

The TAG Hydrothermal Site: Implications of Some Recent Investigations for Marine Hydrothermal Systems

R. P. Von Herzen

Woods Hole Oceanographic Institution, Woods Hole, MA, USA

Abstract. Since its discovery about a decade ago, the TAG hydrothermal site (26°N, 45°W) has been the focus of an intensive series of international investigations, culminating with drilling (ODP Leg 158) in 1995. The focussed high-temperature (~360 °C) hydrothermal flux is among the largest (200-900 MW) of any hydrothermal site, with temperatures and chemistry that have remained relatively constant over the past decade. In contrast, recent nearby measurements of the diffuse flux over the associated sulfide mound show variability over periods of several months. Recent geophysical measurements indicate that the surface sulfides over the 150-200 m diameter mound are relatively thin (few tens of meters), and suggest geometries of the near-surface hydrothermal flow directions unanticipated from the surficial mound morphology.

Introduction.

The discovery of hydrothermal vents along the axes of spreading mid-ocean ridges about 2 decades ago (Corliss et al., 1979) was followed by considerable exploration, continuing up to the present time, using submersibles and ROVs to determine the spatial extent and characterization of such phenomena. The deposition of sulfide minerals in association with most such venting has of course attracted much attention as a result of its analogy with sulfide ore bodies on land. Most of the physical exploration of vents to date has been descriptive, and out of necessity has focussed on the surficial morphology and spatial relationships to ridge structure.

Although we now have a general understanding why high temperature (>100 °C) hydrothermal venting is more common along

ridge axes than elsewhere on the seafloor, many basic questions about the nature of these venting systems have not yet been answered. For example:

- * Why do vents (i.e., focussed high temperature flow) occur, rather than a more broadly distributed, diffuse lower temperature flow?

- * What determines vent spacings along ridge axes, and the ranges of other venting phenomena?

- * What is the distribution of the advected heat flux (focussed vs diffuse)?

- * What is the sub-seafloor structure beneath venting systems?

Some of these more difficult questions are now being approached with new exploration and geophysical tools that have recently become available. Below are summarized some recent investigations in the vicinity of a single large hydrothermal venting system: TAG.

Summary of selected investigations

The TAG (= Trans-Atlantic Geotraverse) hydrothermal site on the mid-Atlantic ridge at about 26 °N latitude, 45 °W longitude, was discovered somewhat more than a decade ago (Rona, 1986) incidental to geological and geophysical investigations of this section of mid-ocean ridges. Since that discovery, intensive international investigations (summarized in Rona and Von Herzen, 1996) have given us a more detailed view of the vigorous (200-900 MW) TAG active hydrothermal venting system and its surrounding geological setting. Located several km east of the neovolcanic axis of the mid-Atlantic ridge (Kleinrock and Humphris, 1996), it is one of the largest focussed venting systems thus far discovered in the world

oceans. The vigorous venting occurs from a ~20-m-diameter, ~10-m high chimney complex near the center of a bi-level oval-shaped mound of sulfide mineralization 150-200 m in diameter and up to 40 m high (Humphris and Kleinrock, 1996), with apparent diffuse venting over much of the mound surface. Other foci of seafloor sulfide mineralization at least as large but without presently active venting are found within a few km of the active site (Rona et al., 1996), with sulfide deposition apparently occurring over a period of at least 140 ka (Lalou et al., 1995).

The TAG active mound is situated at the base of the east wall of the mid-Atlantic ridge axial valley, perhaps located at or near two intersecting fault systems. It is also located near the center of a spreading segment between transform fault offsets, with recent asymmetric (20% faster to the east than west) and perhaps episodic (200-400 ka) seafloor spreading (Kleinrock and Humphris, 1996). Regional gravity (Fujimoto et al., 1996) and magnetic surveys indicate that the oblique spreading zone south of TAG has migrated northward since ~18 Ma. Analyses of seafloor basaltic glasses (Meyer and Bryan, 1996) dredged around TAG indicates that for at least 0.8 Ma, melts were generated at depths of perhaps 15-20 km and were quenched during rapid ascension, suggesting a relatively deeply penetrating hydrothermal system.

