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FILAMENTOUS IRON–SILICA DEPOSITS FROM MODERN AND ANCIENT HYDROTHERMAL SITES

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ABSTRACT

Numerous samples of iron oxide/silica material from sites on the East Pacific Rise, Juan de Fuca/Explorer Ridges, and other areas are porous and consist of branching filaments of iron oxide and amorphous silica (opal A). A similar flamentous microtexture characterizes cherts associated with terrestrial sulfides of oceanic origin. Observation of zonation within these deposits and consideration of conditions necessary for the precipitation of iron oxide and opal A lead us to propose that filamentous structures existed on the seafloor prior to mineral deposition. The presence of organic matter and identifiable filamentous bacteria in one sample suggest that the iron and silica were deposited in association with filamentous microorganisms. These observations are discussed in light of recent reports of bacterial biocatalysis of mineral precipitation at submarine hydrothermal sites.

Keywords: hydrothermal, mineralogy, iron oxide, silica, filamentous bacteria, East Pacific Rise, Juan de Fuca–Explorer Ridges.

SOMMAIRE

De nombreux échantillons de dépôts de fer et de silice prélevés sur les sites hydrothermaux de la ride Est-Pacifique et de la ride de Juan de Fuca - Explorer, ainsi que ceux d'autres régions ont été étudiés. Ces dépôts sont poreux et formés de filaments plus ou moins ramifiés, constitués d'oxydes de fer et de silice amorphe (opale A). Nous avons observé cette même microtexture filamenteuse dans des cherts d'origine océanique associés aux sulfures terrestres. D'après nos observations, ces structures filamenteuses existaient antérieurement à la précipitation des oxydes de fer et de la silice. Dans le cas d'un échantillon de la ride d'Explorer, nous avons vérifié la présence de bactéries filamenteuses et de matière organique. Ces observations sont discutées en fonction des études récentes des accumulations minérales bactériennes sur des sites hydro-thermaux marins.

Mots-clés: activité hydrothermale, minéralogie, oxydes de fer, silice, bactéries filamenteuses, ride Est-Pacifique, rides Juan de Fuca - Explorer.

INTRODUCTION

Deposits of iron oxide mixed with amorphous silica, which form in association with low-temperature venting, are known from sites along the length of the East Pacific Rise (EPR) and Juan de Fuca/ Explorer Ridges, as well as on off-axis seamounts. In addition, iron–silica samples have been collected from the FAMOUS site on the Mid-Atlantic Ridge, and from an active hydrothermal mound in the Okinawa Trough (Uyeda 1987). Similar material is commonly associated with terrestrial massive sulfide deposits that have an oceanic origin. The form of these deposits ranges from cm-thick layers that accumulate on the surface of massive sulfides, to oxide muds and chimney structures deposited directly on basalt (Lonsdale *et al.* 1982, Tunnicliffe *et al.* 1986, Uyeda 1987). The most frequently observed seafloor deposits are of the latter type. The hydrothermal fluids that generate these deposits apparently transport little or no H_2S (Tunnicliffe *et al.* 1986, Hékinian & Fouquet 1985), which is the essential energy source for vent faunal/microbial symbioses. As a result, typical hydrothermal megafaunal organisms such as Vestimentifera, alvinellid polychaetes, and bivalves are not associated with iron–silica deposition. Although this type of venting is widespread, fluid properties and the processes of iron and silica precipitation have been little studied.

This study was initiated following discovery of a still-active iron–silica deposit at Philosopher Vent on Explorer Ridge in the northeast Pacific. There, hydrothermal fluid was discharging at 27°C from a chimney, 1.5 m high. The fluid was enriched in iron and silica over ambient seawater, but contained no H_2S (Tunnicliffe *et al.* 1986). The major constituents of the chimney were amorphous silica (opal A, 73 %), and iron oxide (7.0 %). Microscopic examination revealed the chimney to consist of hollow filaments, 1–2 μm in diameter, and these, together with the presence of organic carbon (1.3 %), led us to investigate the possibility that microorganisms played a role in mineral precipitation. We present here results of morphological and mineralogical investigations of samples from oceanic and terrestrial locations (Fig. 1), and offer an assessment of biological and non-biological mechanisms that could have formed these deposits.

GEOLOGICAL SETTING OF IRON–SILICA DEPOSITS

Locations of all sampling sites are illustrated in

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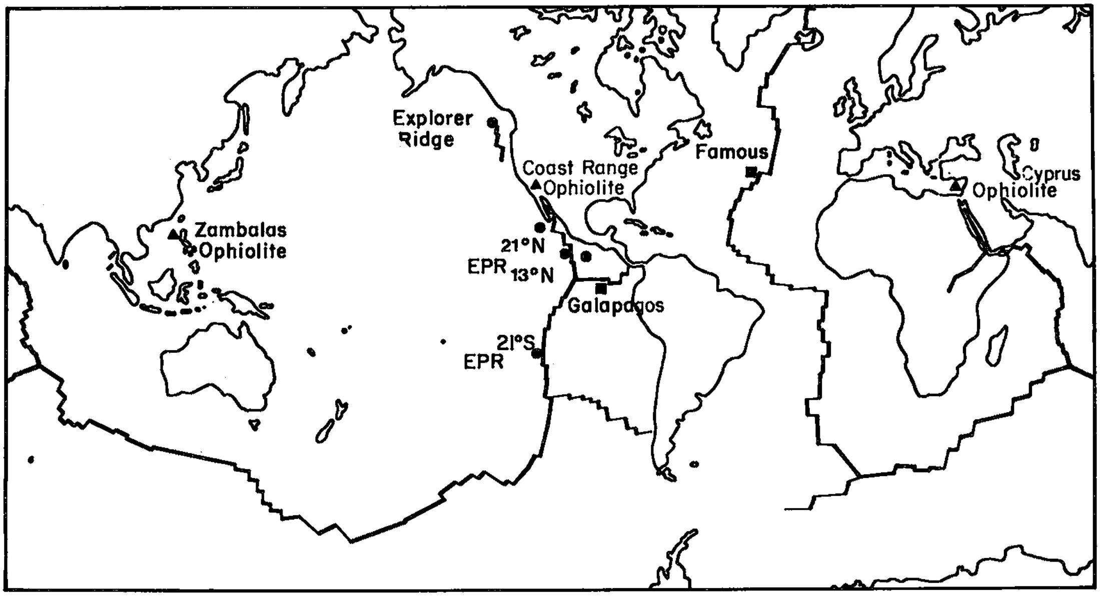

