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Siliceous sublacustrine spring deposits around hydrothermal vents in Lake Taupo, New Zealand

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Abstract: Chimneys around hydrothermal vents at a depth of *c*. 140 m in the Horomatangi Reefs area in Lake Taupo, New Zealand, are composed of amorphous silica (opal-A) with lesser amounts of Mn-, Fe-, and Hg-rich precipitates. Detrital quartz and feldspar grains are found in the surrounding sediments. The associated biota includes fish, bacteria, sponges, crayfish, amphipods, copepods, ostracodes, annelids, and other unidentified organisms. Much of this biota, however, is not preserved in the opal-A deposits. Instead, the silicified biota includes filamentous microbes and diatoms, scattered coccoid microbes, fungal hyphae and spores, rare sponge spicules, and rare worm(?) tubes. The diatoms, coccoid microbes, and fungi were brought into the area with the detrital sediment. In ancient successions, distinction between sublacustrine, terrestrial, and some marine hot spring deposits may be difficult because the precipitates share many similarities. Distinction based on the biota is viable only if palaeoecological information can be inferred from accurately identified organisms. Unfortunately, silicification commonly disguises microbes and precludes their accurate identification. Diagenetic transformation of opal-A to its more stable polymorphs also destroys many original depositional fabrics and silicified microbes. Distinction between the different types of spring deposit may therefore depend on the interpretation of their overall sedimentological and stratigraphic setting.

Amorphous silica (opal-A) is commonly precipitated from hydrothermal waters that ascend to the Earth's surface through vents that are located on land (e.g. Walter 1976), on the floors of lakes (e.g. Remsen *et al*. 1990), and on the sea floor in marginal marine (e.g. Canet *et al*. 2005) and deep water (e.g. Stüben *et al*. 1994; Halbach *et al*. 2002) settings. Siliceous sinter and silicified microbes are well known from modern terrestrial springs and geysers found in Yellowstone National Park (e.g. Walter 1976; Guidry & Chafetz 2003), the Taupo Volcanic Zone (e.g. Jones *et al*. 1997*a*, 2000, 2002; Mountain *et al*. 2003), and the Kenya Rift Valley (e.g. Renaut & Owen 1988; Renaut *et al*. 1998). In comparison, the siliceous sediments that develop around modern sublacustrine spring vents, such as those in Crater Lake (Dymond *et al*. 1989), Yellowstone National Park (e.g. Cuhel *et al*. 2001; Maki *et al*. 2001; Remsen *et al*. 2001; Morgan *et al*. 2003; Shanks *et al*. 2005), Lake Baikal (e.g. Crane *et al*. 1991; Shanks & Callendar 1992), and Lake Taupo (de Ronde *et al*. 2002) are less well-known.

The distinguishing traits of modern terrestrial and sublacustrine spring systems provide the basis for ascribing a hot-spring origin for the Devonian Rhynie and Windyfield cherts of Scotland (e.g. Trewin & Rice 1992, 2004; Fayers & Trewin 2004), the Devonian deposits of the Drummond Basin in Australia (Walter *et al*. 1996, 1998), and many ancient epithermal Au–Ag mineral deposits (e.g. Schalamuk *et al*. 1997). Although sublacustrine hydrothermal systems have been implicated in the genesis of some Mesozoic and Tertiary sequences (e.g. Stollhofen *et al*. 1998; Khadkikar *et al*. 1999), the criteria by which sublacustrine spring deposits can be distinguished from terrestrial spring deposits remain poorly defined.

This study describes amorphous silica deposits found around modern Horomatangi hydrothermal vents at a depth of *c*. 140 m in the eastern part of Lake Taupo, North Island, New Zealand (Fig. 1). This research focuses on the opal-A and its diagenesis, and the silicified biota found in those deposits. The Lake Taupo deposits are then compared with those of other modern sublacustrine vents to determine universal as opposed to local features. These features are then used to compare the sublacustrine deposits with terrestrial spring deposits from geothermal areas of New Zealand (Fig. 1b) and elsewhere. These approaches allow characterization of the sublacustrine deposits and highlight those features that might be useful in distinguishing subaerial from sublacustrine silica deposits in the geological record.

Geological setting

Lake Taupo, located in the central part of the North Island, New Zealand (Fig. 1), occupies a caldera that resulted from *c*. 28 separate eruptions over the last 330 ka (Wilson *et al*. 1984; Wilson 1993). This large (*c*. 620 km^2), deep (187 m), freshwater lake is oligotrophic and warm monomictic, stratifying to a depth of *c*. 35 m during summer (White *et al*. 1980; Vincent 1983).

Two areas with hydrothermal vents, Te Hoata and Te Pupu, are located in the Horomatangi Reefs area in the central east part of Lake Taupo (Fig. 1c). The lake floor around these vent clusters is covered with unconsolidated pumice that is overlain by 5 cm of mud that is, in turn, overlain by a *c*. 1 cm layer of organic flocculent material (de Ronde *et al*. 2002). Mineralized chimneys, composed of opal-A with minor amounts of Mn, Zn, As, Hg, Sb, and S (de Ronde *et al*. 2002, figs 4 and 5), are locally present in this area. Although diffuse venting of gas and water at a temperature of up to 45 °C was seen during the Jago dives, no

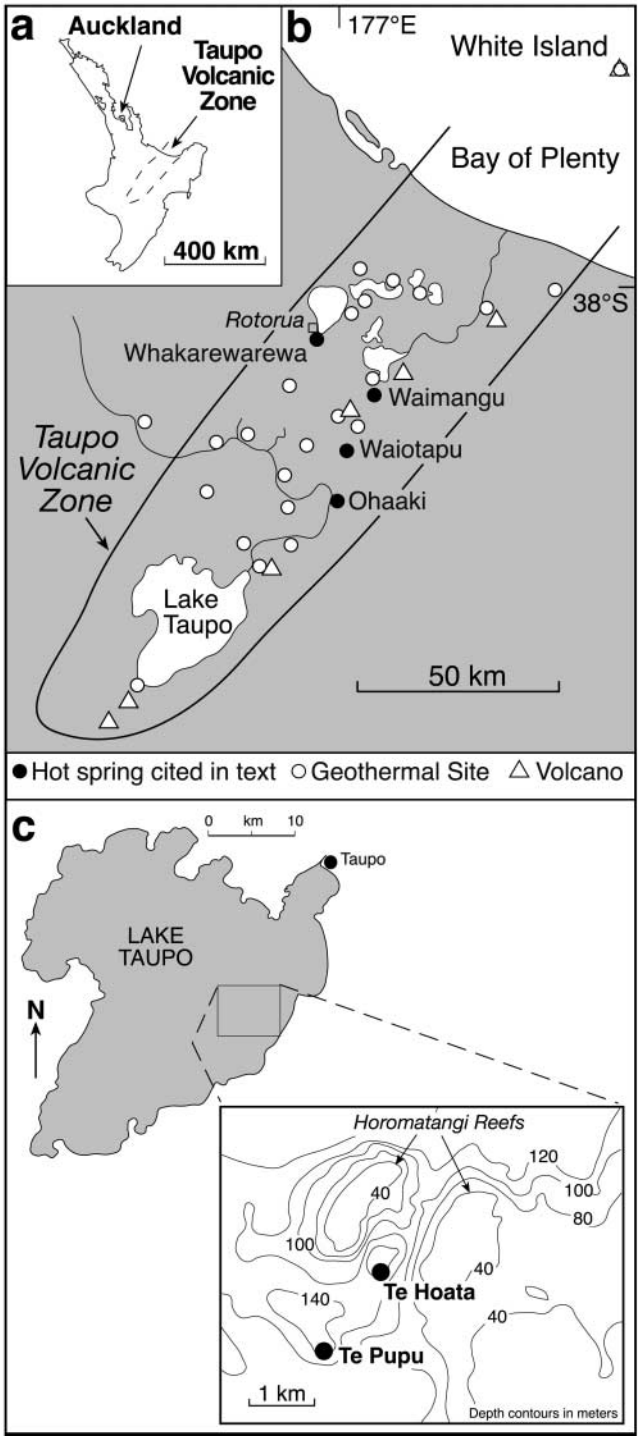


Fig. 1. Location of hydrothermal vents in Lake Taupo. (**a**) Location of Taupo Volcanic Zone on the North Island of New Zealand. (**b**) Location of Lake Taupo relative to terrestrial hydrothermal systems in the Taupo Volcanic Zone. (**c**) Location of the Te Hoata and Te Pupu vent sites in Lake Taupo (inset map modified from de Ronde *et al*. 2002, fig. 1).

actively venting chimneys were detected. However, several fields of dead chimneys, up to 30 cm high, were found at Te Pupu (de Ronde *et al*. 2002). A wood fragment and organic material embedded in one chimney yielded ^{14}C ages of 2086 ± 57 years BP and 1980 ± 57 years BP, respectively (de Ronde *et al*. 2002). The oldest ^{14}C age is coincident with the large Taupo eruption at *c*. AD 186 (Wilson 1993). These ^{14}C dates indicate the maximum possible age of the chimneys because the dates are derived from the wood and not the time when they were incorporated into the chimneys. Thus, deposits are <2000 years old and probably much younger.

Methods of study

Chimneys (Fig. 2) were collected from the floor of Lake Taupo during the joint New Zealand–Germany 'Taupo '98' dive project that used the submersible *Jago* (de Ronde *et al*. 2002). This study focuses on samples collected from the Te Pupu site (Fig. 2). Specifically, the samples consist predominantly of amorphous silica from two chimneys, labelled in the field as samples 583a and 583g (Fig. 2b and d, respectively), and two samples from the lake floor near those chimneys (583b and 583d). The lake floor samples are formed of ash and pumice fragments (up to 3 cm long) held in a coarse sand matrix. The sample surfaces are covered by a thin (1.0–1.5 mm) layer of opal-A, stained red and black, that probably reflects local concentrations of Fe, S, and Hg.

Small fracture samples of the opal-A, broken from the samples, were mounted on stubs and coated with a very thin layer of gold before being examined on a JOEL 6301FE field emission SEM at an accelerating voltage of 5.0 kV. This study is based largely on 470 SEM photomicrographs that were taken from these samples.

Mineral identification relied largely on the chemical composition, as determined by energy dispersive X-ray (EDX) analysis on the SEM (operated with an accelerating voltage of 20 kV) and the morphology of the crystals or precipitate. XRD analysis was of limited use because many of the precipitates are present only in very small amounts and/or are amorphous.

Adobe PhotoShop CS© was used to enhance the contrast and brightness of the digital SEM photomicrographs used in this study.

Chimneys

The term 'chimney' is used here for a tall tubular or upward tapering structure with a central orifice that rises above the lake floor and formed as a result of mineral precipitation from focused discharge of hydrothermal fluids.

