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Heat flow and mineralogy of TAG relict high-temperature hydrothermal zones: Mid-Atlantic Ridge 26°N, 45°W

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Abstract. Submersible investigations employing heat flow measurements (12 stations), sampling and imagery of the two relict high-temperature hydrothermal zones of the TAG field, the Alvin and Mir sulfide zones, elucidate relations between heat sources and mineralization including an active sulfide mound that has been the focus of prior studies. Values of heat flow in the Mir zone and at the margin of the active mound are inversely proportional to distance from adjacent volcanic centers. This observation supports the hypothesis that intrusions at volcanic centers adjacent to the high-temperature hydrothermal zones supply the heat to drive hydrothermal activity. The chronology of hydrothermal deposits in the different zones indicates that the intrusions are episodic with field-wide high-temperature hydrothermal events recurring at intervals of tens of thousands of years, while activity at individual zones may recur at intervals of hundreds to thousands of years. A sequence of hydrothermal deposits ranges to at least 140,000 years ago from massive sulfides forming at the active mound, to recrystallization of sulfides in the active and relict zones, to pyritization of an inactive mound in the Alvin zone; low-temperature mineral phases precipitate before, during and after the sulfides.

Introduction

The TAG hydrothermal field encompasses an assemblage of large active and relict hydrothermal zones similar to assemblages of ancient massive sulfide deposits like the Archean Noranda district of eastern Canada (Franklin et al., 1981). Three high-temperature zones comprising an active sulfide mound and two inactive sulfide zones (the Mir zone and the Alvin zone) and an active Low-Temperature zone lie within a 5 x 5 km area of the floor and wall on the east side of the rift valley near the center of a spreading segment of the Mid-Atlantic Ridge near 26°N, 45°W (Fig. 1; Rona et al., 1993). A microearthquake survey of the TAG segment indicated that the

portion of the axial high including the active sulfide mound is underlain at about 3 km subbottom by a largely solid but still hot magmatic intrusion (Kong et al., 1992). Quartz geobarometry indicates that high-temperature solutions discharging from the active mound equilibrated in a reaction zone about 2 km below the seafloor (Campbell et al., 1988).

At least ten dome-shaped accumulations of pillow flows (diameter 300-800 m; height 10-35 m) interpreted as volcanic centers are present along the axis and on the east side of the rift valley (Zonenshain et al., 1989; Rona et al., 1993). The three high-temperature hydrothermal zones of the TAG field lie near the margins of volcanic centers (Fig. 1). Radiometric dating of hydrothermal precipitates from the three zones reveals an overlapping range of ages to at least 140,000 years (Lalou et al., 1995). High-temperature activity at the active sulfide mound, a feature about 200 m in diameter by 40 m high near the base of the east wall with a black smoker complex (365°C) venting near its center, began about 50,000 years ago and recurred every 5 to 6 x 10³ years between 25,000 and 4,000 years ago with the most recent episode beginning about 60 years ago (Lalou et al., 1995). Ages of lava flow sequences at the adjacent pillow lava dome determined by radiometric and microfossil dating of intercalated sediments are 25,000 to 50,000 years, as old as 5,000 years, and less than 1,000 years with each eruptive episode followed by hydrothermal activity (Zonenshain et al., 1989), consistent with ages of the

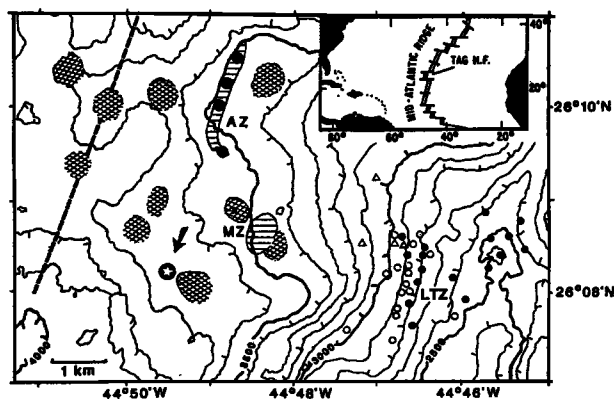


Figure 1. Bathymetric (100 m isobaths) and index maps of the TAG hydrothermal field in the rift valley east of the spreading axis (dashed line) of the Mid-Atlantic Ridge. The active sulfide mound (star at arrow), inactive high-temperature Alvin (AZ) and Mir zones (MZ; lined oval areas), and Low-Temperature zone (LTZ) are shown. The Alvin zone contains the Alvin mound at the southern end and three other mounds (dots). Manganese oxide deposits (open dots), Fe-Mn oxide stains (solid dots), and near-bottom water temperature anomalies (triangles) define the LTZ. Volcanic centers (hatched oval areas) lie at the spreading axis and adjacent to the high-temperature hydrothermal zones.

