

A new type of jarosite deposit on Mars: Evidence for past glaciation in Valles Marineris?

Selby Cull^{1,2}, Patrick C. McGuire^{2,3}, Christoph Gross², Jenna Myers¹, and Nina Shmorchun¹

¹Department of Geology, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010, USA

²Planetary Sciences and Remote Sensing Group, Institute of Geological Sciences, Department of Earth Sciences, Freie Universität Berlin, Berlin 12249, Germany

³Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20723, USA

ABSTRACT

Acid-sulfate minerals such as jarosite are often used as indicators of environmental conditions on Mars. These minerals form in a diverse set of environments on Earth; however, all known Martian jarosite deposits are most likely evaporative, from evaporation of either groundwater or ponded water. Here, we use the Compact Reconnaissance Imaging Spectrometer for Mars and High-Resolution Imaging Science Experiment to report a new jarosite deposit along the southern wall of Ius Chasma. The morphology and geologic context of the Ius deposit are unique on Mars, and difficult to explain with an evaporative or groundwater mechanism. We propose instead that it was deposited along the margins of a past glacier. Such acid-ice interactions would be similar to those reported along the margins of Svalbard glaciers (arctic Norway), and would represent a new style of acid-sulfate formation on Mars.

INTRODUCTION

Jarosite $[(K,Na)Fe^{3+}_3(SO_4)_2(OH)_6]$ was first reported on Mars in 2004 (Klingelhöfer et al., 2004), and has since become a key environmental indicator for past aqueous conditions. Because jarosite forms only in environments with low temperatures and pH of 1.5–3 (Jamieson et al., 2005), its presence in Martian outcrops is interpreted as evidence of localized, highly acidic water-rock interactions.

However, recent studies on jarosite formation on Earth have shown that the mineral can form in diverse acidic environments, including acid-saline lakes in hyperarid climates (Schaefer et al., 2003), acid mine drainage systems (Swayze et al., 2008, and references therein), “acid fog” on the margins of volcanic calderas (Banin et al., 1997), cold acid groundwater springs at, for example, Ellesmere Island, Canada (Battler et al., 2013b), and “acid ice:” low-pH water-rock interactions along the margins of glaciers and permafrost (Lacelle and Lèveillé, 2010; Battler et al., 2013a). To date, Martian jarosite has been detected at several outcrops; however, all of these are interpreted as representing evaporative environments.

Here, we use hyperspectral data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) to map Ius Chasma of the Valles Marineris, and report a new jarosite deposit that does not fit the evaporative model. We use CRISM data, images from the High-Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007), and elevation data from the High/Super-Resolution Stereo Camera (HRSC; Jaumann et al., 2007) to compare the Ius deposit to jarosite deposition environments on Earth and Mars, and we propose that this deposit may represent

the best evidence to date of acid ice-rock interactions on Mars.

Geologic Context: Ius Chasma

Ius Chasma is a western canyon of the Valles Marineris (a 3000-km-long equatorial series of horsts and grabens) (Fig. 1A), comprising two parallel troughs, each ~500 km long, with depths up to 8 km below the plateau, and a general deepening to the east. The troughs are divided by the Geryon Montes, a 5-km-high east-west ridge that has been interpreted as a basement horst brought up in response to extension. The

southern wall of Ius is cut by the Louros Valles, a series of sapping channels that empty into Ius. The upper walls of the canyon are defined by spur-and-gully morphology, transitioning to a smooth basal escarpment at approximately –1900 m to –2000 m elevation (e.g., Chapman et al., 2005).

Previous spectroscopic mapping in Ius Chasma by Roach et al. (2010) showed layers of Fe/Mg-smectite in the walls of Geryon Montes, monohydrated and polyhydrated sulfates in a closed basin in far eastern Ius, and an unidentified hydrated silicate material draped across the smectite and sulfate deposits. Additionally, Milliken et al. (2008) identified opal deposits on the plateau south of the canyon, advancing to the southern rim.

