Knickpoints in Martian channels indicate past ocean levels

Sergio Duran1*, Tom J. Coulthard1 & Edwin R. C. Baynes2

On Mars, the presence of extensive networks of sinuous valleys and large channels provides evidence for a wetter and warmer environment where liquid water was more abundant than it is at present. We undertook an analysis of all major channel systems on Mars and detected sharp changes in elevation along the river long profiles associated with steep headwall theatre-like valleys and terraces left downstream by channel incision. These breaks in channel longitudinal slope, headwalls and terraces exhibit a striking resemblance with terrestrial fluvial features, commonly termed ‘knickpoints’. On Earth, such knickpoints can be formed by more resistant bedrock or where changes in channel base-level have initiated erosion that migrates upstream (such as tectonic uplift or sea level change). We observed common elevations of Martian knickpoints in eleven separate channel systems draining into the Martian Northern lowlands. Numerical modeling showed that the common elevations of some of these knickpoints were not random. As the knickpoints are spread across the planet, we suggest that these Martian knickpoints were formed in response to a common base level or ocean level rather than local lithology. Thus, they potentially represent a record of past ocean levels and channel activity on Mars.

The surface of Mars contains many channels, meanders belts and deltas that may have been formed by flowing water1–5. Within these channels, there are dramatic drops in the channel longitudinal profile often associated with large theatre-shaped headwalls6,7. On Earth, such features are termed ‘knickpoints’8 and can be formed as the result of fluvial erosion over layers of different resistance bedrock9 or where an abrupt fall of the base-level (e.g., sea level) generates a vertical offset in the channel bed profile10. Terrestrial knickpoints are also characterized by their upstream migration over time that can leave abandoned terraces and downstream meander cutoffs11–13. The phenomena of a knickpoint propagating upstream and its dynamics have been scrutinised in many field, numerical and physical modelling studies12,13. Typically, terrestrial base-level change knickpoint erosion has been shown to be triggered by an uplift of the river bed14, a change in the river base-level15 or an uplift in coastal areas effectively leading to relative sea-level changes16,17. Common elevations of knickpoints in different streams can indicate a regional forming mechanism, e.g. the movement of a tectonic fault or a drop in relative sea-level8,18 as seen in Fig. 1, rather than lithological controls18. Furthermore, knickpoint formation and migration can be extremely rapid in response to very large flood events, as well as to exceptional floods19,20.

Decades of satellite exploration on Mars revealed a planet extensively dissected by many fluvial-like channels. Beginning in the Southern highlands and extending down to the Northern lowlands, some channels exceed a thousand kilometers in length and drop several kilometers in elevation21,22. These channel systems have few tributaries but contain theatre-shaped head walls and major knickpoints – sometimes referred to as ‘cataracts’ or ‘inner channel headcuts’, – which previous research has suggested to be caused by episodes of bedrock erosion by high-discharge flows22,23. The geographic distribution, orientation and termination of these flood-eroded channels in the Northern lowlands suggest they once flowed into a standing body of water or ocean24,25. Subject to considerable discussion, the presence of an early Northern ocean is also supported by the estimation of the water needed to carve the Martian valley network26, its abrupt termination27, the identification of possible shorelines28–30 and the subsequent explanation of variations in shoreline topography30. The identification of tsunami deposits in the Chryse Planitia and north-western Arabia gives support to the presence of such a body of water at an elevation of ca. −3,795 m earlier in the Late Hesperian at 3.6 Ga31. In addition, deltaic deposits32 provide evidence for a large standing body of water in the Northern lowlands at an elevation of −2,540 ± 177 m around 3.4 Ga ago (around the latter stages of the Late Hesperian, ages herein based on Neukum chronology33). Whilst the current surface conditions on Mars do not support the presence of liquid water21, whether Mars hosted an early Northern ocean and the subsequent evolution of oceans/bodies of water are of significant importance for understanding the early Martian climate and the transition towards the current hydrologic and environmental conditions.

1Department of Geography, Geology and Environment, University of Hull, Hull, UK. 2Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand. *email: S.Duran@2016.hull.ac.uk
Here, we have analyzed the major channel systems spread across Mars using a systematic and automated procedure to identify channel knickpoints likely formed by base-level changes. These knickpoints are geographically widespread and fall into four common elevation zones with tests showing the lower two have a likelihood of being formed by random processes of less than 5% (see Supplementary Material). This suggests that the lower two knickpoint elevation zones were formed either under periods of two stable ocean levels or during two or more phases of fluvial activity coupled with changing Northern ocean levels.