Around Te Pupu there are areas, several square metres in extent, that encompass numerous inactive chimneys that are up to 10 cm in diameter and up to 30 cm high (Fig. 2). Some chimneys are conical (Fig. 2a and b) whereas others have an irregular, fluted, tubular form and are *c*. 5 cm in diameter (Fig. 2c and d). Some chimneys have hollow interiors that are partly filled with detrital sediment (Fig. 2d). The chimney walls are dominated by opal-A that has a porous, honeycombed texture on its outer surface (de Ronde *et al*. 2002). Black, Mn-rich precipitates commonly line the orifices (Fig. 2d) and pyrite is the dominant sulphide, where present. Mineralized zones in these chimneys (Fig. 2) commonly contain coatings of cinnabar (HgS_2) together with high concentrations of Mn, As, Ba, S and Zn, and with lesser amounts of Sb, Tl, and Mo, elements that are commonly associated with subaerial geothermal systems and epithermal gold deposits (de Ronde *et al*. 2002). Living sponges commonly encrust the dead chimneys around Te Pupu (Fig. 2a).

The possibility that the Lake Taupo structures are exhumed pipes that formed below the sediment–water interface is discounted because: (1) there is no evidence of bedding structures in the outer surfaces of the pipes; (2) the chimneys are formed of porous opal-A that is completely different from the fine-grained volcanic ash (mud) found on the lake floor; (3) none of the lake floor sediment is embedded in the opal-A precipitates that form the chimneys; (4) clean planktonic diatoms occur embedded in the chimney walls. It is possible, however, that parts of the

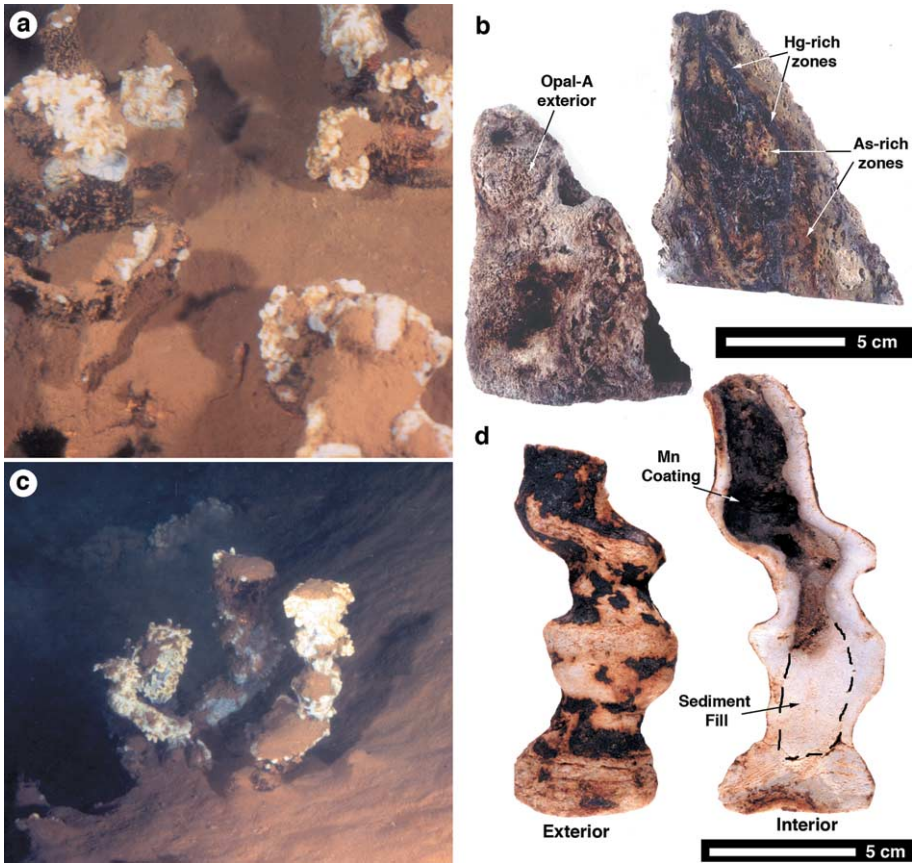


Fig. 2. Chimneys around hydrothermal vents on floor of Lake Taupo. (**a**) Sponges encrusting dead chimneys at Te Pupu. Depth *c*. 127 m. Partly covered with brownish-orange organic material, *c*. 1 cm thick. (**b**) Chimney (sample 583a) from Te Pupu showing cut interior surface with Hg- and As-rich zones (upper right) and exterior surface formed mainly of opal-A (lower left). (**c**) Small-diameter tubular chimneys at Te Pupu at depth of *c*. 130 m, encrusted with white sponges and partly covered by brownish-orange organic-rich sediment. (**d**) Exterior and cut interior surfaces of tubular chimney (sample 583g). The hollow interior partly filled with sediment and upper part coated with Mn-rich precipitates should be noted. Collected from the Te Pupu site.

structures were buried by sediments during different stages during their growth, just as their present roots are probably buried below the sediment surface.

Silicified microbes

The opal-A precipitated around the hydrothermal vents contains silicified filamentous microbes (Figs 3–5), silicified coccoid microbes (Fig. 6), and diatoms (Fig. 7).

Silicified filamentous microbes

Dense arrays of entangled filamentous microbes are present throughout the opaline precipitates (Figs 3 and 4). The silicified filamentous microbes are found alone (Fig. 3b and c) or entwined around diatoms (Fig. 3e). Three morphotypes of silicified filamentous microbes, labelled here FM1 (Fig. 4a–i), FM2 (Fig. 4j–l) and FM3 (Fig. 4m–o), are present. The external diameter of many silicified filaments varies from 1 to 5 μm along their length (Fig. 5). Such variations reflect the amount of opal-A cement precipitated around filaments that had already been replaced by opal-A.

FM1: description. These non-branching silicified filamentous microbes are >100 μm long and have an external diameter of 1–10 μm (Fig. 4a–e). Transverse and longitudinal cross-sections reveal isodiametric lumens, 0.7–1.0 μm in diameter, that are generally open (Fig. 4a–i). Rare specimens, however, show silicified trichomes (Fig. 4d) that reveal septa between cells that are 1.5–2.0 μm long (Fig. 4f–h). The poorly preserved cell wall, if present, is 80–100 nm thick (Fig. 4g and h). There is no evidence of a sheath.

FM2: description. These filaments, less common than FM1, are >50 μm long with an external diameter of 0.15–0.25 μm (Fig. 4i–l). They are intermixed with FM1 (Fig. 4i and k). Their preservation is generally poor, with most specimens being evident only as hollow tubes in the opal-A groundmass (Fig. 4j and k). Scattered specimens contain a poorly silicified trichome (Fig. 4i and l) that provides no information about their architecture. The scant information available indicates that they were unsheathed, non-branching, non-septate filaments.

FM3: description. These filaments, with an external diameter of 1.3–5.0 μm, form loosely intertwined mats (Fig. 4m). Their arcuate form and loosely coiled terminal area make them distinctive (Fig. 4n). The possibility that these filaments have short curled branches cannot be confirmed because large opal-A spheres, which formed as cement, encased the filaments and masked any branch junctions that may be present (Figs 4o and 5). The few transverse cross-sections through these filaments show open lumens, 0.3–0.4 μm in diameter.

Taxonomic affinity. The taxonomic affinity of the silicified filamentous microbes is difficult to establish because of their architectural simplicity and lack of distinctive morphological traits (see Jones *et al*. 2001*b*, 2004). This is certainly true for FM2, which is an unsheathed, non-branching, non-septate filamentous microbe, 150–250 nm in diameter and >50 μm long. Although more is known about FM1 from a morphological perspective, it is still difficult to assign these filaments to a particular group of microbes. Similarly, the thick opal-A coating around most FM3 filaments precludes observation of morphological features that could be used to deduce their taxonomic affinity.

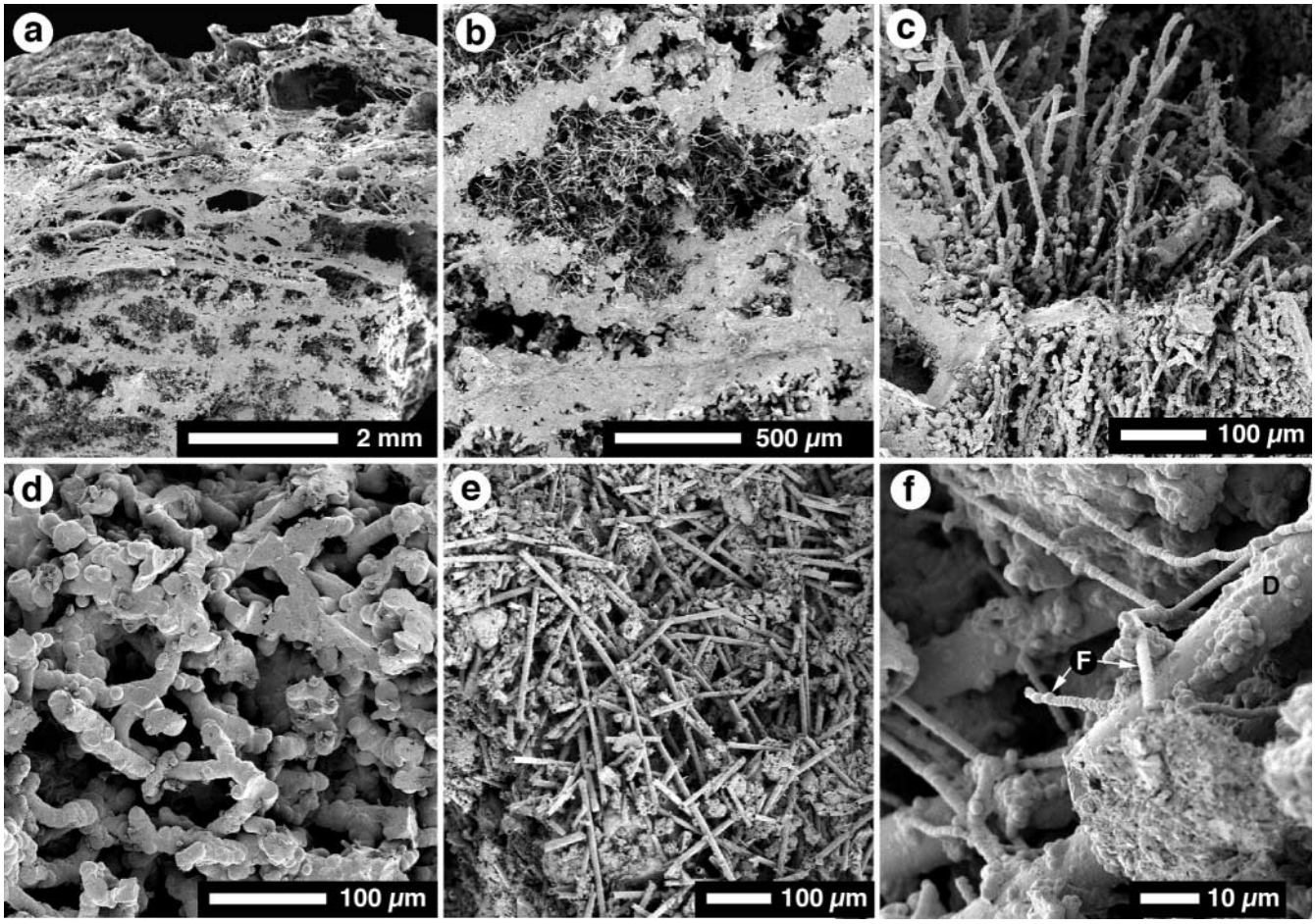


Fig. 3. SEM photomicrographs of opal-A deposits from spring vent on floor of Lake Taupo. (**a**–**d**) from chimney 583a; (**e**) and (**f**) from sample 583d. (**a**) Highly porous opal-A deposit. (**b**) Irregular laminae of featureless opal-A surrounding open areas with numerous silicified filamentous microbes. (**c**) Silicified filamentous microbes in open area of sample. (**d**) Interwoven mat of silicified filamentous microbes. (**e**) Surface of laminae covered with numerous cylindrical diatoms (mostly *Aulacoseira*) that have been coated with opal-A. (**f**) Intermixed opal-A encrusted centric diatoms (*Aulacoseira*) (D) and silicified filamentous microbes (F).

