LIFE AT HIGH ALTITUDE: A COMPARATIVE STUDY OF HIGH VERSUS LOW ALTITUDE HOT SPRING SETTINGS AND ASSOCIATED SINTER TEXTURES FROM EL TATIO, CHILE AND THE TAUPO VOLCANIC ZONE, NEW ZEALAND.

Bridget Y. Lynne

Institute of Earth Science and Engineering, University of Auckland, 58 Symonds St, Auckland 1142, New Zealand.
b.lynne@auckland.ac.nz

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 the 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 New Zealand. If we are to use textural recognition in paleo-sinter outcrops from different elevations to establish hot spring paleo-flow conditions, it is important to understand both hot spring environments and how altitude influences sinter textures. From accurate textural sinter mapping, high temperature locations could be targeted as sites for further exploration with more advanced exploration techniques such as geophysical methods.

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.

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.

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 high altitude hot spring settings are often covered in snow and exposed to freeze-thaw conditions.

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 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 coloured and textured microbial mats at high altitude are thriving at slightly higher temperatures than those at low altitude.

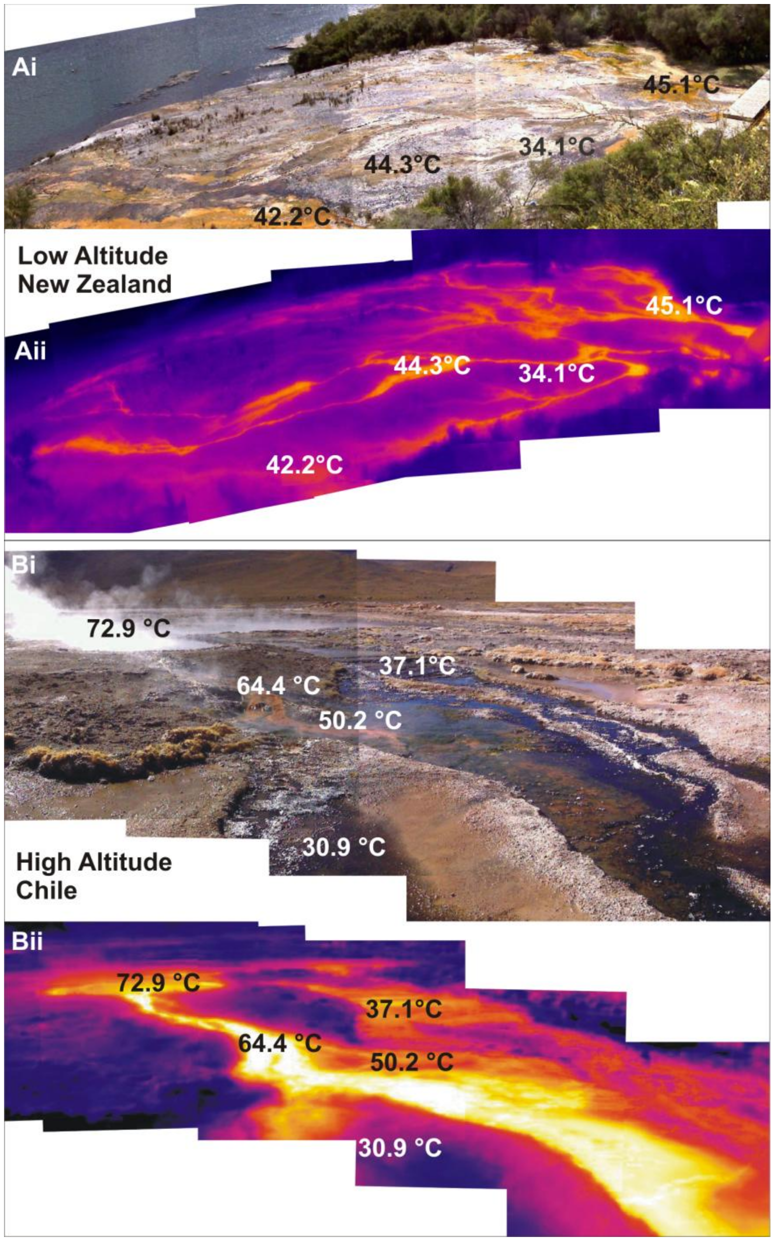

Figure 1: Visible light and infrared images of mid to distal-apron areas at low altitude, Orakei Korako (Ai-Aii) and high altitude of El Tatio (Bi-Bii). (B). Temperatures shown are measured temperatures.

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 *Phormidium)* 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).

