Uncovering the Origin of the Banded Terrain on Mars

The quantity and phases of water present on a planet over time are crucial to understanding its geological history but remain controversial on Mars. The banded terrain is a unique feature of the Hellas basin that could provide insight on the history of water on Mars. Several hypotheses for the formation of this landform imply a significant role for liquid water or water ice. However, the origin of the banded terrain remains a subject of debate, with competing hypotheses having different implications for the history of water on Mars. A leading theory is that the banded terrain may have formed by sediment deformation beneath an ice sheet. We propose to test this theory using numerical modeling and data from the Mars Reconnaissance Orbiter. We will run finite element models of ice and sediment flow to test the hypothesis on two scales: 1) the regional scale of the Hellas basin, testing how the modeled basal velocity distribution compares to the mapped extent of the banded terrain; and 2) the scale of the banded terrain, testing how modeled sediment deformation compares to topography measured using HiRISE and Context Camera (CTX) data. HiRISE is the only instrument that can vertically resolve banded terrain, while CTX provides sufficient horizontal resolution over the extent of the bands. This study will confirm or refute the leading theory for the origin of the banded terrain. Either way, we will constrain the extent of past glaciation on Mars, an important unknown in constraining its water inventory and climate history. Understanding these aspects of Mars' geological history is a critical step towards understanding how water may evolve on terrestrial planets more generally.

• Scientific Justification

The banded terrain holds clues to the history of water on Mars. The quantity and phases of water present on a planet over time are crucial to understanding its geological history but remain controversial on Mars. Today, Mars is cold and dry, with water ice confined to the polar layered deposits (Byrne, 2009) or the subsurface (Levy et al., 2014). In contrast, mineralogy and landforms from earlier periods such as valley networks and deltas, indicate that Mars once had liquid water on its surface (Carr & Head, 2015; Ehlmann & Edwards, 2014; Kite, 2019). Yet, debate continues over whether early Mars was primarily warm and wet, cold and dry, or some other climate scenario (Kite, 2019; Wordsworth, 2016). Some studies of eskers left by past ice sheets suggest a primarily cold and dry climate (Fastook + 2012; Scanlon + 2018), though others come to ambiguous conclusions (Bernhardt + 2013). Further investigations of subglacial landforms are needed to provide a clearer picture of the history of water on Mars.

The banded terrain is a unique feature of the Hellas basin, composed of smooth bands separated by ridges or troughs with curvilinear, lobate, and circular forms (Bernhardt + 2019; Diot + 2014). This morphology suggests viscous deformation (Bernhardt + 2019). Various hypotheses have been proposed for banded terrain formation, and several suggest a significant role for liquid water or water ice.

However, the origin of the banded terrain remains a subject of debate, with competing hypotheses having different implications for the history of water on Mars (Diot + 2015; Kite + 2009; Mangold & Allemand, 2003; Moore & Wilhelms, 2001). The current leading hypothesis is that banded terrain was formed by deformation of sediment beneath an ice sheet (Bernhardt + 2019). Determining the origin of banded terrain is thus critically important to constrain the extent of past glaciation on Mars.

<u>We propose to use finite element models of ice and sediment flow to test the subglacial sediment deformation hypothesis for banded terrain formation.</u> This work advances the objectives of the FINESST program, by: 1) addressing the broad SMD Planetary Science goal of advancing knowledge of the history of the solar system; and 2) addressing a key planetary science question: “How have surface characteristics and compositions of solid bodies been modified by, and recorded, surface processes and atmospheric interactions?” (NASEM, 2022). Regardless of whether our findings confirm or refute the hypothesis, this work will constrain the extent of past glaciation on Mars. As such, this study will establish the next steps for future studies of the banded terrain aiming to quantify important parameters for the history of water on Mars. This is a critical step towards understanding terrestrial planets more generally (Ehlmann + 2016).