Lake Taupo level rose rapidly after the 1.8 ka eruption (Riggs *et al*. 2001) so it is likely that the microbes colonized chimneys that were close to their present depth (140 m) rather than in the photic zone. This implies that they were probably chemotrophs. These filamentous microbes are probably bacteria that lived on nutrients supplied or processed from the hydrothermal fluids expelled from the vents.

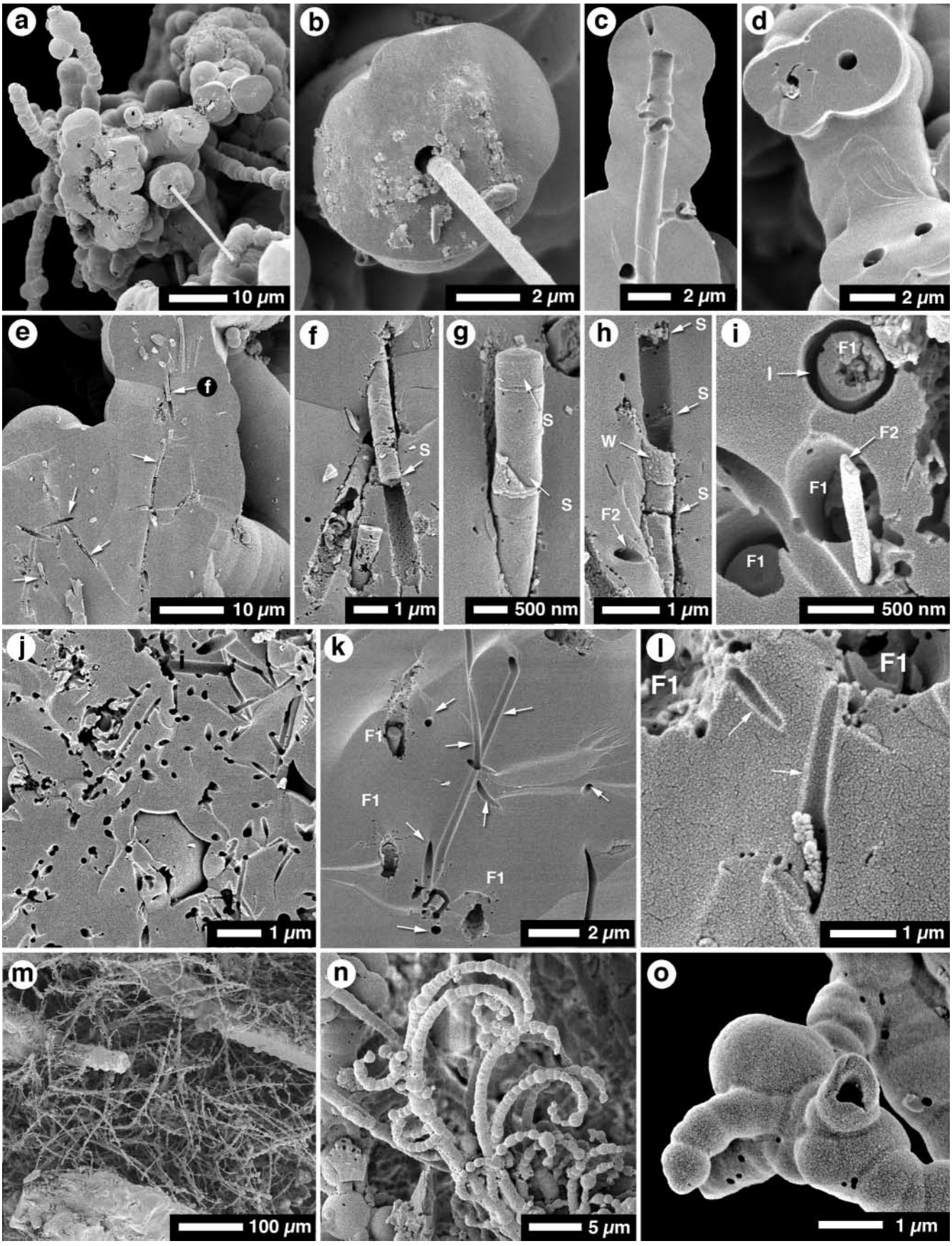
Coccoid microbes

Description. Variably preserved coccoid microbes are found in clusters (Fig. 6a–f) or as isolated, widely scattered specimens (Fig. 6g–i). Some areas of sample 583a contain clusters of subspherical to ovate microbes (1.0–1.6 μm long) that have a thin (<100 nm) multilayered wall (Fig. 6a and b). The smaller specimens are subspherical whereas the more elongate forms have a median constriction (Fig. 6b). The cells are hollow or filled with featureless opal-A.

Clusters of silicified spherical to ovate coccoid microbes, *c*. 1.5 mm long and *c*. 1.0 μm in diameter, are present locally. Their surfaces are smooth or covered with finely granular opal-A spheres. Elsewhere, spherical microbes, 2.0–2.5 μm in diameter, are found in small groups, commonly between silicified filamentous microbes (Fig. 6c). These spheres have a small central opening, *c*. 0.5 μm in diameter, that may be an attachment site (Fig. 6d).

On fractured surfaces, coccoid microbes are evident only as hemispherical depressions and it is commonly difficult to distinguish them from depressions left by abiotic opal-A spheres (Fig. 6e). In many cases, however, the hollow depressions

Fig. 4. SEM photomicrographs of silicified filamentous microbes, FM1, FM2, and FM3. All from sample 583a. (**a**) Interwoven FM1 with variable external diameters and thick opal-A coatings around open lumens. (**b**) Silicified trichome of FM1 extending from lumen. From (**a**). (**c**) Longitudinal cross-sections through silicified FM1 with thick coating of opal-A around open lumen. (**d**) Transverse cross-section through FM1 showing thick opal-A encasing open lumens. (**e**) Longitudinal section through group of FM1 encased by thick layer of opal-A. Arrows indicate silicified trichomes. White letter f indicates position of (**f**). (**f**) Silicified FM1 broken at a septum (S; arrow). (**g**) Silicified trichome of FM1 with septa (S; arrows). (**h**) Silicified trichome of FM1 with septa (S) and silicified wall (W). (Note FM2 (F2) located near FM1.) (**i**) Intermixed FM1 (F1) and FM2 (F2). (Note interspace (I) associated with one of the FM1 filaments.) (**j**) Numerous FM2 in opal-A matrix. (**k**, **l**) FM1 (F1) mixed with FM2 (arrows) embedded in opal-A matrix. (**m**) Loosely interwoven mat of FM3. (**n**) FM3 characterized by curved filaments and loosely coiled terminal areas. (**o**) FM3 with open lumen and perforations through opal-A.



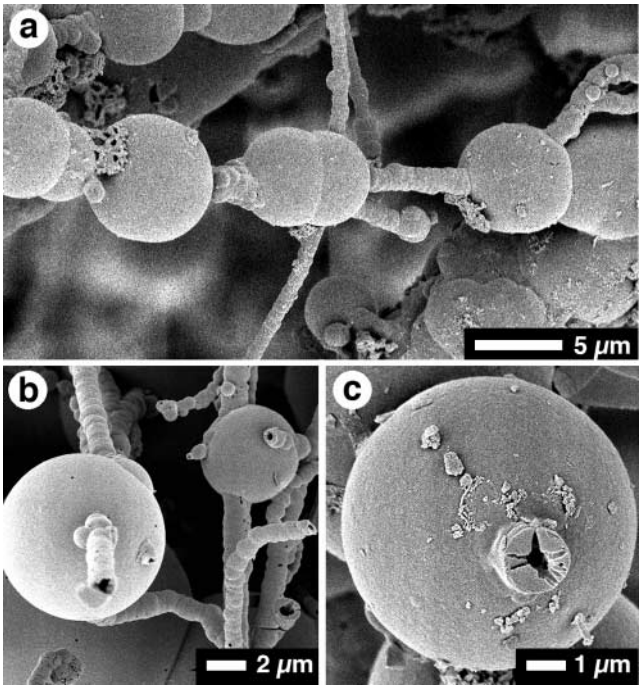


Fig. 5. SEM photomicrographs showing variable diameters of silicified filamentous microbes, all from sample 583a. (**a**) Silicified filament with highly variable external diameters as a result of location of large opal-A spheres. (**b**) Silicified filamentous microbes encased by large, isolated opal-A spheres. (**c**) Silicified filamentous microbe with open lumen encased by large opal-A sphere.

(typically 1–1.5 μm diameter) are encased by a layer (400–500 nm thick) of opal-A that is characterized by a radial pattern (Fig. 6f) that may represent the internal structure of the microbial cell walls.

Spherical bodies, 5–10 μm in diameter, that have distinct attachment sites (Fig. 6g–i) are scattered throughout the deposits. Some of these bodies are ornate (Fig. 6g), whereas others are faceted (Fig. 6h) or smooth (Fig. 6i).

Taxonomic affinity. It is impossible to determine the taxonomic affinity of the coccoid microbes because of their poor preservation (Fig. 6). The thin-walled, ovate microbes characterized by binary fission (Fig. 6b) are probably bacteria. The clusters of spherical to ovate coccoid microbes (Fig. 6c) may be bacteria, whereas the large spherical bodies with well-defined attachment sites (Fig. 6g–i) may be cysts.

Diatoms

Description. Although most diatoms came from the opal-A coating on the surface of the lake floor sample, some were also found in the opal-A of the chimney walls (samples 583a and 583g). Some diatoms (e.g. *Aulacoseira*) are concentrated in large numbers (Fig. 3e), including rare articulated colonies (Fig. 7f), whereas only a few specimens represent others. Locally, the diatoms are intermingled with silicified filamentous microbes (Fig. 3f). Most diatoms are coated by a thin (1–2 μm) layer of opal-A that masks their ornamentation and hinders identification (Fig. 8). The walls of some diatom frustules merge imperceptibly with the surrounding opal-A groundmass (see Renaut & Owen 1988).

Taxonomic affinity. The diatom biota is dominated by *Aulacoseira* cf. *granulata* (Figs 3e and 7a). Associated taxa include *Asterionella formosa* (Fig. 7b), *Cyclotella stelligera* (Fig. 7c), *Synedra ulna*? (Fig. 7d), *Epithemia sorex* (Fig. 7e), *Fragilaria* (Fig. 7f), *Surirella* sp. (Fig. 7g), *Navicula* sp. (Fig. 7h), *Sellaphora bacillum*? (Fig. 7i), *Nitzschia* sp. (Fig. 7j), and *Cocconeis* sp. (Fig. 7k).

