Science Advances
AAAS

advances.sciencemag.org/cgi/content/full/6/49/eabb1669/DC1

Supplementary Materials for

Groundwater production from geothermal heating on early Mars and implication for early martian habitability

Lujendra Ojha*, Jacob Buffo, Suniti Karunatillake, Matthew Siegler

*Corresponding author. Email: luju.ojha@rutgers.edu

Published 2 December 2020, *Sci. Adv.* **6**, eabb1669 (2020)
DOI: 10.1126/sciadv.abb1669

This PDF file includes:

Texts S1 to S5
Figs. S1 to S6
Table S1
References

Supplementary Materials

Text S1. Noachian Water Inventory

At the present, if all of the known ice were to be distributed globally, it would only make ~30 m global equivalent layer (GEL) (62). The distribution of the present-day inventory of water ice above the predicted ice stability line of approximately +1 km during the Noachian would have resulted in regional ice sheets with an average thickness of only 700 m. The Martian water budget during late Noachian is unknown with estimates anywhere between 640m (63) to 5000 m GEL (64). The distribution of these water inventory estimates above the predicted ice stability line would have resulted in ice sheets with an average thickness of 14 - 116 km, however, it is unlikely for the entire global inventory of water in ancient Mars to have been deposited in the southern highlands alone. For our nominal model, we assume a conservative value of 2 km thick ice sheets (similar to the thickness of the Taku glacier on Earth (65, 66) in southern highlands to assess if basal melting would have been possible during the Noachian. This value of ice thickness is extremely conservative and corresponds to roughly ~14% of the 640m GEL estimate and ~1% of the 5000m GEL estimate.

Text S2. The Effect of Icy Highlands on Surface Temperature

We model the thermophysical evolution of ice sheets using mean annual surface temperature of 230 K based on the 3D GCM models of Mars (11). However, the surface temperature could be considerably lower if a substantial portion of Mars was covered by ice. This is because ice is reflective and reduces the amount of energy available to warm the surface. Simulation of ice on early Mars scenarios suggest that global ice coverage could have exceeded 25 – 30 %. In such a scenario, the surface temperature may decrease by almost 25 K. Although, this effect is considerably muted in the presence of a thick CO2 atmosphere with clouds (10) . We ran all the models presented here with a surface temperature of 200 K and found that no melt is produced. If Mars had thicker ice deposits in the Noachian highlands, then it is possible to generate melt even with a 200 K surface temperature. It is conceivable that thick ice deposits on Mars, if they existed, may have been covered by a thin layer of dust or volcanic ash as also observed for recently detected ice sheets (67), thus reducing the total albedo and reducing the problem associated with the icy highlands melt scenario. Both SPLD and NPLD exhibit depositions of ice with varying dust content (68), thus, it is plausible that subsequent dust deposition would have decreased the albedo of icy highlands. While speculative, the layering observed within the NPLD and SPLD suggest that this is not an unlikely scenario to have occurred on Mars.

Text S3. Snow Accumulation Rate

No empirical evidence exists to constrain the snow accumulation rate during the Noachian. We use a nominal accumulation rate of 10 mm yr^{-1}, which is predicted from GCM models. The snow accumulation rate is roughly exponentially dependent on temperature, so if there was a minor addition of greenhouse gases to the atmosphere or if the young Sun was slightly more luminous, then significantly faster accumulation than 10 mm yr^{-1} would have occurred. In general, faster or increased accumulation would have led to increased basal melting. No meltwater would have been generated if the snow accumulation rate was substantially lower than considered here. Some insight about the plausibility of these values may be gathered from terrestrial estimates. The average accumulation of snow over the continent as a whole is estimated to be equivalent to about 150mm of water per year.

Text S4. Th and K Enriched Regions of Mars

We sought to find regions on Mars that are statistically enriched in Th and K. To that end, we used an enhanced Student's t-test parameter, t_i, that measures the error-weighted deviation for each element from its bulk-average on Mars at each 5° × 5° chemical map grid derived from GRS data (69, 70):

$$t_i = \frac{c_i - m}{\sqrt{s_{m,i}^2 + s^2}}; \quad (1)$$

where c_i is the wt% of an element, m is the global arithmetic mean wt%, $s_{m,i}$ is the numerical uncertainty of c_i, and s is the standard deviation of the data. The key difference between the 't_i' used here and the commonly used Student's t parameter is the inclusion of '$s_{m,i}$' in the denominator. Additional information about the enhanced t-test can be found in our previous work (69, 70). Here we define areas of significant enrichment as those with t_i values greater than 1.5 (i.e. statistical confidence in directional deviation > 94 %).

Text S5. Empirical Cumulative Distribution Functions

Empirical Cumulative Distribution Functions (ECDF) for all Noachian terrain reflects all pixels from the 1x1 degree resolution surface heat flow map (interpolated from the original 5x5 degree resolution map) (Fig. 3 (c)). That consists of each pixel where more than 50% of the area corresponds to Noachian age. Meanwhile, for each location where a mineral is detected – often in an outcrop via CRISM data – the surface heat flow is approximated as that of the containing heat flow map pixel. For example, two spatially distinct detections of chloride within the same pixel are assigned the same heat flow value. A value of 'NaN' is ascribed when the location of the hydrous minerals is outside of Noachian terrain and those sites are excluded from further statistical analysis. Matlab command 'cdfplot' is used to create the ECDF plots shown in Figure S6.