FIG. 1. Map showing locations of described samples at active or extinct hydrothermal sites. Dots denote hydrothermally active areas, squares are inactive seafloor sites, and triangles are terrestrial sites where ferruginous cherts are associated with oceanic basalt.

Figure 1. Oceanic samples were collected by submersible except for the Okinawa Trough and Galapagos samples, which were dredged.

Oceanic samples

1. *Philosopher Vent, Explorer Ridge, northeast Pacific*
An active chimney structure, 1.5 m high, was discovered in the eastern rift area of northern Explorer Ridge in 1984 (Tunnicliffe *et al.* 1986). Vent fluid together with dislodged material from the chimney opening were collected by the Pisces IV suction sampler. A subsample was fixed in 5 % formalin. A larger section of the chimney was collected with the manipulator and dried.

2. *12°50'N, EPR*
A small inactive mound of mixed sulfides and oxides was located near the top of the axial graben wall at 12°50'N on the EPR. A fragment of a small oxide chimney, well-cemented by silica, was recovered by the submersible Cyana. This sample is frequently referred to below, in illustration of mineralogical zonation within iron–silica deposits (Figs. 6, 7).

3. *Southeastern Seamount, 13°N, EPR*
A 350-m-high seamount, centered 6 km east of the EPR axis at 12° 42'N, was explored by submersible in 1982 (Hékinian & Fouquet 1985). Hydrothermal sulfides are abundant on the crest and flanks of this seamount, and the sulfides and lava flows are usually covered with Fe hydroxide material that is cemented in silica (Hékinian & Fouquet 1985). Several samples of this oxide were collected by the submersible CYANA.

4. *Red Volcano, 21°N, EPR*
Red Volcano, which lies 20 km west of the EPR near 21° N, is one of the Larson's Seamounts described by Lonsdale *et al.* (1982). Low-temperature hydrothermal venting is associated with iron oxide muds and chimney structures in the 200-m-deep caldera (Lonsdale *et al.* 1982). A 1985 ALVIN cruise to this site collected several tube cores from the soft oxide muds that cover radiating piles of pillow lavas on the caldera floor. Subsamples of these tube cores were fixed in formalin or glutaraldehyde.

5. *21°30'S, EPR*
Hydrothermal venting occurs in talus piles on the wall of the graben at 21°30'S on the EPR. Hot water mixes with seawater in the talus pile, producing a variety of hydrothermal deposits, including sulfide and oxide edifices (Renard *et al.* 1985). The sample examined is a fragment of an inactive oxide chimney that protruded from the talus pile.

6. *FAMOUS site, Mid-Atlantic Ridge*
This sample originates from an oxide mound, 20 × 20 × 1 m thick, found near the axis of Transform Fault "A" at 36°57'N on the Mid-Atlantic Ridge during the FAMOUS program (Hoffert *et al.* 1978). The sample was collected by the submersible CYANA.

7. *Okinawa Trough*
The Okinawa Trough is the back-arc basin of the Ryukyu arc (Fig. 1). Basalts dredged from this area were found to be covered with a cm-thick layer of filamentous iron and silica. Submersible exploration of this area has since revealed active hydrothermal venting in the form of mounds and small spires of iron oxide and silica (Uyeda 1987). We have examined only dredged material.

8. *Galapagos*

An oxide sample was dredged from the area of the Galapagos Ridge polymetallic sulfide deposits near 86°50′ W. No further information is available on the dredged site. The geological setting of the Galapagos sulfide deposits is described by Malahoff (1985).

Terrestrial samples

1. *Troodoos Ophiolite, Cypress*

Inter-pillow cherts were sampled from the Cyprus Troodoos ophiolite. An oceanic origin for these cherts is clear, and an abundance of idiomorphic pyrite replaced by iron oxide suggests a reducing episode related to hydrothermal venting.

2. *Barlo deposit, Phillipines*

This is a sample of pyritic cherts closely associated with the Barlo massive sulfide deposits of the Zambalas ophiolite complex in the Phillipines. A hydrothermal origin for these cherts is clear.

3. *Coast Range ophiolite, California*

Interpillow brecciated chert was sampled from the Coast Range ophiolite in California. Although these cherts are associated with oceanic basalt, brecciation obscures any possible evidence of a hydrothermal origin.

