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Reduced crustal magnetization beneath the active sulfide mound, TAG hydrothermal field, Mid-Atlantic Ridge at 26°N

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ABSTRACT

A detailed near-bottom magnetic field survey was carried out by the submersible *Alvin* over the actively venting mound located within the TAG (Trans-Atlantic Geotraverse) hydrothermal field on the Mid-Atlantic Ridge at 26°08′N, 44°49′W. Three-dimensional analysis of these data clearly shows a distinct zone of reduced magnetization directly beneath the active mound. This magnetization low is consistent with the highly altered upflow zone of a hydrothermal vent system that feeds the actively venting mound structure. In contrast, the sea surface magnetic anomaly is associated with a broad 2×8 km magnetization low elongated along the axis, that includes both the active and inactive mounds. The short-wavelength (250 m), near-bottom magnetic anomaly over the active mound is far too small to produce the long-wavelength (8 km) sea surface magnetic anomaly at TAG however, and even a collection of mounds with similar magnetic structure cannot produce the magnetic moment needed to generate the sea surface anomaly. Other hypotheses, including reversely magnetized crust and structurally thinned crust could account for the sea surface anomaly but are considered unlikely. The existence of vigorous hydrothermal activity at TAG and the lack of microseismic activity in the TAG area suggests that thermal demagnetization is the prime contributor to the sea surface anomaly. The thermal halo associated with a largely solid but still hot intrusion would provide sufficient demagnetization on a kilometer scale to produce the long-wavelength sea surface anomaly. Pervasive alteration at depth would also be an important factor in the destruction of crustal magnetization and is the only way that such a long-wavelength magnetic signal could be preserved in the crust. The overall model of crustal magnetization at a hydrothermal field with discrete zones of demagnetization in the upper crust and a broader zone of demagnetization at depth is consistent with studies of hydrothermal systems in ophiolite suites. These studies show narrow alteration pipes in the upper crust feeding the exhalative seafloor deposits and pervasive alteration at depth which commonly have associated late-stage intrusive bodies [1]. While detailed magnetic surveys may provide some clues to the location of oceanic hydrothermal upflow zones, only drilling will ultimately test these hypotheses.

1. Introduction

A considerable body of literature exists to support the effects of hydrothermal processes upon the magnetic properties of ocean crust. Laboratory studies have shown that magnetic minerals are highly sensitive to the corrosive fluids of hydrothermal systems and are rapidly altered to less magnetic minerals [2,3,4]. The relatively low Curie point temperatures (150–200°C) of young mid-ocean ridge basalt also allow magnetic anomalies to be created by the process of thermal demagnetization [5,6]. Magnetic anomalies have been measured over ancient hydrothermal deposits found in ophiolites [7], extant terrestrial hydrothermal systems [8] and also over deep-sea hydrothermal systems such as in the Red Sea and on the Mid-Atlantic Ridge (MAR) at TAG, 26°N [9]. Despite this evidence, however, the association of an anomalous magnetic signature over deep-sea hydrothermal systems has been the topic of some controversy. Part of the problem has been the small scale (< 1 km) of hydrothermal features relative to the magnetic field observation level (usually at the sea surface, 2–4 km above the seafloor) but also the restriction of two-dimensional (2D) profile analysis of an essentially three-dimensional (3D) feature. In this study, we present a detailed 3D analysis of the TAG hydrothermal system utilizing the *Alvin* submersible magnetometer in a 1990 near-bottom survey of the active mound at TAG. The results of this survey are then compared to the sea surface magnetic data recently collected in a 1989 SeaBeam survey of the MAR from the Kane to Atlantis fracture zones [10] in an effort to better understand and quantify the source and relationship of the observed anomalous magnetic signal to the geologic structure of oceanic hydrothermal systems.

2. Geologic Setting

The Mid-Atlantic Ridge at 26°N is marked by a 15 km wide, 4 km deep axial valley with steep, 2 km high, rift valley walls (Figs. 1 and 2, *upper*). The average spreading rate is approximately 11 km/Myr based on the Brunhes/Matuyama magnetic reversal boundary position [11]. High-temperature hydrothermal venting on the MAR was first discovered in 1985 at the TAG site (26°08′N, 44°49′W) [14] but was hinted at several years earlier by dredge samples, water temperature measurements [9,15], chemical plume sensors [12,13,14] and metalliferous layers in sediment cores [16]. The TAG hydrothermal field is located near the center of a ridge segment on the eastern side of the rift valley at the base of a marginal high, between the depths of 3620 m and

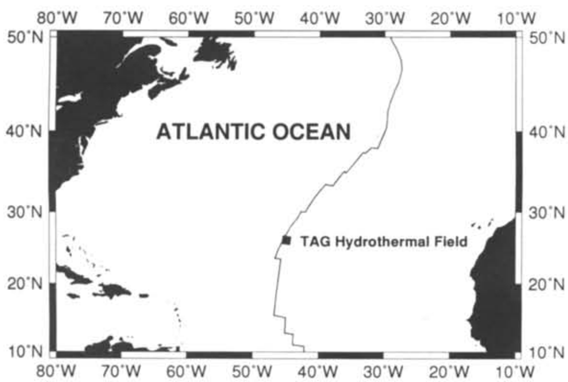

Fig. 1. Location map showing the TAG hydrothermal field (box) located on the northern Mid-Atlantic Ridge axis (solid line) at 26°08′N.

