SILICEOUS SINTER: AN EARLY EXPLORATION TOOL AND DIRECT LINK TO A GEOTHERMAL RESERVOIR

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ABSTRACT
Discharging alkali chloride hot springs are surface expressions of a deeper geothermal reservoir. As the discharging hot spring fluid cools, silica carried in solution precipitates and accumulates to form rocks referred to as siliceous sinter. Distinctive sinter architecture forms depending on the environmental conditions such as water temperature or flow rate. These textures are preserved over time and throughout diagenesis. Geothermal reservoirs may remain long after hot spring discharge ceases. Therefore ancient sinters provide a direct link with a deeper potentially exploitable geothermal resource in areas where there are no active surface manifestations. Recognition of preserved sinter textures enables mapping of broad temperature gradients from high temperature vent to low-temperature distal-apron areas.

Exploitable geothermal systems may exist at depth even when there is no evidence of thermal activity at the surface. For example, the Blundell power plant, Roosevelt, Utah, USA, commissioned in 1984, generates 26 MW (gross) of electrical power (Blackett and Ross, 1992). Currently, at Roosevelt, there are no discharging hot springs. However, an extensive sinter sheet dated 1630-1920 years old represents historic surface flow of alkali chloride water (Lynne et al. 2005). Sinter textures are preserved long after discharge ceases and their recognition allows the mapping of high temperature to low temperature flow gradients across ancient sinter deposits. This technique is useful in the reconnaissance stage of geothermal exploration.

INTRODUCTION
As discharging alkali chloride hot springs cool to temperatures less than 100 °C, the silica carried in solution deposits and accumulates to form rocks known as siliceous sinters (Fournier and Rowe, 1966; Weres and Apps, 1982; Fournier, 1985; Williams and Crerar, 1985). As the silica accumulates, distinctive sinter textures are formed depending on the environmental conditions of the hot spring such as water temperature, pH, flow rate, or water depth. These environmentally significant textures are preserved long after hot spring discharge ceases, and are also preserved during diagenesis (Lynne et al., 2005, 2007, 2008). Therefore, sinters provide a record of alkali chloride hot spring paleo-flows, while their textural characteristics enable the mapping of broad temperature gradients from high temperature vent to low-temperature distal-apron areas.

SINTER ARCHITECTURE
Walter (1976) developed a general framework illustrating the relationship between hot spring water temperature, microbial communities and sinter textures. Cady and Farmer (1996) produced a model that summarizes major biofacies, lithofacies and taphofacies trends along a thermal gradient in modern hot spring settings where each distinctive texture inferred a specific location on the vent to distal-apron flow path. Their model was based on hot springs at Yellowstone National Park but similar trends have been observed around the world (Walter, 1976; Lowe et al., 2001; Lynne and Campbell, 2003).

Thermal settings are represented by a variety of sinter textures. For example, sinter architecture differs for high, mid- and low-temperature pools and discharge channels. Splash zones, deep pool floors, shallow terracettes, fast flowing channels, and turbulent high temperature vents are examples of environmental conditions that produce distinctive sinter textures.
Sinters undergo a 5-step series of silica phase transformations from opal-A to opal-A/CT to opal-CT to opal-C and eventually to quartz (Lynne et al., 2005, 2007, 2008). Over time, and during these silica phase changes, environmentally-significant textures within sinters are preserved (Walter et al., 1996; Trewin, 1994; Rice et al., 1995; Lynne et al., 2005; 2008). Therefore sinter architecture provides a tool whereby former thermal fluid flow pathways can be identified from ancient sinter deposits.

This paper documents some commonly found environmentally-significant sinter textures. The recognition of these textures enables the mapping of hot spring paleo-flow conditions (i.e., temperature, flow rate) and the identification of former hot up-flow zones (i.e., high temperature vents) in areas where hot springs no longer discharge.

HIGH TEMPERATURE TEXTURES (>90 °C)

Spicular, nodular and columnar textures commonly form in high temperature (>90 °C), near-vent environments and are referred to as geyserite. These textures form in the splash zone of eruptive hot springs, pools and geysers, where the sinter surface is intermittently wet and dry (White et al., 1964; Renaut and Jones, 2000). Geyserite architecture consists of stacked, convex laminations within each column, nodule or spicule (Figures 1 and 2).

![Figure 1: Columnar geyserite showing multiple stacked, convex laminations within each column.](image)

The characteristic convex laminations distinguish it from mid-temperature coniform and low-temperature palisade textures.

MID-TEMPERATURE TEXTURES (35-59 °C)

There are several types of environmentally significant mid-temperature sinter textures. Two such textures are referred to as coniform and bubblemat. Both result from the silicification of microbial communities that thrive in mid-temperature water.

Coniform Textures

Microbial communities that form coniform sinter textures consist of long filaments that grow on the base of deep, quiet pools. These pools are often adjacent to high temperature vents. Once the
filamentous microbes become entombed in silica, they decay, leaving hollow tubes which become infilled with secondary silica (Figure 3).

The lack of laminations within the silica infill distinguishes coniform texture from geyserite sinter.

**Bubblemat Textures**

Mid-temperature hot springs and discharge channels flowing over mid-slope settings are inhabited by thin, sheathed filamentous cyanobacteria. The filamentous cyanobacterium *Leptolyngbya* (previously called *Phormidium*) thrives in mid-temperature alkali chloride waters (cf. Walter, 1976; Lowe et al., 2001) and consists of microbes with finely filamentous, < 5 μm exterior diameters (Hinman and Lindstrom, 1996; Campbell et al., 2001; Lynne and Campbell, 2003). As these microbes photosynthesize, released gas accumulates within the mat and forms bubbles. The microbial mat surrounding the bubbles silicifies to produce macro-scale sinter textures of multiple curved laminations with oval or lenticular voids (Figure 4).