DATA AND METHODS

Visible to near-infrared spectra from the CRISM instrument were used to identify compositions in the study area (Fig. 1B). CRISM has a spectral range of 0.362–3.92 μm , spectral resolution of ~6.5 nm/channel, and spatial resolution that ranges from 15 to 19 m/pixel to ~40 m/pixel (Murchie et al., 2007). Images

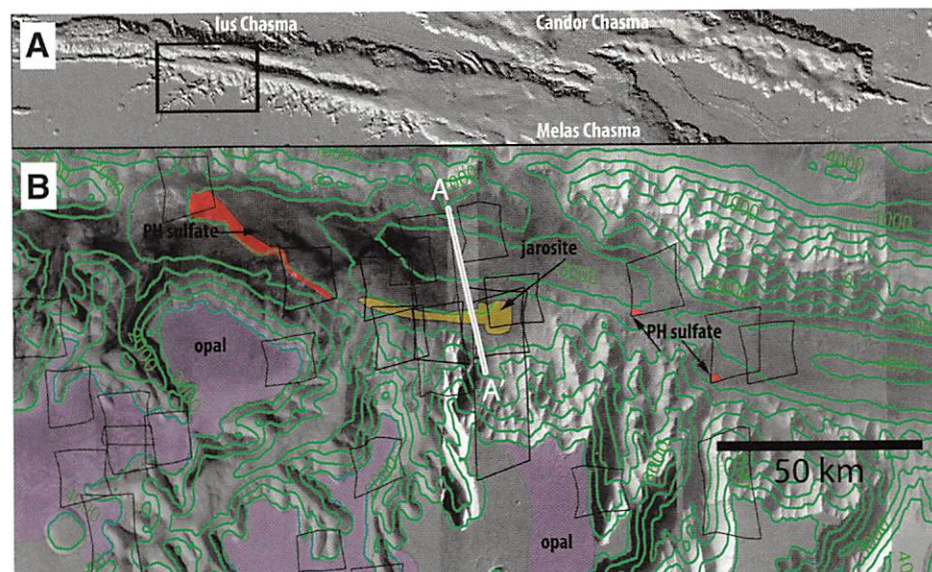


Figure 1. Regional context (A) and study area at Ius Chasma, Mars (B), showing elevations derived from High/Super-Resolution Stereo Camera (HRSC) digital terrain model and unit A (jarosite, yellow), units B and C (opal, light purple), and unit D (polyhydrated sulfates, red). Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) observations included in this study are outlined in black.

were converted to apparent surface reflectance using the volcano scan atmospheric correction approach (Mustard et al., 2008). Units of interest were identified using the mapping indices developed by Pelkey et al. (2007). Pixels exhibiting absorptions in these indices and correlating to distinct geomorphic units observed in images from HiRISE were then averaged together to produce representative spectra for each geomorphic unit. These averaged spectra were then divided by averaged spectra of nearby spectrally bland material to minimize the effects of dust and instrument noise.

Minerals identified included sulfates (monohydrated, polyhydrated, and acid sulfates, such as the jarosite group) and amorphous silica (e.g., opal). Opal was identified using absorptions at 1.42 μm and 1.92 μm , and a broad absorption between 2.17 μm and 2.30 μm . Monohydrated sulfates were identified by H_2O combination at 2.1 and 2.4 μm , and a broad absorption centered at 1.6 μm . Polyhydrated sulfates were identified by H_2O vibrations at 1.45 and 1.95 μm , and an OH combination band at 2.45 μm (Cloutis et al., 2006). The jarosite group is the range of compositions $[\text{AM}_3(\text{SO}_4)_3(\text{OH})_6]$, where A is a monovalent cation like K^+ , Na^+ , or H_3O^+ , and M is Al^{3+} for alunite and Fe^{3+} for jarosite. The positions of jarosite-group absorption bands vary with composition, but can be broadly given as 1.47–1.48 μm (OH stretch), 1.849–1.864 μm (OH stretch + bend combination), a triplet at 2.215, 2.265, and 2.3 μm (OH stretch + bend combination), and weaker absorptions at 2.4–2.42, 2.46, and 2.51 μm (asymmetric SO_4 stretch + OH overtone; Bishop and Murad, 2005).

