Geomorphology of Serpentine and Carbonate-Bearing Terrains in Nili Fossae, Jezero Crater, and Gusev Crater

Elena Lee[1]

[1]Swarthmore College

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Abstract

Carbonates have been detected in several locations on Mars, including Nili Fossae, Jezero Crater, and the Comanche outcrops of the Columbia Hills. Carbonates are intriguing for what they could reveal about potential habitability of past environments; however, their exact formation mechanisms remain ambiguous. Observations support a range of formation mechanisms, such as meteoric alteration of hot olivine tephra, hydrothermal alteration or serpentinization, near-surface weathering of serpentinized material, or aqueous alteration via ephemeral lakes. The associated mineralogy of carbonate-bearing terrain, such as the serpentine deposits detected in Nili Fossae and Jezero, can help constrain the origins of the carbonates. This study examines CRISM and HiRISE images of serpentine and carbonate deposits in Nili Fossae and Jezero Crater to identify common characteristics of serpentine-carbonate terrains. The morphologies of serpentine and carbonate-bearing terrains in Nili Fossae and Jezero are then compared to carbonate deposits in the Columbia Hills. By combining these analyses, this study explores the extent to which the carbonates' histories are analogous and probes into previous serpentine detections in Jezero and Nili Fossae.

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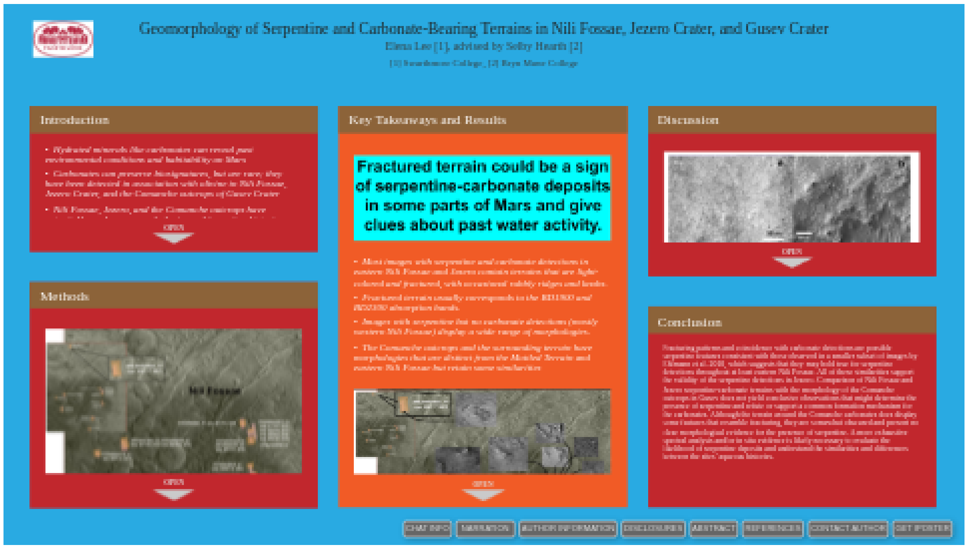

Elena Lee [1], advised by Selby Hearth [2]

[1] Swarthmore College, [2] Bryn Mawr College

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INTRODUCTION

- *Hydrated minerals like carbonates can reveal past environmental conditions and habitability on Mars*

- *Carbonates can preserve biosignatures, but are rare; they have been detected in association with olivine in Nili Fossae, Jezero Crater, and the Comanche outcrops of Gusev Crater*

- *Nili Fossae, Jezero, and the Comanche outcrops have potentially analogous morphologies and formation histories*

- *Analysis of associated mineralogy such as serpentine can constrain the formation mechanism*

- *This study examines the morphology of serpentine and serpentine-carbonate-bearing terrains in Nili Fossae and Jezero and compares them to the Comanche carbonates to evaluate the possibility of serpentine in Gusev and investigate the extent to which the carbonates' histories are analogous*

Hydrated minerals on Mars can illustrate past aqueous environmental conditions and habitability. Carbonates are particularly helpful because of their potential to preserve biosignatures, but they are rare on Mars. Small Mg-rich carbonate deposits have been identified at only a few locations, including Nili Fossae, Jezero Crater, and the Columbia Hills in Gusev Crater (Amador 2018, Horgan 2020, Carter and Poulet 2012). Interestingly, carbonates at all three of these sites co-occur with olivine, an igneous mineral not usually associated with carbonates on Earth. In Nili Fossae and Jezero, serpentine has also been detected with the carbonates. Thus, it is possible that these carbonates formed via similar mechanisms (Morris 2010, Ruff 2019). This study examines the morphology of carbonate-olivine and serpentine deposits and their associated mineralogy at Nili Fossae, Jezero Crater, and the Columbia Hills to investigate how they formed and what they can reveal about past aqueous conditions at these sites (see Fig. 1, Fig. 2).

The carbonate-olivine units in eastern Nili Fossae and Jezero share a common stratigraphy and morphology, and thus possibly a similar formation history as well (Ruff 2019). The units are often bright and polygonally fractured (Ehlmann 2010). The carbonates probably formed from olivine via one of several alteration mechanisms: groundwater percolating through fractured olivine-rich bedrock, olivine-rich tephra deposited on water-rich phyllosilicates leading to hydrothermal alteration (Ehlmann 2008), surface alteration of olivine or serpentinized rocks (Mangold 2007), precipitation from ephemeral lakes when water percolated through olivine, became enriched in Mg^{2+}, and evaporated (Ehlmann 2008, Melezhik 2001), or meteoric precipitation on hot tephra (Horgan 2020).

Figure 1 (modified from Amador et al. 2018): CRISM images in Nili Fossae; green = serpentine detections, purple = carbonate detections, blue = talc/saponite detections. The red rectangle is the area covered by figure 2 in Goudge et al. 2015.

