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Geyserite in hot-spring siliceous sinter: Window on Earth's hottest terrestrial (paleo)environment and its extreme life

Kathleen A. Campbell [a,b,*], Diego M. Guido [c], Pascale Gautret [d,e,f], Frédéric Foucher [b], Claire Ramboz [d,e,f], Frances Westall [b]

[a] School of Environment, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[b] Exobiology Research Group, Centre de Biophysique Moléculaire, CNRS, Rue Charles Sadron, 45071 Orléans cedex 2, France
[c] CONICET-UNLP, Instituto de Recursos Minerales, Calle 64 Esquina 120, La Plata 1900, Argentina
[d] Université d'Orléans, ISTO, UMR 7327, 45071 Orléans, France
[e] CNRS, ISTO, UMR 7327, 45071 Orléans, France
[f] BRGM, ISTO, UMR 7327, BP 36009, 45060 Orléans, France

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A B S T R A C T

Siliceous hot-spring deposits, or sinters, typically form in active, terrestrial (on land), volcanic terrains where magmatically heated waters circulating through the shallow crust emerge at the Earth's surface as silica-charged geothermal fluids. Geyserites are sinters affiliated with the highest temperature (~75–100 °C), natural geothermal fluid emissions, comprising localized, lithologically distinctive, hydrothermal silica precipitates that develop around geysers, spouters and spring-vents. They demarcate the position of hot-fluid upflow zones useful for geothermal energy and epithermal mineral prospecting. Near-vent areas also are "extreme environment" settings for the growth of microbial biofilms at near-boiling temperatures. Microbial biosignatures (e.g., characteristic silicified microbial textures, carbon isotopes, genetic material, lipid biomarkers) may be extracted from modern geyserite. However, because of strong taphonomic filtering and subsequent diagenesis, fossils in geyserite are very rare in the pre-Quaternary sinter record which, in and of itself, is patchy in time and space back to about 400 Ma. Only a few old examples are known, such as geyserite reported from the Devonian Drummond Basin (Australia), Devonian Rhynie cherts (Scotland), and a new example described herein from the spectacularly well-preserved, Late Jurassic (150 Ma), Yellowstone-style geothermal landscapes of Patagonia, Argentina. There, geyserite is associated with fossil vent-mounds and silicified hydrothermal breccias of the Claudia sinter, which is geologically related to the world-class Cerro Vanguardia gold/silver deposit of the Deseado Massif, a part of the Chon Aike siliceous large igneous province. Tubular, filament-like micro-inclusions from Claudia were studied using integrated petrographic and laser micro-Raman analysis, the results of which suggest a biological origin. The putative fossils are enclosed within nodular geyserite, a texture typical of subaerial near-vent conditions. Overall, this worldwide review of geyserite confirms its significance as a mineralizing geological archive reflecting the nature of Earth's highest temperature, habitable terrestrial sedimentary environment. Hot-spring depositional settings also may serve as analogs for early Earth paleoenvironments because of their elevated temperature of formation, rapid mineralization by silica, and morphologically comparable carbonaceous material sourced from prokaryotes adapted to life at high temperatures.

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* Corresponding author at: School of Environment, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand.
E-mail address: ka.campbell@auckland.ac.nz (K.A. Campbell).

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1. Introduction

Geyserite — a dense, finely laminated type of opaline silica deposit (sinter) formed in terrestrial (on land) hot springs — is spatially restricted to geysers, spouters and spring-vent areas splashed or submerged by near-boiling waters (>~75–100 °C; Fig. 1; White et al., 1964; Walter, 1976a). Depending on local conditions around the spring-vent or geyser, laminated siliceous precipitates build up into distinctive knobby, botryoidal, columnar, or wavy stratiform geyserite similar in appearance to stromatolites (Fig. 1; Walter, 1976a; Braunstein and Lowe, 2001). Thermophilic microbial biofilms of mostly filaments, as well as rods and coccoids, are adapted to living in present-day, near-vent fluids and affix to actively silicifying surfaces (e.g., Bott and Brock, 1969; Brock et al., 1971; Reysenbach et al., 1994). However, high-temperature biofilms may not preserve well upon lithification, and thus geyserite has been considered to be an abiogenic stromatolite-like deposit (Allen, 1934; Walter, 1976a,b). Nonetheless for more than 60 years, geyserite and siliceous sinter have been compared to fossiliferous Precambrian cherts as representative "extreme environment" analogs for early life habitats (e.g., Tyler and Barghoorn, 1954; Walter, 1972; Maliva et al., 2005; Van Kranendonk et al., 2008; Djokic et al., 2014; Westall et al., 2015). Recent studies have verified the association of microbial filaments preserved in some modern geyserite (e.g., Cady et al., 1995; Jones and Renaut, 2003), but whether they grew at very high temperatures is open to debate because of dramatic fluctuations in near-vent environmental conditions (Braunstein and Lowe, 2001; Jones et al., 2003; Currie, 2005). In general, geyserite and other types of sinter indicate hot-fluid upflow areas intersecting the Earth's surface at locations closely correlated with structural trends, and hence they are relevant for prospecting for epithermal minerals and geothermal energy resources (Sillitoe, 1993; Guido and Campbell, 2011, 2014; Lynne, 2012). With respect to the geological record of geyserite, old examples are rare (Fig. 2) and those containing pre-Quaternary fossils are non-existent. This paper reviews: (1) the character and spatiotemporal distribution of geyseritic sinters; (2) whether geyserites may be considered a reliable indicator of high-temperature, terrestrial hot-spring activity in the geological record; (3) geyserites as possible stromatolites; and (4) their utility as extreme environment analogs in the search for Earth's earliest fossils and for life on other planets. A new Jurassic (~150 Ma) geyseritic sinter discovery (Guido and Campbell, 2014), situated in an epithermal gold and silver mining district in Argentina, is also presented as a detailed case study in order to evaluate the nature and preservation of fossil geyserite — including possible entombed filaments — from the micron-scale to its regional geological context.

