Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges

Peter A. Rona, Colin W. Devey,
Jérôme Dyment, and Bramley J. Murton
Editors

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Colin W. Devey
Jérôme Dyment
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Cover Photo: Vent shrimp *Rimicaris exoculata* Williams and Rona, 1986, swarming on an active black smoker chimney in the TAG hydrothermal field on the Mid-Atlantic Ridge near latitude 26ºN. Photo credit: IMAX film *Volcanoes of the Deep Sea*, produced by The Stephen Low Company. Reproduced with permission.

2000 Florida Avenue, N.W.

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PREFACE

Presentations at three sessions entitled "Diversity of Hydrothermal Systems at Slow-Spreading Ocean Ridges" convened by P. A. Rona, R. Reves-Sohn, B. J. Murton, J. Dyment, and C. W. Devey at the American Geophysical Union (AGU) 2005 Fall Meeting initiated preparation of this volume. We thank R. Reves-Sohn for his strong constructive role in this process. C. R. German provided highly valued guidance for preparation of the volume. The authors are the heroes of this volume for advancing and communicating knowledge of seafloor hydrothermal systems. We are grateful to the reviewers who did yeoman's duty in advising the authors on how to improve their manuscripts.

This volume is part of the progression of knowledge of seafloor hydrothermal systems and their geologic settings represented by a series of AGU volumes: *Seafloor Hydrothermal Systems: Physical, Chemical, Biological, and Geological Interactions* (edited by S. E. Humphris, R. A. Zierenberg, L. S. Mullineaux, and R. E. Thomson, 1995); *Faulting and Magmatism at Mid-Ocean Ridges* (edited by W. R. Buck, P. T. Delaney, J. A. Karson, and Y. Lagabrielle, 1998); *The Subseafloor Biosphere at Mid-Ocean Ridges* (edited by W. S. D. Wilcock, E. F. DeLong, D. S. Kelley, J. A. Baross, and S. C. Cary, 2004); *Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans* (edited by C. R. German, J. Lin, and L. M. Parson, 2004); and *Magma to Microbe: Modeling Hydrothermal Processes at Oceanic Spreading Centers* (edited by R. P. Lowell, J. S. Seewald, A. Metaxas, and M. R. Perfit, 2008).

The full diversity of hydrothermal systems on slow spreading ocean ridges, reflected in the contributions to this volume, is only now beginning to emerge and opens an exciting new frontier for ocean ridge exploration.

Peter A. Rona
Rutgers, State University of New Jersey

Colin W. Devey
Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR)

Jérôme Dyment
Institut de Physique du Globe de Paris

Bramley J. Murton
National Oceanography Centre

Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges: Introduction

Peter A. Rona,[1] Colin W. Devey,[2] Jérôme Dyment,[3] and Bramley J. Murton[4]

[1]Institute of Marine and Coastal Sciences and Department of Earth and Planetary Sciences, Rutgers, State University of New Jersey, New Brunswick, New Jersey, USA.

[2]Leibniz Institute of Marine Sciences at University of Kiel (IFMGEOMAR), Kiel, Germany.

[3]Institut de Physique du Globe de Paris, Paris, France.

[4]National Oceanography Centre, Southampton, Southampton, UK.

Emerging findings reveal that hydrothermal systems at slow to ultraslow spreading ocean ridges (full spreading rate ≤3 cm a^{-1}) exhibit greater diversity than that at intermediate to fast spreading ridges, related to geological diversity of the lithosphere that hosts the systems. This volume presents studies of hydrothermal systems on slow spreading ocean ridges that convey our present knowledge of their diversity. *Rona* [this volume] places them in the perspective of the development of seafloor hydrothermal research. *Lowell* [this volume] reviews the various heat sources and heat transfer processes at slow spreading ridges, including mantle heat flux, mining of crustal heat, the role of exothermal chemical reactions as the principal heat sources in low-temperature hydrothermal fields, and replenishing magmatic heat sources as the principal heat sources in high-temperature hydrothermal fields. *Edmonds* [this volume] synthesizes the compositional variation of low- and high-temperature fluids discharged from hydrothermal systems hosted in the various lithologies on slow spreading ridges. *Tivey and Dyment* [this volume] explain the use of different magnetic signatures to infer the nature of hydrothermal alteration associated with the diverse geologic settings on slow spreading ocean ridges and the potential application of these signatures for future off-axis exploration.

