The Trans-Atlantic Geotraverse hydrothermal field: A hydrothermal system on an active detachment fault

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Abstract

Over the last ten years, geophysical studies have revealed that the Trans-Atlantic Geotraverse (TAG) hydrothermal field (26°08'N on the Mid-Atlantic Ridge) is located on the hanging wall of an active detachment fault. This is particularly important in light of the recognition that detachment faulting accounts for crustal accretion/extension along a significant portion of the Mid-Atlantic Ridge, and that the majority of confirmed vent sites on this slow-spreading ridge are hosted on detachment faults. The TAG hydrothermal field is one of the largest sites of high-temperature hydrothermal activity and mineralization found to date on the seafloor, and is comprised of active and relict deposits in different stages of evolution. The episodic nature of hydrothermal activity over the last 140 ka provides strong evidence that the complex shape and geological structure of the active detachment fault system exerts first order, but poorly understood, influences on the hydrothermal circulation patterns, fluid chemistry, and mineral deposition. While hydrothermal circulation extracts heat from a deep source region, the location of the source region at TAG is unknown. Hydrothermal upflow is likely focused along the relatively permeable detachment fault interface at depth, and then the high temperature fluids leave the low-angle portion of the detachment fault and rise vertically through the highly fissured hanging wall to the seafloor. The presence of abundant anhydrite in the cone on the summit of the TAG active mound and in veins in the crust beneath provides evidence for a fluid circulation system that entrains significant amounts of seawater into the shallow parts of the mound and stockwork. Given the importance of detachment faulting for crustal extension at slow spreading ridges, the fundamental question that still needs to be addressed is: How do detachment fault systems, and the structure at depth associated with these systems (e.g., presence of plutons and/or high permeability zones) influence the pattern of hydrothermal circulation, mineral deposition, and fluid chemistry, both in space and time, within slowly accreted ocean crust?

Keywords: Hydrothermal fields; Mid-ocean ridges; Faults; Sulfide deposits

1. Introduction

The TAG hydrothermal field on the Mid-Atlantic Ridge (26°08'N) was first located through detection of low temperature hydrothermal activity and mineralization during the NOAA Trans-Atlantic Geotraverse (TAG) project led by Peter Rona in 1972-1973 (Scott et al., 1974a, b; Rona et al., 1975). Since the discovery in 1985 of the first high temperature vents, massive sulfide deposits, and new vent ecosystems in the Atlantic Ocean again by Peter Rona (Rona at el., 1986), the TAG hydrothermal field has served as a major 'type' example of a massive sulfide deposit on a slow-spreading ridge, particularly with its similarities to sulfide deposits in Cyprus (e.g., Herzig et al., 1991; Hannington et al., 1998; Humphris and Cann, 2000). It is one of the most comprehensively studied seafloor hydrothermal fields and has been the focus of numerous geophysical (e.g., Kong et al., 1992, Becker et al., 1996, Evans et al., 1996, Tivey et al., 1993, 1996, 2003; Goto et al., 2003; deMartin et al., 2007; Canales et al., 2007; Zhao et al., 2012; Pontbriand and Sohn, 2014), geochemical (e.g., Edmond et al., 1995; Chiba et al., 1998; Humphris et al., 1998; Tivey et al., 1995, 1998; Humphris and Bach, 2005), and biological (e.g., Van Dover et al., 1988; Galkin and Moskalev, 1990; Copley et al., 1999) investigations. In addition, it is one of only three actively venting seafloor hydrothermal systems to be sampled in the third dimension as part of the Ocean Drilling Program (ODP) (Humphris et al., 1995; Herzig et al., 1998).

Until a few years ago, it was widely accepted that the TAG hydrothermal field is a volcanically-hosted system with circulation patterns similar to those for hydrothermal systems on fast-spreading ridges. The mid-crustal magma body was thought to be larger and deeper (Kong et al., 1992), and the overlying crust was thought to be more tectonized (Kleinrock and Humphris, 1996), but the basic hydrogeological model was conceptually identical – i.e., a system driven by heat from a cooling mid-crustal melt reservoir with circulation through ridge parallel faults and fissures.

Over the last ten years, however, geophysical studies have revealed that the TAG hydrothermal field is located on the hanging wall of an active detachment fault (Tivey et al., 2003; Canales et al., 2007; deMartin et al., 2007). This finding has major implications for our understanding of hydrothermal circulation at slow-spreading mid-ocean ridges. We now know that detachment faulting, which exposes lower crust and upper mantle rocks, accounts for crustal accretion/extension along as much as 50% of the Mid-Atlantic Ridge (Smith et al., 2006; Escartin et al., 2008; Tucholke et al., 2008; MacLeod et al., 2009). In addition, detachment faults host seven of the eleven confirmed active hydrothermal sites on the northern Mid-Atlantic Ridge, suggesting that most of the hydrothermal flux in the northern Atlantic is generated in terrain that was thought to form in regions with low magmatic activity, a prerequisite for detachment formation (Tucholke and Lin, 1994; Tucholke et al., 1998).

Although mineralization related to detachment faulting has been studied in continental settings for about three decades (e.g., Bartley and Glazner, 1985; Spencer and Welty, 1986; Reynolds and Lister, 1987; Roddy et al., 1988; Beaudoin et al., 1991; Smith et al., 1991), the relation of detachment faults to seafloor hydrothermal mineral deposits has only recently been revealed through detailed study of slow-spreading hydrothermal systems. In this paper, we review the current state of knowledge of the TAG hydrothermal field, focusing on the significant advances that have been made in the last decade. We then discuss the outstanding questions that must be addressed to better understand the subsurface hydrogeology and thermal structure of active oceanic detachment faults and their control on the geometry of hydrothermal circulation. Such an understanding would allow better constraints to be placed on the thermal and mass fluxes associated with these hydrothermal systems.

2. Geotectonic setting of the TAG hydrothermal system

The TAG hydrothermal field (Figure 1) is one of the largest sites of high-temperature hydrothermal activity and mineralization found to date on the seafloor. It is located at 26°08'N near the center of a 40-km-long NE-SW trending ridge segment that is bounded to the north and south by non-transform discontinuities at 26°17'N and 25°55'N respectively (Purdy et al., 1990; Sempere et al., 1990). Seafloor spreading rates have been asymmetric over the past 10 million years, with calculated half–spreading rates of 11 mm/yr to the west and 13 mm/yr to the east (McGregor and Rona, 1975; McGregor et al., 1977), and more recently, 8.7 mm to the west and 12.1 mm to the east for just the Central anomaly portion of the ridge (Tivey et al., 2003). The hydrothermal field lies 2.4 km east of the spreading axis adjacent to the eastern axial valley wall. The eastern axial valley wall is steeper than the western wall, and sheeted dikes and gabbro have been recovered from mid-depth (~3000 m) on the wall (Zonenshain et al., 1989; STAG Cruise Report, 2004).

