FRACTURE NETWORKS ON MARS:

Preservation of Surface and Subsurface Environments at Mawrth Vallis

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Abstract

Mawrth Vallis is an outflow channel on Mars that cuts through some of the planet's most ancient terrains, which contain many different types of fractures. The ExoMars rover mission will search for biosignatures on Mars, and this site was proposed as one of the two final candidate landing sites for the rover. A biosignature is any object that shows evidence of past or present life. Fracture networks are a high priority for the mission because they might contain minerals precipitated by fluid interaction, and these minerals could trap and preserve biosignatures, critical for our understanding of ancient processes. In this project, we seek to determine the distribution and origin of large fractures in the Mawrth Vallis region. The Java Mission-Planning and Analysis for Remote Sensing (JMARS) program and satellite images from the High Resolution Imaging Science Experiment (HiRISE) orbiter were both used to map fractures at Mawrth Vallis. Based on similar fractures on Earth, we have interpreted that all of the large fractures formed due to water loss, but a rectangular shape suggests that the fractures formed when rocks contracted at the surface, while curvilinear fractures formed in subaqueous sediments. After contraction, the fractures were filled in by precipitated minerals, causing them to appear bright. These fractures on Mars imply some sort of fluid flow, and precipitated minerals in the fractures may preserve evidence of the environment and ancient life that once existed in that area.

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Keywords

Mawrth Vallis, Mars, fractures, biosignatures, Al-phyllsilicates and hydrated silica, Fe/Mg smectites, fluvial activity

INTRODUCTION

Modern Mars is cold and hyperarid, but there are abundant physical signs of past flowing water, such as valleys, deltas, outflow channels, and lake sediments. One such sign of fluvial activity is Mawrth Vallis, an outflow channel that cuts through some of the most ancient terrains on Mars. This kind of channel formation most likely occurred during the late Noachian era due to rare flooding episodes (e.g., Carr & Head, 2010). As shown in Figure 1, the channel is situated on the dichotomy boundary between the Martian highlands and lowlands at ~25°N, 20°W (Bishop et al., 2008). The area around Mawrth Vallis is composed of a thick sequence of light-toned sedimentary layers dating from the Noachian era (~3.7 billion to 4.0 billion years ago). Orbital spectroscopy has shown that these layers are clay rich, with Al-phyllsilicates and hydrated silica layered on top of Fe/Mg smectites and overlaid by a partially eroded dark capping unit (Loizeau et al., 2015). Most of the layered clay deposits in the area are over 200 meters thick. The clays appear to be inconsistent with hydrothermal activity or groundwater, and regional extent and lack of topographic influence suggest a surface weathering origin for the clays (Noe Dobrea et al., 2010). This layering of Al-phyllsilicates and Fe/Mg smectites can be attributed to a semiarid climate and weathering by rain that produced the paleosols seen in the area today (Carter, Loizeau, Mangold, Poulet, & Bibring, 2015).

These ancient Martian rocks were likely formed in aqueous environments that were habitable for ancient microbial life. Bishop et al. (2008, 2013) showed that an Fe²⁺ mineral layer appears at the areas of transition from Al-phyllsilicates to Fe/Mg smectites. On Earth, Fe²⁺ typically exists in sedimentary rocks

Figure 1. Global MOLA map of Mars with Mawrth Vallis denoted by a white star.

because it precipitated out of reducing fluids (Bishop et al., 2008). The presence of strong redox gradients in the subsurface is a key discovery in the study of the history of Mawrth Vallis, as it could indicate a habitable environment with significant microbial energy sources (Horgan, Rice, Farrand, Sheldon, & Bishop, 2015). In addition, on Earth, organic material and/or microbes are often necessary to reduce Fe, and paleosols have a high preservation potential for this kind of material (Hays et al., 2017). Thus, the clays at Mawrth Vallis have the potential of preserving biosignatures from ancient microbial life.

