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Supplementary Materials for

A Habitable Fluvio-Lacustrine Environment at Yellowknife Bay, Gale Crater, Mars

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Supplementary Text

Drill testing of rock hardness

Data collected during terrestrial drill testing on relevant analog samples provide constraints on the physical properties of the rocks drilled at the John Klein and Cumberland drill sites on Mars. The first two analogs consisted of a feldspathic sandstone and a mud/siltstone collected from the Pliocene age Ridge Basin Group, north of the Golden State Highway Old Road, below the Pyramid Lake Dam north of Castaic, CA. These rocks are estimated to be 5-10 million years old, and buried to depths of several kilometers. The third was a pure kaolinite, obtained from the Standard Industrial Mineral mine in Bishop, CA, and the fourth was a large sample of anhydrite-gypsum collected from the Fish Creek Gypsum deposit located in the Salton Trough, south west of the Salton Sea, CA and owned by U. S. Gypsum Mine company.

Drill testing was performed in a drill hardware testbed at the NASA Jet Propulsion Laboratory that houses a flight duplicate MSL drill assembly (*100*). The drill is mounted to a stage that holds the drill system in place as the rotary percussion drill bit and surrounding sample acquisition tube are fed into rock samples using flight-like drilling algorithms. The drill and its supporting hardware are contained within a vacuum chamber and tests were performed under Mars ambient atmospheric pressure (~10mbar) during drill testing. In an attempt to more closely replicate the likely hydration state of rocks on Mars, all analogue rock samples were baked in an oven at 110^{o} C for a period not less than 2 days prior to drilling in order to drive off adsorbed and loosely bound water to better resemble conditions expected to be present on target rocks on Mars.

While the *Curiosity* rover does not possess a dedicated instrument for direct determination of rock hardness, a hardness test procedure that uses the drill hardware for *in situ* determination of rock hardness and cohesiveness has been developed. MSL "Hardness tests" are performed by measuring the depth of penetration of MSL's spade-shaped drill bit tip after a number of discrete motions that result in drill-rock interaction with a non-rotating drill bit. These include depth measurements after the drill bit is loaded against the rock surface with a 130N force, after the drill is "tapped" against the rock with a single tap of the percussion actuator, and six subsequent depth of penetration measurements after the drill bit is advanced (without rotation) into the rock at increasing levels of percussion energy. The 6 percuss levels increase in energy with level 1-6 having 0.05 J per blow, 0.20, 0.31, 0.45, 0.61, to 0.81 J per blow, respectively. The results of these hardness tests provide insight into the relative resistance to penetration of various analogue rock samples for comparison to data collected during drilling operations on Mars. Figure S3 plots our hardness test results for the four analog samples discussed above along with hardness test results from the John Klein and Cumberland drill samples collected by the *Curiosity* rover on Mars. Note that hardness tests were performed at two locations on the John Klein rock face; one for a mini-drill hole (~20 mm total penetration depth) and one for the full-depth drill hole, from which sample was

collected and delivered to *Curiosity's* onboard analytical instruments. For the Cumberland hardness test, the drill bit tip appears to have advanced deeper into the rock for a given step in the test procedure. In fact, the Cumberland hardness test was terminated at Step 8 because a depth >0.8mm was achieved. Altogether these observations suggest that the Cumberland rock target was less resistant to penetration (i.e., softer) than the John Klein target.

A somewhat different picture emerges from Rate of Penetration (ROP) data, which measures the speed at which the drill bit and its surrounding sample acquisition tube are fed into a rock. While this data is a complex function of the intrinsic rock hardness, the cohesive strength of rock, and the engineering parameters of the drill system, it is interesting to compare data from our analogue samples to ROP data collected on Mars. ROP data collection occurs during rotary-percussive drilling, after the hardness test is performed and after a series of rotary-percussion "hole start" motions are performed that effectively create a shallow pilot hole to keep the drill bit from walking across the rock face during the drilling operation. As shown in Figure S4, the John Klein and Cumberland ROP data fall in between the feldspathic sandstone and kaolinite test data, and appear most similar to data collected on the Ridge group mud/siltstone and the anhydrite-gypsum from the Salton Sea. It is important to note that for *in situ* drilling operations on Mars, the percussion level was intentionally limited to a level lower than the drill system's maximum percussion level, owing to hardware safety concerns for first time drilling operations. These limits were not applied during analogue drill testing on Earth. Therefore, it is possible that a faster ROP could have been realized during John Klein drilling operations had the percussion level been allowed to advance to higher levels. Therefore, the ROP data for John Klein should probably be considered a lower limit on the ROP for this *in situ* drilling operation.

