now quite minor, since the number of events observed is not in much doubt. Only intervals with good observing conditions are counted; for example, the Innisfree meteorite event is not included in this analysis since only one camera station had good conditions. The uncertainties lie in the calibration of the masses. Effects due to the shape of the largest fragment could lead to errors as large as a factor of 3 or 4. Somewhat larger factors would apply when the density of a stone meteorite is assumed for an object that is actually an iron meteorite, but iron and stony-iron meteorites combined account for only 4.4 percent of meteorites from well-classified witnessed falls (*20*). The systematic errors in placing our mass scale should be less than a factor of 2 due to this problem. There could be another error in our use of the factor 2 to convert the mass of the main fragment to the total mass of the fall. By definition the correct factor must exceed 1 and is unlikely to exceed 4, so the mass scale should not be incorrectly positioned by more than a factor of 2 or 3 by the sum of these two effects. As far as we know, our result is the first to be based on instrumental observations of fireballs. The slope of our plot in Fig. 1 should be considerably more secure than that of earlier plots, and uncertainties in log N should not exceed 0.4 over the observed mass range.

Table 1 converts our data to the annual number of meteorite falls expected in specific areas on the earth. For values of log m between 2.0 and 6.0, the total mass deposited on the ground is 142 kg year^{-1} in 10^6 km^2. With a normal recovery rate of one or two dozen meteorites per year for the world, excluding the Antarctic recoveries, it is obvious that a very small portion of the potential harvest is ever located.

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Fossils of Hydrothermal Vent Worms from Cretaceous Sulfide Ores of the Samail Ophiolite, Oman

Abstract. *Fossil worm tubes of Cretaceous age preserved in the Bayda massive sulfide deposit of the Samail ophiolite, Oman, are apparently the first documented examples of fossils embedded in massive sulfide deposits from the geologic record. The geologic setting of the Bayda deposit and the distinctive mineralogic and textural features of the fossiliferous samples suggest that the Bayda sulfide deposit and fossil fauna are remnants of a Cretaceous sea-floor hydrothermal vent similar to modern hot springs on the East Pacific Rise and the Juan de Fuca Ridge.*

Deep-sea hot springs surrounded by metal-rich mineral deposits and communities of unusual organisms have been found recently at several hydrothermal vent fields distributed along the crests of volcanic spreading ridges throughout the eastern Pacific Ocean (*1–6*). These hot springs evidently are common features of medium- to fast-rate spreading centers, where heat from rising magma beneath the spreading axis drives hydrothermal convection of seawater through newly solidified oceanic crust. The circulating seawater is modified by heat and reaction with the basaltic host rock into an oxygen-depleted acidic solution enriched in transition metals and hydrogen sulfide (*7, 8*). When solutions of this composition vent onto the sea floor, a suite of sulfide minerals rich in iron, zinc, and copper is deposited locally (*2, 3, 9–12*). The reduced sulfur in the outflowing hydrothermal solutions is a source of chemical energy for chemolithotrophic bacteria, which apparently constitute the base of a food chain for dense faunal communities clustered around the vents (*13–16*). Although the faunal composition of these communities varies among different vent areas, most com-