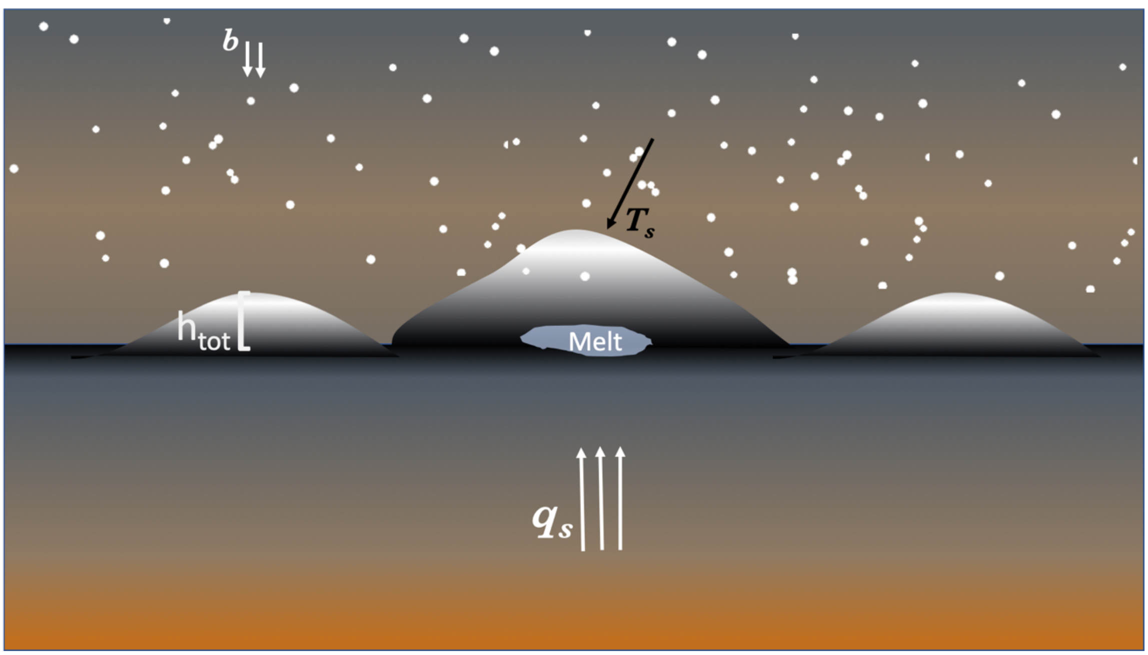

Figure S1. *Schematic showing the setup of our model. For a given snow accumulation/precipitation rate of b (mm yr^{-1}), total thickness of the snow/ice slab (h_{tot}), and surface temperature (T_s), we solve for the surface heat flow (q_s) that can produce meltwater. Melt is only produced for the thickest of the ice slabs.*

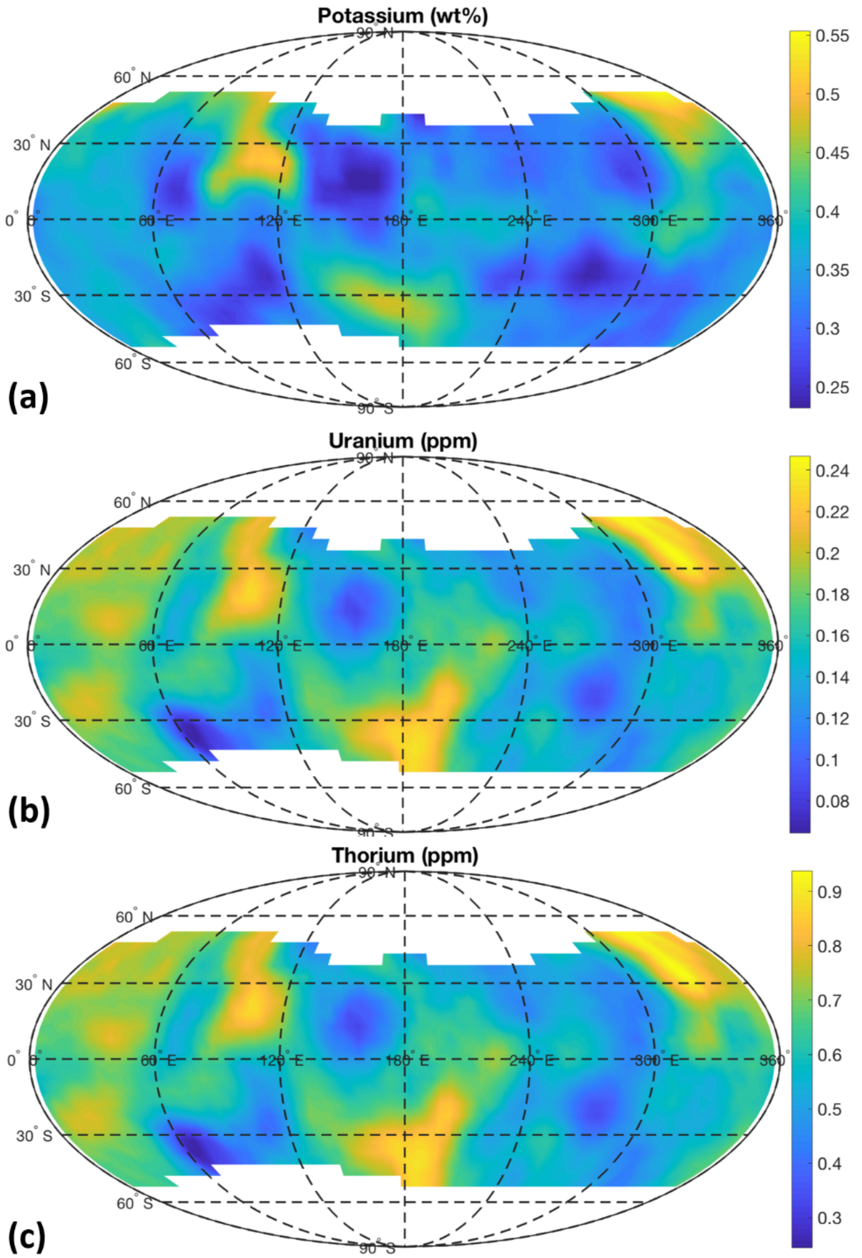

Figure S2. *Distribution of the heat producing elements in the shallow subsurface of Mars. (a) Potassium concentration in the shallow subsurface of Mars at 5°×5° in the mid-latitudes, as derived from Mars Odyssey Gamma Ray Spectrometer suite. (b) Same as (a) but showing the concentration of U calculated using the cosmochemical Th/U ratio. (c) Same as (a) and (b) but showing the concentration of Th. Rapidly increasing H abundance dilutes and increases numerical uncertainty for HPE concentrations in the polar latitudes. A mask has thus been applied to exclude such areas.*