METHODS

A formalin-preserved sample of Philosopher Vent chimney and three glutaraldehyde-preserved samples from Red Volcano were examined by epifluorescence microscopy using acridine orange as a vital stain to detect the presence of microoganisms (Hobbie *et al.* 1977). All other samples were dried geological specimens in which microtexture was examined in polished or thin sections, or by scanning electron microscopy in the case of highly friable material. SEM samples were critical-point dried and coated with gold before examination. Mineralogy of selected samples was determined by X-ray diffraction, and mineralogical zonation was studied in polished and thin sections with polarized light or using the electron microprobe of IFREMER, Centre de Brest. The microprobe was also used to analyze the elemental content of individual filaments, and material that fills interfilament spaces in the more solidified samples.

RESULTS

Macroscopic appearance of samples

The oceanic samples range from unconsolidated oxide sediment to silicified chimney fragments showing considerable layering and mineralogical zonation. Terrestrial samples are ferruginous cherts that range from dark red to black. Basalt fragments, cemented by silica, are common in the Barlo and Coast Range samples.

Sample microtexture

All samples have a filamentous microtexture (Fig. 2A). Electron-microprobe analyses reveal the outer surfaces of the filaments to be composed primarily of silica, which also cements filaments (Fig. 2A). Some filaments are coated in many concentric layers of silica (Fig. 2B). Filament morphology is quite variable, both within and between samples, ranging from short simply-branching filaments to complex filament networks (Figs. 3, 4). A few filaments are hollow.

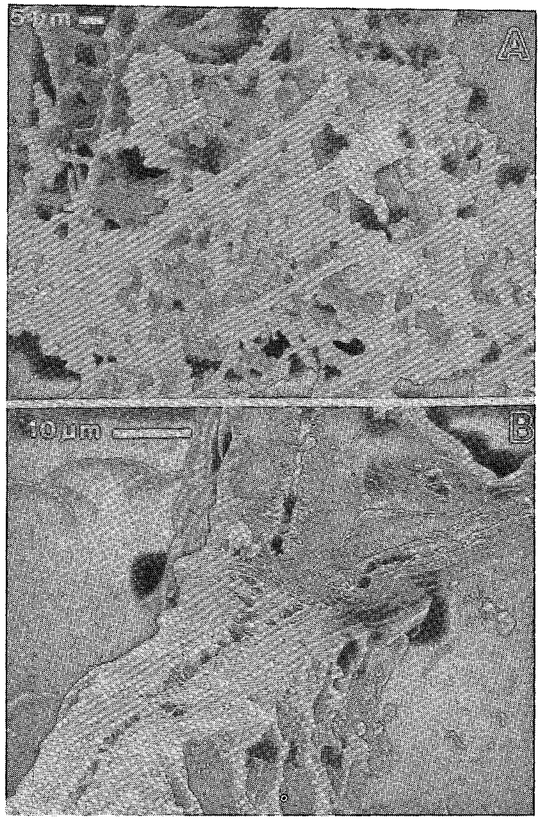

FIG. 2. (A) Low-magnification SEM photograph showing filamentous microtexture of iron–silica deposits (21° 30′ S, EPR). (B) Section of a filament heavily coated in silica. The hollow internal space likely represents the original filament that was covered in concentric layers of deposited silica (21° 30′S, EPR).

Presence of microorganisms

No positively-stained filaments were found in acridine orange – epifluorescence preparations from the Red Volcano sample. Confirmed filamentous microorganisms are present in the Philospher Vent sample, but only a small proportion of the total number of filaments stained positively with acridine orange (Fig. 5). Less than half of 20 examined microscope fields contain recognizable bacteria, whereas

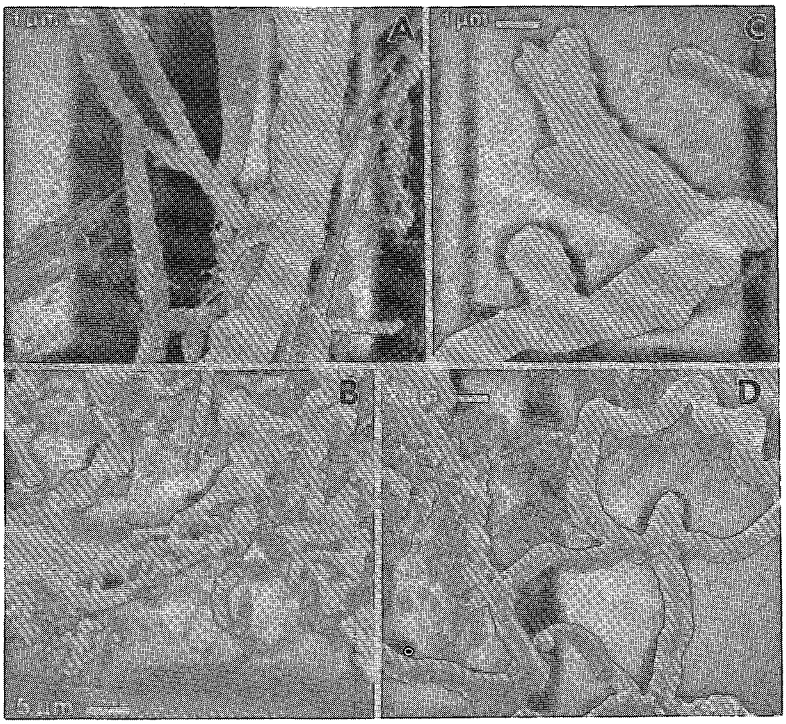

FIG. 3. SEM photographs illustrating variation in filament morphology among the oceanic samples. (A) Long, branching filaments (Philosopher Vent, Explorer Ridge). (B) Short, multibranching filaments. Upper filament in photo is hollow (Red Volcano, near 21° N, EPR). (C) Clustered, branching filaments (FAMOUS area, Mid-Atlantic Ridge). (D) Hyphae-like filament network (Philosopher Vent, Explorer Ridge).

non-staining filaments are abundant throughout the microscopic preparations. Positively-stained filaments and non-staining filaments are similar in diameter and length (Fig. 5).