The first indication that hydrothermal activity at TAG might be related to a detachment fault came from an extensive near-bottom magnetics survey of the TAG ridge segment (Tivey et al., 2003). An axis-parallel linear magnetization low was identified over the eastern rift valley wall, and was modeled as crustal thinning caused by 4 km of horizontal extension along a normal fault. This interpretation was supported by the observation of a gabbroic outcrop a few kilometers east of the TAG field at mid-depth (3000 m) on the eastern valley wall (Zonenshain et al., 1989). In their model, Tivey et al. (2003) suggested that the hydrothermal field is located on the hanging wall of this active detachment fault within 3 km of its termination and, based on results from an early seismic experiment (Kong et al., 1992), that hydrothermal circulation is driven by heat from a mid-crustal magma reservoir.

More recent geophysical studies further constrained the geometry and character of the detachment fault. A study of microearthquakes over an eight month period showed that detachment faulting is accommodated on an ~15 km-long, dome-shaped fault surface that penetrates into the mantle at a steep dip of ~70° over the depth interval of ~3 to >7 km below the seafloor, and rolls over to a low angle of ~20°, becoming aseismic at shallower depths of 2-3 km below the seafloor (Figure 2) (deMartin et al., 2007). An active-source seismic survey revealed that there are no mid-crustal magma bodies beneath the hydrothermal field (Canales et al., 2007), so deMartin et al. (2007) inferred that hydrothermal fluids must penetrate to great depths (>7 km) to extract heat out of a gabbroic intrusion at the root zone of the detachment fault (Figure 2). They suggested that circulation in the middle to lower crust may be focused on the relatively permeable, three-dimensional detachment fault surface, while in the upper crust high temperature fluids rise vertically through the highly tectonized hanging wall (deMartin et al., 2007).

The results of these seismic studies now have been extended to include a three-dimensional *P*-wave tomographic velocity model of the TAG segment that shows added complexity in the crustal structure (Zhao et al., 2012). The model suggests that the fault zone may extend east beneath the volcanic blocks forming the eastern valley wall, and that the across-axis structural asymmetry associated with detachment faulting extends at least 15 km to the east of the ridge axis; thus detachment faulting may have been occurring for at least the last ~1.35 Myr (Zhao et al., 2012). This is in contrast to the estimate of Tivey et al. (2003) based on magnetic studies of ~0.35 Myr, but is consistent with estimates of Smith et al. (2008) and Schouten et al. (2010) of 2 Myr based on morphological characteristics of eastern lineated ridges interpreted to be rafted hanging wall blocks. In addition, the 3D tomographic velocity model contains a 5 km x 8 km low velocity anomaly within the detachment footwall directly beneath the TAG active mound and extending from 1.5 km to at least 4 km below the seafloor. Zhao et al. (2012) consider three options to explain this low velocity region -- a hot gabbro pluton intruding the detachment footwall; serpentinized rocks with hydration of the footwall being enhanced by hydrothermal fluid flow; or a highly fissured zone produced by extensional stresses during footwall exhumation. The very low hydrogen concentrations of TAG active mound vent fluids (Charlou et al., 1996) make the second scenario unlikely (e.g., Nakamura et al., 2009), and with the currently available data, Zhao et al. (2012) are unable to decipher between the other two hypotheses. If there indeed proves to be a hot gabbro pluton directly beneath the TAG active mound, the model of deMartin et al. (2007) will need to be modified (Zhao et al., 2012).

3. Geological and geochemical characteristics of the TAG hydrothermal field

The TAG hydrothermal field is comparable in size to typical volcanic-hosted massive sulfide deposits in a variety of settings (Franklin et al., 1981), including the larger sulfide deposits in Cyprus (Herzig et al., 1991; Hannington et al., 1998; Humphris and Cann, 2000). Zones of low- and high-temperature activity, as well as two major areas of inactive sulfide deposits, have been mapped in a small, 5 × 5 km area on the hanging wall of the detachment fault (Figure 1) (e.g., Rona et al., 1975, 1986, 1993a, b; Thompson et al., 1985; White et al., 1998). The geological and geochemical characteristics of the active and inactive zones have been synthesized in detail by Rona et al. (1993a, b; 1998), Tivey et al. (1995), and Humphris and Tivey (2000); here we provide only a brief overview.

3.1. The TAG active mound

The TAG active mound is the focus of high temperature hydrothermal activity in the TAG hydrothermal field. It lies 2.4 km east of the neovolcanic zone on crust estimated from seafloor spreading rates to be ~100,000 years old at a water depth of about 3670 m. The floor of the rift valley in this area is characterized by intersecting actively-developing, axis-parallel and pre-existing, axis-oblique fault systems (Karson and Rona, 1990; Bohnenstiehl and Kleinrock, 1990; Kleinrock and Humphris, 1996). These likely provide permeable pathways for focusing the upwelling hydrothermal fluids (Kleinrock and Humphris, 1996b; Kleinrock et al, 1996).

The TAG active mound is a circular feature, about 200 m in diameter and about 50 m high, composed of two platforms, with the upper platform asymmetrically superposed on the north-northwest part of the lower platform (Figure 3). Focused, high-temperature (363°C) activity is localized in a cluster of black smoker chimneys at the summit of a 12 m tall conical structure composed of massive anhydrite (mixtures of co-precipitated anhydrite and pyrite ± chalcopyrite) on the top of the mound (Figure 4). Black smoker vent fluid chemistry appears to have been similar over the past 20 years and reflects seawater reaction with basaltic rock (Campbell et al., 1988; Edmond et al., 1995; Edmonds et al., 1996; Gamo et al., 1996; Chiba et al., 2001; Green et al., 2005). Surveys over the eastern part of the upper platform also document recent, less vigorous, widespread black smoker activity emanating from point sources and seeping from small, rift-parallel fissures (Humphris and Kleinrock, 1996). Rock types exposed on the upper platform include black smoker chimneys, plate-like crust samples, and massive anhydrite samples (mixtures of co-precipitated anhydrite and pyrite ± chalcopyrite). On the basis of this, Tivey et al. (1995) hypothesized that the massive anhydrite samples formed during seawater entrainment into the top tier of the mound. The massive anhydrite was then exposed by later mass wasting (Figure 4).

On the southeast edge of the lower platform is the Kremlin area, a small field of numerous bulbous, white smoker chimneys, 1-2 m high (Thompson et al., 1988), whose activity has now ceased (Edmonds et al., 1996). The compositions of the deposits on the lower platform, and of the white smoker fluids (which are enriched in zinc by an order of magnitude over black smoker fluids), result from mixing of black smoker fluid with seawater that is entrained into the mound; this mixing results in precipitation of anhydrite, pyrite and chalcopyrite, a resultant decrease in pH, and subsequent dissolution of sphalerite and metal remobilization (Edmond et al., 1995; Tivey et al., 1995). Mass wasting of the lower platform exposes two other sample types: massive pyrite and red ocherous Fe-oxide samples. These sample types appear to be much older than those on the upper platform. Low-temperature diffuse flow (>50°C) occurs over much of the surface of the mound, and may result from cooling of vent fluids and deposition of sulfide minerals and amorphous silica within the mound (Tivey et al., 1995).

