HYDROTHERMAL VENT DEPOSITS

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Introduction

In April 1979, submersible divers exploring the mid-ocean ridge crest at latitude 21°N on the East Pacific Rise discovered superheated ($380 \pm 30°C$) fluids, blackened by tiny metal-sulfide mineral crystals, spewing from the seafloor through tall mineral conduits (*see* **Hydrothermal Vent Biota. Hydrothermal Vent Fluids, Chemistry of**). The crystalline conduits at these 'black smoker' hydrothermal vents were made of minerals rich in copper, iron, zinc, and other metals. Since 1979, hundreds of similar hydrothermal deposits have been located along the midocean ridge. It is now clear that deposition of hydrothermal mineral deposits is a common process, and is integrally linked to cracking, magmatism, and cooling of new seafloor as it accretes and spreads away from the ridge (*see* **Propagating Rifts and Microplates Mid-ocean Ridge Geochemistry and Petrology, Seamounts and Off-ridge Volcanism. Mid-ocean Ridge Seismic Structure**).

For thousands of years before mid-ocean ridge hot springs were discovered in the oceans, people mined copper from mineral deposits that were originally formed on oceanic spreading ridges. These fossil deposits are embedded in old fragments of seafloor called 'ophiolites' that have been uplifted and emplaced onto land by fault movements. The copper-rich mineral deposits in the Troodos ophiolite of Cyprus are well-known examples of fossil ocean-ridge deposits that have been mined for at least 2500 years; in fact, the word 'copper' is derived from the Latin word 'cyprium' which means 'from Cyprus.'

The mineral deposits accumulating today at hot springs along the mid-ocean ridge are habitats for a variety of remarkable organisms ranging in size from tiny microbes to large worms (*see* **Hydrothermal Vent Biota. Deep-sea Ridges, Microbiology. Hydrothermal Vent Fauna, Physiology of**). The properties of the mineral deposits are inextricably linked to the organisms that inhabit them. The mineral deposits contain important clues about the physical–chemical environments in which some of these organisms live, and also preserve fossils of some organisms, creating a geologic record of their existence.

Hydrothermal vent deposits are thus a renewable source of metals and a record of the physical, chemical, biological, and geological processes at modern and ancient submarine vents.

Where Deposits Form: Geologic Controls

Less than 2% of the total area of the mid-ocean ridge crest has been studied at a resolution sufficient to reveal the spatial distribution of hydrothermal vents, mineral deposits, and other significant small-scale geologic features. Nevertheless, because study areas have been carefully selected and strategically surveyed, much has been learned about where vents and deposits form, and about the geologic controls on their distribution. The basic requirements for hydrothermal systems include heat to drive fluid circulation, and high-permeability pathways to facilitate fluid flow through crustal rocks. On mid-ocean ridges, vents and deposits are forming at sites where ascending magma intrusions introduce heat into the permeable shallow crust, and at sites where deep cracks provide permeability and fluid access to heat sources at depth.

Fast-spreading Ridges

Near- and on-bottom studies along the fast-spreading East Pacific Rise suggest that most hydrothermal mineral deposits form along the summit of the ridge crest within a narrow 'axial zone' less than 500 m wide. Only a few active sites of mineral deposition have been located outside this zone; however, more exploration of the vast area outside the axial zone is needed to establish unequivocally whether or not mineral deposition is uncommon in this region. The overall spatial distribution of hydrothermal vents and mineral deposits along fast-spreading ridges traces the segmented configuration of cracks and magma sources along the ridge crest (*see* **Propagating Rifts and Microplates, Mid-ocean Ridge Geochemistry and Petrology, Seamounts and Off-ridge Volcanism, Mid-Ocean Ridge Seismic Structure**).

Within the axial zone, mineral deposition is concentrated along the floors and walls of axial troughs created by volcanic collapse and/or faulting along the summit of the ridge crest. The majority of the deposits are located along fissures that have opened above magmatic dike intrusions, and along collapsed lava ponds formed above these fissures by pooling and drainage of erupted lava. Where fault-bounded troughs have formed along the summit of the ridge crest, mineral deposition is focused along the bounding faults and also along fissures and collapsed lava ponds in the trough floor. Hydrothermal vents appear to be most abundant along magmatically inflated segments of fast-spreading ridges; however, the mineral deposits precipitated on the seafloor on magmatically active segments are often buried beneath frequent eruptions of new lava flows. The greatest number of deposits, therefore, are observed on inflated ridge segments that are surfaced by somewhat older flows, i.e., along segments where: (1) much heat is available to power hydrothermal vents; and (2) mineral deposits have had time to develop but have not yet been buried by renewed eruptions.

