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Fluidized-sediment pipes in Gale crater, Mars, and possible Earth analogs

David M. Rubin[1], A.G. Fairén[2], J. Martínez-Frías[3], J. Frydenvang[4], O. Gasnault[5], G. Gelfenbaum[6], W. Goetz[7], J.P. Grotzinger[8], S. Le Mouélic[9], N. Mangold[9], H. Newsom[10], D.Z. Oehler[11], W. Rapin[4], J. Schieber[12], and R.C. Wiens[4]

[1]Department of Earth & Planetary Sciences, University of California Santa Cruz, Santa Cruz, California 95064, USA
[2]Centro de Astrobiología (Consejo Superior de Investigaciones Científicas–Instituto Nacional de Técnica Aeroespacial), 28850 Torrejón de Ardoz, Spain, and Department of Astronomy, Cornell University, Ithaca, New York 14853, USA
[3]Instituto de Geociencias (IGEO), CSIC–Universidad Complutense de Madrid, 28040 Madrid, Spain
[4]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[5]Institut de Recherche en Astrophysique et Planétologie, Toulouse 31400, France
[6]U.S. Geological Survey Pacific Coastal and Marine Science Center, Santa Cruz, California 95060, USA
[7]Max Planck Institute for Solar System Research, Göttingen 37077, Germany
[8]Division of Geologic and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA
[9]Laboratoire de Planétologie et Géodynamique de Nantes, UMR6112 CNRS, Université de Nantes, Nantes 44322 Cedex 3, France
[10]Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87131, USA
[11]LZ Technology, NASA Johnson Space Center, Houston, Texas 77058, USA
[12]Department of Geological Sciences, Indiana University, Bloomington, Indiana 47408, USA

ABSTRACT

Since landing in Gale crater, the Mars Science Laboratory rover *Curiosity* has traversed fluvial, lacustrine, and eolian sedimentary rocks that were deposited within the crater ~3.6 to 3.2 b.y. ago. Here we describe structures interpreted to be pipes formed by vertical movement of fluidized sediment. Like many pipes on Earth, those in Gale crater are more resistant to erosion than the host rock; they form near other pipes, dikes, or deformed sediment; and some contain internal concentric or eccentric layering. These structures provide new evidence of the importance of subsurface aqueous processes in shaping the near-surface geology of Mars.

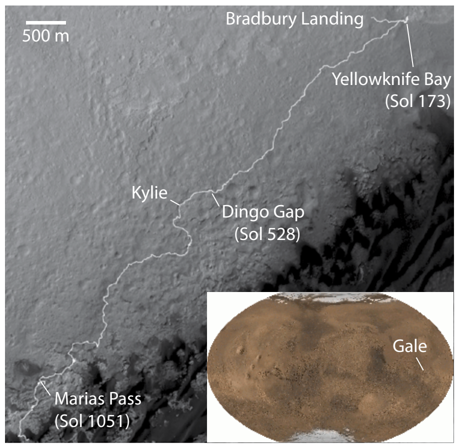

Figure 1. Map showing rover *Curiosity*'s traverse and locations discussed in this paper. Image: NASA/JPL-Caltech/Malin Space Science Systems.

INTRODUCTION

Background

The Mars Science Laboratory rover *Curiosity* landed in Gale crater in August 2012, and since then has traversed a sequence of sedimentary rocks deposited within the crater ~3.6 to 3.2 b.y. ago (Grotzinger et al., 2014, 2015). During this traverse (Fig. 1), the rover has photographed structures that are interpreted as horizontal sections through relatively vertical cylinders or pipes (Figs. 2 and 3; Table 1; additional information about the images is provided in the GSA Data Repository[1]). These features are too small to detect in orbital images (maximum diameter is 60–70 cm), and they have not been seen in previous landed missions. The objectives of this paper are to describe these structures and to interpret their origin by analogy with similar structures on Earth.