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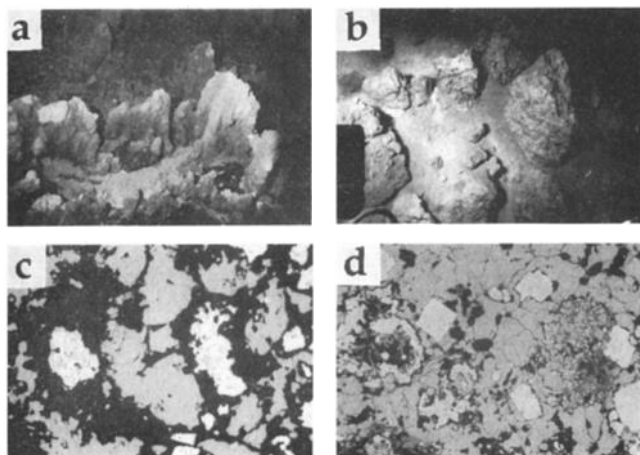


Figure 2. Seafloor photos (a,b) and photomicrographs (c-d) of sulfide textures in thin sections (field of view about 1 mm), as follow:

(a) Inactive intact chimneys up to 2 m high on an unsampled mound in the Alvin zone (Fig. 1); (b) remnants of sulfide chimneys about 1 m high at the top of the Alvin mound in the Alvin zone; (c) Alvin mound sample (ALV2599) with chalcopyrite-rich layer; idiomorphic pyrite (white) with chalcopyrite inclusions; chalcopyrite is undergoing dissolution and oxidation to covellite (dark); (d) Mir zone sample (2188-3-1A) showing recrystallized pyrite and chalcopyrite with interstitial amorphous silica after anhydrite.

hydrothermal precipitates (Lalou et al., 1995) within accuracies of the dating methods. This paper reports the results of heat flow and mineralogical studies at the Alvin and the Mir relict zones based primarily on a 1993 Alvin dive series.

Methods

Conductive heat flow was calculated as the product of in situ measurements of thermal gradient and conductivity using the Alvin heat flow system (Becker et al., this issue). Navigation was performed with a net of four long-baseline (3-5 km) acoustic transponders positioned by the Global Positioning System (GPS) with internal consistency to ± 20 m.

Results

Alvin Zone. The Alvin relict zone contains at least 4 mounds of similar size and shape to the active sulfide mound within an area about 2 km long (NE-SW) by 1 km wide (NW-SE) on normal fault blocks of the lower east wall of the rift valley between depths of 3400 and 3600 m about 2 km northeast of the active sulfide mound (Fig. 1; Rona et al., 1993; Bogdanov et al., 1995). Volcanic centers are present on the east and west sides of the zone. The southernmost mound at 26°09.54'N, 44°48.89'W named the "Alvin mound" is about 200 m in diameter and 28 m high between depths of 3,512 and 3,540 m based on submersible observations (Alvin dive 2599). Heat flow stations in sediment on the western flank and near remnants of sulfide chimneys (Fig. 2b) at the top of the mound recorded background values (0.1-0.3 W/m²; Table 1). A magnetic dipole signature was recorded with the