A mosaic from data from the High/Super-Resolution Stereo Camera (HRSC) (Fig. 1B) was constructed according to procedures described by McGuire et al. (2014), at 75 m/pixel resolution and a bit depth of 8 bits, with Lambert-albedo correction, and atmospheric correction approximated by combining high-pass filtered HRSC images and a low-pass filtered global OMEGA mosaic described in Ody et al. (2012). No edge blending or feathering was used. One strip needed to be inserted manually without any filtering; this strip is in the center of the mosaic and is slightly brighter than the other images at the bottom of the mosaic. Elevation contours generated from the HRSC digital elevation model (DEM) over select areas were compared to raw Mars Orbiter Laser Altimeter (MOLA) Precision Experiment Data Records (PEDR) tracks to confirm elevations of key deposits. Where coverage was available, elevation data presented here were cross-referenced to MOLA PEDR tracks to confirm elevation estimates.

OBSERVATIONS

Four spectrally and morphologically distinct units were mapped. Unit A, on the southern wall of Ius Chasma (Fig. 1B), has absorptions

at 1.470, 1.854, 2.206, 2.264, and 2.4 μm that match laboratory spectra of jarosite (Fig. 2). In HiRISE images, unit A is brighter than the surrounding dust, with distinct horizontal layering (Figs. 3A and 3B, arrows point to layering). The unit caps a break in the slope of the wall, forming a terrace at approximately –1900 to –2000 m (Fig. 4).

Unit A cuts across a region previously mapped by Roach et al. (2010) as transported opal. We also map transported opal (unit B, described below) across this area, but the jarosite layer is spectrally and geomorphically distinct from the opal. Though opal and other forms of amorphous silica have a broad absorption between 2.17 and 2.30 μm , the absorption seen in unit A is clearly a doublet, not one broad absorption (Fig. 2). Additionally, unit A displays a 1.47 μm absorption, not the typical 1.42 μm of opal, and a 1.85 μm absorption instead of opal's 1.92 μm hydration band. In HiRISE images, the jarosite layer appears as a bright deposit with distinct layering, and it is observed to extend laterally for several kilometers at the same elevation. These observations argue against the jarosite being a transported deposit, and suggest that it formed in place.

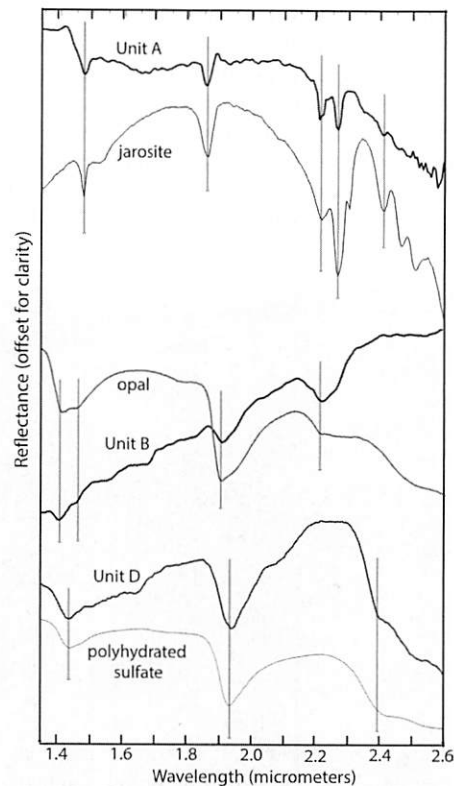


Figure 2. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectra of units A (CRISM image code FRT0001C6A7), B (FRT000076E2), and D (FRT00016626) compared to laboratory spectra of jarosite, opal, and epsomite (polyhydrated sulfate) from the CRISM spectral library. Unit C is not shown because it is spectrally similar to unit B.

Jarosite exists as a range of compositions. K-jarosite has a broad doublet at 1.849–1.864 μm , and absorptions at 1.47 and 2.21 μm (Farrand et al., 2009). Na-jarosite shows absorptions at 1.48, 1.85, 2.22, 2.42, 2.47, and 2.52 μm .