The origin of the banded terrain is debated. A variety of hypotheses have been put forward for the formation of the banded terrain, each with different implications for the geological history of the Hellas basin (Fig. 1). Early hypotheses suggested such varying formation processes as deformation of sediment by icebergs (Moore & Wilhelms, 2001), convection in an impact melt (Kite + 2009), sediment layers deformed by salt diapirism (Mangold & Allemand, 2003), or gravity-driven flow of a thin ice-rich layer (Diot + 2015). More comprehensive and higher resolution observations challenged these hypotheses (Bernhardt + 2016, 2019). These observations of the banded terrain and surrounding area, led to a new, leading hypothesis that banded terrain was formed by deformation of sediment beneath an ice sheet (Bernhardt + 2019). The proposed work will confirm or refute this hypothesis using models of ice and sediment flow.

Understanding how the banded terrain formed will help to understand the climate during its formation. The banded terrain formed during the Hesperian to early Amazonian period of Mars' history, a crucial time when Mars was transitioning from a wetter to a drier climate. Understanding this transitional period provides broader context for interpreting the evolution of habitability on Mars, a key question for ongoing and new missions. Banded terrain is a small part of this larger puzzle, but as of now, its formation remains a mystery. This mystery cannot be solved with observations alone because many different interpretations of the observations are possible. Likewise, comparisons with terrestrial analogues are insufficient, because several different terrestrial landforms have been suggested as analogues and there are inconsistencies between observations of banded terrain and all the potential analogues. Modeling is the key to moving forward, by quantitatively testing the plausibility of possible formation mechanisms.

Simulating the morphology of the banded terrain is key to determining its origin. The morphology of the banded terrain is characterized by key properties such as the length, width, spacing, height, and sinuosity of the constituent bands. These properties are critical to our understanding of the banded terrain's origin relative to other landforms. Similar properties are used to characterize and interpret terrestrial subglacial landforms in conjunction with models (e.g., Dunlop + 2008; Dunlop & Clark 2006).

Key properties of the banded terrain will be measured from HiRISE and CTX images as well as digital terrain models (DTMs) derived from those images (Fig. 2). Obtaining the necessary morphological measurements is possible with a combination of HiRISE and CTX data. CTX images have a resolution of ~6 m/pix and a typical image swath width of ~30 km (Malin + 2007). The resolution is sufficient to resolve the typical widths (~320 m) and spacing (~65 m) of bands and the swath width is large enough to include the typical length of bands (~5 km) (Diot + 2014). There is complete CTX coverage over the banded terrain. HiRISE DTMs are needed to measure the typical height of the bands (~10 m) (Diot + 2014). There are ten existing HiRISE DTMs of banded terrain, with swath widths of ~6 km (McEwen + 2007) sufficient to cover parts of multiple bands. All the CTX and HiRISE data needed are publicly available on the Planetary Data System.

Together, these two datasets will allow full characterization of the morphology of the banded terrain. Our models of ice and sediment flow will simulate the morphology of the subglacial sediment layer over time. This simulated morphology will be compared to the morphology of the banded terrain as measured from imaging and topography datasets.

Finite element models of ice and sediment flow will test the origin of the banded terrain. Ice and subglacial sediment deformation will be simulated using the finite element modeling software COMSOL. COMSOL has been used previously for solving planetary (e.g., Sori, 2021) and terrestrial (e.g., Headley & Ehlers, 2015). ice flow problems. Unlike other codes commonly used for ice flow modeling, COMSOL can couple multiple materials, facilitating the addition of subglacial sediment to the model. Ice and sediment rheology will be modeled using viscous flow laws (Goldsby & Kohlstedt, 2001; Leysinger Vieli & Gudmundsson, 2010). Parameters for the ice rheology are well known, but other parameters, such as surface temperature, heat flux, sediment thickness, sediment rheology parameters, and dust content will be varied over a range of reasonable values. On the regional scale, the basal topography will be defined using MOLA topography of the Hellas basin and the initial ice surface will be parabolic. On the local scale, the basal topography will be based on CTX DTMs of units surrounding the banded terrain.