Table 1. Conductive Heat Flow in TAG Relict Hydrothermal Zones

ALVIN Dive Number (Date)	Station Number	Latitude (N)	Longitude (W)	Water Depth (m)	Water Temp. (°C)	Penetration (m)	Thermal Gradient (°C/m)	Average Thermal Conductivity (W/m·°C)	Heat Flow (W/m ²)	Heat Flow Standard Error (±W/m ²)	Feature
2586 (3 May 1993)	1	26°08.23'	44°48.46'	3539	2.63	0.4	0.639	0.7	0.41	0.11	Southern margin of Mir Zone in carbonate lutite
2586 (3 May 1993)	2	26°08.47'	44°48.46'	3483	2.65	0.4	2.389	0.8	1.91	0.16	Mir zone, subzone 3: carbonate lutite mixed with oxidized sulfide debris at base of scarp c. 5 m high of stratiform oxidized sulfides
2586 (3 May 1993)	3	26°08.51'	44°48.47'	3459	2.65	0.4	12.070	0.8	9.66	0.70	Mir zone, subzone 3: carbonate lutite mixed with metalliferous sediment between small mounds of soft black and yellow layered material overlying stratiform massive sulfides
2586 (3 May 1993)	4	26°08.56'	44°48.46'	3466	2.65	0.5	2.194	0.7	1.33	0.18	Mir zone, subzone 2: carbonate lutite mixed with oxidizing sulfide debris surrounded by large toppled chimneys
2592 (8 May 1993)	1	26°08.62'	44°48.65'	3584	2.65	0.5	0.730	0.9	0.70	0.09	Mir zone, subzone 2: carbonate lutite mixed with red metalliferous sediment at base of west-facing slope of mixed materials
2592 (8 May 1993)	2	26°08.63'	44°48.59'	3520	2.63	0.4	0.249	0.8	0.20	0.03	Mir zone, subzone 1: carbonate lutite mixed with metalliferous sediment
2592 (8 May 1993)	3	26°08.60'	44°48.35'	3468	2.63	0.5	2.050	0.7	1.31	0.13	Mir zone, subzone 2: carbonate sediment mixed with oxidized sulfides surrounded by disintegrating toppled chimneys up to 3 m long
2599 (17 May 1993)	1	26°09.54'	44°48.91'	3525	2.63	0.5	0.048	0.9	0.04	0.07	Alvin zone, southern end: carbonate lutite mixed with red metalliferous sediment on west flank of inactive sulfide mound
2599 (17 May 1993)	2	26°09.54'	44°48.89'	3513	2.63	0.5	0.018	0.8	0.01	0.03	Alvin zone, southern end: carbonate lutite mixed with red metalliferous sediment on top in inactive sulfide mound at southern end of Alvin zone
2188 (16 Jan 1990)	1	26°08.70'	44°48.5'	3463	2.44	0.5	9.921	0.9	8.93	0.96	MIR zone, subzone 2: carbonate lutite mixed with metalliferous sediment interspersed with outcrops of stratiform massive sulfides
2195 (24 Jan 1990)	1	26°08.80'	44°48.5'	3484	2.42	0.5	11.650	0.9	10.49	1.06	MIR zone, subzone 1: carbonate lutite and sulfide debris on bench in slope with outcrops of stratiform sulfide, pillow lava flows and partial sediment cover
2195 (24 Jan 1990)	2	26°08.80'	44°48.5'	3483	2.42	0.2	14.779	0.9	13.30	1.55	Mir zone, subzone 1: 1 m east of station 2195-1
Ship	1-5	---	---	2000-4000	---	---	0.09-0.38	1.0	0.08-0.35	---	Range of background values at 5 stations at Mid-Atlantic Ridge crest between 25°N and 26°N, 45°W (Langseth et al., 1972)
Empirical relation	---	---	---	3000-3700	---	---	---	---	0.76-1.15	---	Relation $q(t) = 11.3/t^{0.6}$ cal cm ⁻² s ⁻¹ between conductive heat flow q and crustal age t for ages between 169 and 385×10^6 (Parsons and Sclater, 1977)

¹Penetration of lowermost thermistor.

²Thermal conductivity calculated from heat pulse (Becker et al., this issue).

³Average thermal conductivity (Rona et al., 1993, Table 5)

steepest gradient over the mound (Tivey et al., this issue) similar to that at the active sulfide mound where modeled as a reduction of magnetization by high-temperature alteration of basalt and confirmed by drilling of an alteration pipe in the hydrothermal upflow zone (Humphris et al., 1995). Sulfides sampled from the flanks and top of the Alvin mound consist of dense (c. 5 g/cc), coarsely crystalline pyrite with minor chalcopyrite and traces of sphalerite (Fig. 2c) coated with a thin (<1 mm) layer of Fe-oxide which protects the interior against rapid oxidation, as noted by Lisitsyn (1989). Atacamite coats portions of the Fe-oxide layer indicating leaching of copper from the sulfides. Radiometric dating of 4 sulfide samples from the Alvin mound yielded ages of $48,000 \pm 5,000$ years (Lalou et al., 1995).