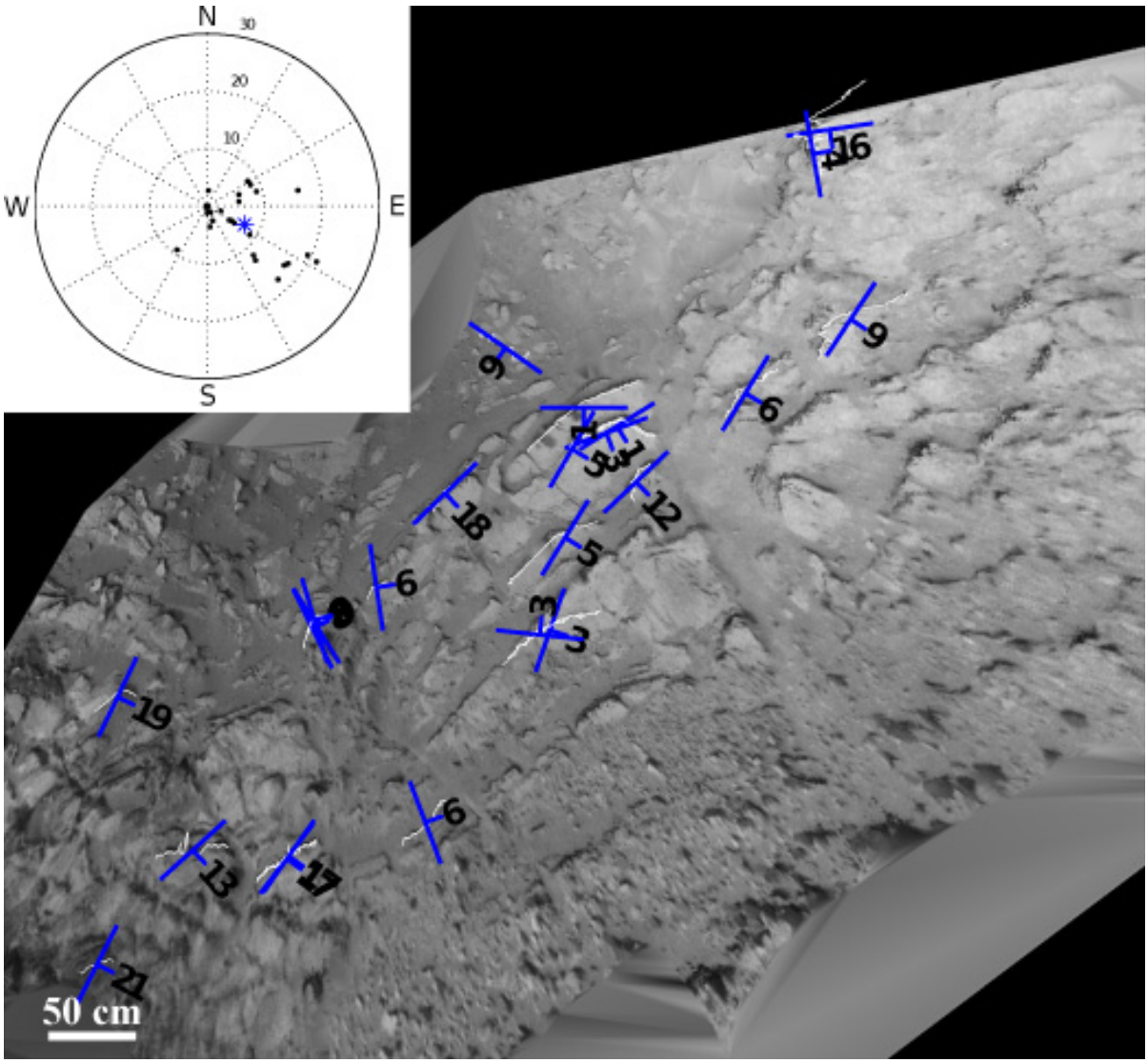


Fig. S1.

Three-dimensional bedding orientation measurements were extracted from Sol 120 Navcam images of the outcrop, which have been vertically projected in this map. Measurements were made via orthogonal regression, via the method of Lewis et al. (*99*). Dip marks denote individual measurements of bedding traces, shown in white. The polar plot shows each measurement that satisfied our error constraints (N=25), along with the mean bedding attitude in blue. In general, cross-strata at Shaler dip to the southeast, at a mean dip of 7 degrees, oriented 64 degrees south of east. Although individual measurements show some scatter in dip azimuth, nearly all beds are oriented within 90 degrees of the inferred mean flow direction, consistent with fluvial transport and associated bedform geometries. See Supplementary Text, below, for image IDs.



Fig. S2

Texture of the "snake" as seen by MAHLI on Sol 149 (6 Jan 2013). Note uniformly fine grain size and presence of pits that may reflect void spaces and, in some cases, erosion of softer components that may represent intraclasts. Image ID: 0149MH0000750010101287C00.

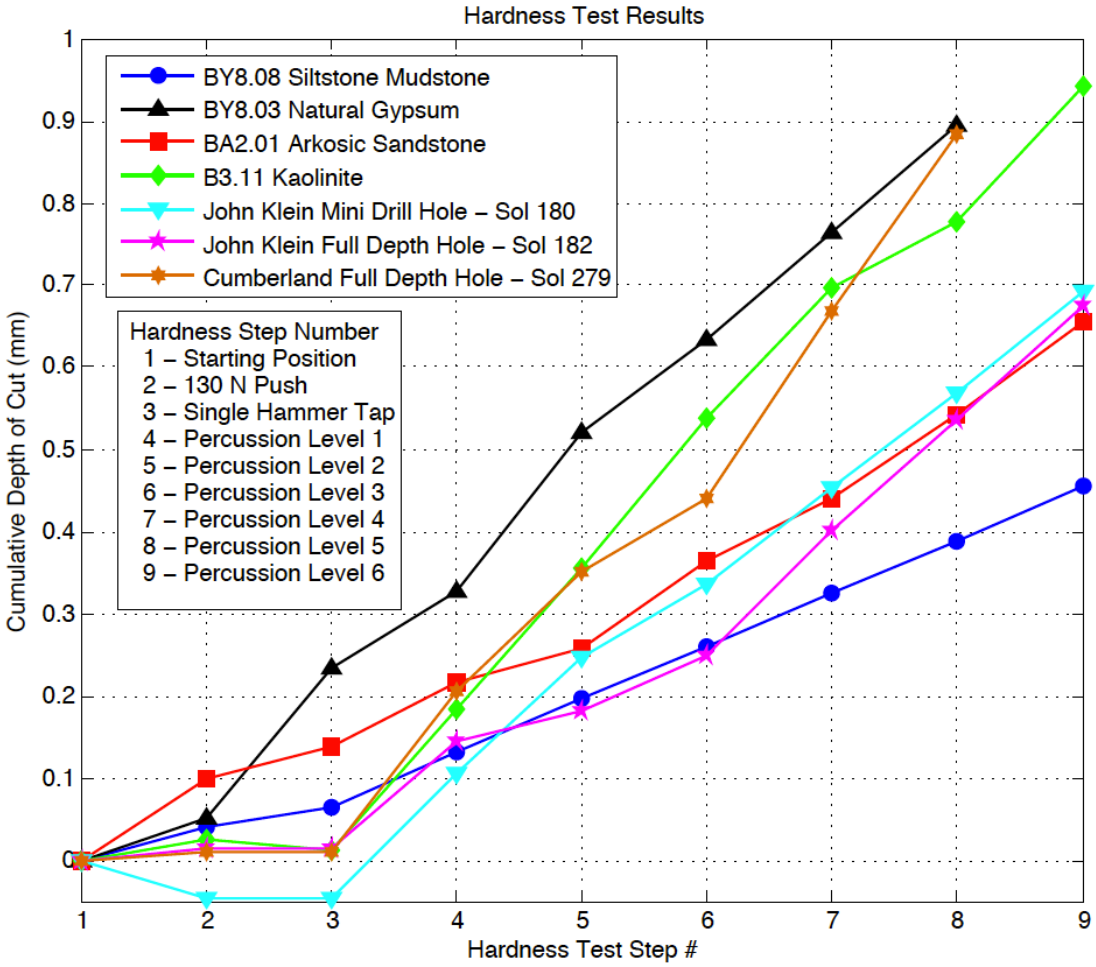


Fig. S3

Hardness test results for analogue samples plotted together with the John Klein and Cumberland data on a graph of cumulative depth of cut (mm) versus Hardness test step #.

