Emerging Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges

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The development of seafloor hydrothermal research has followed a classic scientific progression in which discoveries were initially interpreted as special cases until further exploration revealed their more general significance. The first high-temperature seafloor hydrothermal system was found at the Atlantis II Deep of the slow spreading Red Sea in 1963. At that time, the hydrothermal activity was largely discounted as an anomaly associated with continental rifting rather than as part of an early stage of opening of an ocean basin that could continue with the development of ocean ridges as in the Atlantic. When high-temperature black smoker hydrothermal venting was found on the East Pacific Rise in 1979, the scientific consensus then held that the relatively high rate of magma supply at intermediate to fast spreading rates was required for such activity. Accordingly, high-temperature hydrothermal activity could not occur on the slow spreading half of the global ocean ridge system. High-temperature black smokers like those on the East Pacific Rise were first discovered on a slow spreading ocean ridge at the TAG hydrothermal field on the Mid-Atlantic Ridge in 1985. The scientific consensus then ruled out the possibility for such activity on the ultraslow portion of the ocean ridge system. Plumes indicative of active high-temperature black smokers were found on the ultraslow spreading Gakkel Ridge in the Arctic in 2001, and active black smokers were found on the Southwest Indian Ridge in 2006. A diversity of high-temperature hydrothermal systems remains to be found on ocean ridges, particularly at slow spreading rates.

1. EARLY RIFTING

The first hydrothermal system discovered at a slow spreading divergent plate boundary was the Atlantis II Deep system at 21°N in the Red Sea, which contains the most efficient metallic ore-forming system and the largest seafloor hydrothermal mineral deposit found to date. A temperature and salinity (T-S) anomaly was recorded on a hydrocast made at this site by the Swedish oceanographic research vessel Albatross while transiting the Red Sea on return from the Indian Ocean in 1948 [Bruneau et al., 1953; Pettersson et al., 1951]. The anomaly was overlooked at the time because the cruise geochemist, G. Arrhenius, had left the ship to secure his engagement after the long separation of the expedition. Arrhenius (personal communication, 12 January 2010) now comments, “So our sixty two year happy marriage was saved at the expense of not tying down the discovery of the Red Sea hot brine.”
Fifteen years later in November 1963, scientists traversing the Red Sea on board the British oceanographic vessel HMS Discovery as part of the International Indian Ocean Expedition (1963–1965) noted on their echo sounder profile a reflecting interface anomalously near the seafloor, coincidentally at the same site as the Albatross T-S anomaly [Swallow, 1969]. Water samples of hot brine were recovered from this site by the R/V Atlantis II in July 1963, which is now known as the Atlantis II Deep [Miller, 1964; Swallow, 1969]. Additional deeps containing hot brines and metalliferous sediments were subsequently found in the Red Sea [Charnock, 1964; Swallow and Crease, 1965; Dietrich and Krause, 1969]. At the time of discovery, the Red Sea hot brines and metalliferous sediments were considered an anomalous phenomena related to continental rifting rather than as part of the opening of an ocean basin from early rifting to development of an ocean ridge, as in the Atlantic Ocean.

2. HYDROTHERMAL CIRCULATION AT OCEAN RIDGES

Evidence that hydrothermal circulation is a major process at ocean ridges and the theory of plate tectonics developed together in the late 1960s and 1970s. Hydrothermal circulation and plate tectonics changed the understanding of ocean basins from passive sinks for material derived from land to active sources of new lithosphere and fluids at divergent plate boundaries. Thermal and mineralogical studies provided early evidence for hydrothermal circulation in the ocean lithosphere at ocean ridges. Comparison of the theoretical amount of heat produced by the generation of lithosphere with measurements of conductive heat flow at ridge crests revealed a discrepancy that was attributed to cooling by hydrothermal circulation of seawater through ocean crust and upper mantle [Elder, 1965; Deffeyes, 1970; Lister, 1972; Williams and Von Herzen, 1974; Wolery and Sleep, 1976]. Alteration in ophiolites [Muehlenbachs and Clayton, 1972; Spooner and Fyfe, 1973], the association of metalliferous sediments with ocean ridges [Skornyakova, 1965; Bostrom and Peterson, 1966; Corliss, 1971; Bonatti et al., 1976], and measurement of manganese accumulation rates and fractionation in metalliferous sediments [Bender et al., 1971] and crusts [M. R. Scott et al., 1974] indicated subsea-floor hydrothermal circulation and discharge into the near-bottom water column.

3. GALAPAGOS RIFT

The first discovery of an active hydrothermal system at a submerged ocean ridge was of low-temperature diffuse flow at the intermediate spreading rate Galapagos rift (full rate 6 cm a\(^{-1}\)) at the equator near 86°W longitude in 1977. The discovery was made on the basis of several lines of evidence comprising measurement of anomalously low conductive heat flow indicative of hydrothermal cooling [Williams et al., 1974], delineation of hydrothermal plumes in the water column by detection of the conservative primordial isotope \(^3\)He derived from mantle outgassing associated with small positive temperature anomalies [Weiss et al., 1977], and total dissolvable manganese anomalies [Klinkhammer et al., 1977] in the near-bottom water column. A chemosynthetic vent ecosystem with tubeworms and clams was first imaged [Lonsdale, 1977; Corliss and Ballard, 1977] and sampled [Grassle, 1983] at this site.

