Hydrothermal Activity in the Deep Sea: Intractable Problems and Lots of Questions

by

John M. Edmond and Karen L. Von Damm

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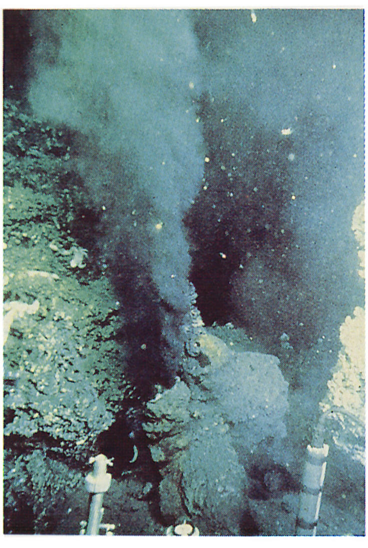
Hot springs on the deep seafloor were first discovered in 1977 on the Galapagos Spreading Center, appropriately enough, northeast of the famous Galapagos Islands. Early formulations of the plate tectonic theory of seafloor spreading identified the mid-ocean ridges as Earth's most important loci of volcanism. This immediately prompted the suggestion that pervasive hydrothermal activity must be associated with the spreading process. Because of the relatively primitive capabilities available for seafloor exploration and the fact that exciting results were coming in from other areas of marine geophysics at the time, these suggestions were not followed up for over a decade. By then a host of indications had accumulated from seafloor and water-column studies that hydrothermal activity must be occurring. These were even persuasive enough to convince the National Science Foundation (NSF) to fund the study of an undiscovered phenomenon!

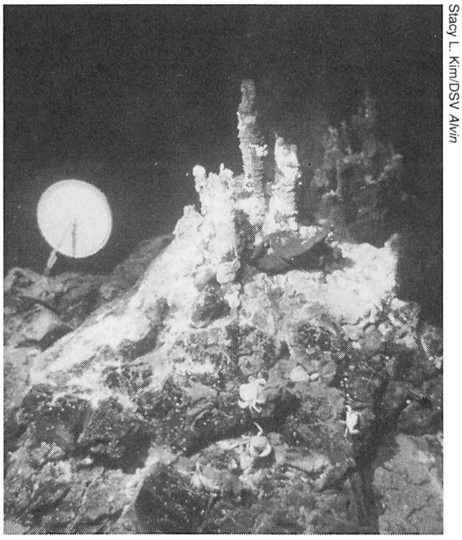
The authors have visited many black smokers in their studies, such as this one on the East Pacific Rise.



Dudley Foster/WHOI

Initial discoveries centered around the hydrothermal vents had ramifications throughout oceanography and beyond. The startling identification of a unique, highly evolved, and well developed chemosynthetic fauna associated with the vent fields proved that hot-spring activity had to be common. It also opened up an entirely new ecosystem to study. The chemical and physical properties of the high-temperature "black smoker" fluids showed them to be responsible for the transport and deposition of mineral ores. Concepts of massive sulfide-ore formation were revolutionized as fluid chemistry and fluxes were found to be important in supporting the chemical mass balance of the oceans themselves. The relatively uniform reactions between seawater and seafloor basalt constitute a geochemical "flywheel" that stabilizes the ocean's composition against variations in river input caused by long-term climatic and tectonic changes. Physical Oceanographer Henry Stommel of the Woods Hole Oceanographic Institution had an idea (which seems to be holding up) that the input of thermal energy, the buoyancy flux, from the vents along the East Pacific Rise (EPR) drives the complex mid-depth circulation in the South Pacific.

Over the last 10 years, hydrothermal activity has been found in all oceanic volcano-tectonic regimes: at mid-ocean ridges over the entire range of spreading rates, on back-arc spreading centers, and on seamounts and submarine hot-spot volcanoes (see *Oceanus*, Winter 1991/92—Mid-Ocean Ridges— for definitions of terms and discussions of phenomena). The necessary ingredients are a large heat source emplaced in a permeable medium and a fluid. Because oceanic crust is formed by the injection of hot magma into a cold, tectonically active substrate, it is riddled with faults and thermal contraction cracks and is highly permeable. Since the hydrostatic pressure exerted by the oceanic water column is high (1,000 meters of water depth exerts 100 atmospheres of pressure), water saturates the crustal fissures and voids, and can be heated to very high temperatures without phase separation (boiling). Thus heat is removed very efficiently. There is a negligible loss of hydraulic head (hydrostatic pressure) as the fluid is emitted on the seafloor (unlike on land) and hence the fluid stream is stable with no "flashing" or geyser activity, much to the comfort of research submarine pilots. The ascending hot-water column generates an updraft around itself, further insulating the submarine from the effects of high temperature. Hot springs are therefore easily accessible for detailed sampling studies.