Rocks along the rover traverse are locally crosscut by veins filled with calcium sulfate and occasionally with other unidentified minerals (Nachon et al., 2014). The veins occur throughout the stratigraphic succession and can be particularly prominent in fine-grained facies, where they resemble fracture networks seen in overpressured and hydraulically fractured mudstones on Earth (Schieber, 2014). Brittle fracture of the mudstone host as well as subhorizontal and horizontal fractures suggest a late diagenetic origin, when the associated fluids exceeded lithostatic pressure.

Previous Work on Fluid Upwelling and Cylindrical Structures on Mars

Orbital studies have shown that subsurface fluid flow has been common on Mars. Chan et al. (2010) described a field of knobs in Candor Chasma and considered a variety of origins, including injected sediment pipes. Other mounds, knobs, and ridges have been attributed to movement of subsurface fluids or fluidized sediment (Allen and Oehler, 2008; Oehler and Allen, 2010; Franchi et al., 2014; Siebach and Grotzinger, 2014; Okubo, 2016). These interpretations were based on satellite imagery of geomorphic features 1–3 orders of magnitude larger than the sedimentary features observed on the ground.

Previous rover investigations also suggest that subsurface fluid flow was common on Mars. The rover *Opportunity* identified post-impact subsurface fluid circulation at Meridiani (Squyres et al., 2012; Arvidson et al., 2014), and the rover *Spirit* found evidence of ancient groundwater activity in Gusev crater (Arvidson et al., 2008).

Mahaney et al. (2010) suggested that sediment pipes on Mars might be favorable targets for astrobiological exploration because the sediment pipes they studied in Utah had clay mineral coatings on some sand grains that contained fossilized fungi, whereas the host rock did not. The potential astrobiological importance of sedimentary pipes on Mars was also discussed by Dohm et al. (2011), Essefi et al. (2014), and Fairén et al. (2016).

[1]GSA Data Repository item 2017002, supplemental information about images (detailed information about image scales, pixel sizes, and formal image names), is available online at www.geosociety.org/pubs/ft2017.htm, or on request from editing@geosociety.org.

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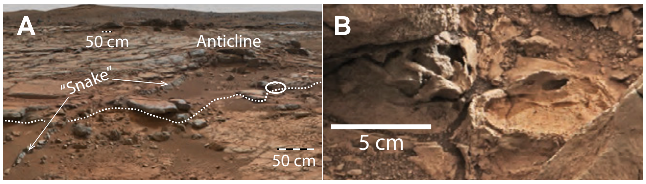

Figure 2. Cylindrical structure at Yellowknife Bay, Mars. A: Index image showing location of the circular structure (within white ellipse) and the nearby "snake" interpreted in Grotzinger et al. (2014) to have formed by injection of fluidized sediment. Dotted line shows contact between the Gillespie Lake and overlying Sheepbed members of the Yellowknife Bay formation. B: Structure with circular cross section showing crude concentric stratification and a crinkly fabric. The upper left of image shows a second structure with similar texture but irregular geometry. For image numbers, see Table 1. Images: NASA/JPL-Caltech/Malin Space Science Systems.

Previous Work on Sedimentary Pipes on Earth

Vertical and subvertical, relatively cylindrical, bodies of sediment on Earth have been attributed to a variety of processes (reviewed by Lowe, 1975; Hunter et al., 1992; Netoff, 2002; Chan et al., 2007; Hurst et al., 2011; Wheatley et al., 2016). The origins can be categorized as (1) upward or downward movement of fluids that formed vertical cavities that were later filled with sediment (Allen, 1961); (2) upward injection of fluidized sediment (Chan et al., 2007; Wheatley et al., 2016); and (3) downward movement of fluidized or brecciated sediment or intact strata (Hunter et al., 1992). In addition to the relatively vertical cylinders or columns that are the focus of this paper, fluidized sediment injectites have a wide variety of geometries including sills, dikes, and irregular bodies (Hurst et al., 2011).