Methods

For this analysis, we selected only large Martian channels with widths greater than 1 km, with no obvious external disruptions to the channel network (e.g. significant craters) and those that flow from the Southern highlands into the Northern lowlands. We covered all longitudes and the location of the channels studied is shown in (Supp. Fig. 2). We used a semi-automated method to identify potential knickpoints by means of the Mars HRSC MOLA Bended global 200 m resolution DEM. Channel networks were highlighted using a flow accumulation method, then a series of MATLAB based tools (see Materials and Methods supplement) that identified breaks in longitudinal channel slope as potential knickpoints. The bottom (lowest) elevation of each knickpoint was then recorded, since it represents the elevation of the contemporaneous ocean level. Each knickpoint was visually checked for features frequently found on terrestrial base-level change knickpoints – e.g. those formed by the movement of a tectonic fault or a drop in relative sea level – and ranked according to how many of these identifiers were present. Such identifiers are: the presence of upslope channel, the identification of vertical incision downstream of the knickpoint, the identification of abandoned terraces downstream of the knickpoint and the identification of incised meanders downstream of the knickpoint (Supp. Figs 4–6). For visual inspection, we used HiRISE (High Resolution Imaging Science Experiment) images of the region where the knickpoint is located. In areas non-covered by HiRISE, we used the Context Camera (CTX) images. On Earth, as base-level change knickpoints migrate upslope, their elevation rise gradually from their base-level as seen in Fig. 1. Thus, knickpoints generated from the same base-level change in separate valleys may have slightly different elevations, so to identify any commonality in the elevation of base-level change knickpoints, we need to look over a range of elevations. Therefore, we assigned a Gaussian Kernel Function for each knickpoint and, subsequently, summed these Kernel functions providing us with a continuous planet-wide Kernel Density Estimate of base-level change knickpoints per elevation (Supp. Fig. 3). This enabled us to identify at which elevations these knickpoints are clustered that we termed knickpoint zones (Supp. Fig. 1). To test the non-random significance of the Kernel Density values displayed in our record, we bootstrapped our sample of 34 knickpoints producing repeated (1,000) resamples with replacements. We assessed whether the clustering of our measured knickpoints were significantly non-random by comparing our record with the bootstrap distribution of resamples (Supp. Fig. 9) which showed the whole record was not significantly non-random. Subsequently, we split our data into knickpoints from zones 1–2 and for 3–4 and carried out the same analysis on each data set (Supp. Figs 10 and 11). These analyses showed that the subsamples for zones 3–4 were significantly non-random, exceeding by some margin the 95% confidence level (Supp. Figs 11 and 12).

Figure 1. Conceptual diagram illustrating how base-level change knickpoints represent dynamic locations recording elevations of the base-level. The left part of the figure represents, seen from above and from the side, fluvial activity on a channel ponding into a base-level. The right part of the figure represents how, subsequent to a change in the base-level, the fluvial activity grades down the channel surface to the elevation of the new base-level. On the top-right figure, the knickpoint marks the boundary in between the part of the landscape adjusted to the new conditions (downstream the knickpoint) and those that are yet to adjust (upstream the knickpoint). On the bottom-right figure, it shows how the knickpoint is formed and migrates upslope as the channel grades down to the new elevation of the base-level. Modified from reference 8 and used under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/). We produced the mosaic in this figure using Adobe’s Illustrator CS6 software (https://www.adobe.com/es/products/illustrator.html).
Discussion

34 potential base-level change knickpoints were identified in 12 major channels spanning the full width of the planet and covering elevations from 900 to −3,500 m, as shown in Figs 2 and 3. None of the channels had equilibrium long profiles, all base-level change knickpoints are located along the Southern edge of the Northern lowlands and every channel contains (at least) one potential base-level change knickpoint.

Our analysis shows four clear elevation zones where there are more than one base-level change knickpoint with the lower two zones having frequencies greater than 2 and 3 respectively, indicating they are unlikely to be random (Fig. 2). Importantly, the lowest two zones have knickpoints from geographically distant channels – thereby making it less likely that the common knickpoint elevation was due to a common geological control (e.g. resistant lithology at the same elevation). Therefore, we suggest that the knickpoints were formed as the non-equilibrium channels adjusted their long profiles to a common – planet wide – base level, as sketched in Fig. 1 and evidenced in Fig. 3. Whilst we cannot completely rule out that the knickpoint zones are due to other controls, we argue that the most likely explanation is that the common knickpoints capture past ocean/sea levels.

