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Hydrothermal Vent Systems

by

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Hydrothermal systems transfer large amounts of heat and mass from Earth's interior to the oceans.

It's difficult to imagine that just 15 years ago no one had ever seen a "black smoker chimney;" now they seem to be found at mid-ocean ridge crests whenever we take a close look. Black smoker chimney is the term used to describe a smokestacklike structure composed of sulfide and sulfate minerals. "Black smoke" refers to the abundance of dark particulates that form when extremely hot (350°C) hydrothermal fluid rapidly exits the chimney opening and mixes with cold (2°C) seawater. These chimneys, which would draw attention no matter what the setting, are all the more spectacular since they cap seafloor hydrothermal vent sites that are oases of activity on the otherwise rather barren terrain of mid-ocean ridge crests.

Hydrothermal systems transfer large amounts of heat and mass from Earth's interior to the oceans. Fluids exiting the chimneys are metal-rich, hot, and acidic, and vent at velocities on the order of meters per second. A striking feature of black smoker chimneys is how remarkably thin their walls are: They vary in thickness from about 5 inches to as little as .25 of an inch. Across this thin layer is a temperature difference of 300°C or greater, and similar steep elemental composition gradients also exist. Chimney structures are thus fascinating subjects for scientific study. Many questions come to mind when first seeing these chimneys in action such as,

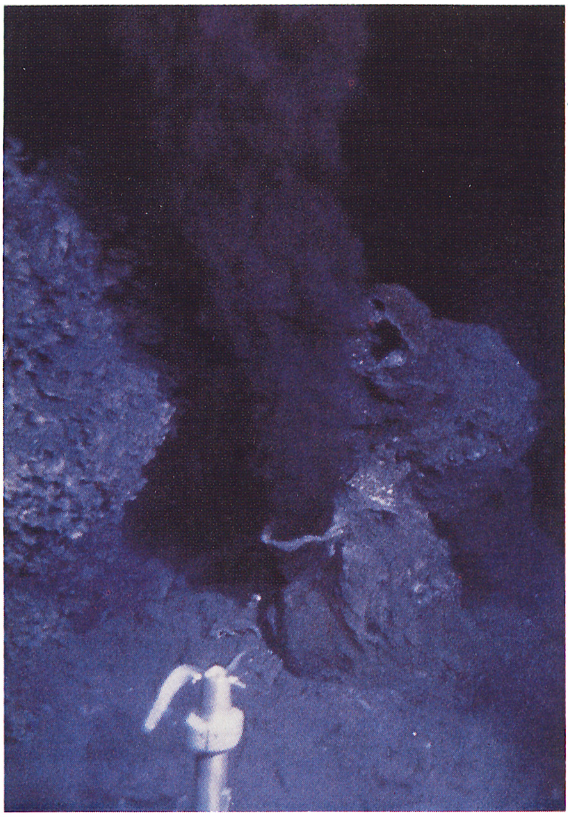
- Where is all the fluid coming from?
- Why is it flowing so fast?
- How did it get so hot?
- Where did all the particulates come from?
- How do the chimneys form? And equally puzzling,
- Why did it take so long to find them?

The existence of large-scale hydrothermal convection (fluid circulation) within oceanic crust near mid-ocean ridges was predicted in the mid-1960s, more than a decade before the first discoveries of active vents. It was recognized that oceanic crust could act as a porous medium, a magma chamber or newly solidified rock as a heat source, and seawater as a convecting fluid. But at this time, ridge crests were not well explored on the scale of tens of meters, the size of most vent fields. In 1977, active hydrothermal vents on mid-ocean ridge crests were first discovered on the Galapagos Rift, venting warm (25°C) fluid. The first discovery of high-temperature fluids actively forming chimneylike mineral deposits occurred in 1979 on the East Pacific Rise at 21°N. Since then numerous additional seafloor vent sites have been discovered in both the Pacific and Atlantic oceans. All detailed studies of vent sites have employed submersibles to photograph and map vent fields, measure temperatures of fluids, collect fluids, and recover fragile chimney samples.