STRUCTURES IN GALE CRATER

Yellowknife Bay

The structure at Yellowknife Bay (Fig. 2) has an outer diameter of 7 cm and a rim that is raised above the local bedrock by ~2–3 cm. The vertical relief is a substantial proportion of the diameter, suggesting that the structure is a cylinder rather than a circular structure confined to a horizontal plane.

Layering within the rim is roughly concentric, with some regions appearing crinkly or irregular. Grain size of the sediment in the structure is generally too fine to resolve in the Mastcam M100 images (each pixel is 0.23 mm wide in Fig. 2B), although the rim contains clasts, mottling, or concretions that are up to a few millimeters in diameter. Adjacent to the cylinder is a more irregular structure with lithology that appears similar to the cylinder rim. The cylinder occurs 2 m from a feature named the "snake" by Grotzinger et al. (2014) that was interpreted as the trace of a clastic dike protruding above the outcrop (Fig. 2A). The cylinder occurs within a few centimeters of the contact between the Sheepbed member and the underlying Gillespie Lake member of the Yellowknife Bay formation (Fig. 2A). Presumably the pipe extends downward into the lower unit, although this cannot be observed in the relatively flat exposure.

The Sheepbed mudstone contains a significant fraction of smectite (22% for the John Klein drill hole and 18% for Cumberland) that was inferred to be diagenetic, along with detrital basaltic minerals and ~30% amorphous material (Vaniman et al., 2014). Although it was not sampled for mineralogy, the overlying Gillespie Lake sandstone has a similar elemental chemistry and hydration level, suggesting the presence of phyllosilicates, likely as matrix or cement.

Dingo Gap

Several cylinders and a deformational structure occur near Dingo Gap, where the rover entered a small canyon (Figs. 3A–3E). The largest cylinder has a diameter of 60–70 cm, a raised rim, and a shallow bowl-shaped interior (Fig. 3B). The rim has a lumpy texture due to some larger rounded grains to 3 mm in diameter (Fig. 3C). Sedimentary rocks at this vicinity include conglomerates and cross-stratified sandstones interpreted as fluvial and eolian deposits, possibly including clinoform beds like those 500 m to the southwest at the Kylie outcrop (Grotzinger et al., 2015). A loose rock on the floor of Dingo Gap contains a soft-sediment deformational structure (Fig. 3D).

The elemental chemistry (determined by ChemCam; Wiens et al., 2012; Maurice et al., 2012) of the walls of this cylinder are typical of surrounding sediments with the exception of magnesium, which was elevated (10–14 wt% MgO), and the hydration level, for which the five observation points were consistently among the highest observed by that instrument. Because ChemCam observations do not distinguish compositions of grains and cement, we do not know if these two observed differences in chemistry are due to different grains within the cylinders, or different post-injection cementation.

Curiosity also photographed a cylinder ~150 m to the west of Dingo Gap (Figs. 3A and 3E); the cylinder is ~20 cm in diameter, and is noteworthy because it contains internal concentric or eccentric layering.

Marias Pass

A pair of structures was observed higher in the Murray formation near Marias Pass (Fig. 3F); they have relatively resistant rims, circular cross

