volcanic ridge, a series of CTD-nephelometer stations along the northern half of their study area, including one station directly above the axial magma chamber itself, reveal no evidence whatsoever for a conventional, black-smoker hydrothermal plume (Fig. 5).

Of course, we would not use this single example to refute the idea that fresh neovolcanic activity can host hydrothermal activity on slow-spreading ridges. In addition to what has already been demonstrated for intermediate and fast-spreading ridges —see, e.g., review by Fornari and Embley [41]— it is also the case that a number of hydrothermal vent-sites have been located along the slow-spreading Mid-Atlantic Ridge which are also hosted by neo-volcanic activity. Such sites, which have been ground-truthed by submersible observations, include Snakepit [42], Broken Spur [43], Lucky Strike [23] and Menez Gwen [24] in addition to the AVR-hosted Steinahóll site on the Reykjanes Ridge [20]. What the 57º45′N AVR case-study does reveal, however, is that we cannot yet make reliable predictions about the presence or absence of hydrothermal venting, using even our most sophisticated interpretations of magmatic–tectonic cycles in isolation (cf. [2,36]).

3.3. The possible role of ridge segmentation

It has become clear, from recent studies of the TAG hydrothermal mound at 26ºN, that not all vent-sites on this slow-spreading ridge are neovolcanically hosted. The TAG mound is one of the largest submarine hydrothermal fields yet discovered in the world's oceans [44] and is much larger than those typically found along the EPR or in the neovolcanically hosted Snakepit and Broken Spur sites, elsewhere along the MAR [41–43]. Radioisotope dating indicates that intermittent high-temperature hydrothermal activity must have persisted at this site over the past 20,000 years [45,46]. In a recent DSL120 sidescan sonar survey of the area, Kleinrock and Humphris [47] demonstrated that the TAG site is located at, and perhaps fed via, the intersection of two cross-cutting fault populations. One set of faults strikes ridge-parallel, largely NNE, but beneath the TAG mound these faults intersect with an older set of faults striking ENE. The later ridge-parallel faults have caused recent extension leading to the opening of fissures within the mound which themselves also host fresh black-smoker venting [47].

More recently, work along the MAR southwest from the Azores Triple Junction has shown that the tectonically controlled venting so clearly demonstrated at TAG may not be an isolated occurrence but, instead, may be relatively widespread along slow-spreading ridges [22]. Towed transmissometer anomalies, coupled with CTD-rosette profiling stations have revealed evidence for a suite of hydrothermal vents, including the FAMOUS and Rainbow hydrothermal areas [26,48], in four different non-transform discontinuities (NTDs). The Rainbow vent site at 36º13.80′N, 33º54.12′W is the first site to be investigated in detail within one of these NTDs and the largest high-temperature vent-field observed in this section of ridge to date. It lies on the west flank of the Rainbow Ridge (water depth 2270–2320 m) and covers a surface of 250 m $\times$ 60 m [26]. Diving investigations have demonstrated that, like TAG, the Rainbow site is located at the intersection of structures related to two dominant fault populations (azimuths: 000º, 040º). Latest bathymetric and submersible observations indicate that these fault patterns both control the form of, and cross-cut, Rainbow Ridge [26,50]. Because the area is characterised by high sedimentation rates and sediment re-working [26,49,50] the assumption can be made that any such exposed structures on the seafloor must result from relatively recent activity. The Rainbow Ridge is considered to have originated as a relict, rifted fault block, rotated down to the east to expose its serpentinised, mixed ultrabasic western face, in-