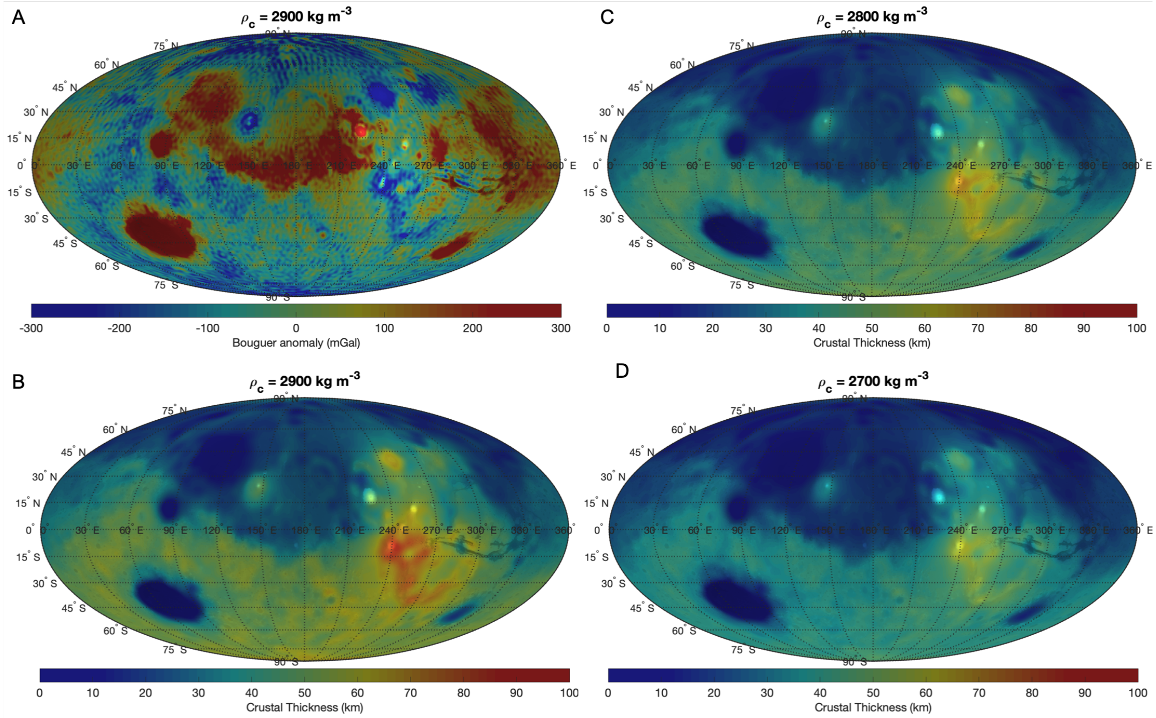

Figure S3. *Bouguer gravity and crustal thickness maps of Mars. (A) An example of a Bouguer gravity anomaly map of Mars assuming a constant density of 2900 kg m^{-3}. (B) – (D) Crustal thickness of Mars derived from downward continuing the observed Bouguer gravity anomaly to a crust-mantle interface for crustal densities of 2900 – 2700 kg m^{-3}.*

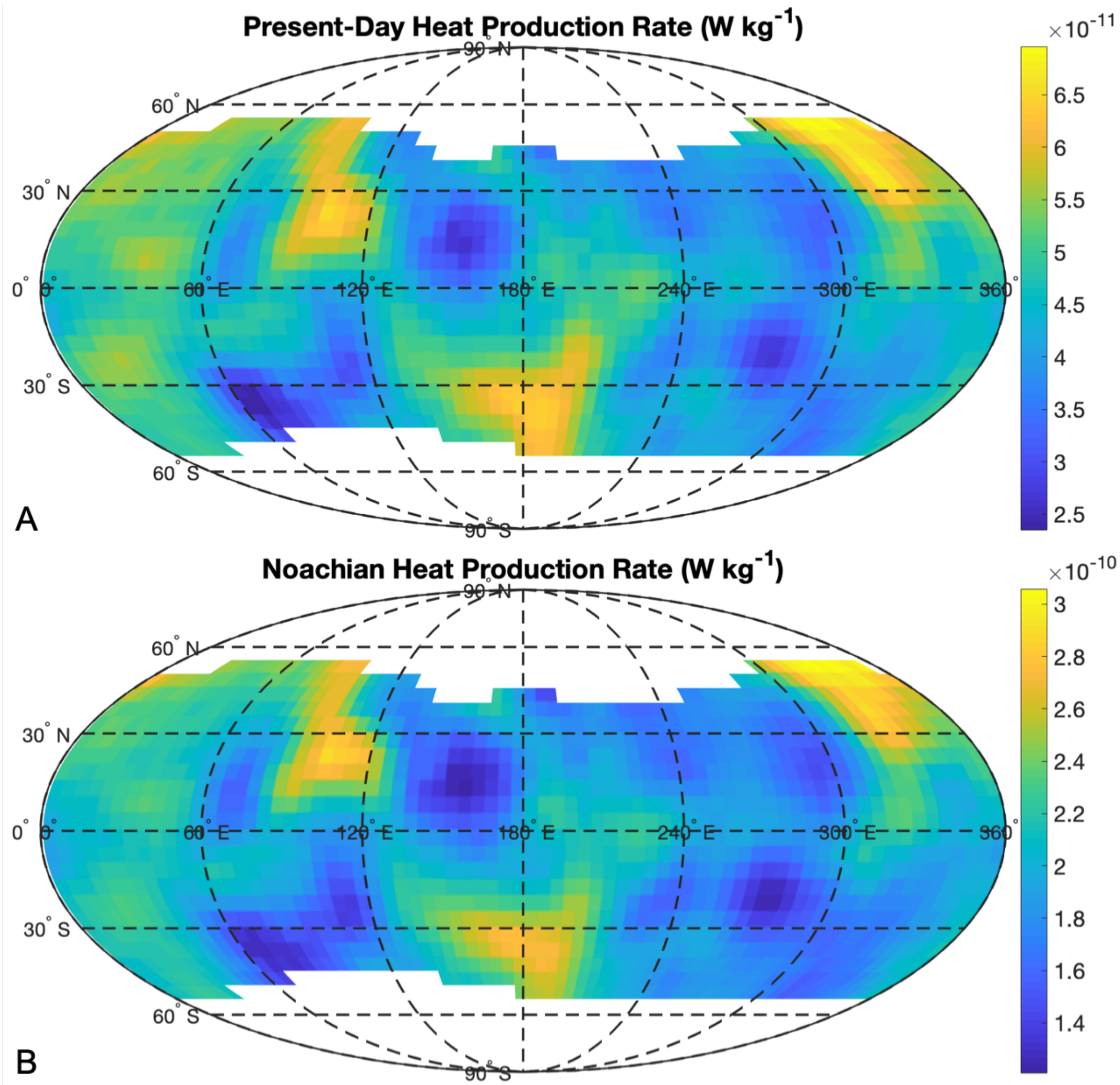

Figure S4. *Current and Noachian crustal heat production rate for Mars. (a) Present day crustal heat production map using HPE abundance maps from Fig. S2 and crustal thickness maps from Fig. S3. (b) Crustal heat production rate during the Noachian with the current lateral HPE variability preserved.*