The clay-rich terrain in Mawrth Vallis also hosts a diverse suite of large fractures and fracture networks, some of which are further indications of subsurface fluid flow in the area. Loizeau et al. (2015) identified four different types of fractures at Mawrth Vallis: small and thin, thick, short, and parallel fractures. According to Loizeau et al. (2015), fracturing of the clay unit occurred after the clay had lithified into solid rock. This process broke the newly formed rock into blocks, and then groundwater flowed through the fractures and left behind precipitated minerals. “Halo-bounded” fractures (a subset of thick and short fractures) were created in this way. Loizeau et al. (2015) also found that the Al clay unit holds the most potential for preserving biosignatures because it is protectively covered by the capping unit and has not been subject to erosional surface processes. Thus, the earlier discovery of at least two watery episodes (surface water that lithified the clay, then subsurface water that filled fractures with precipitated minerals) leaves the possibility of multiple areas for trapped biosignatures. However, the depth and environment (surface vs. subsurface) of the large fractures in the Mawrth Vallis region are not well understood.

The ExoMars program is a European Space Agency project tasked with investigating the possibility of past microbial life on Mars. ExoMars consists of the Schiaparelli lander, a Trace Gas Orbiter (both launched in 2016), and a rover that will launch in 2020. The Trace Gas Orbiter will analyze gases in the Martian atmosphere, and Schiaparelli was meant to test landing sequences on the planet but has since crashed. The ExoMars rover, now colloquially named after Rosalind Franklin, will visit different sites that are important to the investigation of biological activity on Mars. The rover will eventually search for biosignatures on the planet, and Mawrth Vallis was proposed as one of the two final candidate landing sites for the rover, the other being Oxia Planum. A biosignature is any object that shows evidence of past or present life (e.g., Hays et al., 2017). Fracture networks such as those found

in the clay layers at Mawrth are a high priority for this mission because they might contain minerals precipitated by fluid interaction, and these minerals could trap and preserve biosignatures, critical for our understanding of ancient processes and environmental conditions of the planet. However, no map currently exists of the distribution of fractures in the proposed Mawrth Vallis landing ellipse for the ExoMars rover.

The objective of our study was to map the distribution and morphologic properties of fractures within a region of Mawrth Vallis as outlined by two potential landing ellipses for the ExoMars rover. One ellipse was centered at 341.567E, 22.372N and the other at 342.055E, 22.156N. We used HiRISE orbital imagery to look for fractures and fracture patterns, and the physical features of each fracture were analyzed once it was recorded. We identified three key fracture morphologies within the mapping area: rectangular, irregular (linear and curvilinear), and halo-bounded fractures.

We hypothesize that the variety of fracture morphologies present at Mawrth Vallis represents different formation environments, and any precipitated minerals in the fractures could be accessed by a future rover mission such as ExoMars in the search for preserved Martian biosignatures.

MATERIALS AND METHODS

This research project began in July 2018 and eventually extended into the fall semester. Three undergraduate students (Phoebe Kinzelman, Jonathan Forss, and Madison Van Buskirk) along with faculty adviser Professor Briony Horgan were contributors to this project. Each student was responsible for mapping a third of the total outlined landing ellipses and recording all mapped data into a fracture database. The JMARS software application was used to view images, create maps, and build the fracture database. JMARS is an open-source geospatial information system created at Arizona State University and designed to assist researchers with mission planning and data analysis on the surface of other planets. The information system contains a wealth of Martian orbiter data and maps for use in a variety of scientific research projects. The HiRISE camera was primarily used to search for and map fractures (McEwen et al., 2007). HiRISE is one of three cameras on NASA's Mars Reconnaissance Orbiter. Images collected by HiRISE are acquired with a resolution of up to 25 cm per pixel and are used to analyze Martian geology and mineralogy in the visible light spectrum.

Figure 2. Map of the proposed ExoMars landing ellipses for Mawrth Vallis (shown here in white) and the divided mapping area, with the MOLA shaded relief and THEMIS Day IR 100m Global Mosaic layers turned on.