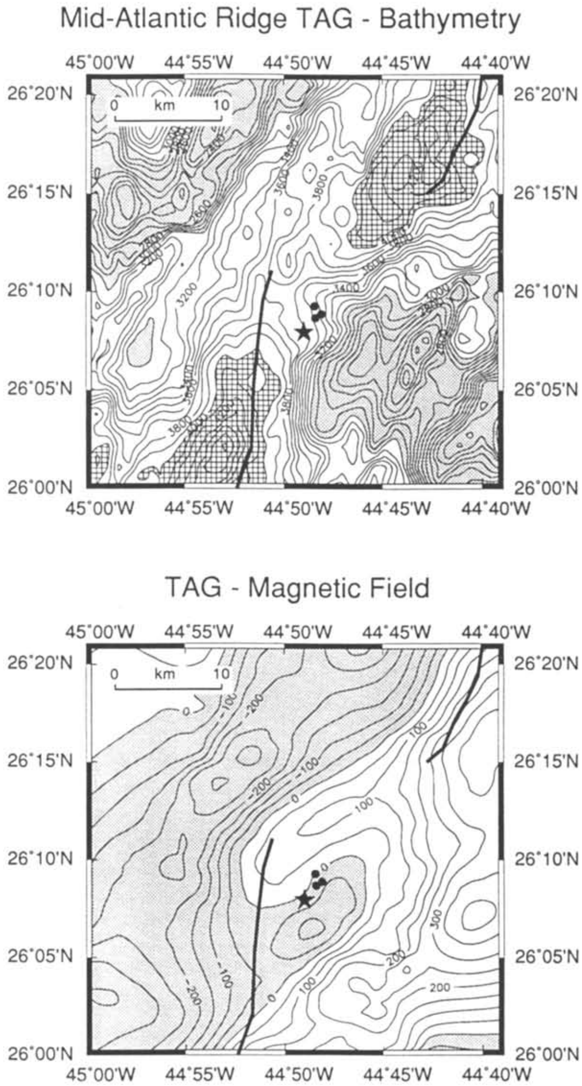

Fig. 2. *Upper figure* shows the Seabeam bathymetry of the TAG area (100 m contours) showing the rift valley and the eastern and western walls. Bathymetry above 3000 m is stippled, and deeper than 4000 m is shown by cross-hatch shading. *Lower figure* shows the sea surface magnetic anomaly field over the TAG area (50 nT contour interval) with the asymmetric Brunhes anomaly and the 3D yin and yang shape of the TAG anomaly low. Negative magnetic field is shown stippled. In both figures the location of the TAG active mound is shown by the star and the relict mound locations by the dots. The axis of spreading is shown by the solid black line. Data from Purdy et al. [10].

3675 m [17] (see Fig. 2, *upper*). Based on simple spreading models, the active mound is located on crust approximately 100,000 yrs old that is consistent with radiochemical dating of sulfide samples

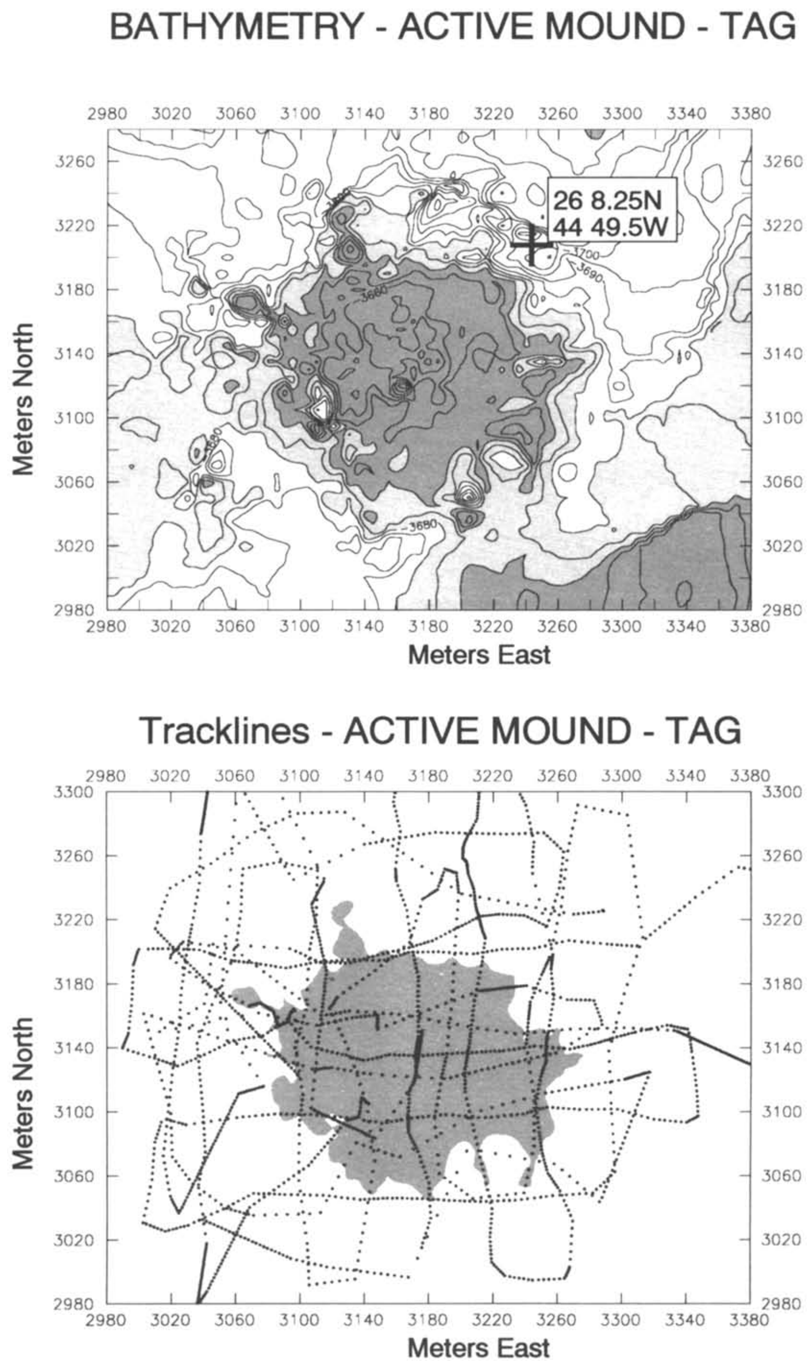

Fig. 3. *Upper figure* shows the detailed bathymetry map of the active mound at TAG (5 m contours) compiled from *Alvin* submersible depth and altitude data. The high-temperature black smoker vents are located on the highest part of the mound near the center. The lower temperature Kremlin vents are located in the southeast quadrant of the mound. *Lower figure* shows the magnetic survey tracklines over the mound made during two *Alvin* submersible dives (2181 and 2184). The active mound outline is shaded in grey.

from the TAG mound, which show an age range of zero to 100,000 yrs [18]. The age-dating results also show a periodicity of 6000 yrs, suggesting cyclic renewal in hydrothermal activity of the mound [17,18]. The active mound itself is approximately 200 m in diameter and 50 m high and is mostly composed of massive sulfides and sulfide debris located on top of a platform of lavas [17]. In addition to the active mound, there is evidence of several inactive sulfide mounds of equal or greater size a few kilometers to the northeast of the active mound, also along the base of the rift valley wall (Fig. 2, *upper*) [19]. Although the crustal structure at the TAG ridge segment is not well constrained, a microseismicity survey noted a distinct lack of earthquakes in the vicinity of the TAG hydrothermal field [20]. This dearth of activity suggests that the crust beneath TAG cannot support brittle failure, and this is consistent with a heat source at depth that promotes hydrothermal fluid circulation and fuels the active black smoker field.