Detailed morphology derived from deep-towed side scan instrumentation (Humphris and Kleinrock, 1996) shows that the TAG mound surface is characterized by two superimposed main edifices, capped by the chimney complex. In addition to seafloor sampling of the sulfides (Tivey et al., 1995), near-seafloor geophysical measurements provide data on the physical properties and geometry of the sulfides at depth, and may be used to infer patterns of shallow pore water flow beneath the mound. High accuracy gravity measurements made in a submersible (Evans, 1996) suggest that a sulfide layer a few tens of meters thick overlies less dense material. In-situ direct current electrical resistivity measurements (Von Herzen et al., 1996) give values for the sulfides

(~0.2 ohm-m) about 1 order of magnitude less resistive than sea water, and indicate (consistent with the gravity measurements) that the sulfides are generally draped (with variable thickness) over more resistive material. Seafloor heat flow values (Becker et al., 1996) are mostly high but scattered (1-100 W/m²) on and peripheral to (several tens of m beyond) the actively venting mound, with a relatively narrow (~20 m) N-S band of very low values (<0.02 W/m²) west of the focussed venting that suggests a hydrothermal recharge zone. This zone is not spatially correlated with any known morphology or structure of the sulfide mound. Scientific drilling (Humphris et al., 1995) indicates a vertical and lateral mineral zonation beneath the TAG mound to depths of 125 m below seafloor, and shows that anhydrite apparently is a relatively common mineral over this depth range beneath the TAG sulfides, in contrast to its only rare occurrence for most hydrothermal ore deposits on land.

Longer term (up to several months) measurements of temperatures, both sub-seafloor (few tens of cm; Kinoshita et al., 1996) and of diffuse venting through the surface of the mound (Schultz et al., 1996), indicate temporal variability of the hydrothermal flow for intermittent periods over several days. Some, but not all, temporal variations may have been caused by the drilling that occurred during the measurement periods. However, visual observations of the drill holes from a submersible several months after they were drilled did not show any significant flow either down or up the holes, in contrast to rather vigorous flow that has been documented for drill holes at other hydrothermal sites (Becker et al., 1994). The water chemistry of the hi-T vent fluids has remained relatively constant over several years, including sampling after drilling (Gamo et al., 1996; Edmonds et al., 1996). The TAG chemistry is similar to that of vents on the East Pacific Rise, indicating that sea water interacts with rock at comparable temperatures (350-400 °C) for both systems. The relative concentrations of dissolved gases (H₂S, CO₂, CH₄, He) are also similar over the period 1993-1995 (Charlou et

al., 1996). Approximately 50% of the trace metals (Cu, Zn, Fe) in the hydrothermal flux are incorporated in the TAG plume as dissolved or particulate phases (Ludford et al., 1996), so that comparable amounts of these elements must be precipitated rapidly from the plume and incorporated as seafloor deposits on or nearby the mound.

At the relict Mir mound located a few km northeast of TAG, the seafloor mineralogy may be zoned laterally, perhaps a result of different phases of mound development (Rona et al., 1996). Modeling of the magnetic anomaly associated with Mir may be interpreted as a negative magnetization contrast at depth, perhaps an effect of anomalous temperatures at depth (Tivey et al., 1996). This interpretation is supported by high heat flow values measured at Mir, in contrast to relatively low values at the ALVIN relict zone further north (Rona et al., 1996).

Implications

For the entire mid-ocean ridge (MOR) system, geophysical data may be used to estimate the total number and frequency of occurrence of vents along the MOR. This estimate is based on the mean thermal energy fluxes of vents compared to the total thermal power (P) available at ridges from the seafloor spreading process. The latter may be simply estimated as:

$$P = \rho c_p \cdot H \cdot V \cdot \Delta T \cdot f$$

where

ρc_p is the volumetric heat capacity of rock (basalt, $\sim 2.3 \text{ J cm}^{-3} \text{ }^\circ\text{C}^{-1}$),

H is the mean effective depth below seafloor of sea water penetration ($\sim 4 \text{ km}$),

V is the mean (full) seafloor spreading rate for all MORs ($\sim 7 \text{ cm/yr}$),

ΔT is the mean effective temperature drop in the rock as a result of cooling by percolation of sea water near the ridge axis ($\sim 1200 \text{ }^\circ\text{C}$, including latent heat effects),

f is the fraction of thermal power dissipated in focussed vents, compared to the total that includes the diffuse flux (~ 0.1).

