Relation Between Volcanism, Tectonism, and Hydrothermal Activity Along the Mid-Ocean Ridges*

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Abstract

Just over 30 years ago, scientists exploring the global mid-ocean ridge system made the spectacular discovery of black smokers—hydrothermal chimneys made of metal sulfide minerals that vigorously discharge hot, particulate-laden fluids into the ocean. These chimneys are the surface manifestation of convection of seawater through the oceanic crust and water-rock reactions that produce hot, hydrothermal fluids that discharge at the seafloor. This hydrothermal circulation process plays an important role in regulating the chemistry of seawater, building mineral deposits, and supporting chemosynthetically based ecosystems.

Early studies focused on hydrothermal systems on the fast-spreading East Pacific Rise, where shallow magma lenses beneath the ridge crest provide heat to drive convection of seawater through the oceanic crust. Ten years later, studies of the slow-spreading Mid-Atlantic Ridge revealed much larger mineral deposits – a surprising result given the lower magma delivery rate and heat availability.

Through the use of different deep-submergence technologies, this presentation explores the characteristics of vents and their associated communities along the mid-ocean ridge, and the varying relations between volcanic and tectonic processes at sites on ridges of different spreading rates. It will focus in particular on how one active hydrothermal system has constructed a large mineral deposit on the Mid-Atlantic Ridge and how recent experiments at that site have shed light on the role tectonics and faulting play in the evolution of long-lived hydrothermal systems.

References

Canales, J.P., R.A. Sohn, and B.J. deMartin, 2007, Crustal structure of the Trans-Atlantic Geotraverse (TAG) segment (Mid-Atlantic Ridge, 26° 10'N): Implications for the nature of hydrothermal circulation and detachment faulting at slow spreading ridges: Geochemistry, Geophysics, Geosystems G super 3, v. 8, p. 8

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deMartin, B., R.A. Sohn, J.P. Canales, and S.E. Humphris, 2007, Kinematics and geometry of active detachment faulting beneath the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge: Geology, 35, 711-714.


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AAPG Distinguished Lecture Series 2008-2009
What is a Hydrothermal Vent?
<table>
<thead>
<tr>
<th></th>
<th>Hydrothermal Fluid</th>
<th>Seawater</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>360–365</td>
<td>2</td>
</tr>
<tr>
<td><strong>Acidity (at 25°C)</strong></td>
<td>3.35</td>
<td>7.8</td>
</tr>
<tr>
<td><strong>Dissolved Oxygen</strong></td>
<td>0</td>
<td>0.076</td>
</tr>
<tr>
<td><strong>Hydrogen Sulfide (mM)</strong></td>
<td>2.3–3.5</td>
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</tr>
<tr>
<td><strong>Sodium (mM)</strong></td>
<td>537</td>
<td>464</td>
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<tr>
<td><strong>Potassium (mM)</strong></td>
<td>17.1</td>
<td>9.8</td>
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<tr>
<td><strong>Calcium (mM)</strong></td>
<td>30.8</td>
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<tr>
<td><strong>Magnesium (mM)</strong></td>
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<tr>
<td><strong>Silica (mM)</strong></td>
<td>20.75</td>
<td>0.2</td>
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<tr>
<td><strong>Chloride (mM)</strong></td>
<td>636</td>
<td>541</td>
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<tr>
<td><strong>Sulfate (mM)</strong></td>
<td>0</td>
<td>27.9</td>
</tr>
<tr>
<td><strong>Manganese (μM)</strong></td>
<td>680</td>
<td>0</td>
</tr>
<tr>
<td><strong>Iron (μM)</strong></td>
<td>5590</td>
<td>0.0015</td>
</tr>
<tr>
<td><strong>Copper (μM)</strong></td>
<td>98–120</td>
<td>0.007</td>
</tr>
<tr>
<td><strong>Zinc (μM)</strong></td>
<td>47–53</td>
<td>0.01</td>
</tr>
</tbody>
</table>
What is the Relation between Hydrothermal Activity and Volcanic-Tectonic Relations on MOR?