Where Is All the Fluid Coming From? Why Does It Circulate? How Does It Get So Hot?

At all of these locations, the general processes of porous media convection, interaction between fluid and rock, and mineral deposition are similar. The schematic cross-sectional view across a ridge axis shows the ridge axis underlain by a heat source, either a magma chamber or newly solidified hot rock. The overlying crust, formed by volcanic activity, is permeable, owing to contraction and cracking as it cools. Seawater percolates down into these cracks, and circulates through hot basalt. Heat is transferred from the hot rock to the fluid.

As water is heated, its physical properties change. It expands, becoming less dense, and its viscosity decreases, so that it flows more easily. If this circulation occurred on land, drastic changes would occur when the temperature of the water reached 100°C, the boiling point of water. But at the depth of mid-ocean ridge crests, 2,000 to 4,000 meters below sea level, at pressures of 200 to 400 bars, the boiling point of seawater is much higher. Fluid can reach temperatures as high as 350°C without boiling. (The boiling point of seawater is 370°C at a pressure of 200 bars, and 404°C at 300 bars.) Fluid of this temperature is extremely buoyant, with a density less than seven-tenths that of seawater. If this fluid finds an open path to the seafloor, for instance a large open crack, or a series of interconnected cracks and void spaces, it will rise rapidly to the surface.



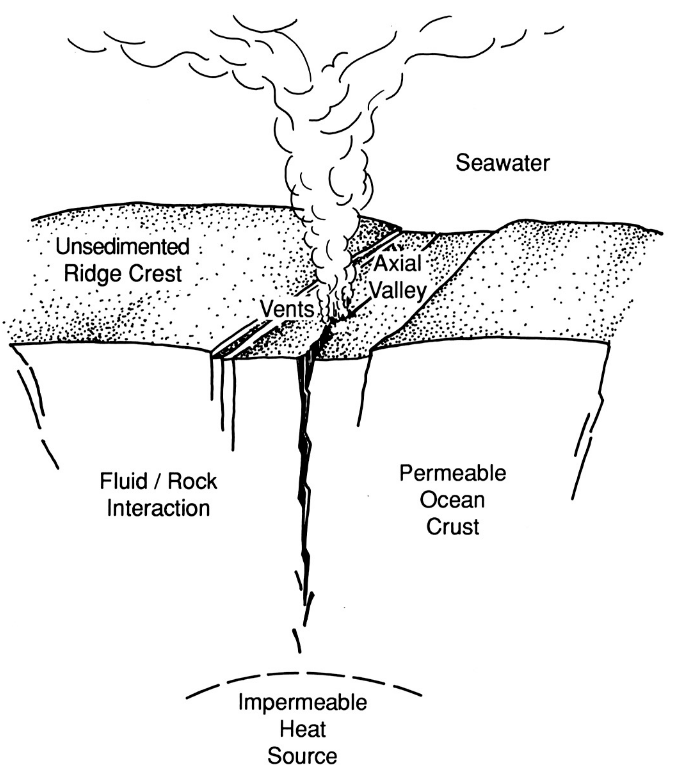
DSV *Alvin*/Dudley Foster

A black smoker chimney from the East Pacific Rise at 21°N vents 350° fluid at velocities on the order of 1 to 5 meters per second. The plume of black particulates (smoke) forms when the hot, low pH vent fluid mixes turbulently with the surrounding cold, higher-pH water.

How Do the Fluids Become Metal-Rich? Where Do the Particulates Come From? How Do Chimneys Form?

As the fluid circulates within the crust, it interacts with basaltic rock at high temperatures. Clay and sulfate minerals precipitate from seawater as it is initially heated, resulting in a modified fluid with little to no magnesium or sulfate, ions that are abundant in seawater. At higher temperatures, metals, silica, and sulfide are leached from the rock. The result is a hot, acidic (low pH) fluid with abundant silica, hydrogen sulfide, and metals, relative to seawater.