We will use these simulations to test the hypothesis of banded terrain formation by subglacial sediment deformation, on two scales: 1) the regional scale of the Hellas basin, testing how the modeled basal velocity distribution compares to the mapped extent of the banded terrain (Fig. 3a); and 2) the scale of the banded terrain, testing how modeled sediment deformation compares to measured morphology (Fig. 3b). The first test is a qualitative one. The basal velocity distribution during banded terrain formation cannot be derived from observations. However, we assume that if banded terrain was formed by intense subglacial deformation, then basal velocity was high in the region where it formed compared to elsewhere in the basin. Therefore, we will compare the simulated basal velocity distribution (Fig. 3c) to the extent of banded terrain as mapped by Bernhardt et al., 2019. The second test is a quantitative one. We will compare distributions of key properties measured from modeled landforms (Fig. 3d) to measurements of banded terrain morphology from HiRISE and CTX data.

The main product of the proposed work will be the simulated morphology of subglacial sediment in Hellas basin. We will also produce additional morphological measurements of the banded terrain using HiRISE and CTX data. We will publicly release these measurements, which can be used in future studies of the banded terrain. Together, the simulated and measured morphology will be important in providing a quantitative test of the hypothesis that subglacial sediment deformation can produce the banded terrain morphology.

Determining how the banded terrain formed is a gateway to more discoveries. The proposed work will confirm or refute the leading hypothesis for the origin of the banded terrain and help to constrain the extent of past glaciation on Mars. This addresses an important question in planetary science: "Where and how have glacial processes sculpted landscapes?" (NASEM, 2022). More broadly, this is important to constraining Mars' water inventory and climate history. For instance, if we find that banded terrain formation by subglacial sediment deformation is plausible, future work using the modeled and measured morphology data products from this study can determine the ice volume and surface temperature most consistent with the observed banded terrain. Our results could also lead to further work using general circulation models (such as in Madeleine et al., 2009) to interpret in detail the atmospheric conditions and processes needed to accumulate and preserve an ice sheet in the Hellas basin. This ties into bigger questions about the early Mars climate and its transition to today's climate. If our results do not support the subglacial sediment deformation hypothesis, this will catalyze deeper investigation into other hypotheses, which could have different but equally interesting implications for the history of water on Mars. This program advances the legacy of some of NASA's major Mars missions, such as the Mars Reconnaissance Orbiter, by interpreting the data taken by instruments on that orbiter. This program also advances several goals of NASA's Mars program, including characterizing Mars' ancient climate and investigating the processes that have created Mars' geologic record (MEPAG, 2020). More broadly, it addresses a major question for the planetary science community: "How have surface characteristics and compositions of solid bodies been modified by, and recorded, surface processes and atmospheric interactions?" (NASEM, 2022).