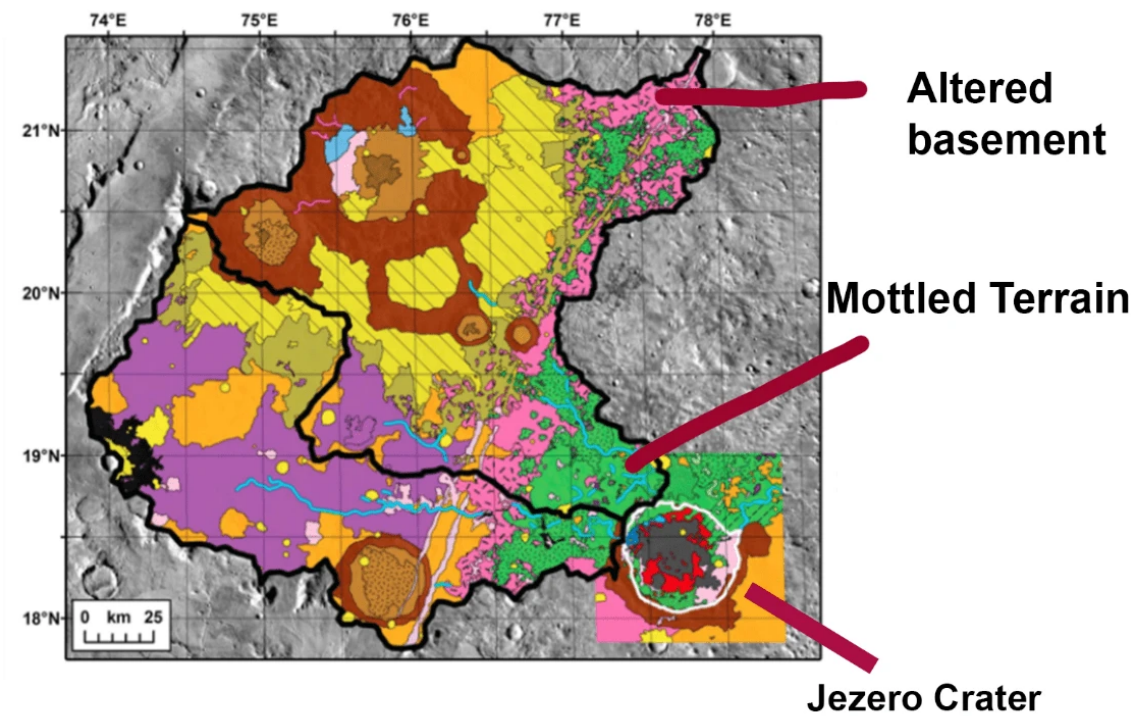

Figure 2 (modified from Goudge et al. 2015, above): mapped units in Nili Fossae and Jezero. Except for the images in Jezero, none of the CRISM serpentine detections lies in a mapped unit, although the detections in eastern Nili Fossae lie near exposures of the Mottled Terrain (green) and altered basement (pink).

Although the Comanche outcrops in Gusev are located far from the carbonate-olivine units in Jezero and Nili Fossae, their morphological similarities suggest they could be analogous (Ruff 2019). The outcrops lie atop olivine-rich rocks that are likely volcanic tephra (McCoy 2008, McSween 2008) and consist of "bouldery knobs and ridges" atop bright fractured terrain, features commonly seen in Nili Fossae and Jezero (Ruff 2019); see Fig. 3. The two main hypotheses for carbonate formation are a volcanism-spurred hydrothermal alteration process or an ephemeral lake (Morris 2010, Ruff 2014).

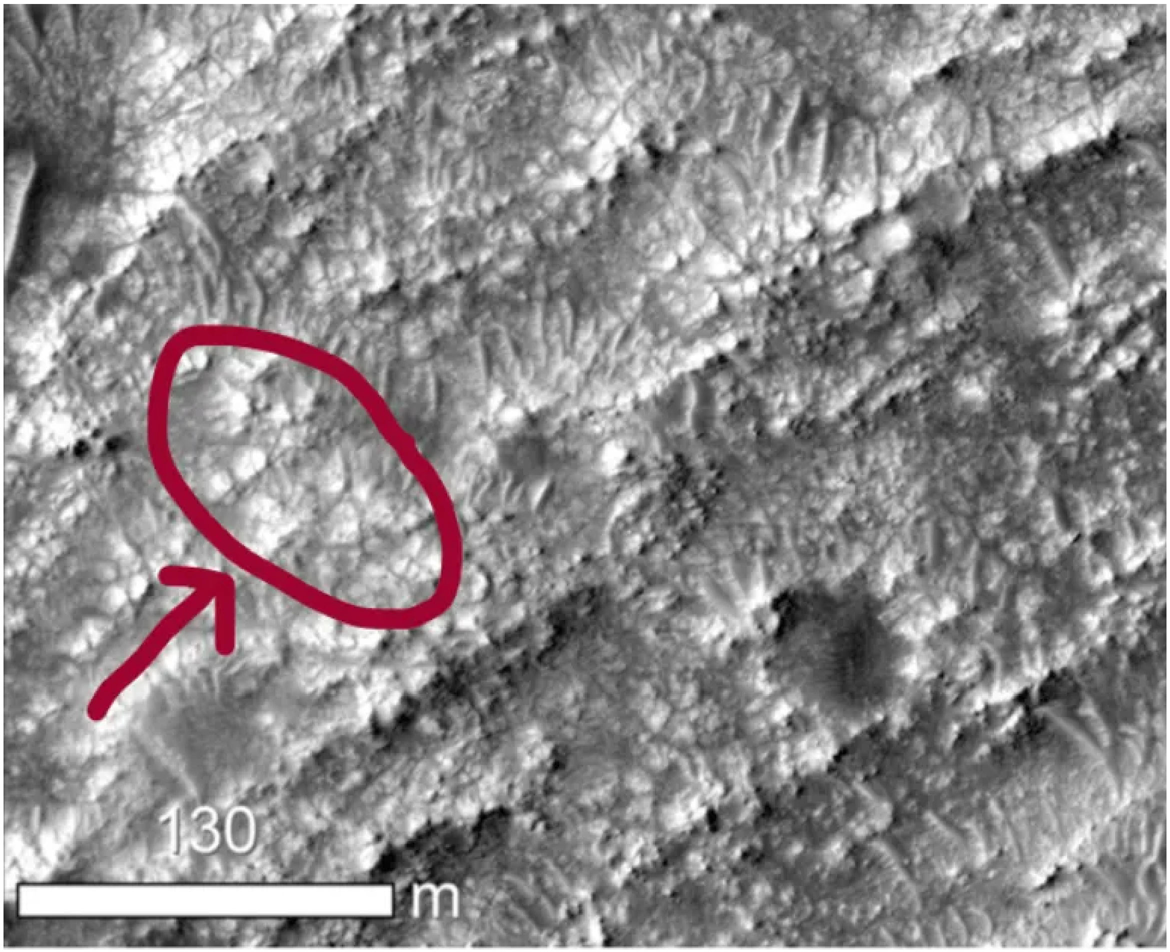

Figure 3 (modified from Horgan et al. 2020) showing the high-albedo fractured appearance of the Mottled Terrain in Jezero. Ehlmann et al. 2010 notes similar fracturing around serpentine deposits in Nili Fossae.

Given the similarities between the three olivine-carbonate-bearing terrains, identifying and comparing associated mineralogies, such as the presence of serpentine, can help constrain the carbonates' origins (Ehlmann 2021, Chevrier and Morisson 2021). Magnesium carbonates can form alongside serpentine in either low-temperature, high-CO_2 hydrothermal systems or through surface weathering of serpentinized olivine (Ehlmann 2021, Chevrier and Morisson 2021).

This study compares the morphologies of possible serpentine-carbonate deposits detected in the Jezero Mottled Terrain (olivine-carbonate unit in Jezero analogous to the unit in Nili Fossae) and Nili Fossae (Amador 2018, Dobrea and Clark 2019, Ehlmann 2009); see Fig. 1 and Fig. 2. The morphologies of Nili and Jezero serpentine-carbonate terrains are then compared to those around the Comanche outcrops (where serpentine has not yet been detected) to evaluate the possibility of serpentine in the Columbia Hills and possibly constrain the formation mechanism of the carbonates.