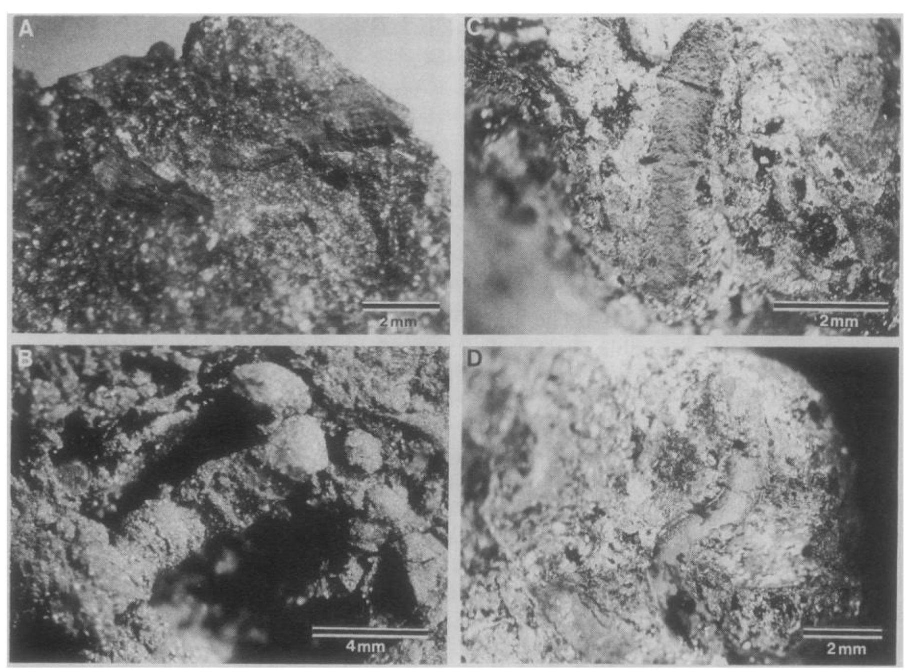

Fig. 1. Fossil worm tube molds and casts in massive zinc- and iron-sulfide from the Bayda mine. (A) Two pyritic tube casts exhibiting longitudinal ornamentation preserved in a sphalerite-quartz matrix. (B) Pyritic tube cast showing numerous closely spaced annulations preserved in a pyrite matrix. (C) Tube mold displaying two prominent annulations. (D) Sinuous tube mold showing two prominent annulations.

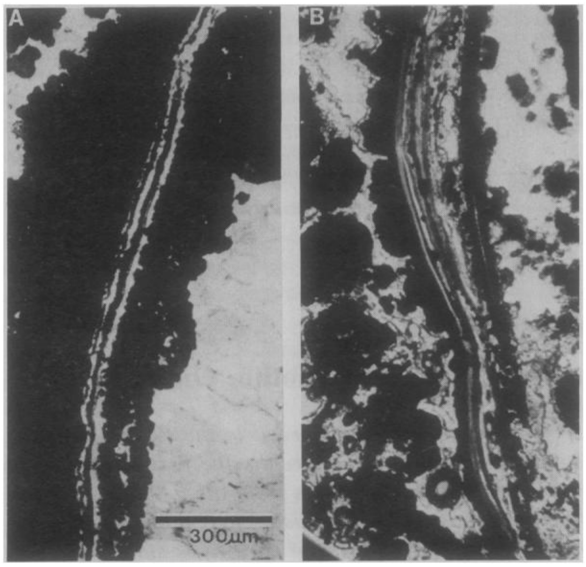

Fig. 2. (A) Pyrite-quartz layering in the walls of fossil worm tubes from the Bayda Mine. (B) Pyrite-amorphous silica layering in the walls of fossil worm tubes from a hydrothermal vent on the East Pacific Rise at latitude 21°N, similar in mineral content, structure, and scale to Bayda fossil worm tubes in (A).

munities include vesicomyid clams, vestimentiferan tube worms, some other types of worms, crabs, and several varieties of fish (*1–3*). Mussels, anemones, barnacles, limpets, siphonophores, and other animals are also present in certain vent areas.

Some species of vent worms thrive remarkably close to the escaping hydrothermal fluids, which may have temperatures as high as 350°C (*2, 8*). Sulfide minerals precipitating within the habitats of these worms envelop and preserve the worm tubes in a sulfide matrix. Many examples of worm tubes fossilized in this fashion have been recovered from deep-sea hot spring deposits (*2, 3, 9, 10*). We report here the presence of similar fossil worm tubes in massive sulfide deposits of early Late Cretaceous age. These worm tubes appear to be the first reported examples of fossils preserved in massive sulfide deposits from the geologic record. Pyritic tubelike features in the Carboniferous Ballynoe barite deposit of the Silvermines district in Ireland (*17*) are linear subparallel structures interpreted as abiogenic conduits for discharging hydrothermal fluids. The Ballynoe tubes do not resemble the Bayda tubes, which we interpret as biogenic in origin.

The geologic characteristics of ancient spreading centers are thought to be preserved in ophiolites, fragments of oceanic crust that have been thrust onto continental margins. The Samail ophiolite in the Sultanate of Oman is a particularly extensive and well-exposed remnant of oceanic crust created at a spreading center in the Tethyan Sea during early Late Cretaceous time, approximately 95 million years ago (*18, 19*). Massive sulfide bodies present in the volcanic section at the top of the Samail ophiolite (*20*) were deposited around hot springs on the Tethyan sea floor.

In January and February 1983, we investigated the massive sulfide deposits in the Samail ophiolite in order to compare these old deposits with sulfide deposits found on the modern sea floor around ridgecrest hot springs. Underground mining for copper ore in the Sohar district of northern Oman permitted ready access to two of the Samail deposits. One of these deposits, the Bayda ore body, apparently accumulated in a sea-floor graben on or near the Tethyan spreading axis. The massive sulfide body at Bayda is bounded on the east and west by broad jasper-impregnated fault zones that strike parallel to the old ridge axis and dip antithetically beneath the ore body. The upper zone of the Bayda deposit, like the modern sea-floor sulfide deposits, is rich in zinc. Some zinc-rich samples from the upper levels of Bayda contain tubular structures that are evidently the casts of Cretaceous hydrothermal vent worms.