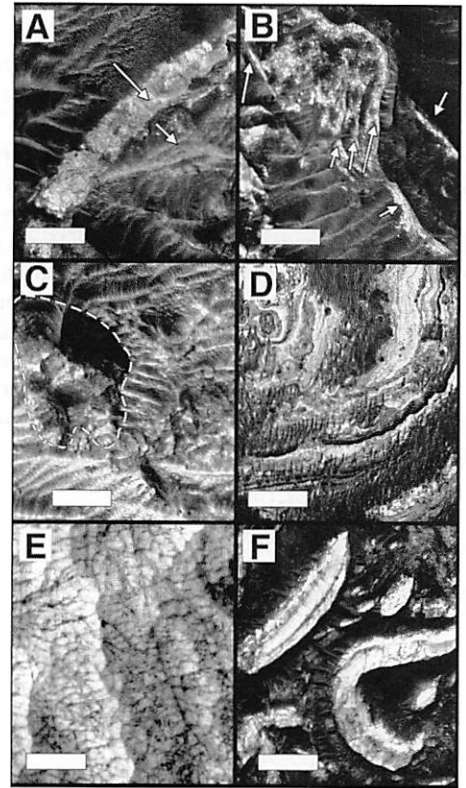


Figure 3. High-Resolution Imaging Science Experiment (HiRISE) image subsets showing mapped unit A (panels A, B; HiRISE image code ESP_013759_1720), unit B (panel C; ESP_013759_1720), unit C (panel D; ESP_023741_1710), and unit D (panels E, F; PSP_003593_1725). White arrows point to layering. Dashed white line distinguishes opal-bearing unit from surrounding dunes. White scale bar is 50 m long.

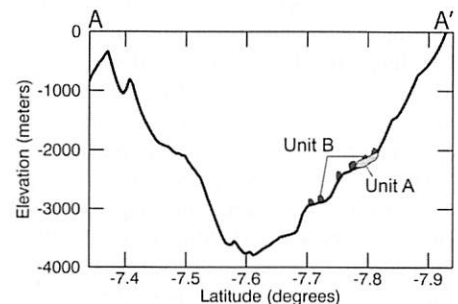


Figure 4. Topographic profile of study area, showing Mars Orbiter Laser Altimeter (MOLA) Precision Experiment Data Records (PEDR) track from orbit 20331. Unit A (jarosite, light gray) follows a ledge on the south wall of Ius Chasma. Unit B (opal, dark gray, vertically exaggerated for visibility) forms discontinuous patches. See Figure 1 for profile location.

Unit A has a 1.85 μm absorption, similar to Na-jarosite; however, its OH absorption is closer to 1.47 μm , more like K-jarosite. Additionally, it more closely resembles K-jarosite in the 2.21 μm region (Fig. 5).

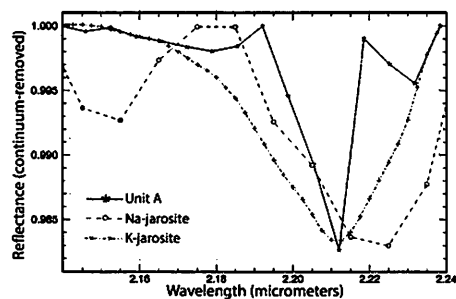


Figure 5. Band centers of the $\sim 2.2 \mu\text{m}$ absorption in unit A, compared to band centers of Na-jarosite and K-jarosite.

Unit B was also mapped on the southern wall of Ius Chasma, and consists of small, discontinuous areas spatially associated with unit A, and with absorptions at 1.405, 1.909, and 2.219 μm (Fig. 2), matching laboratory spectra of opal. In HiRISE images, unit B is intermediate toned, darker than unit A, and appears to represent jumbled, chaotic blocks (Fig. 3C, block outlined in white). No layering is visible in unit B, and it is interpreted as transported material from the plateau above (unit C).

Unit C was mapped on the plateau to the south of the study area (Fig. 1B), corresponding to areas previously mapped as opal by Milliken et al. (2008) and Roach et al. (2010). The unit is spatially extensive, and exhibits absorptions at 1.405, 1.909, and 2.219 μm , spectrally matching unit B (opal). In HiRISE images, unit C is bright to intermediate toned, and represents finely layered deposits (Fig. 3D). Unit C is not observed in contact with unit A or unit B.

Unit D was mapped on the southern wall of Ius Chasma (Fig. 1B). The unit is spatially extensive, and exhibits absorptions at 1.43, 1.93, and 2.4 μm , matching laboratory spectra of polyhydrated sulfates (Fig. 2). In HiRISE images, unit D is light toned and polygonally fractured. It appears as layers or massive units, commonly interbedded with darker material (Figs. 3E and 3F). Unit D is not observed in contact with units A, B, or C. Unit D was mapped at elevations ranging from -1500 to -2000 m, with the lower elevations occurring further east.