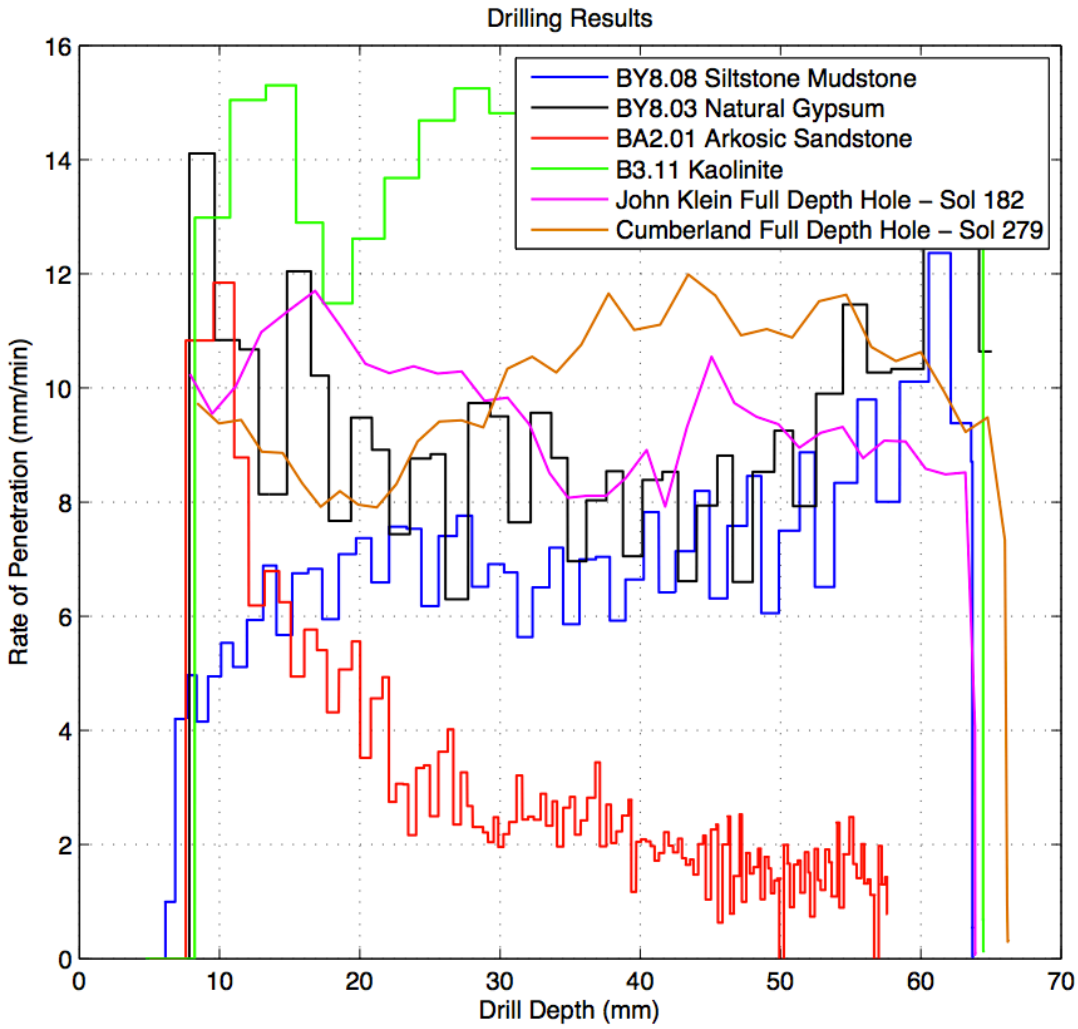


Fig. S4

Rate of Penetration (ROP) results for analog samples plotted together with the John Klein and Cumberland data on a graph of ROP (mm/min) against drill depth (mm).

Table S1.
Stratigraphic Nomenclature

Name	Unit Description	Exposure and Contacts
Glenelg member	Intermixed facies, including those represented by the following outcrops: 1) Bathurst Inlet outcrop • Centimeter- to decimeter-thick beds • Grain size not resolvable with MAHLI; likely fine sand, silt, or clay-sized. • Basaltic composition with a significant enrichment in alkaline elements. 2) Shaler outcrop • Centimeter- to decimeter-thick beds with variable resistance to erosion • Grain size varies from finer than fine sand up to granule, sorted into discrete layers. • Diverse sedimentary structures, including planar lamination, low angle truncations, and trough cross stratification; rare fine-grained layers have vertical cracks filled with more resistant sediment. • Downward-tapering sediment-filled cracks interpreted to have formed by desiccation. • Basaltic composition 3) Point Lake outcrop • 20-50 cm-thick layers of unknown origin • Meter-long fractures define meter-scale polygons; weathered surfaces are rough. • cm-scale vuggy porosity; rare bright, sulfate-filled fractures • Basaltic composition 4) Rocknest outcrop • Decimeter-sized rocks of unknown origin, lacking stratigraphic context • Some rocks show faint planar lamination to low angle cross	• Caps Yellowknife Bay formation stratigraphy. The "cratered surface" map unit, to the southeast of Yellowknife Bay, may represent the expression of the upper surface of a resistant bed near the top of the formation, or the top of the formation itself. • Upper beds (e.g. Bathurst Inlet outcrop) weather resistantly, and typically overlie slopes covered with scree, which may be underlain by facies similar to those in the Shaler outcrop. • Facies represented by the Point Lake and Rocknest outcrops are exposed as discontinuous layers and a $\leq$200 m^2 platform of resistant beds. • Lower contact: sharp with the underlying Gillespie Lake member. • Upper contact: not exposed, or consists of the geomorphic cratered surface.

	lamination or massive; lens-shaped voids interpreted as desiccation cracks. • Some rocks are texturally similar to Point Lake outcrop with rough weathered surfaces. • Basaltic composition with significant enrichment in alkaline elements.	
Gillespie Lake member	• Decimeter-thick beds of uniformly smooth weathering sandstone; • Meter-long fractures define meter-scale polygons; • Medium to very coarse sand with diverse grain colors and some translucent grains at base of the unit • Hints of small-scale cross stratification including possible ripple crests on bedding planes. • Rare millimeter-scale bright, sulfate-filled fractures. • Basaltic composition	• Well exposed and laterally continuous regionally. • Lower contact: sharp with centimeters of relief; lowermost bed always caps a small scarp, often overhanging. Contact is nearly horizontal for 100's m to the east and northeast. • Upper contact: sharp and well exposed under the Point Lake outcrop, but poorly exposed elsewhere.
Sheepbed member	• Decimeter-thick beds with variable resistance to erosion • Abundant meter-long fractures define meter-scale polygons; fractures are centimeters to decimeters wide and sand-filled. • Dominant grain size in upper 50 cm is below the resolution of MAHLI, likely silt to clay-sized. • Variable concentrations of bright cement-filled fractures, hairline fractures, and millimeter-scale bright spherical "hollow nodules", all filled with calcium sulfate. • Dark, raised, intersecting ridges frequently rise above centimeter-scale polygons in meter-diameter patches. Ridges dip in various directions, have a composition similar to that of the host rocks, and show a small magnesium enrichment. • Meter-scale patches contain high concentrations of millimeter-scale nodules, interpreted as concretions. Concretions have the same color as raised ridges. Hollow nodules are also present, as well as some	• The upper 50 cm of this unit weathers recessively and is well exposed to covered in loose sand. • Lower contact: not defined • Upper contact: sharp with centimeters of erosional relief, often overhanging. Regionally mappable due to topographic expression.

	filled with calcium sulfate. • Basaltic composition with~20% smectite, ~50% igneous minerals; and ~30% X-ray amorphous material. Elevated magnetite likely authigenic.	

Table S2.

