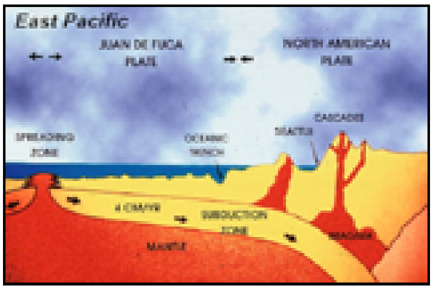
Hydrothermal Vents: Deep and Dark Oases Isolated from the Earth's Changing Surface

Editor's Introduction | Hydrothermal vents have characterised parts of the seafloor since oceans first formed, and modern vents are sites of thriving faunal communities developed around chemical energy sources in the total absence of light. Richard Herrington, of the department of mineralogy at The Natural History Museum, London, examines vents sites and their associated animal life through geological time, aided by discoveries illuminated by modern seafloor exploration techniques, developed less than 30 years ago. These have enabled scientists to speculate about the contribution of vents to the very origins of life, both on Earth and possibly on other planets.



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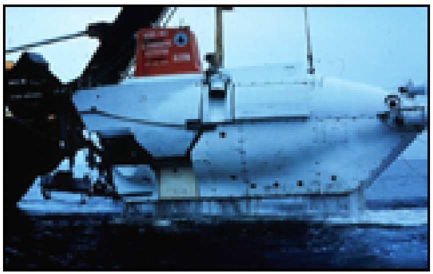
The mid-Pacific spreading centre and the North American subduction zone.

Topographical maps of the Earth's deep oceans revealed for the first time, in the late 1970s, the long, linear ridges of elevated seafloor. These undersea landforms, between Europe/Africa and the Americas, exactly mimic the shape of the continents, and such new information led scientists to develop the theory of plate tectonics, which is now universally embraced. Studies reveal that in the centre of the oceans, new oceanic crust is constantly forming through volcanic processes, whilst, conversely, other parts of the Earth's crust are being consumed, moving back down into the mantle and re-melting, providing a continuous process of recycling of the oceanic and continental crustic surfaces. The sites of this activity have generated great interest within the scientific community, and for researchers at The Natural History Museum, these raised ridges, known as "spreading zones" (where land is moving apart and new crust is forming), have been of particular interest. Oceanic crust is lost at the margins of continents in "subduction zones", and both sites are characterised by much volcanic and other tectonic activity.



R. Hayman

The *Alvin* submarine.

Deep-sea research has only been made possible by the development of highly sophisticated, deep submarine technology in the United States in the 1960s and 1970s. The *Alvin* submarine (named after Alan Vine the geophysicist who, along with Matthews, discovered the magnetic strips in rocks along the mid-ocean ridges) was used to examine, for the first time, these unusual ridges at the centre of the ocean, deep under the surface of the water. The use of photography and sample retrieval techniques has permitted a better understanding of the activities at a far greater depth than was ever previously possible.

The *Alvin*, at a depth of three kilometres and in the total absence of light, was able to record large cracks in the volcanic architecture of the seafloor, close to one of the spreading centres in the Pacific Ocean. At these crack margins, the biggest surprise was the discovery of numerous unique animals. Scientists concluded from this that parts of the deep ocean are actually oases of life which have developed close to hydrothermal vents. These large vents, expelling high-temperature fluids, were discovered close to the spreading zones. Subsequent work shows that these contain dissolved metals and gases, released on contact with the cold sea. Being rich in metals, and at such extreme temperatures, it was almost inconceivable that life would be able to survive, given the toxicity of the material being emitted.The discovery of life around the "black smoker" chimney vents was therefore all the more remarkable.

Colonies of tubeworms, known as vestimentiferans, were found. Chitin-like material, with similar properties to a fingernail, forms a dwelling tube for the worm within. It was discovered that these animals could thrive in the warm water being emitted from the vent sites, where the high temperature vent fluid (more than 350 degrees Celsius) were mixing. In addition to the unusual tubeworms, in places scientists noticed large colonies of vent mussels, and a species of bivalve called *Calyptogena magnifica*, which are extremely large clams. Both were thriving in the warm, mineral-rich water, forming dense clusters around the hydrothermal vents. Despite having a low biodiversity, the vents were providing a huge bio-mass, much like that found in tropical rainforests, and generating an important energy supply, developed in the total absence of sunlight.