Ocean Drilling Program (ODP) Leg 158 elucidated the internal structure of the TAG active mound down to 125 meters below the sea floor, and demonstrated that it exhibits a classic volcanogenic massive sulfide (VMS) structure of a stockwork zone connecting to a sulfide lens. The size of the mound-stockwork complex is estimated to be ~3.9 million tonnes, including ~2.7 million tonnes of massive and semi-massive sulfide at the seafloor and 1.2 million tonnes of mineralized breccias in a subseafloor stockwork (Figure 5) (Humphris et al., 1995; Hannington et al., 1998). Striking features include the dominance of breccias composed of mixtures of clasts that show evidence for incorporation of material that was previously deposited and for reworking of incorporated material, and large and complex anhydrite-rich veins with textures indicating replacement of early massive banded anhydrite by later, coarser grained anhydrite (Humphris et al., 1995). Construction of the deposit is interpreted to be episodic, and involves a combination of sulfide accumulation at the seafloor, significant subsurface entrainment of seawater and precipitation of anhydrite (and pyrite and chalcopyrite), and hydrothermal replacement, mineralization, and zone refinement during periods of activity. This is followed by collapse due to dissolution of anhydrite, mass wasting, and brecciation during periods of inactivity (Humphris et al., 1995). This interpretation is consistent with geochronological studies that suggest that the TAG mound has been active episodically every few thousand years over at least the past 20 kyr, and possibly the past 50 kyr, although this older age was obtained from a dredged sample so its location is not well determined (Lalou et al., 1990; 1993; 1998; You and Bickle, 1998). Current activity is estimated to have begun ~80 yr ago (Lalou et al., 1998). Furthermore, based on energy fluxes and metal inventories, Humphris and Cann (2000) calculated that mineral precipitation may have been extremely rapid, with the TAG active mound forming during ~600 years of hydrothermal activity — only 1-2% of the time during which the deposit is thought to have formed. Tivey et al. (1998) calculated a similar amount of time (~80 to 800 years) for deposition of the ~20,000 m^3 of anhydrite within the mound. An alternative estimate assumed that the ~2.7 million tonnes of massive and semi-massive sulfide accumulated episodically over ~10% of the lifespan of the TAG active mound (~5,000 yrs), with slower accumulation rates of ~360 tonnes per year (Hannington et al., 1998). This accumulation rate, although lower than that calculated by Humphris and Cann (2000), is still significantly more rapid than those estimated for many other vent fields, but is similar to recent estimates for deposits on the Endeavour Segment of the Juan de Fuca Ridge (maximum accumulation rates of ~400 tonnes/yr; Jamieson et al., 2014).

3.2. The Alvin Zone

The axis-parallel fissures and faults at the TAG active mound extend NNE into the Alvin Zone (White et al., 1998). Discontinuous sulfide outcrops, standing and toppled chimneys, and a series of large mounds occur along a strike length of 2.5 km at water depths of 3400–3600 m (Rona et al., 1993a, b; White et al., 1998). Six of the mounds are inactive and reach sizes similar to that of the TAG active mound. All appear to be undergoing oxidation, mass wasting, and dissection by faulting, and some are covered in a thin layer of pelagic sediment (Rona et al., 1993a, b, 1998; White et al., 1998). Age dates for the Alvin (also called Double) Mound suggest that it was hydrothermally active ~48 ± 5 ka. However, a dredged Mn oxide sample attests to an earlier low-temperature episode at ~75 ka (Lalou et al., 1995). A sediment core collected 0.5 km west of the Alvin Zone contains high concentrations of hydrothermally-derived material dating from 6 and 8.5 ka suggesting more recent activity (Metz et al., 1988).

Shimmering Mound is an active mound discovered in 1998 at the northern end of the *Alvin* Zone and 4 km NNE of the TAG active mound (Rona et al., 1998). The mound is about 150 m in diameter with 33-64 m of relief. Clear, low-temperature (22.5°C) fluids discharge through sediments with the appearance of manganese oxides, iron oxyhydroxides, and iron silicates (Rona et al., 1998).

3.3. The Mir Zone

The Mir Zone lies ~2 km east-northeast of the TAG active mound and 4 km from the ridge axis and is presently inactive. It covers an area ~1 km in diameter at a water depth of 3430–3575 m on normal fault blocks on the lower part of the axial valley wall. Descriptions of the morphology of the Mir zone vary. Rona et al. (1993a, b) identified three distinct zones of hydrothermal deposits: a western zone of outcrops of hydrothermal breccias underlying a partial cover of weathered sulfide debris and metalliferous sediments; a zone of semicontinuous sulfides with numerous standing and toppled chimneys; and a zone east of the sulfides of iron hydroxides, iron-rich clays, and manganese oxide crusts. In contrast, Stepanova et al., (1996) described the Mir Zone as a single 400 m diameter mound with similar types of hydrothermal deposits. Based on a later sidescan and bathymetry survey of the area, it appears that the Mir Zone lacks large, distinctive structures, although a small (~100 m in diameter and ~10 m high) mound coincides with sulfide deposits observed by submersible (Rona et al., 1993b; White et al., 1998). A magnetic anomaly consistent with the presence of reduced crustal magnetization is associated with this feature (Tivey et al., 1996).

Geochronological studies suggest that formation of the low temperature hydrothermal deposits in the eastern zone began ~140 ka. High-temperature activity began ~100 ka followed by a major thermal event at 50 ka that continued episodically until ~ 0.6 ka (Lalou et al., 1993, 1995). High heat-flow values in the Mir Zone indicate that this area continues to be thermally active, and suggests that hydrothermal activity may have ceased only recently (Rona et al., 1996).

3.4. The Low Temperature Zone

The Low Temperature Zone was the first site of hydrothermal activity to be detected at the TAG hydrothermal field. It is located ~4 km east of the TAG active mound on the eastern valley wall at a water depth of 3100–2300 m, and covers an area of at least 2 x 3 km. Near-bottom temperature anomalies in the water column and conductive heat-flow anomalies in the sediments suggest ongoing, low-temperature (<20°C) diffuse flow, although no fluids have been observed venting from the deposits

(Rona et al., 1984, 1993b). The zone is characterized by massive layered deposits of iron-rich clays (identified as nontronite by XRD and geochemical analyses), manganese oxides, and iron oxyhydroxides, as well as extensive surficial metal-rich staining of the carbonate ooze (Rona et al., 1984; Thompson et al., 1985). Radiometric dating of five manganese oxide samples suggests that the bulk of the deposits were formed from ~16 to 4 ka, although dates of 100 and 125 ka suggest there may have also been an earlier episode of low-temperature hydrothermal activity (Lalou et al., 1986).

4. Fluid flow and subsurface processes beneath the TAG hydrothermal field

4.1. The role of the detachment fault

The discovery that the TAG hydrothermal field overlays a detachment fault rather than a mid-crustal melt reservoir has reshaped our ideas about sub-surface fluid circulation patterns. The absence of a crustal melt reservoir and the extension of microearthquake activity (and thus the brittle-plastic rheological transition) to depths greater than 7 km suggest that hydrothermal fluids penetrate much deeper into the lithosphere than previously supposed (Canales et al., 2007; deMartin et al., 2007).

