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Ancient ocean on Mars supported by global distribution of deltas and valleys

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The climate of early Mars could have supported a complex hydrological system and possibly a northern hemispheric ocean covering up to one-third of the planet's surface[1–5]. This notion has been repeatedly proposed[1–5] and challenged[6,7] over the past two decades, and remains one of the largest uncertainties in Mars research. Here, we used global databases of known deltaic deposits, valley networks[8] and present-day martian topography to test for the occurrence of an ocean on early Mars. The distribution of ancient martian deltas delineates a planet-wide equipotential surface within and along the margins of the northern lowlands. We suggest that the level reconstructed from the analysis of the deltaic deposits may represent the contact of a vast ocean covering the northern hemisphere of Mars around 3.5 billion years ago. This boundary is broadly consistent with palaeoshorelines suggested by previous geomorphologic, thermophysic and topographic analyses, and with the global distribution and age of ancient valley networks. Our findings lend credence to the hypothesis that an ocean formed on early Mars as part of a global and active hydrosphere.

Marine deltas are among the most typical coastal landforms on Earth. They exhibit a large diversity of morphology as a result of a combination of several factors including climate, geology, river characteristics, basin bathymetry and waves and tide regimes. Nevertheless, they share the characteristic of being formed ideally at the same elevation all over the planet (the mean global sea level), which is approximated by the geoid. Analyses of terrestrial deltas and their correlation across the planet have given clues on worldwide trends and changes of the mean sea level during the geological history of the Earth[9].

In agreement with the terrestrial paradigm, if early Mars had a global hydrosphere cycling water across the planet by integrating precipitation, groundwater reservoirs, ice accumulation regions and surface runoff towards lakes, seas and possibly a northern hemispheric ocean[1–5], deltas opening into the low-lying northern hemisphere would have formed at a systematic elevation across the planet. Likewise, valley networks draining to the site putatively occupied by the ocean should also show termini aligned with the level reconstructed from the delta analysis and in any case they should not be found below this level. By using the co-registered global database of known martian deltaic deposits[10–12] (Supplementary Table S1 and Fig. S1) and valley networks[8] with the topography from the Mars Observer Laser Altimeter[13] (MOLA), we present a direct geological approach for testing the occurrence of an ancient martian ocean and of equipotential surfaces reflecting its margins. Potentially, by also considering deltas formed in closed basins, this analysis gives clues on any global aquifer saturating the crust and systematically emerging on the surface across the planet[4]. In fact, the planet-wide correlation of the present absolute elevation of martian deltas can be used as a proxy (see the Methods section and Fig. 1) for the past mean global sea level and for the level of a global aquifer, assuming that (1) the present topography is a reasonable representation of that at the time of the putative ocean, and that (2) the deltaic deposits formed during an epoch when the ocean was present and the hydrological activity was widespread and persistent. The former assumption is supported by the fact that the main topographic features of Mars should have been largely in place by the end of the Noachian era (∼3.5 Gyr; refs 14,15). In fact, most valley networks on Noachian terrains follow downslope azimuths predicted by present long-wavelength topography resulting mainly from the ancient formation of the Tharsis rise[14]. The second assumption represents the quintessence of an Earth-like hydrosphere and is supported by the evidence that most valley networks, and thus most associated deposits, were formed during an intense phase of widespread fluvial erosion and deposition occurring near the Noachian/Hesperian boundary (∼3.5 Gyr; refs 8,11,12,15–17) and probably related to the formation of a putative ocean into the northern plains. Concurrently, known deltas are typically found as highly eroded remnants within degraded Noachian[10] or, at the latest, Early Hesperian basins[11,12]. Finally, although delta age differences of up to a few hundreds of millions of years are expected, these would be entirely consistent with the estimated duration of a Noachian–Hesperian ocean on Mars[18].

At a global scale, the 52 deltaic deposits analysed here are preferentially located along the crustal dichotomy of the planet or within a few hundreds of kilometres of distance upslope from it and show a regional correlation with the distribution of valley networks and Noachian terrains (Fig. 2). Moreover, clusters of deposits are concentrated within the Memnonia, Arabia Terra, Elysium Planitia and especially Xanthe Terra regions. Figure 2c shows a plot of all of the delta fronts as a function of longitude. The highstand levels of all of the deltaic deposits show a mean value of about −1,848 m with a standard deviation of 1,126 m (**S0** in Fig. 2c). The distribution and elevation of all of the 52 deltas are quite scattered. Therefore, all of the sedimentary deposits as a group cannot be attributed to an ocean and used to make assumptions about its boundaries or about a global hydrostatic aquifer (Fig. 2c).