Image Identification Numbers for Mosaics

Figure 3 Image IDs :

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Figure 7 Image IDs:

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Figure S1 Image IDs:

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NLA_408156347EDR_F0050742NCAM00215M1.IMG,
NLA_408156382EDR_F0050742NCAM00215M1.IMG

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1. J. P. Grotzinger, J. Crisp, A. R. Vasavada, R. C. Anderson, C. J. Baker, R. Barry, D. F. Blake, P. Conrad, K. S. Edgett, B. Ferdowski, R. Gellert, J. B. Gilbert, M. Golombek, J. Gómez-Elvira, D. M. Hassler, L. Jandura, M. Litvak, P. Mahaffy, J. Maki, M. Meyer, M. C. Malin, I. Mitrofanov, J. J. Simmonds, D. Vaniman, R. V. Welch, R. C. Wiens; Mars Science Laboratory Mission and Science Investigation, Mars Science Laboratory Mission and Science Investigation. *Space Sci. Rev.* **170**, 5–56 (2012). doi:10.1007/s11214-012-9892-2

2. R. P. I. Irwin III, A. D. Howard, R. A. Craddock, J. M. Moore, An intense terminal epoch of widespread fluvial activity on early Mars: 2. Increased runoff and paleolake development. *J. Geophys. Res.* **110**, E12S15 (2005). doi:10.1029/2005JE002460

3. M. C. Malin, K. S. Edgett, Sedimentary rocks of early Mars. *Science* **290**, 1927–1937 (2000). doi:10.1126/science.290.5498.1927

4. R. B. Anderson, J. F. Bell III, Geologic mapping and characterization of Gale crater and implications for its potential as a Mars Science Laboratory landing site. *The Mars Journal* **5**, 76–128 (2010). doi:10.1555/mars.2010.0004

5. R. E. Milliken, D. L. Bish, Sources and sinks of clay minerals on Mars. *Philos. Mag.* **90**, 2293–2308 (2010). doi:10.1080/14786430903575132

6. B. J. Thomson, N. T. Bridges, R. Milliken, A. Baldridge, S. J. Hook, J. K. Crowley, G. M. Marion, C. R. de Souza Filho, A. J. Brown, C. M. Weitz, Constraints on the origin and evolution of the layered mound in Gale crater, Mars using Mars Reconnaissance Orbiter data. *Icarus* **214**, 413–432 (2011). doi:10.1016/j.icarus.2011.05.002

7. J. P. Grotzinger, R. E. Milliken, The sedimentary rock record of Mars: Distribution, origins, and global stratigraphy, in *Sedimentary Geology of Mars*, J. Grotzinger, R. E. Milliken, Eds. (SEPM Special Publication, Tulsa, OK, 2012), vol. 102.

8. J. P. Grotzinger, Beyond water on Mars. *Nat. Geosci.* **2**, 231–233 (2009). doi:10.1038/ngeo480

9. A. Fraeman, R. E. Arvidson, J. G. Catalano, J. P. Grotzinger, R. V. Morris, S. L. Murchie, K. M. Stack, D. C. Humm, J. A. McGovern, F. P. Seelos, K. D. Seelos, C. E. Viviano, A hematite-bearing layer in Gale crater: Mapping and implications for past aqueous conditions. *Geology* **41**, 1103–1106 (2013). doi:10.1130/G34613.1

10. This decision was made by the entire MSL Science Team with strong consensus to drive a relatively short distance (~500 m) to examine rocks with higher thermal inertia values that also had an apparently strong spatial association with the AF unit. The prediction based on mapping was that fluvial and/or lacustrine rocks potentially derived from the crater rim might be encountered. The strata exposed at the base of Mt. Sharp are still considered to be the primary mission objective, and the team has established a departure date from Yellowknife Bay of the first week in July 2013.

11. The names used for rock and soil targets studied by Curiosity and reported in this paper are derived from established rock formations of northern Canada. In turn, these names derive from names of local geographic features where they occur, per convention, such as

mountains, streams, lakes, bays, etc. This choice of naming scheme celebrates the city of Yellowknife, Northwest Territories, long known to be a port of departure for geologic mapping expeditions into some of the oldest rocks of North America. Yellowknife crater was designated by the International Astronomical Union, and Yellowknife Bay demarcates the area into which Curiosity descended to study its geologic history.

12. A base map was created based on 25-cm-per-pixel HiRISE visible image data, 1-m-per-pixel elevation data, and 100-m-per-pixel Thermal Emission Imaging System data that was subdivided into 140 1.2- by 1.2-km (0.025°) quadrangles and mapped in detail by more than 30 team members. The group map was compiled, consolidated, and iteratively refined into a single GIS project.

13. In addition, minor units of eolian fill and/or bedforms and ejecta blankets adjacent to larger craters are present but are not discussed further.

14. Bradbury Landing refers to the patch of ground where Curiosity touched down on the surface of Mars. It commemorates the noted science fiction writer Raymond Bradbury and was designated by NASA.

15. E. M. Stolper, M. B. Baker, M. E. Newcombe, M. E. Schmidt, A. H. Treiman, A. Cousin, M. D. Dyar, M. R. Fisk, R. Gellert, P. L. King, L. Leshin, S. Maurice, S. M. McLennan, M. E. Minitti, G. Perrett, S. Rowland, V. Sautter, R. C. Wiens; MSL Science Team, The petrochemistry of Jake_M: A martian mugearite. *Science* **341**, 1239463 (2013). doi:10.1126/science.1239463

16. P.-Y. Meslin, O. Gasnault, O. Forni, S. Schröder, A. Cousin, G. Berger, S. M. Clegg, J. Lasue, S. Maurice, V. Sautter, S. Le Mouélic, R. C. Wiens, C. Fabre, W. Goetz, D. Bish, N. Mangold, B. Ehlmann, N. Lanza, A. M. Harri, R. Anderson, E. Rampe, T. H. McConnochie, P. Pinet, D. Blaney, R. Léveillé, D. Archer, B. Barraclough, S. Bender, D. Blake, J. G. Blank, N. Bridges, B. C. Clark, L. DeFlores, D. Delapp, G. Dromart, M. D. Dyar, M. Fisk, B. Gondet, J. Grotzinger, K. Herkenhoff, J. Johnson, J. L. Lacour, Y. Langevin, L. Leshin, E. Lewin, M. B. Madsen, N. Melikechi, A. Mezzacappa, M. A. Mischna, J. E. Moores, H. Newsom, A. Ollila, R. Perez, N. Renno, J. B. Sirven, R. Tokar, M. de la Torre, L. d'Uston, D. Vaniman, A. Yingst; MSL Science Team, Soil diversity and hydration as observed by ChemCam at Gale crater, Mars. *Science* **341**, 1238670 (2013). doi:10.1126/science.1238670

17. R. M. E. Williams, J. P. Grotzinger, W. E. Dietrich, S. Gupta, D. Y. Sumner, R. C. Wiens, N. Mangold, M. C. Malin, K. S. Edgett, S. Maurice, O. Forni, O. Gasnault, A. Ollila, H. E. Newsom, G. Dromart, M. C. Palucis, R. A. Yingst, R. B. Anderson, K. E. Herkenhoff, S. Le Mouélic, W. Goetz, M. B. Madsen, A. Koefoed, J. K. Jensen, J. C. Bridges, S. P. Schwenzer, K. W. Lewis, K. M. Stack, D. Rubin, L. C. Kah, J. F. Bell 3rd, J. D. Farmer, R. Sullivan, T. Van Beek, D. L. Blaney, O. Pariser, R. G. Deen; MSL Science Team, Martian fluvial conglomerates at Gale crater. *Science* **340**, 1068–1072 (2013). doi:10.1126/science.1237317

18. The morphology of the "bay" is the result of postdepositional erosion, perhaps by eolian processes, as shown by the exposures of stratified rock that record dissection. These are eroded rocks and not, for example, shoreline berms. Therefore, the present-day topography does not reflect that at the time of deposition of those strata.