Detachment faults also have some unique properties that affect hydrothermal processes in ways that are yet to be determined. They are long-lived and continuously active in the sense that they are rooted in the brittle-ductile transition just above the axial magma zone and are able to accommodate continuous motion through ductile deformation at depth. Seismicity rates on the TAG detachment are remarkably steady, and lack the mainshock-aftershock patterns observed for typical extensional or strike-slip fault systems (deMartin et al., 2007). The impact of this steady fault movement on fluid flow may provide a mechanism to maintain high levels of permeability in the deeply penetrating fault zone and in the overlying hanging wall. The ramp-like geometry of the shallow low-angle portion of the detachment fault focuses hydrothermal discharge away from the spreading axis, which may promote interaction with the overlying hanging wall and enhanced degrees of off-axis circulation. In fact, McCaig et al. (2007) presented strontium and oxygen isotopic evidence for focusing of hydrothermal fluid flow along the detachment fault at 15°45’N, thereby enabling hydrothermal activity away from the neovolcanic zone in this region.

While hydrothermal circulation extracts heat from a deep source region, the location of the source region at TAG is unknown but is constrained to lie several kilometers below the hanging wall-footwall interface of the active detachment fault (Canales et al., 2007; Zhao et al., 2012). The model of deMartin et al. (2007) has seawater penetrating to great depths (>7 km) to extract heat out of a gabbroic intrusion at the root zone of the detachment fault, with the detachment fault focusing the upflow of hydrothermal fluids. However, if the low velocity anomaly identified by Zhao et al. (2012) in the detachment footwall beneath the TAG active mound proves to be a hot gabbro pluton that is the source of heat driving hydrothermal circulation, the fluid flow would be considerably more complex as fluids would have to rise vertically through the footwall, across the footwall-hanging wall interface, and through the hanging wall.

Based on studies of two oceanic core complexes in the North Atlantic -- the Atlantis Massif at 30°N and a massif at 15°45'N -- McCaig et al. (2010) extrapolated their observations to explore the possible geometry of hydrothermal circulation and the evolution of the detachment fault at TAG. Their model assumes the geometry suggested by deMartin et al. (2007), and has recharge occurring from many kilometers along strike. After crystallization and rapid hydrothermal cooling below 700°C (constrained by microseismicity), the gabbroic body is picked up in the footwall of the detachment fault. Fluid upflow is focused in the detachment fault, thereby buffering the temperature within the detachment at about 400°C. When the permeability of the overlying crust exceeds that of the fault zone, the hydrothermal fluids ascend through the hanging wall to the seafloor (McCaig et al., 2010). The episodic nature of hydrothermal activity in the TAG hydrothermal field, indicated by the lithologies and textures of the sulfides and underlying stockwork and by the radiometric dating of the sulfides, is explained by successive pulses of molten gabbroic magma intrusion (McCaig et al., 2010). This agrees well with Humphris and Cann (2000) who argued that the principal source of energy driving the TAG hydrothermal system is the latent heat of crystallization of magma that is supplied episodically.

While the detachment fault may be the major pathway for flow of the hydrothermal fluids, the circulation pattern along the ~15 km arc of the dome-shaped detachment is not constrained because most of the studies in the TAG segment have been confined to the ~5 km x 5 km area of the known hydrothermal field (and almost all have been confined to the TAG active mound). In fact, it is not known whether the active Shimmering Mound, 4 km to the NNE, and the TAG active mound are both supplied with fluids from the same upwelling limb of a convection cell or from different convection cells. Two end-member models can be envisioned: a single convection cell with one upwelling limb of hydrothermal fluids that splits into multiple, time-varying upflow paths on the low-angle portion of the detachment fault, and results in a discrete zone of high temperature discharge and mineral deposition; and multiple convection cells whose upwelling limbs are distributed along the fault and give rise to multiple discrete zones of high temperature seafloor hydrothermal activity. If the distribution of active and inactive mineral deposits in the TAG hydrothermal field provides a first-order expression of past and present upflow zones in the subsurface circulation system, then the spatial relationships between the deposits can be used to constrain sub-surface circulation patterns on the detachment fault and within the hanging wall. Such an analysis will require further exploration of the northern parts of the hanging wall and emergent dome to determine the full extent of hydrothermal activity on the detachment fault.

An interesting question concerns the subsurface fluid flow pathways to the diffuse flow at the Low Temperature Zone ~4 km east of the TAG active mound on the valley wall at a water depth of 3100–2300 m. One possibility is that some fluids flow along the low-angle portion of the detachment, and are then discharged at the fault termination. The only constraint on the location of the fault termination is that it must lie to the west of the dike and gabbro outcrops on the valley wall, which have been reported to occur at depths shallower than 3050 m (Zonenshain et al., 1989). While this coincides with the deeper areas of the Low Temperature Zone, it does not explain fluid flow at shallower depths on the eastern valley wall.

4.2. Fluid circulation through the hanging wall and the TAG active mound

While the hydrothermal upflow is likely focused along the relatively permeable detachment fault interface at depth, the high temperature fluids leave the low-angle portion of the detachment fault and rise vertically through the highly fissured hanging wall to the seafloor. Whether the upflow limbs are stationary with respect to the footwall, or whether they migrate with the hanging wall crust is not known. The circular shapes of the large active and relict mounds in the TAG hydrothermal field (which are unlike the tabular or elongate shapes of many ophiolitic massive sulfide deposits (e.g., Koski, 1983)) requires that, at certain sites, fluid upflow is focused within pipe-like zones into the shallow portions of the crust. The intersecting series of faults and fissures provide a mechanism to produce permeable pathways for the high temperature fluids (Karson and Rona, 1990; Bohnenstiehl and Kleinrock, 1990; Kleinrock and Humphris, 1996). These upflow zones (or stockworks) are ~80-100 m in diameter based on drilling and a seafloor magnetics survey at the TAG active mound (Humphris et al., 1995), and on seafloor magnetics surveys of the Alvin and Mir Zones (Tivey et al., 1993, 1996).

The presence of abundant anhydrite in the cone on the summit of the TAG active mound and in veins in the crust beneath provides evidence for a fluid circulation system that entrains significant amounts of seawater into the shallow parts of the mound and stockwork to depths of at least 120 mbsf (Tivey et al., 1995; Humphris et al., 1995, 1996; Lowell and Yao, 2002). Fluid inclusions in anhydrite indicate high temperatures (>337°C) in shallow parts of the mound and a maximum of ~390°C at depth in the stockwork (Petersen et al., 1998; Tivey et al., 1998). These, combined with Sr isotope analyses of anhydrite, provide evidence for significant conductive heating of mixtures of seawater and hydrothermal fluid within the mound (Mills et al., 1998; Tivey et al., 1998).