The hot, buoyant, metal-rich fluid exits the seafloor at velocities on the order of meters per second. When hydrothermal fluid mixes with



A schematic cross section of a seafloor hydrothermal system shows an impermeable heat source (magma chamber or hot rocks) overlain by permeable ocean crust at an unsedimented ridge crest. Fluid circulates within the crust, driven by temperature differences. During this circulation seawater is modified by fluid/rock interaction to hot, metal-rich fluid that is buoyant, and vents on the seafloor.

seawater, changes in pH and temperature result in the precipitation of minerals, the formation of black smoke, and black smoker chimneys. Black smoke is composed dominantly of fine-grained sulfide and oxide minerals (pyrrhotite, chalcopyrite, sphalerite, and amorphous iron oxides). Black smoker chimneys are concentric hollow spires up to 20 feet high, with inner channels .5 to 4 inches in diameter, that vent fluid in excess of 300°C. Early stages of black smoker chimney growth involve emplacement of an anhydrite-rich wall around the vent opening. Anhydrite (calcium sulfate) precipitates when seawater, rich in calcium and sulfate, and hydrothermal fluid, rich in calcium but depleted with respect to sulfate, mix. Anhydrite is an unusual mineral that is more soluble at low temperatures than at high temperatures. In seawater, it is saturated (and therefore should precipitate) at temperatures above approximately 150°C. Once a wall is formed around the vent opening, mixing between hydrothermal fluid and seawater is restricted. The wall gradually becomes less permeable as hydrothermal fluid and seawater mix through the wall, and sulfide and sulfate minerals precipitate. The inner side of the wall is in contact with hydrothermal fluid and chalcopyrite is deposited on this surface. The result is a concentrically zoned structure with an inner channel lined with chalcopyrite, and outer layers composed of varying amounts of anhydrite, and iron, copper-iron, and zinc sulfide minerals (such as pyrite and marcasite, chalcopyrite, bornite, sphalerite, and wurtzite).

Variations Among Vent Sites

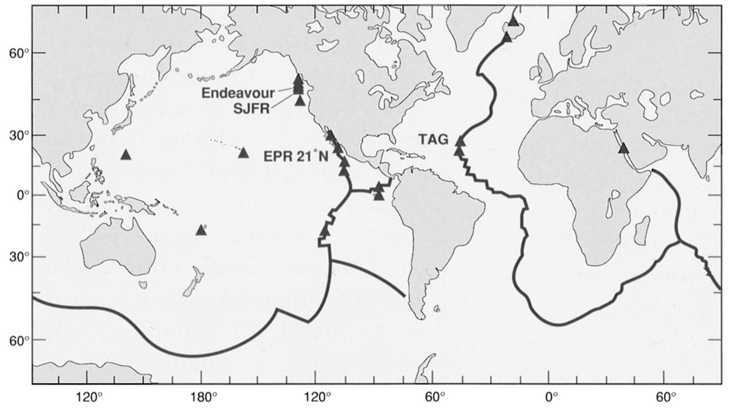
Black smoker chimneys, and fluids with temperatures in excess of 300°C, are found at most active vent sites, reflecting the similarities in the general processes of fluid circulation and mineral deposition occurring at unsedimented mid-ocean ridge crests. Details of these processes, however, vary, resulting in distinct fluid compositions, and differences in the mineralogy, size, and gross morphology of the hydrothermal deposits. Sizes of vent deposits range from relatively small (fields about 10 meters in diameter) to those that resemble ore deposits exposed on land (up to 200 meters in diameter). Variations also exist in fluid composition, maximum fluid temperature, mineralogy, shape of deposits, and geologic setting. While the past decade of research focused on sampling the highest temperature fluids present at each site and the associated mineral precipitates, the focus is now shifting toward understanding the causes of variations and differences among vent sites.

Fluid Composition. All of the solutions sampled at vent sites on unsedimented ridge crests are acidic, sulfide-rich, and capable of carrying large amounts of ore-forming elements. Fluid composition differs from site to site with respect to concentrations of chloride, metals, hydrogen sulfide, silica, and carbon dioxide, as well as pH and temperature. These variations reflect differences in fluid/rock interactions, including the amount of fluid being seen by each piece of rock during fluid circulation, depth of circulation and reaction, mineral assemblages present at each depth, and temperatures of reaction. Fluid composition can also be affected by processes occurring near the surface: Fluid can be cooled and minerals deposited directly beneath the seafloor, either by conduction (heat loss, with no addition of cold seawater) or from mixing with cold seawater.

