Journal of Sedimentary Research
jsedres.geoscienceworld.org

doi: 10.2110/jsr.2005.016
v. 75 no. 2 p. 200–215

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jsedres.geoscienceworld.org

doi: 10.2110/jsr.2005.016
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Textural Preservation in Siliceous Hot Spring Deposits During Early Diagenesis: Examples from Yellowstone National Park and Nevada, U.S.A.

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Abstract

A petrographic, mineralogical, and geochemical investigation reveals evidence for selective preservation of microfacies in siliceous sinters. Plio-Pleistocene sinters from Steamboat Springs, Nevada, contain identical but fewer petrographic textures than Pleistocene sinters from Artist Point, Yellowstone National Park, Wyoming. The latter are preserved in altered sediments of unknown origin. A sequence of pore-filling and mineralogical changes explains the excellent preservation of nine microfacies and two petrographic textures. Plio-Pleistocene Steamboat Springs sinters are preserved in successions of andesitic basalt flows and were likely subjected to a more extreme thermal and a different hydrological environment than those from Yellowstone National Park. Most microfacies were obliterated during postdepositional heating of Steamboat Spring sinters. Differences in diagenetic histories related to depositional environment, water chemistry, and/or subsequent burial must account for the loss of textural evidence between the diagenetic stage represented by Artist Point sinters and that of Steamboat Springs sinters. Hence, early postdepositional history affects both the likelihood and quality of microfossil preservation.

Introduction

Evidence of microbial communities that lived around subaerial hot springs is preserved in associated sinter deposits. Distinctive fabrics that develop as minerals precipitate from cooling solutions characterize these microbial communities (Campbell et al. 2002; Farmer et al. 1997; Guidry and Chafetz 2003c; Jones and Renaut 1996, 1997, 2003b; Jones et al. 1997b, 1998, 2003; Konhauser et al. 2001; Lowe and Braunstein 2003; Lynne and Campbell 2003; Renaut et al. 1996; Rodgers et al. 2002; Trewin et al. 2003; Walter 1976a, 1976b, 1996; Walter et al. 1996; Weed 1889; D.E. White et al. 1956). Modern systems that precipitate silica preserve records of communities of microorganisms, the fabrics of which have been categorized into distinct microfacies (Walter 1976a, 1976b). Similar fabrics as well as evidence of cell preservation have been identified in Paleozoic and older cherts of hot-spring origin (Liebig et al. 1996; Rice et al. 1995; Trewin 1994, 1996; Trewin et al. 2003; Trewin and Rice 1992; Walter et al. 1996; Westall 1999; Westall et al. 2001; D.E. White et al. 1964; White et al. 1989) suggesting the possibility of similar microbial origins and emphasizing the need for additional paleontological, geochemical, and mineralogical research to characterize taphonomic processes.

Silica concentrations in hydrothermal systems are controlled by equilibration with quartz at high temperatures (Henley et al. 1984). Once the fluids reach the surface, silica can precipitate according to the degree of oversaturation. Initially in some cases, only quartz is oversaturated (Hinman and Lindstrom 1996), but, more commonly, other silica polymorphs precipitate (Guidry and Chafetz 2002, 2003c; Iler 1979; Jones and Renaut 2003a, 2004; Lowe and Braunstein 2003; Mountain et al. 2003; Smith et al. 2003; Stauffer et al. 1980; D.E. White et al. 1956). Precipitation is also driven by evaporative concentration of the solution (Campbell et al. 2002; Guidry and Chafetz 2002;

Hinman and Lindstrom 1996; Jones and Renaut 2004; Lowe and Braunstein 2003; Mountain et al. 2003; D.E. White et al. 1956). Silica, originally deposited as X-ray amorphous silica (opal-A; that is, silica with crystal size below the resolution of X-ray diffraction or truly amorphous), undergoes subsequent phase transitions to quartz (Lynne and Campbell 2003; D.E. White et al. 1956; D.E. White et al. 1988) through intermediate phases, e.g., opal-C or opal-CT (Guidry and Chafetz 2003a, 2003b; Herdianita et al. 2000; Lynne and Campbell 2003; Rodgers et al. 2002). Temperature and degree of oversaturation control the rate of these transitions in subaqueous systems (Kastner 1981; Mountain et al. 2003; Williams and Crerar 1985; Williams et al. 1985). In subaerial systems, the amount of water flowing through the system also controls the rate of diagenesis (Guidry and Chafetz 2003b; Hinman 1997; Jones and Renaut 2003a). It is during the transition to crystalline forms that textural detail may be lost.

Here we report two Plio-Pleistocene sinter deposits that span the transformation of opal-A to quartz. Textural, petrographic, and mineralogical descriptions are used to identify microfacies of sinter deposits from Artist Point in Yellowstone National Park (YNP) (Fig. 1) and Steamboat Springs, Nevada (Fig. 2). The number of microfacies and fidelity of textural preservation are then compared to assess diagenetic processes and effects on preservation of microbial features.

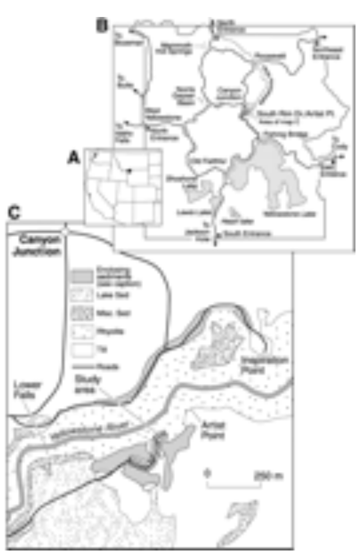

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Figure 1

A, B) Location of Yellowstone National Park in the western United States. **C)** Simplified geological map of the Yellowstone River through the Canyon area showing the sinter-bearing sediments that are the focus of this study (modified from Richmond 1977). The boxed area indicates the location of road cuts sampled in this study.

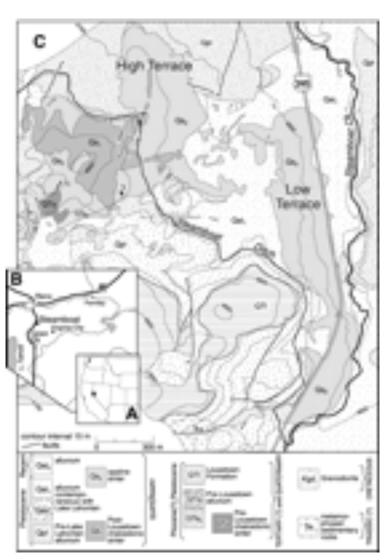

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Figure 2

A, B) Location of the Steamboat Springs site in the western U.S. **C)** Simplified geological map of Steamboat Springs, Nevada, showing the siliceous sinter (QTs) that is the focus of this study (modified from D.E. White et al. 1964).

Geologic Setting: Artist Point, Yellowstone National Park

Yellowstone is a volcano that represents the surface expression of a hot spot in the mantle or at the mantle-core boundary (Christiansen 2001; Smith and Siegel 2000). It has had three major caldera-forming eruptions: 2.2 Ma, 1.4 Ma, and 0.63 Ma. Each eruption occurred in a series of events: (1) heat buildup in a partially melted zone (> 4 km depth), (2) surface expansion and faulting over the hot spot, (3) release of pressure as steam loss and, eventually, ash explosion, and (4) late-stage rhyolitic volcanism filling the depressions and representing the last thermal cooling events in the sequence (Christiansen 2001; Smith and Siegel 2000).

Thermal features associated with the Yellowstone Hot Spot are prominent in Yellowstone National Park (Christiansen 2001; Fournier 1989; Richmond 1976, 1977; Smith and Siegel 2000; Weed 1889). The present configuration of features is thought to have developed since the end of the last ice age approximately 10,000 years ago. Older siliceous sinters are found along the Gibbon River near Norris Geyser Basin and along the Grand Canyon of the Yellowstone at Artist Point (D.E. White et al. 1988). Richmond (1976) places the sinter fragments at Artist Point within deposits of the informal unit, "the alluvial sediments of Inspiration Point," and thus in pre-Bull Lake interglacial stage. D.E. White et al. (1988) report that the Bull Lake glacial period ended 130 ka, and thus the deposits are at least that old. Such post-caldera sediments likely formed when the Canyon rhyolite flow dammed the proto-Yellowstone River at the end of the last eruptive cycle of the Yellowstone volcano, 500-600 ka, forming the lake at whose margins the springs developed (Christiansen 2001; Richmond 1976, 1977). Thus the deposits formed between 130 and 600 ka. Although an attempt was made to date the deposits during our work, the K-feldspars are too weathered to provide dates.

The sinters at Artist Point are variably sized fragments of siliceous sinter in a highly altered matrix of post-caldera sediments (Fig. 3). Post-caldera sediments lie over and between outcrops of the tuff of Uncle Tom's Trail (> 481 ka) and the Canyon flow (481 ka) of the Upper Basin Member of the Plateau Rhyolite (Christiansen 2001). At the southwestern exposure, in-place laminated sinters are interbedded with highly altered, bedded, lacustrine sediments; consistent with Richmond's (1976, 1977) interpretation that the sediments were deposited in a shallow lake or alluvial environment. Elsewhere in the deposit, sediments lack bedding, and sinter fragments are not in place but appear not to have been transported far because of their angularity. However, a lacustrine or alluvial environment does not explain the structure of the enclosing sediments, which lack bedding and sorting. Hydrothermal explosion (eruption) could explain the relationships (Browne and Lawless 2001; Fournier et al. 1991; Muffler et al. 1971). The deposits contain clasts of siliceous sinter, and are matrix supported and poorly sorted, characteristics attributed to most hydrothermal explosion deposits in New Zealand (Browne and Lawless 2001). Such an explosion could redistribute sinters proximal to the vent without extensive disturbance distally. Explosion breccias are observed elsewhere in Yellowstone (Johnson et al. 2003; Morgan et al. 2000; Morgan et al. 2003; Muffler et al. 1971).

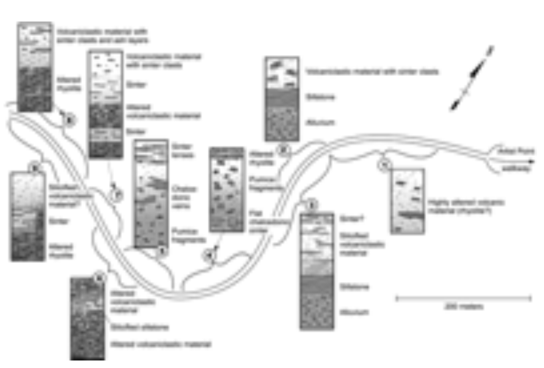

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Figure 3

Locations and stratigraphic sections along Artist Point road cut from which samples were collected.