Importantly, in support of this explanation, the elevations of our knickpoint zones correspond with ocean levels identified in previous research. The detection of deposits likely emplaced by tsunami waves at an elevation of ca. −3,795 m suggesting an ancient shoreline (during early stages of Late Hesperian) in the same regions where knickpoints in zone 4 are located at the elevation of −3,462 ± 20 m. The identification of deltaic deposits found
in widespread locations provides evidence for a large standing body of water (during the latter stages of the Late Hesperian) at an elevation of ca. −2,500 m, thus fully consistent with the past ocean/sea level inferred from the knickpoint zone 3 at −2,485 ± 40 m. Whilst this latter ocean level has been questioned by recent investigations around the Gale Crater39, the similarity in elevation of our knickpoint zone 3 and deltas within other regions closer to them32 (e.g. Tempe Terra or circum-Chryse Region) suggests that (at least) some of these deltaic deposits were most likely formed by global ocean controls. Importantly, our methodology of using knickpoints, for the first time, enables the independent identification of multiple base/ocean levels within the same record.

Further supporting our argument that knickpoints zones 3 and 4 represent past ocean levels, the timing of flows within channels where knickpoints for zones 3 and 4 occur correspond with the dates of corresponding elevation shoreline/tsunami deposits. For knickpoint zone 4, studies indicate the Kasei Valles, Ares Valles, Maja Valles and Mawrth Valles formed or were active around 3.6 Ga ago35–38 concurrent (in geological time) with the emplacement of tsunami deposits39 and the Deuteronilus Shoreline38. For our knickpoint zone 3, studies show periods of flow in the Kasei Valles and Maja valles35,41, as well as channel formation in Mangala Region35,39 around 3.4 Ga ago.

Therefore, we suggest the following scenario led to the formation of these major channels and their knickpoints. (1) At around 3.6 Ga an ocean or major water body was in place at c. −3,500 m (2) Major flows occurred in the Kasei, Ares, Maja and Mawrth Valles, carving both the channels and also incising into the non-equilibrium channel long profile generating knickpoints at or close to the base level (ocean level) (3) Flow stopped in these channels and over the next 0.2 Ga ocean levels rose to c. −2,500 m (4) A second major period of channel flow occurred in the Kasei and Maja Valles, as well as in the Mangala channels, leading to channel incision and the development of new higher knickpoints close to the new base level.

Morphological evidence in the channels suggests that flows were (relatively) short lived. Firstly, the elevation of the bottom of knickpoints can show a small rise in elevation as they retreat upstream from the originating base level (e.g. Fig. 1). In our examples the relatively small difference in elevation between the knickpoint zones and the corresponding shorelines/ocean levels suggests that these knickpoints did not retreat long distances (compared with the scale of these channels), which indicates their forming events may have been short lived or ephemeral. Secondly, most terrestrial knickpoint research is based on the deviation of a channel long profile from an equilibrium profile41 and, visually, our long profiles are clearly not at equilibrium (Supp. Fig. 8), as confirmed using long profile/drainage area analysis (see Supp. Material). This may be explained by the Martian water being sourced differently from Earth channels42, but can also show that such channels flowed for a period insufficient to achieve any equilibrium, thereby supporting episodic or short periods of flow. It is important to note that an equilibrium channel is not a precondition for the presence of knickpoints generated by base level change, as evidenced by those observed by Mackey et al.15, Germanoski & Ritter16 and in the laboratory experiments of Baynes et al.15. Thirdly, the preservation of the lower knickpoints following base level rise suggests that the base/ocean level rose very rapidly, or more likely during a period of no channel flows. Therefore, our results suggest major channel and ocean activity during the Late Hesperian, with two distinct phases of significant channel flows at 3.6 and 3.4 Ga interacting with a Northern ocean at −3,500 m (3.6 Ga) rising to −2,500 m (3.4 Ga).

