

ASSESSING HYDROTHERMAL ALTERATION ON EARLY MARS THROUGH ANALOG ENVIRONMENTS IN NICARAGUA, COSTA RICA, ICELAND, AND HAWAII. B. M. Hynek^{1,2}, T.M. McCollom¹, L. J. McHenry³ and G. E. Alvarado⁴, ¹Laboratory for Atmospheric and Space Physics & ²Dept. of Geological Sciences, University of Colorado-Boulder, Campus Box 600 UCB, Boulder, CO 80303, ³University of Wisconsin-Milwaukee, ⁴Instituto Costarricense de Electricidad - ICE. hynek@lasp.colorado.edu

Introduction: Early Mars had rampant magmatism and volcanism due to the high heat flow on the young planet, but activity continued to the recent past. Outgassing of juvenile gases and crustal water from an early hydrosphere [1] likely provided abundant fumarolic and hot springs environments on and near the enormous volcanoes found globally on Mars. Given the lack of plate tectonics, persistent magmatic plumes are thought to have provided surface volcanism for extended periods of time. In fact, Robbins et al. [2] showed that many of the major volcanoes of Mars had discrete caldera-forming eruptions spanning billions of years, covering most of Mars' observable history (Fig. 1). Analysis of meteorites [e.g. 3-4] and modeling [5] show that Mars requires a wet mantle and that even eruptions in the last billion years had parent magmatic water contents of up to 1.8wt%. All these factors likely led to long-lived hydrothermalism across Mars; key targets for future astrobiological missions.

One prominent example of a potentially gas-dominated or limited water hydrothermal system on Mars is at the Home Plate site in Gusev Crater, examined in detail by the Mars Exploration Rover Spirit [6]. The chemistry and mineralogy has been proposed to represent acid-sulfate alteration of pyroclastic deposits and the isochemical alteration of some rocks and soils suggests low water-rock ratios [6-7], consistent with gaseous alteration by volcanic vapors in a fumarolic setting. Adjacent silica-rich deposits have also been proposed to originate through volcanic exhalations, or as sinter deposits in thermal pools [8-10].

Beyond the rover data, a variety of secondary mineralogies have been detected on Mars from orbiters indicating widespread aqueous alteration of the crust. High temperatures and acidic fluids are implied for some regions such as Noctis Labyrinthus, and locales in Terra Sirenum, Mawrth Vallis, and Syrtis Major [11]. At present, there are few constraints on the paleoenvironmental conditions (temperature, pH, fluid:rock, redox state, etc.) that existed during formation of the widespread and diverse classes of secondary mineralalogies seen on Mars.

Terrestrial Analogs and Motivation: To address the plausible paleoenvironmental conditions at martian hydrothermal systems, we investigated hydrothermal chemical analogs at active acidic volcanic systems in Nicaragua (Cerro Negro, Momotombo, and Telica) [10-12], Costa Rica (Poás, Turrialba, Miravalles, and Rincón

de la Vieja), Iceland (Krafla, Hengill, and Landmannalaugar), and Kilauea (Sulfur Banks, Mauna Ulu, and Mauna Iki). At all these places, recently erupted materials are similar in composition to the martian crust (basalt to andesites) and are undergoing extensive acid-sulfate alteration predominately in gas-dominated settings and small thermal pools. We characterized the secondary mineralogy (XRD, petrography, and SEM-EDS) and measured local variables including temperature, pH, rock and gas composition, and fluid-rock ratio. *The ultimate goal is to use the co-measured environmental conditions and secondary alteration mineral suites to infer the characteristics of relic hydrothermal systems on Mars.*

Terrestrial Analogs: The Nicaraguan magmas are from MORB-like sources and erupt through a thin lithosphere, leading to basaltic volcanism [e.g., 10]. Acid-sulfate alteration of erupted materials is occurring from SO₂(g) leading to sulfuric acid production [10, 12], resulting in very low pH fumaroles and mudpots (generally -1 to 4). In nearby Costa Rica, the volcanics in the study areas represent basalts to andesites from an OIB source, leading to differences in gas/fluid chemistry compared with the Nicaraguan systems. The pools and fumaroles range from a pH 0.29 sulfur-chlorine crater lake at Poás volcano to oxidized or reduced sulfur gas emissions to circum-neutral bicarbonate thermal pools at other volcanoes [e.g., 13]. In both Hawaii and Iceland, the magmas are sourced from deep mantle plumes leading to basaltic volcanism in Hawaii and ferrobasalts to silica-rich rhyolites in Iceland [e.g., 14]. The Hawaiian gases sampled were dominantly oxidized (with abundant SO₂), while the Icelandic fluids/gases ranged from highly oxidized to highly reduced.

Controls on Acid-Sulfate Alteration:

Parent Rock Lithology and Fluid Chemistry. Parent rock lithology has a strong influence on fluid chemistry and thus, secondary mineral precipitation. Our fresh field rocks had a range of cation abundances: Al³⁺ ranged from 12-20 wt%, Fe^T from 7-17 wt%, Ca²⁺ from 7-13 wt%, and Mg²⁺ from 3-9wt%. As expected, dissolution of primary minerals led to significant cations in the fluids available for sulfate precipitation. For example, the alteration of the Mg-rich rocks of Krafla resulted in diverse and abundant Mg-sulfates including hexahydrite, pickeringite, alpersite, and leonite. Condensed gases had less abundance of cations and anions compared with thermal pools and mudpots, where fluids

have a longer residence time, leading to enhanced primary mineral dissolution and additional secondary products.