Intermediate- and Slow-spreading Ridges

Most hydrothermal deposits that have been found on intermediate- and slow-spreading ridge crests are focused along faults, fissures, and volcanic structures within large rift valleys that are several kilometers wide. The fault scarps along the margins of rift valleys are common sites for hydrothermal venting and mineral deposition. Fault intersections are thought to be particularly favorable sites for hydrothermal mineral deposition because they are zones of high permeability that can focus fluid flow. Mineral deposition on rift valley floors is observed along fissures above dike intrusions, along eruptive fissures and volcanic collapse troughs, and on top of volcanic mounds, cones and other constructions. In general at slower-spreading ridges, faults appear to play a greater role in controlling the distribution of hydrothermal vents and mineral deposits than they do at fast-spreading ridges, where magmatic fissures are clearly a dominant geologic control on where vents and deposits are forming.

Structures, Morphologies, and Sizes of Deposits

A typical hydrothermal mineral deposit on an unsedimented mid-ocean ridge accumulates directly on top of the volcanic flows covering the ridge crest. On sedimented ridges, minerals are deposited within and on top of the sediments. Beneath seafloor mineral deposits are networks of feeder cracks through which fluids travel to the seafloor. Precipitation of hydrothermal minerals in these cracks and in the surrounding rocks or sediments creates a subseafloor zone of mineralization called a ‘stockwork’. In hydrothermal systems where fluid flow is weak, unfocused, or where the fluids mix extensively with sea water beneath the seafloor, most of the minerals will precipitate in the stockwork rather than on the seafloor.

Hydrothermal deposits on mid-ocean ridges are composed of: (1) vertical structures, including individual conduits known as ‘chimneys’ (**Figure 1**) and larger structures of coalesced conduits that are often called ‘edifices’; (2) horizontal ‘flange’ structures that extend outward from chimneys and edifices

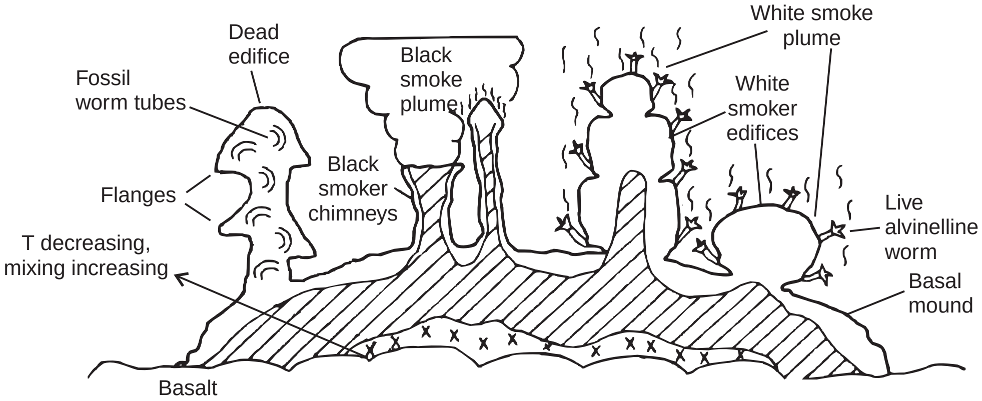


Figure 1 Composite sketch of the mineral structures and zones in hydrothermal mineral deposits on unsedimented ridge crests (modified after Haymon, 1989). Although mound interiors are seldom observed on the seafloor, the simplified sketch of mineral zoning within the mound is predicted by analogy with chimneys and massive sulfide deposits exposed in ophiolites. An outer peripheral zone (unshaded) of anhydrite + amorphous silica + Zn-rich sulfide, dominantly $ZnS + FeS_2$, is replaced in the interior by an inner zone (hatched) of Cu-rich sulfide ($CuFeS_2 + FeS_2$) + minor anhydrite and amorphous silica. The inner zone may be replaced by a basal zone (cross-pattern) of Cu-rich sulfide ($CuFeS_2 + FeS_2$) + quartz. Zones migrate as thermochemical conditions within the mound evolve. Although not shown here, it is expected that zoning around individual fractures cutting through the mound will be superimposed on the simplified zone structure in this sketch.