Mir Zone. The Mir relict hydrothermal zone is an area about 1 km in diameter of predominantly sulfide deposits on the lower east wall between depths of 3,430 and 3,575 m about 2 km east of the active sulfide mound (Fig. 1; Rona et al., 1993a,b; Stepanova et al., this issue). Volcanic centers flank the SE and NW sides of the Mir zone. The zone is divided into three subzones (W-E; Figure 3), as follows:

Subzone 1: Mixed types of hydrothermal deposits and basaltic breccias are exposed in an area about 200 m wide (E-W) of axis-parallel (020°), west-facing normal fault scarps (Lisitsyn et al., 1989; Rona et al., 1993). Radiometric ages determined for massive sulfide fragments recovered from the north end of subzone 1 (Lalou et al., 1995) are $102,000 \pm 7,000$ years (1 specimen), $50,000 \pm 2,000$ years (1 specimen), and $19,000 \pm 1,000$ years (3 specimens). Heat flow comprises high values (10.5 and 13.3 W/m^2) at two stations at the northern end of subzone 1 closest to the western volcanic center and background values (0.2 and 0.7 W/m^2) at two stations at the southern end farthest from the volcanic center (Fig. 3; Table 1).

Subzone 2: Standing and toppled chimneys predominantly composed of sulfides progressively increase in height eastward from less <1 m to about 25 m and exhibit diverse degrees of alteration in an area up to 400 m wide (E-W) by 700

Table 2. Composition of TAG Massive Sulfides

	Mir Zone		Alvin Mound of Alvin Zone		Active Sulfide Mound ("black smoker" chimneys)	
N	17		4		14	
	range	avg.	range	avg.	range	avg.
Au ppm	0.8-15.5	7.6	0.7-1.0	0.9	0.1-1.7	0.4
Ag ppm	10-240	86	<5-30	19	<5-36	10
As ppm	10-210	123	46-117	83	1-134	34
Sb ppm	4-60	19	2-5	3	0.1-8	1.5
Co ppm	5-1100	113	10-23	19	47-1840	430
Se ppm	<2-10	<5	-	<5	15-630	273
Cd ppm	<5-1050	229	-	-	<10-94	13
Mo ppm	40-230	132	45-107	80	9-267	106
Cu wt. %	0.1-26.8	14.6	0.1-5.7	2.0	2.2-31.8	12.2
Fe wt. %	19.6-42.5	29.1	38.4-42.4	40.7	4.8-40.4	19.7
Zn wt. %	0.1-22.0	4.4	0.1-0.5	0.3	0.1-3.3	0.4

m long (N-S). Sulfide composition is similar to that at the active mound with generally larger grains (1-2 mm) and higher average gold contents (Table 2; Fig. 2d) indicative of hydrothermal reworking. A population of small, intact inactive chimneys up to several meters high lies at the base of larger chimneys and also occurs as spires on their tops. Radiometric ages determined for 7 samples from the small chimneys and spires range between 870 ± 200 and 2690 ± 390 years (Lalou et al., 1995). A massive sulfide slab from the northern end of subzone 2 yielded an age of $9,400 \pm 1300$ years (Lalou et al., 1995). Heat flow comprises a high value (8.9 W/m^2) at a station in the NW quadrant of subzone 2 closest to the adjacent volcanic center, and background values (1.3 W/m^2) at two stations in the south central portion of subzone 2 (Fig. 3; Table 1).

Subzone 3: Low-temperature hydrothermal deposits of nontronite and manganese form unconsolidated yellow and black mounds up to several meters high interspersed with calcareous lutite in an area of hummocky topography about 200 m wide (E-W) and 1 km long (N-S). Patchy manganese oxide crusts and black stains occur on the lutite. A manganese oxide crust yielded a radiometric age of $140,000 \pm 20,000$ years; another such crust was <400 years old (Lalou et al., 1995). The low-temperature deposits directly overlie stratiform massive sulfides in the SE quadrant of the zone where subzone 3 onlaps a volcanic center and a high value of heat flow (9.6 W/m^2) was measured (Table 1; Fig. 3); a low value (1.9 W/m^2) was measured at the southern margin.