Woods Hole Oceanographic Institution

Tube worms on the ocean floor.

There are some interesting striated structures on the side of the vent chimneys. The vents are hollow in the centre, with concentric rings of minerals that have grown from the precipitating fluid. Some vent chimneys recovered by the *Alvin* are home to an unusual worm called *Alvinella*, which actually lives on the sides of the growing chimney. This animal has been recorded as the most thermophilic, or heat-tolerant, multicellular organism on the planet, able to live in temperatures above 80 degrees Celsius. It thrives in these conditions right on the edge of the vent chimney, tucked inside its tube.

All animal life forms at the surface of our planet owe the base of their food chain to plant life, whose primary production needs come from sunlight. Deep on the ocean floor, in the absence of any sunlight, there are huge quantities of bacteria growing at the vent sites, forming the basis of the food chain. Some vents have been named "Snow-blowers" because of the dense bacterial floc emanating from the vents. The most primitive organisms known to us are found here, which has led to speculation that vents may have been the site for the origin of life on Earth.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Alvinella worm in its dwelling tube.

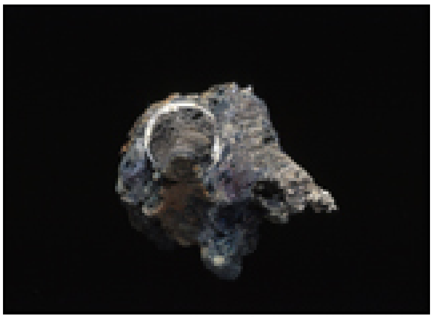
Close to the vents, bacteria are seen to coat all the rock surfaces. Here they live on dissolved hydrogen-sulphide gas in the warm fluid coming up through the seafloor in the hydrothermal vents themselves. As well as forming colonies, it was discovered that vestimentiferan tube-worms themselves contained cells full of bacteria, which are actually thriving inside the body. The worms have no feeding parts themselves and so rely completely on those bacteria to provide nutrients for life in a true symbiotic relationship. The bacteria use the hydrogen sulphide gas emitted from the vent, together with oxygen from the seawater, to produce energy, releasing and combining with carbon dioxide to produce the more complex organic molecules that the animal needs to live. Thus it needs close proximity to the hydrothermal vents, the producers of the hydrogen-sulphide gas.

Despite this gas being highly toxic, the vestimentiferan tube worm has developed clever methods of separating hydrogen sulphide and oxygen inside the body until they're combined in the bacterial cells to produce the energy needed. Similarly, it has been found that the gills of the vent mussel also contain symbiotic bacteria, and in this case, the vent fluid containing hydrogen sulphide is sucked over the gills, feeding the bacteria, which in turn produces complex organic molecules that the mussel can eat to survive. In contrast to the photosynthetic food chain, which operates at the surface, a process of chemosynthesis is occurring--that is, the metabolic synthesis of organic compounds by living organisms derived from reactions involving inorganic chemicals. Chemicals from the hydrothermal vents provide energy to the bacteria which give the tube worms life, and then follow more complex communities of vent animals over time.

The tube worms are sometimes very complex structures with intricately shaped tubes, depending on the environment concerned. The tube acts as a protection for the soft-bodied worm against the acid and very high temperatures that are sometimes reached. The temperature of the water determines the types of animals found: for example, the Alvinellids, also known as palm worms, tolerate very high temperatures, whereas the *Calyptogena* clam live in cooler parts of the vent site.

In addition to the unusual life forms supported, hydrothermal vents are the site of major deposition of metallic minerals containing sulphur (sulphides and sulphates). These form deposits often clearly zoned into areas rich in copper, iron and zinc as well as other metals such as lead, barium, silver and gold. This formation of minerals at vents on the modern seafloor has provided a valuable insight into how ancient ore deposits (found in ancient sea floor deposits that are now preserved in ancient mountain belts exposed at the Earth's surface) were originally formed. Animals living at vent sites can become completely engulfed as the mineral deposits built up, and their preserved remains are left embedded within the chimneys and associated mineral deposits. These can then be found as fossils in the ancient mineral deposits.

Ancient vent sites, their sulphide minerals and fossils vent communities have been studied by scientists at The Natural History Museum in order to test some of the hypotheses proposed for vent animal evolution and indeed some of the ideas concerning the origin of life itself.



