In this illustration, the Alvin explores the base of the 15-story tall smoker dubbed Godzilla.

Black Smokers: Incubators on the Seafloor

Deborah S. Kelley

The Discovery of Black Smokers

In 1977 the scientific community was astonished by the discovery of hot springs on the ocean floor, thousands of meters below sea level. These sulfide chimneys or hot springs supported rich biological communities that thrived in the absence of sunlight. Equally surprising was the finding that these unusual animal colonies were sustained by microorganisms that feed on chemicals in hot water. The chemicals are released from magma

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deep within the oceanic crust, then picked up by superheated seawater which circulates within the basaltic rocks that make up the ocean floor. The sulfide chimneys, which emit hot plumes laden with fine, dark particles of sulfide material became known as “black smokers.” Sulfide is a term for a certain group of minerals that contain sulfur. The areas around black smokers are oases for vibrantly colored tube worm colonies, clams, crabs, and other animals in the desert of the surrounding deep-ocean environment.

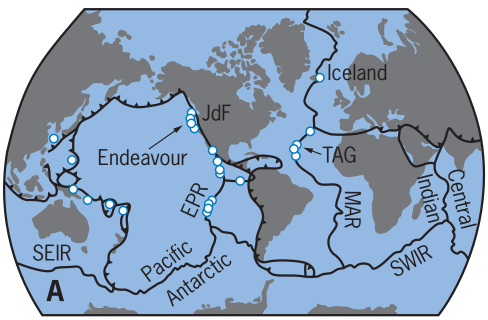
Since that pivotal discovery, numerous underwater hot springs sites have been found along most of the major oceanic spreading centers (Figure 1A). Ongoing discoveries associated with these incredible environments continue to astound us. For example, the black smoker “Godzilla,” discovered along the Endeavour Segment of the Juan de Fuca Ridge in 1991, was as high as a fifteen-story building and towered over the surrounding volcanic terrain before it toppled over in 1996 (Figure 2C). It is now also known that these “rocks” are literally alive with microbes that thrive within their warm, sulfide-rich, water-saturated interiors. Perhaps the most far-reaching idea to come from these hotsprings is that life itself may have originated within these dynamic systems, in which geological, chemical, and biological processes are intimately linked.

What Fuels the Black Smokers?

The spectacular development of vigorously venting black smokers on the ocean floor is fueled by circulation and heating of seawater at depths of 2–8 kilometers within the oceanic crust. The same process also fuels more subdued, lower-temperature venting systems. In volcanically active areas such as the East Pacific Rise (EPR, Figure 1A), the convection of heated seawater, or hydrothermal fluid, is driven by heating from a chamber of molten rock, or magma, at depths of two kilometers below the seafloor. The temperature of this magma is 1,200°C. In contrast, in areas such as the Endeavour Segment (Figure 1A) where there is little current volcanic activity, circulation is believed to be driven by the cracking of hot crystalline rocks, heated to 500–700°C, deep in the ocean crust. Along their downward journey from the ocean floor to depths of 2–8 kilometers beneath it, the fluids undergo significant changes in temperature and chemical composition as they approach the heat source. The fluids obtain their final chemical composition at the deepest point of this circulating process (Figure 1B).

Figure 1A: Global distribution of Black Smokers along the mid-ocean ridges. B. Cross-section of hydrothermal circulation. Cold seawater seeps into the seafloor, circulates near a heat source, becomes hot and buoyant, and flows into focused upwellings at hydrothermal fields.

A



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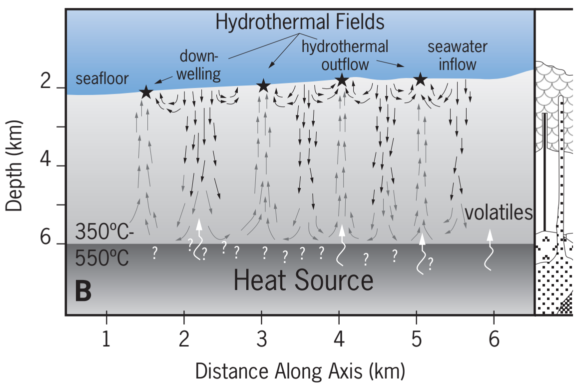

Special Seawater

The composition of the hydrothermal fluid, which is chemically modified, superheated seawater, is determined by three factors: the temperature of the rocks through which the fluids circulate; how much water has previously passed through that same crack network; and the composition of the rock. As cool, dense seawater migrates deep within the crust along the abundant large and fine-scale networks of cracks within these spreading environments, two important changes take place. First, the fluids interact and exchange elements with the surrounding host rock. Elements such as copper, zinc, iron, lead, sulfur, and silica are leached out of the rocks at temperatures of 350–550°C, and are incorporated in the hydrothermal fluid. Other elements such as sodium, magnesium, and calcium are added to the rock, modifying its original composition and mineralogy. In addition, gases such as hydrogen, methane, and carbon dioxide are added to the fluid when these compounds are directly released from magma chambers or leached from the enclosing host rock (Figure 1B). The compounds are critical nutrients for microbiological development at more shallow levels. Second, as the downwelling fluids approach the magma, their physical properties undergo dramatic changes. They become extremely buoyant, their viscosity and density decrease significantly and their ability to carry heat increases. Similar to the way water changes when it's heated in a pan, the now buoyant, metal-rich fluids rise up (through fractures in the seafloor), drawing in cooler fluids in their wake, and a circulation system develops (Figure 1B). This process is called convection.