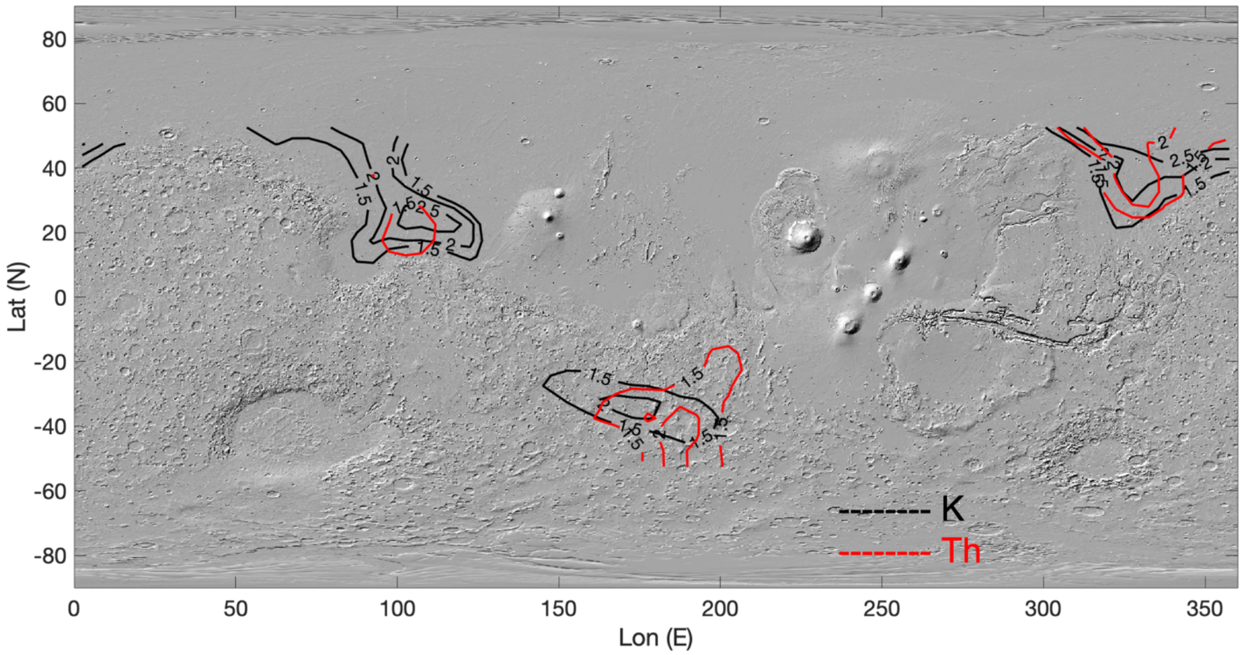

Figure S5. *Contour map showing regions on Mars with significant enrichment of Th and K. The contour labels correspond to a modified 't' parameter that show regions with significant enrichment of Th and K compared to the bulk-average of Mars. The background is the shaded relief map of Mars from Mars Orbiter Laser Altimeter (MOLA).*

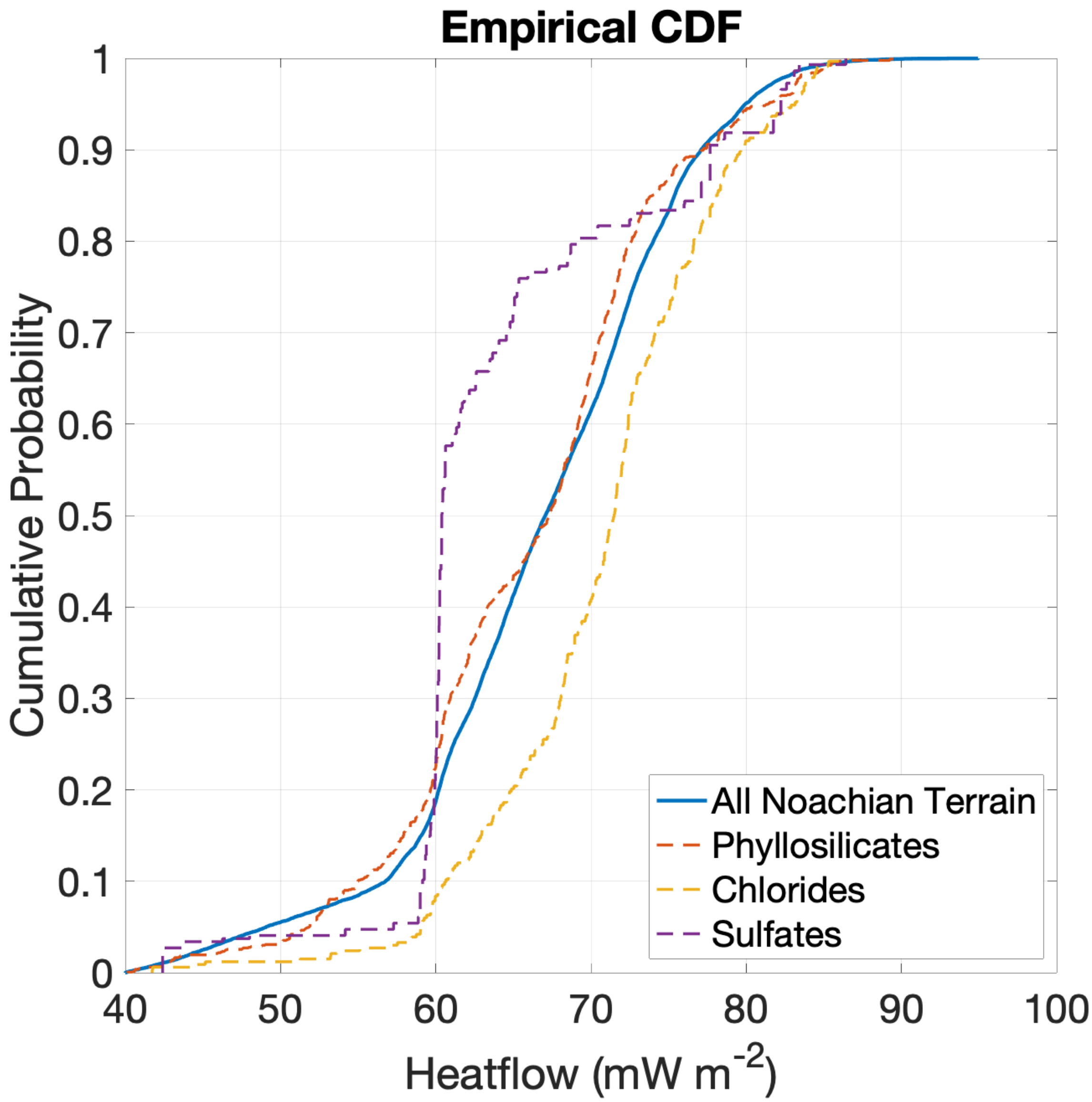

Figure S6. *An Empirical cumulative distribution function (ECDF) plot of surface heat flow values for all Noachian terrain and regions in Noachian terrain that bear various hydrous minerals.*

Table S1: All variables and values used in the thermal simulation.

