MINERALOGICAL CHARACTERIZATION OF A POTENTIAL MARS-ANALOG FIELD SITE: GYPSUM- AND CARBONATE-BEARING FORMATIONS IN THE QUEBRADAS BACK COUNTRY, NEW MEXICO, USA.

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Introduction: The Quebradas Back Country field site is located approximately six miles east of Socorro, NM, USA and provides access to Pennsylvanian and Permian age sedimentary formations that record environments ranging from lacustrine to hypersaline supratidal mudflats [1] in deposits of carbonate, sulfate, and clay minerals [1,2,3,4]. These deposits demonstrate a critical climate transition from cold and wet to largely arid conditions, which may parallel the drying of ancient Mars [5]. The Quebradas sulfate and carbonate deposits can provide insight into the formation and weathering of Mars-relevant sulfates and elucidate potential causes for the prevalence of calcium sulfate and paucity of calcium carbonate on Mars. Deciphering the environmental cues held within evaporites is particularly timely now with mounting evidence for sulfate-rich fluids in Jezero crater [6] and the *Curiosity* rover analyzing the sulfate-bearing unit in Gale crater.

Two sites were examined in the Quebradas Back Country: the Permian Los Vallos formation of the Upper Yeso group, consisting of massive gypsum beds with some claystone, siltstone, and a few dolomite beds that likely formed in a cyclically shallow marine to coastal sabkha environment [4,7]; and the Late Pennsylvanian Tinajas member of the Atrasado formation, a sabkha-like deposit consisting of gypsum-rich carbonate beds [2]. The objectives of this work were to assess the mineralogy and depositional environments of sulfates and carbonates in the Quebradas Back Country; to determine the conditions that led to co-occurrence of carbonate and sulfate minerals; and to assess the site as a mineralogical and geochemical analog for ancient Mars.

Background: Sulfate minerals are abundant on Mars, as demonstrated by orbital and *in situ* rover analyses (e.g., [8,9]). Gypsum, bassanite, and anhydrite are widely distributed in Gale crater and are often found in veins, light-toned fracture fills, and intra-sediment deposits, formed during both sedimentation and diagenetic processes [5]. In contrast, carbonate minerals are less abundant on the martian surface, although geochemical modeling has shown that these minerals would be expected to precipitate in environments likely present on early Mars (e.g., [10,11]). Recent sedimentary rock analysis by Curiosity revealed the presence of siderite in the sulfate unit of Gale crater, which may indicate that early carbonate precipitation exhausted alkalinity and prevented formation of other carbonates, such as calcite [12]. Carbonates and evaporites such as sulfates are important indicators of the ancient aqueous environment on Mars, yet multiple hypotheses exist on the conditions that led to their abundances on the martian surface.

Methods: *Sample collection*. Sampling locations were selected based on the presence of multiple sulfate exposures of different character and/or apparent contact between sulfate and carbonate deposits. Carbonates were distinguished in the field by placing a drop of 10% HCl on the rock surface and observing effervescence. Hand samples were obtained by breaking off pieces with a rock hammer (for well consolidated samples) or digging out with a steel scoopula (for poorly consolidated samples). Samples were stored in plastic whirl-packs or paper-lined sample bags and transported to Johnson Space Center for characterization.

Characterization. Samples were prepared for X-ray Diffraction (XRD) analysis by crushing to <1 mm in a steel mortar and pestle then hand-grinding to <150 μm in ethanol in an agate mortar and pestle. The ground sample was then spiked with a 20 wt% Al_2O_3 micropowder (American Elements) internal standard for quantitative mineralogy, micronized in 200 proof ethanol (Greenfield Global USA, Inc.) in a Retsch XRD-Mill McCrone with agate grinding bodies and a polypropylene grinding jar, then dried in a 50°C oven. XRD analysis of spiked samples was conducted on a Rigaku Mini-Flex XRD with Co Kα radiation at 2-80° 2θ, 0.02° step, 1°/min scanning speed. Quantitative mineralogy was obtained by Rietvield refinement of internal standard spiked sample XRD patterns using JADE Pro 2023 software.

Results: *Los Vallos*. Stratigraphy and mineralogy of the Los Vallos outcrop are shown in **Fig. 1**. The base of the Los Vallos outcrop contained primarily gypsum (78.5 wt%) and bassanite (4.9 wt%) with minor quartz (3.4 wt%) and calcite (2.1 wt%), while the upper part of the outcrop consisted of beds of primarily calcite (46.4-53.2 wt%) and dolomite (13.6-27.5 wt%) with minor quartz (2.0-3.6 wt%) and gypsum (~1 wt%). These were separated by a layer containing calcite (25.8-31.5 wt%), quartz (17.1-24.9 wt%), orthoclase feldspar (6.3-10.6 wt%), and clay minerals (12.8-20.2 wt%) with trace anatase. The clay minerals were primarily muscovite and chlorite, and were likely detrital rather than authigenic. The gypsum-rich layer had ~13 wt% X-ray amorphous material, while the carbonate-rich layers had 23-28 wt% amorphous material.