(**Figure 1**); (3) mounds of accumulated mineral precipitates (**Figure 1**); and (4) horizontal layers of hydrothermal sediments, debris, and encrustations. Chimneys are initially built directly on top of the seabed around focused jets of high-temperature effluents. Chimneys and edifices are physically unstable and often break or collapse into pieces that accumulate into piles of debris. The debris piles are cemented into consolidated mounds by precipitation of minerals from solutions percolating through the piles. New chimneys are constructed on top of the mounds as the mounds grow in size. Hydrothermal plume particles and particulate debris from chimneys settle around the periphery of the mounds to form layers of hydrothermal sediment. Diffuse seepage of fluids also precipitates mineral encrustations on mound surfaces, on volcanic flows and sediments, and on biological substrates, such as microbial mats or the shells and tubes of sessile macrofauna.

The morphologies of chimneys are highly variable and evolve as the chimneys grow, becoming more complex with time. Black smoker chimneys are often colonized by organisms and evolve into 'white smokers' that emit diffuse, diluted vent fluids through a porous carapace of worm tubes (**Figure 1**). Fluid compositions and temperatures, flow dynamics, and biota are all factors that influence the development of chimney morphology. The complexity of the interactions between these factors, and the high degree of spatial–temporal heterogeneity in the physical, chemical, biological and geological conditions influencing chimney growth, account for the diverse morphologies exhibited by chimneys, and present a challenge to researchers attempting to unravel the processes producing these morphologies.

The sizes of hydrothermal mineral deposits on ridges also vary widely. It has been suggested that the largest deposits are accumulating on sedimented ridges, where almost all of the metals in the fluids are deposited within the sediments rather than being dispersed into the oceans by hydrothermal plumes. On unsedimented ridges, the structures deposited on the seabed at fast spreading rates are usually relatively small in dimension (mounds are typically less than a few meters in thickness and less than tens of meters in length, and vertical structures are $< 15\,\mathrm{m}$ high). On intermediate- and slow-spreading ridges, mounds are sometimes much larger (up to tens of meters in thickness, and up to 300 m in length). On the Endeavour Segment of the Juan de Fuca Ridge, vertical structures reach heights of 45 m. The size of a deposit depends on many factors, including: magnitude of the heat source, which influences the duration of venting and mineral deposition; tendency of venting and mineral deposition to recur episodically at a particular site, which depends on the nature of the heat source and plumbing system, and the rate of seafloor spreading; frequency with which deposits are buried beneath lava flows; and the compositions of the vent fluids and minerals. The large deposits found on slower-spreading ridge crests are located on faults that have moved slowly away from the ridge axis and have experienced repeated episodes of venting and accumulated mineral deposition over thousands of years, without being buried by lava flows. The tall Endeavor Segment edifices are formed because ammonia-enriched fluid compositions favor precipitation of silica in the edifice walls. The silica is strong enough to stabilize these structures so that they do not collapse as they grow taller.

How Do Chimneys Grow?

A relatively simple two-stage inorganic growth model has been advanced to explain the basic characteristics of black smoker chimneys (**Figure 2**). In this model, a chimney wall composed largely of anhydrite (calcium sulfate) precipitates initially from sea water that is heated around discharging jets of hydrothermal fluid. The anhydrite-rich chimney wall