A recent study of abundant, very small, local microearthquakes (average M_L = -1) over a 9-month period at the TAG active mound showed that most hypocenters clustered within a narrow depth interval from ~50 to 125 mbsf along the southwest corner of the mound (Pontbriand and Sohn, 2014). They conclude that tectonic extension does not account for most of these events, and invoke reaction-driven cracking in response to anhydrite precipitation as a plausible mechanism. They also calculate a (seismogenic) anhydrite deposition rate of 27-51 m^3/yr (Pontbriand and Sohn, 2014), which falls within the range of 80-800 years calculated by Tivey et al. (1998) to precipitate the 20,000 m^3 of anhydrite estimated to be present in the mound. In summary, the current activity at the TAG mound is significantly influenced by the shallow circulation system that entrains seawater due to the vigorous nature of the current black smoker activity and results in precipitation of abundant anhydrite.

Within the mound itself, fluid flow is likely very complex. Most of the black smoker fluid discharges vigorously through the cluster of large black smoker chimney on top of the cone and is very focused, although some black smoker fluids emanate from cracks in the anhydrite cone and the upper platform. Diffuse flow temperature records exhibit a mix of both episodic and periodic variability. In 1994, semi-diurnal periodic diffuse flow temperature variations were measured, including at three points within the sediment, and were attributed to the effects of tidal currents (Kinoshita et al., 1998). A more detailed study was carried out from June 2003 to June 2004 with variability attributed to shallow subsurface flow modulated by poroelastic effects from tidal loading (Sohn, 2007a, b) as seen in other hydrothermal systems (e.g., Jupp and Schultz, 2004; Crone and Wilcock, 2005). Long-term diffuse flow temperature records alternated between periods of discharge and recharge on timescales of a few hours to a few days (Sohn, 2007a). This suggests that the diffuse flow field is continually being reorganized most likely due to changes in the permeability structure of the mound. The TAG active mound is intrinsically unstable due to processes such as gravitational collapse, mineralization, anhydrite dissolution/precipitation, and earthquakes proximal to the mound. Such mechanisms will perturb the near-surface permeability field and reorganize diffuse flow within the hydrothermal deposit (Sohn, 2007a).

5. Outstanding questions and future directions

Studies at the TAG hydrothermal field over the last ten years have resulted in compelling evidence that the complex shape and geological structure of an active detachment fault system exerts first order, but poorly understood, influences on the hydrothermal circulation patterns, fluid chemistry, and mineral deposition. Furthermore, it should be noted that not all sulfide deposits spatially associated with detachment faults and oceanic core complexes are located on the hanging wall; some are perched high above the axial valley on the exposed fault surface (e.g., the Logatchev (14°45’N, Mid-Atlantic Ridge) and Ashadze (13°N, Mid-Atlantic Ridge) hydrothermal fields (Petersen et al., 2010; Ondréas et al., 2012). Given the importance of detachment faulting for crustal extension at slow spreading ridges, the fundamental question that needs to be addressed is: How do detachment fault systems, and the structure at depth associated with these systems (e.g., presence of plutons and/or high permeability zones), influence the pattern of hydrothermal circulation, mineral deposition, and fluid chemistry, both in space and time, within slowly accreted ocean crust?

While the numerous studies focused on the TAG hydrothermal field, and on the TAG active mound in particular, have made it the best-studied detachment-hosted field to date, very little is known about the hydrogeology of the detachment hanging wall, and the geological structure of the larger-scale detachment zone. Most of the hanging wall, including the entire northern half, has yet to be characterized geologically or with respect to hydrothermal activity, so the number and distribution of active and/or inactive hydrothermal sites along the entire detachment is unknown. The position of the fault termination, which is crucial for accurately constraining the detachment geometry in the shallow subsurface, is unknown across most of the detachment. The geological character of the emergent dome and the extent and location of mid-lower crustal outcrops on the detachment footwall has been determined in only a few transects in the vicinity of the TAG active mound. These are critical gaps in our knowledge, particularly in light of the recent geophysical results, because it means we do not understand how the limbs of hot, uprising fluids are distributed along the fault, how discharge zones are distributed within the hanging wall and how they relate to the relevant geological features, how the shallow geometry of the detachment influences circulation patterns, and how discharge sites change over time. The preponderance of detachment fault-associated hydrothermal systems on slow-spreading ridges (e.g., seven of eleven known active vent fields on the northern Mid-Atlantic Ridge) highlights the need for this increased understanding.

Knowing the distribution, age, and thermal state of all past and present sites of discharge in the hanging wall, along with their geologic context, would provide a means to constrain fluid circulation patterns on the active detachment fault. The distribution of active and inactive mineral deposits along the arc of the detachment provides a first-order expression of past and present upflow zones, thereby constraining the number of discrete upflow zones, and hence convection cells, that form at depth on the detachment. The spatial relationships between the deposits could be used to constrain sub-surface circulation patterns on the detachment fault and within the hanging wall, and to determine relations between mineral deposits and the geometry of detachment.

The assemblage of active and relict deposits in different stages of evolution that comprises the currently known extent of the TAG hydrothermal field attests to the longevity of hydrothermal activity at this location. The chronologic framework of the sulfides extends back to 140,000 years and includes periods when multiple discharge zones were active (Lalou et al., 1986, 1990, 1993, 1995, 1998; You and Bickle, 1998). This provides an excellent opportunity to investigate how the spatial and temporal variability fits into the overall evolution of the field. Peter Rona recognized this, and for many years, advocated for a second scientific ocean drilling expedition to the TAG hydrothermal field. The strategy proposed is to sequentially drill several of the hydrothermal deposits -- from older and colder relict deposits (e.g., the Alvin and Shinkai mounds in the Alvin Zone, and the Mir Zone), to active and low temperature deposits (e.g., Shimmering Mound in the Alvin Zone), and to active and high temperature deposits (e.g., the TAG active mound) -- to elucidate the origin and fate of large massive sulfide deposits, determine the geochemical fluxes during alteration of the upper crust and formation of the mineral deposits, and investigate microbial processes in the deep biosphere. Such a drilling program would also provide the first systematic time series of a modern seafloor hydrothermal assemblage analogous to the clustered mode of occurrence of ancient VMS deposits.

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Figure Captions

Figure 1. Bathymetric map (100 m contours) of the TAG region with microearthquake epicenters (black dots) recorded during an 8-month period from deMartin et al. (2007). Sites of hydrothermal deposits include the TAG active mound (red star), the inactive Mir Zone (M), and the diffuse flow Low Temperature Zone (LTZ). Within the Alvin Zone (A), six inactive (1- Southern mound; 2 - Alvin (or Double) mound; 3 - unnamed mound; 4 - New (or Shinkai) mound; 6 - Northern mound; 7 - unnamed mound) and the active low temperature Shimmering mound (5) have been identified. Nomenclature as summarized in Humphris and Tivey (2000). Gabbro/dike outcrops are also marked (Zonenshain et al., 1989; STAG Cruise Report, 2004). (Modified from an upublished Figure produced by R.A. Sohn).

Figure 2.Schematic cross-section through the detachment fault with interpretation of the hydrogeology and crustal deformation/accretion. Microearthquake hypocenters are shown as black dots. Tomographic results are shown as perturbations against a one-dimensional average model, as opposed to absolute velocities. The detachment fault is exposed at the seafloor from termination (T) to breakaway (B) as identified from magnetic data (Tivey et al., 2003). (From deMartin et al., 2007).