In contrast, 17 of the deltas are not contained in a local basin or were formed at the mouth of tributaries opening into outflow channels or other basins that connect to the northern lowlands (∼33% of total, red squares in Fig. 2, O in Supplementary Table S1). Collectively, these delta front elevations approximate an equipotential surface (hereafter referred to as **S**) at the mean elevation of −2,540 m with a standard deviation of 177 m (Fig. 2). Indeed, a contour traced at this elevation effectively outlines a

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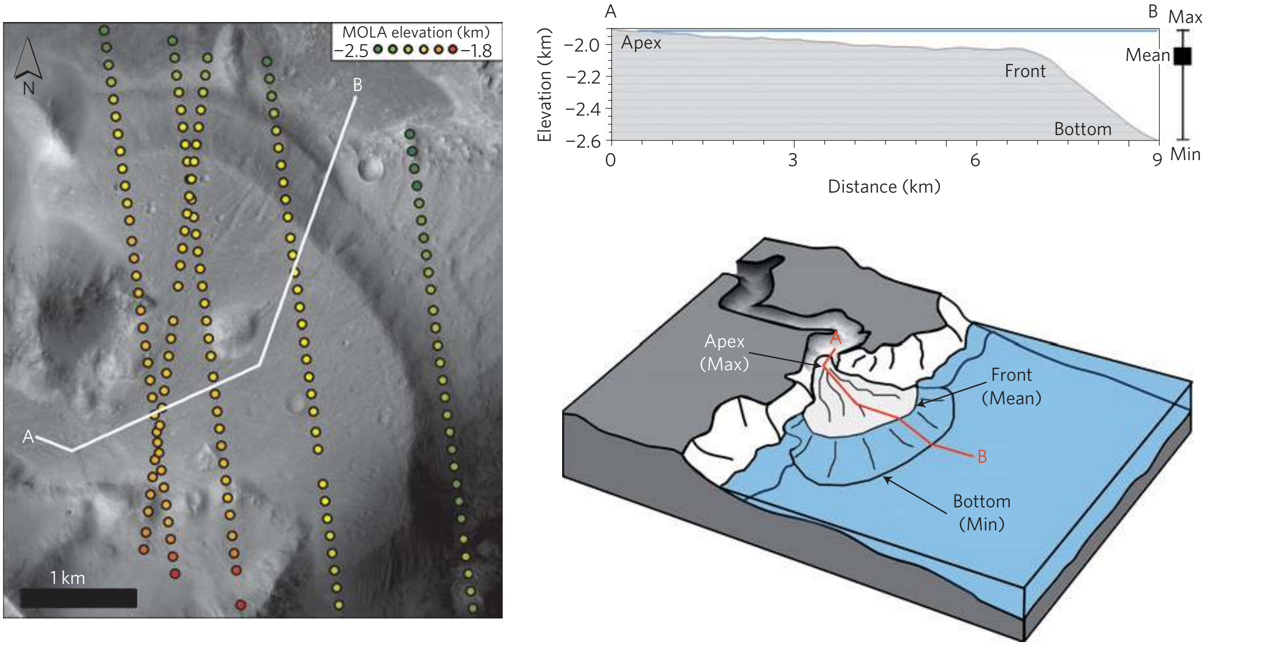
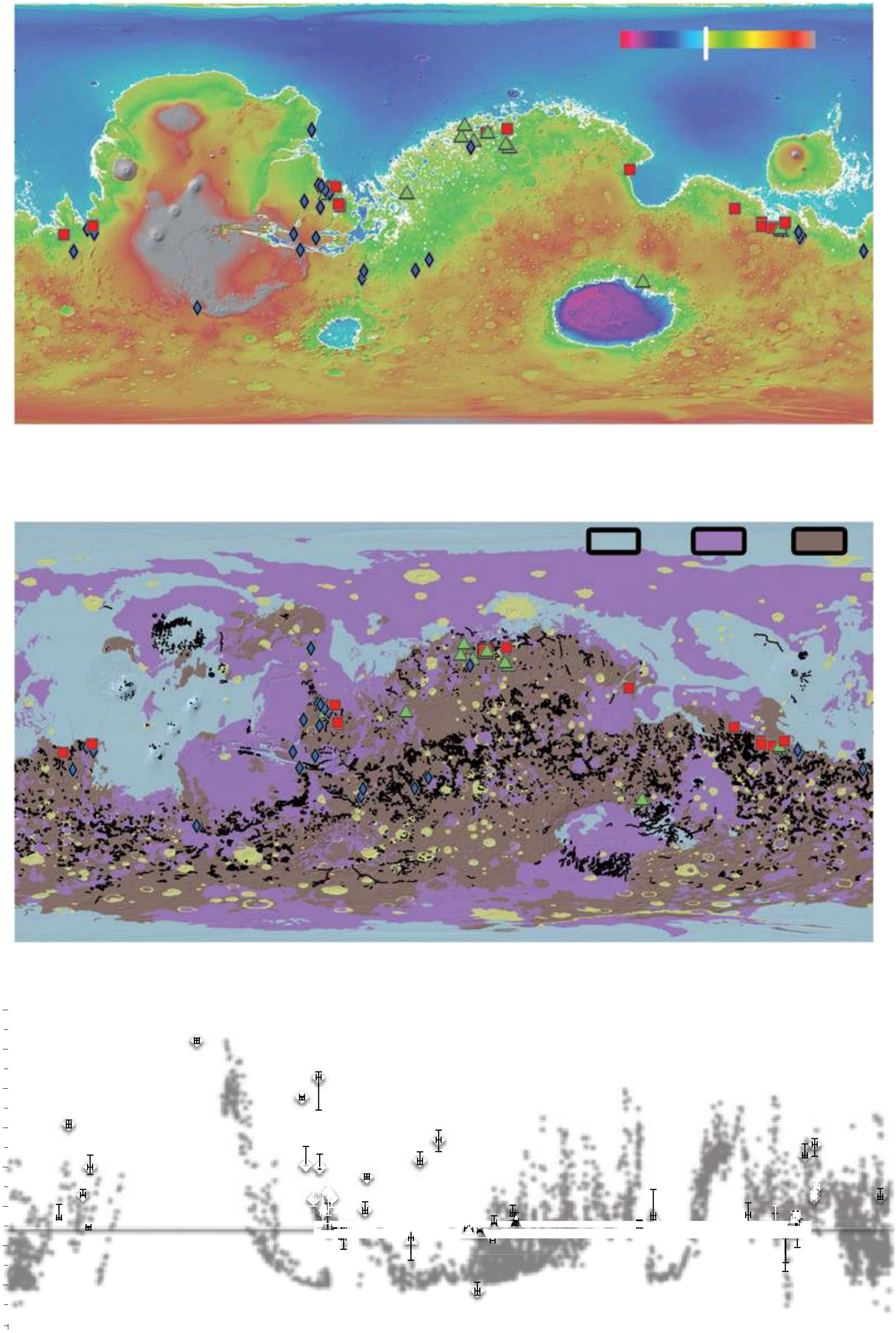