Geologic Setting: Steamboat Springs, Nevada

There are both active and ancient hydrothermal systems at Steamboat Springs, Nevada (Silberman et al. 1979; Thompson and White 1964; D.E. White et al. 1964). The deposits are located at the northeast end of Steamboat Hills in southern Washoe County (Fig. 2). Glaciation occurred at least four times in the Carson Range to the west. Hot-spring sinters formed during each of the Sierran interglacial periods, and thermal activity may have been continuous since the Sherwin, or third youngest Pleistocene, ice age (Silberman et al. 1979; Thompson and White 1964).

The older hot-spring deposits date from pre-Lousetown time and consist almost entirely of siliceous sinter with very little calcium carbonate (D.E. White et al. 1964). Widespread, pre-Lousetown sinters are found as siliceous sinter cobbles in pediment gravels. The pre-Lousetown sinters underlie the Steamboat flows of the Lousetown Formation (2.53 Ma) (Silberman et al. 1979); constraining the oldest sinters to be older than 2.53 Ma. Massive, in-place sinters located north of the pediment gravels are considered inconclusively to be of the same age and are the focus of this study. They are not overlain by any deposits and have no intercalated or laterally adjacent sediments. These siliceous sinters consist of individual beds from 15 to 60 cm thick.

No opal is reported in the siliceous sinters; fine-grained quartz is the dominant mineral (D.E. White et al. 1964). The porosity of the siliceous sinters is low (0 to 20%, averaging 5 to 8%; D.E. White et al. 1964) due to infilling of cavities with chalcedony or quartz. D.E. White et al. (1964) conclude that "the pre-Lousetown siliceous sinter deposits were at one time highly porous opaline sinter, commonly of the fragmental type, that has been changed to its present form by reconstitution of much or all of the opal to chalcedony and quartz."

Mineralogical and microfacies observations from Artist Point are presented first, followed by similar observations from Steamboat Springs.

Artist Point Results

Sinters were collected from a series of road cuts along the Artist Point access road (Fig. 3). They were, for the most part, not in place, and the original spatial relationships among the microfacies are unknown.

Nine microfacies are recognized by textural, mineralogical, and petrographic characteristics (Table 1). They are classified by synoptic relief and proposed biogenicity. Relief refers to the original height of internal structures. Judging by modern systems, relief is interpreted to indicate specific sedimentological and hydrological characteristics of the depositional environment (Braunstein 1999; Braunstein and Lowe 2001; Lowe and Braunstein 2003; Walter 1976b). Low-relief structures suggest shallow-water with variable flow, whereas high-relief structures suggest either deeper water with low flow or splash zones near a vent (Fig. 4).

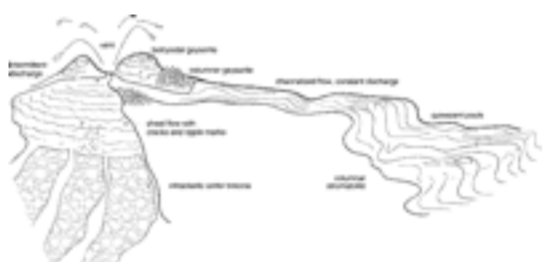

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Figure 4

Schematic sketch of a thermal spring showing the position of various types of sinter microfacies relative to the vent, splash zones, channels, pools, and sheet deposits. The figure is based on observations reported by Guidry et al. (2003a), Walter (1976b), and Walter et al. (1972). Area depicted is 10 to 50 meters across.

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Table 1

Summary of textural, petrographic, and chemical characteristics of microfacies reported herein. All microfacies are found at Artist Point. Only those in italics are found at Steamboat Springs.

Mineralogy

Silica in hydrothermal systems is deposited originally as opal-A, in most cases, and eventually transforms to quartz (Campbell et al. 2001; Guidry and Chafetz 2003a, 2003b, 2003c; Herdianita et al. 2000; Hinman 1995; Hinman and Lindstrom 1996; Jones and Renaut 2003a; Lynne and Campbell 2003; Mountain et al. 2003; Rodgers et al. 2002; Smith et al. 2003; D.E. White et al. 1956; D.E. White et al. 1988). To document the relationship between mineralogy and preservation of microfacies, we undertook an X-ray diffraction (XRD) study and a petrographic study of resin-impregnated thin sections. Generally, the detection limit by XRD is 3 to 10 weight % but may be higher in these silica-rich rocks because of low peak signal-to-noise ratios above the broad background generated by opal-A. Further characterization of specific petrographic features was determined using scanning electron microscopy with energy dispersive spectrometry (SEM/EDS) on polished thin sections. The detection limit of EDS is a few percent depending on the element and configuration.

Quartz is the dominant mineral in Artist Point rocks. It is present as groundmass and as void-filling cement. In two thin sections, quartz, with sweeping extinction pattern in cross-polarized light, is identified by X-ray and electron diffraction. EDS shows Si and O for all quartz.

A silica-rich phase with low birefringence is frequently observed. Only at high magnification is first-order gray observed. XRD and petrographic observations indicated that only small amounts of quartz are present in this silica phase, as indicated by a narrow XRD peak at 26.6° 2θ. XRD patterns showed mainly the broad peak at 21° 2θ associated with opal-A (J.B. Jones and Segnit 1971) with a narrower peak at 22.68° 2θ. In some analyses, there is also a peak at 20.8° 2θ. The latter two peaks suggest opal-C. Kaolinite is also detected by XRD but not petrographically. It is possible that low birefringence stems from the presence of finely interspersed kaolinite. SEM observations indicated that the phase, if it is a single mineral, is highly porous with patches of introduced resin or other organic-rich material present. EDS indicated Si and O, with minor Al and Fe in certain locations. Examination at higher magnification and lower acceleration voltage did not show evidence of contamination by corundum particles that may be associated with grinding, although it cannot be ruled out. On the basis of XRD results, we conclude that this siliceous phase is likely opal-C that is intimately associated with another phase or phases that contains Al and Fe. Kaolinite would account for the Al. Iron oxide is a common weathering product and is present as a rust stain on the surface of some samples.

Observations and Interpretations

Prior researchers have classified sinter microfacies on the basis of hydrodynamics, temperature, and/or presence and form of organisms (Braunstein and Lowe 2001; Campbell et al. 2001; Guidry and Chafetz 2003a, 2003b, 2003c; Jones and Renaut 1996, 1997, 2003b; Jones et al. 1997a, 1997b, 1998; Lowe and Braunstein 2003; Lynne and Campbell 2003; Mountain et al. 2003; Renaut et al. 1996; Renaut et al. 1998; Walter 1976b). Hydrodynamic processes influence the relief of the original siliceous structures by effecting different silica deposition rates (Lowe and Braunstein 2003; Mountain et al. 2003). Temperature also influences deposition rates as well as distribution of organisms (Braunstein and Lowe 2001; Brock 1978; Dove and Rimstidt 1994; Guidry and Chafetz 2003c; Jones et al. 2003; Lynne and Campbell 2003; Mountain et al. 2003; Rimstidt and Barnes 1980; Smith et al. 2003; Walter 1976b; Walter et al. 1972, 1976). Further, the presence or absence of organisms influences silica deposition processes (Cady and Farmer 1996; Guidry and Chafetz 2003c; Jones and Renaut 2003b; Lowe and Braunstein 2003; Phoenix et al. 2003; Smith et al. 2003; Trewin et al. 2003; Walter 1976b; D.E. White et al. 1956). Herein, observations of microfacies are grouped according to the vertical relief of the internal structures. This classification reflects a combination of the effects of hydrodynamics, temperature, and biota, and is generally applicable in a diagenetically altered environment in which the original spatial and stratigraphic relationships have been lost and in which microfossils may be lacking.

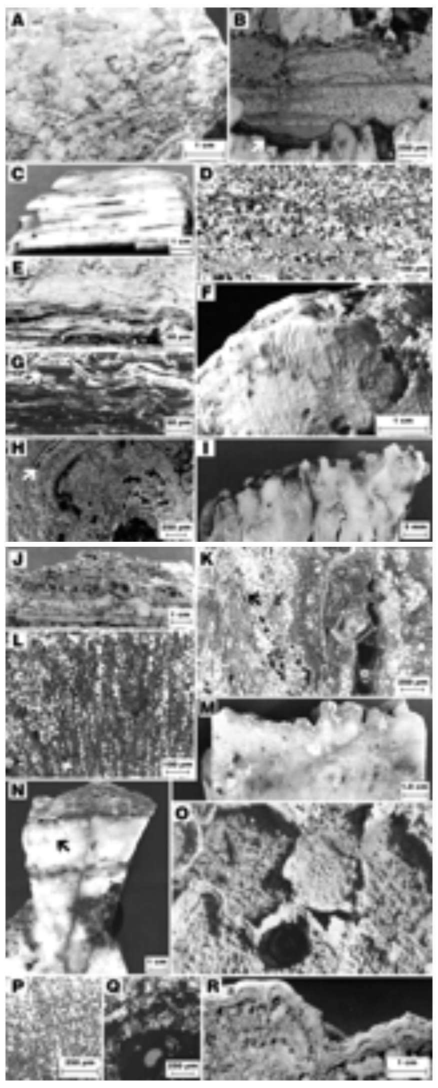
The presence of fenestrae or voids, be they open or filled during diagenesis, their size, and their orientation are also noted in the descriptions. The size, orientation, and shape of fenestrae or voids can be related to similar features from modern hot-spring deposits, providing a link to original depositional conditions, including the possible presence of microorganisms (Campbell et al. 2001; Guidry and Chafetz 2003a; Jones and Renaut 2003a, 2003b; Lynne and Campbell 2003; Walter 1976b, 1996; Walter et al. 1972, 1976). Further, the presence of fenestrae or voids affects porosity and permeability, and therefore diagenesis of hot-spring deposits.

Low-Relief Structures.—These are structures with < 2 mm of relief. Such structures are the *mound armor, stratiform geyserite, streamer fabric,* and *stratiform stromatolite* microfacies. On the basis of comparison with modern analogs (Guidry and Chafetz 2003a; Walter 1976b; Walter et al. 1972, 1976; Walter et al. 1996), we interpret these structures as having formed in stagnant or flowing shallow waters and, in some examples, subjected to episodic drying. Similar, low-relief structures have been described in high-temperature siliceous sinters from Yellowstone (Braunstein and Lowe 2001; Lowe and Braunstein 2003) and in fossiliferous siliceous sinter deposits from New Zealand (Campbell et al. 2001). Salient characteristics are listed in Table 1.