Biofilms

A locally silicified biofilm (up to 1.5 mm thick), present on the surface of the lake floor (sample 583d) around the hydrothermal vents at Te Pupu (Fig. 9a), incorporates a diverse array of microbes (Fig. 9a–f). Broken diatoms, detrital quartz and feldspar grains, an assortment of fungal(?) spores, and rare sponge spicules lie on top of, or partly embedded in, the biofilm (Fig. 9d).

The biofilm is formed primarily of collapsed, poorly preserved filamentous microbes that are 0.1–1.5 μm wide in their flattened form (Fig. 9a). Locally, entangled masses of branching filaments, *c*. 0.5 μm in diameter, lie on the biofilm surface (Fig. 9b). The thin mats, however, include only scattered specimens of poorly silicified filamentous microbes (Fig. 9d). Some of the larger filaments appear septate. Variations in the size and morphology of the filaments indicate that this biota was characterized by several taxa. Unfortunately, the taxonomic affinities of the collapsed, poorly preserved filamentous microbes are unknown, and it is unclear why these filaments were not silicified in the same style as the filamentous microbes found elsewhere in these deposits (Figs 3 and 4). This may be due to the type of microbes involved, because fungi, for example, are less susceptible to silicification than bacteria (e.g. Jones *et al*. 1999). Alternatively, it may reflect the timing and rate of silicification, with silicification occurring after the demise and collapse of the microbes.

Spores that lie on, or are partly embedded in, the biofilm are partly collapsed (Fig. 9e–h). Ornate spores, together with poorly preserved conidia with spores (2.0–2.5 μm in diameter; Fig. 9e) that are spatially associated with collapsed septate hyphae (1.0–1.5 μm wide; Fig. 9f), are similar to *Aspergillus* (Jones *et al*. 2000, fig. 6C–G). The taxonomic affinities of other spores (Fig. 9g and h), which may also be of fungal origin, remain unknown.

Rare sponge spicules lie on top of the biofilms amid detrital quartz and feldspar grains (Fig. 9i). These solid spines, up to 250 μm long and 10 μm in diameter, taper distally, and have a smooth outer surface that is featureless apart from small spines (Fig. 9i).

Associated biota

The biota associated with the hydrothermal vents in Lake Taupo is known from observations made during the dives (de Ronde *et al*. 2002) and subsequent dissection and analysis of sponges harvested from the chimney tops (Rota & Manconi 2004). This biota includes sponges, freshwater crayfish, native fish (*Koaro*, *Gobiomorphus*), amphipods, copepods, ostracodes, annelids, and various unidentified taxa (de Ronde *et al*. 2002; Manconi *et al*. 2002; Rota & Manconi 2004). The sponges, up to 15 cm in diameter and 25 cm high, belong to the genus *Heterorotula* (de Ronde *et al*. 2002; Manconi *et al*. 2002).

None of macrobiota associated with the hydrothermal vents is preserved in the opal-A except the scattered sponge spicules (Fig. 9i) and worm tubes (Fig. 10).

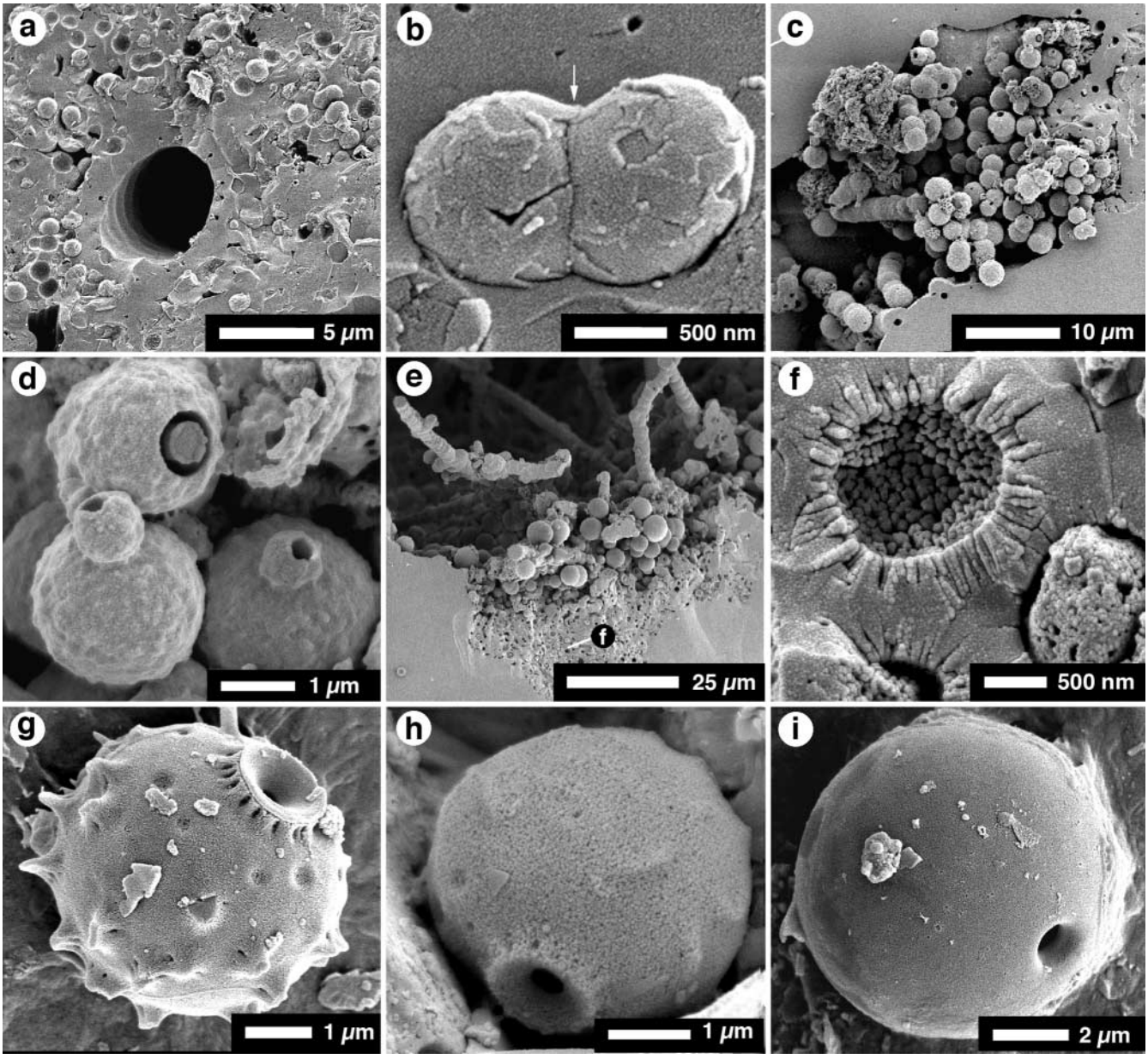


Fig. 6. SEM photomicrographs of coccoid microbes. (**a**–**f**) from sample 583a; (**g**–**i**) from sample 583d. (**a**) Coccoid microbes embedded in opal-A groundmass that surrounds a diatom. (**b**) Coccoid microbe, from (**a**), in process of dividing through binary fission (arrow). (**c**) Group of spores(?) in corner of small cavity in opal-A matrix. (**d**) Enlarged view of spores(?) with possible attachment sites. (**e**) Floor of small cavity with accumulation of coccoid microbes, overlain by filamentous microbes. White letter f indicates location of (**f**). (**f**) Radiating structure in wall that encases one of the hollow coccoid microbes. (**g**–**i**) Algal cysts(?) with well-developed attachment site and variable ornamentation.

Precipitation and diagenesis

Opal-A is the dominant component in the chimneys in the Horomatangi vents area on the floor of Lake Taupo. With a maximum age of 2000 years, and probably a lot less, the chimneys have had a complex diagenetic history that has involved multiple phases of precipitation of opal-A, Mn, Fe, and Hg. These phases of precipitation were periodically interrupted by phases of opal-A dissolution, probably mediated by acidic hydrothermal fluids.

Silica precipitation occurred when ascending silica-rich, hot waters encountered cold lake water, leading to supersaturation. For silica to precipitate, the hot spring fluids must have been cooled rapidly, but were not greatly diluted around the vents. If the fall in temperature was due to simple mixing of lake water with the hydrothermal fluid, precipitation might not have occurred because the fluid mixing line might not have intersected the saturation curve for amorphous silica (see Janecky & Seyfried 1984). Rapid dilution by lake water would have reduced the silica content of the thermal waters below the required level for nucleation and precipitation (Renaut *et al*. 2002).

Mineral precipitation

Opal-A cement. Opal-A spheres, up to 10 μm in diameter, formed as cement around filaments that had previously been replaced by opal-A (Fig. 5). Micropores in the opal-A ground-