METHODS

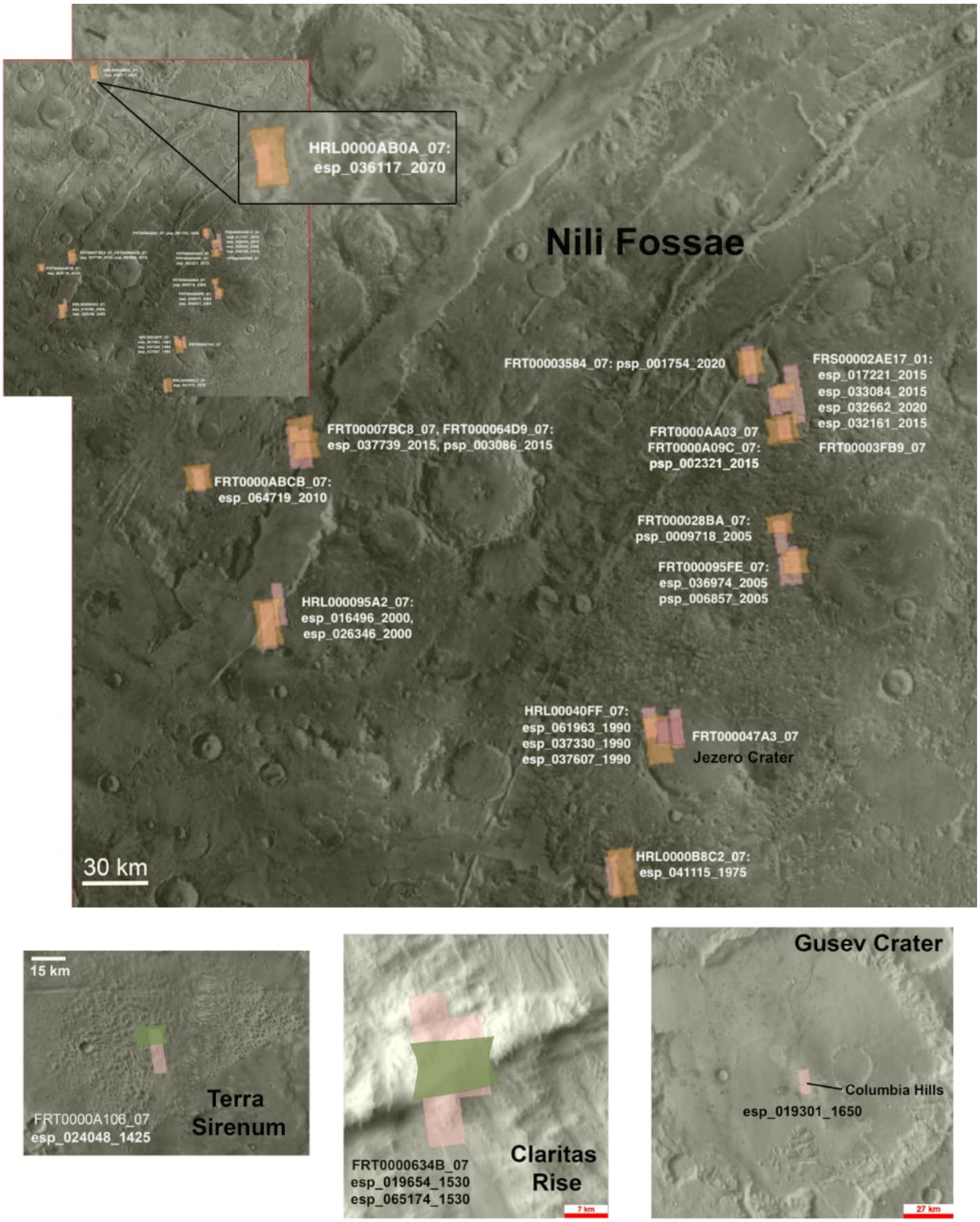

Figure 4: All of the CRISM and HiRISE images analyzed in this study. The hourglass-shaped areas show CRISM coverage and the rectangular areas show HiRISE coverage. The leftmost HiRISE rectangle corresponds to the topmost HiRISE label for each label cluster; all HiRISE labels are listed underneath the CRISM image(s) with which they overlap.

- *Used Adobe Photoshop to analyze Targeted Reduced Data Record (TRDR) CRISM and overlapping Reduced Data Record (RDR) HiRISE images from Mars Orbital Data Explorer (ODE) in Jezero and Nili Fossae identified by Amador et al. 2018 and Ehlmann et al. 2010 to contain serpentine and carbonates*

- *Examined morphologies of serpentine and carbonate-bearing terrain in Jezero and correspondence with CRISM IR derived data products (BD2300, BD1900, BD2100 bands because of 1.9, and 2.3 μm absorption in carbonates and serpentine and 2.12 μm absorption in serpentine)*

- *Examined morphologies of possible serpentine-bearing terrain in Nili Fossae based on comparison with Jezero morphologies, descriptions in Amador et al. 2018, and correspondence with CRISM bands*

- *Compared possible serpentine-carbonate morphologies from Jezero and Nili Fossae to morphologies of Comanche outcrops in Gusev Crater*

This study analyzes satellite images from the the High Resolution Imaging Science Experiment (HiRISE) and the Compact Reconnaissance Imaging Spectrometer (CRISM). The HiRISE images provide a detailed, close-up view of Martian terrains, whereas the CRISM images show where those terrains absorb light at different wavelengths. This CRISM analysis focused on the BD2300 (depth of absorption at 2.3 μm), 1900, and 2100 bands because carbonates and serpentine can both absorb light at 1.9 and 2.3 μm and serpentine has an absorption at 2.12 μm.

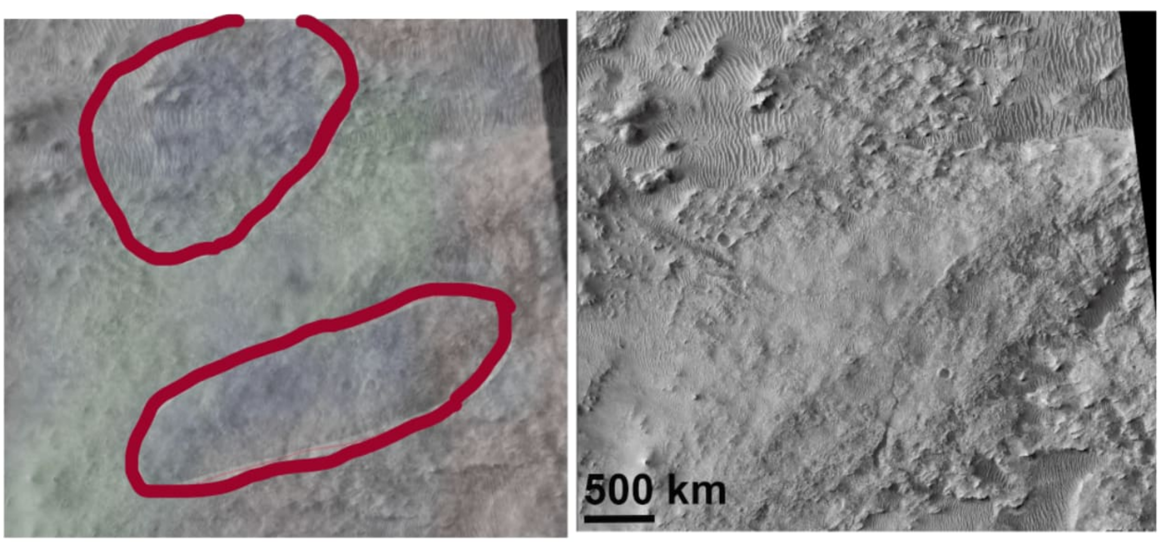

Figure 5: HiRISE image with (left) and without (right) CRISM serpentine and carbonate detections from Noe Dobrea and Clark 2019 overlaid. Serpentine is blue and carbonate/dolomite is green, with areas of high serpentine content outlined in red ovals.