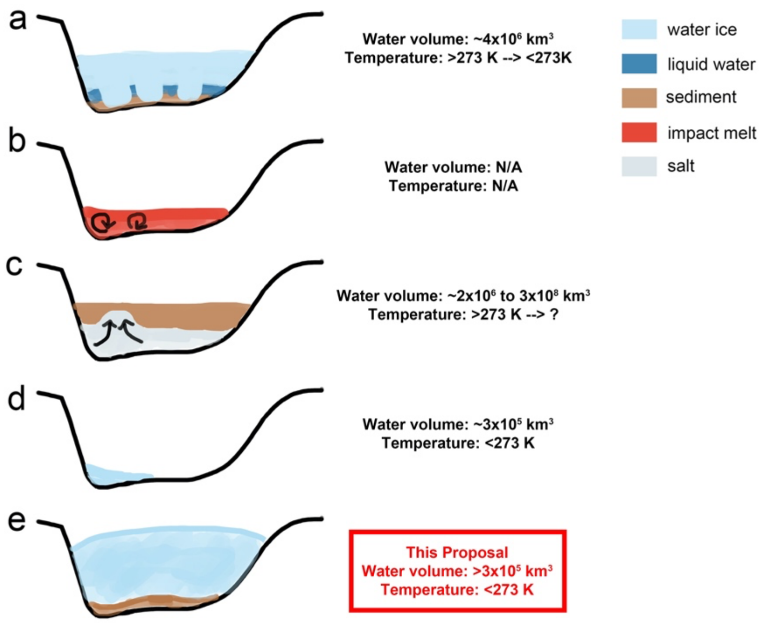

Figure 1: Cross-sections of Hellas basin (not to scale), showing proposed banded terrain formation scenarios and implications for water volume and surface temperature required. These hypotheses remain debated because observations alone allow for multiple interpretations. a) Deformation of sediment by ice blocks in an ice-covered lake (Moore & Wilhelms 2001). b) Convection in impact melt (Kite + 2009). c) Sediment layers deformed by upwelling salt emplaced by large volumes of saline water (Mangold & Allemand 2003). d) Deformation of a thin ice-rich layer (Diot + 2015). e) Deformation of sediment beneath an ice sheet (Bernhardt + 2019). Scenario (e) is the leading hypothesis, in which the ice overburden, in conjunction with varying basal topography and basal properties may lead to a complex stress field consistent with the complex pattern of deformation observed in the banded terrain. **This proposal will test this leading hypothesis, and thus contribute to resolving the problem of the banded terrain's origin.**

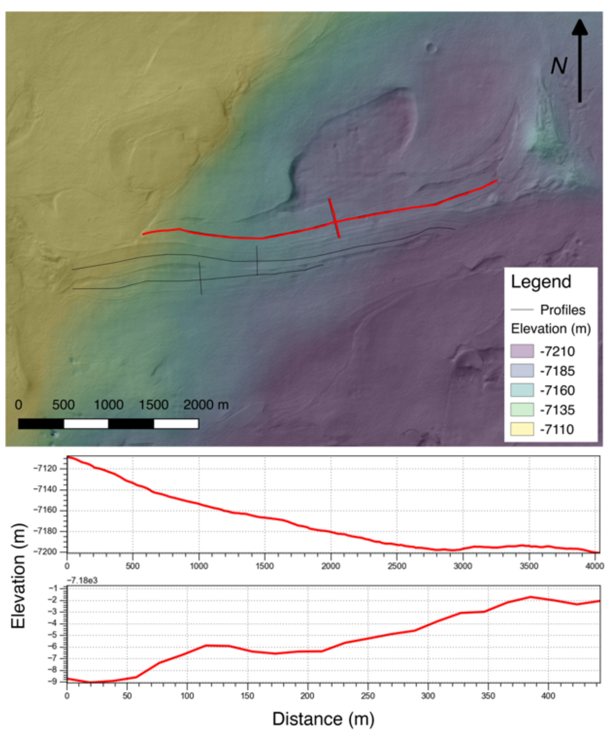

Figure 2: Top panel shows a CTX DTM overlaid on a CTX image of part of the banded terrain, with a profile (in red) taken across the length and width of one band. Bottom two panels show elevation profiles along the length and width of one band. **Measurements of band length, width, spacing, height, and sinuosity from such data will allow for morphological comparison between simulation results and the banded terrain.**