The simplicity of this calculation and the estimates of some parameters may need further explanation. Near (within a few km of) the MOR axis, it is assumed that advective (i.e., venting), rather than conductive, processes dominate the total heat transferred from crust to oceans. The mean (2-sided) spreading rate of MORs ($V = 7 \text{ cm/y} \pm 10\%$) is estimated from the recent rate of crustal accretion ($3.45 \text{ km}^2/\text{y}$) from oceanic spreading centers (Sclater et al., 1981), divided by the total length ($5 \cdot 10^4 \text{ km}$) of these spreading centers. The mean effective depth of hydrothermal cooling at ridge axes may be estimated from seismic data indicating the depth to magma at ridge crests (Baker et al., 1995). Although measurements are sparse, and the relationship of magma depth to spreading rate may be non-linear, a mean depth $H = 4 \text{ km}$ ($\pm 25\%$) for a mean spreading rate of about 7 cm/y may be estimated. ΔT is estimated by the cooling of magma from $\sim 1300 \text{ }^\circ\text{C}$ to $\sim 400 \text{ }^\circ\text{C}$ (hydrothermal temperatures), with the addition of $\sim 300 \text{ }^\circ\text{C}$ as the equivalent temperature drop in basalt to account for the freezing of magma (latent heat, $\sim 3 \cdot 10^5 \pm 10\% \text{ J/kg}$). Finally, it is estimated that the diffuse flux is 1 order of magnitude ($\pm 50\%$) greater than focussed venting (Schultz et al., 1992; Rona and Trivett, 1992).

These parameter values give a thermal power $P = 2.6 \text{ MW}$ per km ridge length for focussed venting. Assuming that an average vent (smoker) transfers 5 MW of thermal power (vent and plume measurements range from ~ 1 to 200 MW), vent spacings should average about 2 km along spreading ridges, or $\sim 25,000$ vents along all ridges. The relative spacing should vary directly with the local spreading rate. From the uncertainties in parameters, the accuracy of this estimate is probably not better than a factor of about 2. The largest uncertainties are the depth of hydrothermal circulation (H), and particularly the relative proportion (f) of the total flux

represented in discrete venting, both of which may be functions of the spreading rate. Hence, the thermal power determined at TAG (200-900 MW; Rudnicki and Elderfield, 1992; Rona et al., 1993) is equivalent to the focussed venting from at least a 200 km length of ridge spreading at the mid-Atlantic rate. Although this estimate may suggest that vents are short-lived, radiometric dating of the sulfides indicates that TAG has been hydrothermally active (although perhaps not continuously) since at least ~50 ka.

Over a world-wide ridge length of ~50,000 km, the total thermal power transferred by near-axis hydrothermal circulation is $\sim 1.3 \cdot 10^{12}$ W, or ~5% of the total oceanic heat flux. This estimate includes both focussed and diffuse flow, with an accuracy primarily determined by the uncertainty in H ($\pm 25\%$). The heat transferred by hydrothermal circulation at greater distances from actively spreading ridge crests (>few km, extending to ~60 Ma seafloor) is estimated as several times this amount (Stein and Stein, 1994), and most of this transfer occurs at lower temperatures (<100 °C).

Future research at TAG and other vent systems.

Further research is required to improve our understanding of the energetics and other important characteristics of TAG and similar MOR vents. Although some measurements of diffuse flow at TAG have been made (Schultz et al., 1996), the mean diffuse flux associated with the focussed venting there is unknown, as is the case for almost all other vent systems. Methods to obtain quantitative surveys need development, perhaps temperature measuring arrays similar to those used by Rona and Trivett (1992) that may be used by submersibles or ROVs to obtain systematic and complete data over selected venting systems.

The sub-seafloor structure of TAG and other MOR vents is almost completely unknown, and is needed to assess 1) the characteristics that allow seafloor vents to exist, and 2) the extent to which the seafloor structure of MOR vents

resembles that of similar ore bodies on land. Near seafloor seismic measurements to determine the 3-D velocity structure beneath vent systems is now technologically feasible. These measurements would ideally be made where other geophysical data are available, such as electrical resistivity tomography, the feasibility of which has been shown at TAG (Cairns et al., 1996).