Sample zonation

Comparison within and among samples reveals a consistent relationship between filament morphology and the mineralogy of material surrounding the filaments. Some samples are very homogenous, showing only a single form of filament–mineral association, whereas others contain several recognizable zones. We distinguish four such associations:

(1) *Zone 1*. Filament branching is frequent and complex. Filaments consist dominantly of iron oxide, with some silica, and have an external diameter of 10 µm (Fig. 6A).

(2) *Zone 2*. Filaments consist of iron oxide embedded in a matrix of silica (Figs. 6B,D,E). Filament branching is less common and iron is less abundant than in Zone 1.

(3) *Zone 3*. Filaments are more elongate (1–2 µm in diameter) and branching is rare. Crystals of barite and pyrite are ubiquitous; wurtzite and marcasite are also present. Pyrite occurs only on the surface of iron oxide filaments. The sulfides, barite, and iron oxides are surrounded by later silica (Fig. 6C).

(4) *Zone 4*. Filaments are short, with simple branching; they consist of finely divided iron oxides coated in silica. Sulfide crystals are abundant and large (>50 µm diam.), and are not directly associated with the filaments. Zone 4 is common in samples from the ophiolite deposits (Figs. 4C,D), but is developed only locally in the oceanic samples (Fig. 6D).

Results of electron-microprobe analyses of individual filaments and interfilament material are presented in Table 1. The data illustrate the iron-rich nature of filaments from Zone 1 (Table 1A). The short filaments from Zone 4 in the ophiolite samples, such as the Barlo deposit, are also very rich in iron (Table 1A). Although filaments in the latter samples are cemented by silica, individual filaments

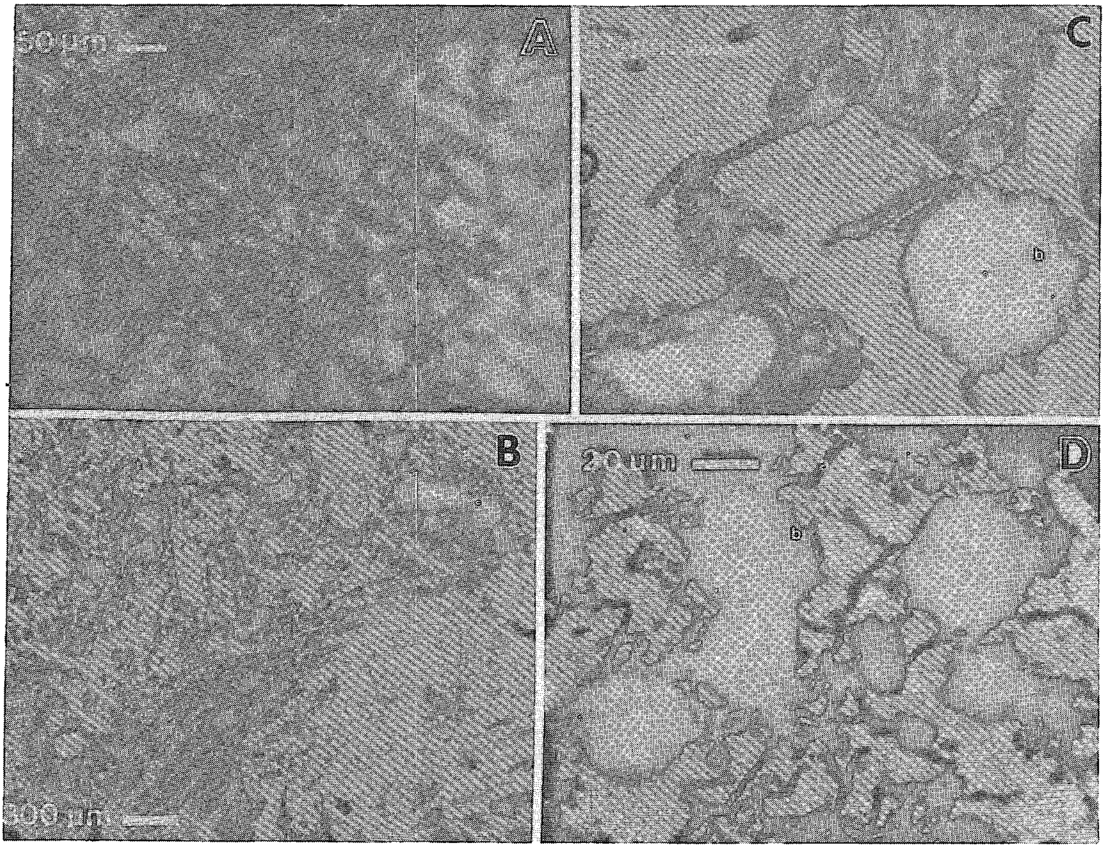

FIG. 4. Terrestrial ferruginous cherts associated with oceanic basalt. (A, B) Filaments in interpillow chert from the Cyprus Troodoos ophiolite. Polished section, reflected light. (C, D) Short, simply branching filaments (a) are common in cherts associated with the Barlo sulfide deposits in the Zambalas ophiolite complex, Philippines (photo C) and in interpillow chert from the Coast Range ophiolite in California (photo D). Filaments are frequently aggregated into iron-rich spherules (b in photo D) that are cemented in silica. Thin sections, transmitted light.

do not seem to have acted as a substratum for silica deposition (Figs. 4C,D, 8). Section B of Table 1 gives examples of filaments from Zones 2–3, where the silica content is equal to or greater than that of iron. The material cementing the filaments consists almost entirely of silica (Table 1C). Other elements checked in the microprobe analyses were Na, K, Mg, Mn, Al, Ca, Cr, and Ti, but only Fe and Si were detected. Obvious sulfide and sulfate mineral crystals were not analyzed.