Figure 1 | Data and methodology used for the analysis of the martian deltaic deposits. Left: Context image of a sedimentary deposit in Nepenthes Mensae (No 14 of Supplementary Table S1). The dots indicate the location of the available MOLA-shot measurements. Right: The topographic profile AB shows the morphometry of the deposit (left panel for location). The bottom schematic diagram illustrates the morphometric indicators used for the extraction of the elevation values for each delta. The error bar defines the maximum water level excursion; the black square corresponds to the delta front (mean water highstand). See the Methods section for explanations.

complete closure within and along the margins of the northern lowlands (Fig. 2 and Supplementary Fig. S2), delineating the boundary of the basin within which the deposits formed. The standard deviation (177 m) of **S** is remarkably small if spread across the entire length of the global contour, comparable to the total variation of the terrestrial geoid (∼200 m), and significantly smaller (up to one order of magnitude) than the dispersed values previously obtained for the elevations of Contact 1 (Arabia shoreline, Fig. 2c) and Contact 2 (Deuteronilus shoreline)[3]. Therefore, the deposits topographically connected to the site occupied by the putative ocean define the closest approximation of an equipotential surface as would be expected if they formed in a single large body of standing water encompassing the northern hemisphere of Mars. Moreover, the **S** level is consistent with large portions of the 'Arabia shoreline' previously identified from geomorphologic and topographic analyses[1,4] (Fig. 2c) and is also close to its average value (−2, 499 m, compare the trendline of this contact with **S** in Fig. 2c). In particular, **S** is consistent with the previous observational evidence at (1) Terra Sirenum, (2) in the northern part of Tempe Terra, (3) along the circum-Chryse Planitia region, (4) within northern Arabia Terra and the fretted terrain regions of Deuteronilus Mensae and finally (5) across the crustal dichotomy along the Nepenthes and Aeolis Mensae regions and the surroundings of Gale crater (Fig. 2).

Notably, a further twelve deltas that formed in closed basins (green triangles in Fig. 2) fall within the error bars of the **S** level. However, to include these deposits in the same group of the **S** level, thus totalling ∼55% of the present global database, it must be assumed that a water table should have intersected the surface at this base level all over the planet. Indeed, the **S** level (−2,540 ± 177 m) is virtually the same as the −2,550 m elevation suggested by theoretical calculations for the global distribution of water during the Noachian[4]. Moreover, the latter value was derived from thermophysical properties of Mars with the assumption that water was saturating the crust and ponding in hydrostatic equilibrium on the surface of the planet[4]. Therefore, the analysis of 29 sedimentary deposits (∼55% of total deltas) supports this thermal-hydraulic reconstruction, implying that a vast ocean and large seas were present in the northern hemisphere and in Argyre and Hellas basins, respectively. Several groundwater-fed palaeolakes would have contemporarily emerged within a region of a few hundreds of kilometres wide upslope from the **S** ocean boundary and the crustal dichotomy and around the rim of Argyre and Hellas within craters deep enough to reach the **S** level (Fig. 2a and Supplementary Fig. S2). The palaeolakes would have been almost entirely concentrated in the topographically gradational zone of Arabia Terra, a province where sedimentary and morphological studies support the occurrence of palaeolakes[19,20] and indicate that putative spring deposits exist within craters[21]. Furthermore, an anomalous concentration of craters with extensive exposures of eroded layered sedimentary deposits[19–22] and other distinguishable spectral and elemental properties (including also an elevated hydrogen content) have been reported for Arabia Terra and interpreted to be the results of a past volatile-rich history[19–22]. Similar layered sequences and other evidence suggestive of past lacustrine activity have also been suggested for Hellas and Argyre[4,22,23] and increasingly reported during the past years also for craters along the rim of the main Hellas basin[24,25], thus making the case for the occurrence of a Noachian basin-wide sea within Hellas[23] and a series of surrounding palaeolakes within a range of elevations compatible with the **S** level[24,25]. Finally, although the analysis of deltas cannot uniquely confirm the occurrence of large seas in Hellas and Argyre, if there was an ocean on the northern plains as a component of a martian global hydrosphere, water must have ponded also in these two basins[4].

The reconstructed equipotential surface is also generally consistent with the distribution and terminations of martian valley networks[8] excluding the region between 30° W and 60° E, that is, the topographically gradational zone of Arabia Terra (Fig. 2). Arabia Terra is characterized by smooth elevation variations[5] and it is possible that the **S** surface may mark a different level of the same ocean previously mapped here at slightly higher elevations