All the CRISM images in Nili Fossae and Jezero in which (Amador 2018) and (Ehlmann 2010) detect serpentine and carbonates were selected for analysis (Fig. 4). A few CRISM images, both within and outside Nili Fossae, that include serpentine detections but no carbonate detections were chosen so as to examine whether the presence of carbonates changes the serpentine's morphological expression. HiRISE images that overlapped with those CRISM images were analyzed in order to investigate which bands correspond to which morphologies. Unfortunately, CRISM band depth maps for the Columbia Hills were insufficient for this analysis.

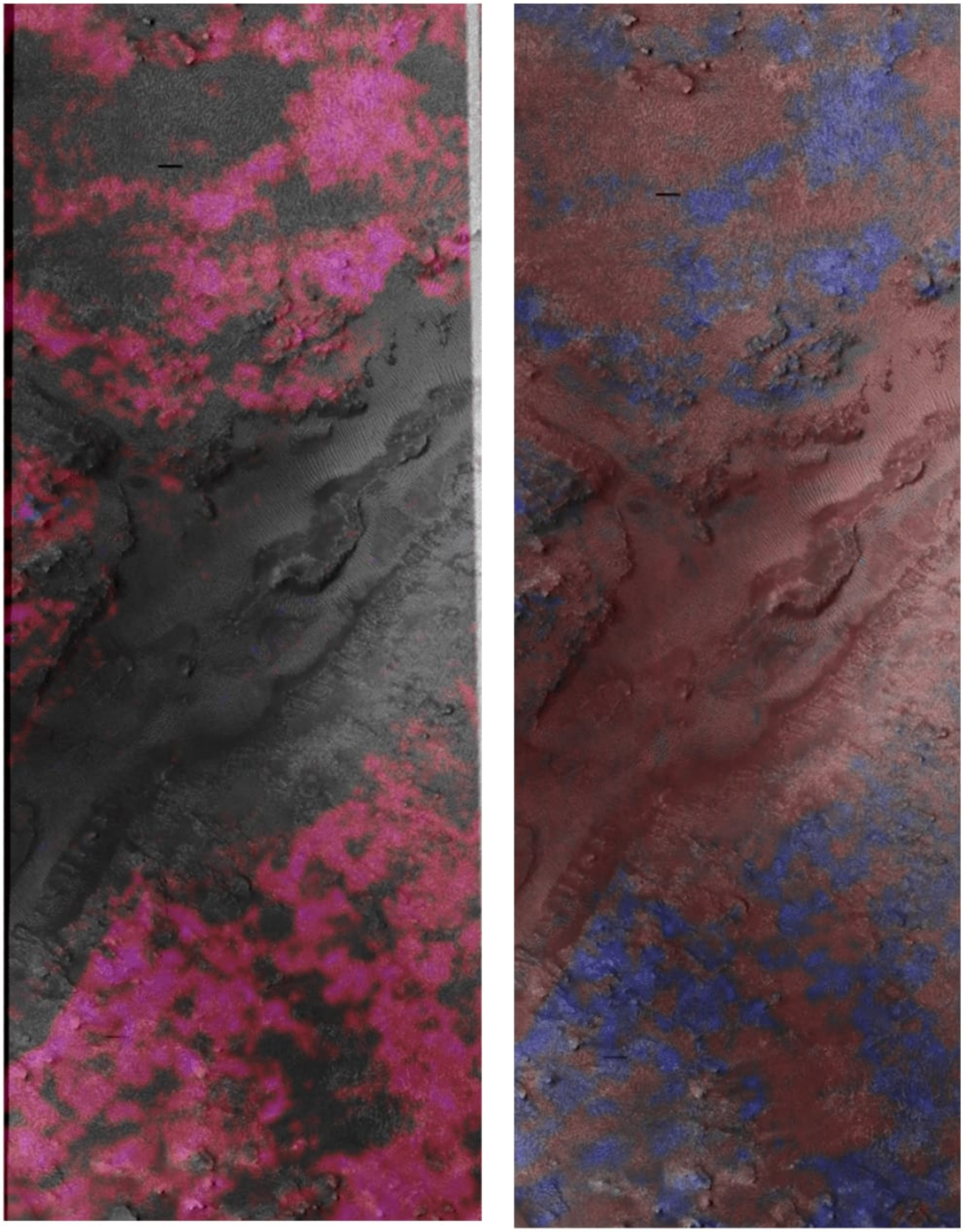

Figure 6: HiRISE Image psp_001754_2020 with ir_phyl CRISM map overlaid (left) and ir_hyd CRISM map (right).

The HiRISE analysis consisted of several steps. In Jezero, the examination focused on the morphology of the areas where the Mottled Terrain (according to the mapping in Goudge 2015) and the serpentine and carbonate detections (mapped in Dobrea and Clark 2019) overlap. In Nili Fossae, the exact locations of the serpentine and carbonate detections from Amador 2018 are unclear. As a result, serpentine-carbonate terrains in Nili were identified by written descriptions from Amador 2018 combined with CRISM band depth maps and comparisons with serpentine-carbonate morphologies in Jezero. Finally, the morphologies corresponding to possible serpentine/serpentine-carbonate outcrops were compared with the morphology around the Comanche outcrops of the Columbia Hills.

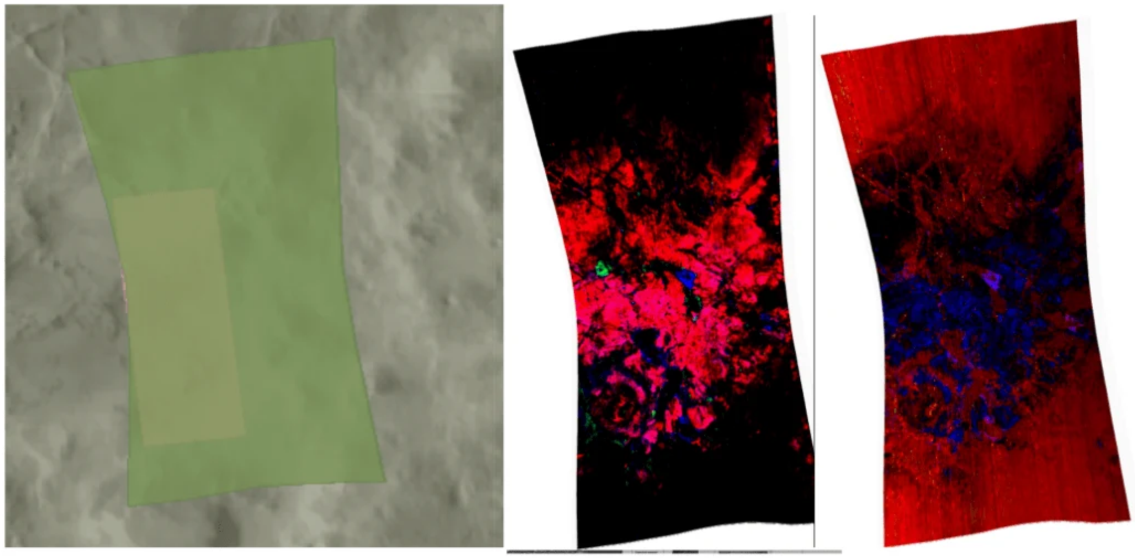

Figure 7: CRISM image HRL0000AB0A_07 (hourglass shape) and overlapping rectangular HiRISE image esp_036117_2070 (left); ir_phyl CRISM derived data map with blue = BD1900, red = BD2300, green = BD2210, pink = BD1900+2300 (middle); ir_hyd map with blue = BD1900 (right).

