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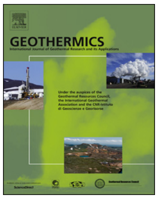

The formation of geyser eggs at Old Faithful Geyser, Yellowstone National Park, U.S.A.

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ABSTRACT

One geyser egg (a smooth, oval, siliceous pebble found in alkali chloride hot pools) from the siliceous sinter slope surrounding Old Faithful Geyser was examined to determine its genesis, sinter architecture and elemental composition. The multi-technique approach included Scanning Electron Microscopy (SEM), petrographic microscopy, X-Ray Diffraction, Energy Dispersive Spectroscopy, iTRAX Core Scanner and Computerised Tomography (CT) scans. The geyser egg architecture consists of alternating smooth and porous concentric bands of opal-A silica around a nucleus. These alternating bands are signatures of changes in the degree of silica oversaturation of the discharging fluid. CT scans mapped changes in density throughout the sample and also showed concentric banding of varying density around a core. SEM observations showed the geyser egg has an abiotic origin with subsequent microbial filamentous void infill creating an abiotic-biotic sinter structure. iTRAX scans revealed the geyser egg preserved signatures of changes in fluid chemistry with time, and that the core is rich in arsenic and calcium. iTRAX scans also documented significantly higher concentrations of gallium in the geyser egg compared to those documented in rhyolites and tuffs from the same area. Unravelling geyser egg formation mechanisms and their microbial content provide useful insights on fluid chemistry, water temperature, and flow conditions in these unique hot spring environments.

1. Introduction

1.1. Siliceous sinter formation mechanisms

Discharging alkali chloride hot springs and geysers create a variety of distinctive siliceous sinter textures that relate to temperature zones and the hydrological settings of subaerial hydrothermal spring discharge. In sinter-depositing hydrothermal systems, alkali chloride water equilibrates with the underlying rocks at temperatures greater than 175 °C (Fournier and Rowe, 1966). As the alkali chloride hydrothermal water discharges at the surface and cools to less than 100 °C, the silica precipitates and accumulates to form siliceous sinters (Fournier and Rowe, 1966; Weres and Apps, 1982; Fournier, 1985; Williams and Crerar, 1985). Silica initially deposits as opal-A (i.e., amorphous or non-crystalline silica). The opal-A silica entombs pollen, diatoms, plants, lithic fragments, older sinter surfaces and microbes that thrive in the hydrothermal water.

Previous studies on siliceous sinter formation mechanisms have been reviewed by Guidry and Chafetz (2002) and include siliceous depositional processes in relation to evaporation, cooling, and wicking (Weed, 1889a,b; White et al., 1956; Eugster, 1980; Campbell et al., 2002; Channing and Butler, 2007), pH changes (Eugster, 1980; Rimstidt and Cole, 1983; Fournier, 1985; Jones et al., 1997), cation effects (Ichikuni, 1970; Rimstidt and Cole, 1983), the roles of hydrodynamics (Renaut et al., 1996; Braunstein, 1999; Braunstein and Lowe, 2001; Iler, 1979; Weres and Apps, 1982; Fournier, 1985; Williams et al., 1985) and microbe–silica interactions in sinter formation (e.g., Weed, 1889a,b; White et al., 1956; Eugster, 1980; Schultze-Lam et al., 1995; Hinman and Lindstrom, 1996; Konhauser and Ferris, 1996; Konhauser et al., 2001; Blank et al., 2002; Lynne and Campbell, 2003; Mountain et al., 2003; Yee et al., 2003; Lynne, 2012).

The interactions between biotic-abiotic controls on sinter formation mechanisms can be complex. For example, Jones and Renaut (1996) report sinters formed by both abiogenic and biogenic processes in