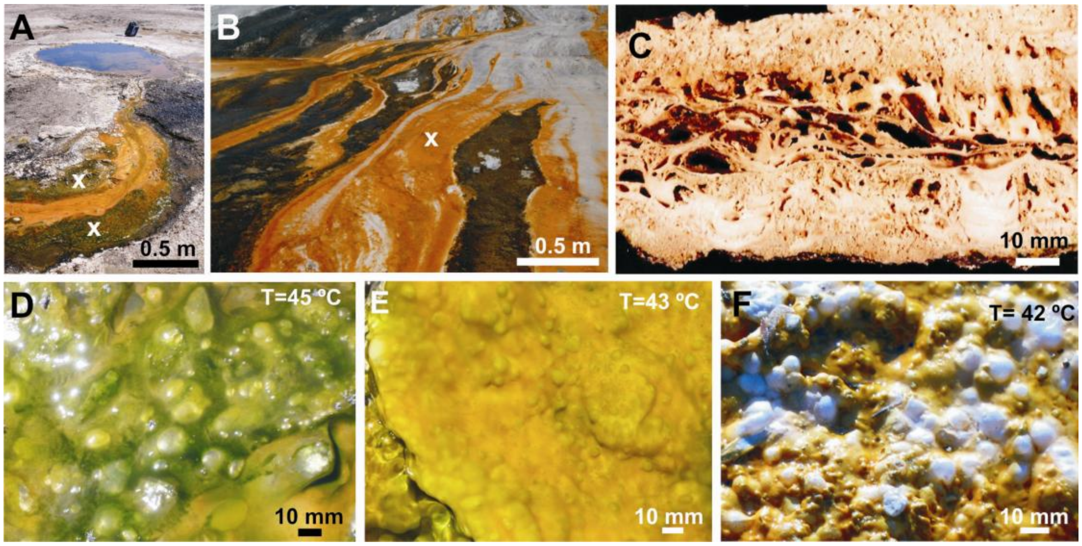

Figure 2: High and low altitude mid temperature hot spring settings where bubblemat microbial mats thrive. (A) High altitude El Tatio hot spring with greenish-yellow bubblemat around edges of discharge channel (site x). (B) Low altitude discharge channel with orange bubblemat in mid-temperature discharge channel areas (site x), Orakei Korako. (C) Preserved bubblemat sinter from Orakei Korako reveals oval voids where oxygen was once trapped forming bubbles. (D) Living microbial bubblemat from discharge channel shown in (A). (E) Living microbial bubblemat from mid temperature discharge channel at Orakei Korako. (F) Partially silicified mid temperature bubblemat from Orakei Korako.

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 and Farmer, 1996). 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 favourable for palisade textures are low-temperature, shallow fluid flowing over micro-terracettes of previously formed sinter (Fig. 3).

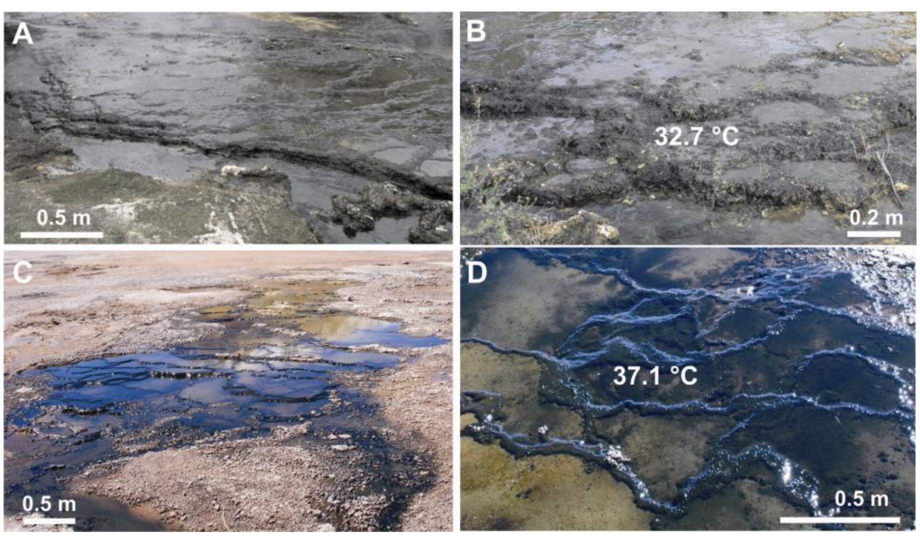

Figure 3: High and low altitude micro-terracettes covered in low temperature, black microbial mats, that typically form palisade sinter textures. (A-B) Low altitude, Orakei Korako. (C-D) High altitude, El Tatio.

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.