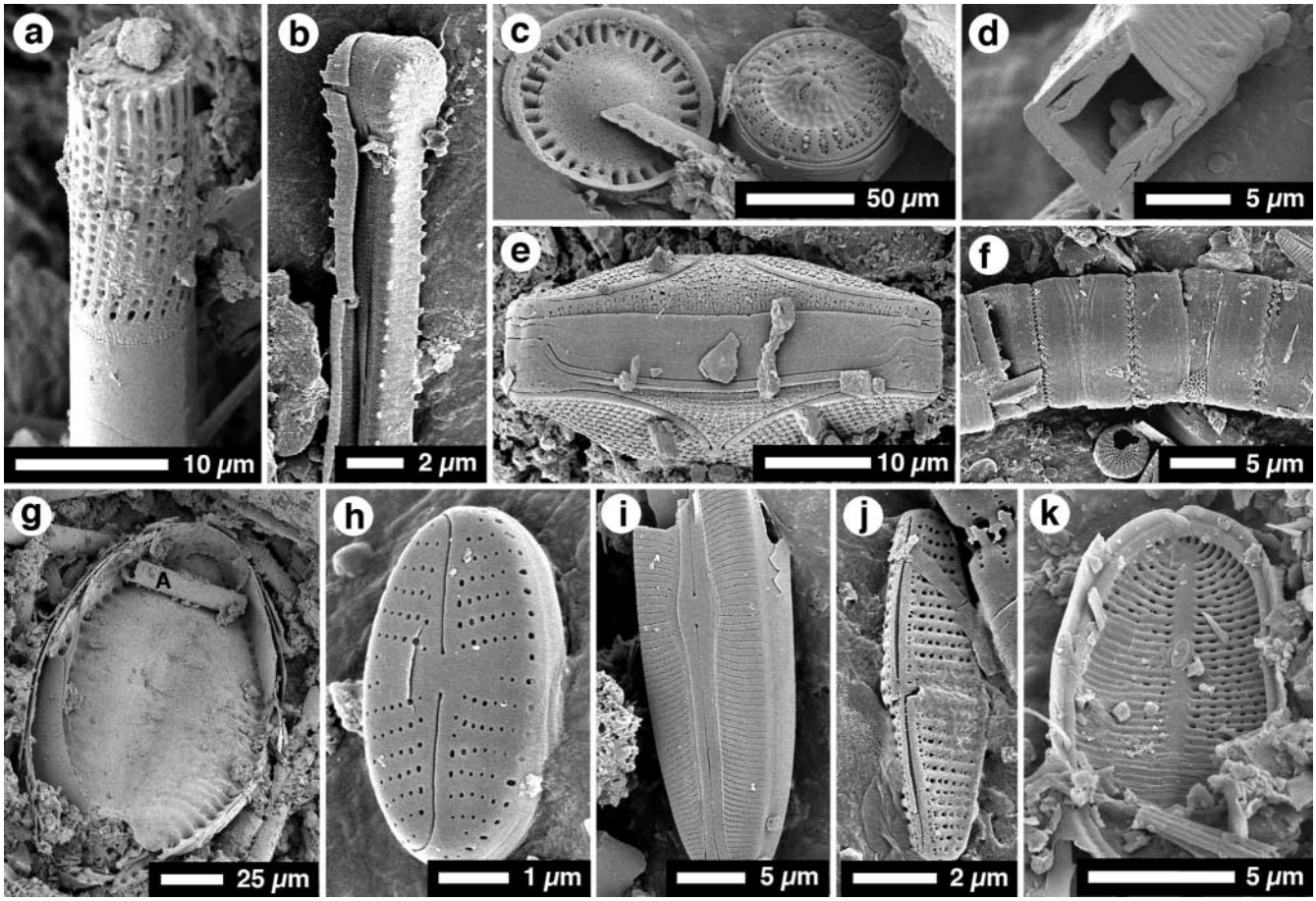


Fig. 7. Diatoms associated with Lake Taupo spring deposits. (**a**–**c**) and (**e**–**k**) from sample 583d; (**d**) from sample 583g. (**a**) *Aulacoseira* cf. *granulata*; (**b**) *Asterionella formosa*; (**c**) *Cyclotella stelligera*; (**d**) *Synedra ulna*?; (**e**) *Epithemia sorex*; (**f**) colony of *Fragilaria*; (**g**) *Surirella* sp.; (**h**) *Navicula* sp.; (**i**) *Sellaphora bacillum*?; (**j**) *Nitzschia* sp.; (**k**) *Cocconeis* sp.

mass are commonly lined with a thin (<5 μm) isopachous layer of opal-A cement that is smooth and mammalated on its cavity-facing surface (Fig. 11b). The lack of visible internal structures in the cement makes it impossible to determine if the cements were precipitated as one phase or if they formed through gradual accretion of thin laminae as in isopachous opal-A cements found elsewhere (e.g. Jones & Renaut 2003*a*, fig. 10E).

Mn–Fe reticulate precipitates. Small, reticulate masses, formed primarily of Mn and Fe, are scattered throughout the deposits (Fig. 12a and b). Many of these precipitates coat the opal-A that mantles the filamentous microbes (Fig. 12b), indicating that the Mn–Fe precipitates probably postdated precipitation of the opal-A cements.

Fe-rich precipitate. Locally, a finely granular, Fe-rich coating covers the opal-A precipitates and diatoms, and fills the interstices between detrital feldspar and quartz grains (Fig. 12c).

Gypsum. Scattered clusters of small (<5 μm long) subhedral to euhedral gypsum crystals are found locally (Fig. 13f). Most of the SO_4 probably originated from the hydrothermal fluids given that the SO_4 concentration in the lake water is only *c.* 5.5 g m^{-3} (Timperley & Vigor-Brown 1986).

Hg-rich precipitate. Some substrates are covered with a black precipitate that is formed of anhedral to euhedral crystals up to 5 μm long (Fig. 12e and f). EDX analysis shows that these crystals are composed mainly of Hg, suggesting that they are probably cinnabar. Probably, the Hg was transported in the vapour phase of the hydrothermal fluids and precipitated when those fluids mixed with the cold ambient lake water (see Stoffers *et al*. 1999; Christenson & Mroczek 2003).

Dissolution

Opal-A dissolution produced surface perforations with associated dissolution tubes (Fig. 13a–d), scalloped surfaces (Fig. 13e), corroded silicified filamentous microbes (Fig. 13f), and partly leached opal-A spheroids (Fig. 14).

Surface perforations and dissolution tubes. The surfaces of the opal-A that encases filamentous microbes are commonly perforated by holes that are <100 nm in diameter (Fig. 13a and b). There is no recognizable pattern to their distribution (Fig. 13a and c). Similar perforations are evident on the surfaces of the isopachous opal-A cement that lines many cavity walls.

Transverse cross-sections through silicified filamentous microbes show that the perforations are the surface expression of small-diameter tubes (Fig. 13c and d) that typically taper toward the exterior surface (Fig. 13b–d). Some tubes stretch only part of the distance between the lumen wall and the exterior surface.

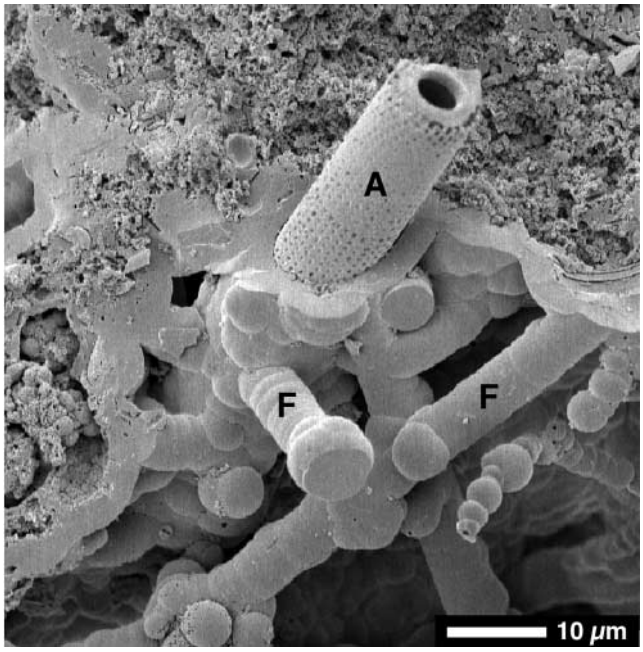


Fig. 8. *Aulacoseira* cf. *granulata* (A) and filamentous microbes (F) encrusted with thick layer of opal-A, from sample 583a.

Some transverse cross-sections reveal only one or two tubes (Fig. 13b and c), whereas others show numerous tubes that are randomly distributed (Fig. 13d) or concentrated into one quadrant of the cross-section.

The dissolution tubes are similar to 'microborings' found in the branches of 'shrubs' that formed around the vent of geyser 124 near Waikite Geyser at Whakarewarewa (Fig. 1a; Jones & Renaut 2003*b*, fig. 14). Those 'microborings' are isodiametric and therefore differ from the tapering morphology of the tubes in the Lake Taupo samples.

Scalloped surfaces. The lumen walls in many silicified filamentous microbes have a scalloped appearance (Fig. 13e) similar to the scalloped surfaces that Jones & Renaut (2003*b*, fig. 11D and E) illustrated from sinter at Waikite Geyser, Whakarewarewa. Those surfaces were attributed to etching by acidic steam (Jones & Renaut 2003*a*); late acidic hydrothermal fluids also probably etched the opal of the silicified filaments.

Corroded silicified filamentous microbes. Some silicified microbes have been severely corroded (Fig. 13f). Such poorly preserved specimens have a ragged appearance with scalloped surfaces similar to those on the lumen walls.

Leached opal-A spheroids?. Some opal-A in the chimneys is

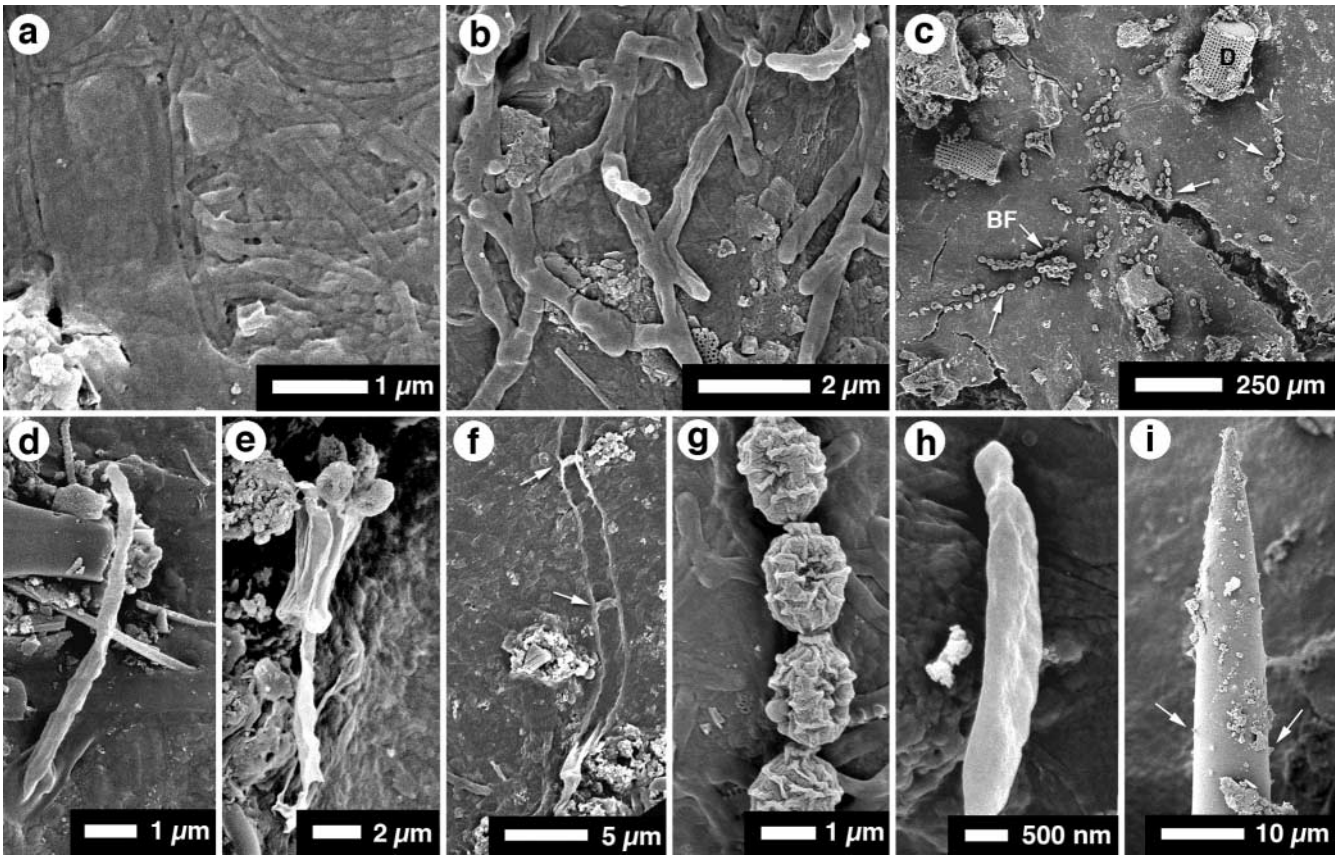


Fig. 9. SEM photomicrographs of biofilm, from surface of sample 583d. (**a**) Surface of silicified biofilm covered with various taxa of collapsed, indeterminate filamentous microbes. (**b**) Surface covered with complex mass of branching fungal hyphae(?). (**c**) Diatoms (D) and chains of fungal spores (arrows) resting on and partly embedded in silicified biofilm (BF). (**d**) Rare silicified microbe associated with silicified biofilm. (**e**) Conidia of *Aspergillus*. (**f**) Septate filament that may be *Aspergillus*. (**g**) Dispersed spores from *Aspergillus*. (**h**) Spores of unknown fungi(?). (**i**) Tapered end of sponge spicule (note small projections from sides of spicule; arrows).