KEY TAKEAWAYS AND RESULTS

Fractured terrain could be a sign of serpentine-carbonate deposits in some parts of Mars and give clues about past water activity.

- *Most images with serpentine and carbonate detections in eastern Nili Fossae and Jezero contain terrains that are light-colored and fractured, with occasional rubbly ridges and knobs.*

- *Fractured terrain usually corresponds to the BD1900 and BD2300 absorption bands.*

- *Images with serpentine but no carbonate detections (mostly western Nili Fossae) display a wide range of morphologies.*

- *The Comanche outcrops and the surrounding terrain have morphologies that are distinct from the Mottled Terrain and eastern Nili Fossae but retain some similarities*

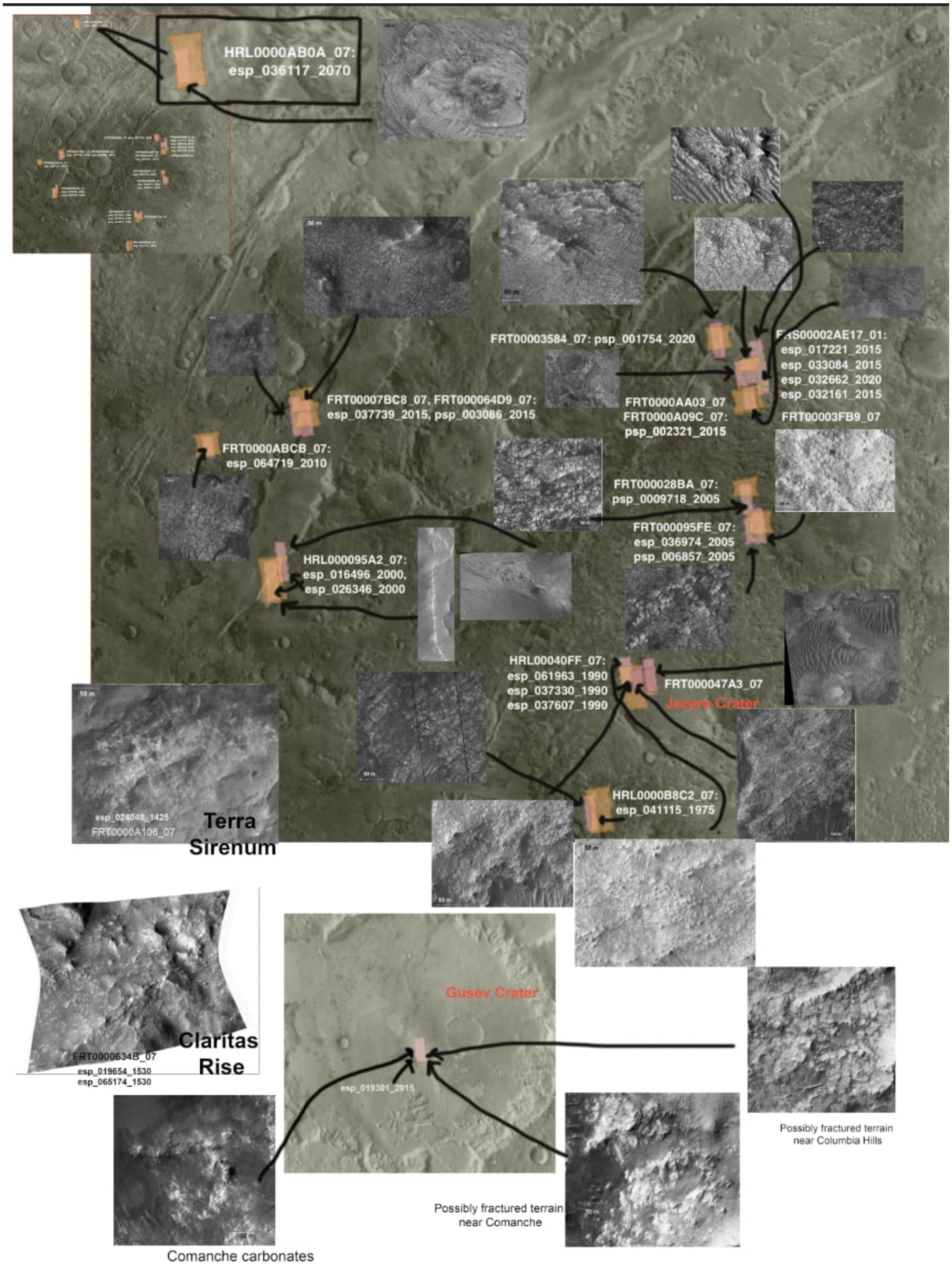

Figure 8: Samples of possible serpentine and/or serpentine-carbonate morphology in the HiRISE locations studied. The black arrows sprouting from each image point to the associated HiRISE image.

In general, serpentine and carbonate detections in the Mottled Terrain of Jezero correspond closely to fractured, high-albedo terrain. The fractures intersect to form polygon-shaped cells of about 5-10 m in diameter and often contain rubbly knobs and ridges such as those pictured in Ruff et al. (2019). In fact, the serpentine detection in esp_061963 corresponds almost exactly to a region with pronounced, rubbly SW-NE-trending ridges (such as those mentioned in Horgan et al. 2020 and Mangold et al. 2007) atop fractured terrain.

In eastern Nili Fossae outside of Jezero, it is unclear in many cases where exactly in the CRISM images Amador et al. (2018) detected serpentine and carbonates, so it is difficult to tell if the serpentines and carbonates had distinct morphologies. Areas that fit these descriptions, however, possess similar fractured terrain to that found in Jezero, although the associated knobs and ridges do not generally have a directional trend and in some cases are not very prominent (Fig. 10). The size of the fracture cells is generally around 5-10 m, although this varies from less than 5 meters to up to 30 m.

In the western portion of Nili Fossae, where some of the images with serpentine detections lack carbonate detections, the serpentine morphologies are far less distinct and more varied, ranging from gentle, textured knobs atop relatively smooth dark terrain to sharp ridges and rough knobs to sharp, lacy ridges. A few images displayed terrain that appeared fractured, but the fractures differed in form or were more obscured than in eastern Nili Fossae.

In terms of CRISM spectra, Jezero and the eastern portion of Nili Fossae display somewhat similar patterns. In Jezero, the BD1900 and BD2300 bands match closely with the carbonate detections from Dobrea and Clark (2019) and have a weak to nonexistent correspondence with the serpentine detections. Where serpentine has been detected alone, however, the BD2300 and BD1900 bands correspond quite closely to the serpentine-bearing terrains (Fig. 9). Since carbonates also have absorption bands around 1.9 and 2.3 μm, perhaps the presence of carbonates sometimes obscures the absorption due to serpentine. In eastern Nili Fossae, fractured terrain matched up fairly closely with the BD1900 and BD2300 bands.