Within each vent site there is a range of exiting fluid temperatures, compositions, and velocities. Scientists hypothesize that at each vent site there is one highest temperature, or end-member solution, and that ranges in temperature and composition within the vent field can be accounted for either by conductive cooling of the end-member solution, or mixing of the solution with seawater.

Location of known seafloor hydrothermal vent sites (closed triangles) are shown below. Solid lines indicate ridges. The lack of known sites on ridge crests in the South Pacific and Indian oceans, and along much of the Mid-Atlantic Ridge, is indicative of areas that have not been adequately explored. SJFR indicates Southern Juan de Fuca Ridge, EPR indicates East Pacific Rise.

Size and Shape of Deposits. Vent sites on the East Pacific Rise at 21°N were the first ones analyzed for both fluid chemistry and mineralogy, and are (to some extent) the type of vent system that all other systems are compared to. At 21°N, chimney structures are up to 6 meters high, and have open channels 1 to 10 centimeters in diameter that are lined with chalcopyrite. Maximum fluid temperatures are 350°C, and flow velocities range from 1 to 5 meters per second. The chimneys sit on top of low-lying basal mounds. The surfaces of these mounds are comprised of fine-grained sulfide-rich mud and partially oxidized sulfide-rich fragments, some of which appear to be pieces of fallen chimneys. The interiors of the mounds have not been sampled or studied in detail. When they are ruptured, small black smokers form, suggesting that the temperature of fluid circulating within the mounds is high. The vent deposits are spaced along the center of a narrow (5-kilometer wide) axial valley at 100- to 1,000-meter intervals, and are located on fresh lava flows. At each of these sites the amount of heat being transported from Earth's interior to the ocean is very large, yet the amount of metal-rich minerals deposited is small relative to ore deposits exposed on land. It is not clear whether these deposits will ever grow to a large size; whether they are truly analogous to ore deposits is thus open to question.



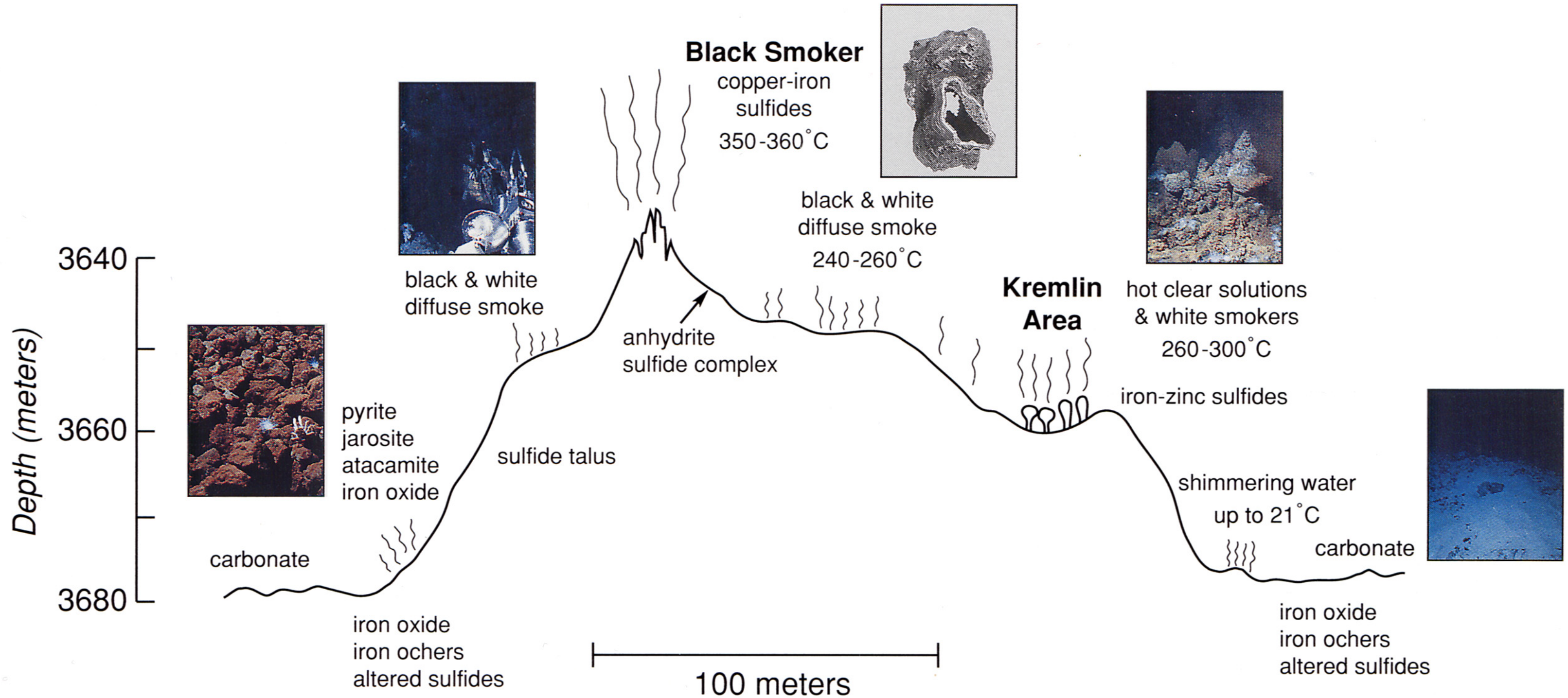
The vent sites with fluid chemistry most different from 21°N are those on the southern Juan de Fuca Ridge. These vent sites are both