Variable	Description	Value	Units
$\dot{b}$	Accumulation Rate	3.1688e-10 (1)	m s^{-1} (cm yr^{-1})
c_{ice}	Specific Heat of Ice	2000	J kg^{-1} K^{-1}
c_v	Specific Heat of Voids	790	J kg^{-1} K^{-1}
c_w	Specific Heat of Melt	3985	J kg^{-1} K^{-1}
f_0	Constant Coefficient	9.5064e-16	-
g	Acceleration Due to Gravity	3.711	m s^{-2}
H	Enthalpy	Calculated	J kg^{-1}
H_S	Enthalpy of Solid Cell	Calculated	J kg^{-1}
H_{tot}	Critical Ice Sheet Thickness	1300, 1400, 1500, 2000	m
k_{ice}	Thermal Conductivity of Ice	2	W m^{-1} K^{-1}
k_v	Thermal Conductivity of Voids	0.012	W m^{-1} K^{-1}
k_w	Thermal Conductivity of Melt	0.6	W m^{-1} K^{-1}
L	Latent Heat of Fusion	334774	J kg^{-1}
n	Ice Deformation Coefficient	3	-
ϕ_v	Void Space Volume Fraction	Calculated	-
ϕ_w	Melt Volume Fraction	Calculated	-
Q	Activation Energy	45600	J mol^{-1}
R	Gas Constant	8.314	J mol^{-1} K^{-1}
ρ	Density	Calculated	kg m^{-3}
ρ_{ice}	Density of Ice	917	kg m^{-3}
ρ_v	Density of Voids	1	kg m^{-3}
ρ_w	Density of Melt	1000	kg m^{-3}
ρ_0	Ice Sheet Surface Density	350	kg m^{-3}
t	Time	-	s
T	Temperature	Calculated	K
T_S	Surface Temperature	230	K
T_m	Melting Temperature	273.15	K
z	Depth	-	m

REFERENCES AND NOTES

1. C. Heberling, R. P. Lowell, L. Liu, M. R. Fisk, Extent of the microbial biosphere in the oceanic crust. *Geochem. Geophys. Geosyst.* **11**, Q08003 (2010).

2. B. L. Ehlmann, C. S. Edwards, Mineralogy of the Martian surface. *Annu. Rev. Earth Planet. Sci.* **42**, 291–315 (2014).

3. B. M. Hynek, M. Beach, M. R. T. Hoke, Updated global map of Martian valley networks and implications for climate and hydrologic processes. *J. Geophys. Res.* **115**, E09008 (2010).

4. C. I. Fassett, J. W. Head III, Valley network-fed, open-basin lakes on Mars: Distribution and implications for Noachian surface and subsurface hydrology. *Icarus* **198**, 37–56 (2008).

5. V. R. Baker, R. G. Strom, V. C. Gulick, J. S. Kargel, G. Komatsu, V. S. Kale, Ancient oceans, ice sheets and the hydrological cycle on Mars. *Nature* **352**, 589–594 (1991).

6. 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, J. D. Farmer, R. Sullivan, T. Van Beek, D. L. Blaney, O. Pariser, R. G. Deen, O. Kemppinen, N. Bridges, J. R. Johnson, M. Minitti, D. Cremers, L. Edgar, 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, E. Stolper, C. Brunet, V. Hipkin, R. Léveillé, G. Marchand, P. S. Sánchez, L. Favot, G. Cody, A. Steele, L. Flückiger, D. Lees, A. Nefian, M. Martin, M. Gailhanou, F. Westall, G. Israël, C. Agard, J. Baroukh, C. Donny, A. Gaboriaud, P. Guillemot, V. Lafaille, E. Lorigny, A. Paillet, R. Pérez, M. Saccoccio, C. Yana, C. A. Aparicio, J. C. Rodríguez, I. C. Blázquez, F. G. Gómez, J. G. Elvira, S. Hettrich, A. L. Malvitte, M. M. Jiménez, J. M. Frías, J. M. Soler, F. J. M. Torres, A. M. Jurado, L. M. Sotomayor, G. M. Caro, S. N. López, V. P. González, J. P. García, J. A. R. Manfredi, J. J. R. Planelló, S. A. S. Fuentes, E. S. Martinez, J. T. Redondo, R. U. O'Callaghan, M. P. Zorzano,

S. Chipera, J. L. Lacour, P. Mauchien, J. B. Sirven, H. Manning, A. Fairén, A. Hayes, J. Joseph, S. Squyres, 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. Kahanpää, 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, J. Schieber, B. Gondet, Y. Langevin, C. Geffroy, D. Baratoux, G. Berger, A. Cros, C. D. Uston, J. Lasue, Q. M. Lee, P. Y. Meslin, E. Pallier, Y. Parot, P. Pinet, S. Schröder, M. Toplis, E. Lewin, W. Brunner, E. Heydari, C. Achilles, D. Oehler, B. Sutter, M. Cabane, D. Coscia, C. Szopa, F. Robert, V. Sautter, M. Nachon, A. Buch, F. Stalport, P. Coll, P. François, 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, A. Treiman, B. Baker, B. Cantor, M. Caplinger, S. Davis, B. Duston, D. Fay, C. Hardgrove, 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, R. Zimdar, K. L. French, K. Iagnemma, K. Miller, R. Summons, F. Goesmann, 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, L. Bleacher, W. Brinckerhoff, D. Choi, P. Conrad, J. P. Dworkin, J. Eigenbrode, M. Floyd, C. Freissinet, J. Garvin, D. Glavin, D. Harpold, P. Mahaffy, D. K. Martin, A. McAdam, A. Pavlov, E. Raaen, M. D. Smith, J. Stern, F. Tan, M. Trainer, M. Meyer, A. Posner, M. Voytek, R. C. Anderson, A. Aubrey, L. W. Beegle, A. Behar, D. Brinza, F. Calef, L. Christensen, J. A. Crisp, L. Deflores, 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. de la Torre Juarez, A. R. Vasavada, C. R. Webster, A. Yen, P. D. Archer, F. Cucinotta, J. H. Jones, 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, L. Leshin, T. Cleghorn, W. Huntress, G. Manhès, 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, E. M. Lee, R. Sucharski, M. Á. de Pablo Hernández, J. J. B. Ávalos, M. Ramos, M. H.

Kim, C. Malespin, I. Plante, J. P. Muller, R. N. González, R. Ewing, W. Boynton, R. Downs, M. Fitzgibbon, K. Harshman, S. Morrison, O. Kortmann, A. Williams, G. Lugmair, M. A. Wilson, B. Jakosky, T. B. Zunic, J. Frydenvang, K. Kinch, S. L. S. Stipp, N. Boyd, J. L. Campbell, R. Gellert, G. Perrett, I. Pradler, S. Vanbommel, S. Jacob, T. Owen, S. Rowland, H. Savijärvi, E. Boehm, S. Böttcher, S. Burmeister, J. Guo, J. Köhler, C. M. García, R. M. Mellin, R. W. Schweingruber, T. McConnochie, M. Benna, H. Franz, H. Bower, A. Brunner, H. Blau, T. Boucher, M. Carmosino, S. Atreya, H. Elliott, D. Halleaux, N. Rennó, M. Wong, R. Pepin, B. Elliott, J. Spray, L. Thompson, S. Gordon, J. Williams, P. Vasconcelos, J. Bentz, K. Nealson, R. Popa, J. Moersch, C. Tate, M. Day, G. Kocurek, B. Hallet, R. Sletten, R. Francis, E. McCullough, E. Cloutis, I. L. Ten Kate, R. Arvidson, A. Fraeman, D. Scholes, S. Slavney, T. Stein, J. Ward, J. Berger, J. E. Moores, Martian fluvial conglomerates at gale crater. *Science* **340**, 1068–1072 (2013).