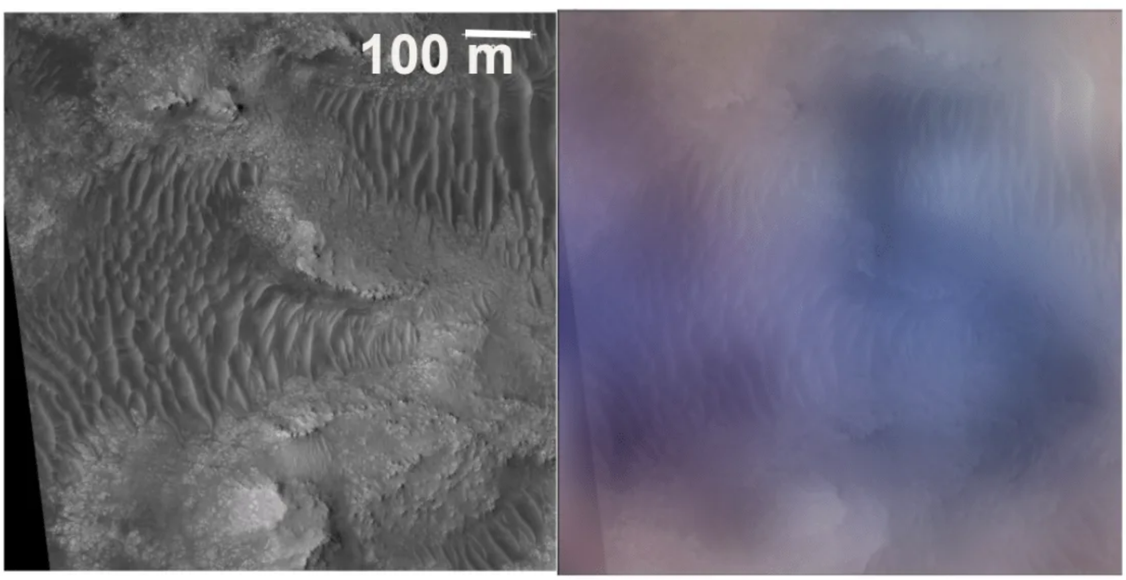

Figure 9: Serpentine images from esp_037607_1990 in Jezero showcasing the close correspondence between serpentine detection in Dobrea and Clark 2019 (blue, reproduced from Dobrea and Clark 2019) and the fractured, ridged terrain.

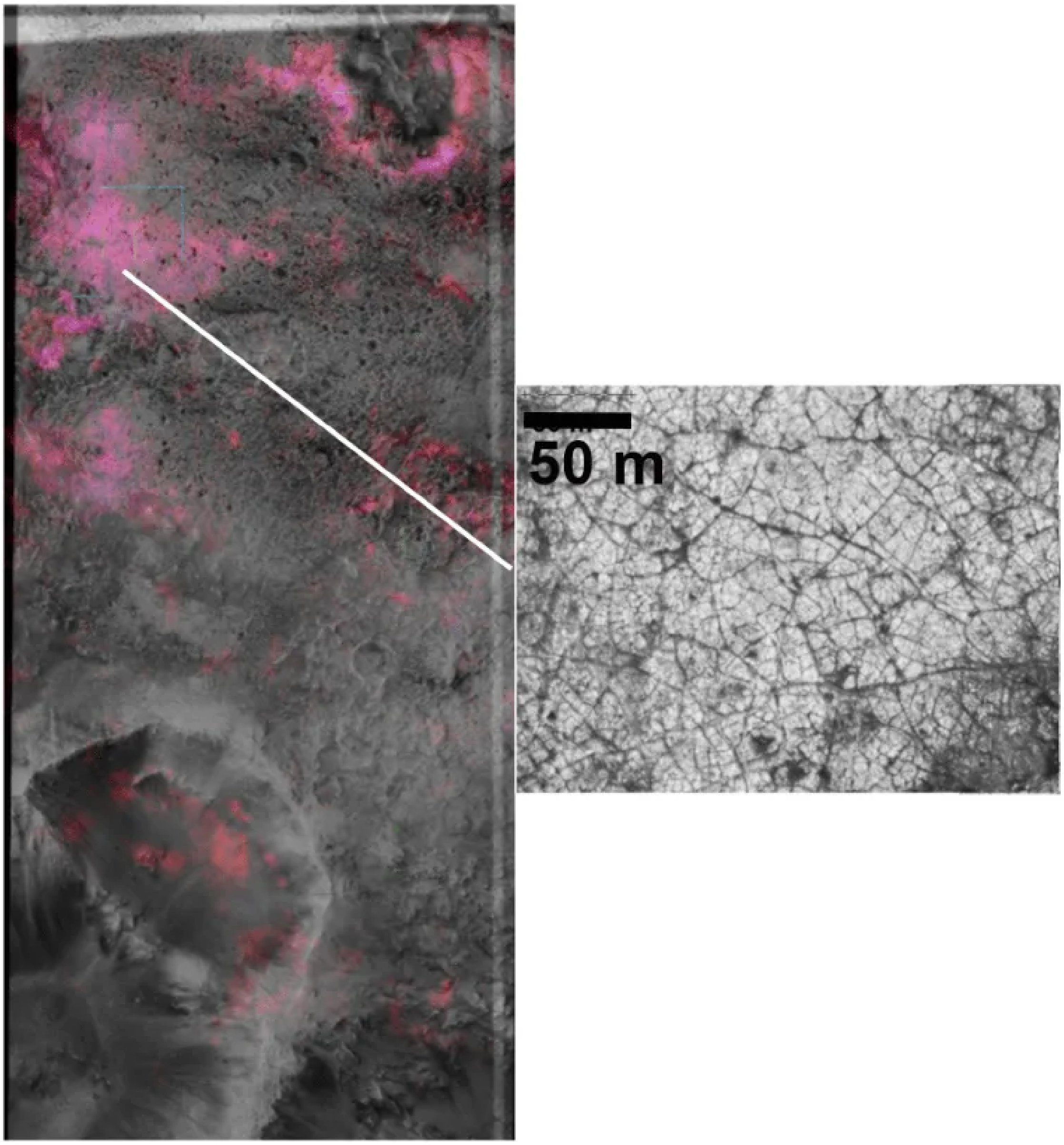

Figure 10

Left: HiRISE image psp_006857_2010 (eastern Nili) with CRISM band depths (pink = BD2300+1900, red = BD2300)

Right: Pale, fractured terrain overlapping with pink CRISM band

In contrast, western Nili Fossae displays little correspondence between fractured terrain and the BD1900 and BD2300 bands (Fig. 11). Although the serpentine detections from Ehlmann et al. (2010) in image esp_064719 do correspond to areas with bright 2300 and 1900 bands, this serpentine-bearing terrain (as described above) is not fractured.