Discussion

Highest heat flow values measured around the margin of the active sulfide mound (5.0 - 16.7 W/m^2 ; except for one value of 0.04 W/m^2) based on denser coverage (20 stations; Becker et al., this issue) occur where the SE quadrant onlaps the adjacent volcanic center (Fig. 3); values within the active mound exhibit a more complex distribution dominated by convection. The volcanic centers may be only coincidental to eruptive cycles and insignificant as heat sources. However, the heat flow measured at the margins of the active mound and in the Mir zone with the highest values closest to adjacent volcanic centers favors an hypothesis that local intrusions at the adjacent volcanic centers supply the heat to drive hydrothermal circulation. The low-temperature hydrothermal

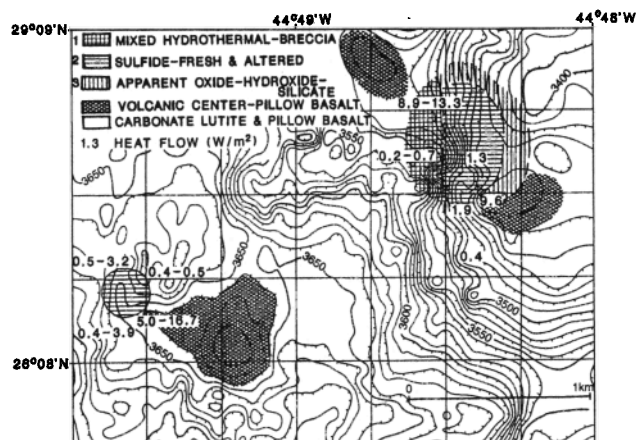


Figure 3. Multibeam bathymetric map (25 m isobaths) showing ranges of values of heat flow (W/m^2) at Mir zone (upper right; Table 1) and around the active sulfide mound (circle at lower left; Becker et al., this issue). Volcanic centers (hatched oval areas) are present adjacent to the Mir zone and active mound. Bar in lower right is 1 km long.

precipitates overlying massive sulfides on the southeast margin of the Mir zone record a waning heat supply beneath the adjacent center. The Alvin mound at the southern end of the Alvin zone over 1 km from a volcanic center (Fig.1) is cold and has apparently ceased activity about 48,000 years ago.

The episodic timing and apparent correlation between hydrothermal activity and extrusive volcanic events suggests that heat was supplied incrementally by multiple small intrusive events at the centers to build multistage deposits. The centers, in turn, may have tapped a larger magmatic source dependent on fault-controlled pathways, such as the intrusion detected beneath the axial high. Thus heat may be supplied by multiple small, episodically replenished intrusions at the centers (e.g., c.2km³; Lowell and Rona, 1985), rather than directly from a volume of magma of sufficient size (30-78 km³) to account for the size of the sulfide deposits (4 x 10⁶ tonnes).

Conclusions

Heat flow and mineralogical observations in the TAG field support conclusions, as follows:

- Values of heat flow at the margins of the inactive Mir zone and the active sulfide mound vary inversely with distance to adjacent volcanic centers supporting the hypothesis that intrusions at the centers supply the heat to drive hydrothermal activity. Petrologic and radiometric studies of the basalts are needed to determine the degree of interconnectivity between small intrusions at the centers and a larger intrusion beneath the axial high.
- The record indicates that intrusive and related hydrothermal activity are episodic, with events affecting the entire field at intervals of tens of thousands of years and individual centers at intervals of 100 to 5,000 years.
- An evolutionary sequence of hydrothermal deposits ranging over at least 140,000 years is present from massive sulfides forming at the active mound, to recrystallization and redistribution of elements in the Mir and Alvin zones resulting in pyritization and precipitation of patchy low-temperature mineral phases.
- Study of the TAG field as an assemblage of deposits rather than as a single active sulfide zone and of ancient volcanic-hosted massive sulfide districts like Noranda where clustering of massive sulfide zones associated with volcanic centers is present on a scale similar to that at TAG will provide mutual new insights.

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