7. M. J. Newman, R. T. Rood, Implications of solar evolution for the earth's early atmosphere. *Science* **198**, 1035–1037 (1977).

8. 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).

9. B. M. Jakosky, D. Brain, M. Chaffin, S. Curry, J. Deighan, J. Grebowsky, J. Halekas, F. Leblanc, R. Lillis, J. G. Luhmann, L. Andersson, N. Andre, D. Andrews, D. Baird, D. Baker, J. Bell, M. Benna, D. Bhattacharyya, S. Bougher, C. Bowers, P. Chamberlin, J. Y. Chaufray, J. Clarke, G. Collinson, M. Combi, J. Connerney, K. Connour, J. Correira, K. Crabb, F. Crary, T. Cravens, M. Crismani, G. Delory, R. Dewey, G. DiBraccio, C. Dong, Y. Dong, P. Dunn, H. Egan, M. Elrod, S. England, F. Eparvier, R. Ergun, A. Eriksson, T. Esman, J. Espley, S. Evans, K. Fallows, X. Fang, M. Fillingim, C. Flynn, A. Fogle, C. Fowler, J. Fox, M. Fujimoto, P. Garnier, Z. Girazian, H. Groeller, J. Gruesbeck, O. Hamil, K. G. Hanley, T. Hara, Y. Harada, J. Hermann, M. Holmberg, G. Holsclaw, S. Houston, S. Inui, S. Jain, R. Jolitz, A. Kotova, T. Kuroda, D. Larson, Y. Lee, C. Lee, F. Lefevre, C. Lentz, D. Lo, R. Lugo, Y. J. Ma, P. Mahaffy, M. L. Marquette, Y. Matsumoto, M. Mayyasi, C. Mazelle, W. McClintock, J. McFadden, A. Medvedev, M. Mendillo, K. Meziane, Z. Milby, D.

Mitchell, R. Modolo, F. Montmessin, A. Nagy, H. Nakagawa, C. Narvaez, K. Olsen, D. Pawlowski, W. Peterson, A. Rahmati, K. Roeten, N. Romanelli, S. Ruhunusiri, C. Russell, S. Sakai, N. Schneider, K. Seki, R. Sharrar, S. Shaver, D. E. Siskind, M. Slipski, Y. Soobiah, M. Steckiewicz, M. H. Stevens, I. Stewart, A. Stiepen, S. Stone, V. Tenishev, N. Terada, K. Terada, E. Thiemann, R. Tolson, G. Toth, J. Trovato, M. Vogt, T. Weber, P. Withers, S. Xu, R. Yelle, E. Yiğit, R. Zurek, Loss of the Martian atmosphere to space: Present-day loss rates determined from MAVEN observations and integrated loss through time. *Icarus* **315**, 146–157 (2018).

10. F. Forget, R. Wordsworth, E. Millour, J. B. Madeleine, L. Kerber, J. Leconte, E. Marcq, R. M. Haberle, 3D modelling of the early martian climate under a denser CO2atmosphere: Temperatures and CO_2ice clouds. *Icarus* **222**, 81–99 (2013).

11. R. Wordsworth, F. Forget, E. Millour, J. W. Head, J. B. Madeleine, B. Charnay, Global modelling of the early martian climate under a denser CO 2 atmosphere: Water cycle and ice evolution. *Icarus* **222**, 1–19 (2013).

12. R. M. Haberle, R. T. Clancy, F. Forget, M. D. Smith, R. W. Zurek, *The Atmosphere and Climate of Mars* (Cambridge Univ. Press, 2017).

13. R. M. Haberle, K. Zahnle, N. G. Barlow, K. E. Steakley, Impact degassing of H2 on early Mars and its effect on the climate system. *Geophys. Res. Lett.* **46**, 13355–13362 (2019).

14. S. W. Squyres, J. F. Kasting, Early mars: How warm and how wet? *Science* **265**, 744–749 (1994).

15. B. L. Ehlmann, J. F. Mustard, S. L. Murchie, Geologic setting of serpentine deposits on Mars. *Geophys. Res. Lett.* **37**, L06201 (2010).

16. B. L. Ehlmann, J. F. Mustard, S. L. Murchie, J.-P. Bibring, A. Meunier, A. A. Fraeman, Y. Langevin, Subsurface water and clay mineral formation during the early history of Mars. *Nature* **479**, 53–60 (2011).

17. S. M. McLennan, J. F. Bell, 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, 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).

18. J. Frydenvang, P. J. Gasda, J. A. Hurowitz, J. P. Grotzinger, R. C. Wiens, H. E. Newsom, K. S. Edgett, J. Watkins, J. C. Bridges, S. Maurice, M. R. Fisk, J. R. Johnson, W. Rapin, N. T. Stein, S. M. Clegg, S. P. Schwenzer, C. C. Bedford, P. Edwards, N. Mangold, A. Cousin, R. B. Anderson, V. Payré, D. Vaniman, D. F. Blake, N. L. Lanza, S. Gupta, J. Van Beek, V. Sautter, P. Y. Meslin, M. Rice, R. Milliken, R. Gellert, L. Thompson, B. C. Clark, D. Y. Sumner, A. A. Fraeman, K. M. Kinch, M. B. Madsen, I. G. Mitrofanov, I. Jun, F. Calef, A. R. Vasavada, Diagenetic silica enrichment and late-stage groundwater activity in Gale crater, Mars. *Geophys. Res. Lett.* **44**, 4716–4724 (2017).

19. D. Baratoux, M. J. Toplis, M. Monnereau, O. Gasnault, Thermal history of Mars inferred from orbital geochemistry of volcanic provinces. *Nature* **472**, 338–341 (2011).

20. R. D. Wordsworth, L. Kerber, R. T. Pierrehumbert, F. Forget, J. W. Head, Comparison of “warm and wet” and “cold and icy” scenarios for early Mars in a 3-D climate model. *J. Geophys. Res. Planets* **120**, 1201–1219 (2015).

21. W. V. Boynton, G. J. Taylor, L. G. Evans, R. C. Reedy, R. Starr, D. M. Janes, K. E. Kerry, D. M. Drake, K. J. Kim, R. M. S. Williams, M. K. Crombie, J. M. Dohm, A. E. Metzger, S. Karunatillake, J. M. Keller, H. E. Newsom, J. R. Arnold, J. Bruckner, P. A. J. Englert, O. Gasnault, A. L. Sprague, I. Mitrofanov, S. W. Squyres, J. I. Trombka, L. d’Uston, H. Wonke, D. K. Hamara, Concentration of H, Si, Cl, K, Fe, and Th in the low- and mid-latitude regions of Mars. *J. Geophys. Res. E Planets* **112**, E12S99 (2007).

22. B. C. Hahn, S. M. McLennan, E. C. Klein, Martian surface heat production and crustal heat flow from Mars Odyssey Gamma-Ray spectrometry. *Geophys. Res. Lett.* **38**, L14203 (2011).

