

Supplementary Material for

The Imprint of Atmospheric Evolution in the D/H of Hesperian Clay Minerals on Mars

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Materials and Methods

Experiment Design

The instruments of the Sample Analysis at Mars (SAM) suite (8) on the Mars Science Laboratory "Curiosity" rover utilized for the multi-step experiment described as the "combustion" experiment because a small volume of O₂ was added at one step in this process, are the quadrupole mass spectrometer (QMS) and the tunable laser spectrometer (TLS). Descriptions of both instruments are described in an earlier publication (8) and the details of data methods and processing described in the Supplemental Material to two recent Science publications (9, 10). The SAM sample manipulation system enabled a quartz cup to be hermetically sealed in an oven and heated to a preset temperature to release gases for analysis. Blank experiments consisted of heating an empty cup and monitoring the evolved gases. Triple portions of powdered sample sieved to a size of <150 microns were delivered to the quartz cup for this experiment using the rover arm's portioning hardware, following acquisition of the powdered sample with the rotary percussive drill. The estimate of the total sample mass delivered from experiments utilizing a testbed drill/sieve system and an analog mudstone was 135 ± 18 mg. Fig. S1 illustrates the elements of the SAM gas processing system.

The combustion experiment required 4 steps over 3 sols uploaded to the SAM instrument suite and executed on sequential sols (martian days). The experiment series was designed to convert reduced carbon to CO₂ for TLS measurements so oxygen from an internal SAM tank was introduced to the manifold and exposed to the sample in selected steps of this experiment. On the first sol the cup with its triple portion of fresh sample was heated to 550°C held for 25 minutes at this temperature and the evolved water measured with the TLS. In this step no oxygen was introduced to the manifold because substantial oxygen was expected from the decomposition of the oxychloride compounds previously detected (28) in these samples. The manifolds and the TLS were then evacuated using the SAM turbomolecular pump. On sol 2 the sample was reheated to 550°C in the presence of ~3.7 micromoles of oxygen. Evolved water was measured with the TLS and a full mass spectrum secured with the QMS. The manifold was then evacuated, the same volume of oxygen again reintroduced to the manifold and over the sample in the cup and the cup heated to ~920°C with again measurements made by both the QMS and TLS. On the third sol the cup was reheated to 920°C with oxygen again introduced over the sample.

Supplementary Text

TLS-SAM Data Processing:

The TLS data were processed according to the detailed description given in the supplemental material in (48). The method involves determining volume mixing ratios for each spectral line and comparing with those calculated using the HITRAN 2012 database (49) for the same conditions of pressure, temperature, path length, spectral laser width, etc. The comparison is made between the integrated areas of the lines to generate mixing ratios of each isotopic component that are then compared to produce isotope ratios. We note that the TLS was calibrated pre-launch by recording spectra for a known water standard "Boulder water" whose isotopic ratios were determined by standard

Isotope Ratio Mass Spectrometry (IRMS). Calibration "multipliers" for the HITRAN 2012 comparison were very close to unity. Although the calibration water sample is somewhat depleted in deuterium (-110 ‰)¹, the large dynamic range of the TLS direct absorption method allows large enrichments to be reliably recorded and measured. In both pyrolysis and combustion evolved gas analysis, TLS cell pressures range from a few mbar up to ~14 mbar, and the line shapes are predominantly Gaussian (Doppler broadening) but with a Lorenzian contribution from pressure broadening by both the target gas itself (self-broadening) and the host gas (foreign broadening) that is helium. Because HITRAN 2012 reports foreign broadening coefficients only for nitrogen broadening, we conducted careful lab measurements to (i) verify the self-broadening coefficients of each water line; and (ii) to determine the helium and carbon dioxide broadening vs that of nitrogen. Our HITRAN 2012 calculations are therefore refined to partition the "foreign" broadening into components from both He and CO₂ to better represent the evolved gas environment in which helium and water vapor are the dominant gases. We note that because of the low pressures of our measurements, this refinement, while more accurate, produces little change to the derived isotope ratios except in the case of significant water vapor. Fig. S2 illustrates the comparison of the observed vs. HITRAN line shapes for the case of highest water abundance, namely the combustion Step 1. Figure S3 compares the observed TLS spectra for low-temperature Cumberland and combustion Step 3 with the HITRAN spectra generated with terrestrial isotope ratios.

Updates to TLS-SAM EGA D/H results:

We earlier reported TLS D/H values for water evolved during pyrolysis of fine-grained material from Rocknest, an Aeolian sand shadow, as published in Science by Webster et al. 2013 (9) and by Leshin et al. 2013 (39). More recently, we have improved our data processing tools as described above to better include self- and foreign-broadening contributions. These improvements do not change the published values in (9) for the D/H of atmospheric water vapor or those of the various isotope ratios in atmospheric carbon dioxide (9), but do lower values of D/H for the EGA pyrolysis results of Rocknest in which helium is the main foreign broadening gas and self-broadening by water is significant. In Table S1 below we provide new results that update and correct the earlier values given in (9) and (39).

We note that during the pyrolysis EGA runs listed above the oven temperature is continually ramped during which a cut is given to TLS for analysis. We consider the low temperature results for Rocknest-3 and Cumberland-2 as representative of the D/H value of adsorbed/interstitial water. However, the high temperature D/H results are always higher than the true structural values since our measured values are a combination of both residual low temperature adsorbed/interstitial water and the higher temperature structural water components. The stepped heating combustion experiments avoid contamination by low temperature water release.

Evolved H₂ contributions to the D/H:

 H_2 is the second most abundant hydrogen-containing molecule released from Cumberland samples in evolved gas experiments and the only released compound containing hydrogen (such as H_2S or chlorinated organic compounds) present in sufficient abundance to impact the high temperature D/H ratio. Fig. S4 illustrates behavior typical of evolved m/z 2 and m/z3 in separate EGA experiments with a continuous ramp. As previously reported (28) an average of 6.7 μ mol/portion of H_2 were

released from the four Cumberland samples leading to an expectation that 20.2 μ mol would have been released from the triple portion delivered for this stepped heating experiment. However, since less than 1.5 μ mol was detected by the QMS in steps 2-4 of the combustion experiment it is clear that the most of the evolved H₂ reacted with the terrestrial O₂ over the hot sample to produce additional water.

The δD of the EGA $\rm H_2$ for six separate experiments (1954 ± 600 ‰) is the same within experimental error as the δD of the high temperature $\rm H_2O$. In addition, an average of 1.4 µmoles of $\rm H_2$ were released in three blank experiments from the SAM oven at high temperatures. Terrestrial D/H from oven wall outgassing serves to lower the measured dD and the required correction is included in the weighted average δD in Table S2. The dD in the evolved $\rm H_2$ from the previous EGA experiments can be established from the QMS measured mass 3/2 ratio with small $\rm H_3^+$ corrections established from measurements on the SAM testbed. Combining the mole weighted $\rm H_2O$ and $\rm H_2$ dD measurements does not substantially change the dD secured from $\rm H_2O$ alone. Inclusion of the background terrestrial $\rm H_2$ outgassed from the oven gives a dD that is higher than without this correction. The good agreement between water released during the second heating to 550°C and on heating to 920°C indicates that the low temperature water was completely eliminated before the high temperature measurements in the combustion experiment.

The mole weighted mean of the δD of H_2O is 1920 ± 51 ‰. The contribution of lesser amounts of H_2 that also is released at high temperatures must also be considered to establish the overall δD of hydrogen containing gases released at $550^{\circ}C$ or above. The observation that the water released during the second heating to $550^{\circ}C$ gives essentially the same δD value as $920^{\circ}C$ water release and the residual water that is released on a second heating to $920^{\circ}C$ (Table S1) gives us confidence that the low temperature adsorbed, smectite interlayer, and structural water from non-clay mineral phases was fully released in the first $550^{\circ}C$ treatment and that the high temperature dehydroxylation of the structural smectite OH gives the D/H of this strongly bound component. After including the mole weighted average δD from both H_2O and the small volume of H_2 plus a small H_2 blank correction the overall high temperature δD is 2056 ± 60 ‰ or 3.06 x SMOW. Since the Step 2 water evolution with 2.9 x SMOW is not impacted by the higher temperature evolved hydrogen, a higher (double) weighting of this measurement leads to the reported 3.0 x SMOW value for the D/H of the water of formation of the sample.

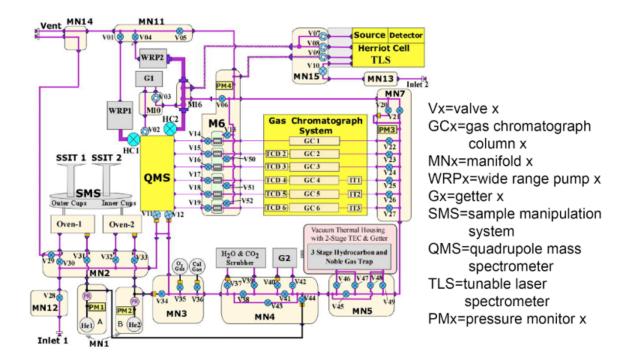


Fig. S1.The SAM gas flow diagram. Instruments and subsystems utilized for the combustion experiment are illustrated.

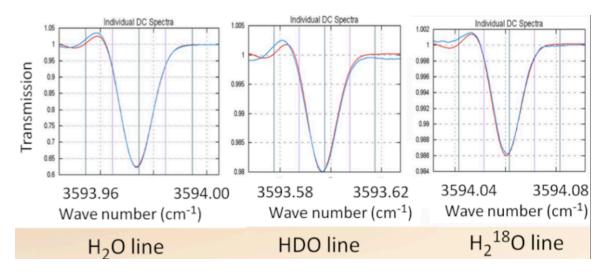


Fig. S2
TLS spectra fit to HITRAN. Comparison between spectral lines recorded by TLS during the first step of the combustion experiment, and those calculated from the HITRAN 2010 line list (48).