A sea surface magnetic anomaly over the TAG area was first reported by McGregor and Rona [12] in a geophysical and seafloor dredging survey of the region. Their 2D profile analysis of these magnetic data suggested that the crust beneath the rift valley in the TAG area is less magnetic than adjacent crust [11,12]. The subsequent discovery of high-temperature venting has increased interest in the possibility that the alteration and thermal effects of hydrothermal activity could generate sufficient crustal demagnetization to produce magnetic anomalies. The original 1972 magnetic data has been recently reanalyzed and interpreted by Wooldridge et al. [21] using 3D magnetic analysis. We present a similar 3D analysis of a more recent (1990) magnetic and Seabeam bathymetry survey of the MAR [10,22] that is free of any navigational ambiguities that are inherent in pre-GPS (Global Positioning Satellite) era surveys (Fig. 2, *lower*). Both studies find that the TAG magnetic anomaly delineated by McGregor and Rona [12] is in fact part of a distinctly 3D anomaly with a peak-to-trough amplitude of 200 nT and peak-to-trough distance of 8 km (Fig. 2, *upper*). The dipole morphology of the TAG anomaly is indicative of a negative 'point-source' within the positively magnetized Brunhes crust [21]. The location of the active mound at TAG (shown by the star in Fig. 2, *lower*) lies along the maximum gradient in the magnetic field within a few kilometers of the center of this anomaly. In addition, the sites of the known extinct hydrothermal mounds mapped to date [19] also appear along this same maximum magnetic field gradient, to the northeast of the active mound (see dots in Fig. 2). This coincidence would suggest that hydrothermal activity plays a major role in the source of the TAG sea surface magnetic anomaly.

In order to evaluate the potential impact of hydrothermal activity on the magnetization of ocean crust and the role that the active TAG mound plays in the generation of the sea surface anomaly, a detailed magnetic study of the mound was carried out by submersible. The practical aspects of seafloor submersible surveys limit the survey to a small region of approximately 500×500 m in area. This implies that such a survey does not sample the entire area represented by the TAG sea surface magnetic anomaly; it will however, allow us to determine the role that the active TAG mound plays in the source of the sea surface anomaly.

3. Submersible magnetics

In January 1990, a detailed magnetic survey of the active mound and adjacent area was performed using a three-axis fluxgate magnetometer mounted on the sample basket of the submersible *Alvin*. These magnetometer data were calibrated on the submersible by having *Alvin* actively spin on descent and ascent, which allowed a determination of the induced field effects of the submersible so that corrections could be applied. Magnetic data were collected during two *Alvin* dives (2181 and 2184) along a draped survey grid over the mound at two elevations (altitudes of 2 m and 20 m) (see Fig. 3). The submarine was navigated using the standard long baseline acoustic transponder technique. Submersible depth and altimetry data from these dives were used to construct a bathymetric map of the active mound (Fig. 3, *upper*). Note that the area of the survey is very small, approximately 350×400 m, but adequately covers the mound and the immediate environs. The total magnetic field was first calculated from the three-component data and cor-

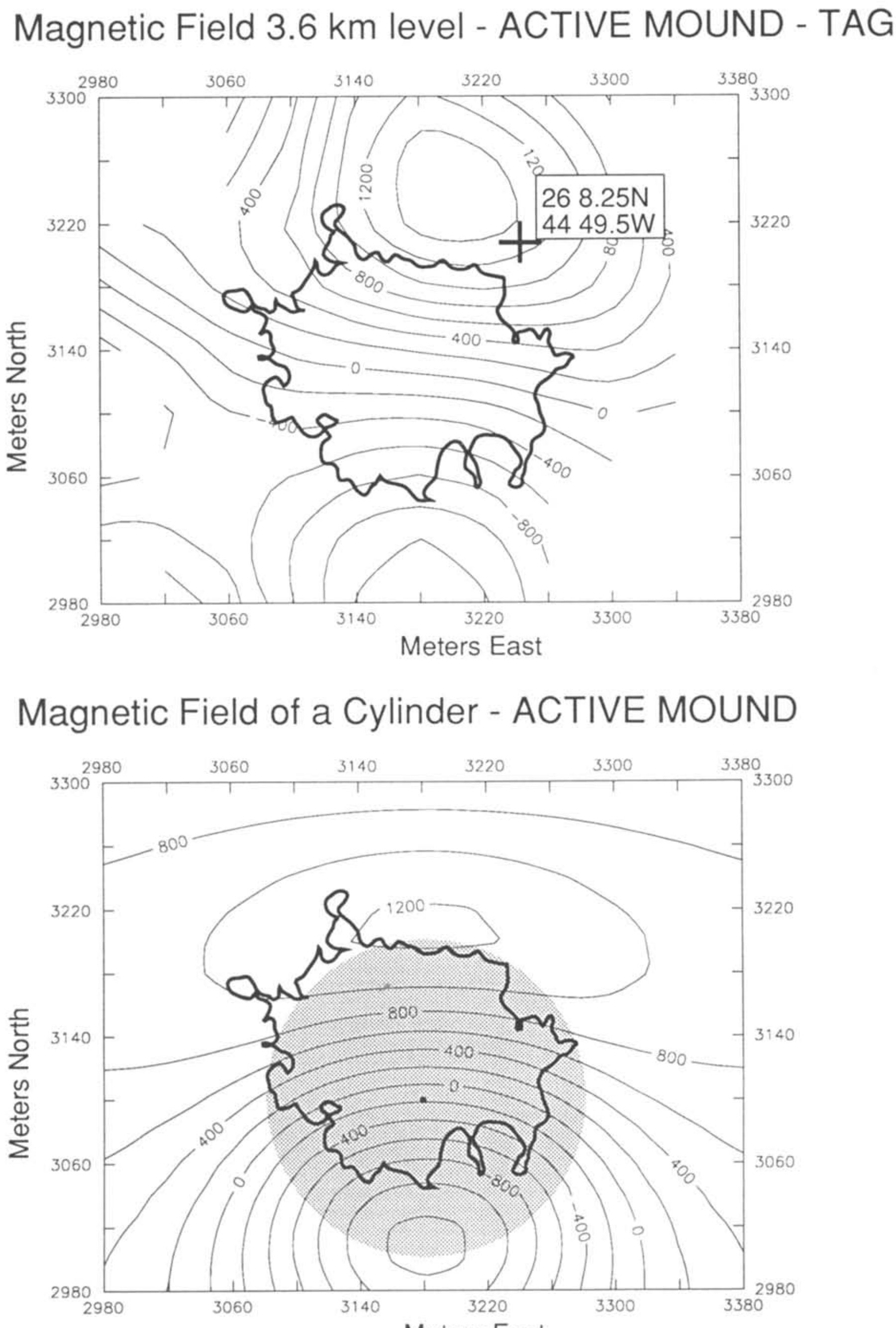

Fig. 4. *Upper figure* shows the near-bottom magnetic field measured over the mound at TAG by the submersible *Alvin* (200 nT contour interval) and continued upward to a level plane at the 3600 m depth. Note the dipole anomaly high/low pair and steep gradient located directly over the mound, indicating a magnetization low beneath the mound. The 3670 m isobath outlining the mound is shown by a bold line. *Lower figure* shows the magnetic field of a forward model of a vertically oriented cylinder (shown shaded) with magnetization of −12 A/m, a depth extent of 500 m and a radius of 100 m, observed 75 m above the seafloor (inclination 45°, declination 0°). Note the similarity of this synthetic field to the observed field in the upper figure.