Stacy L. Kim/DSV *Alvin*

At 9°N on the East Pacific Rise, hydrothermal vent regions take on interesting shapes as minerals precipitate from the plume of hot water as it emerges from the vent.

Two Intractable Puzzles Emerge

When the first Galapagos vent analyses became available, two central problems were apparent that have proved intractable. The first concerns the magnitude of the global flux of hydrothermally altered seawater. The second is identification of the mechanism that controls the variable salinity of these fluids.

Global Flux of Hydrothermally Altered Seawater. Geochemical calculations of the oceanic mass balances of helium and strontium isotopes require that a volume of water equivalent to the entire ocean circulate through the ridge-crest hydrothermal system about every 10 million years, a very short time geologically. Vents are the overwhelming source of the rare helium isotope helium-3 in the oceanic water column. Extensive surveys of helium-3 distribution in the oceans have permitted quite accurate calculations of its inventory. Helium is a very insoluble gas; it is light enough to escape Earth's gravitational field via high-temperature regions in the upper atmosphere. Atmospheric concentrations are therefore extremely low. When deep water mixes into the surface layer, vent-derived helium escapes to the atmosphere, and eventually to space. The rate of this mixing has been calibrated using radioactive carbon to yield a "ventilation" or exposure-to-atmosphere time for the deep ocean

The glaring inconsistency suggests profound ignorance somewhere.

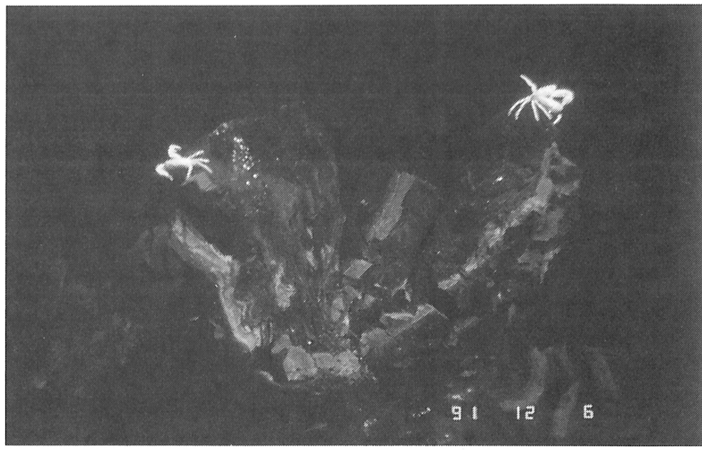
of about 1,000 years. From this information and the average helium concentration in the vent fluids, the fluxes of water, heat, and dissolved constituents can be determined.

Strontium has two major stable isotopes. Strontium-86 is nonradiogenic, whereas strontium-87 is produced by the decay of rubidium-87. Rubidium is relatively concentrated in continental crust by a variety of processes, so continental, fluvial (river-introduced) strontium has a higher strontium-87/strontium-86 ratio than does mantle-derived, hydrothermal strontium. Because strontium has a long residence time in the oceans, its isotope ratio in seawater is homogeneous. The strontium-87/strontium-86 ratio in seawater is 0.7091, intermediate between that in vent fluids (0.7035) and that in the average river (0.712). (The latter is an estimate based on measurements of most of the world's large rivers and many of their tributaries.) Combining these values with average strontium concentration data gives the hydrothermal flux required to balance the river inputs and maintain the observed seawater ratios. This flux calculation agrees with that based on the helium isotopes.

Now comes the puzzle: Early evidence for large-scale hydrothermal activity at spreading centers came from many geophysical observations in the 1960s and 1970s that conductive heat loss from oceanic crust generally increases with crustal age, to a steady-state value at several million to several tens of millions of years. This is the opposite of what would be expected if heat from the active vent areas were lost solely by conduction. The only alternative is large-scale convective cooling by circulating seawater. However, all calculations to date place an upper limit on the amount of heat transported in this manner that is equivalent to a fluid flux that is about one-fifth of that estimated from mass-balance calculations for helium and strontium isotopes. If arguments based on the thermal budget are correct, then deep-sea hydrothermal activity is an interesting, indeed beautiful, phenomenon—but not of great importance to the ocean's general geochemical cycle. If the flux based on isotopes is correct, however, then hydrothermal activity is of central importance. To date nobody has found any serious holes in either of the two approaches. The glaring inconsistency suggests profound ignorance somewhere. We (the geochemists), of course, are convinced that it lies in the geophysics....