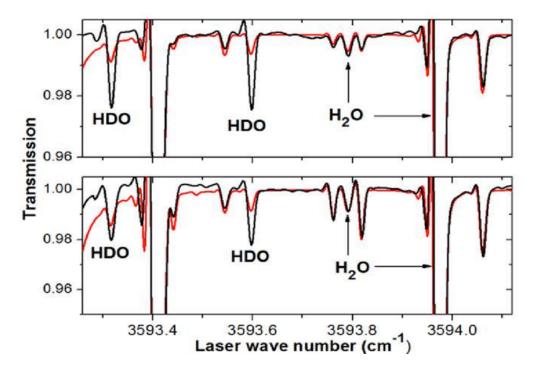


Fig. S3 TLS spectra comparison. (top) Water released during EGA analysis of the second Cumberland sample where a 87°C - 347°C temperature cut was introduced into the TLS giving a δD of $4,434 \pm 25$ ‰ is compared (bottom) with the TLS spectrum of the water released in step 3 of the combustion experiment (δD value of $1,941 \pm 45$ ‰).

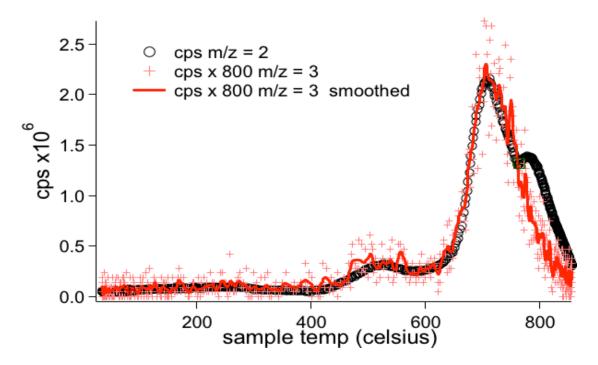


Fig. S4
Evolved H_2 (m/z 20) and HD (m/z 3) for one of the Cumberland EGA experiments. The solid trace gives the smoothed m/z 3 data since counting statistics produce scatter in this signal. The portion of the high temperature m/z 2 data that does not fall on the m/z 3 trace is presumed to be due to residual terrestrial H_2 from the SAM oven consistent with observation of evolved H_2 from the blank experiment.

Table S1. Updated TLS-SAM EGA results for water. For Rocknest 2, 3, and 4, these values correct those published earlier in (9) and (39). The full set of Cumberland results is included here for completeness. 2SEM represents 2 times the standard error from the mean in the data, and ERR is the final error that combines the 2SEM with other systematic errors e.g. from spectral line parameters.

| SAM EGA run name | Temperature cut (°C) | Sol | delta-D water ±2SEM | delta-D water ±ERR | D/H water ±ERR |
|---------------------|----------------------|-----|------------------------|-----------------------|-------------------|
| Rocknest-3 | 234-425 | 101 | 4,231 ±33 | 4,231 ±52 | 5.231 ±0.052 |
| Rocknest-4 | 350-443 | 117 | 3,568 ±49 | 3,568 ±63 | 4.568 ± 0.063 |
| Rocknest-2 | 440-601 | 96 | 3,633 ±38 | 3,633 ±55 | 4.633 ± 0.055 |
| Cumberland-2 | 87-347 | 286 | 4,434 ±25 | 4,434 ±47 | 5.434 ±0.047 |
| Cumberland-3 | 445-755 | 290 | 3,180 ±72 | 3,180 ±82 | 4.180 ± 0.082 |
| Cumberland-5 | 445-755 | 368 | 2,745 ±56 | 2,745 ±69 | 3.745 ± 0.069 |
| Cumberland-6 | 445-755 | 382 | 3,912 ±25 | 3,912 ±47 | 4.912 ±0.047 |
| Cumberland-7 | 157-495 | 415 | 3,859 ±35 | 3,859 ±53 | 4.859 ± 0.053 |
| Combustion Step 1 | 550 | 556 | 2,277 ±36 | 2,277 ±54 | 3.277 ±0.054 |
| Combustion Step 2 | 550 | 557 | 1,891 ±35 | 1,891 ±53 | 2.891 ±0.053 |
| Combustion Step 3 | 920 | 557 | 1,941 ±20 | 1,941 ±45 | 2.941 ±0.045 |
| Combustion Step 4 | 920 | 558 | 1,831 ±84 | 1,831 ±93 | 2.831 ±0.093 |

| Table S2. Water and hydrogen release. Quantities of water and hydrogen released in the combustion, EGA, and blank experiments and mole-averaged D/H values. | | | | |
|--|--|--|--|--|
| Combustion experiment: quantity of water released in steps 1-4. | Step 1: 60.1 μmoles Step 2: 4.9 μmoles Step 3: 14.6 μmoles Step 4: 1.8 μmoles | | | |
| Average quantity of hydrogen released per triple portion equivalent sample volume in 7 EGA Cumberland experiments and average δD | 20.2 μmoles 1954 ± 600 ‰ (2.95 x SMOW) | | | |
| Quantity of hydrogen released in a blank cup experiment. Mole weighted δD of H ₂ O from steps 2-4 from TLS measurement | 1.47 μmoles 1920 ± 51 ‰ (2.92 x SMOW) | | | |
| Mole weighted δD that includes H_2O from steps 2-4 evolved H_2 , and corrections for blank cup experiment H_2 (assumed to be terrestrial D/H and converted into H_2O). The blank correction increases the H_2O δD from the sample above that derived from H_2O alone. | 2056 ± 60 ‰ (3.06 x SMOW) | | | |
| Increased mole weighting of Step 2 D/H (550°C) where evolved H_2 does not come into play and estimates of additional systematic errors gives reported value. ¹ δD (‰) =1000 (R/R _{SMOW} -1), where R=D/H in sample, and R _{SMOW} =D/H in (1.558x10 ⁻⁴). | $\begin{array}{c} 2024 + 59 \% \\ (3.0 \pm 0.2) \text{ x SMOW} \end{array}$ in Standard Mean Ocean Water | | | |

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- 2. R. O. Pepin, Atmospheres on the terrestrial planets: Clues to origin and evolution. *Earth Planet. Sci. Lett.* **252**, 1–14 (2006). doi:10.1016/j.epsl.2006.09.014
- 3. H. Lammer, E. Chassefière, Ö. Karatekin, A. Morschhauser, P. B. Niles, O. Mousis, P. Odert, U. V. Möstl, D. Breuer, V. Dehant, M. Grott, H. Gröller, E. Hauber, L. B. S. Pham, Outgassing History and Escape of the Martian Atmosphere and Water Inventory. *Space Sci. Rev.* **174**, 113–154 (2013). doi:10.1007/s11214-012-9943-8
- 4. B. M. Jakosky, R. O. Pepin, R. E. Johnson, J. L. Fox, Mars atmospheric loss and isotopic fractionation by solar-wind-induced sputtering and photochemical escape. *Icarus* **111**, 271–288 (1994). doi:10.1006/icar.1994.1145
- 5. J. W. Head, R. Greeley, M. P. Golombek, W. K. Hartmann, E. Hauber, R. Jaumann, P. Masson, G. Neukum, L. E. Nyquist, M. H. Carr, Geological Processes and Evolution. *Space Sci. Rev.* **96**, 263–292 (2001). doi:10.1023/A:1011953424736
- 6. M. H. Carr, J. W. Head III, Geologic history of Mars. *Earth Planet. Sci. Lett.* **294**, 185–203 (2010). doi:10.1016/j.epsl.2009.06.042
- 7. M. H. Carr, J. W. Head, Oceans on Mars: An assessment of the observational evidence and possible fate. *J. Geophys. Res.* **108** (E5), 5042 (2003). doi:10.1029/2002JE001963
- 8. P. R. Mahaffy, C. R. Webster, M. Cabane, P. G. Conrad, P. Coll, S. K. Atreya, R. Arvey, M. Barciniak, M. Benna, L. Bleacher, W. B. Brinckerhoff, J. L. Eigenbrode, D. Carignan, M. Cascia, R. A. Chalmers, J. P. Dworkin, T. Errigo, P. Everson, H. Franz, R. Farley, S. Feng, G. Frazier, C. Freissinet, D. P. Glavin, D. N. Harpold, D. Hawk, V. Holmes, C. S.