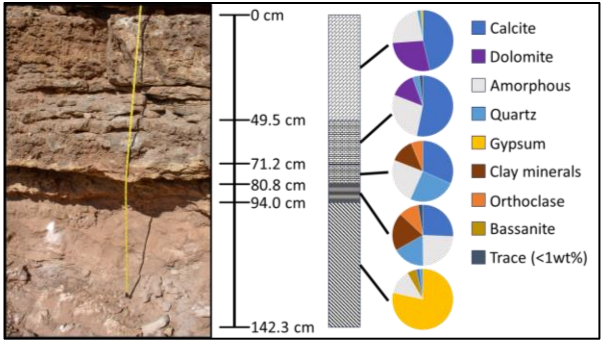

Fig. 1: Los Vallos outcrop with quantitative mineralogy.

Tinajas. Stratigraphy and mineralogy of the Los Vallos outcrop are shown in **Fig. 2**. The base of the Tinajas outcrop was a layered deposit consisting mainly of gypsum (69.8 wt%) and amorphous material (25.8 wt%) with minor bassanite (2.6 wt%) and brushite ($Ca(PO_3OH) \cdot 2H_2O$) (1.9 wt%). This was overlain by a weathered bed containing some calcite (16.6 wt%) but composed primarily of celestine ($SrSO_4$) (83.4 wt%), which has not previously been reported in Quebradas. The celestine bed was intercalated with blocky, finely-laminated layers consisting of only calcite (91.6 wt%), quartz (2.2 wt%), and amorphous material (6.1 wt%).

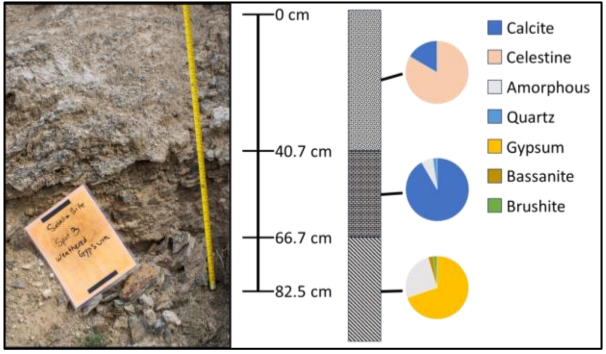

Fig. 2: Tinajas outcrop with quantitative mineralogy.

Discussion: Despite forming in nominally similar depositional environments, the Los Vallos and Tinajas outcrops demonstrated varied size, shape, and texture of sulfate deposits as well as differing degrees of post-depositional alteration. The Tinajas sulfates contained more amorphous material and less bassanite than the Los Vallos sulfates, consistent with their deposition in cooler conditions, and were less well preserved, possibly due to the absence of a resistant carbonate cap or overlying impermeable clay-rich layer. In addition, the presence of abundant celestine at the Tinajas site indicated extensive post-depositional alteration that was not observed at the Los Vallos outcrop. Celestine deposits in carbonate evaporite sequences similar to the Tinajas deposit have been interpreted as the result of interaction between extant Ca-sulfate rich beds and fluids enriched in Sr due to seawater evaporation and burial diagenesis of marine carbonates [13,14]. The celestine-rich layer was also the only sample where carbonates and sulfates occurred together in significant proportions, possibly due to the lower solubility of celestine versus Ca-sulfates at the alkaline pH conditions which permit calcite precipitation [15].

The Los Vallos and Tinajas outcrops are reasonable analogues for sulfate minerals on the surface of Mars. For example, the lithified sandstone-like gypsum of the Los Vallos outcrop may be similar to sulfate deposits observed in Valles Marineris [16], while the Tinajas deposits are diagenetically altered, similar to the sulfates found in Gale crater [5]. These sites could therefore provide insight into the formation and subsequent preservation of multiple deposits on Mars.

The variety of sulfate and carbonate minerals in Quebradas make this field site a promising venue for studies of Mars-analog mineralogy and geochemistry. Our future work will focus on characterizing trace minerals, clay minerals, and amorphous material in our samples; characterizing the chemical relationships between sampled carbonates and sulfates; and investigating transport and reworking of sulfate minerals at the Los Vallos and Tinajas sites.

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