rected for the magnetic field of the submersible before removing the International Geophysical Reference Field (IGRF 1990, [23]). The resultant magnetic anomaly field data were then interpolated onto a grid with 20 m node spacing and continued upward to a level plane above the mound (depth of 3600 m) by using an equivalent layer technique [24]. The magnetic data from the two survey elevations were treated separately and then averaged for the upward-continued field at the 3600 m depth (Fig. 4, *upper*). The upward-continued magnetic field shows a dipole anomaly with a peak-to-trough amplitude of 2800 nT and a peak–trough distance of 250 m. The steepest gradient in the near-bottom magnetic field is found directly over the mound with a magnetic high to the north and low to the south (Fig. 4, *upper*). This anomaly configuration, at this latitude (i.e. inclination 45°), indicates that crustal magnetization reaches a minimum directly beneath the mound. A simple forward model based on a 500 m long cylinder buried at a depth of 75 m (radius 100 m, and magnetization of -12 A/m) beneath the active mound produces a magnetic field that approximates the amplitude and wavelength of the observed near-bottom anomaly (see Fig. 4, *lower*).

The near-bottom magnetic field (Fig. 4, *upper*) can be inverted for crustal magnetization using the three-dimensional Fourier inversion approach of Parker and Huestis [25], which also takes into account the effect of bathymetry. The magnetization solution was bandpass filtered between 10 and 0.1 km after each iteration to ensure convergence of the inversion solution. The main assumptions of the Fourier inversion method are (1) that the magnetization is constant with depth and varies only in the horizontal dimension, (2) the direction of magnetization is fixed in the direction of the geocentric axial dipole and (3) the source region is a magnetized layer of constant thickness (500 m for this study) whose upper boundary is defined by the bathymetry (i.e. the *Alvin* bathymetry, Fig. 3, *upper*). While some plausible geologic justifications can be made for these assumptions (see Parker and Huestis [25]

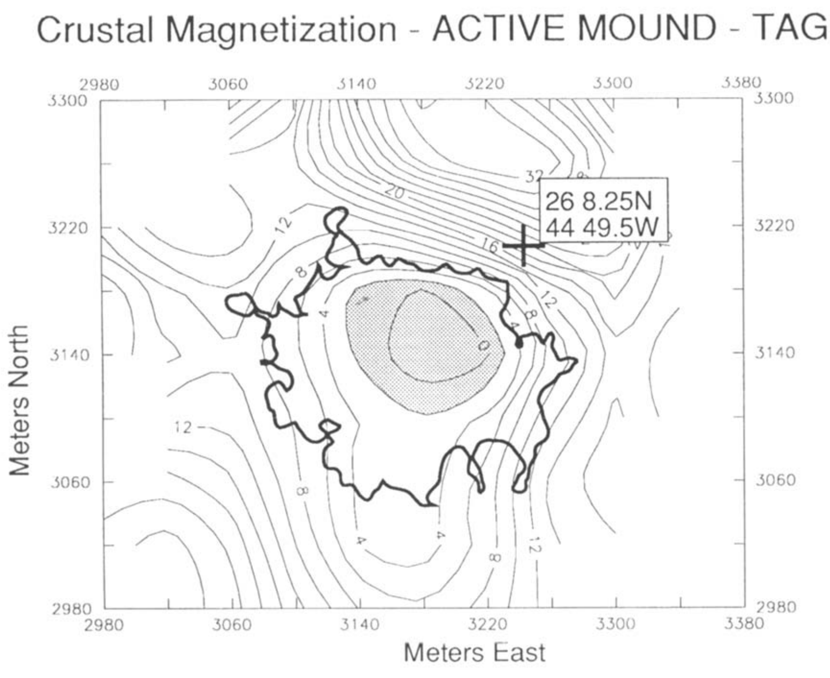

Fig. 5. Crustal magnetization (2 A/m contours) of a 500 m thick constant thickness layer calculated from the observed field and bathymetry using the Parker and Huestis inversion technique [25]. Sufficient annihilator was added to the solution to bring the mean of the area up to 12.5 A/m, equivalent to the mean rock sample NRM's [26]. The 3670 m isobath is shown by the bold line. Note the relative magnetization low directly beneath the mound area and the abrupt contrasts to higher magnetization at the edge of the mound indicating a tightly constrained source region.

for a discussion), they remain a source of error, which along with the inherent non-uniqueness of the inversion process constitutes limitations of the magnetic method in resolving anomalous source bodies.

One measure of the non-uniqueness of the inversion solution is the annihilator function, which is a magnetization that produces no external magnetic field when convolved with the bathymetry. An infinite amount of annihilator may be added to or subtracted from the inversion solution without affecting the magnetic field, but commonly sufficient annihilator is added to the solution to balance the positive and negative magnetization at a reversal boundary, assuming no polarity bias exists. There are no reversal boundaries within the *Alvin* study area, making it difficult to gauge the amount of annihilator to add or subtract from the inversion solution. The topographic effect is, however, minimal so that the annihilator essentially becomes a baseline shift. An estimate of how much annihilator to add can be obtained from the mean level of natural remanent magnetization (NRM) of rock samples collected from the TAG area. Wooldridge et al. [26] measured basalt sample NRM's that ranged from 5 to 29 A/m with a mean of 12.65 A/m. Enough annihilator is added to bring the mean of the calculated magnetization map up to 12.5 A/m.