JMARS comes with three preloaded map data sets: a latitude/longitude grid, a nomenclature layer, and a Mars Orbiter Laser Altimeter (MOLA) colorized shaded relief. We first hid the nomenclature layer and added a map scale bar in order to best see our mapping area. Our base map was a combination of MOLA-colored elevation data made partially transparent over the THEMIS Day Infrared 100-meter/pixel Global Mosaic, a map layer that captures thermal images from the Thermal Emission Imaging System on board the Mars Odyssey orbiter. Daytime thermal images are sensitive to slopes of geological landforms, so the mosaic is helpful because it effectively sharpens elevation maps of Mars. We then began importing shapefiles for our project. Several landing ellipse shapefiles were created and provided by Dr. Christoph Gross of Freie Universität Berlin, including two ellipses with slightly different orientations and centers. Large (111.4 and 135.6 km long) and small (90.7 and 122.6 km long) versions of each ellipse corresponding to lower versus higher probabilities of landing locations were available, but in order to make the November completion deadline prior to the ExoMars landing site workshop, the mapping area was moved to the smaller ellipses. Another map layer was dedicated to the mapping grid, which was split into equal thirds and color-coded to ensure that each student had a unique section to analyze, as shown in Figure 2. Finally, remote sensing data in the visible light spectrum from the HiRISE orbiter was imported as a HiRISE Full Stamps layer in order to find fractures. To ensure that fracture mapping remained consistent, the mapping resolution was restricted to 32,768 pixels per degree (ppd) or occasionally zoomed in to 65,536 ppd to verify interpretations.

Each student was assigned one-third of the area covered by the smaller landing ellipses in order to map the distribution of fractures in the area. The latitude/longitude grid layer was used by each student to split her or his mapping area into 1-km grid squares based on the desired HiRISE image resolution, and each student mapped well over 700 grids on the ellipses. Each grid square was automatically assigned latitude and longitude coordinates within the program. First, individual HiRISE images that corresponded to the grid square of interest were loaded and cataloged using their ID number. The search was limited to bright outcrops within the 1-km grids so that only the obvious fractures were logged. Fractures were logged in the database as “present” with the number 1, “possible” with 2, and “not present” with 3. Any fractures found at the 32,768-ppd resolution were mapped, and the 65,536-ppd zoom resolution was used sparingly in instances where it was difficult to ascertain whether a feature was a fracture or not. Fractures that appeared in two grid squares were mapped as present in both, and any extra information about the surrounding terrain was also noted. In addition, green, yellow, and red box shapes corresponding to grid squares with present, possible, and not present fractures, respectively, were then added so the entire mapping area could be analyzed for overall dispersion trends (Figure 3).

Once a fracture was mapped as either “present” or “possible,” it was analyzed for morphology, including polygonal (rectangular) or irregular (linear/curvilinear) shape, size (short or long), color of clay unit (reddish-brown, blue), density of fractures (high, moderate, low), and brightness. Numbers were also assigned to log the presence of a halo (1 = present, 2 = possible, 3 = not present). All

Figure 3. Completed fracture distribution map. Grids that have definite fractures are outlined in green, possible fractures in yellow, and no fractures in red.

Figure 4. Example of a rectangular fracture network, shown here at 65,536 ppd and outlined in a white box.

Figure 5. Example of an irregular fracture, shown here at 65,536 ppd and outlined in a white box.

Figure 6. Example of possible halo-bounded fractures, shown here at 65,536 ppd and outlined in white boxes.

of the above characteristics of positively identified fractures were then logged in a shapefile database within JMARS.

One difficulty of this project was the inconsistency in fracture analysis that arose from using multiple mappers. Fracture analysis had a tendency to vary from student to student, so a few overlapping regions on the margins of each area were analyzed by the group. Afterward each characteristic of the fractures logged in these shared areas was compared, and any differences in individual analysis were edited to ensure consistency of future fracture mapping.