- Johnson, A. Jones, P. Jordan, J. Kellogg, J. Lewis, E. Lyness, C. A. Malespin, D. K. Martin, J. Maurer, A. C. McAdam, D. McLennan, T. J. Nolan, M. Noriega, A. A. Pavlov, B. Prats, E. Raaen, O. Sheinman, D. Sheppard, J. Smith, J. C. Stern, F. Tan, M. Trainer, D. W. Ming, R. V. Morris, J. Jones, C. Gundersen, A. Steele, J. Wray, O. Botta, L. A. Leshin, T. Owen, S. Battel, B. M. Jakosky, H. Manning, S. Squyres, R. Navarro-González, C. P. McKay, F. Raulin, R. Sternberg, A. Buch, P. Sorensen, R. Kline-Schoder, D. Coscia, C. Szopa, S. Teinturier, C. Baffes, J. Feldman, G. Flesch, S. Forouhar, R. Garcia, D. Keymeulen, S. Woodward, B. P. Block, K. Arnett, R. Miller, C. Edmonson, S. Gorevan, E. Mumm, The Sample Analysis at Mars Investigation and Instrument Suite. *Space Sci. Rev.* 170, 401–478 (2012). doi:10.1007/s11214-012-9879-z
- 9. C. R. Webster, P. R. Mahaffy, G. J. Flesch, P. B. Niles, J. H. Jones, L. A. Leshin, S. K. Atreya, J. C. Stern, L. E. Christensen, T. Owen, H. Franz, R. O. Pepin, A. Steele, C. Achilles, C. Agard, J. A. Alves Verdasca, R. Anderson, R. Anderson, D. Archer, C. Armiens-Aparicio, R. Arvidson, E. Atlaskin, A. Aubrey, B. Baker, M. Baker, T. Balic-Zunic, D. Baratoux, J. Baroukh, B. Barraclough, K. Bean, L. Beegle, A. Behar, J. Bell, S. Bender, M. Benna, J. Bentz, G. Berger, J. Berger, D. Berman, D. Bish, D. F. Blake, J. J. Blanco Avalos, D. Blaney, J. Blank, H. Blau, L. Bleacher, E. Boehm, O. Botta, S. Böttcher, T. Boucher, H. Bower, N. Boyd, B. Boynton, E. Breves, J. Bridges, N. Bridges, W. Brinckerhoff, D. Brinza, T. Bristow, C. Brunet, A. Brunner, W. Brunner, A. Buch, M. Bullock, S. Burmeister, M. Cabane, F. Calef, J. Cameron, J. Campbell, B. Cantor, M. Caplinger, J. Caride Rodríguez, M. Carmosino, I. Carrasco Blázquez, A. Charpentier, S. Chipera, D. Choi, B. Clark, S. Clegg, T. Cleghorn, E. Cloutis, G. Cody, P. Coll, P. Conrad, D. Coscia, A. Cousin, D. Cremers, J. Crisp, A. Cros, F. Cucinotta, C. d'Uston, S. Davis, M. Dav, M. de la Torre Juarez, L. DeFlores, D. DeLapp, J. DeMarines, D. DesMarais, W. Dietrich, R. Dingler, C. Donny, B. Downs, D. Drake, G. Dromart, A. Dupont, B. Duston, J. Dworkin, M. D. Dyar, L. Edgar, K. Edgett, C. Edwards, L. Edwards, B. Ehlmann, B. Ehresmann, J. Eigenbrode, B. Elliott, H. Elliott, R. Ewing, C. Fabre, A. Fairén, K. Farley, J. Farmer, C. Fassett, L. Favot, D. Fay, F. Fedosov, J. Feldman, S. Feldman, M. Fisk, M. Fitzgibbon, M. Floyd, L. Flückiger, O. Forni, A. Fraeman, R. Francis, P. François, C. Freissinet, K. L. French, J. Frydenvang, A. Gaboriaud, M. Gailhanou, J. Garvin, O. Gasnault, C. Geffroy, R. Gellert, M. Genzer, D. Glavin, A. Godber, F. Goesmann, W. Goetz, D. Golovin, F. Gómez Gómez, J. Gómez-Elvira, B. Gondet, S. Gordon, S. Gorevan, J. Grant, J. Griffes, D. Grinspoon, J. Grotzinger, P. Guillemot, J. Guo, S. Gupta, S. Guzewich, R. Haberle, D. Halleaux, B. Hallet, V. Hamilton, C. Hardgrove, D. Harker, D. Harpold, A. M. Harri, K. Harshman, D. Hassler, H. Haukka, A. Hayes, K. Herkenhoff, P. Herrera, S. Hettrich, E. Heydari, V. Hipkin, T. Hoehler, J. Hollingsworth, J. Hudgins, W. Huntress, J. Hurowitz, S. Hviid, K. Iagnemma, S. Indyk, G. Israël, R. Jackson, S. Jacob, B. Jakosky, E. Jensen, J. K. Jensen, J. Johnson, M. Johnson, S. Johnstone, A. Jones, J. Joseph, I. Jun, L. Kah, H. Kahanpää, M. Kahre, N. Karpushkina, W. Kasprzak, J. Kauhanen, L. Keely, O. Kemppinen, D. Keymeulen, M. H. Kim, K. Kinch, P. King, L. Kirkland, G. Kocurek, A. Koefoed, J. Köhler, O. Kortmann, A. Kozyrev, J. Krezoski, D. Krysak, R. Kuzmin, J. L. Lacour, V. Lafaille, Y. Langevin, N. Lanza, J. Lasue, S. Le Mouélic, E. M. Lee, Q. M. Lee, D. Lees, M. Lefavor, M. Lemmon, A. Lepinette Malvitte, R. Léveillé, É. Lewin-Carpintier, K. Lewis, S. Li, L. Lipkaman, C. Little, M. Litvak, E. Lorigny, G. Lugmair, A. Lundberg, E. Lyness, M. Madsen, J. Maki, A. Malakhov, C. Malespin, M. Malin, N. Mangold, G.

Manhes, H. Manning, G. Marchand, M. Marín Jiménez, C. Martín García, D. Martin, M. Martin, J. Martínez-Frías, J. Martín-Soler, F. J. Martín-Torres, P. Mauchien, S. Maurice, A. McAdam, E. McCartney, T. McConnochie, E. McCullough, I. McEwan, C. McKay, S. McLennan, S. McNair, N. Melikechi, P. Y. Meslin, M. Meyer, A. Mezzacappa, H. Miller, K. Miller, R. Milliken, D. Ming, M. Minitti, M. Mischna, I. Mitrofanov, J. Moersch, M. Mokrousov, A. Molina Jurado, J. Moores, L. Mora-Sotomayor, J. M. Morookian, R. Morris, S. Morrison, R. Mueller-Mellin, J. P. Muller, G. Muñoz Caro, M. Nachon, S. Navarro López, R. Navarro-González, K. Nealson, A. Nefian, T. Nelson, M. Newcombe, C. Newman, H. Newsom, S. Nikiforov, B. Nixon, E. Noe Dobrea, T. Nolan, D. Oehler, A. Ollila, T. Olson, M. Á. de Pablo Hernández, A. Paillet, E. Pallier, M. Palucis, T. Parker, Y. Parot, K. Patel, M. Paton, G. Paulsen, A. Pavlov, B. Pavri, V. Peinado-González, L. Peret, R. Perez, G. Perrett, J. Peterson, C. Pilorget, P. Pinet, J. Pla-García, I. Plante, F. Poitrasson, J. Polkko, R. Popa, L. Posiolova, A. Posner, I. Pradler, B. Prats, V. Prokhorov, S. W. Purdy, E. Raaen, L. Radziemski, S. Rafkin, M. Ramos, E. Rampe, F. Raulin, M. Ravine, G. Reitz, N. Rennó, M. Rice, M. Richardson, F. Robert, K. Robertson, J. A. Rodriguez Manfredi, J. J. Romeral-Planelló, S. Rowland, D. Rubin, M. Saccoccio, A. Salamon, J. Sandoval, A. Sanin, S. A. Sans Fuentes, L. Saper, P. Sarrazin, V. Sautter, H. Savijärvi, J. Schieber, M. Schmidt, W. Schmidt, D. Scholes, M. Schoppers, S. Schröder, S. Schwenzer, E. Sebastian Martinez, A. Sengstacken, R. Shterts, K. Siebach, T. Siili, J. Simmonds, J. B. Sirven, S. Slavney, R. Sletten, M. Smith, P. Sobrón Sánchez, N. Spanovich, J. Spray, S. Squyres, K. Stack, F. Stalport, T. Stein, N. Stewart, S. L. Stipp, K. Stoiber, E. Stolper, B. Sucharski, R. Sullivan, R. Summons, D. Sumner, V. Sun, K. Supulver, B. Sutter, C. Szopa, F. Tan, C. Tate, S. Teinturier, I. ten Kate, P. Thomas, L. Thompson, R. Tokar, M. Toplis, J. Torres Redondo, M. Trainer, A. Treiman, V. Tretyakov, R. Urqui-O'Callaghan, J. Van Beek, T. Van Beek, S. VanBommel, D. Vaniman, A. Varenikov, A. Vasavada, P. Vasconcelos, E. Vicenzi, A. Vostrukhin, M. Voytek, M. Wadhwa, J. Ward, E. Weigle, D. Wellington, F. Westall, R. C. Wiens, M. B. Wilhelm, A. Williams, J. Williams, R. Williams, R. B. Williams, M. Wilson, R. Wimmer-Schweingruber, M. Wolff, M. Wong, J. Wray, M. Wu, C. Yana, A. Yen, A. Yingst, C. Zeitlin, R. Zimdar, M. P. Zorzano Mier; MSL Science Team, Isotope ratios of H, C, and O in CO2 and H2O of the martian atmosphere. Science 341, 260–263 (2013). Medline doi:10.1126/science.1237961

P. R. Mahaffy, C. R. Webster, S. K. Atreya, H. Franz, M. Wong, P. G. Conrad, D. Harpold, J. J. Jones, L. A. Leshin, H. Manning, T. Owen, R. O. Pepin, S. Squyres, M. Trainer, O. Kemppinen, N. Bridges, J. R. Johnson, M. Minitti, D. Cremers, J. F. Bell, L. Edgar, J. Farmer, A. Godber, M. Wadhwa, D. Wellington, I. McEwan, C. Newman, M. Richardson, A. Charpentier, L. Peret, P. King, J. Blank, G. Weigle, M. Schmidt, S. Li, R. Milliken, K. Robertson, V. Sun, M. Baker, C. Edwards, B. Ehlmann, K. Farley, J. Griffes, J. Grotzinger, H. Miller, M. Newcombe, C. Pilorget, M. Rice, K. Siebach, K. Stack, E. Stolper, C. Brunet, V. Hipkin, R. Leveille, G. Marchand, P. S. Sanchez, L. Favot, G. Cody, A. Steele, L. Fluckiger, D. Lees, A. Nefian, M. Martin, M. Gailhanou, F. Westall, G. Israel, C. Agard, J. Baroukh, C. Donny, A. Gaboriaud, P. Guillemot, V. Lafaille, E. Lorigny, A. Paillet, R. Perez, M. Saccoccio, C. Yana, C. Armiens-Aparicio, J. C. Rodriguez, I. C. Blazquez, F. G. Gomez, J. Gomez-Elvira, S. Hettrich, A. L. Malvitte, M. M. Jimenez, J. Martinez-Frias, J. Martin-Soler, F. J. Martin-Torres, A. M. Jurado, L. Mora-Sotomayor, G. M. Caro, S. N. Lopez, V. Peinado-Gonzalez, J. Pla-Garcia, J. A. R.