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Vestimentiferan worm dwelling tubes now replaced and overgrown by sulphide minerals.

The Troödos mountains in Cyprus are the site of volcanic rocks formed on the sea floor in the Cretaceous period in the ancient Tethys Ocean. This ocean finally became enclosed towards the end of the Cretaceous period, and during this process, part of the sea floor was thrust up to form part of a belt of mountains running from the Alps through the Carpathians and Balkans, and out eastwards from Turkey. Hydrothermal venting in this ocean formed copper-bearing sulphide deposits first exploited by the Ancient Greeks. These deposits have yielded the casts of gastropods, dated to the Cretaceous period more than 65 million years ago, despite having no shell, have been located well-preserved in the sulphide ore.

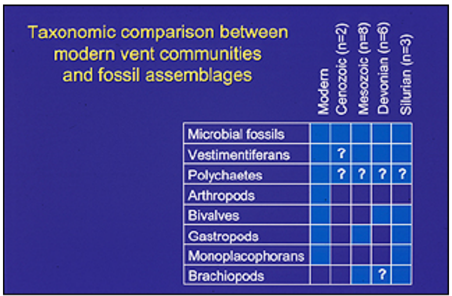
The Bayda copper deposit in Oman was also formed as part of the now-closed Tethys Ocean and contains very well-preserved tube worms within the sulphide minerals. Some specimens show the very distinctive rings of banded sulphide minerals, typical for the preserved worm tubes. Such structures are clearly organic, not mineralogical, and once the animal had died were in-filled with zinc sulphide, sphalerite and quartz. Features from both these deposits compare very closely in morphology with animals living close to modern vent sites, and hence easy identification has been possible.

A small deposit in the San Raphael mountains, on the west coast of California, has been dated to the Jurassic period, a further 50 million years back in geological time. The area is known as an accretionary complex, where rocks originally formed in the Pacific Ocean have been thrust over through tectonic activity. During the process of subduction, volcanic arcs developed, and the deposition is an example of where ocean crust that has been flaked off and pushed up over the North American continent in highly deformed fragments. In these fragments are oases of sulphide ore formed around ancient vent deposits which have been completely preserved over time. Fossils discovered include a rhynchonellid brachiopod completely replaced by sulphide minerals and in-filled with agate. Worm tubes were also discovered, some with flange features and others displaying thin tubes built inside thicker tubes. Unlike the brachiopods, these are often found near modern hydrothermal vent sites, revealing exactly the same structure as the contemporary vent communities, which enables direct comparisons to be made. Silica-rich rocks called cherts were discovered to house tiny micro-fossils, again perfectly preserved in the rocks. They provided the primary food source at the vent sites, and a necessary pre-requisite to the development of the vent community. Deposits of tube worms, brachiopods and now bacteria represent the entire food chain, preserved in one place.

Deposits of sulphide minerals of between 350 and 420 million years old, found in the Ural Mountains, have been highly preserved, not having been deformed or overprinted by metamorphism. The area is characterised by some of the largest open mines in Europe and large lenses of sulphide ore are excavated. In the giant Sibay deposit, tube worms have been discovered dating to around 370 million years old, revealing very characteristic mineralogical structures similar to tubes found elsewhere. A large bivalve has also been extracted, so well preserved in the sulphide minerals that fossilised evidence of wrinkled periostracal traces were found. This is an organic layer that grows around the animal to protect it, something rarely seen in ordinary fossils.

At more than 420 million years old, the oldest known vent assemblage of complex organisms is a deposit called Yaman Kasy, in the Southern Urals, Russia. The fossils were found right on the edge of a large sulphide body, where evidence of partial erosion of that body on the ancient sea floor has produced fragments of the hydrothermal vent chimneys themselves. Course fragments have passed up into finer fragments, with sediment layers consisting of sulphide and iron oxide. In these layers, large casts of a very large inarticulate brachiopod, related to the *Lingula* brachiopod, were also found, its size probably due to the abundant food supply at the vent site. Tube worms were seen lying in the detrital (waste debris) layer surrounding the large sulphide ore, in-filled with the rich minerals that engulfed the animals when they died. Thus a complete history of the vent site 400 million years ago could be determined from this one preserved location on the seafloor.