19. S. M. McLennan, R. B. Anderson, J. F. Bell III, J. C. Bridges, F. Calef III, J. L. Campbell, B. C. Clark, S. Clegg, P. Conrad, A. Cousin, D. J. Des Marais, G. Dromart, M. D. Dyar, L. A. Edgar, B. L. Ehlmann, C. Fabre, O. Forni, O. Gasnault, R. Gellert, S. Gordon, J. A. Grant, J. P. Grotzinger, S. Gupta, K. E. Herkenhoff, J. A. Hurowitz, P. L. King, S. Le Mouélic, L. A. Leshin, R. Léveillé, K. W. Lewis, N. Mangold, S. Maurice, D. W. Ming, R. V. Morris, M. Nachon, H. E. Newsom, A. M. Ollila, G. M. Perrett, M. S. Rice, M. E. Schmidt, S. P. Schwenzer, K. Stack, E. M. Stolper, D. Y. Sumner, A. H. Treiman, S. VanBommel, D. T. Vaniman, A. Vasavada, R. C. Wiens, R. A. Yingst, MSL Science Team, Elemental geochemistry of sedimentary rocks at Yellowknife Bay, Gale crater, Mars. *Science* **343**, 1244734 (2014).

20. S. R. Taylor, S. M. McLennan, *Planetary Crusts: Their Composition, Origin, and Evolution* (Cambridge Univ. Press, Cambridge, 2009).

21. M. E. Schmidt *et al*., APXS of first rocks encountered by Curiosity in Gale crater: Geochemical diversity and volatile element (K and Zn) enrichment. *Lunar Planet. Sci. Conf. 44*, abstract 1278 (2013)

22. N. D. Smith, Some sedimentological aspects of planar cross-stratification in a sandy braided river. *J. Sediment. Petrol.* **42**, 624–634 (1972).

23. G. A. Macdonald, Pahoehoe, aa, and block lava. *Am. J. Sci.* **251**, 169–191 (1953). doi:10.2475/ajs.251.3.169

24. A. Hurst, A. Scott, M. Vigorito, Physical characteristics of sand injectites. *Earth Sci. Rev.* **106**, 215–246 (2011). doi:10.1016/j.earscirev.2011.02.004

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

26. M. El-Tabakh, R. Riccioni, B. C. Schreiber, Evolution of late Triassic rift basin evaporites (Passaic Formation): Newark Basin, Eastern North America. *Sedimentology* **44**, 767–790 (1997). doi:10.1046/j.1365-3091.1997.d01-47.x

27. J. A. Fisher, G. J. Nichols, D. A. Waltham, Unconfined flow deposits in distal sectors of fluvial distributary systems: Examples from the Miocene Luna and Huesca Systems, northern Spain. *Sediment. Geol.* **195**, 55–73 (2007). doi:10.1016/j.sedgeo.2006.07.005

28. D. T. Vaniman, D. L. Bish, D. W. Ming, T. F. Bristow, R. V. Morris, D. F. Blake, S. J. Chipera, S. M. Morrison, A. H. Treiman, E. B. Rampe, M. Rice, C. N. Achilles, J. Grotzinger, S. M. McLennan, J. Williams, J. Bell III, H. Newsom, R. T. Downs, S. Maurice, P. Sarrazin, A. S. Yen, J. M. Morookian, J. D. Farmer, K. Stack, R. E. Milliken, B. Ehlmann, D. Y. Sumner, G. Berger, J. A. Crisp, J. A. Hurowitz, R. Anderson, D. DesMarais, E. M. Stolper, K. S. Edgett, S. Gupta, N. Spanovich, MSL Science Team, Mineralogy of a mudstone at Yellowknife Bay, Gale crater, Mars. *Science* **343**, 1243480 (2014).

29. P. E. Potter, J. B. Maynard, P. Depetris, *Mud and Mudstones* (Springer, Berlin, 2005).

30. P. B. Attewell, I. W. Farmer, *Principles of Engineering Geology* (Chapman and Hall, London, New York, 1976).

31. Supplementary materials are available on *Science* Online.

32. D. Winston, Fluvial Systems of the Precambrian Belt Supergroup, Montana and Idaho, U.S.A. *Fluvial Sedimentology* **Memoir 5**, 343 (1977).

33. D. S. McCormick, J. P. Grotzinger, Distinction of marine from alluvial Facies in the Paleoproterozoic (1.9 Ga) burnside formation, Kilohigok basin, N.W.T., Canada. *J. Sediment. Petrol.* **63**, 398–419 (1993).

34. A. S. Yen, R. Gellert, C. Schröder, R. V. Morris, J. F. Bell III, A. T. Knudson, B. C. Clark, D. W. Ming, J. A. Crisp, R. E. Arvidson, D. Blaney, J. Brückner, P. R. Christensen, D. J. DesMarais, P. A. de Souza Jr., T. E. Economou, A. Ghosh, B. C. Hahn, K. E. Herkenhoff, L. A. Haskin, J. A. Hurowitz, B. L. Joliff, J. R. Johnson, G. Klingelhöfer, M. B. Madsen, S. M. McLennan, H. Y. McSween, L. Richter, R. Rieder, D. Rodionov, L. Soderblom, S. W. Squyres, N. J. Tosca, A. Wang, M. Wyatt, J. Zipfel, An integrated view of the chemistry and mineralogy of martian soils. *Nature* **436**, 49–54 (2005). Medline doi:10.1038/nature03637

35. P. R. Christensen, Regional dust deposits on Mars: Physical properties, age, and history. *J. Geophys. Res. Solid Earth* **91**, 3533–3545 (1986). doi:10.1029/JB091iB03p03533

36. N. T. Bridges, D. R. Muhs, Duststones on Mars: source, transport, deposition, and erosion, in *Sedimentary Geology of Mars* (SEPM Special Publication, Tulsa, OK, 2012), vol. 102, pp. 169–182.

37. N. Mangold, V. Ansan, P. Masson, C. Vincendon, Estimate of aeolian dust thickness in Arabia Terra, Mars: Implications of a thick mantle (>20 m) for hydrogen detection. *Geomorphol.: Relief, Processes, Environ.* **1/2009**, 23–32 (2009).

38. P. M. Sadler, Sediment accumulation rates and the completeness of stratigraphic sections. *J. Geol.* **89**, 569–584 (1981). doi:10.1086/628623

39. A. M. Sarna-Wojcicki, S. Shipley, R. B. Waitt, D. Dzurisin, S. H. Wood, in *The 1980 Eruptions of Mount St. Helens, Washington*, P. W. Lipman, D. R. Mullineaux, Eds. (U.S. Geological Survey Professional Paper, Reston, VA, 1981), vol. 1250, pp. 577–600.