The last step in cataloging fractures was comparing the morphologies of fractures to terrestrial analogs. Earth and Mars undergo similar surface processes, and the similarities between planets make it simpler to determine how something formed on Mars because it likely formed the same way on Earth. Using this method, we can constrain the origin of each mapped fracture.

RESULTS

The database we compiled on each identified fracture included a list of morphological properties that assisted in our naming and classification of different types of fractures. As shown in Figure 4, we named rectangular fractures for their shape and classified them as polygonal fractures because they most often appear in repeating patterns. By contrast, irregular fractures such as in Figure 5 are those that do not show any patterning. Both linear and curvilinear fractures fall under the irregular fracture category, with linear fractures appearing as straight lines and curvilinear fractures appearing as slight curves. Finally, any of these fracture types could appear halo-bounded, partially surrounded by a bright halo-like ring as in Figure 6.

Bright fractures, which were easier to identify using remote sensing methods, were abundant in the southern and central parts of the two ellipses but were less concentrated in the far northern areas. The differences in types of fractures identified are most likely a result of their occurrence in different parts of the area's stratigraphy, with rectangular fractures embedded just below the capping unit, bright fractures in the boundary between Al-phylosilicates and Fe/Mg smectites, halo-bounded fractures in the Fe/Mg smectite layer, and thin fractures throughout, as shown in Figure 7 (adapted from Loizeau et al., 2015).

Figure 7. Stratigraphic column of Mawrth Vallis (adapted from Loizeau et al., 2015).

DISCUSSION AND CONCLUSION

The results of our fracture classifications at Mawrth Vallis allow us to infer what kind of formation environments must have been present for different fracture formation sequences. Rectangular fractures (tessellations) imply contraction at the surface, followed by infill or mineral precipitation in the joints. On Earth, this occurs in sedimentary rocks of a variety of grain sizes due to wetting and drying cycles and often involves salts or carbonates. Mudcracks such as those shown in Figure 8 are a subset of this category. Therefore, the surface origin of the rectangular fractures at Mawrth is consistent with their location in the uppermost section or at the top of the stratigraphy. However, curvilinear fractures may suggest subsurface contraction without drying, usually in saturated subaqueous clay-rich sediments. This morphology is also thought to form during subaqueous compaction and subsequent dewatering (e.g., Cartwright, James, & Bolton, 2003). Therefore, a subsurface and subaqueous origin of the curvilinear fractures at Mawrth is consistent with their location in the Fe/Mg-smectite sediments.

Knowing the different formation environments that existed at Mawrth Vallis is extremely helpful in our search for biosignatures on Mars. As stated in our introduction, the ExoMars rover will launch in 2020 and investigate its final landing site for biosignatures. Mawrth Vallis was on the short list of landing site

Figure 8. Example of mudcracks in Death Valley, California, a terrestrial analog to rectangular fractures at Mawrth Vallis (photograph by Michael C. Rygel, distributed under a CC BY-SA 3.0 license).

candidates for this project because of its mineral-filled fractures, but the distribution of different types of fractures in the area was unknown, as were the kinds of environments that existed to create fractures and preserve biosignatures in the first place. In order to answer these uncertainties, we produced a map of fractures found in two potential landing ellipses as well as a final hypothesis on what kinds of formation environments existed in that area. We hypothesize that rectangular fractures at the top of the layering sequence formed due to desiccation in a subaerial environment and that curvilinear and irregular fractures in Fe/Mg-smectites formed during burial and dewatering of subaqueous sediments. If present, precipitated minerals in shallower rectangular fractures may preserve fluids and biosignatures from surface environments. This may also support the proposed subaqueous mineral deposition of these layers. Finally, precipitated minerals in deeper curvilinear fractures may preserve fluids and biosignatures from subsurface environments.

Though Oxia Planum has been chosen as the final landing site for the ExoMars rover, further analysis of the filled fractures at Mawrth Vallis will prove critical to our understanding of ancient fluvial processes, potential biological processes, and environmental conditions of Mars.

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