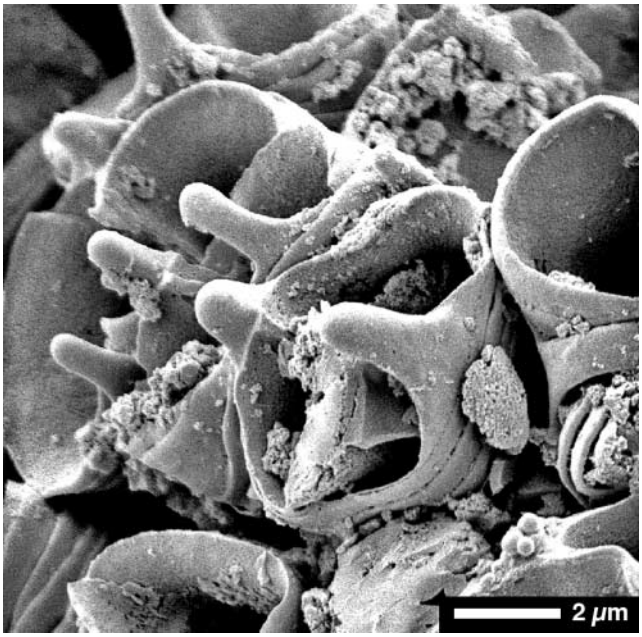


Fig. 10. SEM photomicrograph of worm(?) tube clusters from sample 583a.

formed of tightly interlocking polygonal masses, up to 2 μm long (Fig. 14), that contrast sharply with the opal-A spheres found in many terrestrial hot-spring deposits (e.g. Jones & Renaut 2003*a*, fig. 4). In addition, the surfaces of these polygonal opal-A masses commonly display a rough, etched surface (Fig. 14), producing high microporosity in many of these particles (Fig. 14). Some micropores amid the etched, polygonal opal-A bodies are thinly coated with isopachous opal-A cement that creates a smooth surface around the etched polygonal opal-A masses (Fig. 14). The origin of these particles is unknown, but their polygonal shape suggests competitive growth during diagenesis.

Discussion

The hydrothermal vents and surrounding deposits on the floor of Lake Taupo include a diverse biota, detrital sediments, and various precipitates. The biota is a mixture of resident and non-resident filamentous microbes, coccoid microbes, and diatoms. The recognition of resident as opposed to non-resident (i.e. allochthonous) biota is important from a palaeoecological perspective, especially in the context of ancient samples for which precise environmental parameters are unknown.

The silicified filamentous microbes, FM1, FM2, and FM3, are considered part of the resident biota because they form delicate, loosely interwoven masses that seem to be in a growth position (Fig. 3a–d). In contrast, the scarcity and scattered distribution of the coccoid microbes, including those in geopetal sediments on cavity floors (Fig. 6g), suggests that most of them are probably non-resident.

The diatom flora (Figs 3e and 7) is formed of locally numerous *Aulacoseira* with rare taxa (commonly only single diatoms) that include *Asterionella*, *Cocconeis*, *Cyclotella*, *Epithemia*, *Fragilaria*, *Navicula*, *Nitzschia*, *Sellaphora*, *Surirella*, and *Synedra*. These photosynthetic microbes must be non-resident because they could not live in the deep (*c*. 140 m) dark waters around the vents. This biota is a mixture of planktonic (e.g. *Aulacoseira*, *Asterionella*, *Surirella*), littoral epiphytic (e.g. *Cocconeis*, *Epithemia*, *Synedra*), and littoral (e.g. *Cyclotella*, *Sellaphora*) taxa. The planktonic diatoms probably settled onto the lake floor following their demise whereas the other diatoms were transported into the area, along with the detrital quartz, feldspar, and clay (Fig. 15), by wind-generated currents and waves (see Nelson & Lister 1995).

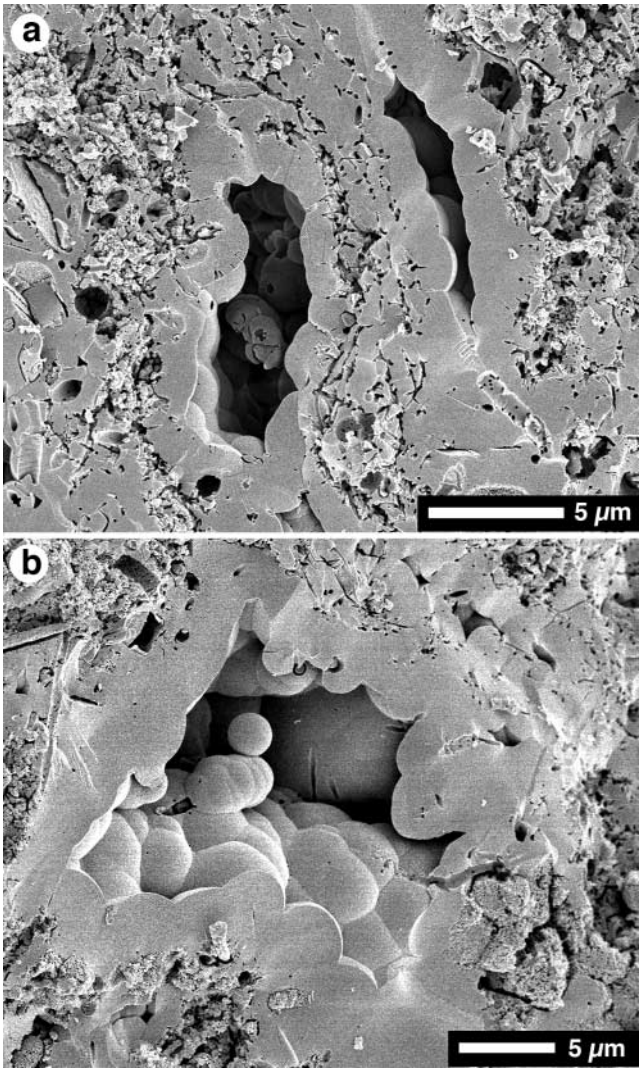


Fig. 11. SEM photomicrographs of opal-A isopachous cements from sample 583a. (**a**) Micropores lined with solid opal-A isopachous cements that contrast sharply with the groundmass, which has high microporosity. (**b**) Isopachous opal-A cement lining micropore.

The biofilm on substrates around the chimneys was generated by resident biota (Fig. 9a). The fungal hyphae and spores, however, are problematical because genera such as *Aspergillus* typify terrestrial settings (Jones *et al*. 2000). The fungi therefore, may be allochthonous.

Despite their relatively young age, the opal-A precipitates in the Lake Taupo chimneys have been diagenetically modified by dissolution and/or late-stage precipitation (Figs 11–13). Textural evidence indicates that the diagenetic environments varied, with alternating periods of dissolution and precipitation being controlled by the hydrothermal fluids expelled from the vents. For example, temporary changes in gas discharge (e.g. CO_2) or acidity levels caused by oxidation of H_2S might have led to dissolution.

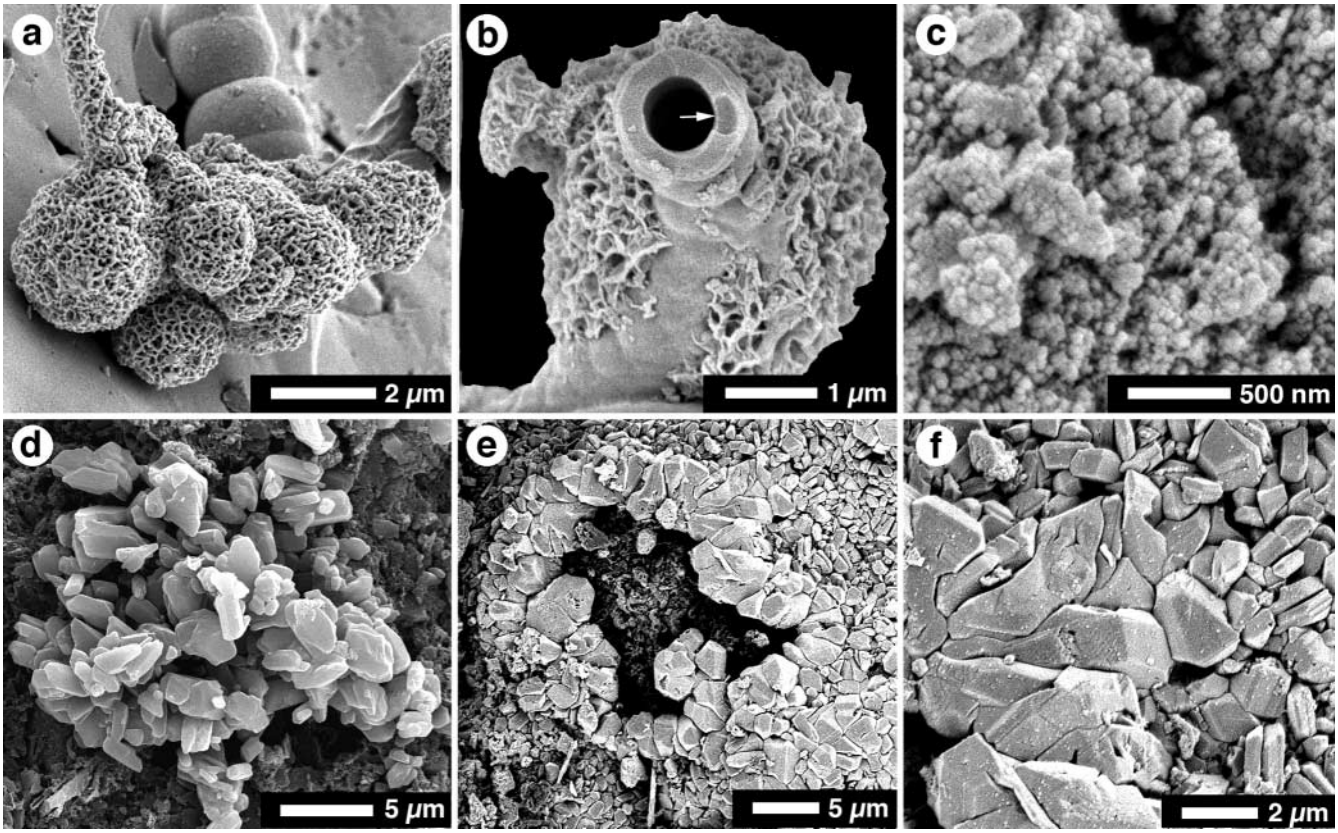


Fig. 12. SEM photomicrographs of precipitates associated with spring deposits on floor of Lake Taupo. (**a**) and (**b**) from sample 583a; (**c**–**f**) from sample 583d. (**a**) Filaments and opal-A spheres coated with reticulate Mn–Fe-rich precipitate. (**b**) Mn–Fe rich precipitate coating opal-A that encases a silicified filament. (Note open lumen and hole perforating opal-A around lumen (arrow).) (**c**) Enlarged view of finely granulated Fe-rich precipitate. (**d**) Cluster of gypsum crystals. (**e**) Crystalline Hg coating surface of sample. (Note larger crystals around opening in coating.) (**f**) Enlarged view of Hg crystals around opening shown in (**e**).

