

TERRESTRIAL AQUEOUSLY ALTERED MAGMATIC DIKE FORMING SULFATE-RICH HYDROTHERMAL FLUIDS TO CONSTRAIN MARTIAN HABITABILITY. B. Baharier¹, J. Sempich¹, K. Olsson-Francis¹, S. L. Potter-McIntyre², J. R. Crandall³, J. Filiberto⁴, S. Perl⁵, S. P. Schwenzer¹, ¹AstrobiologyOU, School of Environment, Earth, and Ecosystems Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK (bea.baharier@open.ac.uk) ²Southern Illinois University, School of Earth Systems and Sustainability, Department of Geology, 1259 Lincoln Drive, Carbondale, IL 62901, USA. ³Eastern Illinois University, Department of Geology & Geography, 600 Lincoln Ave., Charleston, IL 61920, USA, ⁴ARES, NASA Johnson Space Centre, 2101 E NASA Pkwy, Houston, TX 77058, USA, ⁵Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA, 91109, USA

Introduction: Intrusion of magma into a water-bearing crust can create a habitable hydrothermal environment, as seen on Earth [1-3]. As the rock surrounding the intrusion is subjected to heat it can 1) release water, and different chemical species, from pre-existing minerals, and 2) interact with volatiles released from the cooling magma, which can create a geothermal brine with a distinct composition suitable for a range of chemotrophs [1-3]. Hence, studying such environments on Earth is important in the search for life beyond our planet. The geothermal brine's nature is dependent on the host rock and the magmatic properties. On Mars basaltic and sulfur-rich soils are dominant [4-8] and therefore investigating basaltic magmatic interaction with sulfate-rich sediments and their associated habitats is key for recognizing potential habitats on Mars [5-13].

The NASA Perseverance Rover at Jezero Crater has detected aqueously altered igneous rocks, potentially intrusive in origin, with secondary carbonates, sodium perchlorate and sulfates [14]. Such an environment may have been habitable. Therefore, we investigate the intrusion of a magmatic dike into Jurassic sulfate-rich sediments from the San Rafael Swell, Utah, to reconstruct the geothermal fluids and assess their putative habitability.

Geologic Setting: Located in modern Utah, the Jurassic sediments are of the Carmel Formation, which was deposited ~160 Ma ago under the Sundance Sea [15]. The transgression and regression of the sea formed a sequence of arid coastline depositional environments of carbonates, clays, and sulfates [15]. During the Neogene (~ 6.4 Ma) a swarm of dikes intruded the Jurassic sediments [16] potentially creating different localized hydrothermal environments, each one unique to the host rock, magmatic composition, and environmental conditions.

Previous work reported that the unique mineral assemblages change from a higher temperature assemblage in the intrusion contact zone to lower temperature alteration assemblages further from the contact [17]. This indicated that by identifying the small-scale mineralogical changes and the resulting unique fluids, nutrient availabilities that are favorable

for life and the habitability of the environment can be constrained [17].

Methods: Samples were collected from the Carmel Formation along a traverse from a dike, named Awesome dike (AD; N3834.252 W11108.351), and from the direct contact zone with the intruded country rock and successively further away to constrain the geochemical alteration gradient. The samples were prepared as epoxy blocks and thin sections based on the friability and transparency of the sample. Each sample was mapped using a scanning electron microscope with Energy Dispersive Spectroscopy (Cameca SX100).

Modelling Method: The geochemical data was then used to model the fluid composition employing the Geochemist workbench software. The first magmatic alteration was modeled by titrating the precursor magmatic mineral oxide composition [18] into a CO₂-H₂O fluid at a range of hydrothermal temperatures ranging from high to habitable (300-100 °C). The resultant fluid was then mixed at 300 °C with Ca and SO₄ saturated fluid of 25 °C, to simulate primary CaSO₄ mineral dissolution, migration, and reprecipitation during magmatic interaction and cooling. All reactions were completed to equilibrium.

Sample Results: Awesome dike alteration is restricted to calcite pseudomorphs, CaSO₄ veinlets and veins, with minor amounts of Fe-Mg-rich clays within the pseudomorphs zone (Fig. 1). As calcite is not part of the original dike mineralogy it is likely a pseudomorph which was partly replaced by CaSO₄ veinlets and clay. Previous studies on another dike within the SRS found

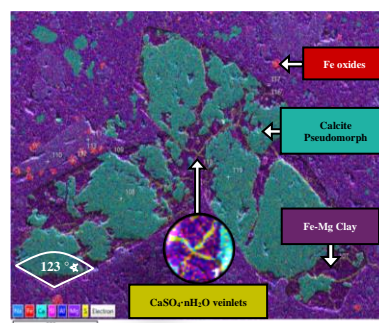


Figure 1. SEM-EDS image of Awesome dike thin section. Central crystal of calcite pseudomorphed after amphiboles partly replaced by CaSO₄·nH₂O veinlets and clay.