The *mound armor microfacies* (Fig. 5A, B) is common at Artist Point. It is chert characterized by thin, dense quartz sheets. Bedding-surface cracks formed as silica cooled and dried between eruptive periods after hot, silica-rich water bathed the surface. Ripple marks formed as water surged in hot springs. In thin section, interlocking quartz crystals define thin discontinuous laminae composed of a single layer of crystals. These laminae are visible only under cross-polarized light. Sheets are separated at irregular intervals by void-filling quartz crystals coated with meniscus cements of amorphous opaline silica (Fig. 5B). Some sheets are separated by an opaque, orange stain, visible in hand samples, which may be iron oxide but the chemical composition could not be confirmed using EDS. Others are separated by volcaniclastic layers containing glass shards. The mound armor microfacies is interpreted as a near-vent microfacies, similar to the silica deposits formed in lower slope, run-out areas of cone geysers (Braunstein and Lowe 2001; Guidry and Chafetz 2003a; Lowe and Braunstein 2003).

Figure 5

Low- and moderate-relief structures: **A)** Mound armor microfacies



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showing bedding surface with ripples and cracks. **B)** Mound armor microfacies showing discontinuous sheets of fine quartz crystals, coarse void-filling quartz crystals, and meniscus cements (cross-polarized light). **C)** Stratiform geyserite microfacies showing dense, thin laminations. **D)** Discontinuous sheets of quartz crystals in stratiform geyserite microfacies (cross-polarized light). **E)** Stratiform stromatolite microfacies showing thin laminae of submicron-size quartz crystals, opaque horizons, and low domical structures. **F)** Photograph of streamer fabric microfacies, **G)** Photomicrograph (cross-polarized light) of Part E. Box shows geopetal fill. **H)** Columnar geyserite microfacies showing opal-C with fine-size quartz crystals. Arrow shows Type 1 fabric. **I)** Columnar stromatolite with ridges and spines microfacies showing tall, well-developed columns. **J)** Columnar stromatolite with ridges and spines microfacies showing short columns over stratiform stromatolite microfacies. **K)** Columnar stromatolite with ridges and spines. Arrow shows Type 2 fabric. **L)** Photomicrograph (cross-polarized light) of columnar stromatolite with domes microfacies showing dense, radially arranged zones of differently sized quartz crystals. **M)** Photograph of columnar stromatolite with domes microfacies showing dense, thick bedding and irregular top. **N)** Generic columnar stromatolite microfacies several centimeters high with dense quartz infilling of pore space; arrow shows mottled area at center of column. **O)** Living microbial mat showing textures that will develop into generic columnar stromatolite microfacies. **P)** Photomicrograph (cross-polarized light) of generic columnar stromatolite microfacies showing long, vertically oriented zones of differently sized quartz crystals. **Q)** Photomicrograph (cross-polarized light) of generic columnar stromatolite microfacies showing the dense quartzose horizon (pearly lustered top) overlying porous zone of combined Types 1 and 2 radial fabric. **R)** Photograph of generic columnar stromatolite microfacies showing combined Types 1 and 2 radial fabric.

Stratiform geyserite microfacies (Fig. 5C, D) constitutes the most abundant fabric type at Artist Point. It is dense, thinly laminated, bedded chert. The beds are preserved in-place in one road cut, but this microfacies generally occurs in large pieces of float. In thin section, the rocks consist of thin, discontinuous sheets of quartz crystals. Some chalcedonic spheres are observed, suggesting formation from a colloidal solution such as observed in Cistern Spring or Porcelain Terrace of Norris Geyser Basin (D.E. White et al. 1988). Silica concentrations in these modern springs exceed 500 to 600 ppm (Thompson and DeMonge 1996) and would be oversaturated with respect to opal-A at surface temperatures (Fournier et al. 1982; Guidry and Chafetz 2003c). Such precipitates form thin sheets covering extensive areas in modern systems and indicate oversaturated silica concentrations (Lowe and Braunstein 2003; D.E. White et al. 1956). The bedding planes are covered with ripple marks and primary, hence, subaqueous cooling cracks. This microfacies is interpreted as forming in pools surrounding gently surging springs that do not have significant discharge, similar to microfacies reported by others for fully subaqueous surfaces on which fine particulate siliceous sediments accumulate (Braunstein and Lowe 2001; Guidry and Chafetz 2003a). It is interpreted as a near-vent microfacies.

Streamer fabric microfacies (Fig. 5F) is uncommon at Artist Point. It is chert with a characteristic bedding-plane fabric indicative of microbial filaments oriented by flowing water (Walter et al. 1972). In thin section, this microfacies has lenticular laminae of very fine-grained quartz and finer-grained opal-A with low domical structures. Campbell et al. (2001) report filamentous textures on the surface of "palisade microfacies." The internal structures reported by Campbell et al. (2001) are not observed in examples of this microfacies from Artist Point and were either not there initially or were obliterated during diagenesis. However, caution must be used in identifying this microfacies solely on the basis of thin section observations; it is very difficult to distinguish from stratiform stromatolite microfacies on the basis of thin sections alone (see below). This microfacies usually overlies stratiform geyserite. In modern systems, streamer fabrics form subaqueously in flowing water (Walter et al. 1972).

Stratiform stromatolite microfacies (Fig. 5E, G) is the most common biogenic fabric at Artist Point. It is chert with few distinguishing macrofabrics identified by the regularity of quartz crystal size. Local domical structures incorporated into otherwise flat laminae defined primary horizontal voids, many of which are lined with microcrystalline quartz. This microfacies is distinguished from mound armor and stratiform geyserite by the lack of horizontal voids lined with quartz crystals in the latter two microfacies. No microfossils are observed. Campbell et al. (2001) describe a "thinly laminated microfacies" with similar characteristics, although their example had obvious microfossils. The flat laminae and voids of the Artist Point examples are reminiscent of the thick, organic-polymer-bound microbial mats underlying modern quiescent pools in which other biogenic features occur (Walter et al. 1976). The voids could result from trapped gas bubbles under the mat surface (Hinman and Lindstrom 1996) and may subsequently be filled with silica (see box in Fig. 5G). In modern systems, this subaqueous microfacies can be extensive. In comparison with modern environments and description of the fossiliferous microfacies of Campbell et al. (2001), this microfacies is interpreted as mineralized microbial mats in which microfossils are not preserved.

Moderate- to High-Relief Structures.—Moderate- to high-relief (2 mm to < 10 cm) structures form mainly in two environments: quiescent but not stagnant pools of variable depth, and splash zones surrounding orifices (Braunstein and Lowe 2001; Cady and Farmer 1996; Guidry and Chafetz 2003c; Lowe and Braunstein 2003). Salient characteristics are in Table 1.

Columnar geyserite microfacies (Fig. 5H) (Braunstein and Lowe 2001; Jones et al. 1997a; Lowe and Braunstein 2003; Walter 1976a) is white to gray chert and is not common at Artist Point. The columns, visible in hand samples and thin sections, are capped by smooth silica coating with pearly luster, which is expressed as tangential laminae in thin section. At Artist Point, columnar geyserite is characterized by uniformly sized quartz crystals arranged in internally layered columns. Small voids separate these columns and are filled either with geopetal sediments or with more coarsely crystalline quartz. Small, locally well-developed columns of silica accumulating near boiling springs in splash zones exhibit columns with similar size and shape (Braunstein and Lowe 2001; Jones et al. 1997a; Walter 1976a). The columnar geyserite microfacies of these ancient rocks is thus inferred to have formed in this environment.

Columnar stromatolite microfacies (CS) is found with three distinctive morphologies; ridges and spines, domes, and generic.

CS with ridges and spines microfacies (Fig. 5I, J, K) is common at Artist Point. It combines a pillared fabric with the bedding plane texture described by Walter et al. (1976) from columnar stromatolites with conical morphology and appears to be similar to the *thin-bedded with conical laminae* microfacies of Walter et al. (1996). This microfacies is similar to the palisade microfacies described elsewhere (Campbell et al. 2001; Lynne and Campbell 2003; Walter et al. 1996) but has slightly larger pillar diameter and length. Individual layers are 2 to 10 mm thick, as opposed to 1-2 mm thick, and consist of fine quartz in a dense, wavy lower horizon and a porous upper horizon that is transected by numerous vertical fenestrae. The surface consists of sinuous ridges and valleys with thin silica sheets spanning the gaps between them like the "columns with conical tops" (*Conophyton weedii*) of Walter et al. (1976). Opaline dendrites extend downward and outward from the peaks (left side of Fig. 5K). The dendrites are distinguished from groundmass by differences in crystal size, lack of infill between strands, or opaque coating. The dendrites are thought to represent former microbial filaments because of their size, orientation, and similarity to *Conophyton* stromatolites (Walter et al. 1976). Coarse quartz crystals and/or iron oxides sometimes fill gaps between dendrites (right side of Fig. 5K). The apices of the spokes of this microfacies point upwards (top left corner of Fig. 5K). Further, the dendrites of this microfacies are 10 to 15 μm thick and hence considerably thinner than those of the columnar stromatolites with domes microfacies. In modern systems, the surface texture of this microfacies, of which the cyanobacterium, *Phormidium* sp., is an essential component, forms in pools between 1 and 10 cm deep (Walter et al. 1976). As Walter et al. (1976) observed such columns growing in water between 32°C and 59°C, we interpret this microfacies in the Artist Point sinter as having formed under subaqueous conditions in this temperature range.

CS with domes microfacies (Fig. 5L, M) is common at Artist Point. It is dense white and gray chert with vertical and radial fenestrae. In hand samples, irregular bedding surfaces have low domical structures with smooth or rough surfaces resembling a row of shrubs. In thin section, the fabric consists of dense, stellate dendrites. The dendrites cover less than a quarter of a circle, with the center of the stellate shape below the rim; that is, the apex of this radial fabric points downward. The dendrites are spokes 50 to 80 μm thick that alternate between coarse quartz crystals or void spaces, and fine quartz crystals. The stellate dendrites distinguish between this microfacies and columnar geyserite, which has tangentially oriented laminae (Fig. 5H). The intergrowth of coarse and fine quartz crystals obscures this microfacies in some examples. Guidry and Chafetz (2003a, 2003c) describe a similar microfacies as *discharge channel/flowpath facies* in which siliceous shrubs are present. Walter et al. (1996) describe a microfacies in Devonian hot spring deposits as *thin-bedded with pustular bedding plane features.* They interpret that microfacies as forming in shallow pools at temperatures less than 30°C and populated with the cyanobacterium *Calothrix* sp. Although Walter et al. (1996) do not describe the internal structures of their examples, similarities in bedding-plane surfaces suggest that they may be equivalent. In modern systems, this microfacies forms in shallow (< 1 cm) pools bounded by small terracette dams and is always subaqueous (Guidry and Chafetz 2003a, 2003c; Walter et al. 1996).

