Final Report

Preliminary Investigation of Apparent Hydrothermalism Associated With Long-Lived Detachment Faulting

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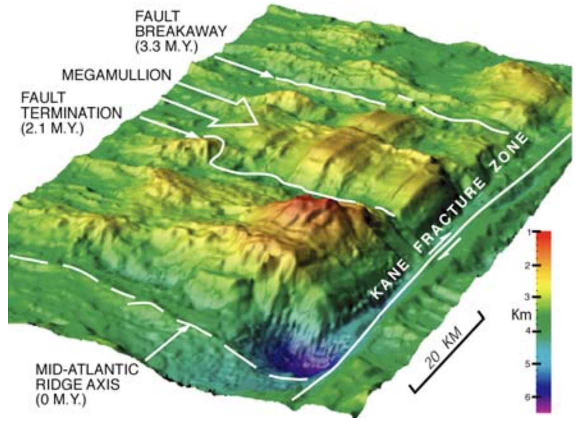
Introduction

In 1996, it was discovered that very long-lived (~1-2 m.y.) normal faults can form at slow-spreading mid-ocean ridges. As the lower block of such a fault (the footwall) is uplifted, it 'rolls over' to form a corrugated, domed edifice termed a megamullion. Studies of megamullions have revealed that the footwalls exhume rocks (gabbros) from the lower oceanic crust, as well as rocks from the upper mantle (ultramafic peridotites, usually altered to serpentinite) that normally lie at a depth of 6-7 km below the seafloor. Recent discoveries at the Lost City and TAG areas on the Mid-Atlantic Ridge also show that such major detachment faults can be intimately linked with flow of hydrothermal fluids. In the Lost City area, low-temperature fluids flow through a serpentinite footwall and precipitate carbonates and brucite, while in the TAG area high-temperature fluids flow through the hanging-wall block that overlies the footwall; this block consists of the shallowest, basalt layer of ocean crust, and the fluids precipitate sulfides and anhydrite. At Kane megamullion, basement is altered mantle peridotite intruded by gabbros; there we have discovered a third apparent kind of relation between hydrothermal fluids and the type of underlying rock, namely low-temperature hydrothermal fluids that flow through dominantly mantle ultramafic rocks but precipitate iron(Fe)-manganese(Mn)-carbonate at the seafloor. We investigated this phenomenon with funding from this grant.

Kane Megamullion is located on the Mid-Atlantic Ridge in 3.3-2.1 million-year-old crust west of the ridge axis and just south of Kane Fracture Zone (Figure 1). The data that we used for our analyses included ROV Jason seafloor video, AUV ABE high-resolution seafloor bathymetry, and seafloor samples, all of which we had previously obtained from the megamullion during R/V Knorr cruise 180-2 in 2004. The Jason and ABE data were used for morphologic and structural analyses and to document specific sample locations. The samples were subjected to geochemical analyses to test for indications of hydrothermal fluid flow.

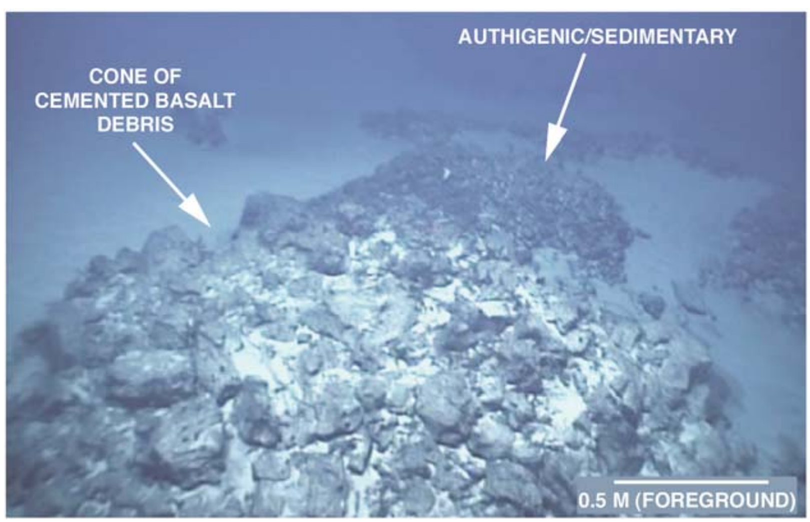
Figure 1. Three-dimensional view of Kane megamullion, looking toward the southwest. The detachment fault surface shows east-west lineated corrugations and forms the seafloor from the fault breakaway to the termination. Most of the ROV Jason, AUV ABE, and sample data analyzed here were obtained from the central, elevated part of the megamullion.