A fundamental requirement for separate channel base-level knickpoints to have preserved the signal of the same base level fall is for there to have been no uplift or subsidence of the surface after the knickpoint formation. However, the emplacement of the Tharsis complex has likely caused a major impact on the Martian topography19,30 as can be seen in the Supp. Fig. 7. Our knickpoint zones 1 & 2 are within areas of negligible/no surface

Figure 3. (1) View of the circum-Chryse highland-lowland boundary region, which consists of Chryse Planitia, Western Arabia Terra, Tempe Terra, Margaritifer Terra and Xanthe Terra. This boundary is breached by the circum-Chryse outflow channels, where Kasei Valles Maja Valles Ares Valles and Mawrth Valles exhibit base-level change knickpoint (red points) at −3,500 m. The shoreline mapped by tsunami deposits, and the body of water comprised, is represented in blue color. (2) View of the circum-Chryse and Sirenum Terra highland-lowland boundary region, where a Northern body of water at −2,550 m (defined by the average elevation of deltaic deposits) is represented by color. Kasei Valles, Maja Valles and Mangala region channels exhibit base-level change knickpoints (blue points) at −2,500 m. The images for both panels (1 & 2) are color-coded shaded-relief MOLA digital elevation models (460 m/pixel). Credit: MOLA Science Team, MSS, JPL, NASA. We produced the mosaic and maps in this figure using Esri’s ArcGIS 10.6 software (http://www.esri.com/software/arcgis).
elevation changes, allowing them to precede (or be concurrent with the early stages of) Tharsis emplacement and still preserve their initial elevation. In contrast, our knickpoint zones 3 & 4 are within the area affected by Tharsis, but their geomorphology (e.g. Kasei Valles incises back into regions constructed by Tharsis volcanism) suggests that they formed after Tharsis emplacement (or during the latter stages of). The topographic distribution of the knickpoints within the knickpoint zone 3, being consistent with deltaic deposits, implies no significant modification of the Martian topography since their formation. Therefore, they suggest a post-Tharsis ocean level consistent with a large portion of the Arabia shoreline28–30, which (in turn) indicates a re-occupation — during the late Hesperian — of the older Arabia ocean level (presumed Noachian in age28). However, variations in such shoreline topography requires further studies on the relationship between the evolution of a Northern ocean and the Tharsis volcano.

At its simplest level, knickpoints are markers of (any) disequilibrium within a channel profile, and can be caused by many reasons (e.g., lithological boundaries, base level fall, periodic flow, etc.). Here, we show (i) there are knickpoints on Mars, (ii) the identified knickpoints are at consistent elevations across the Northern part of the planet and not randomly grouped, (iii) they are located close to known past ocean levels, both in elevation and location, (iv) channels with corresponding knickpoints have flowed at the same time as shoreline records were deposited and (v) the knickpoints are not associated with lithological boundaries. This evidence leads to two options for interpretation: knickpoints could either have been formed by (1) a drop in ocean level and the channels grading to that new base level or (2) periodic switching on of the fluvial network and grading to whatever the ocean level is at that moment in time. Given the known chronology of the ocean elevations (i.e., a rise), the fact the channels are not in equilibrium, and the known occurrence of short periods of channel activity (e.g. outburst floods), this favours interpretation 2.

We quite deliberately avoid discussing mechanisms for channel flow or ocean formation and acknowledge that our findings may complement85 or contradict46 other research. However, our results are consistent with a warmer and wetter early Mars climate and suggest that, at stages in Mars’ history, massive channelized flows interacted with Northern oceans at two distinct levels (as proposed in previous investigations47). Furthermore, these findings indicate a complex, dynamic hydrosphere with an active hydrological cycle and an ocean exerting a global control on channel systems.