Figure 3.High-resolution ROV *Jason* SM2000 bathymetry map of the TAG active mound (Roman and Singh, 2007). Note the circularity of the feature, and the two discrete platforms with the cone and black smoker complex located on the top of the mound. The two small circular features on the south part of the upper platform are ODP re-entry cones emplaced during Leg 158 drilling of the mound.

Figure 4. Schematic diagram of the surficial features of the TAG active mound and inferred patterns of fluid upflow and seawater entrainment. (Modified from Humphris et al., 1995 and Tivey et al., 1995).

Figure 5.The subsurface stratigraphy of the TAG active mound determined by drilling during ODP Leg 158 (modified from Humphris et al., 1995). The entire section is

dominated by breccias composed of mixtures of clasts of different lithologies reflecting the episodicity of venting, entrainment of seawater into and beneath the mound, collapse and breakdown of structures during inactive periods, and recrystallization and cementation of old material during recurring periods of activity.

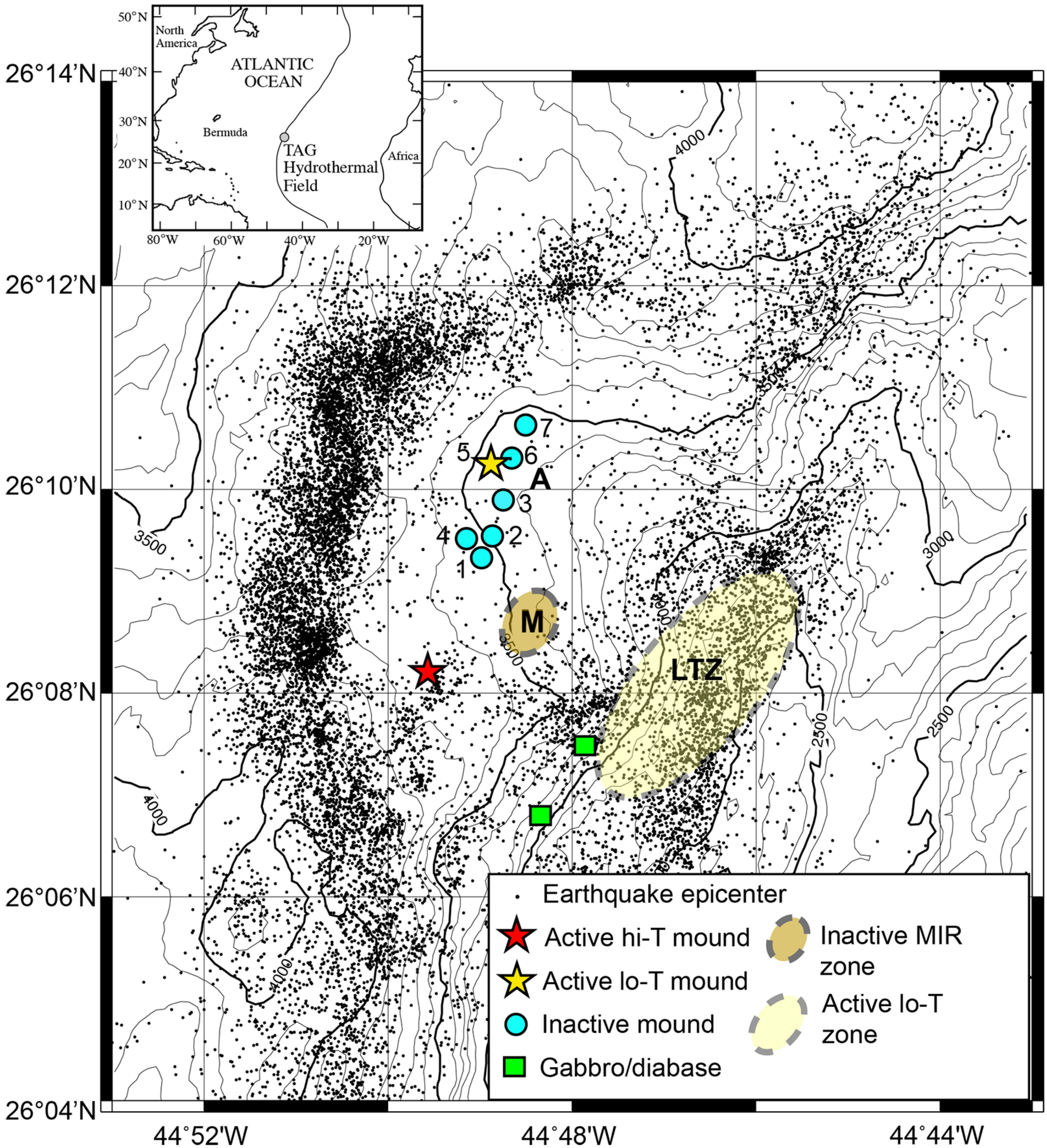

North America
ATLANTIC OCEAN
Bermuda
TAG Hydrothermal Field
Africa
50°N
40°N
30°N
20°N
10°N
80°W
60°W
40°W
20°W
26°14'N
26°12'N
26°10'N
26°08'N
26°06'N
26°04'N
44°52'W
44°48'W
44°44'W
4000
3500
3000
2500
A
M
LTZ
1
2
3
4
5
6
7
Earthquake epicenter
Active hi-T mound
Active lo-T mound
Inactive mound
Gabbro/diabase
Inactive MIR zone
Active lo-T zone