23. M. A. Wieczorek, M. T. Zuber, Thickness of the Martian crust: Improved constraints from geoid-to-topography ratios. *J. Geophys. Res.* **109**, E01009 (2004).

24. S. A Hauck II, R. J. Philips, Thermal and crustal evolution of Mars. *J. Geophys. Res.* **107**, 5052 (2002).

25. A. S. Konopliv, R. S. Park, W. M. Folkner, An improved JPL Mars gravity field and orientation from Mars orbiter and lander tracking data. *Icarus* **274**, 253–260 (2016).

26. L. Ojha, S. Karimi, K. W. Lewis, S. E. Smrekar, M. Siegler, Depletion of heat producing elements in the Martian mantle. *Geophys. Res. Lett.* **46**, 12756–12763 (2019).

27. P. J. McGovern, S. C. Solomon, D. E. Smith, M. T. Zuber, M. Simons, M. A. Wieczorek, R. J. Phillips, G. A. Neumann, O. Aharonson, J. W. Head, Correction to "Localized gravity/topography admittance and correlation spectra on Mars: Implications for regional and global evolution". *J. Geophys. Res.* **109**, E07007 (2004)

28. S. Karimi, A. J. Dombard, D. L. Buczkowski, S. J. Robbins, R. M. Williams, Using the viscoelastic relaxation of large impact craters to study the thermal history of Mars. *Icarus* **272**, 102–113 (2016).

29. M. Grott, D. Breuer, On the spatial variability of the Martian elastic lithosphere thickness: Evidence for mantle plumes? *J. Geophys. Res.* **115**, E03005 (2010).

30. L. M. Parro, A. Jiménez-Díaz, F. Mansilla, J. Ruiz, Present-day heat flow model of Mars. *Sci. Rep.* **7**, 45629 (2017).

31. A.-C. Plesa, M. Grott, N. Tosi, D. Breuer, T. Spohn, M. A. Wieczorek, How large are present-day heat flux variations across the surface of Mars? *J. Geophys. Res. Planets* **121**, 2386–2403 (2016).

32. A. Gando, Y. Gando, K. Ichimura, H. Ikeda, K. Inoue, Y. Kibe, Y. Kishimoto, M. Koga, Y. Minekawa, T. Mitsui, T. Morikawa, N. Nagai, K. Nakajima, K. Nakamura, K. Narita, I. Shimizu, Y. Shimizu, J. Shirai, F. Suekane, A. Suzuki, H. Takahashi, N. Takahashi, Y. Takemoto, K. Tamae, H. Watanabe, B. D. Xu, H. Yabumoto, H. Yoshida, S. Yoshida, S. Enomoto, A. Kozlov, H. Murayama, C. Grant, G. Keefer, A. Piepke, T. I. Banks, T. Bloxham, J. A. Detwiler, S. J. Freedman, B. K. Fujikawa, K. Han, R. Kadel, T. O'Donnell, H. M. Steiner, D. A. Dwyer, R. D. McKeown, C. Zhang, B. E. Berger, C. E. Lane, J. Maricic, T. Miletic, M. Batygov, J. G. Learned, S. Matsuno, M. Sakai, G. A. Horton-Smith, K. E. Downum, G. Gratta, K. Tolich, Y. Efremenko, O. Perevozchikov, H. J.

Karwowski, D. M. Markoff, W. Tornow, K. M. Heeger, M. P. Decowski, Partial radiogenic heat model for Earth revealed by geoneutrino measurements. *Nat. Geosci.* **4**, 647–651 (2011).

33. J. M. Dohm, N. G. Barlow, R. C. Anderson, J. P. Williams, H. Miyamoto, J. C. Ferris, R. G. Strom, G. J. Taylor, A. G. Fairén, V. R. Baker, W. V. Boynton, J. M. Keller, K. Kerry, D. Janes, J. A. P. Rodriguez, T. M. Hare, Possible ancient giant basin and related water enrichment in the Arabia Terra province, Mars. *Icarus* **190**, 74–92 (2007).

34. T. D. Glotch, J. L. Bandfield, L. L. Tornabene, H. B. Jensen, F. P. Seelos, Distribution and formation of chlorides and phyllosilicates in Terra Sirenum, Mars. *Geophys. Res. Lett.* **37**, L16202 (2010).

35. J. R. Michalski, E. Z. N. Dobrea, P. B. Niles, J. Cuadros, Ancient hydrothermal seafloor deposits in Eridania basin on Mars. *Nat. Commun.* **8**, 15978 (2017).

36. B. L. Ehlmann, G. A. Swayze, R. E. Milliken, J. F. Mustard, R. N. Clark, S. L. Murchie, G. N. Breit, J. J. Wray, B. Gondet, F. Poulet, J. Carter, W. M. Calvin, W. M. Benzel, K. D. Seelos, Discovery of alunite in cross crater, terra sirenum, mars: Evidence for acidic, sulfurous waters. *Am. Mineral.* **101**, 1527–1542 (2016).

37. G. J. Taylor, J. D. Stopar, W. V. Boynton, S. Karunatillake, J. M. Keller, J. Brückner, H. Wänke, G. Dreibus, K. E. Kerry, R. C. Reedy, L. G. Evans, R. D. Starr, L. M. V. V. Martel, S. W. Squyres, O. Gasnault, S. Maurice, C. D'Uston, P. Englert, J. M. Dohm, V. R. Baker, D. K. Hamara, D. M. Janes, A. L. Sprague, K. J. Kim, D. M. Drake, S. M. McLennan, B. C. Hahn, Variations in K/Th on Mars. *J. Geophys. Res. E Planets* **112**, E03S06 (2007).

38. D. A. Minton, R. Malhotra, Assessing the massive young sun hypothesis to solve the warm young earth puzzle. *Astrophys. J.* **660**, 1700 (2007).

39. J. A. Guzik, A. N. Cox, Early solar mass loss, element diffusion, and solar oscillation frequencies. *Astrophys. J.* **488**, 905 (1995).

40. J. M. Goldspiel, S. W. Squyres, Groundwater sapping and valley formation on Mars. *Icarus* **148**, 176–192 (2000).

41. R. A. Craddock, A. D. Howard, The case for rainfall on a warm, wet early Mars. *J. Geophys. Res.* **107**, 5111 (2002).

42. S. M. Clifford, A model for the hydrologic and climatic behavior of water on Mars. *J. Geophys. Res.* **98**, 10973–11016 (1993).

43. A. A. Pavlov, G. Vasilyev, V. M. Ostryakov, A. K. Pavlov, P. Mahaffy, Degradation of the organic molecules in the shallow subsurface of Mars due to irradiation by cosmic rays. *Geophys. Res. Lett.* **39**, L13202 (2012).