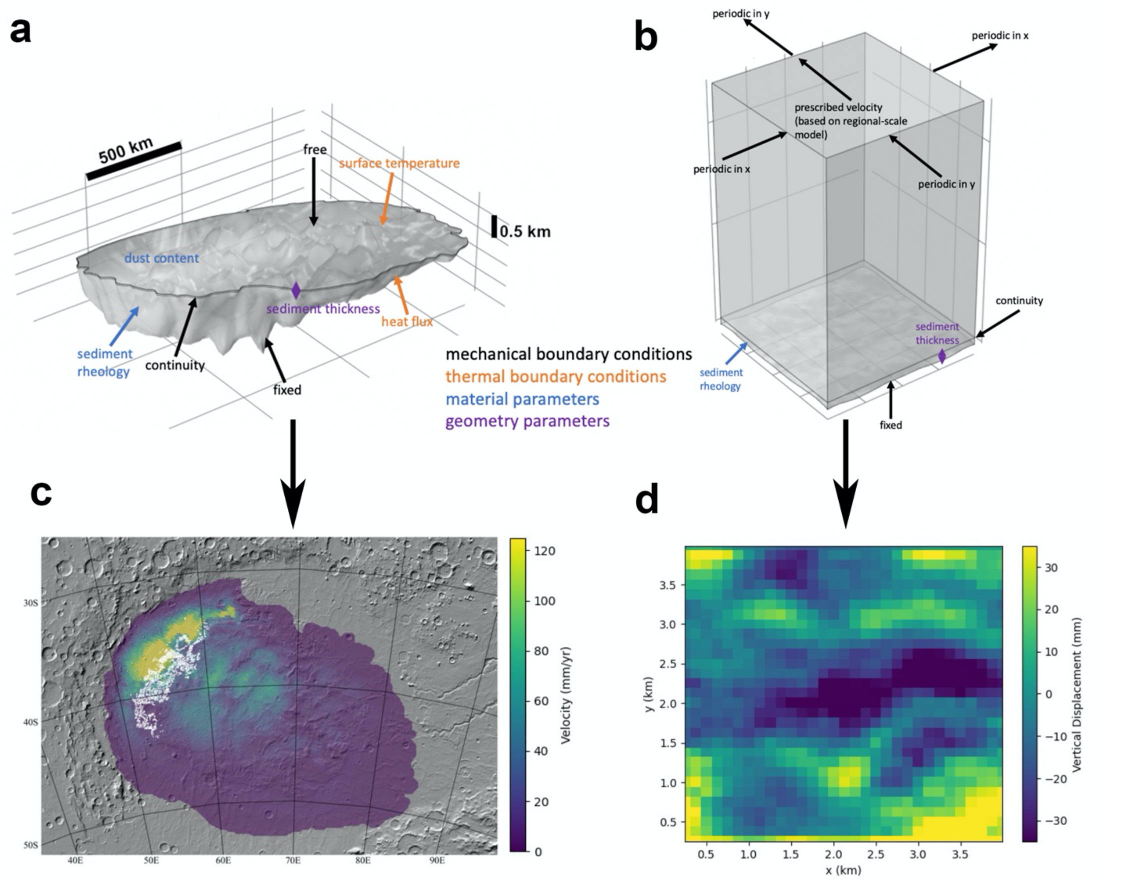

Figure 3: a) Diagram showing boundary conditions and parameters for a regional scale model of ice and sediment flow in Hellas basin. b) Same for local scale model, with dimensions on the order of typical band length. c) Top-down view of the surface of an ice sheet within Hellas basin, showing the horizontal magnitude of velocity at the sediment surface after 600 years, from the regional scale model. The white outline shows the banded terrain region (Bernhardt + 2019). D) Top-down view of the surface of the sediment from the local scale model, showing the vertical component of displacement after 10 years. **The ultimate goal of the proposal is to compare measurements of simulated subglacial sediment morphology (as in d) to banded terrain morphology.**

Bibliography

Bernhardt, H., Hiesinger, H., Reiss, D., Ivanov, M., Erkeling, G., 2013. Putative eskers and new insights into glacio-fluvial depositional settings in southern Argyre Planitia, Mars. Planet. Space Sci. 85, 261–278. https://doi.org/10.1016/J.PSS.2013.06.022

Bernhardt, H., Reiss, D., Hiesinger, H., Ivanov, M.A., 2016. The honeycomb terrain on the Hellas basin floor, Mars: A case for salt or ice diapirism. J. Geophys. Res. Planets 121, 714–738. https://doi.org/10.1002/2016JE005007