Jenkins et al. [1978] measured the ratio of dissolved \(^3\)He to transported heat (7.6 ± 0.5 × 10\(^{-8}\) cal atom\(^{-1}\) \(^3\)He) over the temperature range of the Galapagos hydrothermal solutions (3°C to 13°C). They extrapolated the observed \(^3\)He to heat ratio to the global oceanic flux of \(^3\)He (4 ± 1 atoms cm\(^{-2}\)) estimated by the global integration of the \(^3\)He anomaly measured at mid depth in the water column [Craig et al., 1975] to determine a global seafloor hydrothermal heat flux assumed to be focused at ocean ridges (4.9 ± 1.2 × 10\(^{-8}\) cal a\(^{-1}\)). Edmond et al. [1979] used dissolved silicon concentration as a proxy for temperature and used magnesium as an indicator of mixing with seawater over the narrow temperature range of the Galapagos diffuse vent fluids. They extrapolated measured concentrations of dissolved major and minor elements versus silicon to predict the composition and temperature of a high-temperature end-member solution with zero magnesium at about 350°C. They extrapolated the measured temperature dependence of the concentration anomalies (moles per calorie) to the estimated global seafloor hydrothermal heat flux [Jenkins et al., 1978] to compute global fluxes of the elements. They determined that the hydrothermal fluxes for Mg and SO\(_4\) balance river input, that Li and Rb exceed river input by factors between 5 and 10, and that K, Ba, and Si are between one third and two thirds of river load.

4. EAST PACIFIC RISE

Extinct massive sulfide chimneys were first found on the intermediate spreading rate (full rate 6 cm a\(^{-1}\)) East Pacific Rise at 21°N,103°W in 1978 using the French human-occupied vehicle (HOV) Alvin [Francheteau et al., 1979]. A dive series in the same area the following year with the American HOV Alvin discovered black smoker chimneys discharging hydrothermal solutions [Spiess et al., 1980] with temperature (350°C) and composition of the end-member solutions predicted by Edmond et al. [1979]. This stunning corroboration supported the estimates by Edmond et al. [1979]...
of the large global magnitudes of hydrothermal fluxes from vents on ocean ridges. Estimates of the global seafloor hydrothermal heat flux based on the discrepancy between calculated theoretical heat production by emplacement of lithosphere at divergent plate boundaries and measured conductive heat flow on ocean ridges [Williams and Von Herzen, 1974; Wolery and Sleep, 1976] indicated that a substantial fraction (~40%) of global heat loss derives from the cooling of relatively young oceanic lithosphere by hydrothermal circulation, consistent with the estimate by Jenkins et al. [1978]. The large estimated global magnitudes of chemical and thermal fluxes of hydrothermal circulation assumed to be focused at ocean ridges and the associated chemosynthetic ecosystems effectively launched hydrothermal research at ocean ridges.

A NATO Advanced Research Institute on Hydrothermal Processes at Seafloor Spreading Centers was convened at the University of Cambridge, England, in 1982 and brought together some 63 scientists, virtually the entire seafloor hydrothermal community at that time [Rona et al., 1983]. The participants are now recognized as pioneers and founders of the field (Figure 1). The early hydrothermal discoveries at Pacific Ocean ridges initiated two paradigms at that time: (1) Relatively high magma supply rates at intermediate to fast spreading rates were required to drive high-temperature hydrothermal activity, thus eliminating the slow spreading half of the global ocean ridge system as prospective for such activity. (2) Seafloor hydrothermal systems involve the reaction of seawater convectively driven by magmatic heat with ocean crust; since the compositions of seawater and of ocean crust (basalt and gabbro) are relatively uniform, the solution chemistry at vents on ocean ridges was expected to be uniform. Therefore, J. M. Edmond initially declared that the study of solution chemistry of seafloor hydrothermal systems would be “stamp collecting” [Rona et al., 1982].