44. L. J. Rothschild, R. L. Mancinelli, Life in extreme environments. *Nature* **409**, 1092–1101 (2001).

45. G. Borgonie, A. García-Moyano, D. Litthauer, W. Bert, A. Bester, E. Van Heerden, C. Möller, M. Erasmus, T. C. Onstott, Nematoda from the terrestrial deep subsurface of South Africa. *Nature* **474**, 79–82 (2011).

46. J. P. Cassanelli, J. W. Head, Firn densification in a Late Noachian “icy highlands” Mars: Implications for ice sheet evolution and thermal response. *Icarus* **253**, 243–255 (2015).

47. K. M. Cuffey, W. S. B. Paterson, *The Physics of Glaciers* (Academic Press, 2010).

48. C. Huber, A. Parmigiani, B. Chopard, M. Manga, O. Bachmann, Lattice Boltzmann model for melting with natural convection. *Int. J. Heat Fluid Flow* **29**, 1469–1480 (2008).

49. J. J. Buffo, B. E. Schmidt, C. Huber, Multiphase reactive transport and platelet ice accretion in the sea ice of McMurdo Sound, Antarctica. *J. Geophys. Res. Ocean* **123**, 324–345 (2018).

50. J. L. Fastook, J. W. Head, Glaciation in the Late Noachian Icy Highlands: Ice accumulation, distribution, flow rates, basal melting, and top-down melting rates and patterns. *Planet. Space Sci.* **106**, 82–98 (2015).

51. C. I. Fassett, J. W. Head III, Valley formation on martian volcanoes in the Hesperian: Evidence for melting of summit snowpack, caldera lake formation, drainage and erosion on Ceraunius Tholus. *Icarus* **189**, 118–135 (2007).

52. P. Jansson, R. Hock, T. Schneider, The concept of glacier storage: A review. *J. Hydrol.* **282**, 116–129 (2003).

53. D. Turcotte, G. Schubert, *Geodynamics* (Cambridge Univ. Press, 2014).

54. S. Karunatillake, J. M. Keller, S. W. Squyres, W. V. Boynton, J. Brückner, D. M. Janes, O. Gasnault, H. E. Newsom, Chemical compositions at Mars landing sites subject to Mars Odyssey Gamma Ray Spectrometer constraints. *J. Geophys. Res. E Planets* **112**, E08S90 (2007).

55. G. J. Taylor, W. V. Boynton, J. Brückner, H. Wänke, G. Dreibus, K. E. Kerry, J. M. Keller, R. C. Reedy, L. G. Evans, R. D. Starr, S. W. Squyres, S. Karunatillake, O. Gasnault, S. Maurice, C. d'Uston, P. Englert, J. M. Dohm, V. Baker, D. Hamara, D. M. Janes, A. L. Sprague, K. J. Kim, D. Drake, Bulk composition and early differentiation of Mars. *J. Geophys. Res. E Planets* **112**, 10.1029/2005JE002645 (2007).

56. B. C. Hahn, S. M. McLennan, G. J. Taylor, W. V. Boynton, J. M. Dohm, M. J. Finch, D. K. Hamara, D. M. Janes, S. Karunatillake, J. M. Keller, K. E. Kerry, A. E. Metzger, R. M. S. Williams, Mars Odyssey Gamma Ray Spectrometer elemental abundances and apparent relative surface age: Implications for Martian crustal evolution. *J. Geophys. Res. E Planets* **112**, E03S11 (2007).

57. V. Belleguic, P. Lognonne, M. Wieczorek, Constraints on the Martian lithosphere from gravity and topography data. *J. Geophys. Res. E Planets* **110**, E11005 (2005).

58. S. Goossens, T. J. Sabaka, A. Genova, E. Mazarico, J. B. Nicholas, G. A. Neumann, Evidence for a low bulk crustal density for Mars from gravity and topography. *Geophys. Res. Lett.* **44**, 7686–7694 (2017).

59. G. A. Neumann, M. T. Zuber, M. A. Wieczorek, P. J. McGovern, F. G. Lemoine, D. E. Smith, Crustal structure of Mars from gravity and topography. *J. Geophys. Res. E Planets* **109**, E08002 (2004).

60. M. A. Wieczorek, R. J. Phillips, Potential anomalies on a sphere: Applications to the thickness of the lunar crust. *J. Geophys. Res.* **103**, 1715–1724 (1998).

61. M. Wieczorek, MMesch, E. S. de Andrade, I. Oshchepkov, SHTOOLS: Version 3.4; available at https://doi.org/10.5281/zenodo.61180.

62. M. H. Carr, J. W. Head, Martian surface/near-surface water inventory: Sources, sinks, and changes with time. *Geophys. Res. Lett.* **42**, 726–732 (2015).

63. E. N. Rosenberg, A. M. Palumbo, J. P. Cassanelli, J. W. Head, D. K. Weiss, The volume of water required to carve the martian valley networks: Improved constraints using updated methods. *Icarus* **317**, 379–387 (2019).

64. W. Luo, X. Cang, A. D. Howard, New Martian valley network volume estimate consistent with ancient ocean and warm and wet climate. *Nat. Commun.* **8**, 15766 (2017).

65. GLIMS and National Snow and Ice Data Center, GLIMS Glacier Database (National Snow and Ice Data Center, Boulder, CO, 2005, updated 2012).

66. I. Gärtner-Roer, K. Naegeli, M. Huss, T. Knecht, H. Machguth, M. Zemp, A database of worldwide glacier thickness observations. *Glob. Planet. Chang.* **122**, 330–344 (2014).

67. C. M. Dundas, A. M. Bramson, L. Ojha, J. J. Wray, M. T. Mellon, S. Byrne, A. S. McEwen, N. E. Putzig, D. Viola, S. Sutton, E. Clark, J. W. Holt, Exposed subsurface ice sheets in the Martian mid-latitudes. *Science* **359**, 199–201 (2018).

68. R. J. Phillips, M. T. Zuber, S. E. Smrekar, M. T. Mellon, J. W. Head, K. L. Tanaka, N. E. Putzig, S. M. Milkovich, B. A. Campbell, J. J. Plaut, A. Safaeinili, R. Seu, D. Biccari, L. M. Carter, G. Picardi, R. Orosei, P. S. Mohit, E. Heggy, R. W. Zurek, A. F. Egan, E. Giacomoni, F. Russo, M. Cutigni, E. Pettinelli, J. W. Holt, C. J. Leuschen, L. Marinangeli, Mars North Polar Deposits: Stratigraphy, age, and geodynamical response. *Science* **320**, 1182–1185 (2008).

69. S. Karunatillake, J. J. Wray, S. W. Squyres, G. J. Taylor, O. Gasnault, S. M. McLennan, W. Boynton, M. R. El Maarry, J. M. Dohm, Chemically striking regions on Mars and Stealth revisited. *J. Geophys. Res. E Planets* **114**, E12001 (2009).

70. L. Ojha, S. Karunatillake, K. Iacovino, Atmospheric injection of sulfur from the Medusae Fossae forming events. *Planet. Space Sci.* **179**, 104734 (2019).