Controlling Mechanism for Hydrothermal Fluid Salinity. Seawater entering the ridge crest hydrothermal system has a relatively constant salinity worldwide, but that of emerging vent fluids usually varies between fields, within a range of about one-third to more than double the original value. This is serious business, since high-temperature reactions consume all the seawater sulfate, precipitating it as metal sulfides, leaving chloride as the only significant anion (negatively charged molecule). Thus, from electroneutrality theory, the fluid's cation (positively charged molecule) transport properties are directly proportional to its chloride content. Chloride typically forms very soluble salts, and so is not likely to be precipitated in the water-rock reactions at high temperatures; this is a possibility, however, since there is scanty but tantalizing information on the natural occurrence of "green rust," an iron-hydroxy chloride in basalts whose chemistry shows they have been involved in hydrothermal reactions. While there is sufficient iron available in fresh basalts to affect chloride concentrations through formation of this compound, it would need to have a peculiar chemistry: precipitating to produce low salinities under some conditions and redissolving to yield high salinities as the system properties change. This sounds like smoke and mirrors.

The only alternative suggested to date is that deep in the system, seawater is heated to in excess of approximately 405°C. At this point phase separation occurs, producing a dense, high-salinity brine that coexists with a more voluminous, much fresher phase. This process has been observed both on a shallow seamount (where the phase-separation temperature was much lower) and on the EPR at 9°N where temperatures greater than 400°C were measured in fluids with salinities 100 times lower than that of seawater. The latter finding was in a ridge segment containing abundant evidence for very recent (within days) volcanism, with magmatic intrusions to shallow depths in the crust.



Stephen J. Molyneaux/DSV *Alvin*

Vent animals explore the glassy broken pillow lavas on the East Pacific Rise.

Two major puzzles exist with the phase-separation mechanism, however:
1) Measured temperatures at most hydrothermal vents on the EPR cluster within a narrow range around 350°C, more than 50° lower than the temperatures measured for phase separation, and these temperatures, where data exist, are often quite stable over many years; and
2) There are similar peculiarities in the salinity data.

Salinity values are typically far from the extremes produced by phase separation, and are also constant over time, often to within analytical error. Conductive cooling of vent fluids as they rise through the crust is negligible, given the short transit times (fractions of an hour) and the low thermal conductivity of basalts. It is difficult to imagine temperatures and salinities being controlled by subsurface mixing processes, since these are unlikely to be stable over periods of years. Time-series measurements provide very stringent constraints on a variety of geochemical and geophysical processes: If properties do not change over time, then chance cannot be in control; it must be something fundamental. In the case of ridge-crest hot springs, this realization has come slowly. The puzzles remain.

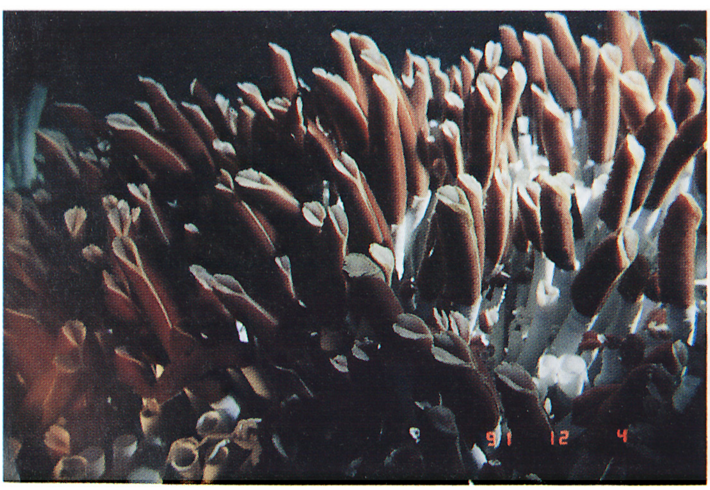
How We Are Attacking the Puzzles

The chemistry of a water sample is the result of many different processes that cannot be directly examined, and are not easily amenable to experimental manipulation. For example, we have not found a way to examine or collect the fluid rising beneath hot springs. In geophysics the interpretation of this kind of information is called an "inverse problem:" From results, one attempts to identify causes. The inversion is constrained by all relevant information. In geochemistry, the properties of the periodic table elements, including valence states (capacity to combine with other elements) compounds formed, and isotopes (stable, radiogenic, and radioactive), can all be considered constraints. The various species are affected to markedly different degrees by particular processes, some strongly by one, others partially by several. Our strategy in attempting to understand the two major puzzles is to find indicator species that discriminate between hypothetical possibilities. For example isotopes of helium and strontium are powerful indicators of high, rather than low, global hydrothermal flux. Volatiles such as the rare gases are partitioned into the "less saline" component upon phase separation; however, the effect is small and may be obscured by sampling artifacts. A chloride-bearing phase, if it exists, must also precipitate bromide in the exact ratio found in seawater. Laws of structural chemistry make this highly unlikely. This exploitation of the resources of the periodic table is only about half complete, but methods for enlarging this fraction are under development.