Manfredi, J. J. Romeral-Planello, S. A. S. Fuentes, E. S. Martinez, J. T. Redondo, R. Urqui-O'Callaghan, M.-P. Z. Mier, S. Chipera, J.-L. Lacour, P. Mauchien, J.-B. Sirven, A. Fairen, A. Hayes, J. Joseph, R. Sullivan, P. Thomas, A. Dupont, A. Lundberg, N. Melikechi, A. Mezzacappa, J. DeMarines, D. Grinspoon, G. Reitz, B. Prats, E. Atlaskin, M. Genzer, A.-M. Harri, H. Haukka, H. Kahanpaa, J. Kauhanen, O. Kemppinen, M. Paton, J. Polkko, W. Schmidt, T. Siili, C. Fabre, J. Wray, M. B. Wilhelm, F. Poitrasson, K. Patel, S. Gorevan, S. Indyk, G. Paulsen, S. Gupta, D. Bish, J. Schieber, B. Gondet, Y. Langevin, C. Geffroy, D. Baratoux, G. Berger, A. Cros, C. d'Uston, O. Forni, O. Gasnault, J. Lasue, Q.-M. Lee, S. Maurice, P.-Y. Meslin, E. Pallier, Y. Parot, P. Pinet, S. Schroder, M. Toplis, E. Lewin, W. Brunner, E. Heydari, C. Achilles, D. Oehler, B. Sutter, M. Cabane, D. Coscia, G. Israel, C. Szopa, G. Dromart, F. Robert, V. Sautter, S. Le Mouelic, N. Mangold, M. Nachon, A. Buch, F. Stalport, P. Coll, P. Francois, F. Raulin, S. Teinturier, J. Cameron, S. Clegg, A. Cousin, D. DeLapp, R. Dingler, R. S. Jackson, S. Johnstone, N. Lanza, C. Little, T. Nelson, R. C. Wiens, R. B. Williams, A. Jones, L. Kirkland, A. Treiman, B. Baker, B. Cantor, M. Caplinger, S. Davis, B. Duston, K. Edgett, D. Fay, C. Hardgrove, D. Harker, P. Herrera, E. Jensen, M. R. Kennedy, G. Krezoski, D. Krysak, L. Lipkaman, M. Malin, E. McCartney, S. McNair, B. Nixon, L. Posiolova, M. Ravine, A. Salamon, L. Saper, K. Stoiber, K. Supulver, J. Van Beek, T. Van Beek, R. Zimdar, K. L. French, K. Iagnemma, K. Miller, R. Summons, F. Goesmann, W. Goetz, S. Hviid, M. Johnson, M. Lefavor, E. Lyness, E. Breves, M. D. Dyar, C. Fassett, D. F. Blake, T. Bristow, D. DesMarais, L. Edwards, R. Haberle, T. Hoehler, J. Hollingsworth, M. Kahre, L. Keely, C. McKay, M. B. Wilhelm, L. Bleacher, W. Brinckerhoff, D. Choi, J. P. Dworkin, J. Eigenbrode, M. Floyd, C. Freissinet, J. Garvin, D. Glavin, A. Jones, D. K. Martin, A. McAdam, A. Pavlov, E. Raaen, M. D. Smith, J. Stern, F. Tan, M. Meyer, A. Posner, M. Voytek, R. C. Anderson, A. Aubrey, L. W. Beegle, A. Behar, D. Blaney, D. Brinza, F. Calef, L. Christensen, J. A. Crisp, L. DeFlores, B. Ehlmann, J. Feldman, S. Feldman, G. Flesch, J. Hurowitz, I. Jun, D. Keymeulen, J. Maki, M. Mischna, J. M. Morookian, T. Parker, B. Pavri, M. Schoppers, A. Sengstacken, J. J. Simmonds, N. Spanovich, M. T. Juarez, A. R. Vasavada, A. Yen, P. D. Archer, F. Cucinotta, D. Ming, R. V. Morris, P. Niles, E. Rampe, T. Nolan, M. Fisk, L. Radziemski, B. Barraclough, S. Bender, D. Berman, E. N. Dobrea, R. Tokar, D. Vaniman, R. M. E. Williams, A. Yingst, K. Lewis, T. Cleghorn, W. Huntress, G. Manhes, J. Hudgins, T. Olson, N. Stewart, P. Sarrazin, J. Grant, E. Vicenzi, S. A. Wilson, M. Bullock, B. Ehresmann, V. Hamilton, D. Hassler, J. Peterson, S. Rafkin, C. Zeitlin, F. Fedosov, D. Golovin, N. Karpushkina, A. Kozyrev, M. Litvak, A. Malakhov, I. Mitrofanov, M. Mokrousov, S. Nikiforov, V. Prokhorov, A. Sanin, V. Tretvakov, A. Varenikov, A. Vostrukhin, R. Kuzmin, B. Clark, M. Wolff, S. McLennan, O. Botta, D. Drake, K. Bean, M. Lemmon, S. P. Schwenzer, R. B. Anderson, K. Herkenhoff, E. M. Lee, R. Sucharski, M. A. P. Hernandez, J. J. B. Avalos, M. Ramos, M.-H. Kim, C. Malespin, I. Plante, J.-P. Muller, R. Navarro-Gonzalez, R. Ewing, W. Boynton, R. Downs, M. Fitzgibbon, K. Harshman, S. Morrison, W. Dietrich, O. Kortmann, M. Palucis, D. Y. Sumner, A. Williams, G. Lugmair, M. A. Wilson, D. Rubin, B. Jakosky, T. Balic-Zunic, J. Frydenvang, J. K. Jensen, K. Kinch, A. Koefoed, M. B. Madsen, S. L. S. Stipp, N. Boyd, J. L. Campbell, R. Gellert, G. Perrett, I. Pradler, S. VanBommel, S. Jacob, S. Rowland, E. Atlaskin, H. Savijarvi, E. Boehm, S. Bottcher, S. Burmeister, J. Guo, J. Kohler, C. M. Garcia, R. Mueller-Mellin, R. Wimmer-Schweingruber, J. C.

- Bridges, T. McConnochie, M. Benna, H. Bower, A. Brunner, H. Blau, T. Boucher, M. Carmosino, H. Elliott, D. Halleaux, N. Renno, B. Elliott, J. Spray, L. Thompson, S. Gordon, H. Newsom, A. Ollila, J. Williams, P. Vasconcelos, J. Bentz, K. Nealson, R. Popa, L. C. Kah, J. Moersch, C. Tate, M. Day, G. Kocurek, B. Hallet, R. Sletten, R. Francis, E. McCullough, E. Cloutis, I. L. ten Kate, R. Kuzmin, R. Arvidson, A. Fraeman, D. Scholes, S. Slavney, T. Stein, J. Ward, J. Berger, J. E. Moores; MSL Science Team, Abundance and isotopic composition of gases in the martian atmosphere from the Curiosity rover. *Science* **341**, 263–266 (2013). Medline doi:10.1126/science.1237966
- 11. M. H. Wong, S. K. Atreya, P. N. Mahaffy, H. B. Franz, C. Malespin, M. G. Trainer, J. C. Stern, P. G. Conrad, H. L. K. Manning, R. O. Pepin, R. H. Becker, C. P. McKay, T. C. Owen, R. Navarro-González, J. H. Jones, B. M. Jakosky, A. Steele, Isotopes of nitrogen on Mars: Atmospheric measurements by Curiosity's mass spectrometer. *Geophys. Res. Lett.* 40, 6033–6037 (2013). doi:10.1002/2013GL057840
- 12. S. K. Atreya, M. G. Trainer, H. B. Franz, M. H. Wong, H. L. K. Manning, C. A. Malespin, P. R. Mahaffy, P. G. Conrad, A. E. Brunner, L. A. Leshin, J. H. Jones, C. R. Webster, T. C. Owen, R. O. Pepin, R. Navarro-González, Primordial argon isotope fractionation in the atmosphere of Mars measured by the SAM instrument on Curiosity and implications for atmospheric loss. *Geophys. Res. Lett.* 40, 5605–5609 (2013). doi:10.1002/2013GL057763
- 13. D. M. Hunten, M. B. Mcelroy, Production and Escape of Hydrogen on Mars. *J. Geophys. Res.* **75**, 5989–6001 (1970). doi:10.1029/JA075i031p05989
- 14. J. A. Grant, S. A. Wilson, N. Mangold, F. Calef III, J. P. Grotzinger, The timing of alluvial activity in Gale crater, Mars. *Geophys. Res. Lett.* **41**, 1142–1149 (2014). doi:10.1002/2013GL058909
- 15. 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
- 16. L. L. Deit, E. Hauber, F. Fueten, M. Pondrelli, A. P. Rossi, R. Jaumann, Sequence of infilling events in Gale Crater, Mars: Results from morphology, stratigraphy, and mineralogy. *J. Geophys. Res. Planets* **118**, 2439–2473 (2013). doi:10.1002/2012JE004322
- 17. T. F. B. Bristow, D.L.; Vaniman, D.T.; Morris, R.V.; Blake, D.F.; Grotzinger, J.P.; Rampe, E.B.; Crisp, J.A.; Achilles, C.N.; Ming, D.W.; Ehlmann, B.L.; King, P.L.; Bridges, J.; Eigenbrode, J.L.; Chipera, S.J.; Moorokian, J.M.' Treiman, A.; Morrison, S.; Downs, R.T.; Farmer, J.D.; Des Marais, D.; Sarrazin, P.; and Mischna, M.; The Origin and Implications of Clay Minerals from Yellowknife Bay, Gale Crater, Mars. *Am. Mineral.* (2015). 10.2138/am-2015-5229
- 18. S. M. F. G. Sheppard, H.A., Stable Isotope Geochemistry of Clay Minerals. *Clay Miner.* **31**, 1–24 (1996). doi:10.1180/claymin.1996.031.1.01
- 19. L. Leshin, Insights into martian water reservoirs from analyses of martian meteorite QUE 94201. *Geophys. Res. Lett.* **27**, 2017–2020 (2000). doi:10.1029/1999GL008455