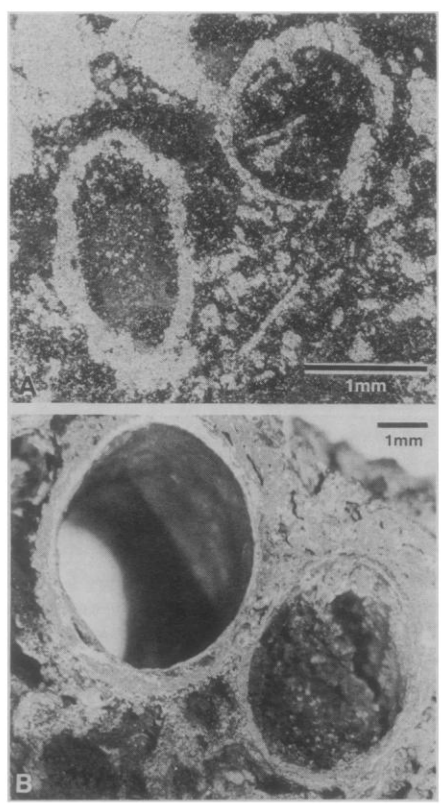

Fig. 3. (A) Cross sections of pyritic fossil worm tubes from Bayda mine preserved in a sphalerite-rich matrix. Scale bar, 1 mm. Polished sample surface. (B) Cross sections of pyritic fossil worm tubes from a hydrothermal vent on the Juan de Fuca Ridge preserved in a sphalerite-rich matrix. Scale bar, 1 mm. Unpolished sample surface. Note resemblance in mineral content, structure, and scale to Bayda fossil worm tubes in (A).

The Bayda fossil tubes are sinuous molds and casts (Fig. 1) preserved in a matrix composed of zinc- and iron-sulfide minerals (sphalerite and pyrite) and minor quartz. Individual tubes are 1 to 5 mm in diameter and are randomly oriented. Three types of tubes can be distinguished: tubes with longitudinal ornamentation (Fig. 1A), tubes with numerous closely spaced annulations (Fig. 1B), and tubes that are distinctly segmented by two prominent annulations (Fig. 1C). Cross sections of the Bayda fossil tubes reveal concentric mineral layering (Fig. 2A). The fossil tubes are often rimmed by a layer as much as 1 mm thick exhibiting interlaminations ≤ 0.5 mm thick of pyrite alternating with either quartz or void space. Analogy with modern samples suggests that the void space originally contained either chitinous tube walls or layers of amorphous silica. In some tubes a massive pyrite rim without interlaminations of quartz and void space rings the tubes. The central cores of tubes either are void or are infilled by sphalerite, quartz, or both. The typical sequence from the exterior to the interior of the tubes is thus pyrite → (void or quartz) → pyrite → sphalerite → quartz. The fossiliferous Bayda samples are associated with massive sulfide that has sulfide-cemented breccia textures and coarse pyrite-sphalerite banding that may represent cyclic precipitation of minerals along the margins of fluid channelways.

The fossil tubes from Bayda are similar to the worm tube structures in massive sulfide samples recovered by the submersible *Alvin* from the East Pacific Rise at latitude 21°N (*9, 10*). The hot springs at 21°N reach temperatures up to 350°C (*2, 8*) and precipitate both "black smoker" mineral chimneys and "white smoker" worm-encrusted chimneys. These chimneys typically rest on top of basal mounds composed of sulfide-cemented chimney debris (*2, 9*). Samples collected from white smokers and basal mounds contain abundant fossilized tubes of two worm species, the polychaete *Alvinella pompejana* Desbruyeres (*9, 21*) and the vestimentiferan *Riftia pachyptila* Jones (*22*). The chitinous tubes of these worms are 5 to 20 mm in diameter and are embedded in a matrix of zinc- and iron-sulfides. The interior surfaces of the tubes are coated with concentric layers of amorphous silica intercalated with fine laminae of pyrite and sphalerite (*9, 10*) (Fig. 2B). The tube centers are often partially or completely filled in with zinc- and iron-sulfides similar to the matrix material.