40. S. M. McLennan, J. F. Bell III, W. M. Calvin, P. R. Christensen, B. C. Clark, P. A. de Souza, J. Farmer, W. H. Farrand, D. A. Fike, R. Gellert, A. Ghosh, T. D. Glotch, J. P. Grotzinger, B. Hahn, K. E. Herkenhoff, J. A. Hurowitz, J. R. Johnson, S. S. Johnson, B. Jolliff, G. Klingelhöfer, A. H. Knoll, Z. Learner, M. C. Malin, H. Y. McSween Jr., J. Pocock, S. W. Ruff, L. A. Soderblom, S. W. Squyres, N. J. Tosca, W. A. Watters, M. B. Wyatt, A. Yen, Provenance and diagenesis of the evaporite-bearing Burns formation, Meridiani Planum, Mars. *Earth Planet. Sci. Lett.* **240**, 95–121 (2005). doi:10.1016/j.epsl.2005.09.041

41. P. Fralick, J. P. Grotzinger, L. Edgar, in *Sedimentary Geology of Mars*, J. P. Grotzinger, R. E. Milliken, Eds. (SEPM Special Publication, Tulsa, OK, 2012), vol. 102.

42. J. D. Kim, N. Yee, V. Nanda, P. G. Falkowski, Anoxic photochemical oxidation of siderite generates molecular hydrogen and iron oxides. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 10073–10077 (2013). Medline doi:10.1073/pnas.1308958110

43. G. Furniss, J. F. Rittel, D. Winston, Gas bubble and expansion crack origin of "molar-tooth" calcite structures in the Middle Porterozoic Belt Supergroup, western Montana. *J. Sediment. Res.* **68**, 104–114 (1998). doi:10.2110/jsr.68.104

44. The term "raised ridges" may seem redundant, but the designation "raised" is meant to denote the substantial height of the ridges compared to their width.

45. P. S. Plummer, V. A. Gostin, Shrinkage cracks: Desiccation or synaeresis? *J. Sediment. Res.* **51**, 1147–1156 (1981).

46. B. R. Pratt, Syneresis cracks: Subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering. *Sediment. Geol.* **117**, 1–10 (1998). doi:10.1016/S0037-0738(98)00023-2

47. M. D. Pollock, L. C. Kah, J. K. Bartley, Morphology of molar-tooth structures in Precambrian carbonates: Influence of substrate rheology and implications for genesis. *J. Sediment. Res.* **76**, 310–323 (2006). doi:10.2110/jsr.2006.021

48. A. Hurst, J. A. Cartwright, D. Duranti, in *Subsurface Sediment Mobilisation*, R. R. H. P. Van Rensbergen, A. J. Maltman, C. K. Morley, Ed. (Geological Society of London Special Publication, London, 2003), vol. 216, pp. 123–137.

49. I. A. Kane, Development and flow structures of sand injectities: The Hind Sandstone Member injectite complex, Carboniferous, UK. *Mar. Pet. Geol.* **27**, 1200–1215 (2010). doi:10.1016/j.marpetgeo.2010.02.009

50. M. Huuse, J. Cartwright, A. Hurst, N. Steinsland, Seismic characterization of large-scale sandstone intrusions, in *Sand Injectities: Implications for Hydrocarbon Exploration and Production*, A. Hurst, J. Cartwright, Eds. (American Association of Petroleum Geologists Memoir, Tulsa, OK, 2007), vol. 87.

51. J. W. Cosgrove, Hydraulic fracturing during the formation and deformation of a basin: A factor in the dewatering of low-permeability sediments. *AAPG Bull.* **85**, 737–748 (2001).

52. D. W. Ming, P. D. Archer Jr., D. P. Glavin, J. L. Eigenbrode, H. B. Franz, B. Sutter, A. E. Brunner, J. C. Stern, C. Freissinet, A. C. McAdam, P. R. Mahaffy, M. Cabane, P. Coll, J. L. Campbell, S. K. Atreya, P. B. Niles, J. F. Bell III, D. L. Bish, W. B. Brinckerhoff, A. Buch, P. G. Conrad, D. J. Des Marais, B. L. Ehlmann, A. G. Fairén, K. Farley, G. J. Flesch, P. Francois, R. Gellert, J. A. Grant, J. P. Grotzinger, S. Gupta, K. E. Herkenhoff, J. A. Hurowitz, L. A. Leshin, K. W. Lewis, S. M. McLennan, K. E. Miller, J. Moersch, R. V. Morris, R. Navarro-González, A. A. Pavlov, G. M. Perrett, I. Pradler, S. W. Squyres, R. E. Summons, A. Steele, E. M. Stolper, D. Y. Sumner, C. Szopa, S. Teinturier, M. G. Trainer, A. H. Treiman, D. T. Vaniman, A. R. Vasavada, C. R. Webster, J. J. Wray, R. A. Yingst, MSL Science Team, Volatile and organic compositions of sedimentary rocks in Yellowknife Bay, Gale crater, Mars. *Science* **343**, 1245267 (2014).

53. J. D. Collinson, Sedimentology of unconformities within a fluvio-lacustrine sequence; Middle Proterozoic of Eastern North Greenland. *Sediment. Geol.* **34**, 145–166 (1983). doi:10.1016/0037-0738(83)90084-2

54. L. B. Aspler, J. R. Chiarenzelli, B. L. Cousens, Fluvial, lacustrine and volcanic sedimentation in the Angikuni sub-basin, and initiation of ~1.84–1.79 Ga Baker Lake Basin, western

Churchill Province, Nunavut, Canada. *Precambrian Res.* **129**, 225–250 (2004). doi:10.1016/j.precamres.2003.10.004

55. H. H. Kieffer, B. M. Jakosky, C. Snyder, M. Matthews, *Mars*, H. H. Kieffer, B. M. Jakosky, C. Snyder, M. Matthews, Eds. (Univ. of Arizona Press, Tucson, AZ, 1992).

56. J. F. Bell III, *The Martian Surface: Composition, Mineralogy, and Physical Properties*, J. F. Bell III, Ed. (Cambridge Univ. Press, New York, 2008).

57. J. C. Andrews-Hanna, K. W. Lewis, Early Mars hydrology: 2. Hydrological evolution in the Noachian and Hesperian epochs. *J. Geophys. Res. Planets* **116**, E02007 (2011). doi:10.1029/2010JE003709

58. C. R. Woese, G. E. Fox, Phylogenetic structure of the prokaryotic domain: The primary kingdoms. *Proc. Natl. Acad. Sci. U.S.A.* **74**, 5088–5090 (1977). Medline doi:10.1073/pnas.74.11.5088

59. E. I. Friedmann, Endolithic microorganisms in the antarctic cold desert. *Science* **215**, 1045–1053 (1982).doi:10.1126/science.215.4536.1045

60. K. O. Stetter, Extremophiles and their adaptation to hot environments. *FEBS Lett.* **452**, 22–25 (1999). Medline doi:10.1016/S0014-5793(99)00663-8

61. M. Rossi, M. Ciaramella, R. Cannio, F. M. Pisani, M. Moracci, S. Bartolucci, Extremophiles 2002. *J. Bacteriol.* **185**, 3683–3689 (2003). Medline doi:10.1128/JB.185.13.3683-3689.2003