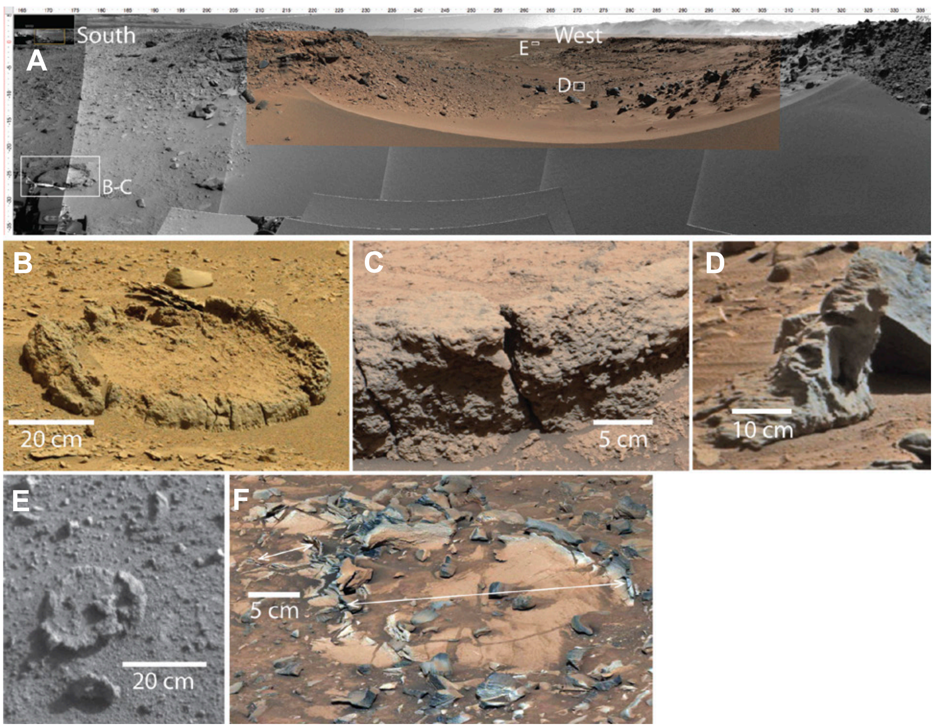

Figure 3. Cylindrical structures at Dingo Gap and Marias Pass, Mars. A: Index image showing location of structures in B–F. B: Cylindrical structure. C: Close-up of wall of B, showing texture of rim. D: Deformational structure located 20 m west of Dingo Gap, likely a loose block rather than bedrock. E: Circular structure with internal layering, located 150 m west of Dingo Gap. F: Pair of cylindrical structures at Marias Pass. Diameters of the structures, indicated by white lines, are 7 cm and 36 cm. For image numbers, see Table 1. Images: NASA/JPL-Caltech/Malin Space Science Systems.

sections, and light toned interiors relative to the surrounding sediment, and occur within lacustrine mudstones (Grotzinger et al., 2015). Elemental chemistry appears to parallel the albedo change from interior to walls. The four ChemCam observations that sampled the interior are high in Si (68–72 wt% SiO_2) and Ti, and low in Mg and Fe (<5 wt% total Fe as FeO), and show relatively strong hydration. We only have two measurements of the darker wall material, but the mean is lower in silicon (54–66 wt% SiO_2) and higher in iron (6–17 wt% total Fe as FeO); magnesium is consistently low in both materials (≤2.1 wt% MgO), while the alkalies are consistently high (3.3–5.6 wt% Na_2O, 1.8–3.2 wt% K_2O). These compositions reflect those of nearby rocks, which contain silica enrichments apparently due to alteration (Newsom et al., 2016; Frydenvang et al., 2016).

TABLE 1. DETAILS OF PIPES AND IMAGES

Location	Name of feature	Image	Sol (Mars day) of image	Diameter (cm)	Nearby geologic features
Yellowknife Bay	none	Figure 2B MR00926	173	10	Sand dike at same stratigraphic level 2 m away
Dingo Gap	Tappers	Figures 3B and 3C MR002083	528	70	Deformational structures located 20 m to the west (Fig. 3E; MR02111)
Dingo Gap (150 m west)	none	Figures 3D and 3E navcam00354	542	20	–
Marias Pass	Hewolf (pair)	Figure 3F ML004625	1051	7, 36	–