2. Overview of hydrothermal systems and geyserite

2.1. Importance of hydrothermal systems

Hot springs on land and in the sea are extreme terrestrial environments, harboring the highest temperature-adapted life forms — hyperthermophilic microbes — known on Earth (Reysenbach et al., 2001; Capece et al., 2013). Marine hydrothermal vents at oceanic spreading centers contain prokaryotes living under high pressures at up to 122 °C (e.g., Kashefi and Lovley, 2003; Takai et al., 2008). Depending on their fluid chemistry, land-based terrestrial hot springs host acid- or alkaline-loving microbes at near-boiling to ambient temperature conditions (Capece et al., 2013). While deep-sea, "black smoker," massive sulfide deposits with entombed microfossils occur in the geological record as far back as the Archean Eon (3.2 Ga; Rasmussen, 2000; Kiyokawa et al., 2006), siliceous hot-spring deposits (sinter) are only as old as the Devonian (~400 Ma; Rice and Trewin, 1988; Cuneen and Sillitoe, 1989). Older sinter is likely but has yet to be recognized. Because proximal vent areas of terrestrial hydrothermal systems host extreme life (e.g., Brock et al., 1971; Reysenbach et al., 1994; Takacs et al., 2001; Blank et al., 2002), and often are mineralizing (Section 2.2), they have been suggested as analog settings for the preservation of early life on Earth and possibly Mars (Bock and Goode, 1996; Farmer and Des Marais, 1999; Farmer, 2000; Cady et al., 2003; Konhauser et al., 2003). Indeed, possible siliceous hot-spring deposits recently have been discovered on Mars (Squyres et al., 2008; Ruff et al., 2011). Moreover, terrestrial hyperthermophiles occupy deep phylogenetic branches (e.g., Reysenbach et al., 1994; Barion et al., 2007). Thus, their heat tolerance has been considered an adaptational remnant of elevated surface temperatures during early bombardment, a time during which life had most likely emerged on Earth (Farmer, 2000; Nisbet and Sleep, 2001), although mesophilic origins of life also have been proposed (e.g., Boussau et al., 2008). Determining the upper temperature limit of terrestrial life, past and present, provides boundary conditions around where and when life may have evolved on a hotter early Earth, the depth to which subsurface microbial worlds may exist, and whether exoplanets and moons may be habitable (Kashefi and Lovley, 2003).

Hot-spring sinters are utilized in prospecting for extractable heat energy and precious metals at shallow crustal depths (e.g., Weissberg, 1969; Rice and Trewin, 1988; Sillitoe, 1993; Fournier et al., 1994; Zimmerman and Larson, 1994; Sherlock et al., 1995; Vikre, 2007; Guido and Campbell, 2011; Lynne, 2012; Rowland and Simmons, 2012). Their spatial association with fluid-transporting faults and hydrothermal eruption breccias, their elemental and isotopic compositions, and their (paleo)environmentally sensitive textures may point to shallow-depth epithermal mineralization, as well as to the relative volumes of water available for paleo-water–rock interactions that may have concentrated ores or reflect paleo-climatic conditions (e.g., Goldie, 1985; Sturchio et al., 1993; McKenzie et al., 2001; Darling and Spiro, 2007; Guido and Campbell, 2014).

2.2. Geyserites as high-temperature deposits of terrestrial hot springs

Dynamic, convective, high-enthalpy geothermal systems predominantly form in volcanic terrains where magmatic heat drives groundwater circulation and water–rock interactions, producing mainly liquid-dominated, alkali chloride geothermal fluids of near-neutral pH with high dissolved silica content (Henley and Ellis, 1983; Renaut and Jones, 2011). Static geothermal systems also are known from terrains without surface evidence for volcanism, heated by above-average conductive heat flow through the crust (Renaut and Jones, 2011). Acidic