Generic CS microfacies (Fig. 5N, O, P, Q, R) is common at Artist Point. It consists of flat to dome-topped columns of varying heights lacking consistent bedding. Columns are delineated by vertical fenestrae. The upper and lower surfaces of the columns comprise quartz crystals while the columns themselves consist of quartz with opal-C or iron-oxide coatings. Two morphologies of columns are observed. One morphology resembles modern thermophilic microbial columns growing in pools several centimeters deep (Fig. 5N, O), shorter examples of which are reported in Walter et al. (1972) and Walter et al. (1996). Fine-grained quartz forms vertical, but not radial, dendrites. In modern systems, the cyanobacterium *Phormidium* sp. forms columns, the height of which is determined by the water depth. These structures form between 32° and 59°C (Walter et al. 1972).

The second columnar morphology takes the form of mounded and linked microbial columns, 1 to 1.5 cm high (Fig. 5P, Q, R). The column links have a pearly luster and consist of several layers of quartz crystals. Cell fragments are found in this columnar morphology; this columnar morphology contains the only recognizable microfossils in the Artist Point microfacies although the taxon cannot be determined. Silica infilling has apparently occurred around radially oriented features interpreted to be the sheaths of filamentous microorganisms. These features are used to distinguish this microfacies from columnar geyserite, which has parallel laminations. The small columns are capped with a curved, dense horizon (1 to 2 mm thick) overlying a porous array of quartz-encased micro-pillars arranged like spokes (Fig. 5P, Q, R). This morphology of columnar stromatolite is interpreted to form in intermittently flowing channels and by a process in which mineral-rich water is wicked from the channel by capillary action to evaporate at the surface of the mat leaving a dense, highly resistant, surface coating (Hinman and Lindstrom 1996).

High-Relief Structures.—Few high-relief (> 10 cm) structures are observed. Only one high-relief microfacies is identified. Salient characteristics are listed in Table 1.

Spicular microfacies (Jones and Renaut 2003b; Walter 1976a; Walter et al. 1996) (Fig. 6A, B) was observed once at Artist Point. It is white chert with botryoidal surfaces and hemispheric bedding, similar to that reported by Guidry and Chafetz (2003a). The hemispheres consist of coalesced spicules of geyserite that may represent water-drop accumulations (Walter 1976a), differences in water content (Jones and Renaut 2003b, 2004), or influences of biofilms on silica deposition (Cady and Farmer 1996). No cellular remains or biofilms are observed in this microfacies. Spicules, coalesced into botryoidal bedforms, are modern examples of this microfacies, which are associated with cone geysers (Braunstein and Lowe 2001; Walter 1976a). In the sample from Artist Point, spicules with internal laminations are observed, as observed by Walter (1976a), Jones and Renaut (2004), and Walter et al. (1996). These features support the interpretation that the s*picular microfacies* of Walter et al. (1996) is present at Artist Point. In modern systems, these hemispheres accrete in splashing zones proximal to geysers (Braunstein and Lowe 2001; Guidry and Chafetz 2003a; Jones and Renaut 2003b; Jones et al. 2003; Walter 1976a; Walter et al. 1996), and we interpret this microfacies as forming in a similar environment.

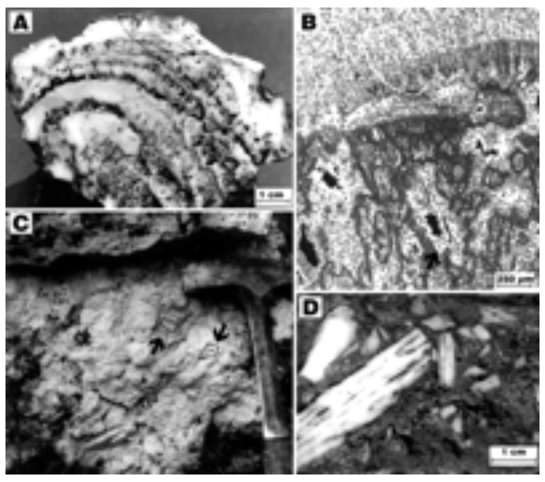

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Figure 6

High-relief structures. **A)** Dense, white spicular geyserite. **B)** Photomicrograph of the same showing fine-size quartz crystals. **C)** Siliceous sinter fragments in silicified enclosing sediments of Artist Point (arrows and boxes show fragments). **D)** Siliceous sinter fragments in unsilicified enclosing sediments of Artist Point.

Other.—Other microfacies are observed and provide evidence in support of the host rocks constituting an explosion breccia. *Matrix-supported breccia* (Fig. 6C, D) contains clasts of sinter, particularly the stratiform geyserite, in a matrix of kaolinite and devitrified glass, which is sometimes silicified. This differs from the sinter breccia reported by Walter (1976b) and Campbell et al. (2001), which is similar to the fragmental-type sinter reported by D.E. White et al. (1964), in that the Artist Point material is matrix-supported, the clasts are randomly oriented, and the matrix is not mainly siliceous, although it may be silicified. The intraclastic breccia and fragmental sinter reported elsewhere (Campbell et al. 2001; Guidry and Chafetz 2003a; Walter 1976b; D.E. White et al. 1964) are clast-supported, the clasts are imbricated, and the matrix is finer-sized grains of the same material as the clasts. With the exception of sinter breccia reported by Campbell et al. (2001), these other examples are bedded, whereas no bedding is observed at Artist Point.

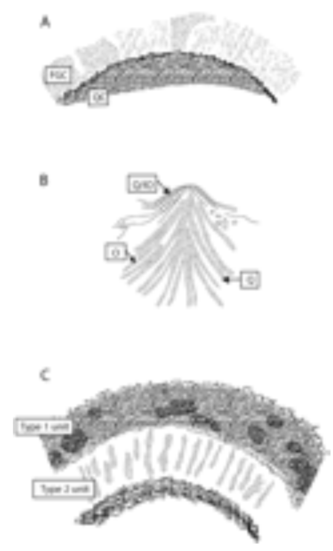
The origin of the breccia is controversial; field relationships cannot be used to distinguish between lahar and hydrothermal breccia. Devitrified glass suggests that the material is volcaniclastic. Lahar and explosion deposits would look the same because both would create a matrix-supported breccia containing clasts of country rock and no distinct bedding. But a lahar would show evidence of transport, which is not observed. Hence, we interpret the breccia formed from a hydrothermal explosion (eruption) (Browne and Lawless 2001).

Petrographic Fabrics

Petrographic fabrics are usually recognized as variations in mineral type and/or crystal size and are related to rock type and microfacies. In Artist Point examples, quartz and opal-C are found in combinations of crystal size and orientation that create distinctive petrographic fabrics.

Two types of radial fabric are observed (Fig. 7) in columnar geyserite and columnar stromatolite microfacies. Type 1 appears as quartz or (rarely) opal in fine-grained caps over "columns" of medium-grained quartz with limited porosity (Figs. 5H, 7A). This fabric is observed in columnar geyserite microfacies. Type 2 appears as mineralized spokes of alternating quartz and opal that project downward from an apex (Figs. 5K, 7B). The spokes are opal and quartz, and the interstices are quartz or empty. Often the apex of the spokes is draped with thin quartz sheets or iron oxides (Fig. 7B). By comparison with living microbial mats in which the spokes are filamentous microbes surrounded by voids (Walter et al. 1972), we infer that the spokes serve as a template for silica deposition either by coating or infusion of the microbial filaments (Campbell et al. 2001; Hinman and Lindstrom 1996; Jones and Renaut 2003a; Jones et al. 1997b, 1998; Lynne and Campbell 2003; Renaut et al. 1998; Walter et al. 1976).

Figure 7



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Schematic drawings, based on multiple thin-section observations of the two types of radial fabrics. Each drawing represents a field of view that is approximately 50 µm wide. **A)** Type 1 radial fabric consists of quartz or (rarely) opal in fine-grained caps (FGC) with some porosity over "columns" of fine- to medium-size quartz crystals with limited porosity (QC). **B)** Type 2 radial fabric consists of alternating quartz (Q) and opal (O) arranged in rays of a fan that project downward from a central point, often draped with quartz or iron oxide (Q/IO). **C)** Combined Types 1 and 2 radial fabrics consisting of quartz with or without opal from underlying portion of Type 1 radial fabric in a porcellanous top overlying radially arranged rays of quartz and opal of Type 2 radial fabric.

A combination of Type 1 caps and Type 2 spokes is observed in columnar stromatolite microfacies. This texture is interpreted to form under subaerial conditions in which fluids are pulled upwards by capillary action to form a dense surficial layer with pearly luster (Figs. 5P, Q, 7C). The spokes in this combined fabric probably formed the same way as the rays of Type 2 fabrics but are usually oriented with the apex downwards and the spokes radiating upwards.

Fabrics perpendicular to bedding are observed as variations in crystal size and/or mineralogy (Fig. 5L). They are similar to Type 2 radial fabrics and are observed in both stratiform and columnar stromatolite microfacies. Their occurrence might represent palisade-type microfacies after Walter et al. (1996) and Campbell et al. (2001). Like Type 2 radial fabrics, perpendicular fabrics form when filamentous microbes are coated and infused with silica, leaving vertically oriented fenestrae, which may become filled with quartz crystals (Jones and Renaut 2003a).

Steamboat Springs Results

Only three microfacies are identified in the pre-Lousetown sinters from Steamboat Springs, all three of which were also noted at Artist Point. The paragenetic sequence is unknown, but the deposit has likely followed the silica diagenetic sequence observed in other siliceous hot-spring deposits (Campbell et al. 2001; Guidry and Chafetz 2003b; Hinman 1995; Lynne and Campbell 2003; Rodgers et al. 2002; D.E. White et al. 1964).

Mineralogy

Quartz is the dominant mineral in these rocks. It is fine grained (< 20 µm) with a few coarse quartz crystals as cavity fills. As in the Artist Point sinters, fine-grained quartz (< 1 µm) with sweeping extinction is also observed. It is present in various stages of recrystallization; that is, the sweeping extinction is not continuous. It is not known what causes this extinction pattern, but the quartz crystals exhibiting this pattern recrystallized or grew to larger crystal sizes (Fig. 8A, B). EDS indicates this mineral consists of Si and O.