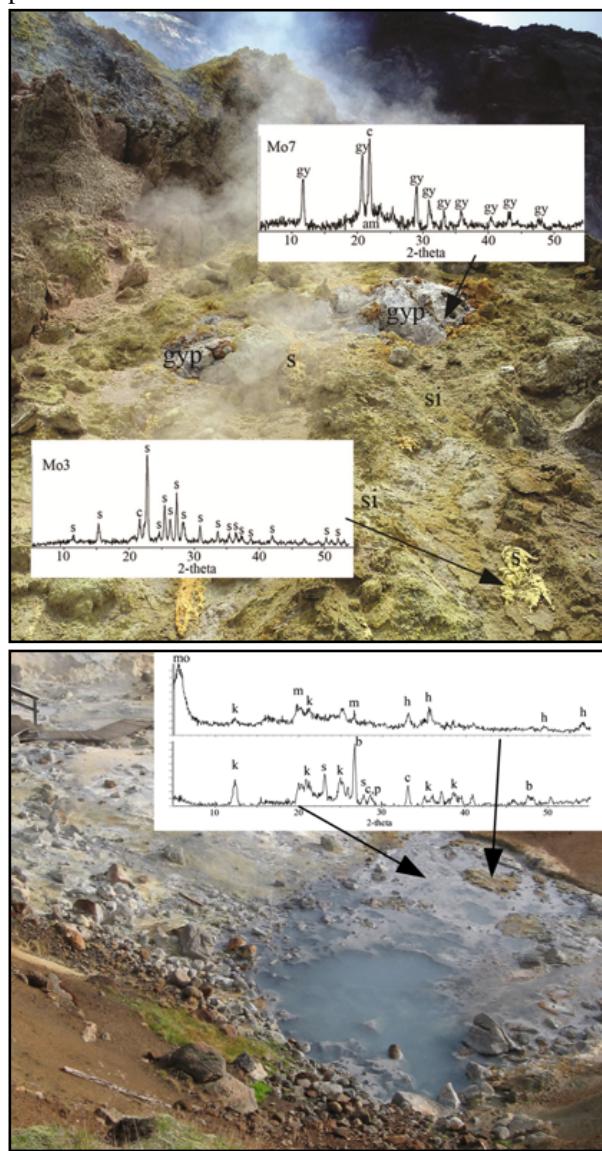


Fig 1. (top) Summit fumaroles of Momotombo (pH ~-1, T ~ 130°C) and XRD diffractograms. **(bottom)** Krafla thermal pool (Leirhnjúkur) (pH = 3.3, T = 25.5°C) with abundant phyllosilicates. gy = gypsum, c = cristobalite, s = sulfur, si = silica, mo = montmorillonite, k = kaolinite, m = muscovite, h = hematite, b = berlinitic, c = chlorargyrite, p = pyrite.

pH. pH of the thermal waters and gas condensates plays an important role on secondary mineral formation. The most acidic systems (pH = -1 to 1) were dominated by amorphous and opaline silica, the high-temperature SiO₂ phase cristobalite, elemental sulfur, and occasional gypsum or natroalunite encrustations (Fig. 1); but the rest of the cations had been leached from the systems.

Moderately acidic systems (pH = 3 to 5.5) typically exhibited abundant amorphous and opaline silica, diverse sulfates (e.g., natroalunite, leonite, jarosite, szomolnokite, halotrichite, aluminite, apjohnite, and pickeringite), Fe oxides-hydroxides (hematite, goethite), phosphates (berlinite, phosphommite, and brushite) and significant phyllosilicates (kaolinite, nontronite, and montmorillonite) (Fig. 1). Circumneutral systems showed opaline silica, carbonates (calcite), the above-listed phosphates, and phyllosilicates (mainly kaolinite, montmorillonite, and nontronite).

Temperature. We assessed systems with fluid and gas temperatures ranging from 40-200°C. This variable had the least defined trends in alteration mineralogy. SiO₂ phases were an exception, with hottest environments exhibiting abundant cristobalite and amorphous silica (Fig. 1), moderate temperature locales with tridymite as a major phase, and low temperature areas with more opaline silica.

Fluid:Rock Ratio. The main result was that higher fluid:rock ratios (or longer-lived systems) resulted in more abundant and diverse phyllosilicates (Fig. 1).

Applications to Mars: From our field results, we argue that the circum-Homestead Plate alteration mineralogies [6-9] can best be explained by acidic (pH ~3 to 5), ~100°C, oxidizing fumaroles and do not require ponded thermal waters. The silica-rich cones on Syrtis Major [15] were likely formed from hot and very acidic outgassing. The phyllosilicates and sulfates found at Noctis Labyrinthus [16] on the flank of the Tharsis rise most likely formed from circulating acidic (pH ~3-5) thermal waters below boiling temperature.

Finally, while phyllosilicate detection on Mars is commonly attributed to neutral-alkaline fluids, we find abundant formation of kaolinite and montmorillonite, and moderate nontronite (Fe-smectite) in high fluid:rock hydrothermal systems with pH as low as 3 (Fig. 1).

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