62. K. H. Nealson, Sediment bacteria: Who's there, what are they doing, and what's new? *Annu. Rev. Earth Planet. Sci.* **25**, 403–434 (1997). Medline doi:10.1146/annurev.earth.25.1.403

63. H. G. Schlegel, *General Microbiology* (Cambridge Univ. Press, Cambridge, ed. 7, 1993).

64. G. Gottschalk, *Microbial Metabolism* (Springer, New York, 1994).

65. R. J. Parkes, G. Webster, B. A. Cragg, A. J. Weightman, C. J. Newberry, T. G. Ferdelman, J. Kallmeyer, B. B. Jørgensen, I. W. Aiello, J. C. Fry, Deep sub-seafloor prokaryotes stimulated at interfaces over geological time. *Nature* **436**, 390–394 (2005). Medline doi:10.1038/nature03796

66. K. H. Nealson, P. G. Conrad, Life: past, present and future. *Philos. Trans. R. Soc. London Ser. B* **354**, 1923–1939 (1999). Medline

67. D. Z. Sousa, A. F. Salvador, J. Ramos, A. P. Guedes, S. Barbosa, A. J. Stams, M. M. Alves, M. A. Pereira, Activity and viability of methanogens in anaerobic digestion of unsaturated and saturated long-chain fatty acids. *Appl. Environ. Microbiol.* **79**, 4239–4245 (2013). Medline doi:10.1128/AEM.00035-13

68. M. S. Milman-Barris, J. R. Beckett, M. B. Baker, A. E. Hofmann, Z. Morgan, M. R. Crowley, D. Vielzeuf, E. Stolper, Zoning of phosphorous in igneous olivine. *Contrib. Mineral. Petrol.* **155**, 739–765 (2008). doi:10.1007/s00410-007-0268-7

69. M. A. Schoonen, Y. Xu, Nitrogen reduction under hydrothermal vent conditions: Implications for the prebiotic synthesis of C-H-O-N compounds. *Astrobiology* **1**, 133–142 (2001).

70. D. P. Summers, R. C. B. Basa, B. Khare, D. Rodoni, Abiotic nitrogen fixation on terrestrial planets: Reduction of NO to ammonia by FeS. *Astrobiology* **12**, 107–114 (2012). Medline doi:10.1089/ast.2011.0646

71. V. I. Oyama, B. J. Berdahl, G. C. Carle, Preliminary findings of the Viking gas exchange experiment and a model for martian surface chemistry. *Nature* **265**, 110–114 (1977). doi:10.1038/265110a0

72. H. P. Klein, The Viking Biological Investigation, General aspects. *J. Geophys. Res.* **82**, 4677–4680 (1977). doi:10.1029/JS082i028p04677

73. M. H. Hecht, S. P. Kounaves, R. C. Quinn, S. J. West, S. M. Young, D. W. Ming, D. C. Catling, B. C. Clark, W. V. Boynton, J. Hoffman, L. P. Deflores, K. Gospodinova, J. Kapit, P. H. Smith, Detection of perchlorate and the soluble chemistry of martian soil at the Phoenix lander site. *Science* **325**, 64–67 (2009). Medline

74. S. W. Squyres, A. H. Knoll, Sedimentary rocks and Meridiani Planum: Origin, diagenesis, and implications for life of Mars. *Earth Planet. Sci. Lett.* **240**, 1–10 (2005). doi:10.1016/j.epsl.2005.09.038

75. L. A. Leshin, P. R. Mahaffy, C. R. Webster, M. Cabane, P. Coll, P. G. Conrad, P. D. Archer Jr., S. K. Atreya, A. E. Brunner, A. Buch, J. L. Eigenbrode, G. J. Flesch, H. B. Franz, C. Freissinet, D. P. Glavin, A. C. McAdam, K. E. Miller, D. W. Ming, R. V. Morris, R. Navarro-González, P. B. Niles, T. Owen, R. O. Pepin, S. Squyres, A. Steele, J. C. Stern, R. E. Summons, D. Y. Sumner, B. Sutter, C. Szopa, S. Teinturier, M. G. Trainer, J. J. Wray, J. P. Grotzinger; MSL Science Team, Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity rover. *Science* **341**, 1238937 (2013). doi:10.1126/science.1238937

76. R. E. Milliken, G. A. Swayze, R. E. Arvidson, J. L. Bishop, R. N. Clark, B. L. Ehlmann, R. O. Green, J. P. Grotzinger, R. V. Morris, S. L. Murchie, J. F. Mustard, C. Weitz, Opaline silica in young deposits on Mars. *Geology* **36**, 847–850 (2008). doi:10.1130/G24967A.1

77. R. V. Morris, G. Klingelhöfer, C. Schröder, D. S. Rodionov, A. Yen, D. W. Ming, P. A. de Souza Jr., I. Fleischer, T. Wdowiak, R. Gellert, B. Bernhardt, E. N. Evlanov, B. Zubkov, J. Foh, U. Bonnes, E. Kankeleit, P. Gütlich, F. Renz, S. W. Squyres, R. E. Arvidson, Mössbauer mineralogy of rock, soil, and dust at Gusev crater, Mars: Spirit's journey through weakly altered olivine basalt on the plains and pervasively altered basalt in the Columbia Hills. *J. Geophys. Res. Planets* **111**, E02S13 (2006). doi:10.1029/2005JE002584

78. R. V. Morris *et al*., Mossbauer mineralogy of rock, soil, and dust at Meridiani Planum, Mars: Opportunity's journey across sulfate-rich outcrop, basaltic sand and dust, and hematite lag deposits. *J. Geophys. Res.* **111**, E12S15 (2006).

79. J. F. Bell 3rd, S. W. Squyres, R. E. Arvidson, H. M. Arneson, D. Bass, W. Calvin, W. H. Farrand, W. Goetz, M. Golombek, R. Greeley, J. Grotzinger, E. Guinness, A. G. Hayes, M. Y. Hubbard, K. E. Herkenhoff, M. J. Johnson, J. R. Johnson, J. Joseph, K. M. Kinch, M. T. Lemmon, R. Li, M. B. Madsen, J. N. Maki, M. Malin, E. McCartney, S. McLennan, H. Y. McSween Jr., D. W. Ming, R. V. Morris, E. Z. Dobrea, T. J. Parker, J. Proton, J. W. Rice Jr., F. Seelos, J. M. Soderblom, L. A. Soderblom, J. N. Sohl-Dickstein, R. J. Sullivan, C. M. Weitz, M. J. Wolff, Pancam multispectral imaging results from the

Opportunity Rover at Meridiani Planum. *Science* **306**, 1703–1709 (2004). doi:10.1126/science.1105245

80. R. M. Cornell, U. Schwertmann, *The Iron Oxides: Structure, Properties, Reactions, Occurrence and Uses* (Wiley-VCH, Weinheim, Germany, ed. 2, 2003).