Zonation is most commonly observed in the compact oceanic chimney fragments, where a progressive transition from zones 1 to 3 is often discernible over distances of 20 mm or less (Figs. 6A, 7). This may reflect oxidation of iron sulfides after deposition, with the degree of oxidation depending upon the duration of exposure to seawater. However, oxidation does not explain the transition from iron-rich to silica-rich zones; also, oxidation is applicable only to iron–silica deposits located on top of earlier sulfides, and not to those directly on basalt.

DISCUSSION

The most unusual aspect of these deposits is their filamentous morphology, for which there is no apparent mineralogical explanation. Lebedev (1967) described the formation of tubular and spherical structures of amorphous silica during the crystallization of silicious gels. However, the solutions that precipitated the gels were dense and viscous, with a much greater silica concentration than modern hydrothermal fluids, and contained only silica. In the present study the disposition of silica is directly linked to the morphology of iron oxide filaments upon which the silica precipitates. Thus, although

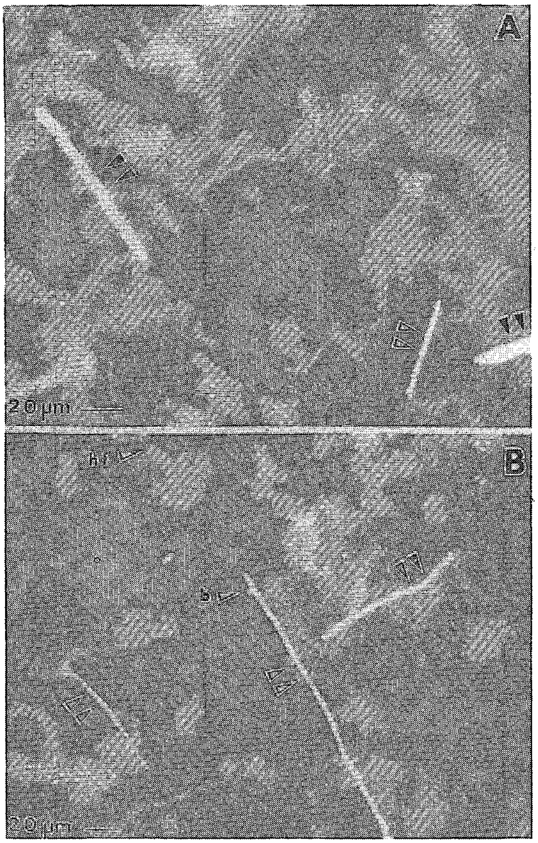

FIG. 5. Photos of acridine-orange/epifluorescence preparations of formalin-fixed samples from Philosopher Vent, Explorer Ridge. Positively stained filaments, which fluoresce green, are marked with double arrows. All other filaments are illuminated by reflected light only. In photo B, elementary branching or budding (b) is evident on one of the fluorescing filaments. Hollow, non-stained filaments (hf) are also visible in photo B.

there is some structural resemblance between these filaments and those described by Lebedev, the origins do not seem to be attributable to the same process. Similarly, although sulfide or basalt surfaces could provide solid support for dendritic growth, this process is unlikely to have led to vertical growth of filamentous mounds or chimney structures in a liquid medium. The resemblance of these filaments to those produced by microorganisms, together with the presence of filamentous bacteria in the Philospher Vent sample, raise the possibility that they represent microbial filaments that were mineralized by iron oxide and silica. Such filaments could have provided substrata for nucleation and accumulation of minerals, as was proposed by Jonasson & Walker (1987) in their study of base metal sulfides in hydrothermal deposits.

Filamentous bacteria are very abundant around hydrothermal vents. A filamentous morphology is common in taxonomic groups of sulfur and metal-oxidizing bacteria, which are the basis of the food web in this environment. Branching filaments, such as those observed here, are not included in the inventory of filamentous bacteria from the Galapagos vents (Jannasch & Wirsen 1981). Baross & Deming (1985) reported branching microbial filaments associated with iron and silica precipitations on the outer wall of a black-smoker chimney that are very similar to the filaments reported here. We also have observed this type of filament embedded in opal that replaced anhydrite at the outer edge of a black smoker. Branching filaments are known from several prokaryote groups, notably among iron- and manganese-depositing bacteria (Ghiorse 1984, Zavarzin 1981) and among the actinomycetes, which have been little studied in the marine environment (Weyland 1981).

Iron and manganese bacteria are ubiquitous in the biosphere, and often are assumed to be involved in the formation of ferromanganese films, crusts, concretions, and particles in soils, sediments, and fluid environments. These two groups of organisms are often discussed collectively because of their similar morphology and the fact that some forms accumulate both Fe and Mn. Fe and Mn are deposited both specifically and non-specifically on the surface of bacterial cells. Although a few cases of enzymatic metal precipitation have been demonstrated, Ghiorse (1984) pointed out that biological responsibility for Fe and Mn deposition is difficult to study and is more often taken as self-evident than clearly proven. In the field, natural populations are rarely abundant enough to allow microbial-mediated Fe or Mn precipitation to be distinguished from purely physicochemical mechanisms, and many commonly observed Fe- and Mn-depositing bacteria are difficult or impossible to cultivate in the laboratory. Another obstacle to clarification of this problem is the rarity of situations where microbial deposits are large enough to attract the attention of both microbiologists and geochemists. An integrated approach involving these two disciplines is essential to advancing our understanding of microbial Fe and Mn deposition.