Finally, knowledge of the temporal variability of venting is probably important for a full understanding of vent processes. Some of the TAG investigations suggest significant local variability over periods of several months, although it is not clear whether these are important for the entire vent system. At least the fluid chemistry of the focussed TAG venting seems relatively constant over the past decade of measurements. Technological developments now allow many parameters to be measured continuously and automatically at reasonable cost in the oceans over periods of at least several years, and much should be learned about marine hydrothermal systems from the establishment of such data observatories.

Acknowledgements. I am indebted to many colleagues who have carried out research programs at TAG in recent years for data, analyses, and ideas. P. Rona helped to broaden my perspective of marine hydrothermal systems. This paper was stimulated by the JAMSTEC symposium, and its preparation was supported in part by NSF grants and WHOI.

References

- Baker, E.T., C.R. German, and H. Elderfield, 1995. Hydrothermal plumes over spreading center axes: Global distributions and geological inferences. *In* Humphris, S.E., et al. (eds.), Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions, Amer. Geophys. Un., 47-71.
- Becker, K., R.H. Morin, and E.E. Davis, 1994. Permeabilities in the Middle Valley hydrothermal system measured with packer and flowmeter experiments. *In* Mottl, M.J.,

- E.E. Davis, A.T. Fisher, and J.F. Slack (eds.), Proc. ODP, Sci. Results, 139: College Sta., TX (Ocean Drilling Program), 613-626.
- Becker, K., R. Von Herzen, J. Kirklin, R. Evans, D. Kadko, M. Kinoshita, O. Matsubayashi, R. Mills, A. Schultz, and P. Rona, 1996. Conductive heat flow at the TAG active hydrothermal mound: Results from 1993-1995 submersible surveys. *Geophys. Res. Lett.*, 23, 3463-3466.
- Cairns, G.W., R.L. Evans, and R.N. Edwards, 1996. A time domain electromagnetic survey of the TAG hydrothermal mound. *Geophys. Res. Lett.*, 23, 3455-3458.
- Charlou, J.L., J.P. Donval, P. Jean-Baptiste, P. Rona, and A. Dapigny, 1996. Gases and helium isotopes in high temperature solutions sampled before and after ODP Leg 158 drilling at TAG hydrothermal field (26°N, MAR). *Geophys. Res. Lett.*, 23, 3491-3494.
- Corliss, J.B., et al., 1979. Submarine thermal springs on the Galapagos rift. *Science*, 203, 1073-1083.
- Edmonds, H.N., C.R. German, Y. Huh, T. Gamo, and J.M. Edmond, 1996. Continuation of the hydrothermal fluid chemistry time series at TAG and the effects of the ODP drilling. *Geophys. Res. Lett.*, 23, 3487-3490.
- Evans, R.L., 1996. A seafloor gravity profile across the TAG hydrothermal mound. *Geophys. Res. Lett.*, 23, 3447-3450.
- Fujimoto, H., N. Seama, J. Lin, T. Mtsumoto, T. Tanaka, and K. Fujioka, 1996. Gravity anomalies of the mid-Atlantic ridge north of the Kane fracture zone. *Geophys. Res. Lett.*, 23, 3431-3434.
- Gamo, T., H. Chiba, H. Masuda, H.N. Edmonds, K. Fujioka, Y. Kodama, H. Nanba, and Y. Sano, 1996. Chemical characteristics of hydrothermal fluids from the TAG mound of the mid-Atlantic ridge in August 1994: Implications for spatial and temporal variability of hydrothermal activity. *Geophys. Res. Lett.*, 23, 3483-3486.
- Humphris, S.E., and M.C. Kleinrock, 1996. Detailed morphology of the TAG active hydrothermal mound: Insights into its formation and growth. *Geophys. Res. Lett.*, 23, 3443-3446.
- Humphris, S.E., P.M. Herzig, D.J. Miller, et al., 1996. Proc. ODP, Init. Reports, 158, College Sta., TX (Ocean Drilling Program), 384 pp.
- Kinoshita, M., O. Matsubayashi, and R.P. Von Herzen, 1996. Sub-bottom temperature anomalies detected by long-term temperature monitoring at the TAG hydrothermal mound. *Geophys. Res. Lett.*, 23, 3467-3470.
- Kleinrock, M.C., and S.E. Humphris, 1996. Structural asymmetry of the TAG rift valley: Evidence from a near-bottom survey for episodic spreading. *Geophys. Res. Lett.*, 23, 3439-3442.
- Lalou, C., J.-L. Reyes, E. Bricet, P.A. Rona, and G. Thompson, 1995. Hydrothermal activity on a 10⁵-year scale at a slow spreading ridge, TAG hydrothermal field, mid-Atlantic ridge 26°N. *J. Geophys. Res.*, 100, 17855-17862.
- Ludford, E.M., M.R. Palmer, C.R. German, and G.P. Klinkhammer, 1996. The geochemistry of Atlantic hydrothermal particles. *Geophys. Res. Lett.*, 23, 3503-3506.
- Meyer, P.S., and W.B. Bryan, 1996. Petrology of basaltic glasses from the TAG segment: Implications for a deep hydrothermal heat source. *Geophys. Res. Lett.*, 23, 3435-3438.
- Rona, P.A., M.D. Hannington, C.V. Raman, G. Thompson, M.K. Tivey, S.E. Humphris, C. Lalou, and S. Petersen, 1993. Active and relict sea-floor hydrothermal mineralization at the TAG hydrothermal field, mid-Atlantic ridge. *Econ. Geol.*, 88, 1989-2017.
- Rona, P.A., G. Klinkhammer, T.A. Nelsen, J.H. Trefrey, and H. Elderfield, 1986. Black smokers, massive sulphides and vent biota at the mid-Atlantic ridge. *Nature*, 321, 33-37.
- Rona, P.A., J.S. Petersen, K. Becker, R.P. Von Herzen, M.D. Hannington, P.M. Herzig, J. Naka, C. Lalou, and G. Thompson, 1996. Heat flow and mineralogy of TAG relict