DISCUSSION

Jarosite has been reported at several locations on Mars, and, in each of these cases, the geologic context favors an evaporative origin. The jarosite at Meridiani Planum occurs as a cement in a widespread layered deposit (McLennan et al., 2005), in a region of Mars that global hydrology models predict experienced exten-

sive groundwater upwelling and evaporation (Andrews-Hanna et al., 2007). The jarosite at Mawrth Vallis occurs as layers within a 3×5 km topographic basin that is situated at the low point of a regional depression, leading to its interpretation as a former pond of evaporating acidic groundwater (Farrand et al., 2009). The jarosite at Noctis Labyrinthus occurs as layers isolated in a closed depression, and has been interpreted as forming from evaporation of fluids enriched in magmatic sulfur (Thollot et al., 2012). The jarosite at Ophir Chasma occurs as layers along the canyon floor, pointing again to evaporating groundwater (Wendt et al., 2011). In each of these cases, the jarosite is restricted to areas of natural groundwater emergence or pooling water. In contrast, the sulfates on the southwestern wall of Ius are not inside a closed basin or a topographic low, making pooling and evaporating water unlikely. Although parts of eastern Valles Marineris have been proposed as past sites of large basin-filling lakes (e.g., Warner et al., 2013), the lack of a closed basin at Ius argues against this. Additionally, as the deposit is not flat lying (doesn't correspond to a single water table) and occurs halfway up a valley wall, groundwater interactions are similarly unlikely. Acidic groundwater moving along an impermeable bedding plane until released and evaporated at the wall would be expected to produce an acid-sulfate deposit that followed a single bedding layer, instead of deepening to the east as is observed here. Both groundwater and evaporating pooling water are unlikely candidates within the geologic context of southern Ius Chasma.

Acid sulfates have also been hypothesized to form on Mars through basalt weathering by sulfur dioxide and water vapor ("acid fog;" e.g., Banin et al., 1997; McCollom and Hynek, 2005). On Earth, this process has been shown to produce jarosite near fumaroles and calderas of volcanoes such as Kilauea, Hawaii (Seelos et al., 2010), and Cerro Negro, Nicaragua (Hynek et al., 2011). There, the jarosite appears as coatings on preexisting surfaces. However, this is a poor model to explain the Ius acid sulfates. The acid-sulfate deposit reported here occurs as distinct layers (Figs. 3A and 3B), far from known volcanic vents. Additionally, a volcanic weathering model would fail to explain why only a single package of layers within the southern wall was altered.

We propose instead that the layer of sulfates between -1500 and -2000 m, and jarosite between -1900 and -2000 m, on the southern wall of Ius represents glacially deposited evaporative salts. Many authors have speculated on the role of ice in shaping the Valles Marineris (e.g., Chapman et al., 2005; Thaisen et al., 2008), noting that ice may have been deposited within the canyons during periods of high planetary obliquity, when today's equatorial regions

would have existed at high latitudes (Jakosky and Carr, 1985; Forget et al., 2006). If such spatially extensive ice deposits existed in Valles Marineris during the Noachian or Hesperian, they could have resulted in sulfate deposition similar to that proposed by Niles and Michalski (2009), McAdam et al. (2008), or Catling et al. (2006). The ice deposition model proposes that, because the Noachian and Hesperian were times of elevated atmospheric sulfur as a result of more intense volcanism (Wanke and Dreibus, 1994), ice deposits forming on Mars during that time incorporated volcanic sulfur compounds and dust into their lattices. Sunlight heating these grains in the upper layers of ice (or sunlight heating wall rock at the ice-rock interface of a glacier) would have caused minor melting around the sulfur-rich grains. The weathering sulfur-rich minerals would have produced acidic water, and ultimately acid-sulfate minerals. A similar mechanism has been documented along the margins of Svalbard glaciers (arctic Norway), where the proglacial zone and adjacent moraines undergo cyclical evaporation and freeze concentration of groundwater that results in the deposition of acid-sulfate salts such as jarosite (e.g., Cooper et al., 2002).