Although the study of submarine hydrothermal phenomena is a relatively recent area of research, there are already indications that this is an environment where iron bacteria can be very abundant and occur in association with significant iron deposits. Iron oxide muds are known from several shallow-water hydrothermal areas within the ancient caldera of the island of Santorini, notably near the small volcanic islands of Palea Kameni and Nea Kameni (Bos-

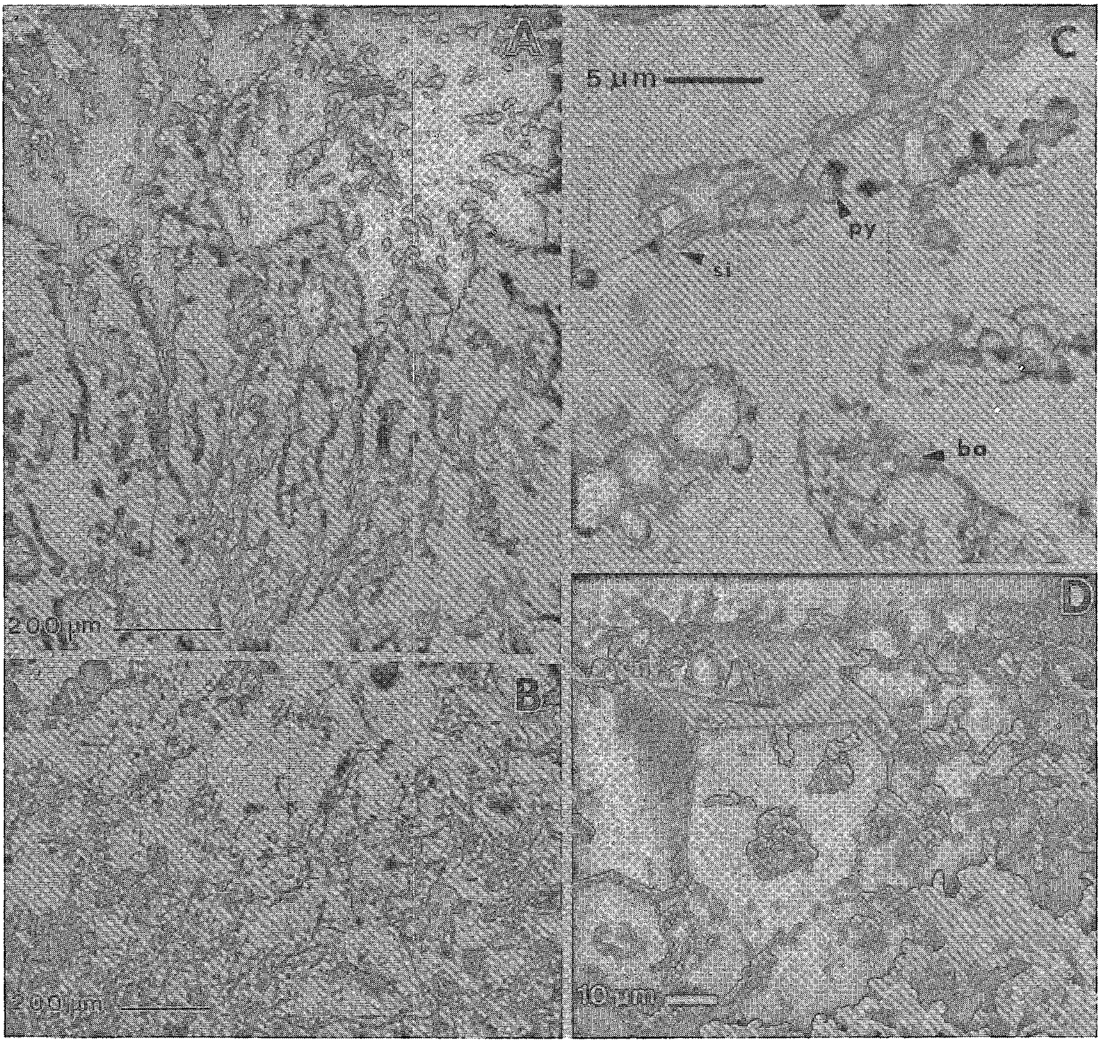

FIG. 6. Distinguishable filament–mineral associations in iron–silica deposits. Photos A–C are thin sections (transmitted light). All examples are from the same chimney fragment from 12° 50′N, EPR. (A) Transition from zone 1 (iron-rich) to zone 2 (silica-rich) over a distance of 2 mm. At the top of the photo, in an iron-rich zone (iron is dark), filament branching is extensive and iron accumulation is intense. Lower in the section, branching and iron accumulation decrease, and mineralization by opal becomes more important. (B) Transition from zone 2 (top of photo) to zone 3 (bottom) is marked by the appearance of sulfide. Dark particles in lower half of photo are pyrite crystals. Filaments are narrower, contain less iron (dark lines) and are coated in silica. (C) Higher magnification of zone 3 illustrating formation of pyrite crystals (py) on filament surfaces before coating by silica (si). A large crystal of barite (ba) is also present. (D) Scanning electron micrograph of zone 4, where short, simply branching filaments are associated with larger crystals of pyrite and, in this photo, hexagonal crystals of wurtzite. Only a small amount of silica deposition has occurred in this sample.