The work of scientists at The Natural History Museum has greatly assisted our understanding of evolutionary processes at vent sites over geological time. Some of the vent animals have changed, and new organisms have replaced the role of earlier species. However, others may have remained more or less the same: for example tube worms are evident at all the vent sites so far explored, but brachiopods, gastropods, bivalves, and microbes are to be found at different stages. The vent sites have provided evidence of how animals adapted to different environments, and indicate that communities were established very early on in geological time.



Taxonomic comparison between modern vent communities and fossil assemblages

	Modern	Cenozoic (n=2)	Mesozoic (n=8)	Devonian (n=6)	Silurian (n=3)
Microbial fossils	🟦	🟦	🟦	🟦	🟦
Vestimentiferans	🟦	?	🟦	🟦	🟦
Polychaetes	🟦	?	?	?	?
Arthropods	🟦				
Bivalves	🟦			🟦	🟦
Gastropods	🟦		🟦		🟦
Monoplacophorans	🟦				🟦
Brachiopods			🟦	?	🟦

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Variations in animal groups found at hydrothermal vents through geological time.

Microbes have been there since the beginning, with tubeworms developing very early on. Bivalves and gastropods came later, taking longer to adapt to the conditions of the sites. For example, at the Silurian vents, brachiopods appear to be more common than bivalves, possibly because brachiopods were the more common group and therefore more able to colonise the vents than bilvalves. Likewise, modern vent sites are dominated by bivalves and gastropods, which are far more prolific today than, say, 100 million years ago. Hydrothermal vent sites may provide refuges for very unusual organisms isolated from surface climate changes which may have led to extinctions of other organisms. Vents may conversely offer an environment where new species can adapt very rapidly, coming and going over geological time. Being so ephemeral in nature, vents turn on and off in less than a million years, and this may also explain the specific changes in the organisms seen in the fossil assemblages through geological time.

Studies of communities of multicellular organisms have gone back over 400 million years, nearly as far back as is possible. Before the Cambrian period--more than 500 million years ago--there are only micro-fossils in the geological record. However, scientists now have evidence of Cambrian bacteria from large sulphide deposits at Mount Windsor in Australia. There is chemical evidence of bacterial activity back in the rocks formed at vent sites which formed in Western Australia 3.5 billion years ago. With this comes the conclusion that as soon as oceans formed, hydrothermal vent activity started, and bacterial life thriving at vents seems to be a natural consequence. The discovery of thermophilic bacteria has lead to the suggestions that hydrothermal vents are candidates for the origin of life itself. These very early bacteria owe their life to the chemical energy seen at vent sites, thriving without sunlight and getting their energy from chemical reactions instead. Hydrothermal vents are not the only candidate for the origin of life, but most scientists now believe that life must have began as chemosynthetic life. Since the surface of the planet back in the Archean period (the earlier part of the Precambrian aeon, more than 3.5 billion years ago), was extremely hostile, ultra-violet light damage would almost certainly have destroyed many of the organisms. It follows that organisms must have developed either in the deep ocean or deep inside the Earth's surface. It is likely that these deep-living organisms were thermophilic, and therefore hydrothermal venting may have been important for their development.

Scientists are now considering how these theories and investigation methods could be employed in the search for life on other planets. If life did begin on Earth as soon as oceans appeared, with the right conditions (water and an energy source) in place, then why not on other planets? Recent work has shown that one of the moons of Jupiter--Europa--may have water on its surface. Evidence suggests that because of its close proximity to Jupiter, there must be body forces causing Europa's core to be molten. The surface of Europa is covered in ice, which, over time, has broken up and reformed into icebergs, but the core is considered to be molten. The liquid water and a magmatic core suggest the possibility of hydrothermal vents. NASA is planning to send a probe to Europa within the next 20 years, which will penetrate the ice layer in search of water and vent debris. Work carried out on Earth has suggested that if the basic ingredients for the origins of life are there, there is a chance of discovering vent-based life forms, and if so, they may resemble some of the fossil forms discovered here on Earth.

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(www.nhm.ac.uk/mineralogy/index.html)

Books:

Title: Ecology of Deep-Sea Hydrothermal Vents
Format: Hardcover
Author: Van Dover, Cindy
Date: 01-MAR-00
ISBN: 069105780X

Title: Deep Ocean
Format: Paperback
Author: Tony Rice
Date: 01-SEP-00
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Title: Deep-Sea Biology
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