81. G. N. Schrauzer, T. D. Guth, Hydrogen evolving systems. 1. The formation of molecular hydrogen from aqueous suspensions of iron(II) hydroxide and reactions with reducible substrates, including molecular nitrogen. *J. Am. Chem. Soc.* **98**, 3508–3513 (1976). doi:10.1021/ja00428a019

82. W. D. Grant, Life at low water activity. *Philos. Trans. R. Soc. London Ser. B* **359**, 1249–1267 (2004). Medline doi:10.1098/rstb.2004.1502

83. A. H. Knoll, J. Grotzinger, Water on Mars and the prospect of martian life. *Elements* **2**, 169–173 (2006). doi:10.2113/gselements.2.3.169

84. J. P. Williams, J. E. Hallsworth, Limits of life in hostile environments: No barriers to biosphere function? *Environ. Microbiol.* **11**, 3292–3308 (2009). Medline doi:10.1111/j.1462-2920.2009.02079.x

85. N. J. Tosca, A. H. Knoll, S. M. McLennan, Water activity and the challenge for life on early Mars. *Science* **320**, 1204–1207 (2008). doi:10.1126/science.1155432

86. S. Fendrihan, M. Dornmayr-Pfaffenhuemer, F. W. Gerbl, A. Holzinger, M. Grösbacher, P. Briza, A. Erler, C. Gruber, K. Plätzer, H. Stan-Lotter, Spherical particles of halophilic archaea correlate with exposure to low water activity—implications for microbial survival in fluid inclusions of ancient halite. *Geobiology* **10**, 424–433 (2012). Medline doi:10.1111/j.1472-4669.2012.00337.x

87. C. Demergasso, E. O. Casamayor, G. Chong, P. Galleguillos, L. Escudero, C. Pedrós-Alió, Distribution of prokaryotic genetic diversity in athalassohaline lakes of the Atacama Desert, Northern Chile. *FEMS Microbiol. Ecol.* **48**, 57–69 (2004). Medline doi:10.1016/j.femsec.2003.12.013

88. A. Kish, G. Kirkali, C. Robinson, R. Rosenblatt, P. Jaruga, M. Dizdaroglu, J. DiRuggiero, Salt shield: Intracellular salts provide cellular protection against ionizing radiation in the halophilic archaeon, Halobacterium salinarum NRC-1. *Environ. Microbiol.* **11**, 1066–1078 (2009). Medline doi:10.1111/j.1462-2920.2008.01828.x

89. L. R. Dartnell, L. Desorgher, J. M. Ward, A. J. Coates, Modelling the surface and subsurface martian radiation environment: Implications for astrobiology. *Geophys. Res. Lett.* **34**, L02207 (2007). doi:10.1029/2006GL027494

90. A. I. López-Archilla, I. Marin, R. Amils, Microbial community composition and ecology of an acidic aquatic environment: The Tinto River, Spain. *Microb. Ecol.* **41**, 20–35 (2001). Medline

91. J.-P. Bibring, Y. Langevin, J. F. Mustard, F. Poulet, R. Arvidson, A. Gendrin, B. Gondet, N. Mangold, P. Pinet, F. Forget, M. Berthé, J. P. Bibring, A. Gendrin, C. Gomez, B. Gondet, D. Jouglet, F. Poulet, A. Soufflot, M. Vincendon, M. Combes, P. Drossart, T. Encrenaz, T. Fouchet, R. Merchiorri, G. Belluci, F. Altieri, V. Formisano, F. Capaccioni, P. Cerroni, A. Coradini, S. Fonti, O. Korablev, V. Kottsov, N. Ignatiev, V. Moroz, D. Titov,

L. Zasova, D. Loiseau, N. Mangold, P. Pinet, S. Douté, B. Schmitt, C. Sotin, E. Hauber, H. Hoffmann, R. Jaumann, U. Keller, R. Arvidson, J. F. Mustard, T. Duxbury, F. Forget, G. Neukum, Global mineralogical and aqueous mars history derived from OMEGA/Mars Express data. *Science* **312**, 400–404 (2006). doi:10.1126/science.1122659

92. T. F. Bristow, R. E. Milliken, Terrestrial perspective on authigenic clay mineral production in ancient martian lakes. *Clays Clay Miner.* **59**, 339–358 (2011). doi:10.1346/CCMN.2011.0590401

93. S. L. Murchie, J. F. Mustard, B. L. Ehlmann, R. E. Milliken, J. L. Bishop, N. K. McKeown, E. Z. Noe Dobrea, F. P. Seelos, D. L. Buczkowski, S. M. Wiseman, R. E. Arvidson, J. J. Wray, G. Swayze, R. N. Clark, D. J. Des Marais, A. S. McEwen, J.-P. Bibring, A synthesis of martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. *J. Geophys. Res. Planets* **114**, E00D06 (2009). doi:10.1029/2009JE003342

94. A. G. Fairén, V. Chevrier, O. Abramov, G. A. Marzo, P. Gavin, A. F. Davila, L. L. Tornabene, J. L. Bishop, T. L. Roush, C. Gross, T. Kneissl, E. R. Uceda, J. M. Dohm, D. Schulze-Makuch, J. A. Rodríguez, R. Amils, C. P. McKay, Noachian and more recent phyllosilicates in impact craters on Mars. *Proc. Natl. Acad. Sci. U.S.A.* **107**, 12095–12100 (2010). Medline doi:10.1073/pnas.1002889107

95. H. L. James, A. F. Trendall, Banded iron formation: Distribution in time and paleoenvironmental significance, *Mineral Deposits and the Evolution of the Biosphere: Dahlem Workshop Report*, H. D. Holland, A. M. Schidlowski, Eds. (Springer, Berlin, Heidelberg, New York, 1982), vol. 3.

96. A. Bekker, J. F. Slack, N. Planavsky, B. Krapez, A. Hofmann, K. O. Konhauser, O. J. Rouxel, Iron formation: The sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric processes. *Econ. Geol.* **105**, 467–508 (2010). doi:10.2113/gsecongeo.105.3.467

97. J. P. Grotzinger, in *Controls on Carbonate Platforms and Basin Development*, P. D. Crevello, J. L. Wilson, J. F. Sarg, J. F. Read, Eds. (SEPM Special Publication, Tulsa, OK, 1989), vol. 44, pp. 79–106.

98. J. P. Grotzinger, N. P. James, in *Carbonate Sedimentation and Diagenesis in the Evolving Precambrian World*, J. P. Grotzinger, N. P. James, Eds. (SEPM Special Publication, Tulsa, OK, 2000), vol. 67, pp. 3–20.

99. K. W. Lewis, O. Aharonson, J. P. Grotzinger, R. L. Kirk, A. S. McEwen, T. A. Suer, Quasi-periodic bedding in the sedimentary rock record of Mars. *Science* **322**, 1532–1535 (2008). doi:10.1126/science.1161870

100. R. C. Anderson, L. Jandura, A. B. Okon, D. Sunshine, C. Roumeliotis, L. W. Beegle, J. Hurowitz, B. Kennedy, D. Limonadi, S. McCloskey, M. Robinson, C. Seybold, K. Brown, Collecting samples in Gale crater, Mars; an Overview of the Mars Science Laboratory sample acquisition, sample processing and handling system. *Space Sci. Rev.* **170**, 57–75 (2012). doi:10.1007/s11214-012-9898-9