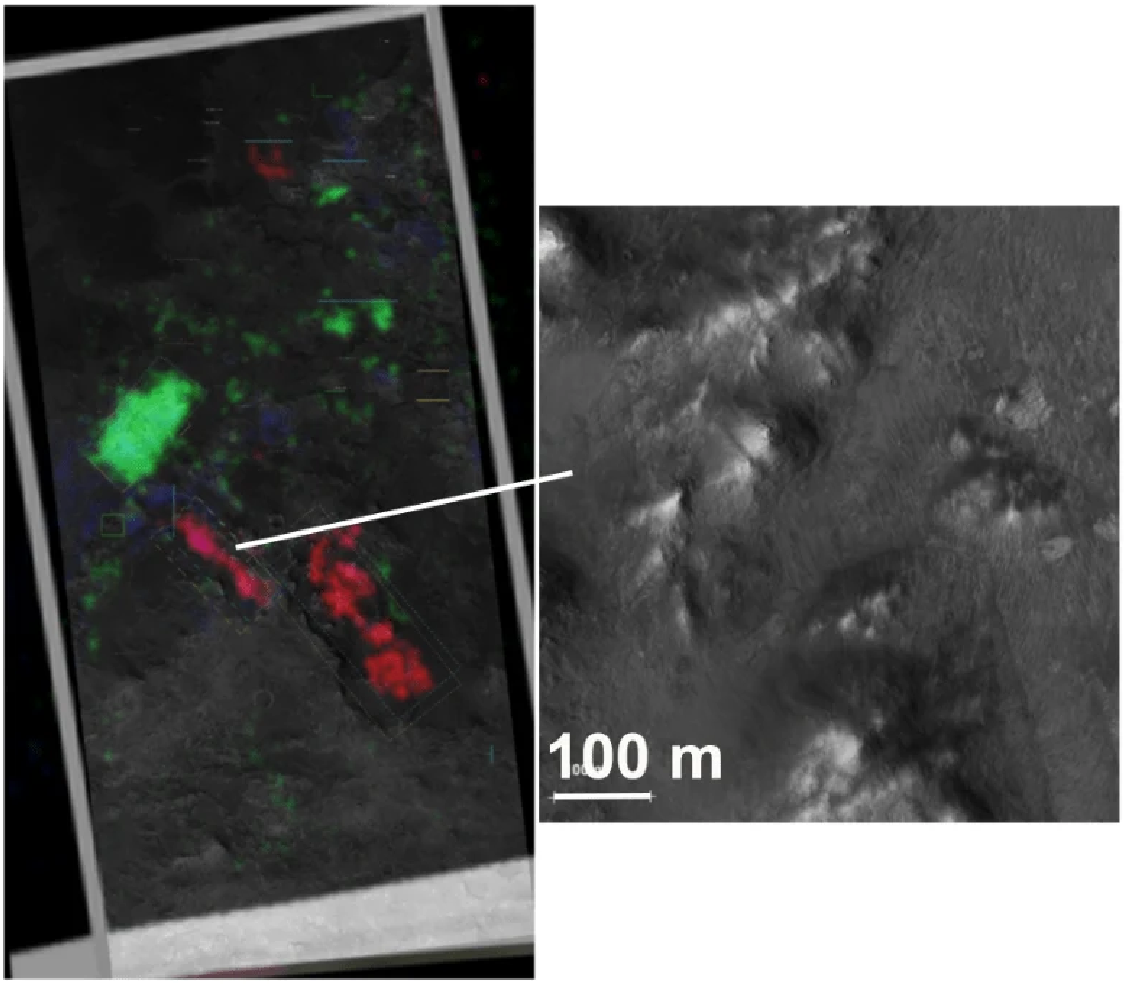

Figure 11

Left: HiRISE image esp_064719_2010 with CRISM band depths (green = BD2210, red = BD2300, pink = BD2300+1900) overlaid.

Right: Smooth, gentle knobs of serpentine deposits detected in Ehlmann et al. 2010, overlapping with pink CRISM band. No fractured terrain is visible.

The morphologies of the Comanche outcrops do not bear a striking resemblance to carbonate or serpentine morphologies in Nili Fossae and Jezero (Fig. 12). The Comanche outcrops themselves are rough, rubbly knobs and protrusions that somewhat resemble the ridges and knobs found in Nili Fossae and Jezero, but the formations in Comanche appear less like aligned ridges and more like chaotic bumps. No fractured terrain is visible on the Comanche outcrops themselves, but one area approximately 150 m to the southeast and another in the southwest outskirts of the Columbia Hills display some evidence of possible fracturing. The pattern is rather obscured, however, and is not as pervasive as in Nili Fossae and Jezero.

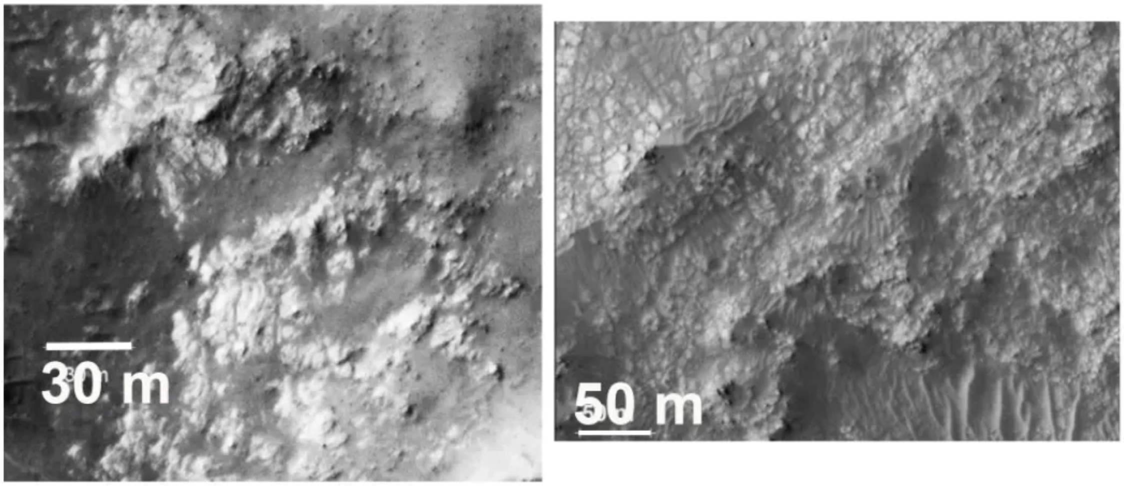

Figure 12: Potentially fractured terrain ~150 m SE of Comanche outcrops (left) versus fractured serpentine-bearing terrain in Jezero (esp_061963_1990, right)