DISCUSSION

Interpretation of Pipes in Gale Crater

Here we suggest that the cylinders in Gale crater are best interpreted as pipes of injected sediment rather than infilling of vertical cavities. We base this interpretation on two observations. First, where layering is observed in the pipes (Figs. 2B and 3E) it is relatively vertical and lacks horizontal fill. Second, several of the pipes occur near other rare structures that are interpreted to have formed by movement sediment; the cylinder at Yellowknife Bay occurs only 2 m laterally and within a few centimeters vertically of the "snake," a sand dike (Fig. 2A), and the cylinders at Dingo Gap occur near a rock containing deformed sediment (Fig. 3D). Deformational structures are commonly associated with injectites (Hurst et al., 2011), and Wheatley et al. (2016) used an association with deformed sediment to argue that cylinders on the Colorado Plateau formed by sediment injection.

Although the structures observed at Marias Pass occur as a pair (Fig. 3F), they do not occur near other examples of sediment flow, and the case for their origin is weaker. They are included here to document their occurrence and because their circular planforms and raised rims are consistent with injected pipes.

Earth Analogs

The geologic characteristics and abundance of pipes on the Colorado Plateau (central USA) make them a good analog for those we describe from Mars. Hurst et al. (2011) compiled a literature review of dozens of occurrences of injectites having diverse geometries; of the five reported occurrences they categorized as vertical cylinders (which they term columnar intrusions) four are from Jurassic deposits of the Colorado Plateau, and one is from South Australia (Mount, 1993). Pipes are also associated with other geometries of injectites at six other locations, including a large complex near Santa Cruz, California (Thompson et al., 2007; Sherry et al., 2012), although these pipes are not necessarily vertical.

Wheatley et al. (2016, their table 1) list 26 published accounts of Colorado Plateau pipes, describing 30 locations (their figure 1), some of which contain multiple swarms, which in turn contain as many as hundreds of pipes; they stated (p. 12), "The Colorado Plateau is known for its abundance of clastic pipes." Those pipes (Fig. 4), like those we describe from Mars, commonly have preferentially cemented rims, concentric or eccentric layering, association with dikes (Hannum, 1980) and/or soft-sediment deformation, and clustering (although the Mars examples are not as clustered as those of Wheatley et al., 2016). The reported range of host lithologies and facies of the Colorado Plateau pipes (sandstones, shales, siltstones, and limestones deposited in eolian, interdune, fluvial, sabkha, and marine environments) is broad enough to encompass the rocks that contain the pipes in Gale crater (if the marine deposits of the Colorado Plateau are comparable to the lacustrine rocks on Mars). Much of the work on sediment pipes has focused on behavior of the noncohesive flowing sediment, but plugging of the walls with sediment as fine as clay helps to prevent leakage from the pipes; this confines and maintains the flows (Lowe, 1975; Mount, 1993). The finer sediment in more poorly sorted deposits may aid with this plugging. Although we have less information than terrestrial studies of pipes, making it impossible to identify the single best analog, geologic characteristics of the Colorado Plateau pipes, as well as their abundance and publication history, make them an appropriate analog.

Unanswered Questions

An important question regarding origin of sediment pipes on both Mars and Earth is whether sediment movement was dominantly upward or downward. Determining the direction of sediment movement is surprisingly difficult even in the excellent exposures on the Colorado Plateau; determining flow direction from the limited images of the Mars pipes is not possible. Observed downward movement might occur either by net flow into a cavity that was dissolved in evaporites, as described by Hunter et al. (1992) (sulfates are common along the rover traverse), or by late-stage collapse following dominantly upward movement (Chan et al., 2007). Some observations are ambiguous even in good exposures on Earth. For example, upturned beds in the host rock adjacent to a pipe can be attributed to drag by upward flow within the pipe (Wheatley et al., 2016) or to measurable down-dropping of the host rock relative to a pipe supported at its base (Hunter et al., 1992, their figure 12). Interpretations may also be complicated if upward and downward movement of sediment occur simultaneously or where high-permeability pipes focus post-emplacement fluid flow (Martínez-Frías et al., 2007; Sherry et al., 2012; Wheatley et al., 2016).