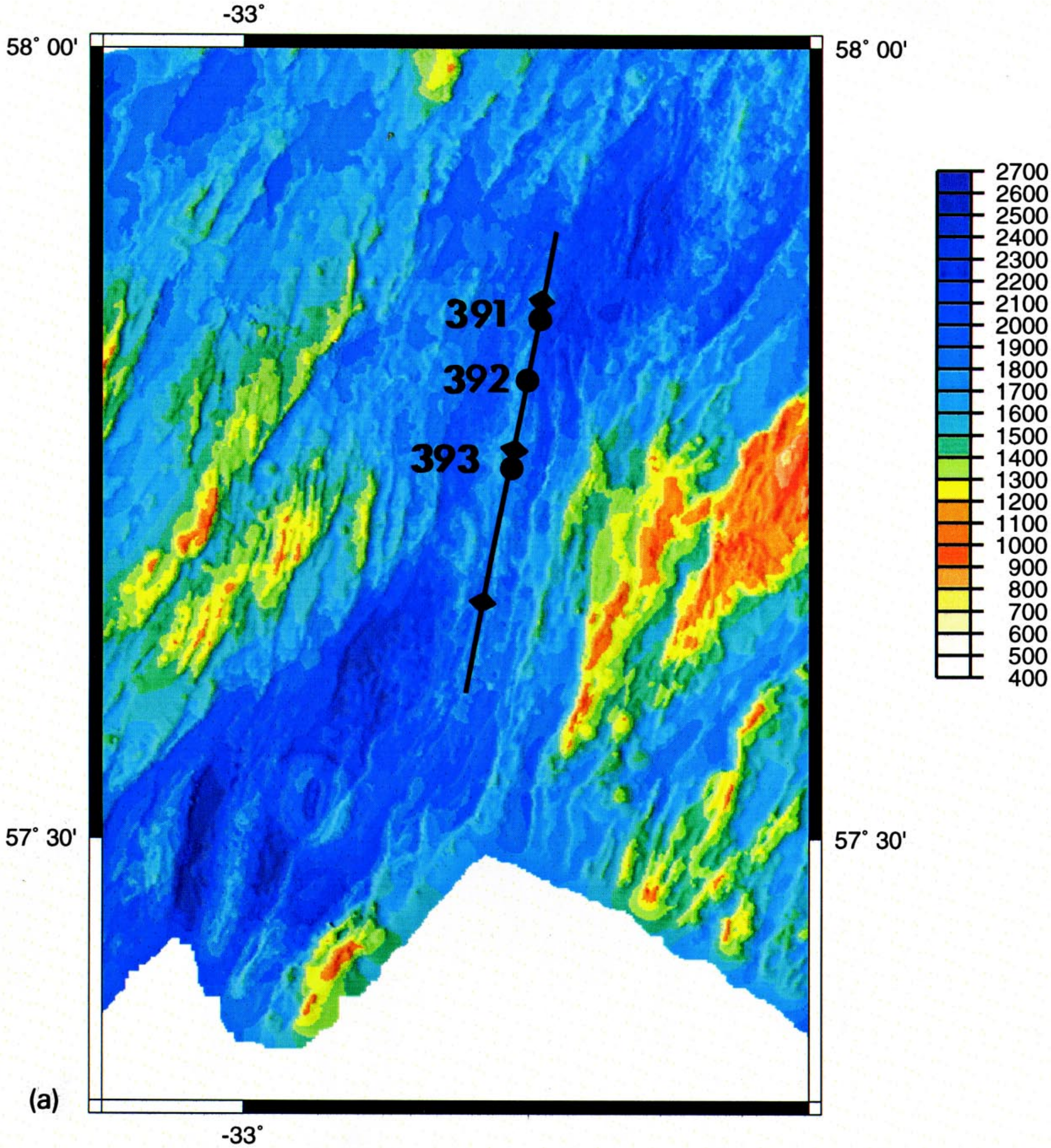

Fig. 5. (a) Swath bathymetric map of the 57º45′N AVR area, Reykjanes Ridge. Solid circles show the locations for CTD vertical profile stations shown in (b). Line and diamonds show the along-axis tow of the CSEM transmitter and locations of combined seismic and electromagnetic instrumentation for the AMC study [38]. Bathymetry data courtesy of C. Peirce and R. Searle (Univ. Durham, UK) and M. Sinha (Univ. Cambridge, UK). (b) Vertical profiles of nephelometer data above the northern half of the 57º45′N axial volcanic ridge (Stns. 391–393) showing no evidence for plume particle enrichments.