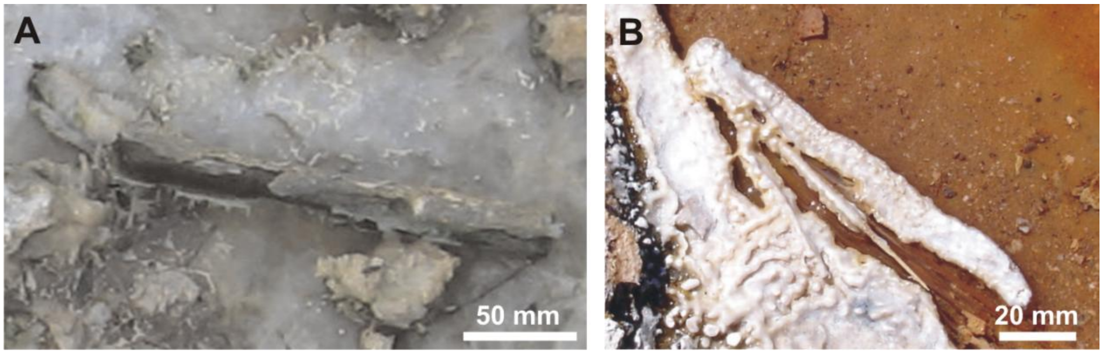

Figure 4: Silicification of plant material in modern hot springs. (A) Plant stem partially coated with silica in a low altitude hot spring discharge channel at Orakei Korako. (B) Plant material coated in silica in high altitude hot spring setting of El Tatio.

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).

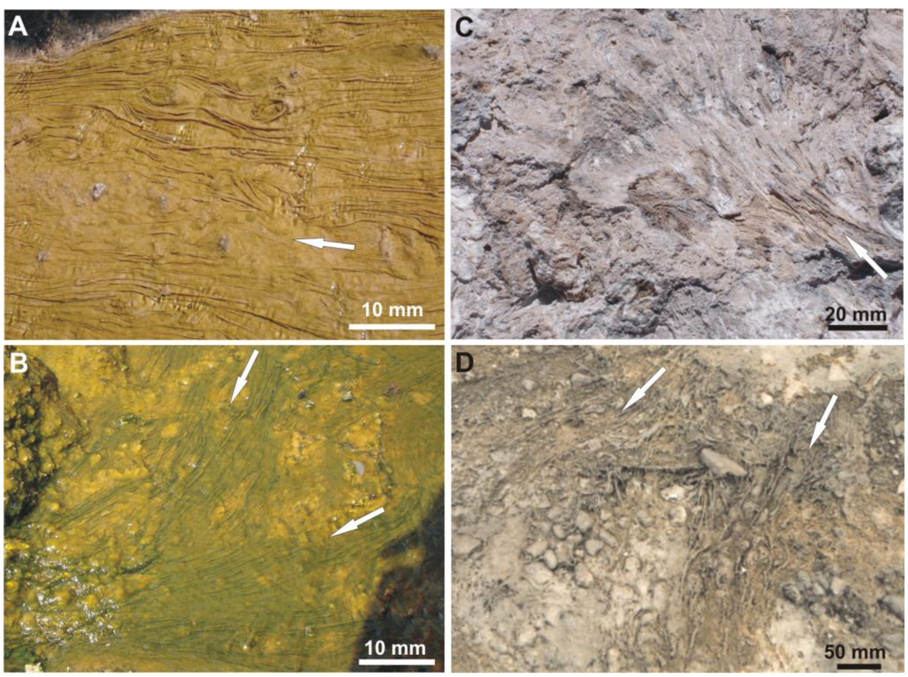

Figure 5: Streamer fabric forming in fast flowing water indicates flow direction (arrows). (A-B) Living streamer mats at the high altitude hot springs of El Tatio (A) and low altitude hot springs of Orakei Korako (B), display long streamers stretched out in the flow direction producing almost identical textures. (C-D) Preserved streamer fabric in former high flow rate discharge channels, in a high altitude sinter at El Tatio, (C) and low altitude sinter at Orakei Korako (D).

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). This architecture develops where small oscillations occur due to wind-driven wave surge or small pulses of fluid, 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).