The vent site most analogous to ore deposits exposed on land is the active TAG mound located at 26°N on the Mid-Atlantic Ridge.

similar and different when compared to those on the East Pacific Rise. On the southern Juan de Fuca Ridge, chimneys and spires are the dominant form of mineral deposition, and vent sites are located in the center of the axial valley on fresh basalt. The morphology and mineralogy of the chimneys, however, differ from those at 21°N. In general the chimneys are small (2 to 6 feet tall), and instead of exhibiting strong concentric zonation around a large open channel, they are texturally more complex and contain multiple small (1- to 10-millimeter-diameter) fluid channels. Flow rates are less than at 21°N. Mineralogy is dominated by zinc sulfide (wurtzite and sphalerite) instead of copper-iron sulfide, and the innermost copper-rich layer that is common in East Pacific Rise chimneys is absent. Some of these differences are accounted for by the lower temperature (less than 300°C) and different composition of the venting fluid that is forming the deposits, the most striking of which is the chlorinity: Chloride concentration is up to twice that of seawater, and metal concentrations (except copper) are also high since metals are present in solution as chloride complexes (for example, iron chloride, lead chloride, and zinc chloride). Low copper content could reflect that either the temperature of the fluids never got high enough to leach copper from basaltic rock during fluid circulation, or that copper-iron sulfides had been deposited in the subsurface directly beneath the vent sites. Again, as with the deposits at 21°N, the amount and distribution of material deposited on the southern Juan de Fuca Ridge is not currently analogous to ore deposits.

The vent site most analogous to ore deposits exposed on land is the active TAG (Trans-Atlantic Geotraverse) mound located at 26°N on the Mid-Atlantic Ridge. The irony of this is that in the early 1980s researchers felt that the slow-spreading Mid-Atlantic Ridge could not sustain high-temperature hydrothermal activity. Hydrothermal systems transfer large amounts of heat from magma or newly solidified rock; on slow-spreading ridges (spreading at a half-rate of 13 millimeters per year as opposed to 30 millimeters per year at 21°N), such heat was not thought to be available. The TAG mound, however, is not only active, but larger in diameter by an order of magnitude than mounds at sites in the faster-spreading Pacific Ocean.