5. MID-ATLANTIC RIDGE

The majority consensus that favored intermediate to fast spreading for high-temperature hydrothermal activity advocated that seafloor hydrothermal research be focused on ocean ridges in the Pacific and criticized such work elsewhere as a waste of resources. A minority view contended that the slow spreading portion of the global ocean ridge system was prospective for the occurrence of high-temperature hydrothermal systems. Evidence favoring the occurrence of high-temperature hydrothermal activity on slow spreading

ocean ridges included the Atlantis II Deep hydrothermal system in the Red Sea and the spectacular diversity of hydrothermal systems on Iceland as an emergent section of the slow spreading Mid-Atlantic Ridge. The trans-Atlantic geotraverse (TAG) project was initiated in 1970 to develop a standard crustal section across the central North Atlantic [Rona and Orlin, 1971], as a contribution to the International Decade of Ocean Exploration [Intergovernmental Oceanographic Commission, 1974]. The crustal section comprised a 330-km-wide corridor that followed mean flow lines of seafloor spreading between points that were conjugate in the Bullard et al. [1965] fit prior to opening of the Atlantic (Cape Hatteras, North America and Cap Blanc, northwest Africa). In addition to conducting underway geotraverses (bathymetry, magnetics, and gravity [Rona, 1980]), the TAG project studied representative areas of the continental margins, abyssal plain, and Mid-Atlantic Ridge within the corridor.

Dredging of the east wall of the section of the axial valley of the Mid-Atlantic Ridge within the TAG corridor unexpectedly recovered patchy manganese crusts that were thicker (centimeters), more fractionated (~40% Mn), and more rapidly accumulated (radiometrically measured rates to 200 mm 10^-6 a^-1) than hydrogenous crusts previously recovered from ocean ridges. These properties indicated a hydrothermal origin for the manganese crusts [M. R. Scott et al., 1974]. In the same area of the east wall, thermistor tows recorded near-bottom temperature anomalies (0.01°C–0.1°C) with gradients that warmed downward, indicative of hydrothermal discharge from the seafloor [Rona et al., 1975; Lowell and Rona, 1976; Rona, 1978]. Water sampling in this area of the east wall revealed near-bottom anomalies of 3He [Jenkins et al., 1980] and water column anomalies of dissolved and particulate manganese and iron oxides [Klinkhammer et al., 1984]. A metalliferous component is present in cores recovered from thin sediments (typically several centimeters thick with up to 1 mm thickness in discrete ponds) in this area. The sediments are characterized by relatively rapid metal accumulation rates [Scott et al., 1978] and metal contents varying from disseminated [Shearman et al., 1983] to distinct layers including metals indicative of high-temperature discharge (Cu, Fe, and Zn [Metz et al., 1988]). These lines of evidence indicated proximal ongoing low- and high-temperature hydrothermal activity in this area named the trans-Atlantic geotraverse or TAG hydrothermal field [R. B. Scott et al., 1974]. The remaining challenge was to track the elusive thermal and chemical hydrothermal anomalies as wisps in the water column and the metals in the seafloor sediments to their source.

In 1984, N. A. Ostenso, the distinguished geophysicist who was then serving at a high level of the National Oceanic and Atmospheric Administration (NOAA), obtained congressional funding to initiate the NOAA Vents Program, dedicated to studying seafloor hydrothermal systems [Hammond et al., 1991]. The funding provided support to lease a long-baseline acoustic navigation system for use on an August 1985 cruise of the NOAA ship Researcher to the TAG field. Working within the fixed transponder navigation framework, deep-sea camera-temperature tows and water sampling tracked hydrothermal signals to their source near the base of the east wall of the axial valley [Rona et al., 1986]. The source is a massive sulfide mound some 200 m in diameter and 35 m high between water depths of 3635 and 3670 m surmounted by vigorously venting black smoker chimneys. The active high-temperature sulfide mound is populated by a vent ecosystem dominated by the shrimp Rimicaris exoculata [Williams and Rona, 1986], different from the ecosystem at Pacific vent sites. TAG is the first high-temperature hydrothermal system, massive sulfide deposit, and vent ecosystem found in the Atlantic and the first found on any slow spreading ocean ridge.

The summary in the article that reports this Atlantic discovery [Rona et al., 1986, p. 33] states: “The discovery of black smokers, massive sulfides and vent biota in the rift valley of the Mid-Atlantic Ridge demonstrates that this assemblage of hydrothermal phenomena is not limited to intermediate- to fast-spreading oceanic ridges. Hydrothermal exchange processes may thus be important at the ridges which extend though the Atlantic Ocean and western Indian Ocean, comprising more than half the 55,000-km global length of seafloor spreading centres.” This statement sets the scene for the present volume with subsequent discoveries of active high-temperature hydrothermal systems on the slow spreading southern Mid-Atlantic Ridge in 2006 [Haase et al., 2007; Devey et al., this volume], the Central Indian Ridge in 2000 [Hashimoto et al., 2001; Van Dover et al., 2001], the ultraslow Southwest Indian Ridge in 2006 [Tao et al., 2007; Sauter and Cannat, this volume], the Arctic Mid-Ocean Ridge beginning in 1997 [Hannington et al., 2001; Kuhn et al., 2003; Pedersen et al., this volume], and plumes indicative of high-temperature black smoker venting on the ultraslow spreading Gakkel Ridge in 2002 [Edmonds et al., 2003]. A diversity of high-temperature hydrothermal systems remains to be found on ocean ridges particularly at slow spreading rates.

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