Other Questions About Hydrothermal Activity Abound

While ridge-crest hydrothermal activity is now regarded as a normal oceanographic phenomenon, we actually know surprisingly little about it. In addition to the fundamental problems outlined above, there are deceptively simple questions outstanding: What is the relationship between spreading rate and hydrothermal output? Is it simply linear, or is it responsive to different tectonic styles and, hence, crustal permeabilities that accompany differing spreading rates? How long does a vent field last? Huge fields with millions of metric tons of precipitated sulfide ore have been discovered on the Mid-Atlantic Ridge and on Northeast Pacific ridges. However, on the faster-spreading systems of the Tropical and South Pacific, the many fields found to date are much smaller, on the order of tens of thousands of metric tons, or less. Are they soon buried by the more frequent eruptive events, or does a more fundamental reason explain this size difference? For example, one could ask: Where is the reaction zone located, relative to the chamber or plumbing system that supplies the fluid magma? What is the mechanism of heat exchange? How do a vent field's physical and chemical characteristics evolve over time? At 9°N on the EPR, we witnessed areally pervasive, chaotically disorganized venting, baked clams and tube worms that had not been scavenged, and an absence of usual biota around many of the vent fields. All evidence suggests an extremely young system. Elsewhere on the EPR, hot springs occur in small, discrete clusters separated from one another by several hundred meters to several kilometers of completely inactive terrain. Are these contrasting styles "snapshots" of different stages in the system's life cycle, or are they unrelated in time?

Hydrothermal vents support a varied and specialized fauna. Tube worms such as these from 9°N on the East Pacific Rise are an intriguing—if common—sight.



E. Garland/DSV *Alvin*

There are equally fascinating biological questions. At 9°N the overwhelming presence of bacterial mats is unique among the systems observed so far. Among them, productivity is enormous. Sheets of hot water pour out of the bottom like inverted waterfalls, sweeping great clouds of bacteria into the water column. Approaching the ridge axis in DSV *Alvin* was like driving in a blizzard. Grazing organisms were rare. Do these mats provide an initial food source for immigrant larvae? (See Hydrothermal Vent Plumes: Larval Highways in the Deep Sea?, *Oceanus*, Fall 1991.) Why are these mats largely absent at the other EPR fields? The fauna found at the two Atlantic sites is distinctly different from that of the EPR: no big tube worms or clams; instead, there are swarms of shrimp, white anemones, and a peculiar solitary mussel that appears to be quite rare (see The Biology of Deep Sea Vents, *Oceanus*, Winter 1991/92). The vent fields found in the back-arc spreading systems of the Western Pacific appear to be more like the Atlantic in faunal characteristics than the Eastern Pacific. Are there grand faunal provinces separated by barriers of old, inactive crust? If so, these isolated provinces may be ancient, having diverged in their evolution after the last major episode of plate-tectonic reorganization both juxtaposed and fragmented preexisting provinces. One could go on.

The "discovery epoch" of the last 15 years was quite haphazard and uncoordinated, based on individual effort and luck. The RIDGE (Ridge Inter-Disciplinary Global Experiments) Initiative and InterRidge Program (see *Oceanus*, Winter 1991/92) have been developed to remedy this situation and replace it with a systematic approach involving much closer cooperation among oceanographic disciplines in the US and other countries. Many countries in Europe and the Pacific Rim are developing parallel programs. The hope, over the next decade, is to mount a global effort to advance our understanding of perhaps the most prominent, and certainly the most dynamic, feature on Earth, the spreading ridges in the deep ocean.


Rod Catanach/WHOI

Author John Edmond leaves DSV Alvin *following a dive to a hydrothermal vent field.*

John M. Edmond went directly to the Massachusetts Institute of Technology after finishing his formal studies in chemistry and geochemistry, and was bald in three years. He is interested in the processes controlling the chemistry of natural waters and associated sediments in space and time. He is a persistent, dedicated, and completely unsuccessful gardener, and also the doting father of two boys.

Karen L. Von Damm graduated from the MIT/WHOI Joint Program in Oceanography/Applied Ocean Science and Engineering after completing her thesis on the chemistry of black smokers. She spent several years at the United States Geological Survey at Menlo Park, California, and a spell with the Department of Energy. She recently accepted a position at the University of New Hampshire.