The Mid-Atlantic Ridge is the archetype of slow spreading ocean ridges and, under a variety of geographic names, extends from the Arctic Mid-Ocean Ridge southward to (but not including) the Southwest Indian Ridge. *Pedersen et al.* [this volume] show that, contrary to prediction, hydrothermal activity exceeds what would be expected by extrapolation from observations on faster spreading ridges. Taking advantage of Iceland as the part of the Mid-Atlantic Ridge most accessible to surface and subsurface studies, *Elders and Friðleifsson* [this volume] report encountering an active rhyolitic magma intrusion 2.1 km below the surface in their drilling of a geothermal recovery well in the Krafla field.

Many hydrothermal fields have been found on the northern Mid-Atlantic Ridge since the discovery of the TAG hydrothermal field in the axial valley at 26°N in 1985. Of these, investigation of the Lucky Strike hydrothermal field described by *Crawford et al.* [this volume] is the first to clearly reveal an axial magma chamber reflector similar to those seismically imaged at faster spreading axes in the Pacific. *Devey et al.* [this volume] describe the first five hydrothermal fields discovered on the southern Mid-Atlantic Ridge and present criteria to guide ongoing exploration.

Sauter and Cannat [this volume] describe the ultraslow spreading (full rate 1.4 cm a^{-1}) Southwest Indian Ridge as a melt-poor end-member of the ridge system with thin or no crust similar to the Gakkel Ridge in the Arctic Ocean.

Detachment faulting and associated core complexes represent a fundamental mode of crustal extension initially recognized in continental crust and emerging as a major mode of deformation of oceanic lithosphere, as presented by *John and Cheadle* [this volume]. *McCaig et al.* [this volume] review geological and geochemical data to show the key role of detachment faulting in spreading of ocean lithosphere and hydrothermal circulation over the whole range of slow spreading settings and apply findings to a detachment fault zone at the TAG hydrothermal field.

Geochemical and thermal outputs of serpentinization reactions are widespread on magma-poor sections of slow spreading ridges where hydrothermal circulation accesses and hydrates mantle peridotites. *Cannat et al.* [this volume] estimate significant hydrogen and abiogenic methane fluxes generated by serpentinization reactions related to hydration of mantle-derived ultramafic rocks that outcrop in detachment faults and magma-starved sections predominantly of the axial valley. *Charlou et al.* [this volume] demonstrate that ongoing serpentinization is mainly responsible for hydrogen and abiogenic methane production at axial ultramafic exposures that are common along sections of the northern Mid-Atlantic Ridge. They extrapolate a global hydrogen flux from the flux measured at the Rainbow field and infer significance for generation of abiogenic hydrocarbons with implications for energy and life. *Seyfried et al.* [this volume] combine theoretical reaction path models with experimental data to determine fluid-mineral equilibria controls on the chemistry of vent fluids discharging from ultramafic-hosted hydrothermal systems (e.g., Rainbow and Logatchev) on the Mid-Atlantic Ridge.

Mineralization is a byproduct of hydrothermal systems. *Fouquet et al.* [this volume] contribute a comprehensive review of similarities and differences of high- and low-temperature mineralization produced by ultramafic-hosted (peridotites and serpentinites) and mafic-hosted (basalt) hydrothermal systems on slow spreading ocean ridges.

Hydrothermal ecosystems can be grouped into several bio-geographic provinces, sometimes showing variations within sections of slow spreading ocean ridges. *Kelley and Shank* [this volume] present an overview of geologic settings and associated macrofauna on slow spreading ocean ridges. *Le Bris and Duperron* [this volume] relate distribution, abundances, and nutritional role of two chemosynthetic mussel species to available electron donors and energy sources in hydrothermal fluids to explain their adaptation to diverse hydrothermal systems along the Mid-Atlantic Ridge.

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C. W. Devey, Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR), Kiel D-24148, Germany.

J. Dyment, Institut de Physique du Globe de Paris, CNRS-UMR 7154, F-75252 Paris CEDEX 05, France.

B. J. Murton, National Oceanography Centre, Southampton, University of Southampton Waterfront Campus, European Way, Southampton SO14 3ZH, UK.

P. A. Rona, Institute of Marine and Coastal Sciences, Rutgers, State University of New Jersey, 71 Dudley Rd., New Brunswick, NJ 08901-8521, USA. (rona@marine.rutgers.edu)

Emerging Diversity of Hydrothermal Systems on Slow Spreading Ocean Ridges

Peter A. Rona

Institute of Marine and Coastal Sciences and Department of Earth and Planetary Sciences Rutgers, State University of New Jersey, New Brunswick, New Jersey, USA

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; *Deffayes,* 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 ($7.6 \pm 0.5 \times 10^{-8}$ 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