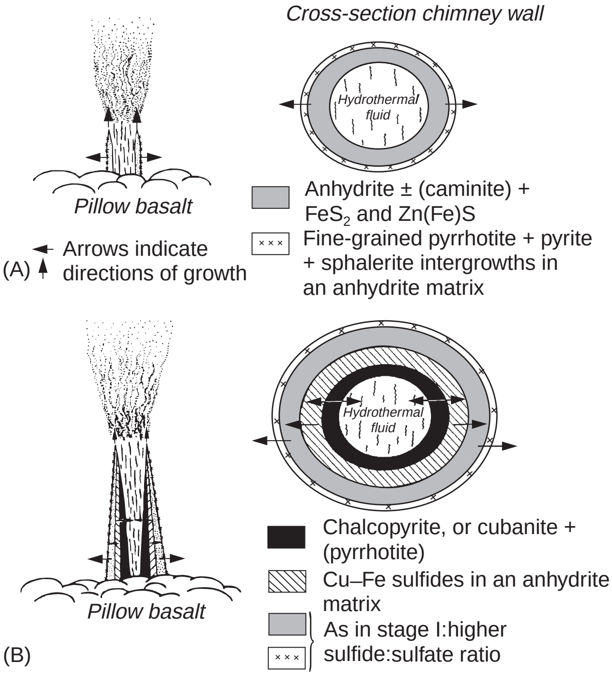


Figure 2 Two-stage model of black smoker chimney growth. (A) Stage I, sulfate-dominated stage; (B) stage II, sulfide replacement stage. During stage II, several different sulfide mineral zonation sequences develop, depending on permeability and thickness of chimney walls, hydrodynamic variables, and hydrothermal fluid composition.

precipitated during stage I contains only a small component of metal sulfide mineral particles that crystallize because of rapid chilling of the hydrothermal fluids. In stage II, the anhydrite-rich wall continues to grow upward and to thicken radially, protecting the fluid flowing through the chimney from very rapid chilling and dilution by sea water. This allows metal sulfide minerals to precipitate into the central conduit of the chimney from the hydrothermal fluid. The hydrothermal fluid percolates outward through the chimney wall, gradually replacing anhydrite and filling voids with metal sulfide minerals. During stage II, the chimney increases in height, girth and wall thickness, and both the calcium sulfate/metal sulfide ratio and permeability of the walls decrease. Equilibration of minerals with pore fluid in the walls occurs continuously along steep, time–variant temperature and chemical gradients between fluids in the central conduit and sea water surrounding the chimney. This equilibration produces sequences of concentric mineral zones across chimney walls that evolve with changes in thermal and chemical gradients and wall permeability.

The model of chimney growth described above is accurate but incomplete, as it does not include the effects on chimney development of fluid phase separation, biological activity, or variations in fluid composition. Augmented models that address these complexities are needed to fully characterize the processes governing chimney growth.

Elemental and Mineral Compositions of Deposits

Ridge crest hydrothermal deposits are composed predominantly of iron-, copper- and zinc sulfide minerals, calcium- and barium-sulfate minerals, iron oxide and iron oxyhydroxide minerals, and silicate minerals (**Table 1**). These minerals precipitate from diverse processes, including: heating of sea water; cooling of hydrothermal fluid; mixing between sea water and hydrothermal fluid; reaction of hydrothermal minerals with fluid, sea water, or fluid–sea water mixtures; reaction between hydrothermal fluid and seafloor rocks and sediments; and reactions that are mediated or catalyzed biologically. This diversity in the processes and environments of mineral precipitation results in the deposition of many different minerals and elements (**Tables 1** and **2**). High concentrations of strategic and precious metals are found in some deposits (**Table 2**). The deposits are potentially valuable, if economic and environmentally safe methods of mining them can be developed.