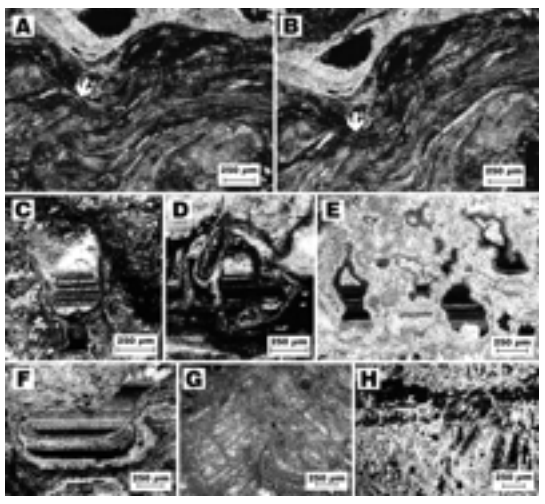

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Figure 8

Photomicrographs of Steamboat Springs siliceous sinters. **A)** Photomicrograph of stratiform stromatolite microfacies. Quartz with sweeping extinction pattern (arrow). **B)** Same view as Part A but with different orientation. **C)** Photomicrograph of geopetal silica deposits filling voids. Uncommon example of initial coarse filling becoming finer over time with the last event once again precipitating coarse quartz crystals. Deposition of geopetal deposits is preceded by a complex series of void-lining precipitates in this example. **D)** Photomicrograph of geopetal silica deposits filling voids. Initial filling is fine becoming coarser over time. **E)** Photomicrograph of geopetal silica deposits filling void space. Two of the three exhibit the more common pattern of fine to coarse quartz crystals while central geopetal fill exhibits the coarse to fine crystal precipitation pattern. **F)** Photomicrograph of geopetal silica deposits filling voids. Three separate void-filling events are depicted here, all with initial deposition of fine crystals followed by coarser crystals. **G)** Photomicrograph of columnar stromatolite with ridges and spines microfacies exhibiting Type 2 fabric. **H)** Photomicrograph of probable example of parallel fabric.

Some samples also contain low-birefringence silica. The low-birefringence mineral is X-ray amorphous and is identified as opal-A. It is present in layers and is often associated with fenestrae. EDS indicates that only Si and O are present.

Observations and Interpretations

The most common biogenic microfacies at Artist Point, the stratiform and generic columnar stromatolite microfacies, are also the most common at Steamboat Springs. Streamer fabric microfacies is also observed. The most common microfacies at Artist Point, stratiform geyserite microfacies, is not identified at Steamboat Springs. Its absence may indicate lack of distinguishing characteristics after diagenetic changes.

One significant difference between sinters from Artist Point and those from Steamboat Springs is the greater abundance of geopetal fills at the latter location. At Steamboat Springs, geopetal fills are common in most examples (Fig. 8C–F) but are entirely absent from some. Geopetal fills at Steamboat Springs show complex patterns of fluid evolution as multiple sequences of silica phase and crystal size progressions. For example, several filling events are recorded as progressions from coarse to fine crystal sizes (Fig. 8F). The descriptions below are mostly related to descriptions of the same microfacies at Artist Point.

Stratiform stromatolite microfacies is the most common purported biogenic fabric at Steamboat Springs. The characteristics described earlier for the microfacies at Artist Point are used to distinguish this microfacies here. It is thinly laminated chert with regularly sized quartz crystals. Domical structures are of somewhat higher relief (up to 5 mm), but otherwise laminae are flat and delineate primary horizontal voids (Fig. 8A, B). As at Artist Point, geopetal fills are observed in this microfacies. Other primary horizontal voids are lined with large (up to 10 μm) equant quartz crystals, microcrystalline quartz, or chalcedony.

Columnar stromatolite microfacies is much less common at Steamboat Springs than at Artist Point. The CS with ridges and spines microfacies is the only one of the columnar stromatolite microfacies found at Steamboat Springs (Fig. 8G). As at Artist Point, this microfacies consists of fine-grained quartz with upward-pointing stellate dendrites suggestive of the conical morphology observed by Walter et al. (1996). As at Artist Point, fewer geopetal fills are observed in the columnar stromatolite microfacies.

Streamer fabric microfacies is observed at Steamboat Springs and shows the same surface features as that of Artist Point. As at Artist Point, this microfacies is nearly indistinguishable from the stratiform stromatolite microfacies in thin section. It is characterized by a linear, bedding-plane fabric indicative of microbial filaments oriented by flowing water (Walter et al. 1972). In thin section, this microfacies is characterized by very fine-grained quartz crystals.

Petrographic Textures

Identical but fewer petrographic textures are observed in Steamboat Springs sinters as compared to Artist Point sinters. Laminated sinters (Fig. 8A, B) and Type II fabric (Fig. 8G) are present. A perpendicular fabric may be present in one sample (Fig. 8H). The abundance of sinter types in modern sinters at Steamboat Springs suggests that diagenesis is responsible for the textural loss.

Discussion

The occurrence of microfacies in sinters at Artist Point and Steamboat Springs provides an opportunity to evaluate preservational events. These two deposits have reached different degrees of silica diagenesis. Steamboat Springs is mostly in the quartz phase, whereas Artist Point still has significant amounts of opal. Petrography, mineralogy, and the presence of fewer microfacies at Steamboat Springs than at Artist Point is probably a consequence of the greater diagenesis at the former site but may be the result of original differences. Both possibilities are considered below. The lack of definitive microfossils at either location contrasts with Devonian Drummond Basin sinters (Walter et al. 1996) and Pleistocene Umukuri sinters (Campbell et al. 2001; Lynne and Campbell 2003). Because only one microfacies from Artist Point contains probable microfossils, links between microfacies and microbes in the following discussion can be inferred only on the basis of interpretations from other sites where microfossils have been identified (Campbell et al. 2001; Guidry and Chafetz 2003a; Konhauser et al. 2003; Lynne and Campbell 2003; Walter et al. 1996). This discussion thus focuses on interpreting microfacies in terms of the physicochemical environment of silica deposition and diagenesis.

Textural Variability

Examples of low-relief microfacies are more numerous than other types at both sites, because of either original abundance or preservation. Further, low-relief structures appear to be denser and more diagenetically advanced than higher-relief microfacies. Two factors likely contribute to this. First, two low-relief microfacies (mound armor, stratiform geyserite) form close to the vent and hence are subjected to high temperatures (Table 1). Second, three low-relief microfacies (stratiform geyserite, streamer fabric, and stratiform stromatolite) are deposited subaqueously and thus could be expected to precipitate from hot, silica-rich waters almost continuously under constant chemical and thermal conditions. Nucleation and deposition rates would be fairly constant. Hence, the initial phase precipitated in these low-relief structures is of uniform crystal size. These microfacies have similar characteristics at both sites. However, void-fills reflect postdepositional fluid compositions, and might be different between the two areas.

In stratiform-type microfacies, some voids begin filling with coarse quartz crystals and progress toward finer-grained quartz and opal (Figs. 5B, 8E, 9A). To form large crystals, silica must have precipitated from marginally oversaturated solutions (Williams et al. 1985). Such conditions would be achieved at low silica concentrations or, more likely because of the proximity of stratiform-type microfacies to vents, at high temperature. A slower rate of formation of nuclei at lower levels of saturation leads to formation of fewer larger crystals (Dove and Rimstidt 1994; Iler 1979). Upon cooling, smaller crystals formed as oversaturation increased, increasing the rate of nucleation (Iler 1979; Williams et al. 1985). This progression suggests changes in thermal conditions. The opposite would be expected if precipitates formed from isothermal oversaturated solutions. In that case, as silica precipitated and saturation decreased, the rate of nucleation and deposition would decrease, and the crystal size would become coarser (Figs. 5G, 8C, D, 9B). As a consequence, the progressive change in crystal size in void-fills can be used to infer the thermal history during silica precipitation (Dove and Rimstidt 1994; Iler 1979; Williams and Crerar 1985). If progression from coarser to finer is observed, then infilling occurred shortly after deposition while the fluids were initially hot and then cooled. If the observed sequence is reversed, then infilling must have occurred under isothermal conditions. Sinters at Artist Point exhibit both patterns. Sinters at Steamboat Springs exhibit dominantly fine-to-coarse sequences indicating isothermal conditions. It appears that Artist Point experienced a range of thermal conditions during void-filling whereas Steamboat Springs experienced a more limited range.

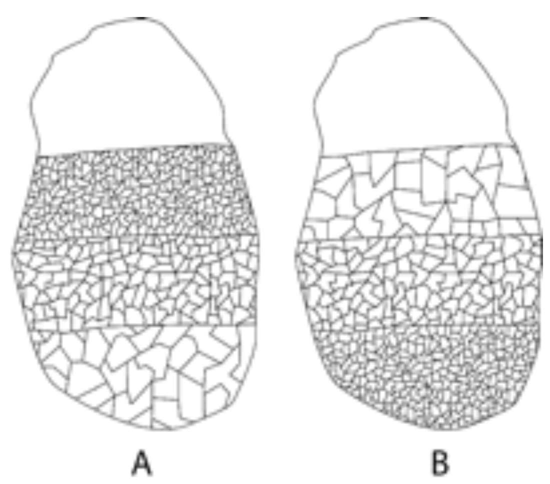

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Figure 9

Simplified schematic drawing of the difference in geopetal-fill crystal sizes as a consequence of differences in nucleation and growth rates. **A)** Crystal sizes of quartz formed during filling of void under initially high and

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subsequently decreasing temperatures. **B)** Crystal sizes of quartz formed during filling of void under isothermal conditions.

Crystal size, textures, and silica mineralogy in sinters with microbial textures are more variable than those without such textures. The former have large voids, which are largely absent in sinters without microbial textures. Slower rates of deposition and diagenesis at lower depositional temperatures of mat-fabric sinters could result in greater variety of silica phases and crystal sizes.

Crystal size is partially dependent on the timing of precipitation and/or diagenesis, and is controlled by the temperature of deposition, the original texture and pore size, and/or the presence of microbial structures (Campbell et al. 2001; Guidry and Chafetz 2003b; Hinman 1995, 1997; Lynne and Campbell 2003; Rodgers et al. 2002). The effect of initial silica deposition on crystal size is well illustrated in the Type 2 fabric. Here, the crystal and pore size of the fabric is much more variable than in the dense surfaces of Type 1 fabrics (Fig. 5P, Q, R). Information about dense surfaces, like Type 1 fabrics, is lost more quickly during diagenesis than that contained in the more variably sized crystals in Type 2 fabrics, which may explain why Type 1 fabrics are not observed at Steamboat Springs. The following sequence of events explains the formation of Type 2 fabrics. (1) Microbial mat is infused with silica that precipitates as opal-A. (2) Remaining pore space is filled with coarser-grained quartz, preserving original thickness and dendritic structure. (3) Silica in microbial remnants recrystallizes (Fig. 8G). Similar diagenetic and taphonomic progressions have been suggested (Campbell et al. 2001; Guidry and Chafetz 2003b; Hinman 1997; Jones and Renaut 2003a). Most textural information is lost in the third step (Lynne and Campbell 2003). Steamboat Springs sinters have reached this stage. Loss of textural information biases the geological record of microbial signatures (Walter 1977).