- 20. J. P. Greenwood, S. Itoh, N. Sakamoto, E. P. Vicenzi, H. Yurimoto, Hydrogen isotope evidence for loss of water from Mars through time. *Geophys. Res. Lett.* **35**, 5203 (2008). doi:10.1029/2007GL032721
- 21. T. Usui, C. M. O. D. Alexander, J. Wang, J. I. Simon, J. H. Jones, Origin of water and mantle-crust interactions on Mars inferred from hydrogen isotopes and volatile element abundances of olivine-hosted melt inclusions of primitive shergottites. *Earth Planet. Sci. Lett.* **357**, 119–129 (2012). doi:10.1016/j.epsl.2012.09.008
- 22. H. Kurokawa, M. Sato, M. Ushioda, T. Matsuyama, R. Moriwaki, J. M. Dohm, T. Usui, Evolution of water reservoirs on Mars: Constraints from hydrogen isotopes in martian meteorites. *Earth Planet. Sci. Lett.* **394**, 179–185 (2014). doi:10.1016/j.epsl.2014.03.027
- 23. T. Owen, The Contributions of Comets to Planets, Atmospheres, and Life: Insights from Cassini-Huygens, Galileo, Giotto, and Inner Planet Missions. *Space Sci. Rev.* **138**, 301–316 (2008). doi:10.1007/s11214-008-9306-7
- 24. P. Eberhardt, M. Reber, D. Krankowsky, R. R. Hodges, The D/H and 18O/16O ratios in water from comet P/Halley. *Astron. Astrophys.* **302**, 301 (1995).
- 25. D. Bockelée-Morvan *et al.*, Deuterated water in comet C 1996 B2 (Hyakutake) and its implications for the origin of comets. *Icarus* **133**, 147–162 (1998). doi:10.1006/icar.1998.5916
- 26. R. Meier, T. C. Owen, D. C. Jewitt, H. E. Matthews, M. Senay, N. Biver, D. Bockel e-Morvan, J. Crovisier, D. Gautier, Deuterium in comet C/1995 O1 (Hale-Bopp): Detection of DCN. *Science* **279**, 1707–1710 (1998). Medline doi:10.1126/science.279.5357.1707
- 27. P. Hartogh, D. C. Lis, D. Bockelée-Morvan, M. de Val-Borro, N. Biver, M. Küppers, M. Emprechtinger, E. A. Bergin, J. Crovisier, M. Rengel, R. Moreno, S. Szutowicz, G. A. Blake, Ocean-like water in the Jupiter-family comet 103P/Hartley 2. *Nature* 478, 218–220 (2011). Medline doi:10.1038/nature10519
- 28. C. M. O. D. Alexander, R. Bowden, M. L. Fogel, K. T. Howard, C. D. Herd, L. R. Nittler, The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets. *Science* 337, 721–723 (2012). Medline doi:10.1126/science.1223474
- J. P. Grotzinger, D. Y. Sumner, L. C. Kah, K. Stack, S. Gupta, L. Edgar, D. Rubin, K. Lewis, J. Schieber, N. Mangold, R. Milliken, P. G. Conrad, D. DesMarais, J. Farmer, K. Siebach, F. Calef 3rd, J. Hurowitz, S. M. McLennan, D. Ming, D. Vaniman, J. Crisp, A. Vasavada, K. S. Edgett, M. Malin, D. Blake, R. Gellert, P. Mahaffy, R. C. Wiens, S. Maurice, J. A. Grant, S. Wilson, R. C. Anderson, L. Beegle, R. Arvidson, B. Hallet, R. S. Sletten, M. Rice, J. Bell 3rd, J. Griffes, B. Ehlmann, R. B. Anderson, T. F. Bristow, W. E. Dietrich, G. Dromart, J. Eigenbrode, A. Fraeman, C. Hardgrove, K. Herkenhoff, L. Jandura, G. Kocurek, S. Lee, L. A. Leshin, R. Leveille, D. Limonadi, J. Maki, S. McCloskey, M. Meyer, M. Minitti, H. Newsom, D. Oehler, A. Okon, M. Palucis, T. Parker, S. Rowland, M. Schmidt, S. Squyres, A. Steele, E. Stolper, R. Summons, A. Treiman, R. Williams, A. Yingst, M. S. Team, O. Kemppinen, N. Bridges, J. R. Johnson, D. Cremers, A. Godber, M. Wadhwa, D. Wellington, I. McEwan, C. Newman, M. Richardson, A. Charpentier, L. Peret, P. King, J. Blank, G. Weigle, S. Li, K. Robertson, V. Sun, M. Baker, C. Edwards, K. Farley, H. Miller, M. Newcombe, C. Pilorget, C. Brunet, V. Hipkin, R. Leveille, G. Marchand, P. S. Sanchez, L. Favot, G. Cody, L.

Fluckiger, D. Lees, A. Nefian, M. Martin, M. Gailhanou, F. Westall, G. Israel, C. Agard, J. Baroukh, C. Donny, A. Gaboriaud, P. Guillemot, V. Lafaille, E. Lorigny, A. Paillet, R. Perez, M. Saccoccio, C. Yana, C. Armiens-Aparicio, J. C. Rodriguez, I. C. Blazquez, F. G. Gomez, J. Gomez-Elvira, S. Hettrich, A. L. Malvitte, M. M. Jimenez, J. Martinez-Frias, J. Martin-Soler, F. J. Martin-Torres, A. M. Jurado, L. Mora-Sotomayor, G. M. Caro, S. N. Lopez, V. Peinado-Gonzalez, J. Pla-Garcia, J. A. R. Manfredi, J. J. Romeral-Planello, S. A. S. Fuentes, E. S. Martinez, J. T. Redondo, R. Urqui-O'Callaghan, M.-P. Z. Mier, S. Chipera, J.-L. Lacour, P. Mauchien, J.-B. Sirven, H. Manning, A. Fairen, A. Hayes, J. Joseph, R. Sullivan, P. Thomas, A. Dupont, A. Lundberg, N. Melikechi, A. Mezzacappa, J. DeMarines, D. Grinspoon, G. Reitz, B. Prats, E. Atlaskin, M. Genzer, A.-M. Harri, H. Haukka, H. Kahanpaa, J. Kauhanen, M. Paton, J. Polkko, W. Schmidt, T. Siili, C. Fabre, J. Wray, M. B. Wilhelm, F. Poitrasson, K. Patel, S. Gorevan, S. Indyk, G. Paulsen, D. Bish, B. Gondet, Y. Langevin, C. Geffroy, D. Baratoux, G. Berger, A. Cros, C. d'Uston, O. Forni, O. Gasnault, J. Lasue, Q.-M. Lee, P.-Y. Meslin, E. Pallier, Y. Parot, P. Pinet, S. Schroder, M. Toplis, E. Lewin, W. Brunner, E. Heydari, C. Achilles, B. Sutter, M. Cabane, D. Coscia, C. Szopa, F. Robert, V. Sautter, S. Le Mouelic, M. Nachon, A. Buch, F. Stalport, P. Coll, P. Francois, F. Raulin, S. Teinturier, J. Cameron, S. Clegg, A. Cousin, D. DeLapp, R. Dingler, R. S. Jackson, S. Johnstone, N. Lanza, C. Little, T. Nelson, R. B. Williams, A. Jones, L. Kirkland, B. Baker, B. Cantor, M. Caplinger, S. Davis, B. Duston, D. Fay, D. Harker, P. Herrera, E. Jensen, M. R. Kennedy, G. Krezoski, D. Krysak, L. Lipkaman, E. McCartney, S. McNair, B. Nixon, L. Posiolova, M. Ravine, A. Salamon, L. Saper, K. Stoiber, K. Supulver, J. Van Beek, T. Van Beek, R. Zimdar, K. L. French, K. Iagnemma, K. Miller, F. Goesmann, W. Goetz, S. Hviid, M. Johnson, M. Lefavor, E. Lyness, E. Breves, M. D. Dyar, C. Fassett, L. Edwards, R. Haberle, T. Hoehler, J. Hollingsworth, M. Kahre, L. Keely, C. McKay, L. Bleacher, W. Brinckerhoff, D. Choi, J. P. Dworkin, M. Floyd, C. Freissinet, J. Garvin, D. Glavin, D. Harpold, D. K. Martin, A. McAdam, A. Pavlov, E. Raaen, M. D. Smith, J. Stern, F. Tan, M. Trainer, A. Posner, M. Voytek, A. Aubrey, A. Behar, D. Blaney, D. Brinza, L. Christensen, L. DeFlores, J. Feldman, S. Feldman, G. Flesch, I. Jun, D. Keymeulen, M. Mischna, J. M. Morookian, B. Pavri, M. Schoppers, A. Sengstacken, J. J. Simmonds, N. Spanovich, M. T. Juarez, C. R. Webster, A. Yen, P. D. Archer, F. Cucinotta, J. H. Jones, R. V. Morris, P. Niles, E. Rampe, T. Nolan, M. Fisk, L. Radziemski, B. Barraclough, S. Bender, D. Berman, E. N. Dobrea, R. Tokar, T. Cleghorn, W. Huntress, G. Manhes, J. Hudgins, T. Olson, N. Stewart, P. Sarrazin, E. Vicenzi, M. Bullock, B. Ehresmann, V. Hamilton, D. Hassler, J. Peterson, S. Rafkin, C. Zeitlin, F. Fedosov, D. Golovin, N. Karpushkina, A. Kozyrev, M. Litvak, A. Malakhov, I. Mitrofanov, M. Mokrousov, S. Nikiforov, V. Prokhorov, A. Sanin, V. Tretyakov, A. Varenikov, A. Vostrukhin, R. Kuzmin, B. Clark, M. Wolff, O. Botta, D. Drake, K. Bean, M. Lemmon, S. P. Schwenzer, E. M. Lee, R. Sucharski, M. A. P. Hernandez, J. J. B. Avalos, M. Ramos, M.-H. Kim, C. Malespin, I. Plante, J.-P. Muller, R. Navarro-Gonzalez, R. Ewing, W. Boynton, R. Downs, M. Fitzgibbon, K. Harshman, S. Morrison, O. Kortmann, A. Williams, G. Lugmair, M. A. Wilson, B. Jakosky, T. Balic-Zunic, J. Frydenvang, J. K. Jensen, K. Kinch, A. Koefoed, M. B. Madsen, S. L. S. Stipp, N. Boyd, J. L. Campbell, G. Perrett, I. Pradler, S. VanBommel, S. Jacob, T. Owen, H. Savijarvi, E. Boehm, S. Bottcher, S. Burmeister, J. Guo, J. Kohler, C. M. Garcia, R. Mueller-Mellin, R. Wimmer-Schweingruber, J. C. Bridges, T. McConnochie, M. Benna, H. Franz, H. Bower, A.