Table 1 Minerals occurring in ocean ridge hydrothermal mineral deposits

Mineral group/name	*Chemical formula*
Sulfides/Sulfosalts	
Most abundant	
Sphalerite	Zn(Fe)S
Wurtzite	Zn(Fe)S
Pyrite	FeS_2
Chalcopyrite	$CuFeS_2$
Less abundant	
Iss-Isocubanite	Variable $CuFe_2S_3$
Marcasite	FeS_2
Melnicovite	FeS_{2-x}
Pyrrhotite	$Fe_{1-x}S$
Bornite–Chalcocite	Cu_5FeS_4–Cu_2S
Covellite	CuS
Digenite	Cu_9S_5
Idaite	$Cu_{5.5}FeS_{6.5}$
Galena	PbS
Jordanite	$Pb_9As_4S_{15}$
Tennantite	$(Cu,Ag)_{10}(Fe,Zn,Cu)_2As_4S_{23}$
Valeriite	$2(Cu,Fe)_2S_2 3(Mg,Al)(OH)_2$
Sulfates	
Anhydrite	$CaSO_4$
Gypsum	$CaSO_4 \cdot H_2O$
Barite	$BaSO_4$
Caminite	$MgSO_4 \cdot xMg(OH)_2 \cdot (1–2x)H_2O$
Jarosite–Natrojarosite	$(K,Na)Fe_3(SO_4)_2(OH)_6$
Chalcanthite	$CuSO_4 \cdot 5H_2O$
Carbonate	
Magnesite	$MgCO_3$
Calcite	$CaCO_3$
Elements	
Sulfur	S
Oxides/Oxyhydroxides	
Goethite	FeO(OH)
Lepidocrocite	FeO(OH)
Hematite	Fe_2O_3
Magnetite	Fe_3O_4
Psilomelane	$(Ba,H_2O)_2Mn_5O_{10}$
‘Amorphous’ Fe-compounds	
‘Amorphous’ Mn-compounds	
Silicates	
Opaline silica	$SiO_2 \cdot nH_2O$
Quartz	SiO_2
Talc	$Mg_3Si_4O_{10}(OH)_2$
Nontronite	$(Fe,Al,Mg)_2(Si_{3.66}Al_{0.34})O_{10}(OH)_2$
Illite-smectite	
Aluminosilicate colloid	
Hydroxychlorides	
Atacamite	$Cu_2Cl(OH)_3$

Chimneys can be classified broadly by composition into four groups: sulfate-rich, copper-rich, zinc-rich and silica-rich structures. Copper-rich chimney compositions are indicative of formation at

Table 2 Ranges of elemental compositions in bulk midocean ridge hydrothermal mineral deposits

Element	*Ranges*[a]
Cu	0.1–15.0 wt%
Fe	2.0–44.0 wt%
Zn	< 0.1–48.7 wt%
Pb	0.003–0.6 wt%
S	13.0–52.2 wt%
SiO_2	< 0.1–28.0 wt%
Ba	< 0.01–32.5 wt%
Ca	< 0.1–16.5 wt%
Au	< 0.1–4.6 p.p.m.
Ag	3.0–303.0 p.p.m.
As	7.0–918.0 p.p.m.
Sb	2.0–375.0 p.p.m.
Co	< 2.0–3500.0 p.p.m.
Se	< 2.0–224.0 p.p.m.
Ni	< 1.5–226.0 p.p.m.
Cd	< 5–1448 p.p.m.
Mo	1.0–290.0 p.p.m.
Mn	36.0–1847.0 p.p.m.
Sr	2.0–4300.0 p.p.m.

[a] Data sources: Hannington *et al.* (1995) and Haymon (1989).

temperatures above 300°C. Sulfate-rich compositions are characteristic of active and immature chimneys. Many chimneys are mineralogically zoned, with hot interior regions enriched in copper, and cooler exterior zones enriched in iron, zinc, and sulfate (**Figures 1** and **2**). Mounds exhibit a similar gross mineral zoning, and those which are exposed by erosion in ophiolites often have silicified (quartz-rich) interiors (**Figure 2**). Seafloor weathering of deposits after active venting ceases results in dissolution of anhydrite, and oxidation and dissolution of metal-sulfide minerals. Small deposits that are not sealed by silicification or buried by lava flows will not be well preserved in the geologic record.

Chimneys as Habitats

Chimney and mound surfaces are substrates populated by microbial colonies and sessile organisms such as vestimentiferan and polychaete worms, limpets, mussels, and clams. It is likely that pore spaces in exterior regions of chimney walls are also inhabited by microbes. All of these organisms that are dependent on chemosynthesis benefit from the seepage of hydrothermal fluid through active mineral structures, and from the thermal and chemical gradients across mineral structures. The structures provide an interface between sea water and hydro thermal fluid that maintains tolerable temperatures for biota, and allows organisms simultaneous access to the chemical constituents in both sea water and hydrothermal fluid. However, organisms attached to active mineral structures must cope with changes in fluid flow across chimney walls (which sometimes occur rapidly), and with ongoing engulfment by mineral precipitation.