How Black Smokers Form

The exact physical and chemical processes by which hydrothermal vents begin to develop are still poorly understood. In young hydrothermal systems, plumes of hot water that rise through the crust beneath the seafloor have to displace the surrounding cooler seawater saturating the shallow portions of the oceanic crust. In order for the high-temperature fluids to reach the seafloor, the channels through which this water rises must become progressively insulated by deposition of minerals. Once a venting system is established, however, the black smokers grow and evolve as the high temperature fluids vent onto the seafloor. The metal-rich fluids, heated to 350–400°C, mix turbulently with oxygen-rich, cold (2°C) seawater. This drastic temperature change causes solids to precipitate from the fluid. This process generates particles of sulfide minerals such as pyrite, chalcopyrite, and sphalerite, and sulfates such as anhydrite and barite.

Much of the fine-grained sulfide particles are carried upward into the buoyant, jet-like plumes that spew out of the vent at more than a meter per second; the particles are carried 100–200 meters up into the overlying ocean water, forming broad, extensive hydrothermal plumes. Some of these particles sink back to the ocean floor, oxidize and become sediment, and some are scavenged by microbial communities that live within the plumes. Sulfide and sulfate minerals that are not carried away in the hydrothermal plumes are deposited at the opening of the vent, causing the vent to grow upward over time. The chimney walls fracture periodically, which allows hot fluids to eject along the sides of the chimneys, and causes outward growth. These fluids may engulf and eventually fossilize tube worm colonies growing on the outer surfaces of the vents. In many oceanic systems, the high temperature (over 350–400°C), acidic, oxygen-poor, and sulfur- and metal-rich hydrothermal fluids boil as they rise up through the plumbing system beneath the black smokers. This boiling generates gas-rich vapors. In other, cooler systems, vents emit metal-rich water that may contain up to twice as much salt as the surrounding seawater. All of these processes come together at the seafloor in the formation of black smoker chimneys.

Different Formations Reflect Different Conditions

The spacing, growth rates, and mineralogical evolution of black smoker chimneys are complex and not well understood. Black smokers' shapes vary depending on different spreading environments, even when only a few hundred meters separate them (Figure 2). Along the mid-ocean ridge system, one of the largest single known deposits occurs on the Mid-Atlantic Ridge, a slow-spreading environment. The entire deposit, known as TAG (Figure 1A), is a large sulfide mound measuring 250 meters in diameter, and 50 meters high; it was probably formed by individual venting structures that combined into one deposit over time. Active venting is maintained by a black smoker complex located on the top of the mound that hosts multiple, spire-shaped chimneys up to fifteen meters high, with fluid temperatures of around 370°C (700°F). White smokers on the margins of the mound discharge fluids at 265–300°C. Their venting fluids are white because the dark sulfide minerals precipitate within the mound before the fluids exit the chimney. Scientists think that in this area of active faulting, large intersecting faults have channeled flow to the hydrothermal mound episodically over a 50,000-year period.

In contrast to the large sulfide mounds that may typify deposits on the slow-spreading Mid-Atlantic Ridge, black smokers at the fast-spreading East Pacific Rise commonly occur as

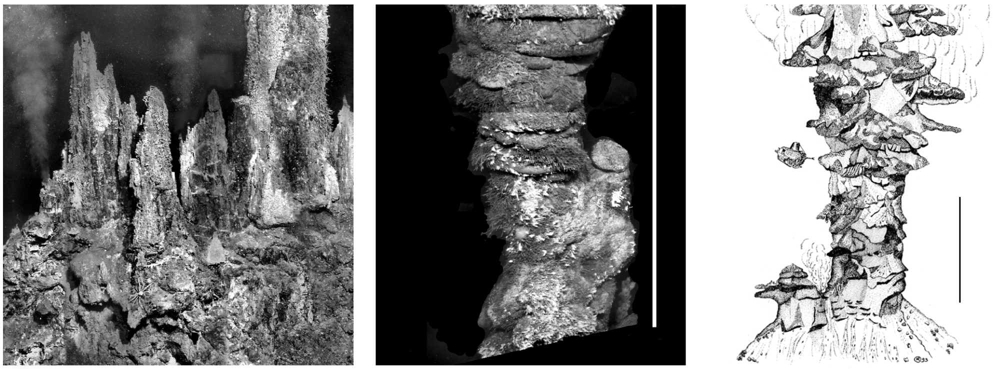

Figure 2A: The Mothra Hydrothermal Fields host at least five sulfide chimney clusters, such as "Faulty Towers."