- Brunner, H. Blau, T. Boucher, M. Carmosino, S. Atreya, H. Elliott, D. Halleaux, N. Renno, M. Wong, R. Pepin, B. Elliott, J. Spray, L. Thompson, S. Gordon, A. Ollila, J. Williams, P. Vasconcelos, J. Bentz, K. Nealson, R. Popa, J. Moersch, C. Tate, M. Day, R. Francis, E. McCullough, E. Cloutis, I. L. ten Kate, D. Scholes, S. Slavney, T. Stein, J. Ward, J. Berger, J. E. Moores; MSL Science Team, A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale crater, Mars. *Science* 343, 1242777 (2014). Medline doi:10.1126/science.1242777
- 30. D. W. Ming, P. D. Archer, 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, D. L. Bish, W. B. Brinckerhoff, A. Buch, P. G. Conrad, D. J. Des Marais, B. L. Ehlmann, A. G. Fairen, 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-Gonzalez, 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, O. Kemppinen, N. Bridges, J. R. Johnson, M. Minitti, D. Cremers, L. Edgar, J. Farmer, A. Godber, M. Wadhwa, D. Wellington, I. McEwan, C. Newman, M. Richardson, A. Charpentier, L. Peret, P. King, J. Blank, G. Weigle, M. Schmidt, S. Li, R. Milliken, K. Robertson, V. Sun, M. Baker, C. Edwards, B. Ehlmann, J. Griffes, M. Newcombe, C. Pilorget, M. Rice, K. Siebach, K. Stack, C. Brunet, V. Hipkin, R. Leveille, G. Marchand, P. S. Sanchez, L. Favot, G. Cody, L. Fluckiger, D. Lees, A. Nefian, M. Martin, M. Gailhanou, F. Westall, G. Israel, C. Agard, J. Baroukh, C. Donny, A. Gaboriaud, P. Guillemot, V. Lafaille, E. Lorigny, A. Paillet, R. Perez, M. Saccoccio, C. Yana, C. Armiens-Aparicio, J. C. Rodriguez, I. C. Blazquez, F. G. Gomez, J. Gomez-Elvira, S. Hettrich, A. L. Malvitte, M. M. Jimenez, J. Martinez-Frias, J. Martin-Soler, F. J. Martin-Torres, A. M. Jurado, L. Mora-Sotomayor, G. M. Caro, S. N. Lopez, V. Peinado-Gonzalez, J. Pla-Garcia, J. A. R. Manfredi, J. J. Romeral-Planello, S. A. S. Fuentes, E. S. Martinez, J. T. Redondo, R. Urqui-O'Callaghan, M.-P. Z. Mier, S. Chipera, J.-L. Lacour, P. Mauchien, J.-B. Sirven, H. Manning, A. Hayes, J. Joseph, R. Sullivan, P. Thomas, A. Dupont, A. Lundberg, N. Melikechi, A. Mezzacappa, J. DeMarines, D. Grinspoon, G. Reitz, B. Prats, E. Atlaskin, M. Genzer, A.-M. Harri, H. Haukka, H. Kahanpaa, J. Kauhanen, O. Kemppinen, M. Paton, J. Polkko, W. Schmidt, T. Siili, C. Fabre, M. B. Wilhelm, F. Poitrasson, K. Patel, S. Gorevan, S. Indyk, G. Paulsen, J. Schieber, B. Gondet, Y. Langevin, C. Geffroy, D. Baratoux, G. Berger, A. Cros, C. d'Uston, O. Forni, O. Gasnault, J. Lasue, Q.-M. Lee, S. Maurice, P.-Y. Meslin, E. Pallier, Y. Parot, P. Pinet, S. Schroder, M. Toplis, E. Lewin, W. Brunner, E. Heydari, C. Achilles, D. Oehler, D. Coscia, G. Israel, G. Dromart, F. Robert, V. Sautter, S. Le Mouelic, N. Mangold, M. Nachon, F. Stalport, F. Raulin, J. Cameron, S. Clegg, A. Cousin, D. DeLapp, R. Dingler, R. S. Jackson, S. Johnstone, N. Lanza, C. Little, T. Nelson, R. C. Wiens, R. B. Williams, A. Jones, L. Kirkland, B. Baker, B. Cantor, M. Caplinger, S. Davis, B. Duston, K. Edgett, D. Fay, C. Hardgrove, D. Harker, P. Herrera, E. Jensen, M. R. Kennedy, G. Krezoski, D. Krysak, L. Lipkaman, M. Malin, E. McCartney, S. McNair, B. Nixon, L. Posiolova, M. Ravine, A. Salamon, L. Saper, K. Stoiber, K. Supulver, J. Van Beek, T. Van Beek, R. Zimdar, K. L. French, K. Iagnemma, K. Miller, F. Goesmann, W. Goetz, S. Hviid, M. Johnson, M. Lefavor, E. Lyness, E.

Breves, M. D. Dyar, C. Fassett, D. F. Blake, T. Bristow, L. Edwards, R. Haberle, T. Hoehler, J. Hollingsworth, M. Kahre, L. Keely, C. McKay, M. B. Wilhelm, L. Bleacher, D. Choi, J. P. Dworkin, M. Floyd, J. Garvin, D. Harpold, A. Jones, D. K. Martin, E. Raaen, M. D. Smith, F. Tan, M. Meyer, A. Posner, M. Voytek, R. C. Anderson, A. Aubrey, L. W. Beegle, A. Behar, D. Blaney, D. Brinza, F. Calef, L. Christensen, J. A. Crisp, L. DeFlores, J. Feldman, S. Feldman, I. Jun, D. Keymeulen, J. Maki, M. Mischna, J. M. Morookian, T. Parker, B. Pavri, M. Schoppers, A. Sengstacken, J. J. Simmonds, N. Spanovich, M. T. Juarez, A. Yen, F. Cucinotta, J. H. Jones, E. Rampe, T. Nolan, M. Fisk, L. Radziemski, B. Barraclough, S. Bender, D. Berman, E. N. Dobrea, R. Tokar, R. M. E. Williams, T. Cleghorn, W. Huntress, G. Manhes, J. Hudgins, T. Olson, N. Stewart, P. Sarrazin, E. Vicenzi, S. A. Wilson, M. Bullock, B. Ehresmann, V. Hamilton, D. Hassler, J. Peterson, S. Rafkin, C. Zeitlin, F. Fedosov, D. Golovin, N. Karpushkina, A. Kozyrev, M. Litvak, A. Malakhov, I. Mitrofanov, M. Mokrousov, S. Nikiforov, V. Prokhorov, A. Sanin, V. Tretyakov, A. Varenikov, A. Vostrukhin, R. Kuzmin, B. Clark, M. Wolff, O. Botta, D. Drake, K. Bean, M. Lemmon, S. P. Schwenzer, R. B. Anderson, E. M. Lee, R. Sucharski, M. A. P. Hernandez, J. J. B. Avalos, M. Ramos, M.-H. Kim, C. Malespin, I. Plante, J.-P. Muller, R. Ewing, W. Boynton, R. Downs, M. Fitzgibbon, K. Harshman, S. Morrison, W. Dietrich, O. Kortmann, M. Palucis, A. Williams, G. Lugmair, M. A. Wilson, D. Rubin, B. Jakosky, T. Balic-Zunic, J. Frydenvang, J. K. Jensen, K. Kinch, A. Koefoed, M. B. Madsen, S. L. S. Stipp, N. Boyd, S. VanBommel, S. Jacob, T. Owen, S. Rowland, E. Atlaskin, H. Savijarvi, E. Boehm, S. Bottcher, S. Burmeister, J. Guo, J. Kohler, C. M. Garcia, R. Mueller-Mellin, R. Wimmer-Schweingruber, J. C. Bridges, T. McConnochie, M. Benna, H. Bower, H. Blau, T. Boucher, M. Carmosino, H. Elliott, D. Halleaux, N. Renno, M. Wong, R. Pepin, B. Elliott, J. Spray, L. Thompson, S. Gordon, H. Newsom, A. Ollila, J. Williams, P. Vasconcelos, J. Bentz, K. Nealson, R. Popa, L. C. Kah, C. Tate, M. Day, G. Kocurek, B. Hallet, R. Sletten, R. Francis, E. McCullough, E. Cloutis, I. L. ten Kate, R. Kuzmin, R. Arvidson, A. Fraeman, D. Scholes, S. Slavney, T. Stein, J. Ward, J. Berger, J. E. Moores, Volatile and Organic Compositions of Sedimentary Rocks in Yellowknife Bay, Gale Crater, Mars. Science 343, 1245267 (2013). Medline doi:10.1126/science.1245267

31. 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. P. Grotzinger, S. M. McLennan, J. Williams, J. F. Bell 3rd, H. E. Newsom, R. T. Downs, S. Maurice, P. Sarrazin, A. S. Yen, J. M. Morookian, J. D. Farmer, K. Stack, R. E. Milliken, B. L. Ehlmann, D. Y. Sumner, G. Berger, J. A. Crisp, J. A. Hurowitz, R. Anderson, D. J. Des Marais, E. M. Stolper, K. S. Edgett, S. Gupta, N. Spanovich, C. Agard, J. A. Alves Verdasca, R. Anderson, D. Archer, C. Armiens-Aparicio, R. Arvidson, E. Atlaskin, S. Atreya, A. Aubrey, B. Baker, M. Baker, T. Balic-Zunic, D. Baratoux, J. Baroukh, B. Barraclough, K. Bean, L. Beegle, A. Behar, S. Bender, M. Benna, J. Bentz, J. Berger, D. Berman, J. J. Blanco Avalos, D. Blaney, J. Blank, H. Blau, L. Bleacher, E. Boehm, O. Botta, S. Bottcher, T. Boucher, H. Bower, N. Boyd, B. Boynton, E. Breves, J. Bridges, N. Bridges, W. Brinckerhoff, D. Brinza, C. Brunet, A. Brunner, W. Brunner, A. Buch, M. Bullock, S. Burmeister, M. Cabane, F. Calef, J. Cameron, J. I. Campbell, B. Cantor, M. Caplinger, J. Caride Rodriguez, M. Carmosino, I. Carrasco Blazquez, A. Charpentier, D. Choi, B. Clark, S. Clegg, T. Cleghorn, E. Cloutis, G. Cody, P. Coll, P. Conrad, D. Coscia, A. Cousin, D. Cremers, A. Cros, F. Cucinotta, C. d'Uston, S. Davis, M. K. Day, M. de la