Several observations support a glacial origin for the Ius deposit. First, the sulfate layer must be a superficial deposit, because it cuts vertically across several layers within the canyon wall. Second, the sulfate layer follows the transition from the upper spur-and-gully morphology to the lower smooth basal morphology. This transition line has been interpreted by others (e.g., Mège and Bourgeois, 2011; Gourronc et al., 2014) as a glacial trimline: the maximum elevation of a glacier within a valley. The proposed trimline runs at approximately -1900 to -2000 m elevation, and is marked by a distinct lateral bench (Fig. 4), a horizontal break in the slope of the wall that Gourronc et al. (2014) have interpreted as either a lateral moraine or kame terrace. The sulfates cap the break in the slope of the wall, supporting the hypothesis that these are deposited as part of a lateral moraine. Unlike unit B (opal), which occurs above, below, and apparently overlying unit A, the acid-sulfate unit occurs as distinct layers (Figs. 3A and 3B), suggesting that the unit was emplaced along the ledge, not transported there later, as unit B appears to have been. The challenges of preserving such a deposit on the walls of a Valles Marineris chasm could explain why the acid sulfates are found along only one portion of the basin, the other areas having been altered, buried, or eroded over time.

The jarosite-polyhydrated sulfate layer stretching across the southwestern wall of Ius Chasma represents a new style of acid-sulfate deposit for Mars, neither enclosed within an evaporative basin nor following a distinct water table. Its occurrence along the ridge of a pro-

posed glacial trimline, and the likelihood that past Mars ice deposits would have led to sulfate deposition, are evidence in support of past glaciation within Valles Marineris.

ACKNOWLEDGMENTS

Cull acknowledges support from Bryn Mawr College and the Research Alumni Program of the Freie Universität Berlin. McGuire acknowledges support from the CRISM Science Team. McGuire and Gross acknowledge support from the German Aerospace Center (DLR) Space Administration on behalf of the Federal Ministry for Economic Affairs and Energy, grant 50QM1301 (HRSC on Mars Express). We thank Alexander Dumke, Sebastian Walter, and Stephan van Gassel at the Freie Universität Berlin for collaborative work on HRSC mosaicking and DTM generation. We also thank Paul Niles, Ed Cloutis, and an anonymous reviewer for comments that improved this manuscript.