• Volcanism and tectonism on the fast-spreading EPR

• The TAG active mound on the slow-spreading MAR

• Seismicity and fluid flow at TAG (STAG) experiment

• Implications for volcanic-tectonic relations and hydrothermal flow on slow spreading ridges
Autonomous Underwater Vehicle
Locations of known hydrothermal activity along the global mid-ocean ridge system

- • = Known active sites  ○ = Active sites indicated by midwater chemical anomalies
Magma is delivered to the base of the crust (Moho), rises within the crust as diapirs, and flows along the axis at a shallow level.
At slow-spreading ridges, magma bodies are thought to be ephemeral, cooling quickly, and no permanent melt lens resides within the crust.

Sinton and Detrick, 1992
The TAG Segment

• 40 km long; hourglass shape

• Bounded by NTDs

• Axial depths >3700 m; shoals at center to 3550 m

• Asymmetric spreading: 
  ~11 mm/yr to west
  ~13 mm/yr to east
The TAG Active Mound: A BIG mineral deposit!
Estimated Tonnage of the Active TAG Mound

- Total Mass of Sulfide \(3.9 \times 10^6\) tonnes
  - Exposed Mound \(2.7 \times 10^6\) tonnes
  - Subseafloor Stockwork \(1.2 \times 10^6\) tonnes
- Total Mass of Fe \(2.3 \times 10^6\) tonnes
- Total Mass of Cu \(30-60 \times 10^3\) tonnes
- Total Mass of Zn \(15.2 \times 10^3\) tonnes

(Note: 1 tonne = \(10^3\) kg)
Based on a simple chemical mass balance model

Humphris & Cann (2000)
Other Results of Chemical Mass Balance Model

• Size of alteration zone (based on Cu budget):
  \[1-2 \times 10^{12} \text{ kg} \ (0.4-0.7 \text{ km}^3)\]

• Heat to drive a 1000 MW hydrothermal system cannot be supplied from the steady state energy flux from crustal accretion
The Heat Source at TAG?

**Location**
- Is it in the neovolcanic zone with fluid flow pathways provided by large faults?
- Are there discrete, off-axis volcanic centers providing heat locally?

**Nature**
- Extraction of latent heat from magma chambers?
- Extraction of specific heat from hot rocks across cracking fronts?
The Seismics at TAG (STAG) Experiment (2003-2004)

Objectives

• To determine the location of the heat source for the TAG mound

• To investigate linkages between fluid flow, seismic activity, and tidal pressures to understand the hydraulics of the TAG mound

Components

¶ 4 oceanographic cruises
¶ Microbathymetry map of TAG mound
¶ 9 months seismicity data on 13 OBS
¶ 3 seismic refraction lines
¶ 12 months fluid exit T at 21 sites
¶ 6 months tidal pressure data
OBS Deployments
- 19,232 earthquakes with magnitudes $1 \leq M_L \leq 4$ located (35,000 detected)
- 2 zones of activity:
  -- arc around the eastern wall protrusion
  -- parallel to ridge axis beneath eastern wall
- Focal mechanisms consistent with:
  -- normal faulting around arc
  -- antithetic normal faulting dipping east
Conclusions about the TAG System

• TAG lies on the hanging wall of a detachment fault that extends >7 km below the seafloor. The large high velocity body beneath the TAG active mound is interpreted to be lower crustal rocks uplifted by tectonic extension along the detachment fault.

• The lack of a low velocity zone within the upper 4 km of crust in the vicinity of the TAG mound indicates the system extracts thermal energy from deeper crustal regions (>7 km).

• The heat source driving hydrothermal circulation is likely magmatic intrusions at the spreading axis mined by the fault.

• Hydrothermal systems could be a common feature of the hanging walls of oceanic detachment faults, which has implications for the distribution of hydrothermal activity and associated thermal and chemical fluxes.
Conclusions

• The distribution of hydrothermal systems along fast-spreading ridges is controlled dominantly by the presence or absence of a shallow axial magma chamber:

  Magmatic/volcanic control more important than tectonic processes at fast-spreading ridges.

• The location of hydrothermal systems along slow-spreading ridges is controlled dominantly by faulting:

  Tectonic control is more important in general than magmatic/volcanic process at slow-spreading ridges.
Detachment Faulting at TAG

Geophysical Evidence

• Magnetization low beneath eastern rift valley wall indicates crustal thinning

• Progression from altered gabbros through pillows along eastern valley wall

Tivey et al. (2003)
DSPL SeaLogger® temperature probe:
High T: 152-460°C
Intermediate T: -2-124°C
VEMCO Minilog-T data logger: –2 to 70°C.