Hurst et al. (2011) noted that fluidized sediment pipes are merely one kind of sand injectite on Earth, and they can be associated with larger injectite bodies. We have not observed such

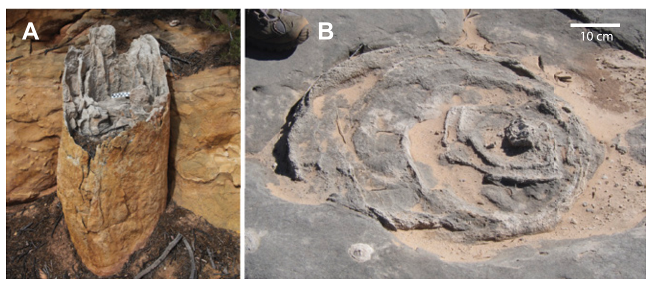

Figure 4. Fluidized sediment pipes in the Middle Jurassic Carmel Formation and Page Sandstone 12 km southeast of Escalante, Utah, USA (1.5–3.0 km north of Harris Wash and 1.7–3.5 km east of Hole in the Rock Road; N37.70883°, W111.49130°). A: Eroding pipe with resistant rim and crude concentric structure. Squares on scale bar are 1 cm. B: Horizontal section showing eccentric structure with a crinkly fabric. Eccentricity reflects lateral migration of the pipe axis, as observed in experiments of Ross et al. (2011).

larger bodies on Mars, but we cannot rule out this possibility.

Mangold et al. (2015) used geochemical data to suggest that during diagenesis of the Sheepbed mudstone, fluids were expelled into the overlying sandstone due to overpressure. Such overpressurization would aid formation of pipes, but, as is the case for many pipes on Earth, we don't know which processes caused fluidization (earthquakes, impacts, collapse following dissolution of evaporites or carbonates, hydrothermal processes, and/or overpressurization due to burial and compaction).

CONCLUSIONS

The rover *Curiosity* photographed cylinders that resemble fluidized sediment pipes on Earth. These cylinders are elevated above the outcrop surfaces, have preferentially cemented rims and concentric or eccentric internal layering, and are associated with other fluidized sediment features (a dike and deformational structures). They are interpreted to have formed by injection of fluidized sediment, likely triggered by impacts, overpressurized fluids, earthquakes, or by collapse into cavities formed by dissolution of evaporites. These structures are yet another indicator of the importance of aqueous processes in shaping the geology of Mars.

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REFERENCES CITED

Allen, C.C., and Oehler, D.Z., 2008, A case for ancient springs in Arabia Terra, Mars: Astrobiology, v. 8, p. 1093–1112, doi:10.1089/ast.2008.0239.

Allen, J.R.L., 1961, Sandstone-plugged pipes in the Lower Red Sandstone of Shropshire, England: Journal of Sedimentary Petrology, v. 31, p. 325–335, doi:10.1306/74D70B6E-2B21-11D7-8648000102C1865D.

Arvidson, R.E., et al., 2008, Spirit Mars rover mission to the Columbia Hills, Gusev Crater: Mission overview and selected results from the Cumberland Ridge to Home Plate: Journal of Geophysical Research, v. 113, E12S33, doi:10.1029/2008JE003183.

Arvidson, R.E., et al., 2014, Ancient aqueous environments at Endeavour Crater, Mars: Science, v. 343, 6169, doi:10.1126/science.1248097.

Chan, M., Netoff, D., Blakey, R., Kocurek, G., and Alvarez, W., 2007, Clastic-injection pipes and syndepositional deformation structures in Jurassic eolian deposits: Examples from the Colorado Plateau, *in* Hurst, A., and Cartwright, J., eds., Sand injectites: Implications for hydrocarbon exploration and production: American Association of Petroleum Geologists Memoir 87, p. 233–244, doi:10.1306/1209867M871350.