The resultant magnetization is shown in Fig. 5 and convincingly demonstrates that crustal magnetization reaches a minimum directly beneath the mound. Abrupt transitions to higher magnetization occur at the edges of the mound to further delineate the magnetization minimum. The extension of the low magnetization zone to the south may indicate a possible dip of the source body in this direction. The high magnetization area found 100 m north of the mound was investigated as possibly being due to an artifact of the bordering process, which is required by the Fourier method, but a number of different bordering approaches showed that this is not the case. This suggests that the magnetization high is a geologic feature, perhaps indicating the presence of recent lava flows similar to those observed by Zonenshain et al. [27] to the south and west of the mound. The magnetization minimum in Fig. 5 could represent either reversely magnetized crust or demagnetized crust, but since the reduced magnetization barely goes negative this suggests that the crust is not reversely magnetized but demagnetized (i.e. reduced to zero). Although qualitative, this observation along with the tightly constrained areal extent and localization of the crustal magnetization minimum directly beneath the active mound suggests that demagnetization by hydrothermal processes rather than reversed magnetization is the most likely explanation for this low, although the latter cannot be ruled out by these data. The Wooldridge et al. [26] study also notes that the basaltic rock samples show little or no oxidation or hydrothermal alteration, implying that if alteration of the upper crust is taking place it is occurring in discrete areas as exemplified by the near-bottom survey. Alternatively, altered rocks may have been covered by more recent and more magnetic lavas. It is interesting to note, however, that the most altered rocks in the Wooldridge et al. [26] study were from stratigraphically deeper sections of the crust.

The amplitude of the magnetization low in Fig. 5 is approximately 12 A/m relative to the mean magnetization of the surrounding area. This magnetization contrast multiplied by source body volume gives a magnetic dipole moment of the order of 10^8 Am^2 for this near-bottom anomaly. This is equivalent to the magnetic moment of a pipe-like, cylindrical body of radius 100 m, length (depth) 500 m and a magnetization contrast of 12 A/m. The magnetic field of such a body (Fig. 4, *lower*) is capable of reproducing the general form and amplitude of the observed near-bottom anomaly (Fig. 4, *upper*).

3.1 A geologic model of the active mound magnetic anomaly field

The location of a discrete zone of reduced magnetization directly beneath the hydrothermal mound is consistent with the presence of an upflow zone where hydrothermal fluids are channelled upward from a region at depth to be discharged at the seafloor vents. Upflow zones are typically marked by a stockwork zone which generally shows significant alteration and replacement of the host rock by secondary minerals within a tightly constrained area, i.e. an alteration pipe [28]. In oceanic crust, such intense alteration and replacement would totally destroy any original magnetic minerals, with magnetite replaced by non-magnetic sphene [2]. The dimensions of upflow zones or alteration pipes have been studied in some detail in ophiolite suites and range from a few tens of meters to several of hundreds of meters in diameter, which is consistent with the magnetic field observations of the TAG active mound [29,30,31]. At the Pitharokhoma deposit in Cyprus, the alteration pipes are approximately 100 m in diameter and extend vertically for several hundred meters, usually terminating at the dike-extrusive interface [29]. The central stockwork zone of the alteration pipes at the Mathiati deposit in Cyprus are also of the order of 180×60 m, and extend to an unknown depth. Evidence in the oceanic environment of a stockwork zone was mapped on the Galapagos rift at 85°50′W in 1985 and showed a sharply defined, 100 m wide zone of pervasively altered basalt directly beneath extinct vent structures [30]. Magnetic anomalies have also been measured over alteration pipes, with the well-defined 2000 nT magnetic anomaly low (200 m wavelength) over the Agrokipia mine stockwork in Cyprus being a prime example [7]. An estimation of the magnetic moment of the Agrokipia anomaly based on an 8 A/m contrast for a body with a volume of 8×10^6 m^3 gives a value of the same order of magnitude (10^8 Am^2) as the magnetic moment calculated for the active mound at TAG from the submersible data. Thus the model of a spatially confined ‘pipe-like’ upflow zone that is non-magnetic is a well-established geologic model which can easily explain the near-bottom magnetic results over the TAG active mound in the appropriate geologic context of a hydrothermal vent system.

4. Sea surface anomaly field

An important aspect of this study is the relationship of the near-bottom magnetic anomaly to the TAG sea surface magnetic field and how the distribution of hydrothermal mounds relates to

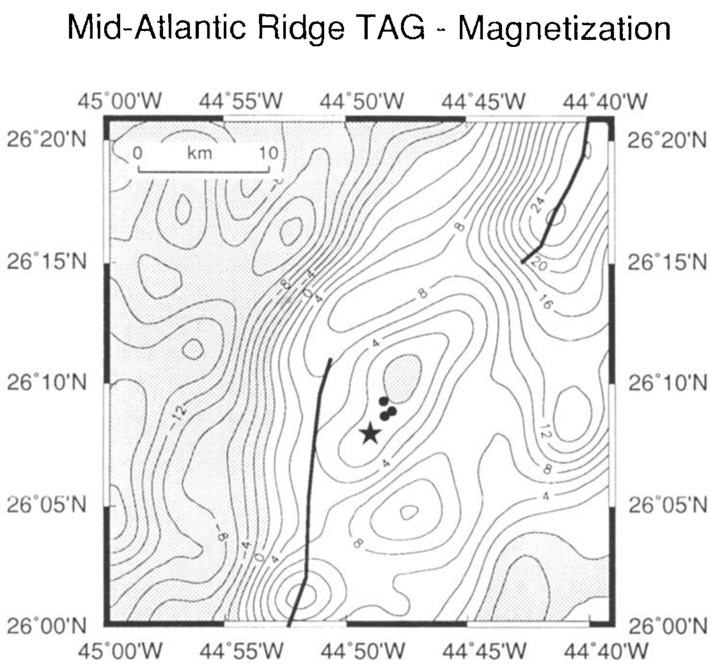

Fig. 6. Figure shows the crustal magnetization map of the TAG area (contour interval 2 A/m) calculated using the Fourier inversion technique of Parker and Huestis [25]. The source layer thickness is 0.5 km. Reversed magnetization (Matuyama epoch) is shown shaded gray, while positive Brunhes-aged crust is shown in white. The location of the TAG active mound is shown by the black star and the relict mounds by the dots. The axis of spreading is shown by the solid black line. Note the elongate magnetization low within the central Brunhes anomaly that includes both the active and inactive mounds.

