Keywords
Siliceous sinter, architecture, high and low altitude hot springs

ABSTRACT

Hot alkali chloride fluids ascend from deep geothermal reservoirs and discharge at the surface as hot springs. As the silica-rich fluid discharges and cools to below 100 °C, the silica carried in solution precipitates and accumulates to form a rock referred to as siliceous sinter. Hot springs display broad temperature gradients from high temperature vent to low-temperature distal-apron areas. Distinctive sinter textures form, depending on environmental conditions such as flow rate or water temperature. These textures are preserved over time and throughout diagenesis. As sinters and deep geothermal reservoirs remain long after hot spring discharge ceases, sinter textures can be used to create maps of paleo-flow conditions and to establish the locations of historic hot up-flow zones. But does altitude make a difference? Can our knowledge of preserved low altitude sinter textures be applied to high altitude sinters? This study compares the modern high altitude hot springs of El Tatio, Chile with the modern low altitude hot springs of Orakei Korako, New Zealand. If we are to use textural recognition in paleo-sinter outcrops from different elevations to establish hot spring paleo-flow conditions and to map the locations of historic hot up-flow zones.

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, at Roosevelt Hot Springs, near Milford, Utah, USA, commissioned in 1984, generates 36 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.

Hot spring settings and associated sinter textures are widely documented for low altitude settings. Only rare accounts have been published on high altitude hot spring settings (Jones and Renaut, 1997; Fernandez-Turiel et al., 2005; Phoenix et al., 2006). Differences between high and low altitude settings do exist. For example, the boiling point is lower at higher altitude and evaporation is greater, both of which influence silica precipitation. Also at high altitude different microbial communities may exist which will influence the textures formed during silica precipitation and sinter formation. High altitude hot spring settings are often exposed to freeze-thaw conditions which may also influence both the formation of sinters and their preservation potential.

The purpose of this study is to address questions such as: (1) are high altitude hot spring environments and associated sinter textures similar to low altitude settings; and (2) can our knowledge of preserved low altitude sinter textures be applied to high altitude sinters? This preliminary study of high altitude sinters from El Tatio, Chile, and the Taupo Volcanic Zone, New Zealand

1. 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, microbial community, 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.

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Tatio, Chile and low altitude sinters from Orakei Korako, New Zealand compares some commonly found and well documented low altitude hot spring settings, with identical high altitude hot spring environments, focusing on the microbial mats present, in an effort to see if environmentally-significant sinter textures are likely to be similar regardless of altitude.

2. Results

Paired visible light photographs and infrared images were taken of high and low altitude settings showing the vent, mid-slope and distal-apron areas (Fig. 1). This enables a comparison of low altitude settings with high (>60 °C), mid (35-59 °C) and low temperature (<35 °C) thermal gradients, to similar high altitude settings and temperature gradients. Figure 1 reveals that similar colored and textured microbial mats at high altitude are thriving at slightly higher temperatures than those at low altitude.

2.1. Mid-Temperature Texture (35-59 °C)

2.1.1. Bubblemat Texture

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 *Pionhilum*) thrives in mid-temperature alkali chloride waters (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 (Fig. 2).

2.2. Low-Temperature Textures (<35 °C)

2.2.1. Palisade Texture

Low-temperature alkali chloride hot-springs commonly support the cyanobacterium *Calothrix* and form sinters that contain coarsely filamentous, sheathed cyanobacteria (Cassie, 1989; Cady 1989).
These microbes consist of an inner tubular filament mould or trichome of porous cellular material, and thick outer sheaths, with a total exterior diameter of >8 μm. Sinter architecture consists of closely-packed, vertically-stacked, micro-pillar structures referred to as palisade texture. Environmental conditions favorable for palisade textures are low-temperature, shallow fluid flowing over micro-terracettes of previously formed sinter (Fig. 3).

### 2.2.2. Plant-Rich Texture

Plant-rich sinters are common within geothermal systems (Fig. 4). 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 moulds are distinctive in outcrop, where they appear as circular or elongated tubes.

### 2.3. Fast Flowing Water

#### 2.3.1. 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. Almost identical living and silicified streamer mats have been observed at El Tatio and Orakei Korako (Fig. 5).

### 2.4. Non-Overflowing, Non-Boiling Pools

#### 2.4.1. Lily Pad Texture

Lily pad structures form around the perimeters of non-overflowing, non-boiling, hot springs (Fig. 6, next page). This architecture develops where small oscillations occur due to wind-driven wave surge or small pulses of hot spring flow, but where the water does not overflow the pool or channel rim. Lily pad sinter architecture forms by capillary motion of the water reaching and wetting the aerial sinter surface. Silica accretes to sinter surfaces parallel to the pool water level, forming lily pad structures that are broad, low-amplitude, and irregular-shaped (Renaut et al., 1996; Lowe et al., 2001; Lowe and Braunstein, 2003).

### 2.5. Intermittently Overflowing Pools

#### 2.5.1. Digitate Sinter Rims

High temperature pools and discharge channels that intermittently overflow favor the formation of a digitate sinter rim. This textural type consists of irregular-shaped sinter surfaces with smooth knobs and ridges separated by crevices and discontinuous horizons of laminated sinter (Fig. 7, next page; Lowe et al., 2003).
and Braunstein, 2003). Silica accretes to older sinter surfaces wherever overflow takes place. Silica accumulation is both vertical and horizontal however; silica deposition is greater in the horizontal direction.

2.6. Intermittent Flow

2.6.1. 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 are generally <5 mm diameter and form in turbulent shallow pools near high and mid-temperature hot spring vents (Fig. 8A-B). They consist of only a few concentric laminae around a nucleus (Campbell et al., 2001). Oncoids contain a much more complex internal structure of multiple concentric laminae and are generally at least 10 mm in diameter (Fig. 8C; Jones and Renaut, 1997). Oncoids form by rotating in intermittent flow on a sinter terrace.

3. 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 where 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 textural mapping provides a valuable exploration technique in the search for hidden geothermal resources. This preliminary study will be followed up with further research projects specifically examining a variety of high altitude hot spring settings at El Tatio and their associated sinter textures. This will enable mapping of both high and low altitude paleo-flow conditions from historic sinters and former hot spring locations.

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