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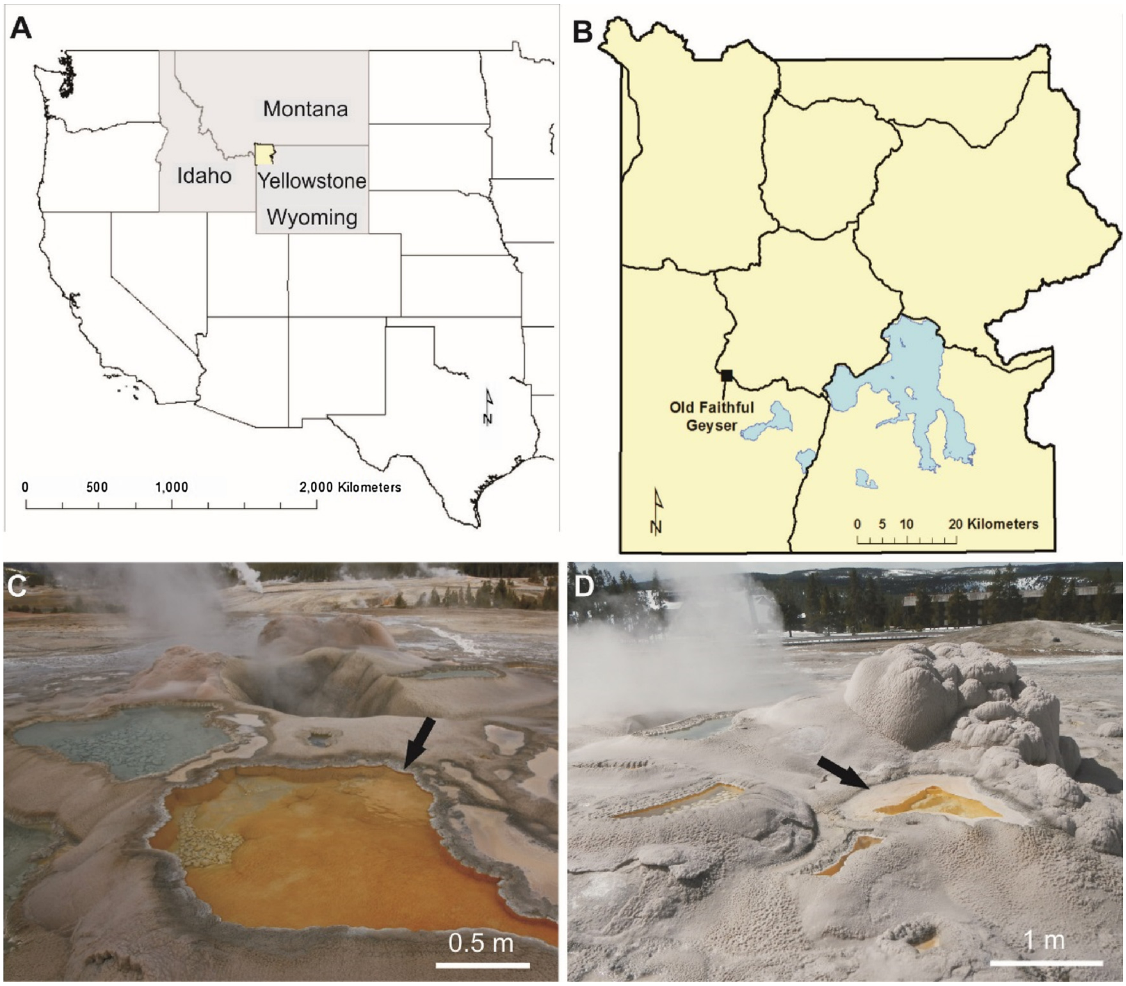

Fig. 1. Location map and site photographs. **(A)** Location of Yellowstone National Park, USA. **(B)** Location of Old Faithful Geyser in Yellowstone National Park. **(C–D)** Site photographs of hot pools with geyser eggs. **(C)** Old Faithful vent and digitate sinter texture (arrow) around pool containing geyser eggs. **(D)** Pool (arrow) containing geyser eggs.

Kenya and New Zealand. Lowe and Braunstein (2003) state that both abiotic and biotic siliceous sinter may develop where geyserite sinter forms around eruptive alkali chloride hydrothermal pools in Yellowstone. If silica saturation concentrations are high, rapid precipitation occurs through abiotic means and at a faster rate than microbial growth (i.e., abiotic control is dominant). However, where precipitation is slower microbial biofilms are able to grow at a rate which is faster than silica deposition, and therefore microbial biofilms serve as a biotic template for continued silica growth (i.e., biotic control dominant).

1.2. Siliceous sinters at Yellowstone National Park, USA

Previous siliceous sinter studies at Yellowstone have focused on a variety of topics. Walter (1976) developed a general depositional framework that illustrates the relationship between different types of sinter and dominant mat-forming micro-organisms along a hydrothermal gradient. Cady et al. (1995) studied the biogenicity of columnar and spicular geyserites from Yellowstone. Cady and Farmer (1996) document the mode of fossilization, including encrustation and permineralization trends of microbial communities and suggest that preservation of thermophilic micro-organisms is controlled by varying rates of population growth, decomposition of organic matter, and silica accumulation. They further examined modern siliceous sinters at Yellowstone to evaluate how biotic and abiotic factors contribute to the morphogenesis and microstructural development of sinter. They produced a biofacies, lithofacies, and taphofacies model for siliceous sinters that summarises major trends in early preservation of hydrothermal spring systems. Lowe et al. (2001) classified modern sinter deposits into major sub-environments (e.g., vent pool, vent outflow, channel and terrace, distal apron, marsh apron), and their associated biological zones. They found that microbial community distributions reflect temperature zones. Inagaki et al. (2001) report that silica is deposited on the surfaces of microbes which influences the structure of the siliceous sinter. Studies by Guidry and Chafetz (2003) have concluded that microbial morphologies may be retained in the siliceous sinter deposit but that distinctive organic components are not well preserved after burial and that preservation of the microbial community is partially determined by its location with respect to the vent through to the spring discharge channel. Hinman and Lindstrom (1996) report differences in silica deposition rates which were attributed to flow dynamics and a seasonal air temperature of Octopus Spring at Yellowstone. Guidry and Chafez (2002) emphasises the role of cooling in reaching super-saturation in Yellowstone Springs. Jones et al. (2001) and Lowe and Braunstein (2003) summarised previous studies on high-temperature siliceous sinter formation and note there is a debate as to whether abiotic or biotic processes are responsible for their formation. Lowe and Braunstein (2003) reported that repeated wetting and drying and capillary effects control the deposition, morphology and microstructure of most high-temperature sinters outside of the sub-aqueous zone. They report microbial filaments are abundant on and within high-temperature sinter but do not provide the main controls on morphology or structuring except in biofilms developed on sub-aqueous surfaces.