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References
1. Craddock, R. A. & Howard, A. D. The case for rainfall on a warm, wet early Mars. J. Geophys. Res. 107(E11), 5111 (2002).
2. Baker, V. R. et al. Fluvial geomorphology on Earth-like planetary surfaces: a review. Geomorphology 245, 149–182 (2015).
3. Perkins, J. P., Finnegan, N. J. & de Silva, S. L. Amplification of bedrock canyon incision by wind. Nature Geoscience 8, 305–310 (2015).
4. Baker, V. R. & Kohl, C. R. Martian channel morphology: Maja and Kasei Valles. Journal of Geophysical Research 84, 7961–7983 (1979).
5. Pacifici, A., Komatsu, G. & Pondrelli, M. Geological evolution of Ares Vallis on Mars: Formation by multiple events of catastrophic flooding, glacial and periglacial processes. Icarus 202, 60–77 (2009).
6. Dijkstra, R. A., Whipple, K. X., Lamb, M. P. & Heimsath, A. M. The role of waterfalls and knickzones in controlling the style and pace of landscape adjustment in the western San Gabriel Mountains, California. Geol. Soc. Am. Bull. 127(3–4), 560–583 (2015).
7. Lamb, M. P. et al. Can springs cut canyons into rock. J. Geophys. Res. 111, 7002 (2006).
8. Baynes, E. R. C. et al. River selforganisation inhibits discharge control on waterfall migration. Scientific Reports 8, 2444 (2018).
9. Pazzaglia, F. J. & Gardner, T. W. Fluvial terraces of the lower Susquehanna River. Geomorphology 8, 83–113 (1993).
10. Castillo, M., Bishop, P. R. & Jansen, D. J. Knickpoint retreat and transient channel morphology triggered by base-level fall in small bedrock river catchments: the case of the Isle of Iura, Scotland. Geomorphology 180, 1–9 (2013).
11. Finnegan, N. J. & Dietrich, W. E. Episodic bedrock strathe terrace formation due to meander migration and cutoff. Geology 39(2), 143–146 (2011).
12. Havty, I. et al. Evolution of vertical knickpoints (waterfalls) with resistant caprock: Insights from numerical modelling. J. Geophys. Res. 115, F03028 (2010).
13. Lague, D. The stream power river incision model: evidence, theory and beyond. Earth Surf. Proc. Landf. 39, 38–61 (2014).
14. Attal, M. et al. Testing fluvial erosion models using the transient response of bedrock rivers to tectonic forcing in the Apeninnes, Italy. J. Geophys. Res. 116, F02005 (2011).
15. Crosby, B. T. & Whipple, K. X. Knickpoint initiation and distribution within fluvial networks: 236 waterfalls in the Waipaoa River, North Island, New Zealand. Geomorphology 82, 16–38 (2006).
16. Farías, M. et al. Late Miocene high and rapid surface uplift and its erosional response in the Andes of central Chile (33°–35°S). Tectonics 27, TC1005 (2008).
17. Lamb, M. P., Howard, A. D., Dietrich, W. E. & Perron, J. T. Formation of amphitheatre-headed valleys by waterfall erosion after large-scale slumping on Hawaii. Geological Society of America 119, 805–822 (2007).
18. Pederson, J. L. & Tressler, C. Colorado River long-profile metrics, knickzones and their meaning. Earth Planet. Sc. Lett. 345–348, 171–179 (2012).
19. Anton, L., Matzer, A. E., Stokes, M., Munoz-Martín, A. & De Vicente, G. Exceptional river gorge formation from exceptional floods. Nature Communications 6, 7963 (2015).
20. Larsen, U. J. & Lamb, M. P. Progressive incision of the Channeled Scablands by outburst floods. Nature 538, 229–232 (2016).
21. Baker, V. R. Water and the Martian landscape. Nature 412, 228–236 (2001).
22. Burr, D. M., Carling, P. A. & Baker, V. R. Megaflooding on Earth and Mars. Cambridge University Press. (2009).
23. Goudge, T. A. & Fassett, C. I. Incision of Licus Vallis, Mars, from multiple lake overflow floods. J. Geophys. Res: Planets 123, 405–420 (2018).
24. Clifford, S. M. & Parker, T. J. The evolution of the Martian hydrosphere: Implications for the fate of a primordial ocean and the current state of the northern plains. Icarus 154, 40–79 (2001).
25. Head, J. W. III. et al. Possible Ancient Ocean on Mars. Evidence from Mars Orbiter Laser Altimeter Data. Science 286, 2134–2137 (1999).
26. Luo, W., Cang, X. & Howard, A. D. New Martian valley network volume estimate consistent with ancient ocean and warm and wet climate. Nature Communications 8, 15766 (2017).
27. Hynek, B. M., Beach, M. & Hoke, M. R. T. Updated global map of Martian valley networks and implications for climate and hydrologic processes. *J. Geophys. Res.* 115, E09008 (2010).