Figure 1

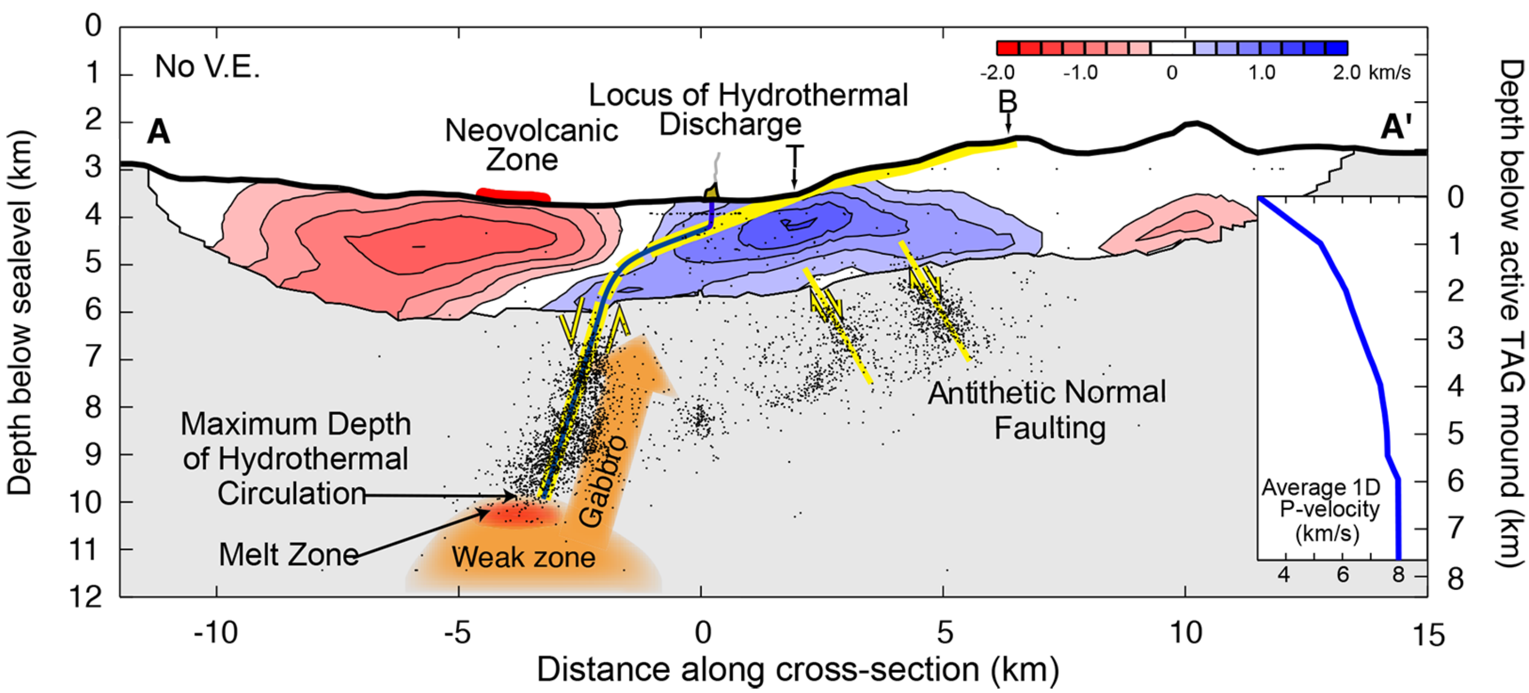

No V.E.
Locus of Hydrothermal Discharge
Neovolcanic Zone
A
A'
B
T
-2.0
-1.0
0
1.0
2.0 km/s
Antithetic Normal Faulting
Maximum Depth of Hydrothermal Circulation
Melt Zone
Gabbro
Weak zone
Average 1D P-velocity (km/s)
Depth below sealevel (km)
Depth below active TAG mound (km)
Distance along cross-section (km)