Information on the biota associated with modern sublacustrine springs is sparse because there are few documented examples (Table 1). In Crater Lake, Oregon, bacterial mats grow preferentially in the warm waters around the hydrothermal vents, where they are associated with lithified Fe- and Mn-rich crusts (Dymond *et al*. 1989). In Lake Baikal, hydrothermal vents at a depth of 440 m are surrounded by bacterial mats, sponges, gastropods, and amphipods (Crane *et al*. 1991; Shanks & Callendar 1992). In Yellowstone Lake, substrates around the sublacustrine springs are inhabited by bacteria, sponges, nematodes, protozoans, and oligochaete worms (Remsen *et al*. 1990; Cuhel *et al*. 2001; Maki *et al*. 2001; Remsen *et al*. 2001; Morgan *et al*. 2003; Shanks *et al*. 2005). Given that diatomaceous oozes cover much of the floor of Yellowstone Lake (Remsen *et al*. 2001), it is not surprising that diatoms are found in the silica precipitated around the vents (Morgan *et al*. 2003, fig. 4C). Filamentous mats, sponges (Tiercelin *et al*. 1989, 1993), and diatoms (Cocquyt 1999) are also present on the lake floor around sublacustrine thermal springs in Lake Tanganyika.

The chimney-like morphology of the Lake Taupo deposits is common to many sublacustrine hot springs. Chimneys, which are typically several times taller than their basal diameter, have also been termed spires (e.g. Shanks *et al*. 2002). Their formation implies that their parent fluids discharged at the same focused location for a sufficient period of time to permit vertical growth. Not all sublacustrine thermal springs, however, produce chimneys. Although most upward fluid-flow paths are controlled by faults or fractures (e.g. Coussement *et al*. 1994), thermal fluid discharge on some lake floors is diffuse, emanating from many small vents or porous sediments (e.g. Rai & Absar 1996; Schulze-Makuch 2002; Tarits *et al*. 2006). If discharge is highly diffuse, mineral precipitation may not occur around vents because the thermal fluids may become rapidly diluted to levels below saturation as they mix with larger volumes of cooler lake water.

Evidence for silica precipitation under diffuse conditions is seen at Lakes Bogoria and Baringo in the central Kenya Rift. Subfossil, lithified silica deposits are exposed on Ol Kokwe Island near the centre of Lake Baringo (Renaut *et al*. 2002; Tarits *et al*. 2006), and at Ng'wasis (formerly Mwanasis) at the south end of Lake Bogoria (Renaut & Owen 1988). At both sites, Si-rich spring waters discharged from clusters of small vents through the lake floor when lake levels were higher (up to 15 m at Baringo; 10 m at Bogoria) than today (Renaut & Owen 1988; Renaut *et al*. 2002). As a result, pebbles and coarse sands on the lake floor are cemented by opal-A and locally covered by crusts of opal-A up to 15 cm thick.

Similarities between the Kenya Rift deposits and those of the Lake Taupo vents include: (1) their dominant opal-A composition; (2) diatom biotas dominated by planktonic freshwater species, including *Aulacoseira*; (3) the presence of non-resident coccoid cells, pollen, and spores; (4) the presence of silicified biofilms; (5) the presence of pore-lining and -filling opal-A cements. Differences include the following: (1) chimneys are absent in the Kenyan examples because of the diffuse discharge

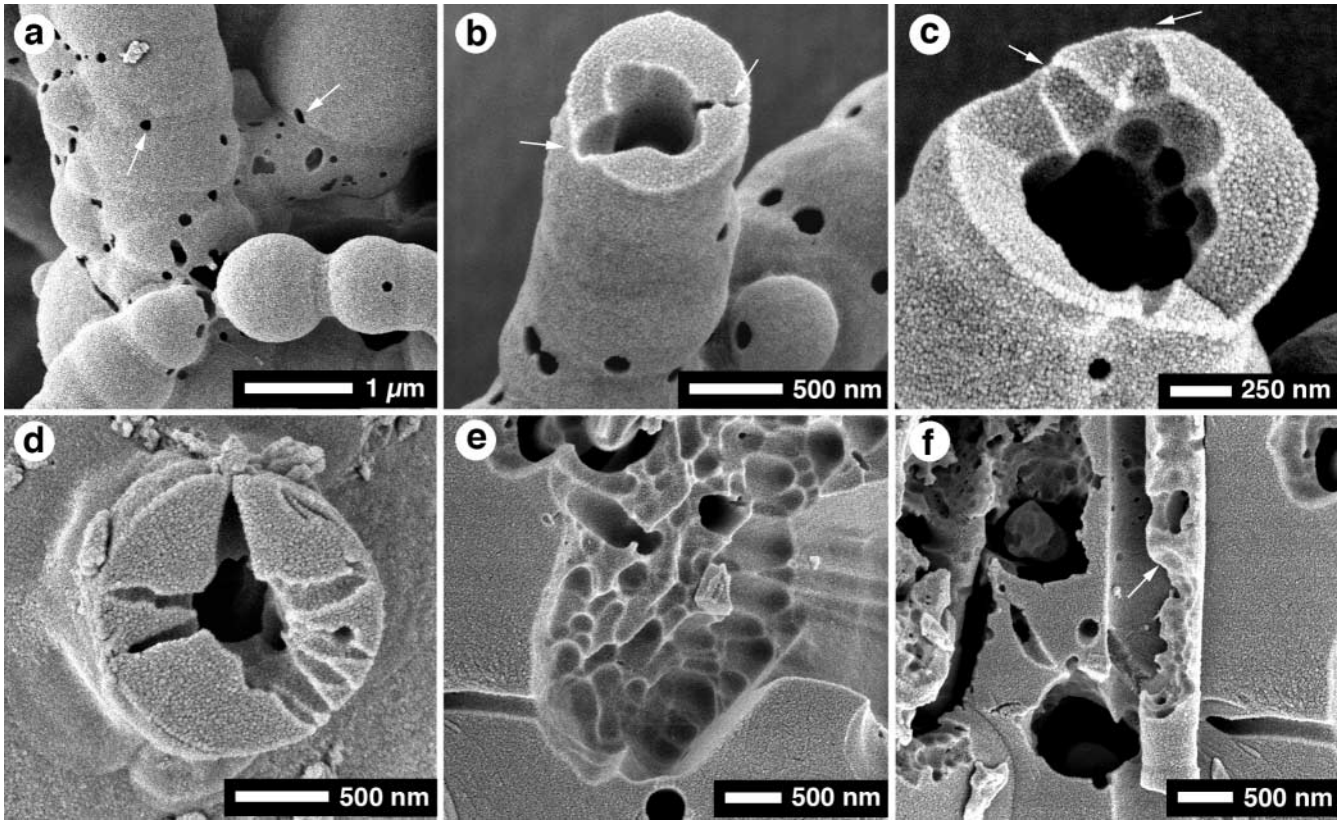


Fig. 13. SEM photomicrographs of etched silicified filamentous microbes, all from sample 583a. (**a**) Exterior surfaces of silicified filamentous microbes pieced by numerous small holes (arrows). (**b**) Transverse cross-section through filament showing holes on exterior surfaces and holes stretching from exterior surface to lumen (arrows). (**c**) Transverse cross-section through filament showing holes stretching from exterior surface to lumen (arrows) and scalloping on lumen wall. (**d**) Transverse cross-section through filament showing numerous holes that taper outward from lumen to exterior surface. (**e**) Scalloped surface of lumen wall in silicified filament. (**f**) Silicified microbe almost completely lost as a result of etching.

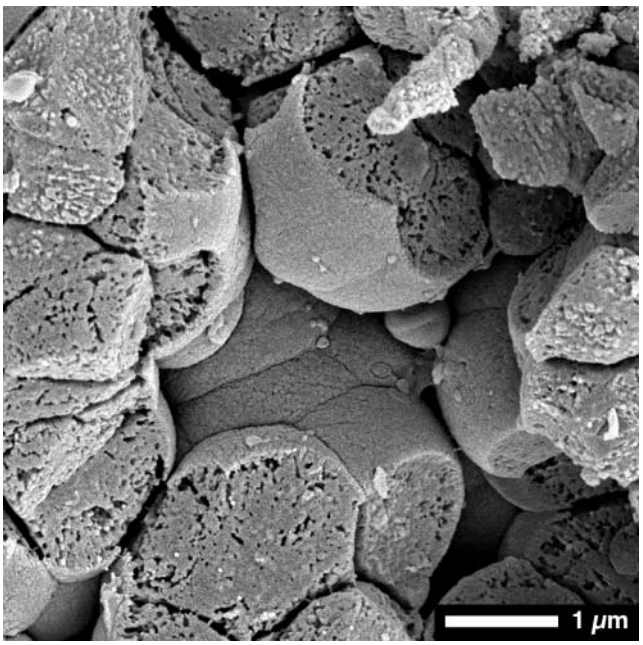


Fig. 14. SEM photomicrograph of thin isopachous opal-A layer coating walls of micropore in etched polygonal opal-A masses, sample 583a.

through permeable gravels; (2) the Kenyan vents may have remained in the photic zone during silica precipitation; (3) the littoral setting of the Kenyan chimneys that formed during periods of deeper lower-energy water was prone to littoral wave erosion when lake levels fell; (4) the accessory minerals, with fluorite present in the Bogoria deposits.

The silica deposits forming the chimneys and covering the lake floor around the hydrothermal vents in Lake Taupo are, in some respects, similar to siliceous sinters found around terrestrial spring and geyser vents, including those in the Taupo to Rotorua area, NE of Lake Taupo (Fig. 1b). Comparisons of sublacustrine and terrestrial spring deposits can be considered under the general categories of large-scale features, mineralogy, biota, and diagenesis (Table 1).