REFERENCES CITED

- Andrews-Hanna, J., Phillips, R., and Zuber, M., 2007, Meridiani Planum and the global hydrology of Mars: *Nature*, v. 446, p. 163–166, doi:10.1038/nature05594.
- Banin, A., Han, F., and Kan, I., 1997, Acidic volatiles and the Mars soil: *Journal of Geophysical Research*, v. 102, p. 13,341–13,356, doi:10.1029/97JE01160.
- Battler, M., Osinski, G., Lim, D., Davila, A., Michel, F., and Craig, M., 2013a, Characterization of the acidic cold seep emplaced jarositic Golden Deposit, NWT, Canada, as an analogue for jarosite deposition on Mars: *Icarus*, v. 224, p. 382–398, doi:10.1016/j.icarus.2012.05.015.
- Battler, M., Osinski, G., and Banerjee, N., 2013b, Mineralogy of saline perennial cold springs on Axel Heiberg Island, Nunavut, Canada, and implications for spring deposits on Mars: *Icarus*, v. 224, p. 364–381, doi:10.1016/j.icarus.2012.08.031.
- Bishop, J., and Murad, E., 2005, Visible and infrared spectral properties of jarosite and alunite: *American Mineralogist*, v. 90, p. 1100–1107, doi:10.2138/am.2005.1700.
- Catling, D., Wood, S., Leovy, C., and Montgomery, D., 2006, Light-toned layered deposits in Juventae Chasma, Mars: *Icarus*, v. 181, p. 26–51, doi:10.1016/j.icarus.2005.10.020.
- Chapman, M., Soderblom, L., Cushing, G., 2005, Evidence of very young glacial process in central Candor Chasma, Mars: 36th Lunar and Planetary Science Conference, 14–18 March 2005, Abstract 1850.
- Cloutis, E., Hawthorne, F., Mertzman, S., Krenn, K., Craig, M., and Marcino, D., 2006, Detection and discrimination of sulfate minerals using reflectance spectroscopy: *Icarus*, v. 184, p. 121–157, doi:10.1016/j.icarus.2006.04.003.
- Cooper, R., Wadhwa, J., and Tranter, M., 2002, Groundwater hydrochemistry in the active layer of the proglacial zone, Finsterwalderbreen, Svalbard: *Journal of Hydrology (Amsterdam)*, v. 269, p. 208–223, doi:10.1016/S0022-1694(02)00279-2.
- Farrand, W., Glotch, T., and Rice, J., 2009, Discovery of jarosite within the Mawrth Vallis region of Mars: Implications for the geologic history of the region: *Icarus*, v. 204, p. 478–488, doi:10.1016/j.icarus.2009.07.014.
- Forget, F., Haberle, R., and Montmessin, F., 2006, Formation of glaciers on Mars by atmospheric precipitation at high obliquity: *Science*, v. 311, p. 368–371, doi:10.1126/science.1120335.
- Gourronc, M., Bourgeois, O., Mège, D., Pouchat, S., Bultel, B., Massé, M., Le Deit, L., Le Mouélic, S., and Mercier, D., 2014, One million cubic kilometers of fossil ice in Valles Marineris: Relicts of a 3.5 Gy old glacial landscape along the Martian equator: *Geomorphology*, v. 204, p. 235–255, doi:10.1016/j.geomorph.2013.08.009.
- Hynek, B., McCollom, T., and Rogers, K., 2011, Cerro Negro volcano, Nicaragua: An assessment of geological and potential biological systems on early Mars, in Garry, W.B., and Bleacher, J.E., eds., *Analogs for Planetary Exploration: Geological Society of America Special Paper 483*, p. 279–285, doi:10.1130/2011.2483(18).
- Jakosky, B., and Carr, M., 1985, Possible precipitation of ice at low latitudes of Mars during periods of high obliquity: *Nature*, v. 315, p. 559–561, doi:10.1038/315559a0.
- Jamieson, H., Robinson, C., Alpers, C., Nordstrom, D.K., Poustovetov, A., and Lowers, H.A., 2005, The composition of coexisting jarosite minerals and water from the Richmond Mine, Iron Mountain, California: *The Canadian Mineralogist*, v. 43, p. 1225–1242.
- Jaumann, R., G. Neukum, T. Behnke, and the HRSC Co-Investigator Team, 2007, The high-resolution stereo camera (HRSC) experiment on Mars Express: *Planetary and Space Science*, v. 55, p. 928–952, doi:10.1016/j.pss.2006.12.003.
- Klingelhöfer, G., Morris, R., Bernhardt, B., Schroder, C., Rodinov, D., and de Souza, P., 2004, Jarosite and hematite at Meridiani Planum from Opportunity's Mossbauer spectrometer: *Science*, v. 306, p. 1740–1745, doi:10.1126/science.1104653.
- Lacelle, D., and Léveillé, R., 2010, Acid drainage generation and associated Ca-Fe-SO₄ minerals in a periglacial environment, Eagle Plains, northern Yukon, Canada: An analogue for low temperature sulfate formation on Mars: *Planetary and Space Science*, v. 58, p. 509–521, doi:10.1016/j.pss.2009.06.009.
- McAdam, A., Zolotov, M., Mironenko, M., Leshin, L., and Sharp, T., 2008, Preferential low-pH dissolution of pyroxene in plagioclase-pyroxene mixtures: Implications for martian surface materials: *Icarus*, v. 196, p. 90–96, doi:10.1016/j.icarus.2008.01.008.