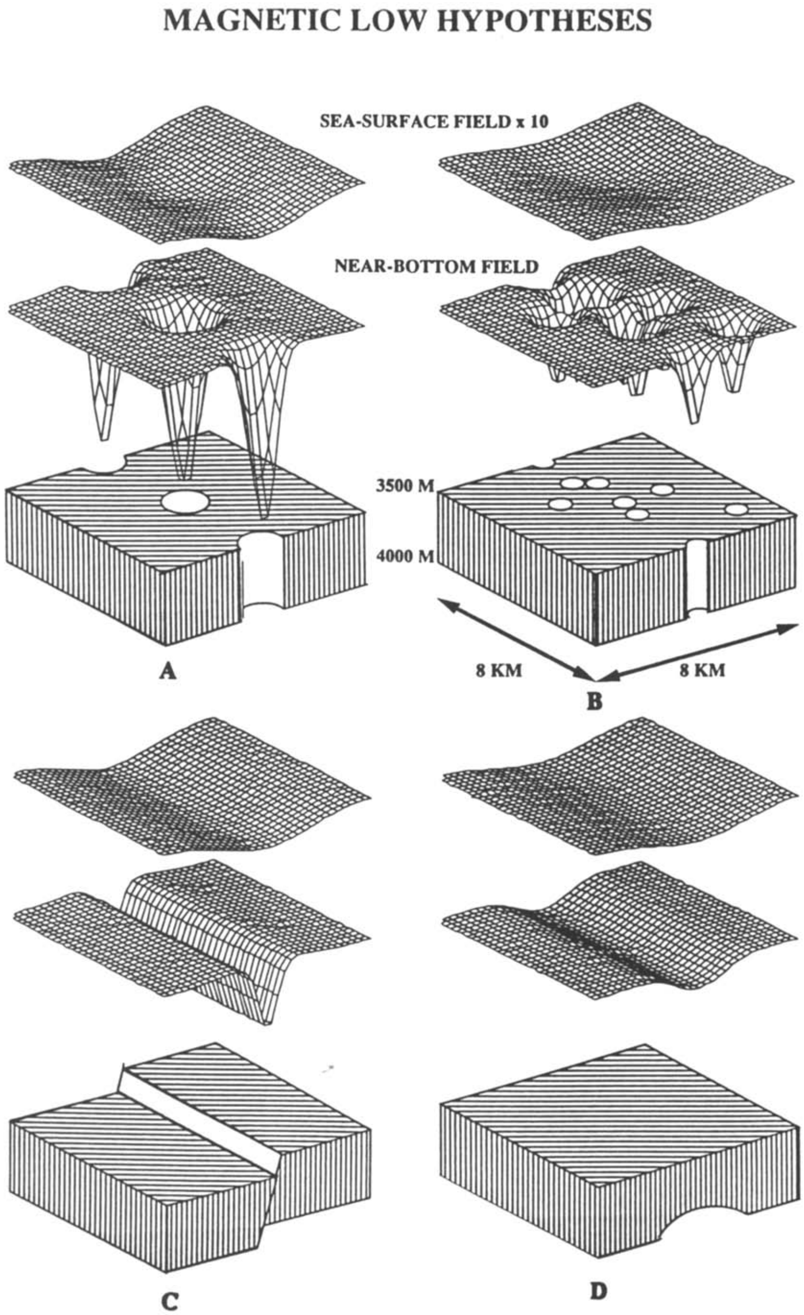

Fig. 7. Forward models for the source of the sea surface magnetic low anomaly over TAG. Each model has a cartoon block model of normally magnetized crust ($8 \times 8 \times 0.5$ km block and mesh size 0.25 km) with a near-bottom magnetic anomaly field calculated at 0.5 km above the source and a sea surface magnetic anomaly field calculated at 3.5 km above the source. In all cases the sea surface field is virtually indistinguishable between the different models. In contrast, the near-bottom field does show characteristic differences in the anomaly field for the different hypotheses. Model (A) shows the effect of individual demagnetized upflow zones producing a magnetic low at the sea surface. Model (B) shows the cumulative effect of a number of upflow zone magnetization holes that would produce a shotgun pattern in the near-bottom anomaly field and a smooth anomaly at the sea surface. Model (C) shows structural thinning of the magnetic source layer by normal faulting can produce a linear magnetic feature with a clear association with the normal fault location. Model (D) shows the effect of thermal demagnetization at the base of the source layer would produce a smoothly varying anomaly.

the sea surface magnetic anomaly. Before addressing this point certain aspects of the sea surface field warrant investigation. A 3D inversion of the TAG sea surface magnetic data (Fig. 2, *lower*) for crustal magnetization using the Parker and Huestis Fourier technique [26] is shown in Fig. 6. The inversion was obtained assuming a constant thickness layer (0.5 km) whose upper boundary is defined by the Seabeam topography (Fig. 2, *upper*) with a bandpass filter of 100 km to 4 km at each iteration to ensure convergence of the solution. A small amount of annihilator was added to balance the magnetization solution at the Brunhes–Matuyama reversal boundary. The computed magnetization (Fig. 6) shows a NE–SW trending elongate magnetization low with a 2–4 A/m contrast within the Brunhes positive anomaly. The TAG magnetization low is located along the eastern side of the rift valley, encompassing the entire TAG hydrothermal field with the active mound at the southern end and the extinct mounds to the northeast near the center of the magnetization low (Fig. 6). While the magnetic field of a small pipe-like body at depth beneath the active mound at TAG can reproduce the near-bottom field, this body produces a very small effect at the sea surface (< 1 nT in amplitude) and thus clearly cannot be responsible for the observed anomaly. Calculating a magnetic moment for the sea surface anomaly using the area enclosed by the 2 A/m contour (48 km^2), and multiplying by the model layer thickness of 0.5 km and the magnetization contrast (2 A/m) gives a value of approximately 5×10^{10} Am^2. This value is several orders of magnitude larger than the magnetic moment calculated for the active mound. This source magnitude difference and the location of the active mound towards the southern end of the sea surface crustal magnetization low both argue strongly against the active mound as the sole source of the TAG sea surface anomaly. Furthermore, it appears as though the area of lowest magnetization is a few kilometers to the north of the known extinct mounds, suggesting the possibility of more hydrothermal mounds in this relatively unsurveyed region. We will now discuss the different possible model sources for the sea surface anomaly using the near-bottom results as a constraint.

5. Discussion

There are a number of possible hypotheses for the source of the TAG sea surface magnetic anomaly low, which include hydrothermal alteration, thermal demagnetization and structural thinning of the magnetic source layer. Figure 7 summarizes these various hypotheses with forward models of each situation showing that while the sea surface observations cannot distinguish between these models, near-bottom surveys may be able to. An additional hypothesis that must be considered is the presence of reversely magnetized crust. The possibility of reversely magnetized crust within the normally magnetized rift valley of the MAR was first suggested in the FAMOUS expedition [32] but was later refuted [6]. Although reversely magnetized crust cannot be ruled out as a source of the TAG anomaly low, it appears unlikely that such a discrete zone of crust would be found coincident with a major hydrothermal vent system, at a ridge segment summit, with little or no tectonic disturbance. We therefore discard the embedded reversed crust hypothesis in favor of more likely alternatives that are consistent with the hydrothermal setting of the TAG region.