Results of Mapping Using Jason and ABE data

Seafloor mapping using the Jason and ABE data revealed two basic kinds of features that are interpreted to be the result of hydrothermal fluid flow. The first and most prominent of these are consolidated cones or mounds of mixed rock debris and cemented sediment that visually appears to be enriched in Fe-Mn-rich hydrothermal precipitates (Figure 2). The cones have variable shapes and sizes. They range from conical, to dome-shape, to elongate or ridge-like and have heights ranging between 1 to 8 meters, with flank slopes of about 30 degrees to near-vertical. Compositions of the cone surfaces, documented from samples taken by ROV Jason, range from nearly pure rock debris (primarily basalt, but occasionally gabbro and serpentinite), to coarse cemented breccias of mixed composition, to nearly pure sediment. Some of the sedimentary cones show flow structures; these structures suggest that Fe-Mn-rich deposits were precipitated inside the cones from hydrothermal fluids, thus forcing sediment to flow out of the cones. In total, more than 60 cones of rock debris and/or sediment were documented across the central part of Kane megamullion from the Jason video data.

Figure 2. Video image from Jason showing cone of basalt rock debris cemented by Fe/Mn-rich deposits. The cone at the rear of the image is entirely sediment enriched in Fe and Mn.



The second kind of feature that may be related to hydrothermal fluid flow is cemented, slabby sedimentary layers that also appear to be Mn- and Fe-rich. In some places, these slabs are on the flanks or at the bases of the cones described above, but in other places they occur on relatively smooth seafloor. This latter form is sometimes cracked in linear to polygonal patterns, with upturned ridges produced at the cracks. The upturned ridges suggest compression induced by addition of material within the sedimentary layers, presumably as a result of precipitation from hydrothermal fluids.

Results of Mineralogical and Geochemical Analyses

During the Knorr cruise a suite of samples was collected from cemented cones of rock debris using the manipulators on ROV Jason. In addition, marlstones that appeared to contain interlayered beds of carbonate and Fe-Mn oxyhydroxides were sampled by Jason from slabby sedimentary deposits on the megamullion surface.

To test our hypothesis that the Fe-Mn deposits were precipitated from hydrothermal fluids, we selected thirteen samples for mineralogical and geochemical analyses. The selected samples included both breccias from the cones and examples of the layered marlstones (Figure 3).

Figure 3. At top is Sample JAS116-24, a cemented basalt breccia from one of the cones.

At bottom is Sample KN180-2-16-18. This is a deposit consisting of carbonate ooze that is interlayered with Fe-Mn oxyhydroxide. Scales are in centimeters.

We analyzed thin sections of the samples and also conducted X-ray diffraction analyses. This revealed that there are two types of breccias from the cones. Some have serpentinite clasts and are cemented with carbonates in which microfossils replaced by Fe-Mn oxyhydroxides are clearly visible. Other breccias have basaltic clasts (as in Figure 3, top) and are cemented with quartz. The layered marlstones (Figure 3, bottom) consist of layers of Fe-Mn oxyhydroxides interbedded with layers of carbonate ooze in which Fe-Mn oxyhydroxides both cement and replace the microfossils. This association indicates that warm fluids rich in iron and manganese flowed through the rock debris and the carbonate sediment from below and then precipitated within those deposits.

The geochemical analyses of both bulk rock and separates provided evidence for two types of Fe-Mn oxyhydroxide deposits. We used Fe/Mn ratios, and trace- and rare-earth-element concentrations to discriminate between 1) hydrothermally derived Fe-Mn oxyhydroxides and 2) Fe-Mn hydroxides precipitated directly from seawater. The Fe-Mn oxyhydroxides within the serpentine breccia cement, as well as the Fe-Mn rich layers of the marlstones are hydrothermal in origin. The Fe-Mn oxyhydroxide that forms the outer coating of the basalt breccias, as well as some upper layers in the marlstones, has been precipitated directly from seawater. The latter observation shows that some of the samples are sufficiently old to have accumulated hydrogenous Fe-Mn crusts since the time of their original formation.

Model of Hydrothermal Circulation

Jason sampling and associated dredge sampling during the Knorr 180-2 cruise showed that the Kane megamullion consists dominantly of serpentinite with gabbro intrusions, but it also showed that pillow-basalt debris is widely scattered across the surface of the footwall; the basalt debris apparently was clipped from the overlying hanging wall as the detachment fault slipped over a period of 1.2 million years. To explain the formation of the unusual cones of cemented, largely basaltic rock debris on the megamullion surface, we propose that hydrothermal fluids rose along the subsurface fault when it was active and that they vented at numerous point sources at and near the seafloor trace of the fault (red arrows, Fig. 4). These fluids would have percolated through the hanging-wall basalts, precipitating Fe, Mn, and carbonate minerals to bond patches of the basalt debris and also cement them to the footwall. As the footwall continued to be exhumed, the surrounding, uncemented debris wasted away down the slope of the exposed fault surface, which probably dipped 25°-35° based on observations at the Kane and other megamullions. The final result was that perched, cemented cones of rock debris were carried 'piggyback' on the footwall to their present positions.