Like the Bayda fossil tubes, the tubes at 21°N are preserved in zinc- and iron-rich sulfides and exhibit concentric interior layers of silica and sulfide (Fig. 2, A and B). In basal mounds at 21°N, we find sulfide-cemented breccia containing fossiliferous fragments, massive sulfide clasts, and broken chimney pieces with sulfide banding. These textural features are also observed in the fossiliferous, zinc-rich massive sulfide samples from Bayda mine in Oman.

Fossiliferous sulfide materials recovered from hydrothermal vents on the southern Juan de Fuca Ridge in the northeast Pacific (*3, 23*) are almost identical in appearance to the Bayda worm tube samples (Fig. 3, A and B). Photographs of the sea floor taken with a deep-tow camera show that hydrothermal sulfide deposits in this area form blankets and low-relief mounds populated by a diverse biota including slender tube worms up to 0.5 m long (*3, 23*). These worms occur in dense clusters and as solitary, evenly spaced individuals. The worms are anchored in fissures and fractures in the sulfide blanket that serve as outlets for hydrothermal fluids. Banded sulfide fragments dredged from these vents contain abundant, closely spaced tubular molds of the tall thin tube worms (Fig. 3B). The tubes are 3 to 8 mm in diameter, penetrate to a depth of 4 cm into a sulfide substrate, and are oriented at random angles to the oxidized surface of the sample originally in contact with seawater.

Like the Bayda fossil tubes, these tubes have a cross section with a concentrically laminated construction. The outermost tube ring generally consists of colloform pyrite and marcasite with growth forms convex outward against the porous iron- and zinc-sulfide matrix of the host rock. This outer pyritic wall, which ranges in thickness from 0.1 to 1 mm, thickens where colloform masses protrude into cavities in the matrix. The outer pyrite layer invariably encloses a thin (30 to 40 μm) layer of amorphous silica that has a fibrous and weakly birefringent appearance in microscopic thin sections. Interior to the silica layer, within the central void, some tubes show only a scattering of pyrite and sphalerite crystals, whereas others are completely choked with layers of iron- and zinc-sulfide. Most commonly the inner sulfide layers form a complete ring of variable thickness consisting of colloform pyrite (and lesser sphalerite) with growth laminae oriented toward the tube interior. Within the inner sulfide ring, pyrite crystals and discontinuous wisps of silica are dispersed through the central void. Thus, the normal sequence through many tubes from exterior to interior is pyrite → silica → pyrite (+ sphalerite), a sequence markedly similar to that observed in the fossil tubes from the Bayda mine in the Samail ophiolite.

The presence of hydrothermal vent worm fossils in a sulfide deposit of early Late Cretaceous age is compelling evidence that vent communities similar to modern ones were well established along Tethyan spreading centers; however, we have not determined whether these fossil worms are ancestral forms that have evolved since the Cretaceous into the types of worms found at vents today. Morphological comparison of the Bayda fossils with modern vent worms will be required once more extant worm species are collected and described. A long evolutionary history for vent communities is suggested by the high degree of endemism characteristic of hydrothermal vent faunas, but this endemism may also result from a rapid rate of evolution (*24*). The possibility that endemic organisms found at modern vents have evolved recently and independently of any organisms that lived around ancient vents cannot be ruled out on the basis of current data. At least two endemic vent animals, the primitive stalked barnacle *Neolepas zevinae* Newman (*25*) and the limpet *Neomphalus fretterae* McLean (*26*), however, are interpreted as relict Mesozoic forms (the latter suggested to be a limpet derivative of the extinct Euomphalacea), which survived widespread Late Cretaceous extinctions by taking refuge in the deep-sea hydrothermal vent habitat. Newman (*25*) and McLean (*26*) suggest that *Neolepas* and *Neomphalus* joined Mesozoic hot spring communities on shallow, accessible portions of spreading centers (near intersections of ridgecrests with continents or around islands formed on ridgecrests) and eventually escaped severe predation pressures in neritic Cretaceous environments by migrating downward along spreading centers to deepwater hot springs.

On the basis of the Cretaceous Bayda fossil worm tubes described here and the presence of relict Mesozoic fauna in modern vent communities, we predicate that marine hydrothermal vent faunas were prolific along spreading centers of the Cretaceous Tethyan Sea. A careful search for fossils or other evidence of life in hydrothermal deposits of the Paleozoic and Precambrian eras is needed to investigate the history of the hydrothermal vent faunas through time beyond the Cretaceous worm tubes of the Samail ophiolite to the beginning of habitation of the hot springs on the ocean floor.

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