Multiple mound hypothesis: Although we ruled out the single mound hypothesis as a source of the sea surface anomaly, could a combination of several mounds with demagnetized pipes (Fig. 7B) generate the anomaly? In support of this, the sea surface magnetization inversion low appears to encompass both the active mound and the relict mounds (Fig. 6) [14,19]. The individual contributions of these relict mounds is unknown at present but by assuming the relict mounds have a similar structure to the active mound we can estimate the number of 'pipe-like' bodies needed to produce the sea surface anomaly. Comparing magnetic moments calculated from the sea surface magnetic anomaly (5×10^{10} Am^2) and the near-bottom anomaly (ca. 10^8 Am^2), several hundreds of mounds would be needed to produce the sea surface anomaly, which is clearly not realistic. This also implies that the source region for sea surface anomaly is likely to be more regional in extent and probably deeper in the crust. This is also supported by the lack of significant hydrothermal alteration of the basaltic rock samples collected from the TAG region in the Wooldridge et al. [26] study.

Structural thinning: A non-hydrothermal mechanism for creating the magnetic low at TAG is through structural thinning of the source layer at a normal fault (Fig. 7C). Depending on the dip and displacement of the fault, the magnetic source layer will be locally thinned, resulting in a mag-

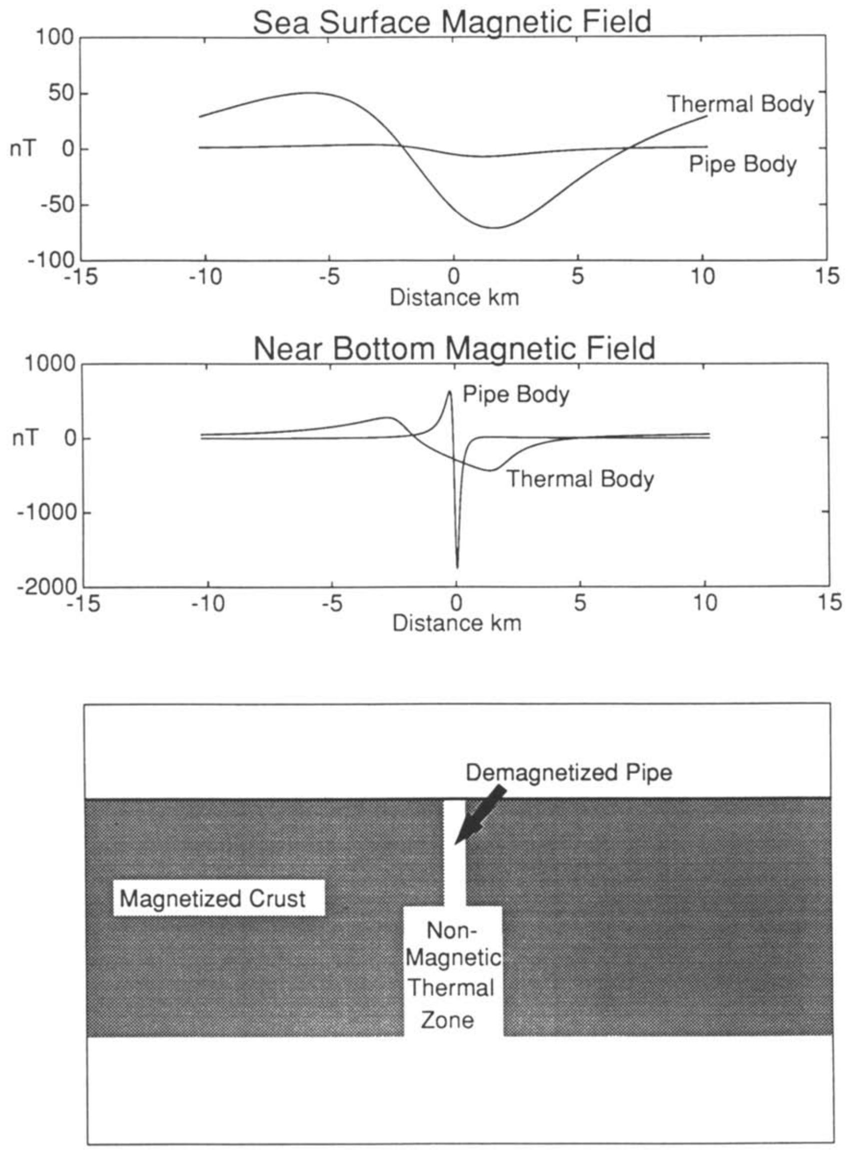

Fig. 8. Cartoon showing the relationship between the sea surface and near-bottom magnetic anomaly signature and the simplified vertical structure of a hydrothermal vent system. In the upper two figures, the magnetic field profiles due to the narrow non-magnetic pipe and the broad area of demagnetization at depth are plotted for two different observation levels, altitude of 100 m, i.e. near-bottom, and altitude of 4 km, i.e. sea surface. The profiles are along the magnetic meridian with a field inclination of 45°; north is to the right. The narrow upflow zone (diameter 100 m) consists of highly altered and non-magnetic rock and produces a large-amplitude, short-wavelength near-bottom magnetic anomaly but relatively little effect at the sea surface. The deeper demagnetized zone forms a halo around a heat source such as a late-stage intrusion and thins the magnetic source on a broader kilometer scale resulting in a long-wavelength anomaly that produces the majority of the magnetic signal at the sea surface but only contributes to the regional gradient in the near-bottom survey. Note that while this model is consistent with the observed magnetic field data it is not required by the data due to the non-uniqueness of potential field inverse methods.

netic anomaly low. The orientation of the TAG sea surface magnetization low along the boundary fault of the rift valley suggests that such structural and tectonic thinning may be present. If this were the case all major faults should show this same type of anomalous magnetic feature. This is simply not observed and there are many examples along the MAR axis where substantial rift valley walls are found which do not show any associated magnetic anomaly. Block rotation and back-tilting are other important effects that could degrade the magnetic signal. Karson and Rona [33] report back-tilting in the TAG area but it is not of sufficient magnitude to severely affect the magnetic signal. In summary, although structural thinning is an important mechanism for the disruption of magnetic anomalies, it appears unlikely that this is a primary contributor to the TAG sea surface magnetic low.

Curie isotherm model: Finally, a model of the sea surface magnetic low that is most consistent with the hydrothermal setting of the TAG region is a thinned magnetic layer due to a raised Curie isotherm level within the crust (Fig. 7D). The active hydrothermal mound within the TAG hydrothermal field is proof that hot rock exists at depth to provide the thermal drive for a hydrothermal system to be present. The lack of any microearthquake activity in the TAG area also suggests that an intrusive body of hot and ductile rock exists at depth [20]. Kong et al. [20] infer from the seismic data that this intrusive body is likely to be mostly solidified but that the thermal effect is still significant enough to influence the seismic properties. These two observations both indicate that a zone of high temperature exists at depth which could easily result in crustal thermal demagnetization on a scale that would be consistent with the wavelength of the observed sea surface anomaly. Such a zone may represent the thermal haloes surrounding a localized late-stage intrusive event that are quite commonly associated with ophiolite ore deposits [1,31,34].