- high-temperature hydrothermal zones: Mid-Atlantic ridge 26°N, 45°W. *Geophys. Res. Lett.*, 23, 3507-3510.
- Rona, P.A., and D.A. Trivett, 1992. Discrete and diffuse heat transfer at ASHES vent field, Axial Volcano, Juan de Fuca ridge. *Earth Plan. Sci. Lett.*, 109, 57-71.
- Rona, P.A., and R. P. Von Herzen, 1996. Introduction to special section on measurements and monitoring at the TAG hydrothermal field, mid-Atlantic ridge 26°N, 45°W. *Geophys. Res. Lett.*, 23, 3427-3430.
- Rudnicki, M.D., and H. Elderfield, 1996. Theory applied to the mid-Atlantic ridge hydrothermal plumes: The finite difference approach. *J. Volc. Geoth. Res.*, 50, 161-172.
- Schultz, A., J.R. Delaney, and R.E. McDuff, 1992. On the partitioning of heat flux between diffuse and point source seafloor venting. *J. Geophys. Res.*, 97, 12299-12314.
- Schultz, A., P. Dickson, and H. Elderfield, 1996. Temporal variations in diffuse hydrothermal flow at TAG. *Geophys. Res. Lett.*, 23, 3471-3474.
- Sclater, J.G., B. Parsons, and C. Jaupart, 1981. Oceans and continents: Similarities and differences in the mechanisms of heat loss. *J. Geophys. Res.*, 86, 11535-11552.
- Tivey, M.A., P.A. Rona, and M.C. Kleinrock, 1996. Reduced crustal magnetization beneath relict hydrothermal mounds: TAG hydrothermal field, mid-Atlantic ridge, 26°N. *Geophys. Res. Lett.*, 23, 3511-3514.
- Tivey, M.K., S.E. Humphris, G. Thompson, M.D. Hannington, and P.A. Rona, 1995. Deducing patterns of fluid flow and mixing within the TAG active hydrothermal mound using mineralogical and geochemical data. *J. Geophys. Res.*, 100, 12527-12555.
- Von Herzen, R.P., J. Kirklin, and K. Becker, 1996. Geoelectrical measurements at the TAG hydrothermal mound. *Geophys. Res. Lett.*, 23, 3451-3454.

R. P. Von Herzen, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA (e-mail: rvonh@whoi.edu)