Preservation Potential of Microfacies

Preservation potential of microfacies in ancient hot-spring deposits is of primary importance. Because mechanical erosion focuses on structures with higher relief, such structures may have a lower preservation potential. However, it is not only relief that determines whether a given microfacies is preserved in the geologic record. Pore filling and transition to more stable silica phases are of greater importance (Lynne and Campbell 2003). Temperature, ionic strength, and chemistry control silica speciation and rates of silica deposition (Hinman 1990, 1998; Iler 1979; Kastner et al. 1977; Mountain et al. 2003; Williams and Crerar 1985; Williams et al. 1985). These factors can accelerate or deter silica deposition; thus, it is important to compare conditions at Artist Point and Steamboat Springs to determine differences in depositional and diagenetic conditions. In addition, paleohydrology is important in determining the timing and extent of the solution-reprecipitation reactions that lead to silica diagenesis (Guidry and Chafetz, 2003c; Hinman 1997; Lynne and Campbell 2003). The initial chemical conditions at Artist Point and Steamboat Springs can be approximated by comparing modern analogs for each location.

Depositional Parameters.—The sinters of Artist Point were deposited on the shores of proto-Lake Yellowstone (Christiansen 2001; Richmond 1976) and, as evidence presented herein suggests, may have been altered by hydrothermal explosion. Modern hot springs are found in the West Thumb and Potts Basins on the shores of Lake Yellowstone. Small hydrothermal explosion deposits have been observed as redistributed sinter around the vents of some hot springs in these two basins (Taylor and Grigg 1999). Evidence of older, larger sublacustrine explosions are found on the lake floor and in surrounding deposits (Johnson et al. 2003; Morgan et al. 2003). The sinters at Potts and West Thumb Basins are dominantly low- to moderate-relief microfacies. With few exceptions, most springs there do not build edifices or precipitate significant amounts of geyserite (Taylor and Grigg 1999). Thus, the depositional environment and resulting deposits at West Thumb and Potts Basins are similar to those of Artist Point because of their near-lake environment and dominance of low- to moderate-relief microfacies.

Several periods of thermal activity have occurred at Steamboat Springs since deposition of the older siliceous sinters (Silberman et al. 1979; Thompson and White 1964; D.E. White et al. 1964). Thus modern deposits there are probably adequate analogs for the 2.4 Ma siliceous sinters described here. The present depositional environment comprises a broad, sinter-covered slope with small geyserite cones, hot springs with runoff channels, and breccia interfluves.

Modern features have edifices and geyserites not present in the older siliceous sinters.

Chemical Variations.—Water chemistry is another factor constituting depositional environment. Differences in water chemistry could affect mineral solubility, which could explain loss of microfacies variability at Steamboat Springs. Chemically, the two modern analogs are similar (Table 2). While some differences would affect the speciation of silica (e.g., higher activities of silicofluoride complexes in Yellowstone waters than in Steamboat waters), the saturation indices for silica minerals would be largely unaffected. So silica deposition rates, as dictated by degree of oversaturation, are not driving differences in microfacies preservation between Artist Point and Steamboat Springs sinters.

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Table 2

Comparative water chemistry for West Thumb Geyser Basin and Steamboat Springs, Nevada.

Concentrations of silica and other elements indicate source temperature. Geothermometry suggests similar temperatures at both sites (Table 2) of < 200°C based on silica concentrations and of < 210°C based on alkali feldspar geothermometry (Henley et al. 1984). Thus chemical and thermal parameters known to affect silica deposition are similar in the modern analogs, and by inference, in Artist Point and Plio-Pleistocene Steamboat Springs. Hence, loss of microfacies is more likely a consequence of postdepositional conditions.

Postdepositional Environment.—The postdepositional conditions at these two sites are critical to understanding diagenetic changes. These areas have greatly different postdepositional histories. Both sinters were buried beneath alpine glaciers at least twice since deposition (Christiansen 2001; Richmond 1976; Silberman et al. 1979; Thompson and White 1964; D.E. White et al. 1964), but the siliceous sinters of Steamboat Springs also were buried by the andesitic basalt of the Lousetown Formation (D.E. White et al. 1964). Both events have implications for thermal and hydrologic history of the postdepositional environment.

The postdepositional thermal environment at Artist Point was somewhat extreme. Ice thickness at Artist Point is estimated to have been 250 meters (Richmond 1976). The boiling curve for water indicates a maximum temperature of 260°C at this depth (Bargar and Fournier 1988). Hence the Artist Point siliceous sinters were exposed to higher temperatures after deposition. Elevated temperatures would promote more rapid silica diagenesis than ambient surface temperatures. It is not known whether thermal activity at Artist Point ceased prior to glaciation, but evidence for subglacial silica cementation has been observed elsewhere in Yellowstone (D.E. White et al. 1988). If subglacial thermal activity persisted, then isothermal silica deposition would be expected. Evidence is found for this as finer to coarser crystal-size progression in void-fills. Reversed size progressions argue for deposition under cooling conditions.

In addition to burial under glacier ice, Steamboat Springs also experienced other conditions. The timing of the eruption of the Lousetown Formation relative to the formation of the Pre-Lousetown siliceous sinters is unknown, except to say the eruption postdates sinter deposition. The influence of igneous sills on diagenesis has been documented in the Guaymas Basin. Isotopic studies on silica minerals and calcite near the Guaymas Basin sills suggest that temperatures were at least 150°C within a few meters of the sill, and possibly up to 300°C directly adjacent to it (Kastner 1982; Kastner and Siever 1983). Indeed, fluid-inclusion temperatures are 260°C at Steamboat Springs (White and Heropoulos 1983) so geothermometric calculations based on modern chemistry may be low for Steamboat Springs. In addition to thermal conditions at least as extreme as those at Artist Point, the hydrologic conditions were altered from pre-basalt conditions as well. If the springs were still active when the Lousetown Formation erupted, the overlying heat source could induce heat convection promoting rapid, isothermal silica diagenesis in the underlying sediments (Kastner 1982; Kastner and Siever 1983). This series of events may be unique to Steamboat Springs, but the common co-occurrence of volcanic rocks and siliceous sinters highlights the potential to preserve or obliterate microfacies at any stage of preservation.

Similarities are noted in postdepositional conditions at Artist Point and

Steamboat Springs. Temperatures at both sites neared 260°C, on the basis of calculations for Artist Point (Bargar and Fournier 1988) and fluid-inclusion data for Steamboat Springs (White and Heropoulos 1983). It is more difficult to determine differences in hydrological conditions. Judging by crystal sizes and void-fill progressions, Steamboat Springs seems to have undergone silica diagenesis in isothermal, saturated conditions, whereas Artist Point had a wider range of thermal and hydrologic conditions during silica diagenesis, which may have contributed to loss of microfacies.

Conclusions

Given that most hot-spring systems have a similar suite of sinter textures (Walter 1976a, 1976b), it is likely that Steamboat Springs was initially very similar to Artist Point in the number of microfacies. Subsequent diagenesis obliterated many fabrics, resulting in fewer microfacies at the older site. Two microfacies observed at Artist Point that form near the hot-spring vent are also observed at Steamboat Springs. Only one of the remaining seven microfacies found at Artist Point is also identified at Steamboat Springs, supporting Guidry and Chafetz's (2003a) observation that preservation is more likely closer to the vent, where depositional processes are dominated by abiotic processes (Braunstein and Lowe 2001; Guidry and Chafetz 2003a, 2003b). The groundmass of siliceous sinters from Steamboat Springs has a more limited quartz crystal size than do the same microfacies from Artist Point. One explanation for uniform crystal size is rapid crystallization of primary opal under isothermal conditions. The dominance of fine to coarse void-filling at Steamboat Springs supports an isothermal history whereas Artist Point exhibits coarse to fine void-filling sequences more frequently than Steamboat Springs. Recrystallization under isothermal conditions has obliterated many primary textures of the rock by rapidly transforming silica and filling pore space simultaneously. Such rapid recrystallization under isothermal conditions could have resulted from the emplacement of the overlying andesitic basalt flow. The heat generated would have been sufficient to rapidly convert opal-A to quartz. The flow created an impermeable cap trapping high-temperature, silica-saturated water and resulting in quartz precipitation. At Artist Point, similar thermal conditions occurred below glacier ice but hydrologic conditions would not have been the same.

The textures observed in the Pleistocene sinter deposits of Artist Point, Yellowstone National Park, and the Plio-Pleistocene deposits of Steamboat Springs, Nevada, suggest that diagenetic processes promote preferential preservation of some microfacies (Campbell et al. 2001; Guidry and Chafetz 2003a, 2003b; Lynne and Campbell 2003). This conclusion is consistent with the observations of Lynne and Campbell (2003) that silica-phase mineralogy controls microfossil preservation, but it differs from their conclusion in that some microfacies are still recognizable regardless of silica phase while others are lost. For example, under extreme diagenetic conditions, such as those that probably occurred at Steamboat Springs, low-relief, near-vent microfacies are commonly preserved and common moderate-relief microfacies are rarely preserved. On the other hand, excellent textural preservation is observed at Artist Point, as well as in other locations (Drummond Basin, Australia, Walter et al. 1996; and Scotland, Trewin 1996). A combination of thermal and hydrologic histories account for these differences.

Acknowledgments

This manuscript benefited from the comments of R. Renaut, N. Trewin, K. Campbell, N. Herdianita, D. Budd, K. Schubel, G. Hinman, and anonymous reviewers. We appreciate their efforts. This work was supported by grants from the Montana Space Grant Consortium (N. Hinman), NASA-JoVe Program (N. Hinman) and NASA-Exobiology Program (D. Des Marais). We appreciate the support of The University of Montana and Macquarie University.

Received February 1, 1999.
Accepted September 16, 2004.

References

Bargar, K.E., and Fournier, R.O., 1988, Effects of glacial ice on subsurface temperatures of hydrothermal systems in Yellowstone National Park, Wyoming: fluid-inclusion evidence: *Geology*, v. 16, p. 1077–1080. »CrossRef »GeoRef »Abstract/FREE Full Text »Web of Science

Braunstein, D.C., 1999, The role of hydrodynamics in the structuring and growth of high-temperature (>73°C) siliceous sinter at neutral to alkaline hot springs and geysers, Yellowstone National Park [unpublished Ph.D. thesis]: Stanford University, 163 p.

Braunstein, D., and Lowe, D.R., 2001, Relationship between spring and geyser activity and the deposition and morphology of high temperature (>73 degrees C) siliceous sinter, Yellowstone National Park, Wyoming, USA: *Journal of Sedimentary Research*, v. 71, p. 747–763. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Brock, T.D., 1978, Thermophilic microorganisms and life at high temperatures: New York, Springer-Verlag, 465 p.

Browne, P.R.L., and Lawless, J.V., 2001, Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere: *Earth-Science Reviews*, v. 52, p. 229–331.