DISCUSSION

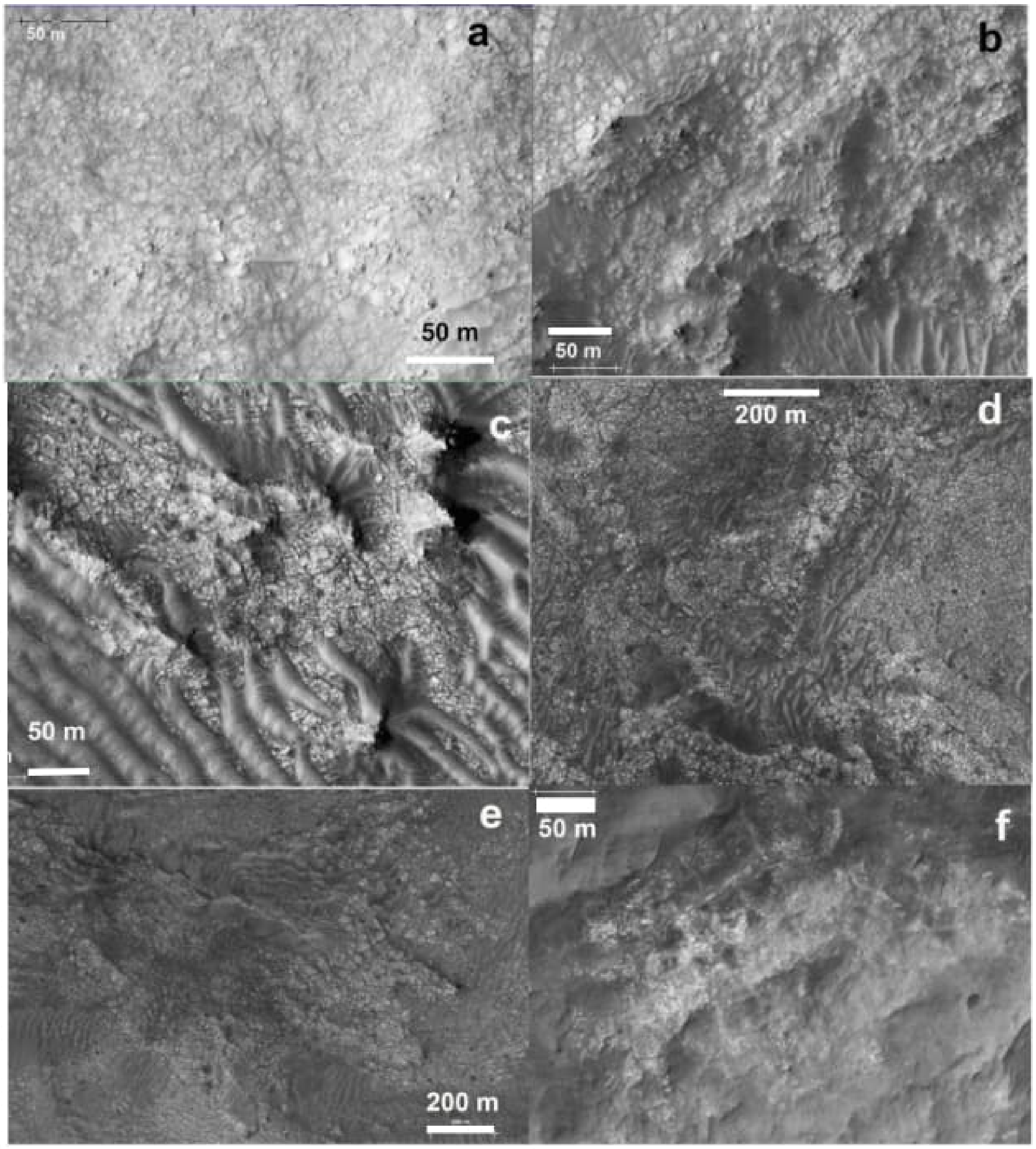

Figure 13

a: Dolomite (carbonate-bearing) terrain in Jezero, HiRISE image esp_061963_1990

b: Serpentine detection in esp_061963_1990

c: Fractured, ridged/knobby terrain in esp_002321_2015 (possibly both carbonate and serpentine-bearing)

d: Amador et al. 2017 serpentine detection in esp_017221_2015

e: Amador et al. 2017 carbonate detection in esp_032161_2015

f: Obscured possible fracturing in region of Amador et al. 2018 serpentine detection in esp_024048_1425 (Terra Sirenum)

- *The spectral and morphological similarities in the fractured terrain suggest that the serpentine detections in Jezero are consistent with the Nili Fossae detections.*

- *Evidence regarding the presence of serpentine in the Columbia Hills or a possible common formation mechanism for the carbonates in Nili Fossae, Jezero, and Gusev is inconclusive.*

Overall, regions with serpentine and carbonate deposits together in Nili Fossae and Jezero seem to share several features in common: a) light-colored terrain fractured into small, ~5-10 m cells; b) fractured terrain overlapping closely with areas containing BD1900 and BD2300 bands; and c) rubbly knobs and ridges. Regions where only serpentine (and not carbonate) has been detected, which are more common in western Nili Fossae, present a wider variety of morphologies and are not usually fractured, suggesting that different processes might have been at work to form serpentine in western Nili Fossae and/or that fractured terrain could be an indication of serpentine and carbonates together but not serpentine alone. There are a few exceptions to these patterns in western Nili Fossae (i.e. faint fracturing is visible in a few places); it is possible that key spectral signatures are too weak to detect in these areas and/or the fracturing visible in western Nili Fossae formed differently from the fracturing in eastern Nili Fossae. It is also possible that the fractured terrain is not actually diagnostic of serpentine or carbonate deposits, although a complete lack of association seems unlikely given the close relationship between CRISM bands and HiRISE morphology in some of the images.

CONCLUSION

Fracturing patterns and coincidence with carbonate detections are possible serpentine features consistent with those observed in a smaller subset of images by Ehlmann et al. 2010, which suggests that they may hold true for serpentine detections throughout at least eastern Nili Fossae. All of these similarities support the validity of the serpentine detections in Jezero. Comparison of Nili Fossae and Jezero serpentine-carbonate terrains with the morphology of the Comanche outcrops in Gusev does not yield conclusive observations that might determine the presence of serpentine and refute or support a common formation mechanism for the carbonates. Although the terrain around the Comanche carbonates does display some features that resemble fracturing, they are somewhat obscured and present no clear morphological evidence for the presence of serpentine. A more exhaustive spectral analysis and/or in situ evidence is likely necessary to evaluate the likelihood of serpentine deposits and understand the similarities and differences between the sites' aqueous histories.

DISCLOSURES

Thank you to Selby Hearth for her guidance, compassion, and patience with my endless questions and requests for editing help. Thank you also to my family for taking care of and putting up with me this summer, to the Swarthmore Physics/Astronomy Department for supporting me, and to Swarthmore College and the Baltimore/Broad Summer Research Fellowship for providing the funding for my research.

AUTHOR INFORMATION

Elena Lee is an undergraduate at Swarthmore College pursuing a special major in geophysics.

Selby Hearth is Associate Professor of Geology at Bryn Mawr College.

ABSTRACT

Carbonates have been detected in several locations on Mars, including Nili Fossae, Jezero Crater, and the Comanche outcrops of the Columbia Hills. Carbonates are intriguing for what they could reveal about potential habitability of past environments; however, their exact formation mechanisms remain ambiguous. Observations support a range of formation mechanisms, such as meteoric alteration of hot olivine tephra, hydrothermal alteration or serpentinization, near-surface weathering of serpentinized material, or aqueous alteration via ephemeral lakes. The associated mineralogy of carbonate-bearing terrain, such as the serpentine deposits detected in Nili Fossae and Jezero, can help constrain the origins of the carbonates. This study examines CRISM and HiRISE images of serpentine and carbonate deposits in Nili Fossae and Jezero Crater to identify common characteristics of serpentine-carbonate terrains. The morphologies of serpentine and carbonate-bearing terrains in Nili Fossae and Jezero are then compared to carbonate deposits in the Columbia Hills. By combining these analyses, this study explores the extent to which the carbonates' histories are analogous and probes into previous serpentine detections in Jezero and Nili Fossae.

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