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# MAGMATIC INTRUSIONS INTO THE SULFUR-RICH CARMEL FORMATION ON THE COLORADO PLATEAU, USA: IMPLICATIONS FOR THE MARS 2020 MISSION.

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**Introduction:** Magmatism is a critical process throughout the geological history of Earth and Mars, and one of the few processes capable of producing significant changes in the Martian surface and subsurface past the Noachian [1]. The interaction between mafic magmatism and host rock has the potential to contribute to the surface volatile species, key among which is sulfur. On Earth, mafic magmas intruding sulfur-rich sediments are uncommon; in contrast, sulfur–rich soils exist with a near global extent on Mars, and ample evidence exists for ancient mafic magmatism [2–7]. The intrusion of mafic magmas into sulfur-rich sediments is therefore expected on Mars, and is especially pertinent concerning proposed landing sites for NASA Mars 2020 and the ESA ExoMars missions, both of which contain a potential volcanic capping unit in direct contact with sulfate bearing sediments [1,3,4,8,9]. The NASA Mars 2020 lading site, Jezero Crater, hosts Syrtis Major volcanics overlying sulfate material, while the ExoMars landing site, Mawrth Vallis, includes a magmatic flow that covers sediments hosting sulfate minerals such as jarosite [10–18]. However, the interaction between sulfur-bearing sediments and mafic volcanism on Mars has yet to be studied in depth, which is now timely through its presence at Jezero Crater, Northeast Syrtis Major, and Mawrth Vallis. This study aims to fill this gap in our scientific knowledge pertaining to the mineralogy, alteration, and hydrothermal system of mafic volcanics intruding sulfur-rich sediments.

Here we investigate an analog of this process; a mafic dike intruding the sulfur-rich Jurassic Carmel Formation of the San Rafael Group. Approximately 200 dikes, sills, and breccias can be found in proximity to the San Rafael Swell in Utah, and represent an Earth analog for a scenario of mafic magma intruding sulfur-rich sediments [19,20].

**Geologic Setting**: By the Middle Jurassic, the Sundance Sea had extended southward and covered much of the area that is now Utah. The migration of the sea significantly impacted the Middle Jurassic landscape, and several transgressive/regressive events triggered the deposition of the Carmel Formation [21].

**Miocene Mafic Dikes in the Middle Jurassic Carmel Formation:** The Carmel Formation was deposited in a sabkha environment (i.e., coastal flats that experience episodic flooding followed by evaporation) leading the the development of extensive evaporitic deposits rich in clays and salts [22,23]. With approximately 200 dikes, sills, and breccias intruding the Jurassic San Rafael Group [19,20], the primary section of interest is the Carmel Formation.

**Methods:** We carried out an investigation of a field site near the San Rafael Swell, Utah. During two field seasons (2016, 2017), we sampled a number of dikes intruding the sulfur rich sediments of the San Rafael Group [24,25]. Six samples (37–41,43) were collected from one locality where a mafic dike intrudes the Carmel Formation. The six samples represent a 'cross-section' across the dike and host rock, and were analyzed via VNIR spectrometry using the TerraSpec 4 Hi-Res Spectrometer (Figs. 1,2).

*Figure 1: Dike intruding the Carmel Formation labeled with arrows showing positions of samples plotted in figure 2. Rectangle in image A represents field of view in image B.*

**Results:** A sub-vertical mafic dike intrudes the sulfur-rich siltstones of the Carmel Formation (Fig. 1). The dike has a thickness of approximately 1 meter, and cuts through layered sulfates (each vein approximately 3 cm in thickness) in the host rock that run hrozintally on either side of the intrusion for several meters. The dike itself is also cut by sulfates, which were identified in the field based on crystal habit and hardness. The sulfates within the dike are likely indicative of the remobilization of sulfur-rich fluids. A contact aureole/baked zone extends perpendicularly on either side of the dike for several feet as evidenced by color changes (reddish tan – green/grey), and changes in lithology (siltstone – clay/mud).

We analyzed baked sediments adjacent to the dike (39, 40), sulfates from within the baked zone (37, 38, 41), and sulfate recovered from within the dike (43) using VNIR (Fig. 2). The VNIR was used mainly to constrain the sulfate mineralogy (which dominates most of the samples), but ongoing data analyses will investigate the minor minerals well. Further, ongoing XRD of all samples will constrain the bulk mineralogy of the samples, with a focus on the clay mineralogy.

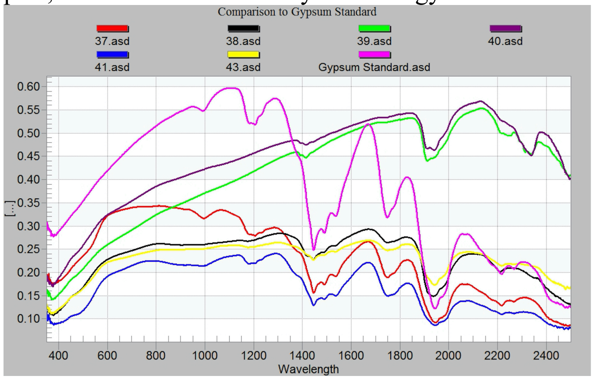

***Figure 2:*** *Preliminary reflectance data for baked sediment and sulfates from the Carmel Formation in proximity to the mafic dike. Data is plotted alongside a gypsum standard for reference. Samples 39 and 40 are baked sediments, samples 37, 38, and 41 are sulfates from within the baked zone, and sample 43 is sulfate recovered from within the dike.*

The samples from the baked zone, including sulfate samples recovered from within the dike itself, produced spectra with minima consistent with gypsum (Fig 2), with little to no other minima present; therefore, suggesting these samples are dominated by gypsum, with possibly minor phyllosilicates. However, the baked sediments in contact with and near the dike produced reflectance specta which are quite dissimilar to both the sulfate samples from our outcrop as well as the gypsum standard. The minima in their spectra are less well defined, suggestive of amorphous material or phyllosilicates. There is some evidence for sulfates with a peak at ~1950 but the distinguishing peaks at 1700 and ~1450 are not present in this sample. This suggests that phyllosilicates with possibly dehydrated sulfates are likely in this sample, consistent with a baked mud origin. All samples have minor calcite and hematite. Ongoing XRD analyses will help confirm the detailed mineralogy of these samples, including the specific phyllosilicate mineralogy.

**Conclusions**: Our results show that the interaction of heat and fluids from the dike persists for meters in either direction away from the dike; however, the detailed nature of the exact mineralogy and chemical changes are ongoing. Our preliminary work shows that sulfur is easily remobilized, as evidenced by the sulfate veins perpendicular to and cross cutting the dike. Further, the sediments adjacent to the dike show evidence of high temperature dehydration and recrystallization. This is particularly important for future studies of Mars at Jezero Crater where the volcanic capping unit is in direct contact with sulfate-bearing sediments. While the Mars 2020 rover will not likely make it to this contact, our work is showing how immense the alteration aerole is affecting the mineralogy. Therefore, float rocks analyzed in Jezero, and potentially bedrock as well (depending on the porosity of the system) will likely be affected and our ongoing results will help constrain the mineralogy that we should expect to encounter, and offers a direct comparison of VNIR data with more detailed mineralogy data, which is especially important for those locations that will only be investigated by remote sensing, e.g., MastCamZ multispectral imaging on Mars2020.

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