tröm & Widenfalk 1984). Hanert (1973) found stalks showing the morphological characteristics of the iron bacteria *Galionella ferruginea* to be very abundant in sediments from "Iron Bay" on NE Palea Kameni. These stalks occurred in such masses that Hanert concluded that *G. ferruginea* played an important role in iron sedimentation. Recently, three observations of iron oxide accumulation by filamentous bacteria have been reported from deep-sea hydrothermal environments. Tunnicliffe & Fontaine (1987) described extra-cellular accumulation of iron hydroxide by sheathed bacteria that colonize the surface of

TABLE 1. MICROPROBE COMPOSITIONS OF FILAMENT AND INTERFILAMENT MATERIAL

Sample	Fe(wt.%)	Si(wt.%)	Fe/Si	SD(n=5)
		A. Iron-Rich Filaments		
21°30'S, EPR	46	4	11.5	4.7
12°50'N, EPR	40	17	2.35	0.03
Philos. Vent	32	18	1.83	0.10
Red Volc.	50	6	8.33	2.00
Barlo	48	.01	480	----
		B. Iron-Silica Filaments		
12°50'N, EPR	26	26.2	1.0	0.24
12°50'N, EPR	21	30	0.7	0.20
Philos. Vent	14	29	0.48	0.12
Philos. Vent	27	20	1.35	0.30
		C. Interfilament Material		
21°30'S, EPR	3.5	33.5	0.104	0.06
12°50'N, EPR	0.25	44	0.006	0.002
12°50'N, EPR	4	41	0.097	0.09
Barlo	3	44	0.068	0.014

Both Fe and Si occur as oxides. Data for iron-rich filaments and non-silica filaments are analyses centered on filament axes. Analyses for interfilament material are for cementing material between filaments, exclusive of any obvious mineral crystals. All analyses represent volumes of 1 μm^{-3} in samples.

vestimentiferan tubes. They proposed that such accumulations lead to spontaneous abiotic precipitation of iron and the formation of iron oxide spires around empty worm tubes. Alt (1986) extensively studied the iron oxide muds from Red Volcano near 21° N, EPR, and concluded that the muds essentially consist of bacterial filaments coated with Fe oxides. Numerous filament morphologies are described, including branching filaments. Although little microbiological evidence is given, Alt suggested names of several genera for the different filament types, and proposed that the bacteria actively oxidize hydrothermal ferrous iron as an energy source.

Extensive bacterial mats occur at an active hydrothermal site on Loihi Seamount (Karl & Brittain 1988). Warm (up to 30°C), sulfide-depleted vent fluids diffuse up through the bacterial mats, apparently resulting in the accumulation of iron oxide precipitate around the bacterial filaments (Karl & Brittain 1988). Karl & Brittain (1988) hypothesized that ferrous iron may be used as an energy source by the bacteria.

The presence of organic carbon and identifiable bacterial filaments in the sample from Philosopher Vent confirms that microbial growth does occur within the chimney structure. The similarity in size between filaments that did stain with acridine orange and those that did not stain suggests that all filaments in the sample have a microbial origin. However, the scarcity of living bacteria in the Philosopher Vent material precludes observation of the initial stages of iron and silica accumulation on bacterial filaments, such as in the study of Tunnicliffe & Fontaine (1987). Thus, even for this sample it is not possible to conclude that microbial growth precedes and enhances iron and silica deposition. We have not yet had the opportunity to examine live material or preserved samples from sites other than Philospher Vent and Red Volcano.

Biological structures and debris can influence both mineral and trace-element accumulation at hydrothermal vents by forming physicochemical microenvironments (Juniper 1988, Juniper *et al.* 1986, 1988). If filamentous structures were located on sulfide mounds and basalt surfaces, they would

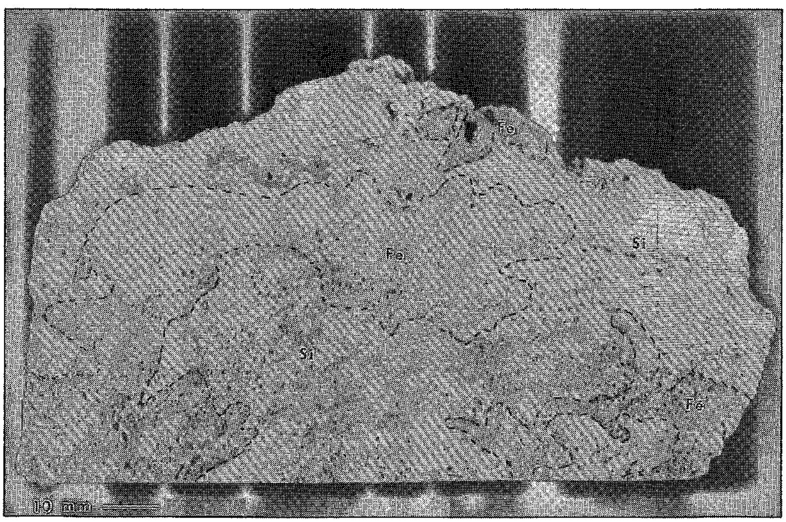

FIG. 7. Distribution of filament–mineralogical zones in a chimney fragment from 12° 50′N, EPR. Iron-rich areas (Fe), corresponding to zones 1–2, are outlined with dashed lines. Silica-rich zones (Si) correspond to zones 2–3. Note the porous nature of even this intensively-cemented sample.