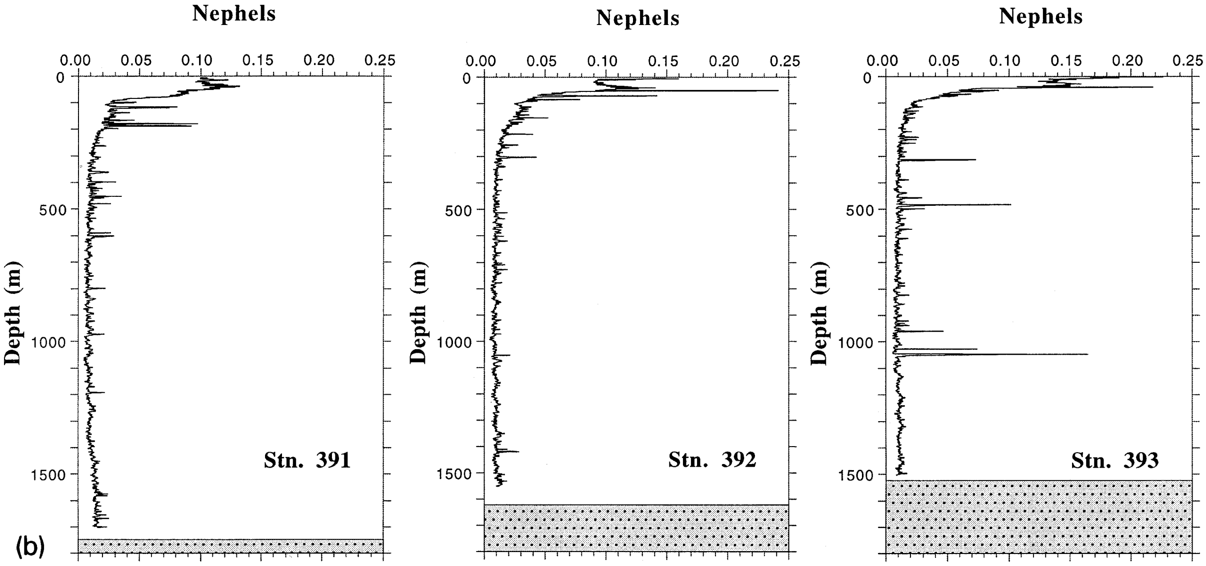

Fig. 5 (continued).

cluding the extreme western boundary of the vent field: a 25 m high fault scarp in which stockwork mineralisation is observed [26,50]. The orientations of the principal structures are those predicted by a combination of strike-slip and normal extension, as would be expected in *any* broad right-lateral ridge offset [51].

The detailed observations from submersible investigations at Rainbow [26] have provided precise confirmation of our earlier predictions based upon combined deep-towed sidescan sonar and water column properties in this area [22]. This lends support to our predictions that similar hydrothermal venting should also be expected in other NTDs where the same combination of sidescan and water column anomalies has been observed [22]. Indeed, the same argument could be extended further to argue that high-temperature hydrothermal venting may be relatively widespread in the NTDs of slow-spreading ridges in general. To argue such a case beyond purely empirical observations, however, requires some understanding of what the mechanism might be to sustain such hydrothermal circulation.

3.4. Possible mechanisms for venting in NTDs

Because we have no information on the subsurface configuration of the faults outcropping in the vicinity of the Rainbow hydrothermal field, any extrapolation to depth must remain speculative. Nevertheless, a first interpretation, based upon the preferential location of the Rainbow vents at the intersection of lineaments parallel to the principal NE–SW and N–S fault azimuths [26], would be that fluid circulation at Rainbow may be controlled by flow along active, open, fault surfaces. This would also be consistent with the apparent predominance of focussed high-temperature flow at this site with respect to lower-temperature diffuse flow [26]. For high-temperature hydrothermal circulation to be sustained within an NTD, however, a heat-source is required in addition to any fluid-circulation pathway. This would appear to contradict our current understanding of the second-order segmentation of slow spreading ridges in which maximum magmatic activity is concentrated toward segment centres and away from NTDs (e.g. [52]).