Bernhardt, H., Reiss, D., Ivanov, M., Hauber, E., Hiesinger, H., Clark, J.D., Orosei, R., 2019. The banded terrain on northwestern Hellas Planitia: New observations and insights into its possible formation. Icarus 321, 171–188. https://doi.org/10.1016/j.icarus.2018.11.007

Byrne, S., 2009. The Polar Deposits of Mars. Annu. Rev. Earth Planet. Sci. 37, 535–560. https://doi.org/10.1146/annurev.earth.031208.100101

Carr, M.H., Head, J.W., 2015. Martian surface/near-surface water inventory: Sources, sinks, and changes with time. Geophys. Res. Lett. 42, 726–732. https://doi.org/10.1002/2014GL062464

Diot, X., El-Maarry, M.R., Guallini, L., Schlunegger, F., Norton, K.P., Thomas, N., Sutton, S., Grindrod, P.M., 2015. An ice-rich flow origin for the banded terrain in the Hellas basin, Mars. J. Geophys. Res. Planets 120, 2258–2276. https://doi.org/10.1002/2015JE004956

Diot, X., El-Maarry, M.R., Schlunegger, F., Norton, K.P., Thomas, N., Grindrod, P.M., 2014. The geomorphology and morphometry of the banded terrain in Hellas basin, Mars. Planet. Space Sci. 101, 118–134. https://doi.org/10.1016/j.pss.2014.06.013

Dunlop, P., Clark, C.D., 2006. The morphological characteristics of ribbed moraine. Quat. Sci. Rev. 25, 1668–1691. https://doi.org/10.1016/j.quascirev.2006.01.002

Dunlop, P., Clark, C.D., Hindmarsh, R.C.A., 2008. Bed Ribbing Instability Explanation: Testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment. J. Geophys. Res. 113, F03005. https://doi.org/10.1029/2007JF000954

Ehlmann, B.L., Anderson, F.S., Andrews-Hanna, J., Catling, D.C., Christensen, P.R., Cohen, B.A., Dressing, C.D., Edwards, C.S., Elkins-Tanton, L.T., Farley, K.A., Fassett, C.I., Fischer, W.W., Fraeman, A.A., Golombek, M.P., Hamilton, V.E., Hayes, A.G., Herd, C.D.K., Horgan, B., Hu, R., Jakosky, B.M., Johnson, J.R., Kasting, J.F., Kerber, L., Kinch, K.M., Kite, E.S., Knutson, H.A., Lunine, J.I., Mahaffy, P.R., Mangold, N., McCubbin, F.M., Mustard, J.F., Niles, P.B., Quantin-Nataf, C., Rice, M.S., Stack, K.M., Stevenson, D.J., Stewart, S.T., Toplis, M.J., Usui, T., Weiss, B.P., Werner, S.C., Wordsworth, R.D., Wray, J.J., Yingst, R.A., Yung, Y.L., Zahnle, K.J., 2016. The sustainability of habitability on terrestrial planets: Insights, questions, and needed measurements from Mars for understanding the evolution of Earth-like worlds. J. Geophys. Res. Planets 121, 1927–1961. https://doi.org/10.1002/2016JE005134

Ehlmann, B.L., Edwards, C.S., 2014. Mineralogy of the Martian Surface. Annu. Rev. Earth Planet. Sci. 42, 291–315. https://doi.org/10.1146/annurev-earth-060313-055024

Fastook, J.L., Head, J.W., Marchant, D.R., Forget, F., Madeleine, J.B., 2012. Early Mars climate near the Noachian-Hesperian boundary: Independent evidence for cold conditions from basal melting of the south polar ice sheet (Dorsa Argentea Formation) and implications for valley network formation. Icarus 219, 25–40. https://doi.org/10.1016/j.icarus.2012.02.013

Goldsby, D.L., Kohlstedt, D.L., 2001. Superplastic deformation of ice: Experimental observations. J. Geophys. Res. Solid Earth 106, 11017–11030. https://doi.org/10.1029/2000JB900336