Sublacustrine silica deposits at vents with focused discharge may include chimneys and a peripheral apron of siliceous crusts. Subaerial mounds are commonly more ornate than sublacustrine mounds (Jones & Renaut 2003*b*) and subaerial vents can probably be distinguished by the draping nature of the beds that precipitate during gravitational flow around the circumference of the chimney (Guidry & Chafetz 2003). Similarly, gravitational cements would not be expected in sublacustrine chimneys (Guidry & Chafetz 2003). Ambiguous features might be present, however, if the thermal outflow from the sublacustrine vent was saline and denser than the ambient lake water, and therefore flowed down the sides of the mound and across the substrate as a density current. Outward projecting flanges, which form on marine chimneys where hot buoyant fluids escape through the

Fig. 15. SEM photomicrograph showing detrital clay and angular grains of quartz (Si) with scattered diatoms (*Aulacoseira*), sample 583a.

vent walls and pond beneath the flange (e.g. Delaney *et al*. 1992; Kerr & Turner 1996; Kelley *et al*. 2001), cannot form by the same mechanism in subaerial mounds. By analogy with marine hydrothermal vents, the proximal areas near tall silica chimneys are also likely to contain cemented chimney debris and talus, resulting from chimney collapse (see Hannington *et al*. 2001; Früh-Green *et al*. 2003). Where thermal upflow was diffuse or large chimneys did not develop, however, it may be more difficult to distinguish subaerial from sublacustrine silica on morphology alone, particularly after diagenesis. Small (centimetre-scale) chimneys, such as the Taupo examples, are potentially more ambiguous because small chimney-like features have been observed in some subaerial vent mounds. However, the peripheral outflow apron with terraces and other subaerial sinters produced by oriented surface flow (e.g. Guidry & Chafetz 2003) would not be expected in sublacustrine deposits and is probably the best morphological evidence for terrestrial precipitation.

The minerals that form in and around spring vents are controlled mainly by the composition of the hydrothermal fluids and, in some cases, their interaction with lake water. Opaline silica, carbonate minerals (calcite, aragonite), and sulphide minerals are common around sublacustrine and terrestrial thermal springs. Examples of sulphides include those in Lake Tanganyika (Tiercelin *et al*. 1989, 1993; Tanganydro Group 1992; Pflumio *et al*. 1994) and Lake Taupo (de Ronde *et al*. 2002). Similarly, other minerals such as Mn–Fe crusts (Nicholson 1990) are known from both types of thermal springs.

Hot spring deposits, irrespective of setting, commonly have a diverse biota. Bacterial mats are found around most sublacustrine spring vents (Table 1). The filamentous microbes present in the Lake Taupo deposits, for example, are probably chemotrophs able to live in dark waters at a depth of 140 m. The silicified microbes (Figs 3a–d and 4), however, are morphologically similar to many silicified microbes in subaerial sinters of the

Table 1. *Comparison of sublacustrine spring deposits from Lake Taupo, Lake Baikal, Crater Lake, Yellowstone Lake, Ng'wasis (Lake Bogoria), and Ol Kokwe (Lake Baringo)*

	Modern focused vents				Subfossil diffuse vents	
	Lake Taupo	Crater Lake	Lake Baikal	Yellowstone Lake	Ng'wasis, L. Bogoria	Ol Kokwe, L. Baringo
Water depth (m) of vents	140–165		440	<1–133	<12	<15
Water *T* (°C), vents	45 (maximum)			20–120	>90*	>90*
T (°C) in bacterial mats		4.7–9.5	⩾16			
Ambient Water *T* (°C)	12	3.5	3.7	4–18 (seasonal)	18–30*	18–30*
Ambient Water pH	7.6			4.0–8.6	8–10.5*	7.5–9*
Chimneys	Present	Present	Present	Present	Absent	Absent
Planktonic lacustrine diatoms	×			×†	×	×
Bacterial mats	×	×	×	×	×	×
Coccoid microbes	×				×	×
Sponges	×		×	×		
Gastropods			×		×	×
Amphipods	×		×	×		
Worms	×			×		
Molluscs (excluding gastropods)					×	×
Ostracodes					×	×
Non-resident microbes	×					×
Pore-lining and -filling opal-A cement	×				×	×
Isopachous calcite cement					×	×
Mn–Fe precipitates	×	×		×	×	
Fe precipitates	×					
Sulphides					×	
Hg crystals	×					
Fluorite					×	
Etching and dissolution of opal-A	×					

Data sources: Lake Taupo, de Ronde *et al*. (2002); Lake Baikal, Crane *et al*. (1991) and Shanks & Callendar (1992); Crater Lake, Dymond *et al*. (1989); Yellowstone Lake, Maki *et al*. (2001) and Remsen *et al*. (2001); Ng'wasis, Lake Bogoria (formerly Mwanasis), Renaut & Owen (1988); Ol Kokwe, Lake Baringo, Renaut *et al*. (2002). The deposits at Ng'wasis and Ol Kokwe are lithified subfossil deposits considered to be the product of sublacustrine spring activity.
*Estimated based on modern values.
†Assumed to be present given lake floor covered with diatomaceous ooze; also shown by Morgan *et al*. (2003, fig. 4C).

Taupo–Rotorua region (e.g. Jones *et al*. 1997*b*, 2001*a*; Jones *et al*. 2002). Thus, it may be difficult to separate sublacustrine from terrestrial spring microbes. Many sublacustrine springs have a diverse associated biota that includes sponges, gastropods, amphipods, worms, and molluscs (Table 1). Although present in the lake floor sediments and as living samples, these organisms are absent or difficult to detect in the mineral deposits around the vents. In the opal-A deposits collected from Lake Taupo, for example, only one sponge spicule (Fig. 9i) and one group of worm tubes (Fig. 10) were found.

Diatoms are commonly associated with hot springs, irrespective of where they form. The diatom biota around the Lake Taupo vents is composed largely of planktonic, epiphytic littoral taxa that are alien to the lake floor. The dominant taxon, *Aulacoseira* cf. *granulata*, forms a near monospecific flora in some samples. Nelson & Lister (1995) noted that it is common over the central parts of the lake floor, and Hawes & Smith (1994) showed that *A. granulata* dominates in Lake Taupo in water >20 m deep during winter. In contrast, this diatom is rare (<6% of flora) in the subaerial, acidic and alkaline, hot spring systems of the Taupo to Rotorua region (Fig. 1b). Similarly, other diatoms (e.g. *C. stelligera*) found in the Lake Taupo spring deposits are rare in the subaerial systems. *Pinnularia* is common in many subaerial springs on the North Island but absent from the Lake Taupo sublacustrine spring samples. Other diatoms found in various terrestrial springs but not in the Lake Taupo sublacustrine spring deposits include: *A. granulata* var. *angustissima*, *A. distans*, *Frustulia rhomboides*, *Nitzschia amphibia*, *N. fonticola*, *N. inconspicua*, *Navicula confervaceae*, *Anomoeoneis serians* var. *brachysira* f. *thermalis*, and *Amphora veneta*.

The biota preserved in spring deposits can provide valuable, sometimes quantitative, information about the ecological conditions under which the deposits formed (see Mpawenayo & Mathooko 2004; Owen *et al*. 2004). Such interpretations, however, depend on accurate identifications and knowledge of preferred habitats. Although viable with extant taxa, this may not be case with extinct diatoms for which detailed palaeoecological information is unavailable. Without such information, for example, it may be impossible to distinguish resident from non-resident components of the biota (Table 2). Diatoms and sponges are also of limited usefulness when interpreting ancient sinters. The earliest known non-marine diatoms date from the early Eocene, and they become common only from the Miocene onwards (e.g. Owen 2002).

The problem of recognizing sublacustrine as opposed to terrestrial spring deposits is further complicated by diagenesis. Although the Lake Taupo deposits are <2000 years old, etching has already partly destroyed some of the silicified filamentous microbes (Fig. 13). With time and/or changing conditions, opal-A transforms to moganite, cristobalite, or opal-CT and eventually to quartz (e.g. Rodgers *et al*. 2004). Such transformations, promoted by time, high *T*, and/or high pH (e.g. Fournier 1985), involve the loss of water (H_2O and OH), replacement, and recrystallization (e.g. Herdianita *et al*. 2000). These diagenetic changes may significantly modify or destroy the original fabrics and silicified organisms in a siliceous spring deposit. In some ancient successions, therefore, it may become difficult to confirm if a chert was hydrothermal in origin, let alone determine if it originated in a sublacustrine, submarine or terrestrial setting.

A well-preserved biota that contains taxa that can be identified in terms of extant species may provide valuable insights into the conditions associated with an old spring system. If the biota is poorly preserved or palaeoecological information cannot be derived from the biota, the distinction between sublacustrine and terrestrial spring deposits will probably rest on the large-scale features of the deposit and its geological and stratigraphic setting (Table 2). The overall stratigraphy may offer important clues because sublacustrine spring deposits will normally be associated with lake deposits, whereas terrestrial spring deposits will be

Table 2. *Comparison of deposits and biota associated with sublacustrine and terrestrial hot springs*

Feature	Sublacustrine deposit	Terrestrial deposit
General features		
Large-scale features (e.g. geyserite, terraces)	Absent	Common
Associated deposits	Lacustrine	Terrestrial or lacustrine
Chimneys	Focused vents (past) Diffuse vents (present)	Rare to absent
*Precipitates**		
Opal-A	Present	Present
Calcite	Present	Present
Barite	Present	Present
Fluorite	?	Present
Sulphides	Common	Scattered
Fe–Mn precipitates	Common	Present
Biota		
Filamentous microbes	Common	Common
Coccoid microbes	Present	Present
Planktonic lacustrine diatoms	Common	Rare
Epiphytic and epilithic diatoms	?	Common
Sponges	Common	Absent
Gastropods	Present	Rare
Amphipods	Present	Rare
Worms	Present	?
Non-resident biota	Common	Rare
Diagenesis		
Pore-lining and -filling opal-A*	Present	Present
Pore-lining and -filling calcite*	Present	Present
Etching and dissolution of opal-A	Yes	Yes

*Presence and type of precipitates largely dependent on composition and saturation levels of water.

associated with soils, fluvial, or other terrestrial deposits. Some caution must be exerted, however, because hot spring vents in the shallow littoral zones of lakes may become terrestrial if there is a drop in lake level or if the spring deposit builds up above water level. Conversely, terrestrial hot springs located along the shores of a lake may become sublacustrine if the lake level rises. This is a common situation in continental rifts (Renaut & Tiercelin 1994), and can lead to intercalation of subaerial and sublacustrine deposits in the same spring mound.

Conclusions

Chimneys and lake floor sediments recovered from the area around hydrothermal vents at a depth of *c*. 140 m on the floor of Lake Taupo are composed mainly of opal-A with various Fe-, Mn-, Hg-, As-, and S-rich precipitates and, in places, detrital quartz and feldspar grains. Although up to *c*. 2000 years old, these deposits have undergone diagenetic modifications through repeated phases of opal-A dissolution and precipitation. The silicified biota in these deposits is formed of filamentous and coccoid microbes, diatoms, fungal hyphae and spores, sponge spicules, and worm(?) tubes. Much of this biota, however, is allochthonous.

The precipitates and biota in the Lake Taupo deposits are similar to those associated with sublacustrine siliceous spring deposits from Crater Lake, Yellowstone Lake, Lake Baikal, Lake Bogoria, and Lake Baringo. Some features of these deposits are, however, also similar to those found in terrestrial or submarine spring deposits. In some cases, it may be difficult to distinguish between these types of deposits in ancient successions. In most cases, however, interpretation of the setting of ancient spring deposits will probably have to rely on preserved large-scale features and the overall sedimentological and stratigraphic context rather than the characteristics of the precipitates and nature of the biota. For hot spring deposits formed predominantly of amorphous silica, diagenetic transformation of the opal-A to the more stable phases may destroy many of the original depositional fabrics and/or silicified microbes. For ancient successions, such diagenesis will further reduce the possibility of determining if the spring deposits formed on the lake floor or in a terrestrial setting.

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