Cady, S.L., and Farmer, J.D., 1996, Fossilization processes in siliceous thermal springs: trends in preservation along thermal gradients, *in* Bock, G.R., and Goode, J.A., eds., Evolution of Hydrothermal Ecosystems on Earth (and Mars?): Ciba Foundation Symposium 202, New York, John Wiley, p. 150–173.

Campbell, K.A., Sannazzaro, K., Rodgers, K.A., Herdianita, N.R., and Browne, P.R.L., 2001, Sedimentary facies and mineralogy of the late Pleistocene Umukuri silica sinter, Taupo volcanic zone, New Zealand: *Journal of Sedimentary Research*, v. 71, p. 727–746. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Campbell, K.A., Rodgers, K.A., Brotheridge, J.M.A., and Browne, P.R.L., 2002, An unusual modern silica-carbonate sinter from Pavlova Spring, Ngatamariki, New Zealand: *Sedimentology*, v. 49, p. 835–854. » **CrossRef** » **GeoRef** » **Web of Science**

Christiansen, R.L., 2001, The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana: U.S. Geological Survey, Professional Paper 729-G, p. 145.

Dove, P.M., and Rimstidt, J.D., 1994, Silica-water interactions, *in* Heaney, P.J., Prewitt, C.T., and Gibbs, G.V., eds., Silica: Physical Behavior, Geochemistry and Materials Applications: Washington, D.C., Mineralogical Society of America, Reviews in Mineralogy 29, p. 259–308.

Farmer, J.D., Cady, S.L., Des Marais, D.J., and Walter, M.R., 1997, Fossilization processes in modern thermal springs: clues for assessing the biogenecity of ancient hydrothermal deposits (abstract): Conference on early Mars: Geologic and hydrologic evolution, physical and chemical environments and the implications for life: Lunar and Planetary Institute, LPI Contribution 916, p. 31.

Fournier, R.O., 1989, Geochemistry and dynamics of the Yellowstone National Park hydrothermal system: *Annual Review of Earth and Planetary Sciences*, v. 17, p. 13–53. » **CrossRef** » **Web of Science**

Fournier, R.O., Rosenbauer, R.J., and Bischoff, J.L., 1982, The solubility of quartz in aqueous sodium chloride solution at 350 degrees C and 180 to 500 bars: *Geochimica et Cosmochimica Acta*, v. 46, p. 1975–1978. » **CrossRef** » **GeoRef** » **Web of Science**

Fournier, R.O., Thompson, J.M., Cunningham, C.G., and Hutchinson, R.A., 1991, Conditions leading to a recent small hydrothermal explosion at Yellowstone National Park: *Geological Society of America, Bulletin*, v. 103, p. 1114–1120. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Guidry, S.A., and Chafetz, H.S., 2002, Factors governing subaqueous siliceous sinter precipitation in hot springs: examples from Yellowstone National Park, USA: *Sedimentology*, v. 49, p. 1253–1267. » **CrossRef** » **GeoRef** » **Web of Science**

Guidry, S.A., and Chafetz, H.S., 2003a, Anatomy of siliceous hot springs: examples from Yellowstone National Park, Wyoming, USA: *Sedimentary Geology*, v. 157, p. 71–106. » **CrossRef** » **GeoRef** » **Web of Science**

Guidry, S.A., and Chafetz, H.S., 2003b, Depositional facies and diagenetic alteration in a relict siliceous hot-spring accumulation: examples from Yellowstone National Park, U.S.A.: *Journal of Sedimentary Research*, v. 73, p. 806–823. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Guidry, S.A., and Chafetz, H.S., 2003c, Siliceous shrubs in hot springs from Yellowstone National Park, Wyoming, U.S.A.: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1571–1583. » **CrossRef** » **Web of Science**

Henley, R.W., Truesdell, A.H., and Barton, P.B.J., 1984, Fluid-mineral equilibria in hydrothermal systems: *Society of Economic Geologists, Reviews in Economic Geology*, v. 1, p. 1–267.

Herdianita, N.R., Browne, P.R.L., Rodgers, K.A., and Campbell, K.A., 2000, Mineralogical and textural changes accompanying ageing of silica sinter: *Mineralium Deposita*, v. 35, p. 48–62. » **CrossRef** » **GeoRef** » **Web of Science**

Hinman, N.W., 1990, Chemical factors influencing the rates and sequences of silica phase transitions: effects of organic constituents: *Geochimica et Cosmochimica Acta*, v. 54, p. 1563–1574. » **CrossRef** » **GeoRef** » **Web of Science**

Hinman, N.W., 1995, Silica diagenesis: Mortar Geyser Complex, Yellowstone National Park, USA: 8th International Symposium on Water-Rock Interaction, p. 511–514.

Hinman, N.W., 1997, Hydrological processes in microbial preservation: Instruments, Methods, and Missions for the Investigation of Extraterrestrial Microorganisms: Proceedings of the International Society for Optical Engineering (SPIE), v. 3111, p. 335–341.

Hinman, N.W., 1998, Sequences of silica phase transitions: effects of Na, Mg, K, Al and Fe ions: *Marine Geology*, v. 147, p. 13–24. » **CrossRef** » **GeoRef** » **Web of Science**

Hinman, N.W., and Lindstrom, R.F., 1996, Seasonal changes in silica deposition in hot spring systems: *Chemical Geology*, v. 132, p. 237–246. » **CrossRef** » **GeoRef** » **Web of Science**

Iler, R.K., 1979, The Chemistry of Silica: New York, John Wiley & Sons, 866 p.

Johnson, S.Y., Stephenson, W.J., Morgan, L.A., Shanks, W.C.I., and Pierce, K.L., 2003, Hydrothermal and tectonic activity in northern Yellowstone Lake, Wyoming: *Geological Society of America, Bulletin*, v. 115, p. 954–971. » **CrossRef** » **GeoRef**

» Abstract/FREE Full Text » Web of Science

Jones, B., and Renaut, R.W., 1996, Influence of thermophilic bacteria on calcite and silica precipitation in hot springs with water temperatures above 90C: evidence from Kenya and New Zealand: *Canadian Journal of Earth Sciences*, v. 33, p. 72–83. » Web of Science

Jones, B., and Renaut, R.W., 1997, Formation of silica oncoids around geysers and hot springs at El Tatio, northern Chile: *Sedimentology*, v. 44, p. 287–304. » CrossRef » GeoRef » Web of Science

Jones, B., and Renaut, R.W., 2003a, Hot spring and geyser sinters: the integrated product of precipitation, replacement, and deposition: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1549–1569. » CrossRef » Web of Science

Jones, B., and Renaut, R.W., 2003b, Petrography and genesis of spicular and columnar geyserite from the Whakarewarewa and Orakeikorako geothermal areas, North Island, New Zealand: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1585–1610. » CrossRef » Web of Science

Jones, B., and Renaut, R.W., 2004, Water content of opal–A: implications for the origin of laminae in geyserite and sinter: *Journal of Sedimentary Research*, v. 74, p. 117–128. » GeoRef » Abstract/FREE Full Text » Web of Science

Jones, B., Renaut, R.W., and Rosen, M.R., 1997a, Biogenicity of silica precipitation around geysers and hot–spring vents, North Island, New Zealand: *Journal of Sedimentary Research*, v. 67, p. 88–104. » CrossRef » GeoRef » Abstract/FREE Full Text » Web of Science

Jones, B., Renaut, R.W., and Rosen, M.R., 1997b, Vertical zonation of biota in microstromatolites associated with hot springs, North Island, New Zealand: *Palaios*, v. 12, p. 220–236. » CrossRef » GeoRef » Abstract/FREE Full Text » Web of Science

Jones, B., Renaut, R.W., and Rosen, M.R., 1998, Microbial biofacies in hot–spring sinters: A model based on Ohaaki Pool, North Island, New Zealand: *Journal of Sedimentary Research*, v. 68, p. 413–434. » GeoRef » Abstract/FREE Full Text » Web of Science

Jones, B., Renaut, R.W., and Rosen, M.R., 2003, Silicified microbes in a geyser mound: the enigma of low–temperature cyanobacteria in a high–temperature setting: *Palaios*, v. 18, p. 87–109. » GeoRef » Abstract/FREE Full Text » Web of Science

Jones, J.B., and Segnit, E.R., 1971, The nature of opal I. Nomenclature and constituent phases: *Journal of the Geological Society of Australia*, v. 18, p. 57–67.

Kastner, M., 1981, Authigenic silicates in deep–sea sediments: formation and diagenesis, *in* Emiliani, C., ed., The Oceanic Lithosphere: New York, Wiley, p. 915–979.

Kastner, M., 1982, Evidence for two distinct hydrothermal systems in the Guaymas Basin, *in* Curray, J.R., Blakeslee, J., Platt, L.W., Stout, L.N., Moore, D.G.A., Eduardo, J., Aubry, M.P., Gerhard, E., Fornari, D.J., Gieskes, J.M., Guerrero, C.L., Kastner, M., Kelts, K.R., Lyle, M., Matoba, Y., Molina–Cruz, A., Niemitz, J., Rueda–Gaxiola, J., Saunders, A.D., Schrader, H., Simoneit, B.R.T., and Vacquier, V., eds., Initial Reports of the Deep Sea Drilling Project: College Station, Texas, Texas A & M University, Ocean Drilling Program, p. 1143–1157.

Kastner, M., and Siever, R., 1983, Siliceous sediments of the Guaymas basin: the effect of high thermal gradients on diagenesis: *Journal of Geology*, v. 91, p. 629–641. » GeoRef » Web of Science

Kastner, M., Keene, J.B., and Gieskes, J.M., 1977, Diagenesis of siliceous oozes—I. chemical controls on the rate of opal–A to opal–CT transformation – an experimental study: *Geochimica et Cosmochimica Acta*, v. 41, p. 1041–1059. » CrossRef » GeoRef » Web of Science

Konhauser, K.O., Phoenix, V.R., Bottrell, S.H., Adams, D., and Head, I.M., 2001, Microbial–silica interactions in Icelandic hot spring sinter: possible analogues for some Precambrian siliceous stromatolites: *Sedimentology*, v. 48, p. 415–433. » CrossRef » GeoRef » Web of Science

Konhauser, K.O., Jones, B., Reysenbach, A.L., and Renaut, R.W., 2003, Hot spring sinters: keys to understanding Earth's earliest life forms: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1713–1724. » CrossRef » Web of Science

Liebig, K., Westall, F., and Schmitz, M., 1996, A study of fossil microstructures from the Eocene Messel formation using transmission electron microscopy: *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, v. 4, p. 218–231.