Figure 2B: The "Smoke and Mirrors" black smoker chimney.

Figure 2C: "Godzilla", a towering 15-story black smoker. Note that although each of these hydrothermal vents is located along the Juan de Fuca Ridge, their shape and structure vary greatly.

small, discrete individual structures rarely more than fifteen meters tall. Individual venting sites may be spaced 200–300 meters apart, and most venting occurs within shallow, fault-bounded central valleys, called grabens, which are located at the crest of the summit. In this volcanically active area, the small size of the deposits is probably due to at least two factors. First, molten basaltic rock frequently erupts and covers the hydrothermal vents and associated biological communities. Second, magma moves up from the magma chamber into the shallow underlying crust, which disturbs the fluid flow channels that had been established to feed hydrothermal vents. This causes the vents to shut down until the channels become reestablished, or even to relocate on a new site.

Somewhere in between these configurations is the Endeavour Segment of the Juan de Fuca Ridge, an extremely active hydrothermal area 300 kilometers off the coast of Washington State. It is one of the best-studied underwater environments. Active faulting (rather than volcanic activity) along this segment has produced a one kilometer wide, 100–200 meters deep graben in which four known vent fields are spaced 2–3 kilometers apart (Figure 1B). The fields, which are generally 400–500 meters long, host abundant large sulfide structures on top of which stand abundant black smokers. Areas where lower-temperature fluids vent more weakly are also common. In three of the fields, the most common sulfide forms include large, irregularly-shaped structures (up to eighteen meters tall) that host vigorously venting 350–400°C black smoker chimneys on their tops (Figure 2B). Lower-temperature venting of nutrient-rich hydrothermal fluids through the porous chimney walls support rich and diverse colonies of tube, sulfide, and palm worms, galatheid crabs, and a variety of snails and limpets (Figure 3A). On actively venting structures, these animal communities are so dense that they obscure the underlying host rock. Many structures are characterized by stair-step arrays of large sulfide ledges that form an almost tree-like structure (Figure 2C). The most spectacular of these structures, "Godzilla" in the Endeavour Segment's High Rise Field, was forty-five meters high and contained 15–16 tiers of ledges up to seven meters in length which trapped 330°C fluids. This structure collapsed sometime in 1996.

In contrast to the steep mound and ledge shapes that typify most of the sulfide structures in the three other hydrothermal fields at Endeavour, the recently-discovered Mothra Hydrothermal Field hosts at least five sulfide clusters composed of multiple, isolated, and fused pinnacles that reach up to twenty-four meters in height (Figure 2A). Many structures are awash in cooler, slower-moving hydrothermal fluids (30–210°C) that support dense and diverse biological communities composed predominantly of a variety of worms, snails, and crabs. These animals colonize the steep outer surfaces of active chimneys. Venting fluids from some of these steep, isolated pinnacles reach 305°C. Horizontal fractures, marked by dense colonies of single-celled organisms that include filamentous bacteria and microbial mats, commonly cut the sulfide structures, and toppled structures are fairly common. Mothra is the largest hydrothermal field on the Endeavour, reaching over 500 meters in length.

Life in Extreme Environments

Within the walls of active smokers, where highly-specific combinations of thermal and chemical conditions exist, the limits to life are beginning to be defined. That is what makes the study of these and similar sulfide chimneys particularly exciting and important to underwater researchers (Figure 3A). Until twenty years ago, no one thought life would be possible under these conditions. Many microorganisms recovered from these extreme environments belong to the domain Archaea, considered the most ancient of hyper-thermophilic organisms, those that thrive in 100°C water. In addition, scientists believe that the sulfide structures provide a window into processes similar to those operating deep within the seafloor, but which are not easily accessible with our current technologies. They are conducting intensive research into the linked mineralogical and biological interactions that take place within black smokers and the lower-temperature fluids around them.

The origin of hydrothermal systems is extremely ancient. For several related reasons, scientists theorize that life on the early Earth may have arisen in environments like these. One reason is that relentless collisions with large planetary bodies may have rendered both the shallow early ocean and the proto-continents uninhabitable. Furthermore, microbial life exists within hydrothermal systems that rely on chemosynthesis for energy in the absence of the sunlight. The study of black smokers is crucial to a broad range of microbiological and geological inquiries. Subsurface environments like these, both hot and oxygen-free, are believed to mimic most closely the conditions of Earth's earliest subsurface. From these studies, it is clear that volcanically active planets that contain liquid water may harbor life. Black smokers can thus be viewed as natural laboratories for studying microbial metabolisms thought to be ancient on Earth—and perhaps elsewhere.

Figure 3A: Highly specific combinations of thermal and chemical conditions support dense communities of diverse life forms on the sulfide chimneys. B. Cross-section showing internal structure of the sulfide chimney. C. Nutrient-rich hydrothermal fluids vent through the porous chimney walls supporting colonies of tube, sulfide, and palm worms, Galatheid crabs and a variety of snails and limpets.