Torre Juarez, L. DeFlores, D. DeLapp, J. DeMarines, W. Dietrich, R. Dingler, C. Donny, D. Drake, G. Dromart, A. Dupont, B. Duston, J. Dworkin, M. D. Dyar, L. Edgar, C. Edwards, L. Edwards, B. Ehresmann, J. Eigenbrode, B. Elliott, H. Elliott, R. Ewing, C. Fabre, A. Fairen, K. Farley, C. Fassett, L. Favot, D. Fay, F. Fedosov, J. Feldman, S. Feldman, M. Fisk, M. Fitzgibbon, G. Flesch, M. Floyd, L. Fluckiger, O. Forni, A. Fraeman, R. Francis, P. Francois, H. Franz, C. Freissinet, K. L. French, J. Frydenvang, A. Gaboriaud, M. Gailhanou, J. Garvin, O. Gasnault, C. Geffroy, R. Gellert, M. Genzer, D. Glavin, A. Godber, F. Goesmann, W. Goetz, D. Golovin, F. Gomez Gomez, J. Gomez-Elvira, B. Gondet, S. Gordon, S. Gorevan, J. Grant, J. Griffes, D. Grinspoon, P. Guillemot, J. Guo, S. Guzewich, R. Haberle, D. Halleaux, B. Hallet, V. Hamilton, C. Hardgrove, D. Harker, D. Harpold, A.-M. Harri, K. Harshman, D. Hassler, H. Haukka, A. Hayes, K. Herkenhoff, P. Herrera, S. Hettrich, E. Heydari, V. Hipkin, T. Hoehler, J. Hollingsworth, J. Hudgins, W. Huntress, S. Hviid, K. Iagnemma, S. Indyk, G. Israel, R. Jackson, S. Jacob, B. Jakosky, E. Jensen, J. K. Jensen, J. Johnson, M. Johnson, S. Johnstone, A. Jones, J. Jones, J. Joseph, I. Jun, L. Kah, H. Kahanpaa, M. Kahre, N. Karpushkina, W. Kasprzak, J. Kauhanen, L. Keely, O. Kemppinen, D. Keymeulen, M.-H. Kim, K. Kinch, P. King, L. Kirkland, G. Kocurek, A. Koefoed, J. Kohler, O. Kortmann, A. Kozyrev, J. Krezoski, D. Krysak, R. Kuzmin, J. L. Lacour, V. Lafaille, Y. Langevin, N. Lanza, J. Lasue, S. Le Mouelic, E. M. Lee, Q.-M. Lee, D. Lees, M. Lefavor, M. Lemmon, A. L. Malvitte, L. Leshin, R. Leveille, E. Lewin-Carpintier, K. Lewis, S. Li, L. Lipkaman, C. Little, M. Litvak, E. Lorigny, G. Lugmair, A. Lundberg, E. Lyness, M. Madsen, P. Mahaffy, J. Maki, A. Malakhov, C. Malespin, M. Malin, N. Mangold, G. Manhes, H. Manning, G. Marchand, M. Marin Jimenez, C. Martin Garcia, D. Martin, M. Martin, J. Martinez-Frias, J. Martin-Soler, F. J. Martin-Torres, P. Mauchien, A. McAdam, E. McCartney, T. McConnochie, E. McCullough, I. McEwan, C. McKay, S. McNair, N. Melikechi, P.-Y. Meslin, M. Meyer, A. Mezzacappa, H. Miller, K. Miller, M. Minitti, M. Mischna, I. Mitrofanov, J. Moersch, M. Mokrousov, A. Molina Jurado, J. Moores, L. Mora-Sotomayor, R. Mueller-Mellin, J.-P. Muller, G. Munoz Caro, M. Nachon, S. Navarro Lopez, R. Navarro-Gonzalez, K. Nealson, A. Nefian, T. Nelson, M. Newcombe, C. Newman, S. Nikiforov, P. Niles, B. Nixon, E. Noe Dobrea, T. Nolan, D. Oehler, A. Ollila, T. Olson, T. Owen, M. A. de Pablo Hernandez, A. Paillet, E. Pallier, M. Palucis, T. Parker, Y. Parot, K. Patel, M. Paton, G. Paulsen, A. Pavlov, B. Pavri, V. Peinado-Gonzalez, R. Pepin, L. Peret, R. Perez, G. Perrett, J. Peterson, C. Pilorget, P. Pinet, J. Pla-Garcia, I. Plante, F. Poitrasson, J. Polkko, R. Popa, L. Posiolova, A. Posner, I. Pradler, B. Prats, V. Prokhorov, S. W. Purdy, E. Raaen, L. Radziemski, S. Rafkin, M. Ramos, F. Raulin, M. Ravine, G. Reitz, N. Renno, M. Richardson, F. Robert, K. Robertson, J. A. Rodriguez Manfredi, J. J. Romeral-Planello, S. Rowland, D. Rubin, M. Saccoccio, A. Salamon, J. Sandoval, A. Sanin, S. A. Sans Fuentes, L. Saper, V. Sautter, H. Savijarvi, J. Schieber, M. Schmidt, W. Schmidt, D. D. Scholes, M. Schoppers, S. Schroder, S. Schwenzer, E. Sebastian Martinez, A. Sengstacken, R. Shterts, K. Siebach, T. Siili, J. Simmonds, J.-B. Sirven, S. Slavney, R. Sletten, M. Smith, P. Sobron Sanchez, J. Spray, S. Squyres, F. Stalport, A. Steele, T. Stein, J. Stern, N. Stewart, S. L. S. Stipp, K. Stoiber, B. Sucharski, R. Sullivan, R. Summons, V. Sun, K. Supulver, B. Sutter, C. Szopa, F. Tan, C. Tate, S. Teinturier, I. ten Kate, P. Thomas, L. Thompson, R. Tokar, M. Toplis, J. Torres Redondo, M. Trainer, V. Tretyakov, R. Urqui-O'Callaghan, J. Van Beek, T. Van Beek, S. VanBommel, A. Varenikov, A. Vasavada, P. Vasconcelos, E.

- Vicenzi, A. Vostrukhin, M. Voytek, M. Wadhwa, J. Ward, C. Webster, E. Weigle, D. Wellington, F. Westall, R. C. Wiens, M. B. Wilhelm, A. Williams, R. Williams, R. B. M. Williams, M. Wilson, R. Wimmer-Schweingruber, M. Wolff, M. Wong, J. Wray, M. Wu, C. Yana, A. Yingst, C. Zeitlin, R. Zimdar, M.-P. Zorzano Mier; MSL Science Team, Mineralogy of a mudstone at Yellowknife Bay, Gale crater, Mars. *Science* **343**, 1243480 (2014). Medline doi:10.1126/science.1243480
- 32. V. Ansan, N. Mangold, New observations of Warrego Valles, Mars: Evidence for precipitation and surface runoff. *Planet. Space Sci.* **54**, 219–242 (2006). doi:10.1016/j.pss.2005.12.009
- 33. K. W. Lewis, O. Aharonson, Stratigraphic analysis of the distributary fan in Eberswalde crater using stereo imagery. *J. Geophys. Res. Planets* **111** (E6), 6001 (2006). doi:10.1029/2005JE002558
- 34. T. Owen, J. P. Maillard, C. de Bergh, B. L. Lutz, Deuterium on Mars: The Abundance of HDO and the Value of D/H. *Science* **240**, 1767–1770 (1988). Medline doi:10.1126/science.240.4860.1767
- 35. V. A. Krasnopolsky, G. L. Bjoraker, M. J. Mumma, D. E. Jennings, High-resolution spectroscopy of Mars at 3.7 and 8 mu m: A sensitive search for H2O2, H2CO, HCl, and CH4, and detection of HDO. *J. Geophys. Res. Planets* **102** (E3), 6525–6534 (1997). doi:10.1029/96JE03766
- 36. G. L. Villanueva *et al.*, Water on Mars: global maps of H2O, HDO and D/H obtained with CRIRES at VLT and NIRSPEC at Keck II. *AGU Fall Meeting Abstracts* **52**, 05 (2010).
- 37. R. E. Novak, M. J. Mumma, G. L. Villanueva, Measurement of the isotopic signatures of water on Mars; Implications for studying methane. *Planet. Space Sci.* **59**, 163–168 (2011). doi:10.1016/j.pss.2010.06.017
- 38. G. L. Villanueva, M. J. Mumma, B. P. Bonev, R. E. Novak, R. J. Barber, M. A. DiSanti, Water in planetary and cometary atmospheres: H2O/HDO transmittance and fluorescence models. *J. Quant. Spectrosc. Radiat. Transf.* **113**, 202–220 (2012). doi:10.1016/j.jqsrt.2011.11.001
- 39. J. T. Shafer, A. D. Brandon, T. J. Lapen, M. Righter, A. H. Peslier, B. L. Beard, Trace element systematics and 147Sm- 143Nd and 176Lu- 176Hf ages of Larkman Nunatak 06319: Closed-system fractional crystallization of an enriched shergottite magma. *Geochim. Cosmochim. Acta* 74, 7307–7328 (2010). doi:10.1016/j.gca.2010.09.009
- 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, O. Kemppinen, N. Bridges, J. R. Johnson, M. Minitti, D. Cremers, J. F. Bell, L. Edgar, J. Farmer, A. Godber, M. Wadhwa, D. Wellington, I. McEwan, C. Newman, M. Richardson, A. Charpentier, L. Peret, P. King, J. Blank, G. Weigle, M. Schmidt, S. Li, R. Milliken, K. Robertson, V. Sun, M. Baker, C. Edwards, B. Ehlmann, K. Farley, J. Griffes, H. Miller, M. Newcombe, C. Pilorget, M. Rice, K. Siebach, K. Stack, E. Stolper, C. Brunet, V. Hipkin, R. Leveille, G. Marchand, P. S.