28. Parker, T. S., Saunders, R. S. & Schneeberger, D. M. Transitional morphology in West Deuteronilus Mensae, Mars: Implications for modification of the lowland/highland boundary. *Icarus* 82, 111–145 (1989).
29. Citron, R., Manga, M. & Hemingway, D. J. Timing of oceans on Mars from shoreline deformation. *Nature* 555, 643–646 (2018).
30. Perron, J. T., Mitrovica, J. X., Manga, M., Matsuyma, I. & Richards, M. A. Evidence for an ancient Martian ocean in the topography of deformed shorelines. *Nature* 447, 840–843 (2007).
31. Rodríguez, J. A. P. et al. Tsunami waves extensively resurfaced the shorelines of an early Martian ocean. *Scientific Reports* 6, 25106 (2016).
32. Di Achille, G. & Hynek, B. M. Ancient Ocean on Mars supported by global distribution of deltas and valleys. *Nature Geoscience* 3, 459–463 (2010).
33. Michael, G. G. Planetary surface dating from crater size-frequency distribution measu-ments: Multiple resurfacing episodes and differential isochron fitting. *Icarus* 226, 885–890 (2013).
34. Rivera-Hernández, F. & Palucis, M. C. Do deltas along the crustal dichotomy boundary of Mars in the Gale crater region record a northern ocean? *Geophysical Research Letters.* https://doi.org/10.1029/2019GL083046 (2019).
35. Neukum, G. et al. The geologic evolution of Mars: Episodicity of resurfacing events and ages from cratering analysis of image data and correlation with radiometric ages of Martian meteorites. *Earth and Planetary Science Letter* 294, 204–222 (2010).
36. Warner, N., Gupta, S., Kim, J.-R., Lin, S.-Y. & Muller, J.-P. Retreat of a giant catacar in a long-lived (3.7–2.6 Ga) Martian outflow channel. *Geology* 38, 71–74 (2010).
37. Gross, C., Wendt, L., Dumke, A. & Neukum, G. Juventae Chasma and Maja Valles, Mars: Further Evidence for Multiple Flooding Events. 40th Lunar and Planetary Science, The Woodlands Tx., abs. #1890 (2009).
38. Michalski, J. R. & Noe Dobrea, E. Z. Evidence for sedimentary origin of clay minerals in the Mawrth Vallis region, Mars. *Geology* 10, 951–954 (2007).
39. Ivanov, M. A., Erkeling, G., Hiesinger, H., Bernhardt, H. & Reiss, D. Topography of Deuterounius contact on Mars: evidence for an ancient water/mud ocean and long-wavelength topographic readjustments. *Planet. Space Sci.* 144, 49–70 (2017).
40. Chapman, M. G., Gudmundsson, M. T., Russel, A. J. & Hare, T. M. Possible Juventae Chasma sub-ice volcanic eruptions and Maja Valles ice outburst floods on Mars: Implications of Mars Global Surveyor crater densities, geomorphology and topography. *Journal of Geophysical Research* 108(E10), 5113 (2003).
41. Berlin, M. M. & Andersson, R. S. Modeling of knickpoint retreat on the Roan Plateau, western Colorado. *Journal of Geophysical Research*, 112 (2007).
42. Kereszturi, A. Cross-sectional and longitudinal profiles of valleys and channels in Xanthe Terra on Mars. *J. Geophys. Res.* 110, E12S17 (2005).
43. Mackey, B. H., Scheingross, J. S., Lamb, M. P. & Farley, K. A. Knickpoint formation, rapid propagation and landscape response following coastal cliff retreat at last interglacial sea-level highstand: Kaua’i Hawai’i. *GSA Bulletin* 126(7–8), 925–942 (2014).
44. Germanoski, D. & Ritter, D. F. Tributary response to local base level lowering below a dam. *River Research and Applications.* 226, 885–890 (2013).
45. Ramirez, R. R. & Craddock, R. A. The geological and climatological case for a warmer and wetter early Mars. *Nature Geoscience* 11, 230–237 (2018).
46. Wordsworth, R., et al. Global modelling of the early Martian climate under a denser CO2 atmosphere: Water cycle and ice evolution. *Icarus* 222(1), 1–19 (2013).
47. Baker, V. R., et al. Ancient oceans, ice sheets and the hydrological cycle on Mars. *Nature* 352, 589–594 (1991).

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Author contributions
S.D. and T.C. designed and conceived the study. S.D. collected and analyzed the data; S.D. and T.C. interpreted the data. S.D., T.C. and E.B. discussed and interpreted the results. S.D. and T.C. wrote the manuscript, with input from E.B.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to S.D.

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