Void dimensions indicate where you are in the discharge channel. Oval voids parallel to the bedding plane form on pool floors. Flattened oval voids form in discharge channels and elongated voids indicate fast flowing water.

**Figure 3:** Quartzose coniform sinter from Coromandel Penninsula, New Zealand, (~3 million year old). (A) Cross-sectional view of coniform texture with quartz infilling individual columns (arrows). (B) Plan view of coniform texture reveals white colored silica around filamentous molds. Arrows indicate opaque silica infill.

**Figure 4:** Quartzose bubblemat sinter from the High Terrace, Steamboat Springs, Nevada, USA. 11,493 ± 70 year old. (A) Oval voids indicate former sites of gas accumulation (arrows). (B) Flattened oval voids formed in a discharge channel (arrows).
LOW-TEMPERATURE TEXTURES (<35 °C)

**Palisade Textures**
Low-temperature alkali chloride hot-springs commonly support the cyanobacterium *Calothrix* and form sinters that contain coarsely filamentous, sheathed cyanobacteria (Cassie, 1989; Cady and Farmer, 1996). These microbes consist of an inner tubular filament mold or trichome of porous cellular material, and thick outer sheaths, with a total exterior diameter of >8 μm. Often the trichome decays and secondary silica infills the void. Silica infill consists of silica that is not laminated. Sinter architecture consists of closely-packed, vertically-stacked, micro-pillar structures referred to as palisade texture (Figure 5).

**Figure 5:** Quartzose palisade sinter reveals near-vertical, micro-pillar, filamentous structures. (A) 11,493 ± 70 year old sinter from the High Terrace, Steamboat Springs, Nevada, USA, showing palisade horizon (inside dotted lines). (B) 1920 ± 160 year old sinter from Opal Mound, Roosevelt, Utah, USA, showing two distinct palisade horizons (arrows).

Environmental conditions favorable for palisade textures are low-temperature, shallow fluid flowing over micro-terraces of previously formed sinter. Palisade textures are visible at the macro-scale with lamination thicknesses controlled by water depth (commonly < 5 mm thick).

**Plant-rich Textures**
Plant-rich sinters are common within geothermal systems (Figure 6).

**Figure 6:** Plant-rich sinter from ancient outcrops in New Zealand. (A) Opal-A plant-rich sinter reveals hollow circular molds (arrows). Pukemoremore, New Zealand. (B) Quartzose plant-rich sinter shows elongated molds of former plant stems and hollow tubular molds (arrows). Umukari, New Zealand.

They represent distal-apron, low-temperature areas where shifting channels have drowned reeds, grasses or small plants. The orientation of plant stems may be random or if the flow of water is swift enough the plant stems may be aligned with the channel flow direction. Plant material can also be transported by wind and water before it becomes silicified. Silicified plant molds are distinctive in outcrop where they appear as circular or elongated tubes (Campbell et al., 2001).

**Streamer Textures**
In fast flowing channels microbial communities form long strands which are aligned in the flow direction (Smith et al., 2003). When these microbes become silicified the fabric formed is referred to as streamer texture (Figure 7).
Oncoidal and Pisoidal Textures
Sinter oncoids and pisoids are circular nodules that rotate in alkali chloride fluid and grow by accreting silica to their exterior surface. Pisoids (generally <5 mm diameter) form in turbulent shallow pools near high and mid-temperature hot spring vents (Figure 8).

Breccia Sinter Textures
Several processes may form brecciated sinter deposits. Hydrothermal eruptions, freeze/thaw, hydraulic fracturing and trampling by wildlife all brecciate sinter sheets. Hot spring discharge may be intermittent allowing sinter surfaces to dry, crack and brecciate. Upon further discharge of thermal water the brecciated sinter fragments become cemented into a newly-formed sinter (Figure 9).

SINTER DATING

14C Accelerator Mass Spectroscopy (AMS) was used to date entombed plant material in sinter samples from New Zealand and the US. Sinter dating provides a temporal context for the spatial distribution of sinters and hot spring paleo-flow paths. Dating also distinguishes those sinters that may be sufficiently young (i.e., ~<50,000 years) to be related to a potentially exploitable geothermal resource at depth, from those that are less likely to be associated with a useable resource based on age.

Sinter dating enables fluid flow migration trends to be identified on both a local and regional scale. The timing of discharging fluids can be related to the geology and structure of the area. The identification of geologic and structural controls to fluid flow such as the location of faults, the timing of fault movements, topography or stratigraphy, enhances our understanding of the deeper geothermal system.

CONCLUSION
Sinters form from discharging alkali chloride hot springs and provide evidence at the surface of a deeper geothermal reservoir. Long after hot spring
discharge ceases, sinter textures are preserved and an exploitable geothermal system may remain at depth. Therefore, sinters may be the only evidence at the surface of a hidden geothermal resource. The recognition and mapping of preserved environmentally-significant textures in ancient sinters reveals hot spring paleo-flow conditions and temperature gradient profiles from high temperature vents to low-temperature distal-apron slopes. Sinter dating reveals the timing of discharging hot springs, enables the tracking of discharging fluids on a regional scale and identifies sinters that are most likely to be related to a blind geothermal resource. Sinter textural mapping combined with sinter dating, provides a simple tool that assists existing exploration techniques used in the search for hidden geothermal resources.

REFERENCES


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