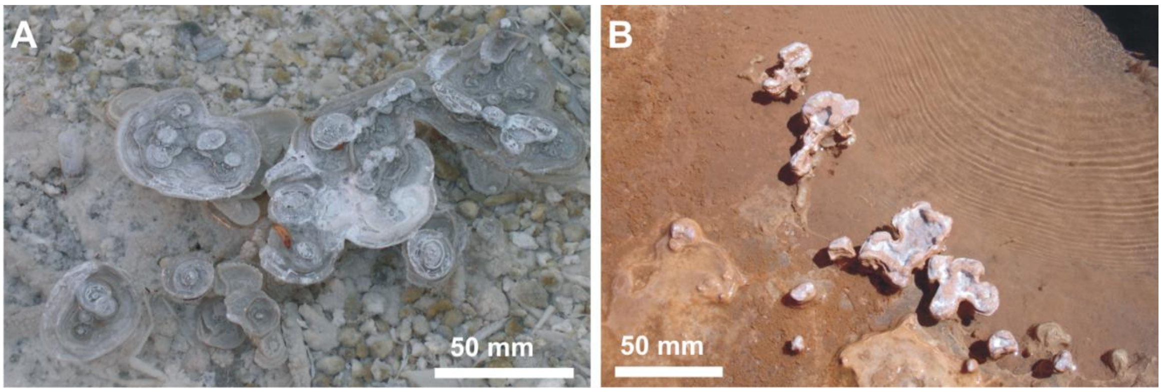

Figure 6: Lily pad textures form at the air-water interface in modern hot springs. (A) Lily pads fan out over water surface in low altitude hot spring at Orakei Korako. (B) Lily pad structures in high altitude hot spring at El Tatio. Note ripples in upper right corner migrating across pool surface towards lily pads.

2.5. Intermittently overflowing pools

2.5.1. Digitate sinter rims

High temperature pools and discharge channels that intermittently overflow favour 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; Lowe 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.

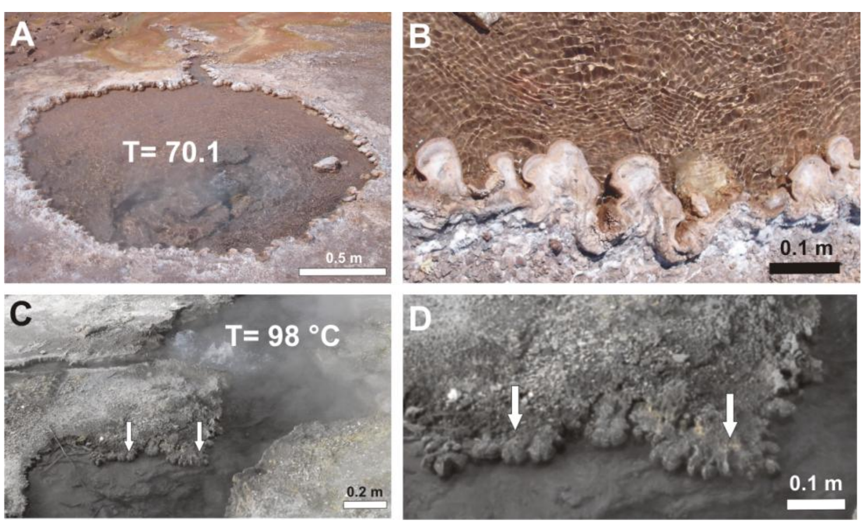

Figure 7: Digitate sinter rim around high temperature (> 60 °C) surging pools and channels where water intermittently overflows. (A-B) High altitude hot spring with digitate rim, El Tatio. Note ripples from surging water can be seen reflecting off the pool rim. (C-D) Surging high temperature, low altitude pool with digitate rim (arrows). Orakei Korako.

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.

Figure 8: High and low altitude oncoids and pisoids. (A) High altitude pisoids on intermittently wet sinter apron surrounding high temperature geyser, El Tatio. (B) Low altitude pisoids on currently-dry sinter apron. Orakei Korako. (C) Oncoids on intermittently wet sinter apron at El Tatio.

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 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 textural mapping provides a simple tool that assists existing exploration techniques used 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.

ACKNOWLEDGEMENTS

I would like to thank the University of Chile and the Andean Geothermal Center of Excellence (CEGA) for funding the trip to El Tatio. Special thanks to Prof. Diego Morata, Pablo Sanchez and Constanza Nicolau.

REFERENCES

Blackett, R.E. and Ross, H.P.: Recent exploration and development of geothermal resources in the Escalante Desert region, southwestern Utah. In: Harty, K.M., (Eds.), *Engineering and Environmental Geology of Southwestern Utah 1992,* Utah Geological Association Publication, **21**, Field Symposium, pp. 261-280. (1992).

Cady, S.L. and Farmer, J.D.: Fossilization processes in siliceous thermal springs: trends in preservation along thermal gradients. In: Bock, G.R., Goode, J.A. (Eds.), Evolution of Hydrothermal Ecosystems on Earth (and Mars?). *Proceedings of the CIBA Foundation Symposium 1996*, **202**, Wiley, Chichester, U.K., pp. 150-173. (1996).