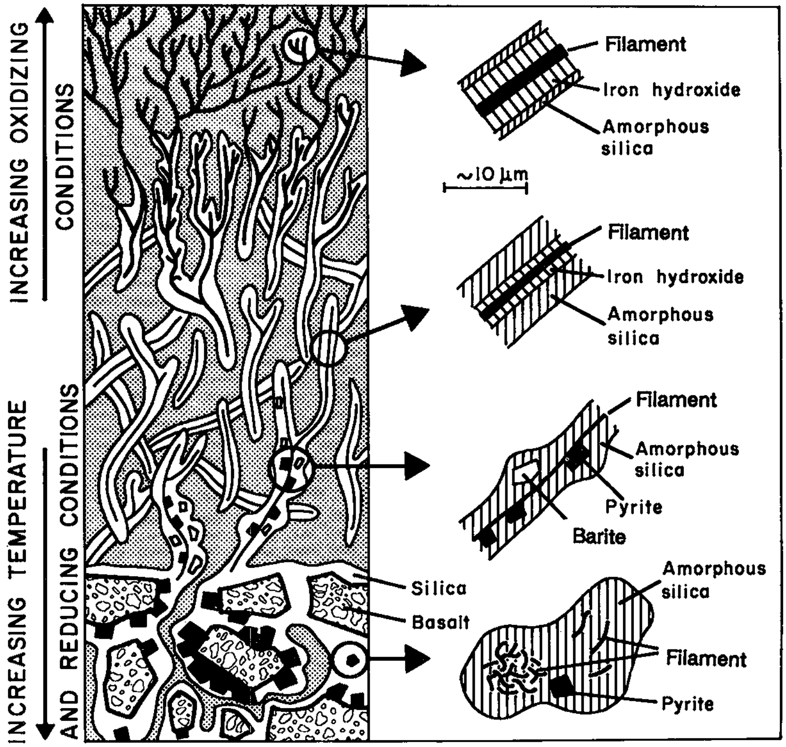

FIG. 8. Illustration of how observed mineralogical zonation in samples may be produced by physicochemical gradients within a filamentous microbial structure that also provides a scaffolding for iron–silica precipitation. This simplified conception is based on observations of microtexture and zonation in all samples. The depicted filamentous structure (left of Fig. 8) would be several tens of mm in thickness. If such a structure overgrew areas of diffuse venting, hydrothermal fluid would flow upward through it (from the bottom to the top of the Figure) before mixing with overlying seawater. The upper part of the structure (upper part of Figure), nearest the seawater interface, would be more oxidizing and favor extensive iron precipitation on the abundant filaments. Lower in the structure, conditions would be more reducing and vent fluid less diluted by overlying seawater, resulting in opal formation overtaking iron oxidation as the dominant depositional process.

act as an interface between seawater and hydrothermal fluids transporting iron and silica (Fig. 8). Passage of hydrothermal fluid through a filamentous mat would favor localized oxidation and trapping of iron by retarding dispersion into seawater. The filaments would also provide substrata for mineral precipitation. Ghiorse (1984) described how iron can associate non-specifically with acidic extracellular polymers (bacterial slime) such that, once iron oxides have been formed by microbial biocatalysis, further binding and oxidation of iron can occur autocatalytically. Aggregations or mats of filaments could also have produced mm-scale redox gradients, causing iron oxides and iron sulfides to precipitate in distinct zones (Fig. 8). Similar-scale physicochemical gradients have been described within mats of the filamentous sulfur bacteria *Beggiattoa*, which thrives at the interface between reducing, H_2S-rich sediments and oxygen-bearing seawater (Moller *et al.* 1985, Nelson *et al.* 1986). Jonasson & Walker (1987) proposed that microbial filaments facilitate metal sulfide deposition by locally altering redox conditions and by providing surface sites for metal adsorption. They suggested that direct precipitations from hydrothermal fluids on microbial scaffolding can lead to development of constructional deposits of sulfides, oxides and silicates. Iron deposition within a microbial structure could thus explain both the filamentous nature of these deposits and the observed mineralogical zonation.

Iron oxide filaments clearly served as a scaffolding for silica precipitation. Restricted mixing within the filamentous structures may also have been important to this process. Inorganic precipitation of opal A is rare, probably because initially high-temperature solutions which are rich in silica are diluted upon mixing with seawater. Although cooling occurs, the dilution prevents silica saturation (Haymon & Kastner 1981). To precipitate significant amounts of silica, with minimal mixing, conductive cooling is necessary. A porous, filamentous structure, partly filled by iron oxides, could limit mixing and allow enough conductive cooling to permit silica saturation and precipitation of opal A. Less mixing in the internal part of the structure could account for increased silica precipitation, as well as the observed increase in the proportion of sulfide phases (Fig. 8). A similar process likely operates during silica replacement in sulfides (Tivey & McDuff 1987, Jonasson & Walker 1987).

Filamentous iron–silica deposits are a common feature of present-day and ancient hydrothermal sites. The similarity in geological setting, mineralogy, and filamentous microtexture of the ancient cherts and the modern, more porous seafloor deposits suggests a similar process of formation. Microbial iron accumulations occur in many different hydrothermal environments, and several examples of quantitatively significant effects have recently been proposed. Aggregations of microbial filaments could provide both a scaffolding for mineral precipitation, and create a local microenvironment that favors precipitation of metals and silica. Morphological comparisons and the finding of organic carbon and intact bacterial filaments within one sample suggest that at least some of the iron–silica deposits described here form in association with filamentous microorganisms. Further studies of the initial stages of deposit formation and microbial growth are needed to verify the significance of biocatalysis in the precipitation of iron and silica.

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