Chan, M.A., Ormö, J., Murchie, S., Okubo, C.H., Komatsu, G., Wray, J.J., McGuire, P., McGovern, J.A., and the HiRISE Team, 2010, Geomorphic knobs of Candor Chasma, Mars: New Mars Reconnaissance Orbiter data and comparisons to terrestrial analogues: Icarus, v. 205, p. 138–153, doi:10.1016/j.icarus.2009.04.006.

Dohm, J.M., et al., 2011, An inventory of potentially habitable environments on Mars: Geological and biological perspectives, *in* Garry, W.B., and Bleacher, J.E., eds., Analogs for planetary exploration: Geological Society of America Special Paper 483, p. 317–347, doi:10.1130/2011.2483(21).

Essefi, E., Komatsu, G., Fairén, A.G., Chan, M.A., and Yaich, C., 2014, Models of formation and activity of spring mounds in the Mechertate-Chrita-Sidi El Hani system, eastern Tunisia: Implications for the habitability of Mars: Life, v. 4, p. 386–432, doi:10.3390/life4030386.

Fairén, A.G., et al., 2016, The Argyre region as a prime target for in situ astrobiological exploration of Mars: Astrobiology, v. 16, p. 143–158, doi:10.1089/ast.2015.1396.

Franchi, F., Rossi, A.P., Pondrelli, M., and Cavalazzi, B., 2014, Geometry, stratigraphy and evidences for fluid expulsion within Crommelin crater deposits, Arabia Terra, Mars: Planetary and Space Science, v. 92, p. 34–48, doi:10.1016/j.pss.2013.12.013.

Frydenvang, J., et al., 2016, Discovery of silica-rich lacustrine and eolian sedimentary rocks in Gale crater, Mars: Houston, Texas, Lunar and Planetary Institute, Lunar and Planetary Science XLVII, abs. 2349.

Grotzinger, J.P., et al., 2014, A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars: Science, v. 343, p. 1242777, doi:10.1126/science.1242777.

Grotzinger, J.P., et al., 2015, Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars: Science, v. 350, aac7575, doi:10.1126/science.aac7575.

Hannum, C., 1980, Sandstone and conglomerate-breccia pipes and dikes of the Kodachrome Basin area, Kane County, Utah: Brigham Young University Geology Studies, v. 27, p. 1–50.

Hunter, R.E., Gelfenbaum, G., and Rubin, D.M., 1992, Clastic pipes of probable solution-collapse origin in Jurassic rocks of the southern San Juan basin, New Mexico: U.S. Geological Survey Bulletin 1808-L, 19 p.

Hurst, A., Scott, A., and Vigorito, M., 2011, Physical characteristics of sand injectites: Earth-Science Reviews, v. 106, p. 215–246, doi:10.1016/j.earscirev.2011.02.004.

Lowe, D.R., 1975, Water escape structures in coarse-grained sediments: Sedimentology, v. 22, p. 157–204, doi:10.1111/j.1365-3091.1975.tb00290.x.

Mahaney, W.C., Netoff, D.I., Dohm, J., Hancock, R.G.V., and Krinsley, D., 2010, Grain coatings: Diagenesis of Jurassic sandstones in south-central Utah and implications for targeting fossil microbes on Mars: Sedimentary Geology, v. 230, p. 1–9, doi:10.1016/j.sedgeo.2010.06.015.

Mangold, N., et al., 2015, Chemical variations in Yellowknife Bay Formation sediments analyzed by the Curiosity rover on Mars: Journal of Geophysical Research, v. 120, p. 452–482, doi:10.1002/2014JE004681.

Martínez-Frías, J., et al., 2007, Isotopic signatures of extinct low-temperature hydrothermal chimneys in the Jaroso Mars analog: Planetary and Space Science, v. 55, p. 441–448, doi:10.1016/j.pss.2006.09.004.