Campbell, K.A., Sannazzaro, K., Rodgers, K.A., Herdianita, N.R., Browne, P.R.L.: Sedimentary facies and mineralogy of the Late Pleistocene Umukuri silica sinter, Taupo Volcanic Zone, New Zealand. *Journal of Sedimentary Research* **71**, 727-746. (2001).

Cassie, V.: A taxonomic guide to thermally associated algae (excluding diatoms) in New Zealand. *Bibliotheca Phycologica*, **78**, 1-159. (1989).

Fernandez-Turiel J. L., Garcia-Valles M., Gimeno-Torrente D., Saavedra-Alonso J., Martinez-Manent S.: The hot spring and geyser sinters of El Tatio, northern Chile. *Sedimentary Geology*, **180**, 125-147. (2005).

Fournier, R.O.: The behaviour of silica in hydrothermal solutions. *Reviews in Economic Geology*, **2,** 45-62. (1985).

Fournier, R.O., and Rowe, J.J.: Estimation of underground temperatures from the silica content of water from hot springs and steam wells. *American Journal of Science,* **264**, 685-697. (1966).

Hinman, N.W., and Lindstrom, R.F.: Seasonal changes in silica deposition in hot spring systems. *Chemical Geology* **132**, 237-246. (1996).

Jones, B., and Renaut, R.W.: Formation of silica oncoids around geysers and hot springs at El Tatio, northern Chile. *Sedimentology* **44,** 287-304. (1997).

Lowe, D.R., Anderson, K.S., Braustein, D.: The zonation and structuring of siliceous sinter around hot springs, Yellowstone National Park, and the role of thermophilic bacteria in its deposition. In: Reysenbach, A.L., Voytek, M., Mancinelli, R. (Eds.), *Thermophiles: Biodiversity, Ecology and Evolution,* (2001), Kluwer Academic/Plenum Publishers, New York, pp. 143-166. (2001).

Lowe, D.R., and Braunstein, D.: Microstructure of high-temperature (>73 ºC) 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* **40**, 1611-1642. (2003).

Lynne, B.Y., and Campbell, K.A.: 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* **40**, 1679-1696. (2003).

Lynne, B.Y., Campbell, K.A., Moore, J., Browne, P.R.L.: Diagenesis of 1900-year-old siliceous sinter (opal-A to quartz) at Opal Mound, Roosevelt Hot Springs, Utah, U.S.A. *Sedimentary Geology*, **119**, 249-278. (2005).

Lynne, B.Y., Campbell, K.A., James, B., Browne, P.R.L., Moore, J.N.: Tracking crystallinity in siliceous hot-spring deposits. *American Journal of Science,* **307**, 612-641. (2007).

Lynne, B.Y., Campbell, K.A., Moore, J.N., Browne, P.R.L.: Origin and evolution of the Steamboat Springs siliceous sinter deposit, Nevada, U.S.A. *Sedimentary Geology*, **210**, 111-131. (2008).

Phoenix, V.R., Bennett, P.C., Engel, A.S., Tyler, S.W., Ferris, F.G. : Chilean high-altitude hot spring sinters: a model system for UV screening mechanisms by early Precambrian cyanobacteria. *Geobiology,* **4,** 15-28. (2006).

Renaut, R.W., Jones, B., Rosen, M.R..: Primary silica oncoids from Orakeikorako hot springs, North Island, New Zealand. *Palaios* **11**, 446-458. (1996).

Smith, B.Y., Turner, S.J., Rodgers, K.A.: Opal-A and associated microbes from Wairakei, New Zealand: the first 300 days. *Mineralogical Magazine,* **67**, 563-579. (2003).

Walter, M.R.: Hot-springs sediments in Yellowstone National Park. In: Walter, M.R. (Ed.), *Stromatolite, Developments in Sedimentology,* **20**, Amsterdam, Elsevier, pp. 489-498. (1976).

Walter, M.R., Des Marais, D., Farmer, J.D., Hinman, N.W., 1996. Lithofacies and biofacies of mid-Paleozoic thermal spring deposits in the Drummond basin, Queensland, Australia. *Palaios* **11**, 497-518. (1996).

Weres, O., and Apps, J.A.: Prediction of chemical problems in the reinjection of geothermal brines. In: Marasimhan, T.N., (Ed.), Recent Trends in Hydrogeology. *Geological Society of America, Special Paper,* **189**, pp. 407-426. (1982).

Williams, L.A., and Crerar, D.A.: Silica diagenesis, II. General mechanisms: *Journal of Sedimentary Petrology,* **55**, 312-321. (1985).