- McCollom, T., and Hynek, B., 2005, A volcanic environment for bedrock diagenesis at Meridiani Planum on Mars: *Nature*, v. 438, p. 1129–1131, doi:10.1038/nature04390.
- McEwen, A.S., et al., 2007, Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE): *Journal of Geophysical Research*, v. 11, E05S02, doi:10.1029/2005JE002605.
- McGuire, P., Walter, S., van Gassel, S., Dumke, A., Dunker, T., Gross, C., and Michael, G., 2014, Global HRSC image mosaics of Mars: Dodging for high-pass filtering, combined with low-pass-filtered OMEGA mosaic: Eighth International Conference on Mars, Pasadena, California, Ext. Abs. 1118.
- McLennan, S., et al., 2005, Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars: *Earth and Planetary Science Letters*, v. 240, p. 95–121, doi:10.1016/j.epsl.2005.09.041.
- Mège, D., and Bourgeois, O., 2011, Equatorial glaciations on Mars revealed by gravitational collapse of Valles Marineris wall slopes: *Earth and Planetary Science Letters*, v. 310, p. 182–191, doi:10.1016/j.epsl.2011.08.030.
- Milliken, R., Swayze, G., Arvidson, R., Bishop, J., Clark, R., and Ehlmann, B., 2008, Opaline silica in young deposits on Mars: *Geology*, v. 36, p. 847–850, doi:10.1130/G24967A.1.
- Murchie, S., et al., 2007, Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO): *Journal of Geophysical Research*, v. 112, E05S03, doi:10.1029/2006JE002682.
- Mustard, J., et al., 2008, Hydrated silicate minerals on Mars observed by the CRISM instrument on MRO: *Nature*, v. 454, p. 305–309, doi:10.1038/nature07097.
- Niles, P., and Michalski, J., 2009, Meridiani Planum sediments on Mars formed through weathering in massive ice deposits: *Nature Geoscience*, v. 2, p. 215–220, doi:10.1038/ngeo438.
- Ody, A., Poulet, F., Langevin, Y., Bibring, J., Bellucci, G., Altieri, F., Gondet, B., and Vincendon, M., 2012, Global maps of anhydrous minerals at the surface of Mars from OMEGA/MEx: *Journal of Geophysical Research*, v. 117, E00J14, doi:10.1029/2012JE004117.
- Pelkey, S., et al., 2007, CRISM multispectral summary products: Parameterizing mineral diversity on Mars from reflectance: *Journal of Geophysical Research*, v. 112, E08S14, doi:10.1029/2006JE002831.
- Roach, L., Mustard, J., Swayze, G., Milliken, R., Bishop, J., Murchie, S., and Lichtenberg, K., 2010, Hydrated mineral stratigraphy of Ius Chasma, Valles Marineris: *Icarus*, v. 26, p. 254–268.
- Schaefer, M., Dyar, M., and Benison, K., 2003, Mossbauer spectroscopy of Mars-analog rocks from an acid saline environment: *NASA Technical Report 20030111385*, 2 p.
- Seelos, K., Arvidson, R., Jolliff, B., Chemtob, S., and Morris, R., 2010, Silica in a Mars analog environment: Ka'u Desert, Kilauea Volcano, Hawaii: *Journal of Geophysical Research*, v. 115, E00D15, doi:10.1029/2009JE003347.
- Swayze, G.A., Desborough, G.A., Smith, K.S., Lowers, H.A., Hammarstrom, J.M., Diehl, S.F., Leinz, R.W., and Driscoll, R.L., 2008, Understanding jarosite—From mine waste to Mars, in Verplanck, P.L., ed., *Understanding Contaminants Associated with Mineral Deposits: U.S. Geological Survey Circular 1328*, p. 8–13.
- Thaisen, K., Schieber, J., Dumke, A., and Hauber, E., 2008, Geomorphologic evidence for significant glacial and fluvial activity in Candor Chasma, Mars: 39th Lunar and Planetary Science Conference, 10–14 March 2008, Abstract 2358.
- Thollot, P., Mangold, N., Ansan, V., Milliken, R., and Bishop, J., 2012, Most Mars minerals in a nutshell: Various alteration phases formed in a single environment in Noctis Labyrinthus: *Journal of Geophysical Research*, v. 211, E00J06, doi:10.1029/2011JE004028.
- Wanke, H., and Dreibus, G., Wright, I.P., 1994, Chemistry and accretion history of Mars: *Philosophical Transactions of the Royal Society of London, Series A, Mathematical and Physical Sciences*, v. 349, p. 285–293, doi:10.1098/rsta.1994.0132.
- Warner, N., Sowe, M., Gupta, S., and Dumke, A., 2013, Fill and spill of giant lakes in the eastern Valles Marineris region of Mars: *Geology*, v. 41, p. 675–678, doi:10.1130/G34172.1.
- Wendt, L., Gross, C., Kneissl, T., and Sowe, M., 2011, Sulfates and iron oxides in Ophir Chasma, Mars, based on OMEGA and CRISM observations: *Icarus*, v. 213, p. 86–103, doi:10.1016/j.icarus.2011.02.013.

Manuscript received 16 July 2014

Revised manuscript received 5 August 2014

Manuscript accepted 6 August 2014

Printed in USA