Figure 2

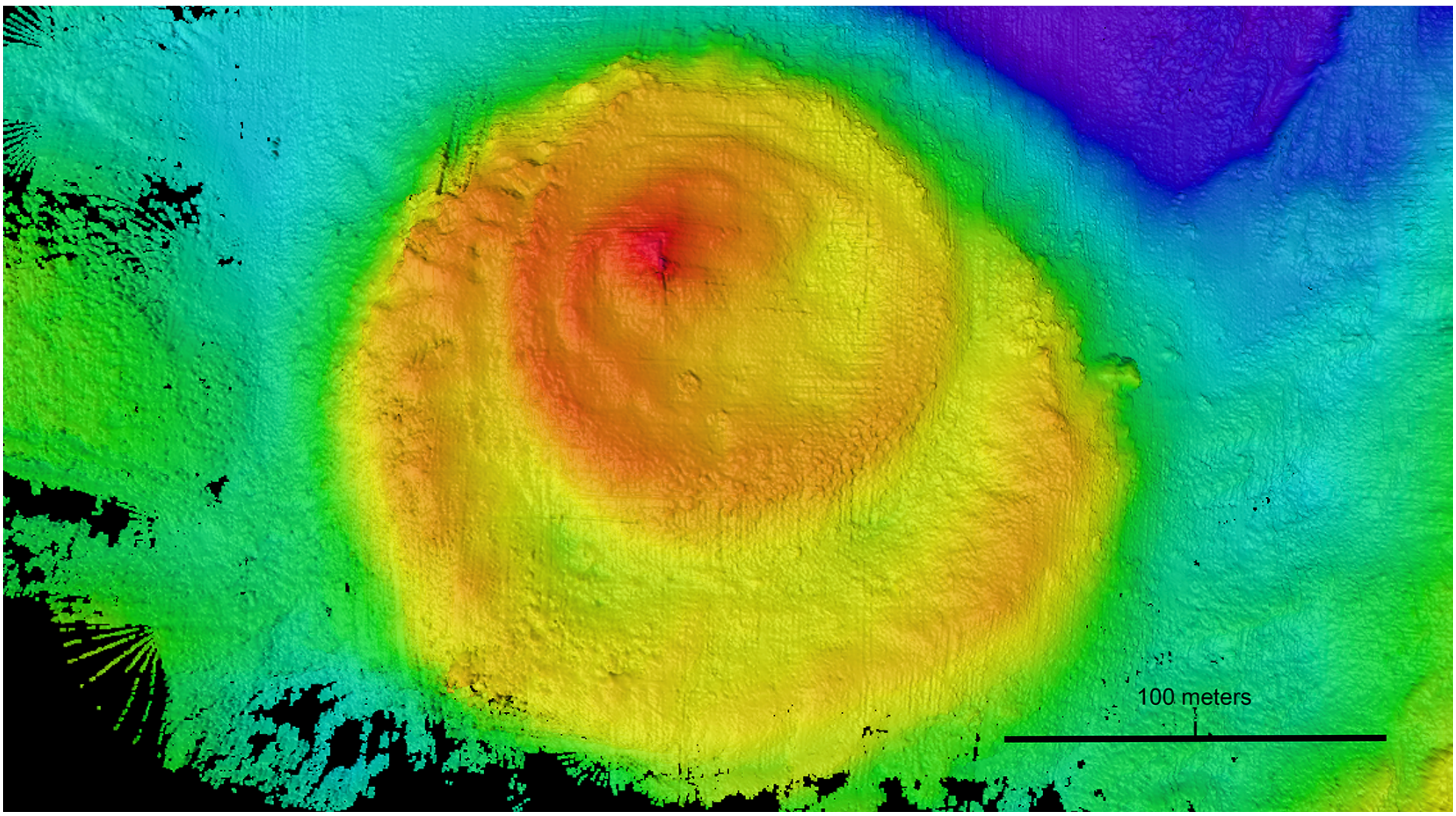


Figure 3

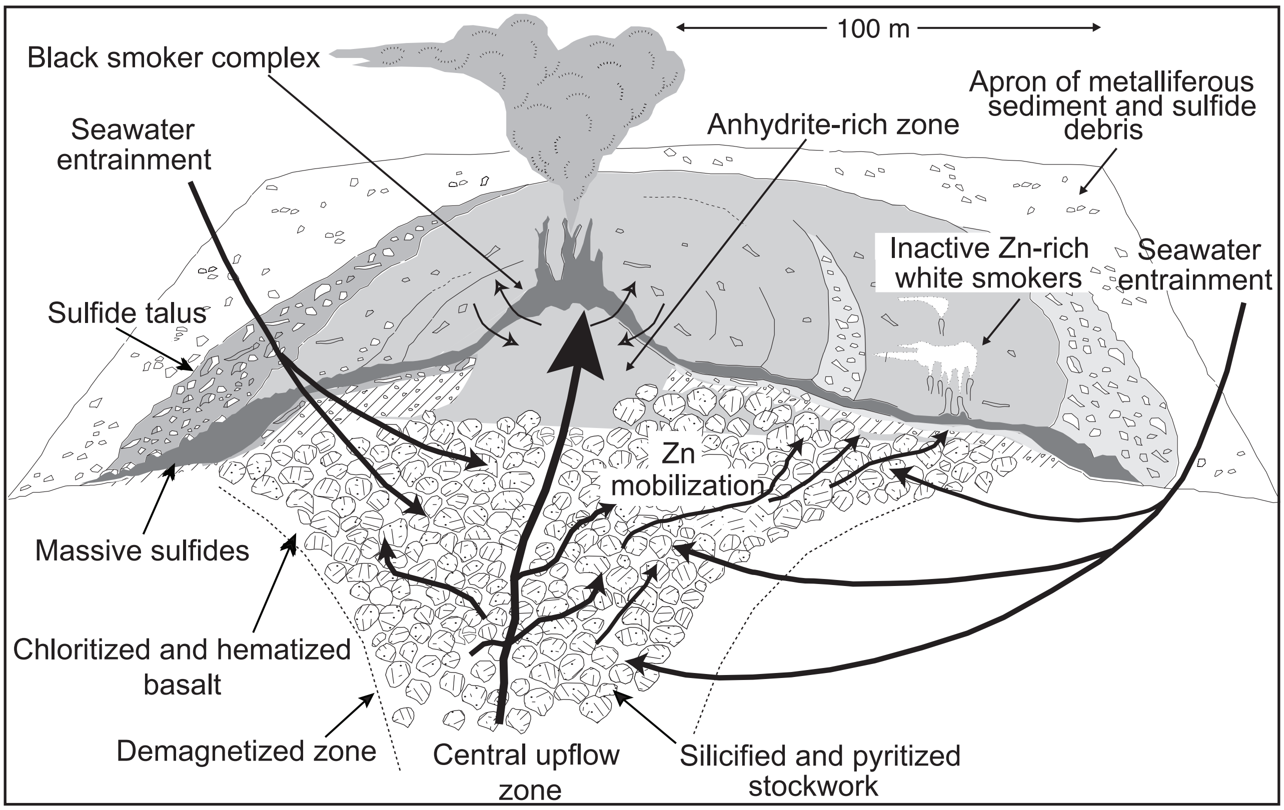
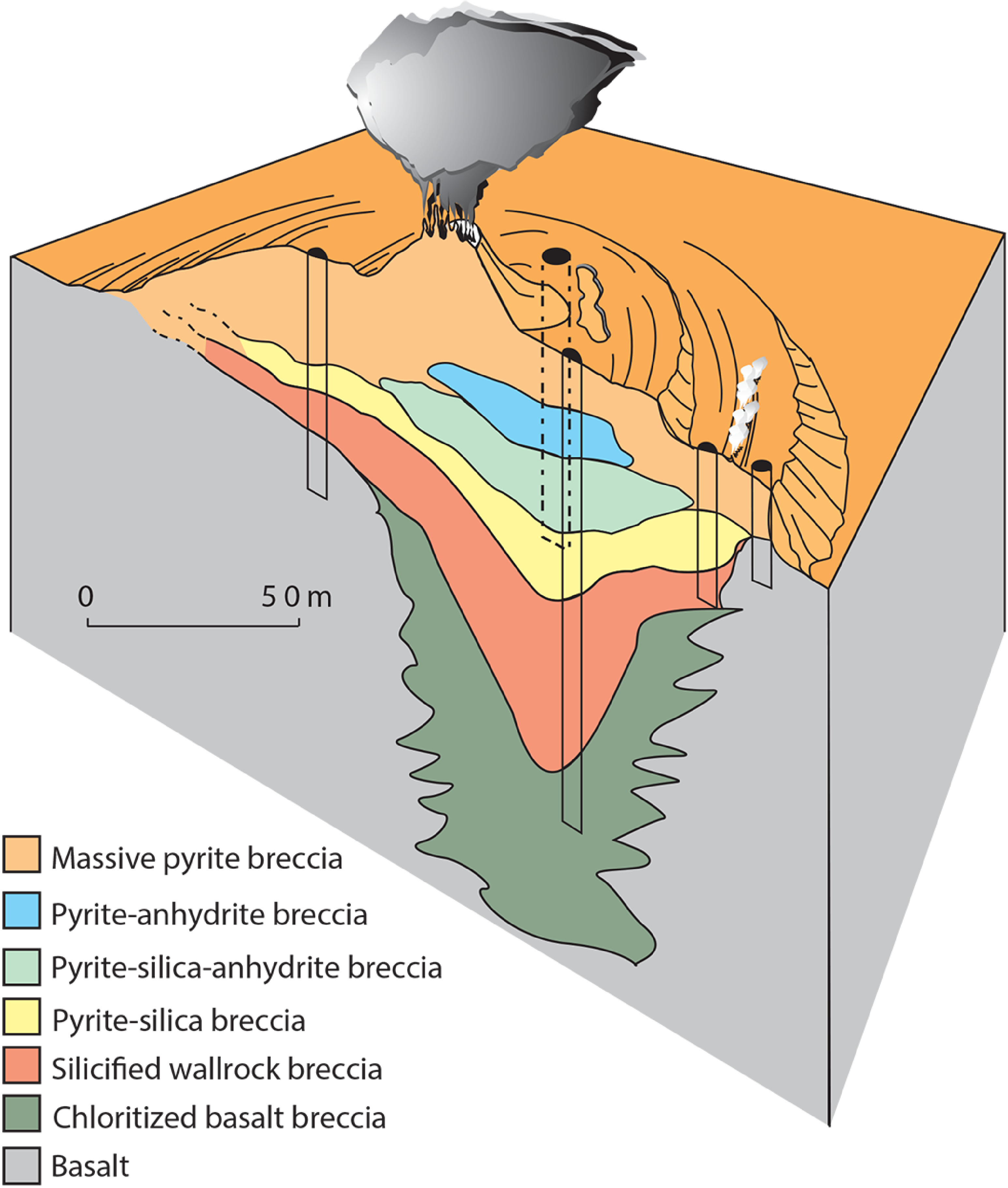

100 m
Black smoker complex
Apron of metalliferous sediment and sulfide debris
Seawater entrainment
Anhydrite-rich zone
Inactive Zn-rich white smokers
Seawater entrainment
Sulfide talus
Zn mobilization
Massive sulfides
Chloritized and hematized basalt
Demagnetized zone
Central upflow zone
Silicified and pyritized stockwork

Figure 4



0
50 m
Massive pyrite breccia
Pyrite-anhydrite breccia
Pyrite-silica-anhydrite breccia
Pyrite-silica breccia
Silicified wallrock breccia
Chloritized basalt breccia
Basalt

Figure 5