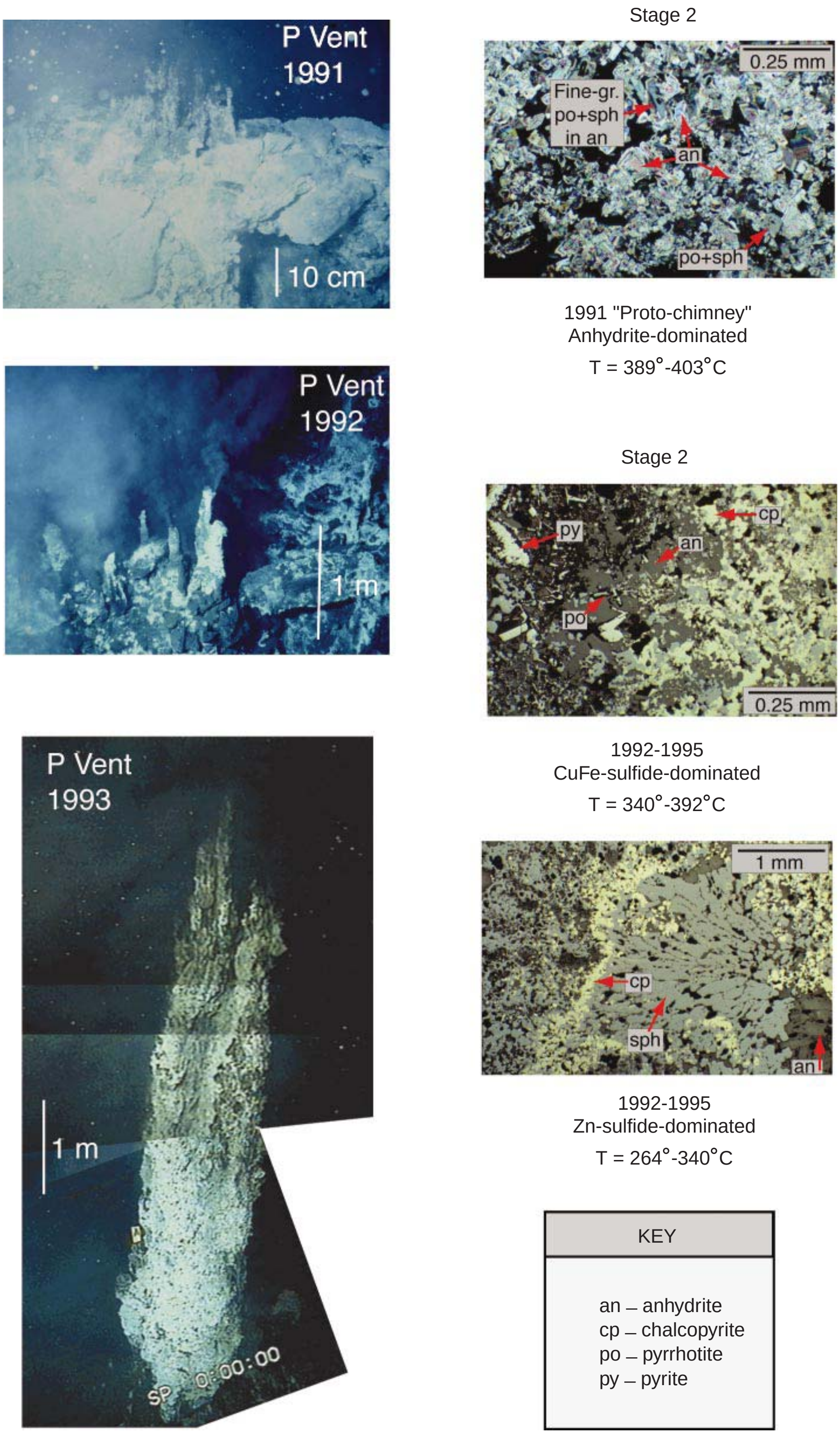
Some organisms actively participate in the precipitation of minerals; for example, sulfide-oxidizing microbes mediate the crystallization of native sulfur crystals, and microbes are also thought to participate in the precipitation of marcasite and iron oxide minerals. Additionally, the surfaces of organisms provide favorable sites for nucleation and growth of amorphous silica, metal sulfide and metal oxide crystals, and this facilitates mineral precipitation and fossilization of vent fauna (**Figure 3**).