The active TAG mound is 200 to 250 meters in diameter and is located at the east side of a wide axial valley that is coated with carbonate sediment. The outer low-lying portion of the mound is composed of carbonate ooze, metalliferous sediment, sulfide blocks, and basalt talus. The inner portion of the mound is 150 to 170 meters in diameter, and is covered entirely with hydrothermal precipitates. The edges of the inner mound are steep talus slopes of sulfide and iron-oxide material that rise 20 meters above the outer mound. The center of the mound is dominated by a cluster of black smoker chimneys venting fluid at temperatures up to 363°C.The composition of this fluid is similar to fluids from the East Pacific Rise vent sites. The chimneys are chalcopyrite and anhydrite rich, and sit atop a 10- to 20-meter high, 40- to 50-meter-diameter cone of sulfide and sulfate. The surface of the cone is platelike. It is composed of chalcopyrite and pyrite with interspersed blocks of corroded massive anhydrite. Black smoke seeps from small, fingerlike protrusions and cracks in the cone surface and flows upward along the surface into the plume of black smoke above.



A cross section of the active TAG mound shows the wide range of hydrothermal precipitates. The basalt floor around the mound is covered with a layer of carbonate sediment. Steep talus slopes of sulfide (pyrite) and red to yellow iron-oxide material lead up to the top of the mound. The mound is capped by a cluster of black-smoker chimneys venting 350° to 360° fluid. Fluid samples were recovered from these vents using titanium water samplers. The black smoker chimney samples recovered are similar to chimney samples from other sites: Outer layers (dark) are composed of mixed sulfide and anhydrite, the inner layer is chalcopyrite. High temperature fluids and chimney samples of distinctly different compositions are present in the south-east quadrant of the mound (the Kremlin Area). The zinc-rich white smoker chimneys stand 1 to 2 meters high, and vent clear 260° to 300° fluids.

Cross-section illustration by Geoff Thompson. Photo credits, from left to right: Stephen Molyneaux; Carl Worsen and Cindy Van Dover; M. Sulanowska (sample is actually from Endeavor segment); Mark Hannington; and Peter Rona and Mark Hannington.

How the active TAG mound grew to such large size is a current study topic.

At a lower elevation in the southeast quadrant of the mound, lower temperature fluids (300°C and lower) exit "white smoker" chimneys. These chimneys, which are mineralogically and structurally very similar to spires from the southern Juan de Fuca Ridge site, are composed dominantly of sphalerite (zinc sulfide) and exhibit numerous millimeter-diameter flow conduits. The fluid venting from this portion of the mound is not only cooler than fluid venting from the cluster of black smokers, but is copper poor and has a low pH relative to the higher temperature fluids. The lower temperature fluid may form as a result of conductive cooling of the 363°C end-member solution. Diffuse, low-temperature fluids emanate from the remainder of the top of the mound, which is composed of fragile amorphous iron-oxide and silica crusts and blocky to bulbous lobes of mixed zinc, iron, and copper-iron sulfides. The overall size and concentric zonation of the mound, with highest temperatures in the center, and lower temperature sulfides and iron-oxides distributed near the outside, are similar to ore deposits exposed on land. How the active TAG mound grew to such large size is a current study topic, and whether or not deposits in the faster spreading Pacific will ever attain this size is unknown.

A New Set of Questions

Studies done in the last decade on seafloor hydrothermal systems have led to an understanding of the basic processes involved in hydrothermal circulation and mineral deposition—and have also shown how little we know. The next decade of research will address such questions as,

- What is the extent of hydrothermal venting at mid-ocean spreading centers and back-arc basins?
- What is the significance of variations in fluid composition, temperature, flow rate, and composition of solid precipitates among hydrothermal sites?
- How long are vent sites active?
- Does fluid composition change with time, and if so, on what time scale?
- What proportion of minerals is deposited at the vent site versus dispersed into the water column as black smoke?

All of these questions must be answered to estimate the contribution from hydrothermal processes to global heat budgets and geochemical cycles. While we now have a general understanding of hydrothermal vent systems, we still have much to learn, and large sections of the mid-ocean ridge system have yet to be explored.

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