In addition to thermal demagnetization, the interaction of hot rock and hydrothermal fluids at depth in the 'reaction zone' could also result in pervasive alteration adding to the crustal demagnetization effect [35,36,37,38]. It is impossible to distinguish between these two processes at an active hydrothermal field such as TAG, since both processes may be operating. At extinct hydrothermal fields, however, where the crust has cooled below the Curie point, only the residual effects of alteration should be apparent. If there is only limited magnetic mineral alteration at depth any large-scale anomaly should dissipate with age and extinct hydrothermal systems will only produce small upflow zone scale anomalies of the type measured in the TAG *Alvin* survey. In this case, it would then be virtually impossible to find extinct hydrothermal deposits on the basis of a sea surface anomaly signature. The existence of anomalies over ophiolites shows, however, that alteration is an important process and the magnetization of the deeper crustal sections (i.e. the dike and gabbros) may be sufficiently destroyed to produce a permanent magnetic anomaly [7,9,35–38]. This has important implications for the search and exploration of ancient hydrothermal deposits that reside off-axis.

A model can thus be constructed that accounts for both the long-wavelength sea surface magnetic anomaly and the short-wavelength near-bottom magnetic structure of the TAG hydrothermal field (Fig. 8). By analogy to ophiolite deposits, the shallow crustal structure is marked by narrow, well-defined alteration pipes that are demagnetized relative to the host rocks and thus produce short-wavelength magnetic anomalies. These contribute relatively little to the overlying sea surface magnetic anomaly. The crust at depth is marked by pervasive alteration and intrusive bodies giving rise to broad-scale, regional magnetic anomalies as measured at the sea surface (Fig. 8). A single deep alteration and thermally demagnetized zone may be the source for the entire TAG hydrothermal field or there may be a number of zones, such as localized intrusive events, specific to each group of mounds. Seismic data would be unlikely to resolve such structure, but a more regional near-bottom magnetic survey encompassing the entire TAG area should be able to test this hypothesis. It must be emphasized however that the magnetic data does not require the source to be arranged as shown by the model in Fig. 8, merely that the magnetic field of this geometry is consistent with the magnetic observations and the other geophysical and geologic observations.

Finally, to demonstrate that the TAG anomaly is not a unique feature and that other examples of this type of discrete anomaly exist, a qualitative inspection of the sea surface magnetic data from the 1989 Kane to Atlantis fracture zone MAR survey was carried out. At least three other areas that have anomalously magnetic features similar to the TAG anomaly can be identified along the MAR axis at 24°23′N, 26°45′N and 29°33′N. These areas all have 3D magnetic anomalies that are found within the rift valley, usually near the rift valley boundary faults, similar to the TAG geologic setting. At least one of these areas (24°23′N) has additional evidence of past hydrothermal activity [39]. No anomalous features are found outside the rift valley, although the data coverage in this study does not extend much beyond the first set of abyssal hills outside the rift valley. The likelihood of finding off-axis deposits is low due to a number of aging and evolutionary processes that affect oceanic crust as it moves away from the rift axis. These processes include tectonic disruption, volcanic and sedimentary burial and progressive low-temperature alteration that reduces the available magnetization contrast. Since these anomalously magnetic features do exist however, it indicates that sea surface magnetic surveys can at least detect anomalous areas despite the resolution limitations. Near-bottom surveys can reveal a more direct correlation between the geologic features and anomalous magnetization but this is dependent on the altitude and areal coverage of the survey. A larger area would have to be surveyed to fully describe the sea surface magnetic low region. This type of survey is possible using deeptow or autonomous underwater vehicles which can cover longer distances and provide greater areal extent than is possible with submersible surveys. Deeptow surveys would provide a better link to the sea surface field but would not be able to detect the short-wavelength anomalies (< 100 m) associated with individual mounds, unless the survey altitude is kept within 100 m of the seafloor.

6. Conclusions

In conclusion, we identify a distinct zone of reduced magnetization directly beneath the active mound within the TAG hydrothermal field. This 100 m diameter magnetization low is consistent with the highly altered upflow zone of a hydrothermal vent system that feeds the actively venting mound structure. In contrast, the sea surface magnetic anomaly is associated with a broad 2×8 km magnetization low that is elongated along the rift axis and encompasses both the active and inactive mounds which lie to the south of the magnetization minimum. The near-bottom magnetic anomaly over the active mound is far too small to produce the observed sea surface magnetic anomaly however, and even a collection of mounds with similar magnetic structure cannot produce the magnetic moment needed to generate the sea surface anomaly. Other hypotheses, including reversely magnetized crust and structurally thinned crust, could account for the sea surface anomaly but are considered unlikely. The broad-wavelength sea surface anomaly is proposed to be the result of a deeper thermal and alteration zone that characterizes the reaction zone of a hydrothermal system. This view is also supported by the seismic data, which show a lack of earthquake activity in the vicinity of the TAG hydrothermal field [20]. While such a model is not required by the data due to the non-uniqueness of potential field data, this magnetic model is consistent with the geometry of hydrothermal systems studied in ophiolite suites, which show narrow alteration pipes feeding the exhalative deposits [1,29,30,31,37]. At depth, late-stage intrusive bodies are also found commonly associated with ophiolite hydrothermal deposits and could provide both the thermal drive for the hydrothermal system and the demagnetization and alteration to produce the more regional magnetic field anomaly [37,38]. The off-axis location of the TAG hydrothermal field and the episodic rejuvenation may be a reflection of this intrusive behavior.

Although a larger near-bottom survey covering the entire sea surface magnetization low region is necessary to fully relate the near-bottom magnetic field to the sea surface field, the *Alvin* survey does place bounds on the spatial detection level required to measure the individual mound anomalies with a maximum survey altitude and line spacing of 50 m to detect a typical 100 m diameter pipe. The use of 3D analysis techniques are also critical to understanding the inherently localized nature of a hydrothermal system both in the near-bottom environment and at the sea surface. Finally, the TAG sea surface magnetic anomaly is not a unique feature and at least three other anomalously magnetic areas can be identified along the Mid-Atlantic Ridge axis between the Kane and Atlantis fracture zones. Although the verification of these areas as active or inactive vent sites awaits future detailed studies, the mapping and analysis of 3D magnetic anomalies shows considerable promise in locating significant hydrothermal deposits on the deep seafloor.

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