Fossil Record of Hydrothermal Vent Organisms

Fossil molds and casts of worm tubes, mollusc shells, and microbial filaments have been identified in both modern ridge hydrothermal deposits and in Cretaceous, Jurassic, Devonian, and Silurian deposits. This fossil record establishes the antiquity of vent communities and the long evolutionary history of specific faunal groups. The singular Jurassic fossil assemblage preserved in a small ophiolite-hosted deposit in central California is particularly

Figure 3 (Right) On left: a time series of seafloor photographs showing the morphological development of a chimney that grew on top of lava flows erupted in 1991 on the crest of the East Pacific Rise near 9°50.3′N (Haymon *et al.*, 1993). Within a few days-to-weeks after the eruption, anhydrite-rich 'Stage 1 Protochimneys' a few cm high had formed where hot fluids emerged from volcanic outcrops covered with white microbial mats (top left). Eleven months later, the chimney consisted of cylindrical 'State 2' anhydrite-sulfide mineral spires approximately one meter in height, and as-yet unpopulated by macrofauna (middle left). Three and a half years after the eruption, the cylindrical conduits had coalesced into a 7 m-high chimney structure that was covered with inhabited Alvinelline worm tubes (bottom left). On right: photomicrographs of chimney samples from the eruption area that show how the chimneys evolved from Stage 1 (anhydrite-dominated; top right) to Stage 2 (metal-sulfide dominated) mineral compositions (see text). As the fluids passing through the chimney cooled below $\sim$330°C during Stage 2, the CuFe-sulfide minerals in the chimney walls (middle right) were replaced by Zn-and Fe-sulfide minerals (bottom right).

Morphological and Mineralogical Evolution of Chimneys
on the East Pacific Rise at 9°-10°N



interesting because it contains fossils of vestimentiferan worms, gastropods and brachiopods, but no clam or mussel fossils. In contrast, modern and Paleozoic faunal assemblages described thus far include clams, mussels and gastropods, but no brachiopods. Does this mean that brachiopods have competed with molluscs for ecological niches at vents, and have moved in and out of the hydrothermal vent environment over time? Fossilization of organisms is a selective process that does not preserve all the fauna that are present at vents. Identification of fossils at the species level is often difficult, especially where microbes are concerned. Notwithstanding, it is important to search for more examples of ancient fossil assemblages and to trace the fossil record of life at hydrothermal vents back as far as possible to shed light on how vent communities have evolved, and whether life on earth might have originated at submarine hydrothermal vents.

Summary

Formation of hydrothermal deposits is an integral aspect of seafloor accretion at mid-ocean ridges. These deposits are valuable for their metals, for the role that they play in fostering hydrothermal vent ecosystems, for the clues that they hold to understanding spatial–temporal variability in hydrothermal vent systems, and as geologic records of how life at hydrothermal vents has evolved. From these deposits we may gain insights about biogeochemical processes at high temperatures and pressures that can be applied to understanding life in inaccessible realms within the earth's crust or on other planetary bodies. We are only beginning to unravel the complexities of ridge hydrothermal vent deposits. Much exploration and interdisciplinary study remains to be done to obtain the valuable information that they contain.

See also

Deep-sea Ridges, Microbiology. Hydrothermal Vent Fluids, Chemistry of. Hydrothermal Vent Biota. Hydrothermal Vent Fauna, Physiology of. Mid-ocean Ridge Geochemistry and Petrology. Mid-ocean Ridge Seismic Structure. Propagating Rifts and Microplates. Seamounts and Off-ridge Volcanism.

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HYDROTHERMAL VENT ECOLOGY

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Introduction

Most of the ocean floor is covered with a thick layer of sediment and is populated by sparse and minute, mud-dwelling and mud-consuming invertebrates. In striking contrast, the volcanic basalt pavement of mid-ocean ridges hosts hydrothermal vents and their attendant lush communities of large invertebrates that ultimately rely on inorganic chemicals for their nutrition. Vents themselves are sustained by tectonic forces that fracture the basalt and allow sea water to penetrate deep within the ocean crust, and by volcanism, which generates the hot rock at depth that strips sea water of oxygen and magnesium. The