Secondary minerals associated with Lassen fumaroles and hot springs: Implications for martian hydrothermal deposits

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ABSTRACT

The active hot springs, fumaroles, and mud pots of the southwestern Lassen hydrothermal system include various alteration environments, which produce a range of hydrothermal mineral assemblages. Analysis of water, mineral precipitates, altered sediment, and rock samples collected at and near these features at Sulphur Works, Bumpass Hell, Little Hot Springs Valley, and Growler and Morgan Hot Springs reveals conditions ranging from ~100 °C acid-sulfate fumaroles (e.g., Sulphur Works and Bumpass Hell) to near-neutral hot springs (e.g., Growler and Morgan), and includes both oxidizing and reducing conditions. Resulting hydrothermal minerals include a wide variety of sulfates (dominated by Al-sulfates, but also including Fe2+, Fe3+, Ca, Mg, and mixed-cation sulfates), sulfides (pyrite and marcasite), elemental sulfur, and smectite and kaolinite clays. Most altered samples contain at least one silica phase, most commonly quartz, but also including cristobalite, tridymite, and/or amorphous silica. Quartz and other silica phases are not as abundant in the less altered rock samples, thus their abundance in some hydrothermally altered sediment samples suggests a detrital origin, or formation by hydrothermal alteration (either modern or Pleistocene); this requires a high degree of diagenetic (or epigenetic) maturation. These results support a previously identified model that the Lassen hydrothermal system involves the de-coupling of a vapor phase (which becomes acidic as it oxidizes near the surface, producing acid-sulfate fumaroles at higher elevations at Sulphur Works and Bumpass Hell) from the residual near neutral thermal waters that emerge as hot springs at lower elevations (Growler and Morgan). Because both acid-sulfate fumarole and near-neutral sinter-producing hot springs have been invoked to explain the silica-rich deposits observed by the Mars Exploration Rover Spirit near Home Plate in the Columbia Hills on Mars, Lassen can serve as a useful terrestrial analog for comparison.

Keywords: Mars, hydrothermal alteration, sulfate minerals, element mobility

INTRODUCTION

The Lassen hydrothermal system in northern California is the largest active hydrothermal field in the Cascades, with widespread fumaroles, hot springs, and mud pots (e.g., Ingebritsen et al. 2016). These fluids and gases represent varied temperature, pH, and oxidation conditions, and interact with the dacitic to andesitic host rocks, producing a range of alteration minerals related to variable hydrothermal conditions.

Cascade volcanic activity in the Lassen area began ~3.5 Ma ago, with both short-lived calc-alkaline volcanism and longer-term volcanism associated with a series of five volcanic centers, which included both silicic and andesitic products. These longer-lived volcanic centers (Yana, Maicl, Dittmar, Latour, and the still active Lassen) developed hydrothermal systems at various stages during their histories (e.g., John et al. 2005, 2009) but often late, as circulating groundwater was heated by cooling silicic magma at depth (Muffler and Clynne 2015). Volcanism associated with the Lassen Volcanic Center started about 825 000 years ago with the Rockland caldera complex (825 000–611 000 years) followed by the Brokeoff Volcano (550 000–350 000 years), and finally the Lassen dome field (~315 000–0 years). In addition to the currently active Lassen hydrothermal system, two relict hydrothermal systems have been identified associated with Brokeoff Volcano. Current active hydrothermal activity is in places superimposed upon the eroded and exposed remnants of these older hydrothermal systems, which can complicate efforts to isolate the effects of the modern hydrothermal system.

Currently, acid sulfate fumarole and/or hot water discharge areas include Bumpass Hell, Sulphur Works, the Pilot Pinnacle area, and Little Hot Springs Valley in the southwestern part of the park (with Growler and Morgan Hot Springs several kilometers south beyond the park boundaries), along with Devil’s Kitchen, Boiling Springs Lake, Drakesbad Hot Spring, and Terminal Geyser to the southeast (Fig. 1). Most are steam-heated acid-sulfate systems, though Drakesbad, Growler, and Morgan Hot Springs discharge more neutral, chlorine-rich hydrothermal fluids and lower Sulphur Works and upper Little Hot Springs Valley have some bicarbonate-dominated springs in addition to their acid-sulfate fumaroles and hot springs (Muffler et al. 1982; Thompson 1985; Clynne et al. 2003). Most of the hydrothermal waters are isotopically consistent with exchanged local meteoric waters suggesting a local source, though some signatures of mantle-derived volatiles (CO2, H2S, N2) are observed at...