Lowe, D.R., and Braunstein, D., 2003, Microstructure of high–temperature (>73 degrees C) siliceous sinter deposited around hot springs and geysers, Yellowstone National Park: the role of biological and abiological processes in sedimentation: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1611–1642. » CrossRef » Web of Science

Lynne, B.Y., and Campbell, K.A., 2003, Diagenetic transformations (opal–A to quartz) of low– and mid–temperature microbial textures in siliceous hot–spring deposits, Taupo volcanic zone, New Zealand: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1679–1696. » CrossRef » Web of Science

Morgan, L., Shanks, P., Finn, C., and Chaffee, M., 2000, Field Trip Guide to New Discoveries in Yellowstone National Park: Results from Integrated Geoscience Studies in the Greater Yellowstone Area, U.S Geological Survey.

Morgan, L.A., Shanks, W.C.I., Lovalvo, D.A., Johnson, S.Y., Stephenson, W.J., Pierce, K.L., Harlan, S.S., Finn, C.A., Lee, G., Webring, M., Schulze, B., Duehn, J., Sweeney, R., and Balistrieri, L., 2003, Exploration and discovery in Yellowstone Lake: results from high–resolution sonar imaging, seismic reflection profiling, and submersible studies: *Journal of Volcanology and Geothermal Research*, v. 122, p. 221–242. » CrossRef » GeoRef » Web of Science

Mountain, B.W., Benning, L.G., and Boerema, J.A., 2003, Experimental studies on New Zealand hot spring sinters: rates of growth and textural development:

Canadian Journal of Earth Sciences, Special Issue, v. 40, p. 1643–1667. »**CrossRef** »**Web of Science**

Muffler, L.J.P., White, D.E., and Truesdell, A.H., 1971, Hydrothermal explosion craters in Yellowstone National Park: *Geological Society of America, Bulletin*, v. 82, p. 723–740. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Web of Science**

Phoenix, V.R., Konhauser, K.O., and Ferris, F.G., 2003, Experimental study of iron and silica immobilization by bacteria in mixed Fe–Si systems: implications for microbial silicification in hot springs: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1669–1678. »**CrossRef** »**Web of Science**

Renaut, R.W., Jones, B., and Rosen, M.R., 1996, Primary silica oncoids from Orakeikorako Hot Springs, North Island, New Zealand: *Palaios*, v. 11, p. 446–458. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Web of Science**

Renaut, R.W., Jones, B., and Tiercelin, J.J., 1998, Rapid *in situ* silicification of microbes at Loburu hot springs, Lake Bogoria, Kenya Rift Valley: *Sedimentology*, v. 45, p. 1083–1103. »**CrossRef** »**GeoRef** »**Web of Science**

Rice, C.M., Ashcroft, W.A., Batten, D.J., Boyce, A.J., Caulfield, J.B.D., Fallick, A.E., Hole, M.J., Jones, E., Pearson, M.J., Rogers, G., Saxton, J.M., Stuart, F.M., Trewin, N.H., and Turner, G., 1995, A Devonian auriferous hot spring system, Rhynie, Scotland: *Geological Society of London, Journal*, v. 152, p. 229–250. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Web of Science**

Richmond, G.M., 1976, Surficial Geologic History of the Canyon Village Quadrangle, Yellowstone National Park, Wyoming, for use with Map I–652: U.S. Geological Survey, Bulletin 1427, p. 35.

Richmond, G.M., 1977, Surficial Geologic Map of the Canyon Village Quadrangle, Yellowstone National Park, WYO, Map I–652: U.S. Geological Survey.

Rimstidt, J.D., and Barnes, H.L., 1980, The kinetics of silica–water reactions: *Geochimica et Cosmochimica Acta*, v. 44, p. 1683–1699. »**CrossRef** »**GeoRef** »**Web of Science**

Rodgers, K.A., Browne, P.R.L., Buddle, T., Greatrex, R.A., Hampton, W.A., Pastars, D., and Smith, B.Y., 2002, Minerals and microbes among the hot springs of New Zealand: *Mineralogical Society (London), Bulletin*, v. 134, p. 3–8.

Silberman, M.L., White, D.E., Keith, T.E.C., and Dockter, R.D., 1979, Duration of hydrothermal activity at Steamboat Springs, Nevada, from ages of spatially associated volcanic rocks: U.S. Geological Survey, Professional Paper 458–D, p. 1–13.

Smith, B.Y., Turner, S.J., and Rodgers, K.A., 2003, Opal-A and associated microbes from Wairakei, New Zealand: the first 300 days: *Mineralogical Magazine*, v. 67, p. 563–579. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Web of Science**

Smith, R.B., and Siegel, L.J., 2000, Windows into the Earth: The Geologic Story of Yellowstone and Grand Teton National Parks: Oxford, U.K., Oxford University Press, 256 p.

Stauffer, R.E., Jenne, E.A., and Ball, J.W., 1980, Chemical studies of selected trace elements in hot-spring drainages of Yellowstone National Park: U.S. Geological Survey, Professional Paper 1044–F, p. 1–20.

Taylor, R.C., and Grigg, L.B., 1999, Potts Hot Spring Basin Survey 1997–1998, v. P9: Palmdale, California, GOSA Store and Press, 370 p.

Thompson, G.A., and White, D.E., 1964, Regional geology of the Steamboat Springs area, Washoe County, Nevada: U.S. Geological Survey, Professional Paper 458–A, 52 p.

Thompson, J.M., and DeMonge, J.M., 1996, Chemical analyses of hot springs, pools, and geysers from Yellowstone National Park, Wyoming, and vicinity, 1980–1993: U.S. Geological Survey, Open-File Report 96–68, 66 p.

Trewin, N.H., 1994, Depositional environment and preservation of biota in the lower Devonian hot springs of Rhynie, Aberdeenshire, Scotland: *Royal Society of Edinburgh, Transactions*, v. 84, p. 433–443.

Trewin, N.H., 1996, The Rhynie cherts: an early Devonian ecosystem preserved by hydrothermal activity, *in* Bock, G.R., and Goode, J.A., eds., Evolution of Hydrothermal Ecosystems on Earth (and Mars?): Ciba Foundation Symposium 202, New York, John Wiley, p. 131–145.

Trewin, N.H., and Rice, C.M., 1992, Stratigraphy and sedimentology of the Devonian Rhynie chert locality: *Scottish Journal of Geology*, v. 28, p. 37–47. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Web of Science**

Trewin, N.H., Fayers, S.R., and Kelman, R., 2003, Subaqueous silicification of the contents of small ponds in an early Devonian hot-spring complex, Rhynie, Scotland: *Canadian Journal of Earth Sciences*, Special Issue, v. 40, p. 1697–1712. »**CrossRef** »**Web of Science**

Walter, M.R., 1976a, Geyserites of Yellowstone National Park: an example of abiogenic "stromatolites," *in* Walter, M.R., ed., Stromatolites: Amsterdam, Elsevier, Developments in Sedimentology 1976, p. 88–112.

Walter, M.R., 1976b, Hot-springs sediments in Yellowstone National Park, *in* Walter, M.R., ed., Stromatolites: Amsterdam, Elsevier, Developments in Sedimentology 1976, p. 489–498.

Walter, M., 1977, Biased record of early life: *American Scientist*, v. 65, p. 405–562.

Walter, M.R., 1996, Ancient hydrothermal ecosystems on Earth: a new palaeobiological frontier, *in* Bock, G.R., and Goode, J.A., eds., Evolution of Hydrothermal Ecosystems on Earth (and Mars?): Ciba Foundation Symposium 202, New York, John Wiley, p. 112–130.

Walter, M.R., Bauld, J., and Brock, T.D., 1972, Siliceous algal and bacterial stromatolites in hot spring and geyser effluents of Yellowstone National Park: *Science*, v. 178, p. 402–405. »**CrossRef** »**GeoRef** »**Abstract/FREE Full Text** »**Medline** »**Web of Science**

Walter, M.R., Bauld, J., and Brock, T.D., 1976, Microbiology and morphogenesis of columnar stromatolites (*Conophyton*, *Vacerrilla*) from hot springs in Yellowstone National Park, *in* Walter, M.R., ed., Stromatolites: Amsterdam, Elsevier, Developments in Sedimentology 1976, p. 273–310.

Walter, M.R., Desmarais, D., Farmer, J.D., and Hinman, N.W., 1996, Lithofacies and biofacies of mid-Paleozoic thermal spring deposits in the Drummond Basin, Queensland, Australia: *Palaios*, v. 11, p. 497–518. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Medline** » **Web of Science**

Wood, W.H., 1889, On the formation of siliceous sinter by the vegetation of hot springs: U.S. Geological Survey, 9th Annual Report, 1887–1888, p. 613–676.

Westall, F., 1999, Fossil Bacteria, *in* Seckbach, J., ed., Enigmatic Microorganisms and Life in Extreme Environments: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 73–88.

Westall, F., deWit, M.J., Dann, J., van der Gaast, S., de Ronde, C.E.J., and Gerneke, D., 2001, Early Archaen fossil bacteria and biofilms in hydrothermally, influenced sediments from the Barberton Greenstone Belt, South Africa: *Precambrian Research*, v. 1–2, p. 93–116.

White, D.E., and Heropoulos, C., 1983, Active and Fossil Hydrothermal Convection Systems of the Great Basin, The Role of Heat in the Development of Energy and Mineral Resources in the Northern Basin and Range Province: Davis, California, Geothermal Resources Council, Special Report, p. 41–53.

White, D.E., Brannock, W.W., and Murata, K.J., 1956, Silica in hot, spring waters: *Geochimica et Cosmochimica Acta*, v. 10, p. 27–59. » **CrossRef** » **GeoRef** » **Web of Science**

White, D.E., Thompson, G.A., and Sandberg, C.H., 1964, Rocks, structure, and geologic history of Steamboat Springs thermal area, Washoe County, Nevada: U.S. Geological Survey, Professional Paper 458-B, 63 p.

White, D.E., Hutchinson, R.A., and Keith, T.E.C., 1988, The geology and remarkable thermal activity of Norris Geyser Basin, Yellowstone National Park, Wyoming: U.S. Geological Survey, Professional Paper 1456, 84 p.

White, N.C., Wood, D.G., and Lee, M.C., 1989, Epithermal sinters of Paleozoic age in north Queensland, Australia: *Geology*, v. 17, p. 718–722. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Williams, L.A., and Crerar, D.A., 1985, Silica diagenesis, II. General mechanisms: *Journal of Sedimentary Petrology*, v. 55, p. 312–321. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text** » **Web of Science**

Williams, L.A., Parks, G.A., and Crerar, D.A., 1985, Silica diagenesis, I. Solubility controls: *Journal of Sedimentary Petrology*, v. 55, p. 301–311. » **CrossRef** » **GeoRef** » **Abstract/FREE Full Text**

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