The closest expression of neovolcanic activity at the seafloor in the Rainbow area, as observed by TOBI sidescan data, is some 15–20 km distant in the south AMAR segment [22]. We can only speculate on the extent of any *subsurface* magmatic intrusions away from the segment centre and towards Rainbow Ridge, beneath the extensively sedimented axial floor. However, the new models of Gràcia et al. [51] would predict along-segment migration of the locus of the extrusive centre and this may support the suggestion that some associated lateral thermal flux may contribute to the heat flux represented by the Rainbow hydrothermal system. The requirement of a magmatic budget to sustain Rainbow-like high-temperature hydrothermal venting at segment ends continues to present problems in the general case, however, if one assumes that the processes associated with the axial magma chamber beneath the 57º45′N AVR on the Reykjanes Ridge are indeed representative of slow-spreading ridges in general [38]. Modelling of the emplacement volume for magma beneath the 57º45′N AVR, coupled with the ridge-spreading rate, would suggest that no high-temperature hydrothermal circulation could be sustained over more than 10–20% of the period between successive magmatic emplacement events —i.e. continuous hydrothermal venting could not be sustained at any one location for more than 1–2 ka [38,39]. Set against this is the case of the TAG hydrothermal field where radiometric dating indicates that the site has been exhibiting prolonged hydrothermal venting over a period of 10–20 ka [45,46]. Although no similar radiometric dating has yet been conducted at the newer location, the Rainbow hydrothermal field is comparable in lateral extent to the TAG system [26], requiring either that venting comparable to present-day activity has been extant over relatively long (order 10 ka) time-scales at Rainbow, or that vigorous hydrothermal venting, even more pronounced than at present, has existed there in the recent past. Either scenario would require a more significant heat source than can be accounted for from our present understanding of magmatism associated with second-order ridge segmentation.

An alternate source of heat could be linked to the observation that the Rainbow hydrothermal field is hosted entirely by ultramafic rocks [26]. Gràcia et al. [51] have recently presented a model in which exposure of ultramafic massifs should be favoured at second-order segment NTDs and it is certainly the case that such ultramafic outcrops have been identified elsewhere at segment ends along the slow-spreading MAR (e.g. [52–54]) whilst being almost entirely absent from the faster-spreading East Pacific Rise [55]. Further, Charlou et al. [56] have demonstrated that ultramafic outcrops at the ridge–transform intersection of the 15º20′N fracture zone are rich in precisely the same dissolved reduced gases, H_2 and CH_4, that would be predicted to be produced from hydrothermal serpentinisation of peridotite in the oceanic crust [57]. Exactly the same dissolved reduced gases are also extremely enriched in the first vent-fluids collected from the Rainbow hydrothermal field [58]. Although the serpentinisation reactions involved are strongly exothermic, however, [59] it remains contentious whether such processes could proceed sufficiently rapidly and/or extensively to support the high-temperature flux represented by the Rainbow hydrothermal field [60]. Nevertheless, structures identical to those which host the Rainbow site are increasingly being recognised elsewhere along the slow-spreading Mid-Atlantic Ridge (E. Gràcia and L.M. Parson, unpubl. data) and these may also host vigorous hydrothermal venting [22]. Whilst observations of vigorous NTD-hosted hydrothermal venting apparently contradict our current best understanding of magmatic–tectonic processes along slow-spreading ridges, therefore, they seem certain to remain an area of immediate interest for continuing research.

4. Summary

Hydrothermal activity has been investigated along three different sections of the slow-spreading Mid-Atlantic Ridge: 11º20′–30ºN, 36–38ºN and the Reykjanes Ridge, 57º45′–63º06′N. In total, the incidence of venting along all three sections compares well with the simple linear predictive model of Baker et al. [11] which relates plume incidence to ridge spreading-rate. On a section-by-section basis, however, direct observations depart from the model by up to an order of magnitude. This may result from a statistically non-representative length of ridge crest being considered, but we propose that the underlying magmatism and tectonics of each area may also be important. Along the Reykjanes Ridge, where a low incidence of both tectonic segmentation and hydrothermal venting has been reported, conventional black-smoker plumes are almost completely absent, even directly above a recently imaged axial magma chamber. One possible explanation for these observations could be that hydrothermal venting along the Reykjanes Ridge manifests itself as some form of pervasive diffuse flow which does not support production of mid-water neutrally buoyant plumes. Along the oblique and segmented MAR 36–38ºN, by contrast, abundant evidence for black-smoker hydrothermal plumes is observed, in both segment centres and the broad non-transform discontinuities which characterise the segment ends of this ridge-section. In the first such example investigated by submersible, to date, an extensive and vigorous sulphide deposit has been reported hosted by ultramafic rocks [26]. Whilst the exact mechanisms to support this system remain problematic, we propose that vigorous hydrothermal venting in a segment-end NTD is focussed along deep-penetrating active fault-surfaces with the requisite heat supply provided by some combination of along-axis magmatic intrusions coupled with an additional thermal flux resulting from peridotite serpentenisation.

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