calcite pseudomorph after olivine based on morphology and weathering patterns [19]. However, such patterns were not found in AD, and their interfacial angles were distinct. Based on the calcite interfacial angles ($\sim 120^\circ$ – 126° , Fig. 1), it is likely the calcite pseudomorphed after amphiboles which is also found in other intrusions in the SRS [18]. Based on previous work on other local intrusions amphibole chemistry [18] and their mineral formula recalculation [20], the precursor was likely a ferri-kaersutite amphibole, which has Fe^{2+} , Fe^{3+} , Mg, Ca, Na and K [19]. Calcite and Fe-Mg clays are persistent through the alteration path while CaSO_4 is absent in the contact zone and reappears further away from the contact.

Model Results: The reaction of amphibole with a low salinity CO_2 - H_2O fluid at water-rock (W/R) ratios between 330 and 500 resulted in the precipitation of calcite and clay (Fig. 2A). At high temperatures, more carbonate is precipitated. When more CO_2 is added to the system other carbonates such as dolomite and siderite form, however, calcite is the only carbonate detected in AD. Moreover, when a larger mass is reacted calcite is no longer the dominant mineral. This initial reaction formed a Ca-carbonate-saturated fluid with a pH of 6.1. When the CaSO_4 saturated fluid was mixed in, anhydrite (CaSO_4) veinlets within the calcite start to precipitate at 0.11 mixing fractionation and the pH decreased to 5.6 (Fig. 2B). As the reaction progressed towards a 1-to-1 mixing fractionation, anhydrite is the dominant species and the pH increased to 6.9. When the fluid cooled the pH progressively increased to a final value of 7.9 at 25°C .

Discussion and Conclusion: The calcite pseudomorphs formed by alteration of amphibole with H_2O - CO_2 rich fluid at initial uninhabitable hydrothermal temperatures (over 122°C [21]). The fluid formed at a high W/R ratio, and thus the hydrothermal environment was likely short-lived. This is also evident by the amphibole replacement and the mostly unaltered other minerals in the dike. Although amphibole is a durable double-chain silicate, dissolution kinetic rates can be affected by intrinsic and extrinsic factors [22] and therefore simple leaching based on polymerization cannot rule out amphibole as a precursor to calcite.

By the time the sulfate-rich fluids mixed with the dike fluids and gradually cooled to habitable conditions, the fluids have altered to form a sulfate-rich solution with a moderately acidic pH to a relatively diluted fluid as the calcite and CaSO_4 oversaturate and precipitate at a moderately alkaline pH. This suggests that the geochemical alteration occurred spatially and also through a short time scale changing the habitability potential and habitat type.

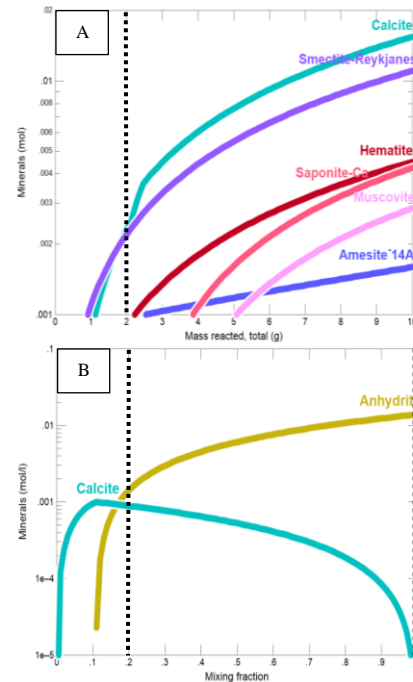


Figure 2. A. Model results of amphibole titration into H_2O -0.3 mol/l of CO_2 fluid at 300°C , max titration at 2g before forming undetected minerals. B. Fluid mixing between first fluid and CaSO_4 saturated fluids. First forming veinlets, and gradually completely replacing calcite forming large anhydrite veins.

Although aqueously altered igneous rocks have been detected at Jezero Crater, unlike AD, they are olivine-rich and likely altered by low-temperature fluids at low W/R ratios [23]. Moreover, so far amphiboles have not been detected on the surface of Mars. However, interestingly, kaersutite has been found within martian meteorites [24]. The lack of amphiboles on Mars may be due to detectability bias, dust coverage or subsurface locations as they form within evolved and volatile-rich magmas [25]. However, this work presents a potential short-lived reaction path of complete amphibole alteration into calcite and eventually CaSO_4 which is abundant on the surface of Mars today.

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