Maurice S., et al., 2012, The ChemCam instruments on the Mars Science Laboratory (MSL) rover: Science objectives and mast unit: Space Science Reviews, v. 170, p. 95–166, doi:10.1007/s11214-012-9912-2.

Mount, J.F., 1993, Formation of fluidization pipes during liquefaction: Examples from the Uratanna Formation (Lower Cambrian), South Australia: Sedimentology, v. 40, p. 1027–1037, doi:10.1111/j.1365-3091.1993.tb01378.x.

Nachon, M., et al., 2014, Calcium sulfate veins characterized by ChemCam/Curiosity at Gale crater, Mars: J: Journal of Geophysical Research, v. 119, p. 1991–2016, doi:10.1002/2013JE004588.

Netoff, D., 2002, Seismogenically induced fluidization of Jurassic erg sands, south-central Utah: Sedimentology, v. 49, p. 65–80, doi:10.1046/j.1365-3091.2002.00432.x.

Newsom, H.E., et al., 2016, The materials at an unconformity between the Murray and Stimson formations at Marias Pass, Gale crater, Mars: Houston, Texas, Lunar and Planetary Institute, Lunar and Planetary Science XLVII, abs. 2397.

Oehler, D.Z., and Allen, C.C., 2010, Evidence for pervasive mud volcanism in Acidalia Planitia, Mars: Icarus, v. 208, p. 636–657, doi:10.1016/j.icarus.2010.03.031.

Okubo, C.H., 2016, Morphologic evidence of subsurface sediment mobilization and mud volcanism in Candor and Coprates Chasmata, Valles Marineris, Mars: Icarus, v. 269, p. 23–37, doi:10.1016/j.icarus.2015.12.051.

Ross, J.A., Peakall, J., and Keevil, G.M., 2011, An integrated model of extrusive sand injectites in cohesionless sediments: Sedimentology, v. 58, p. 1693–1715, doi:10.1111/j.1365-3091.2011.01230.x.

Schieber, J., 2014, A seal breach on Mars—How we closed in on a mudstone and teased information from images and comparison with experimental and Earth analogs: American Association of Petroleum Geologists Datapages/Search and Discovery Article #90189.

Sherry, T.J., Rowe, C.D., Kirkpatrick, J.D., and Brodsky, E.E., 2012, Emplacement and dewatering of the world's largest exposed sand injectite complex: Geochemistry, Geophysics, Geosystems, v. 13, Q08008, doi:10.1029/2012GC004157.

Siebach, K.L., and Grotzinger, J.P., 2014, Volumetric estimates of ancient water on Mount Sharp based on boxwork deposits, Gale Crater, Mars: Journal of Geophysical Research, v. 119, p. 189–198, doi:10.1002/2013JE004508.

Squyres, S.W., et al., 2012, Ancient impact and aqueous processes at Endeavour Crater, Mars: Science, v. 336, p. 570–576, doi:10.1126/science.1220476.

Thompson, B.J., Garrison, R.E., and Moore, J.C., 2007, A reservoir-scale Miocene injectite near Santa Cruz, California, *in* Hurst, A., and Cartwright, J., eds., Sand injectites: Implications for hydrocarbon exploration and production: Association of Petroleum Geologists Memoir 87, p. 151–162.

Vaniman, D.T., et al., 2014, Mineralogy of a mudstone at Yellowknife Bay, Gale crater, Mars: Science, v. 343, 1243480, doi:10.1126/science.1243480.

Wheatley, D.F., Chan, M.A., and Sprinkel, D.A., 2016, Clastic pipe characteristics and distributions throughout the Colorado Plateau: Implications for paleoenvironment and paleoseismic controls: Sedimentary Geology, doi:10.1016/j.sedgeo.2016.03.027.

Wiens R.C., et al., 2012, The ChemCam instruments on the Mars Science Laboratory (MSL) rover: Body unit and combined system performance: Space Science Reviews, v. 170, p. 167–227, doi:10.1007/S11214-012-9902-4.

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