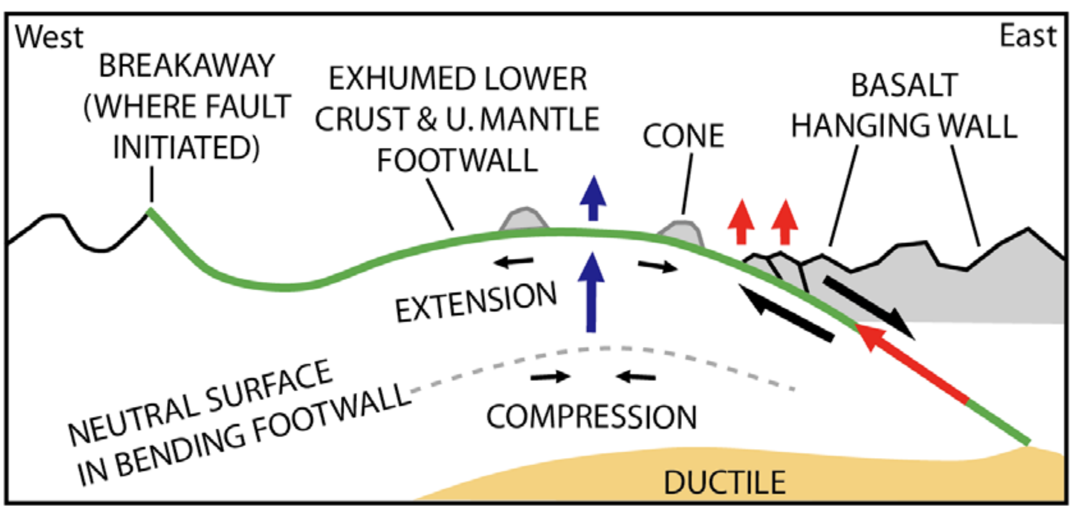


Figure 4. Schematic cross-section of Kane megamullion showing detachment fault surface in green (fault slip in the subsurface is indicated by large black arrows). Inferred fluid flow up the subsurface fault plane and through the lip of the hanging wall (red arrows) is interpreted to cement hanging-wall basalts to the footwall, forming cones observed on the surface of the megamullion. Fluids may also be forced from the bending footwall (blue arrows) by effects of compression/extension as illustrated.

In addition to fluids rising along the fault plane, other fluids may have flowed vertically through the footwall (blue arrows, Fig. 4). Bending of the footwall as it 'rolled over' put the upper part into extension and the lower part in compression, which would have promoted upward flow of fluids. Because parts of the footwall continued to bend even after they were exhumed, such vertical flow could have persisted for tens of thousands of years or more. This flow would leave the low-temperature hydrothermal signature that we observe within sediments that settled and accumulated on the footwall. Our geochemical results indicate that the hydrothermal cementation affected some sedimentary layers more than others; this is consistent with video observations that show unusual patterns of erosion and coloration in the slabby marlstone sediments preserved on the footwall.

Significance of Our Findings

Our mineralogical and geochemical analyses of deposits from Kane megamullion confirm that there was flow of Fe-Mn-rich hydrothermal fluids along the detachment fault during the period when the fault was actively slipping. This is the first reported occurrence of Fe-Mn deposits resulting from hydrothermal discharge associated with a dominantly ultramafic substrate. The association of the hydrothermal deposits with unique, cemented cones of rock debris indicates that point-source venting of hydrothermal fluids at numerous locations along the traces of major detachment faults (and perhaps along shorter-lived normal faults) may be a common occurrence. Furthermore, hydrothermal deposits within flat-lying sediments on the footwall indicate that hydrothermal fluids continued to be expelled from within the footwall for some time after the detachment fault surface was exposed. These findings imply that hydrothermal fluid flow associated with normal faults and their deforming footwalls in slow-spreading ocean crust are likely to be a much more common phenomenon than has hitherto been recognized. Hydrothermal discharge from the oceanic crust can result in precipitation of major metal deposits, depending on the content of dissolved elements in the fluids; thus our results also suggest strong potential that economic mineral deposits may be broadly distributed across slow-spreading oceanic crust.

Preliminary results of our investigation were presented at the 2007 Fall AGU meeting (Tucholke et al., 2007), and since that time, we have completed petrographic and geochemical analyses of the samples. Our complete results are being written up and will be published in the peer-reviewed scientific literature.

Reference

Tucholke, B. E., H. J. B. Dick, M. A. Tivey, and S. E. Humphris, Cemented mounds perched on the Kane megamullion detachment surface: A new manifestation of hydrothermal venting? *EOS Trans. Am. Geophys. Union,* 88 (52), Fall Meeting Suppl., Abstract T23B-1412, 2007.