Headley, R.M., Ehlers, T.A., 2015. Ice flow models and glacial erosion over multiple glacial-interglacial cycles. Earth Surf. Dyn. 3, 153–170. https://doi.org/10.5194/esurf-3-153-2015

Kite, E.S., 2019. Geologic Constraints on Early Mars Climate. Space Sci. Rev. 215, 10. https://doi.org/10.1007/s11214-018-0575-5

Kite, E.S., Manga, M., Perron, J.T., 2009. Evidence for Past Kilometer-Scale Overturn(s) in Deformed, Layered Terrain Near the Deepest Point on Mars, in: Lunar and Planetary Science Conference.

Levy, J.S., Fassett, C.I., Head, J.W., Schwartz, C., Watters, J.L., 2014. Sequestered glacial ice contribution to the global Martian water budget: Geometric constraints on the volume of remnant, midlatitude debris-covered glaciers. J. Geophys. Res. Planets 119, 2188–2196. https://doi.org/10.1002/2014JE004685

Leysinger Vieli, G.J.-M.C., Gudmundsson, G.H., 2010. A numerical study of glacier advance over deforming till. Cryosph. 4, 359–372. https://doi.org/10.5194/tc-4-359-2010

Madeleine, J.-B., Forget, F., Head, J.W., Levrard, B., Montmessin, F., Millour, E., 2009. Amazonian northern mid-latitude glaciation on Mars: A proposed climate scenario. Icarus 203, 390–405. https://doi.org/10.1016/j.icarus.2009.04.037

Malin, M.C., Bell, J.F., Cantor, B.A., Caplinger, M.A., Calvin, W.M., Clancy, R.T., Edgett, K.S., Edwards, L., Haberle, R.M., James, P.B., Lee, S.W., Ravine, M.A., Thomas, P.C., Wolff, M.J., 2007. Context Camera Investigation on board the Mars Reconnaissance Orbiter. J. Geophys. Res. 112, E05S04. https://doi.org/10.1029/2006JE002808

Mangold, N., Allemand, P., 2003. Ductile Deformation in Hellas Floor: Salt Diapirs or Crustal Domes?, in: Sixth International Conference on Mars.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). J. Geophys. Res. 112, E05S02. https://doi.org/10.1029/2005JE002605

MEPAG, 2020. Mars Scientific Goals, Objectives, Investigations, and Priorities: 2020. D. Banfield, ed., 89 p. white paper posted March, 2020 by the Mars Exploration Program Analysis Group (MEPAG) at https://mepag.jpl.nasa.gov/reports.cfm

Moore, J.M., Wilhelms, D.E., 2001. Hellas as a possible site of ancient ice-covered lakes on Mars. Icarus 154, 258–276. https://doi.org/10.1006/icar.2001.6736

National Academies of Sciences, Engineering, and Medicine, 2022. Origins, Worlds, Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.

Scanlon, K.E., Head, J.W., Fastook, J.L., Wordsworth, R.D., 2018. The Dorsa Argentea Formation and the Noachian-Hesperian climate transition. Icarus 299, 339–363.

https://doi.org/10.1016/J.ICARUS.2017.07.031
Sori, M.M., 2021. Can Triton's Internal Heat Be Inferred From Its Ice Cap? Geophys. Res. Lett. 48, e2020GL090518. https://doi.org/10.1029/2020GL090518
Wordsworth, R.D., 2016. The Climate of Early Mars. Annu. Rev. Earth Planet. Sci. 44, 381–408. https://doi.org/10.1146/annurev-earth-060115-012355

- **Technical Description**

  ENTER YOUR TEXT HERE.

- **Special Requirements (if any)**

  ENTER YOUR TEXT HERE.

- **Justify Coordinated Parallel Observations (if any)**

  ENTER YOUR TEXT HERE.

- **Justify Duplications (if any)**

  ENTER YOUR TEXT HERE.

- **Analysis Plan (AR only)**

  ENTER YOUR TEXT HERE.