Sanchez, L. Favot, G. Cody, L. Fluckiger, D. Lees, A. Nefian, M. Martin, M. Gailhanou, F. Westall, G. Israel, C. Agard, J. Baroukh, C. Donny, A. Gaboriaud, P. Guillemot, V. Lafaille, E. Lorigny, A. Paillet, R. Perez, M. Saccoccio, C. Yana, C. Armiens-Aparicio, J. C. Rodriguez, I. C. Blazquez, F. G. Gomez, J. Gomez-Elvira, S. Hettrich, A. L. Malvitte, M. M. Jimenez, J. Martinez-Frias, J. Martin-Soler, F. J. Martin-Torres, A. M. Jurado, L. Mora-Sotomayor, G. M. Caro, S. N. Lopez, V. Peinado-Gonzalez, J. Pla-Garcia, J. A. R. Manfredi, J. J. Romeral-Planello, S. A. S. Fuentes, E. S. Martinez, J. T. Redondo, R. Urqui-O'Callaghan, M.-P. Z. Mier, S. Chipera, J.-L. Lacour, P. Mauchien, J.-B. Sirven, H. Manning, A. Fairen, A. Hayes, J. Joseph, R. Sullivan, P. Thomas, A. Dupont, A. Lundberg, N. Melikechi, A. Mezzacappa, J. DeMarines, D. Grinspoon, G. Reitz, B. Prats, E. Atlaskin, M. Genzer, A.-M. Harri, H. Haukka, H. Kahanpaa, J. Kauhanen, O. Kemppinen, M. Paton, J. Polkko, W. Schmidt, T. Siili, C. Fabre, M. B. Wilhelm, F. Poitrasson, K. Patel, S. Gorevan, S. Indyk, G. Paulsen, S. Gupta, D. Bish, J. Schieber, B. Gondet, Y. Langevin, C. Geffroy, D. Baratoux, G. Berger, A. Cros, C. d'Uston, O. Forni, O. Gasnault, J. Lasue, Q.-M. Lee, S. Maurice, P.-Y. Meslin, E. Pallier, Y. Parot, P. Pinet, S. Schroder, M. Toplis, E. Lewin, W. Brunner, E. Heydari, C. Achilles, D. Oehler, D. Coscia, G. Israel, G. Dromart, F. Robert, V. Sautter, S. Le Mouelic, N. Mangold, M. Nachon, F. Stalport, P. Francois, F. Raulin, J. Cameron, S. Clegg, A. Cousin, D. DeLapp, R. Dingler, R. S. Jackson, S. Johnstone, N. Lanza, C. Little, T. Nelson, R. C. Wiens, R. B. Williams, A. Jones, L. Kirkland, A. Treiman, B. Baker, B. Cantor, M. Caplinger, S. Davis, B. Duston, K. Edgett, D. Fay, C. Hardgrove, D. Harker, P. Herrera, E. Jensen, M. R. Kennedy, G. Krezoski, D. Krysak, L. Lipkaman, M. Malin, E. McCartney, S. McNair, B. Nixon, L. Posiolova, M. Ravine, A. Salamon, L. Saper, K. Stoiber, K. Supulver, J. Van Beek, T. Van Beek, R. Zimdar, K. L. French, K. Iagnemma, F. Goesmann, W. Goetz, S. Hviid, M. Johnson, M. Lefavor, E. Lyness, E. Breves, M. D. Dyar, C. Fassett, D. F. Blake, T. Bristow, D. DesMarais, L. Edwards, R. Haberle, T. Hoehler, J. Hollingsworth, M. Kahre, L. Keely, C. McKay, M. B. Wilhelm, L. Bleacher, W. Brinckerhoff, D. Choi, J. P. Dworkin, M. Floyd, J. Garvin, D. Harpold, A. Jones, D. K. Martin, A. Pavlov, E. Raaen, M. D. Smith, F. Tan, M. Meyer, A. Posner, M. Voytek, R. C. Anderson, A. Aubrey, L. W. Beegle, A. Behar, D. Blaney, D. Brinza, F. Calef, L. Christensen, J. A. Crisp, L. DeFlores, B. Ehlmann, J. Feldman, S. Feldman, J. Hurowitz, I. Jun, D. Keymeulen, J. Maki, M. Mischna, J. M. Morookian, T. Parker, B. Pavri, M. Schoppers, A. Sengstacken, J. J. Simmonds, N. Spanovich, M. T. Juarez, A. R. Vasavada, A. Yen, F. Cucinotta, J. H. Jones, E. Rampe, T. Nolan, M. Fisk, L. Radziemski, B. Barraclough, S. Bender, D. Berman, E. N. Dobrea, R. Tokar, D. Vaniman, R. M. E. Williams, A. Yingst, K. Lewis, T. Cleghorn, W. Huntress, G. Manhes, J. Hudgins, T. Olson, N. Stewart, P. Sarrazin, J. Grant, E. Vicenzi, S. A. Wilson, M. Bullock, B. Ehresmann, V. Hamilton, D. Hassler, J. Peterson, S. Rafkin, C. Zeitlin, F. Fedosov, D. Golovin, N. Karpushkina, A. Kozyrev, M. Litvak, A. Malakhov, I. Mitrofanov, M. Mokrousov, S. Nikiforov, V. Prokhorov, A. Sanin, V. Tretyakov, A. Varenikov, A. Vostrukhin, R. Kuzmin, B. Clark, M. Wolff, S. McLennan, O. Botta, D. Drake, K. Bean, M. Lemmon, S. P. Schwenzer, R. B. Anderson, K. Herkenhoff, E. M. Lee, R. Sucharski, M. A. P. Hernandez, J. J. B. Avalos, M. Ramos, M.-H. Kim, C. Malespin, I. Plante, J.-P. Muller, R. Ewing, W. Boynton, R. Downs, M. Fitzgibbon, K. Harshman, S. Morrison, W. Dietrich, O. Kortmann, M. Palucis, A. Williams, G. Lugmair, M. A. Wilson, D. Rubin, B. Jakosky, T. Balic-Zunic, J. Frydenvang, J. K. Jensen, K. Kinch, A. Koefoed, M. B.

- Madsen, S. L. S. Stipp, N. Boyd, J. L. Campbell, R. Gellert, G. Perrett, I. Pradler, S. VanBommel, S. Jacob, S. Rowland, E. Atlaskin, H. Savijarvi, E. Boehm, S. Bottcher, S. Burmeister, J. Guo, J. Kohler, C. M. Garcia, R. Mueller-Mellin, R. Wimmer-Schweingruber, J. C. Bridges, T. McConnochie, M. Benna, H. Bower, H. Blau, T. Boucher, M. Carmosino, H. Elliott, D. Halleaux, N. Renno, M. Wong, B. Elliott, J. Spray, L. Thompson, S. Gordon, H. Newsom, A. Ollila, J. Williams, P. Vasconcelos, J. Bentz, K. Nealson, R. Popa, L. C. Kah, J. Moersch, C. Tate, M. Day, G. Kocurek, B. Hallet, R. Sletten, R. Francis, E. McCullough, E. Cloutis, I. L. ten Kate, R. Kuzmin, R. Arvidson, A. Fraeman, D. Scholes, S. Slavney, T. Stein, J. Ward, J. Berger, J. E. Moores; MSL Science Team, Volatile, isotope, and organic analysis of martian fines with the Mars Curiosity rover. *Science* 341, 1238937 (2013). Medline doi:10.1126/science.1238937
- 41. Details of measurement procedures and treatment of uncertainties are provided in Supplementary Materials.
- 42. T. Usui, C. M. O. D. Alexander, J. Wang, J. I. Simon, J. H. Jones, in 44 th Lunar and Planetary Science Conference. (2013), vol. 1454.
- 43. L. A. Leshin, Insights into martian water reservoirs from analyses of martian meteorite QUE94201. *Geophys. Res. Lett.* 27, 2017–2020 (2000). doi:10.1029/1999GL008455
- 44. H. Lammer, E. Chassefière, Ö. Karatekin, A. Morschhauser, P. B. Niles, O. Mousis, P. Odert, U. V. Möstl, D. Breuer, V. Dehant, M. Grott, H. Gröller, E. Hauber, L. B. S. Pham, Outgassing History and Escape of the Martian Atmosphere and Water Inventory. *Space Sci. Rev.* **174**, 113–154 (2013). doi:10.1007/s11214-012-9943-8
- 45. M. H. Carr, J. W. Head, in 45th Lunar and Planetary Science Conference. (2014), vol. 1427.
- 46. F. Tian *et al.*, in *Comparative Climatology of Terrestrial Planets*, S. J. Mackwell, Ed. (2013), pp. 567-581.
- 47. H. Lammer, H. I. M. Lichtenegger, C. Kolb, I. Ribas, E. F. Guinan, R. Abart, S. J. Bauer, Loss of water from Mars: Implications for the oxidation of the soil. *Icarus* **165**, 9–25 (2003). doi:10.1016/S0019-1035(03)00170-2
- 48. R. O. Pepin, Evolution of the martian atmosphere. *Icarus* **111**, 289–304 (1994). doi:10.1006/icar.1994.1146
- 49. R. A. DiBiase, A. B. Limaye, J. S. Scheingross, W. W. Fischer, M. P. Lamb, Deltaic deposits at Aeolis Dorsa: Sedimentary evidence for a standing body of water on the northern plains of Mars. *J. Geophys. Res. Planets* **118**, 1285–1302 (2013). doi:10.1002/jgre.20100