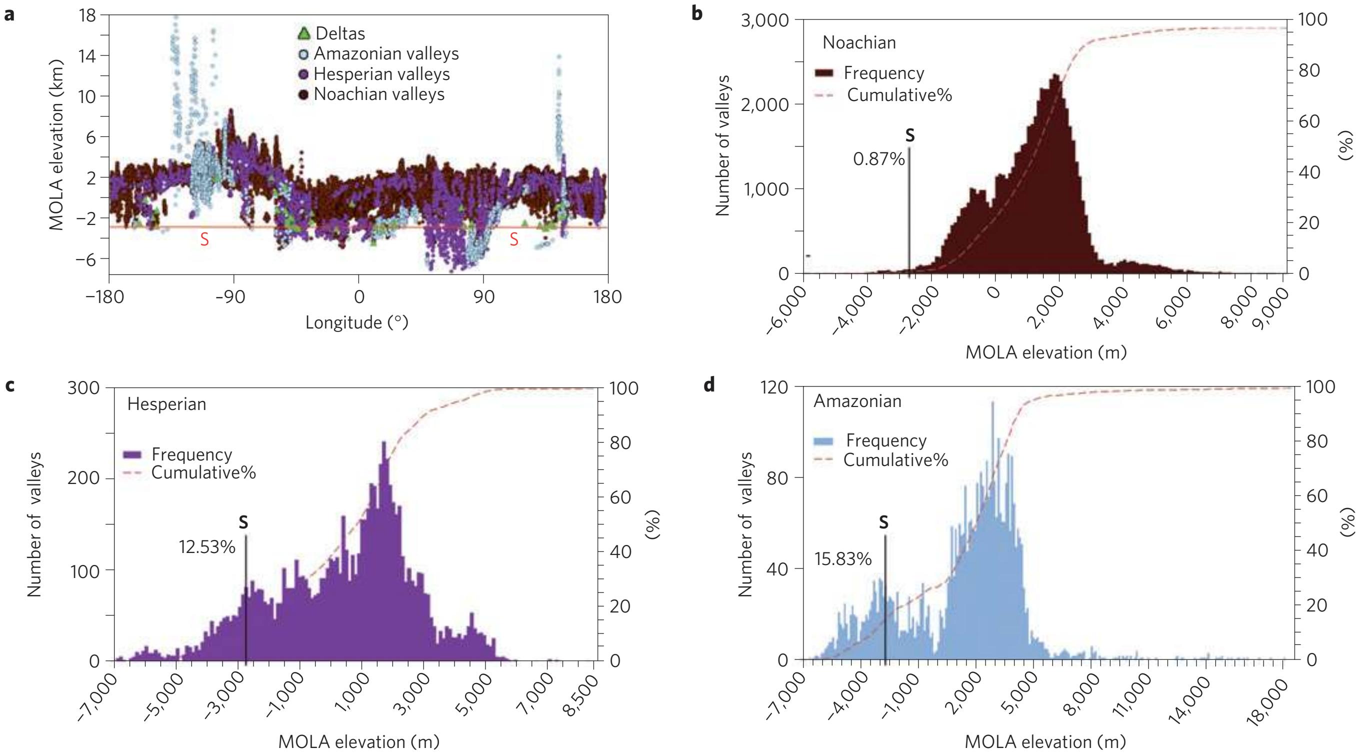


Figure 3 | Distribution and elevation of martian valley networks. a, Elevations of the vertices (both the upper—the initiations, and the lower—the termini) of the martian valleys[8] and of deltas as a function of longitude. The red line shows the **S** boundary. **b–d**, Histograms showing the distribution of Noachian, Hesperian and Amazonian valley vertices (binned at 100 m), respectively, versus MOLA elevations with cumulative frequency (dashed red line): less than 1% of the Noachian valleys terminate below **S** . Hesperian valleys occurring along the eastern walls of Valles Marineris and Hellas Basin (**a**) show more widely distributed (12–16%) terminations below **S** .

Table 1 | Volume, surface area and water/land ratio of the putative ocean.

Ocean level	Volume* (km^3)	GWE† (m)	Surface (km^2)	Water/land ratio
S(−2,540 ± 177 m)	1.24×10^8	547.88	8.11×10^7	0.357

*See the Methods section for details. For comparison, total volume of oceans on Earth is 1.4×10^9 km^3.

†GWE = Global water equivalent layer obtained by spreading the corresponding water volumes over the entire surface of the planet.

with respect to **S** (ref. 5). This discrepancy could also be due to climatic variations similar to those during glacial/interglacial periods on Earth[9]. Figure 3 shows the elevations of all of the vertices (both the upper—the initiations, and the lower—the termini) of the valley segments at a global scale: (1) valley termini show a particularly good alignment with **S** around Terra Sirenum, Aeolis/Nepenthes Mensae and Chryse Planitia, all regions where several valley networks and channels open into the northern plains, (2) most of the valleys terminate at higher elevation with respect to **S**, as would be expected if a planet-wide body of standing water was present at this level. Specifically, less than 1% of Noachian valleys are located at lower elevations, and 12–16% of Hesperian and Amazonian valleys show terminations below the **S** level (Fig. 3). The latter observation probably suggests a progressive retreat of the ocean after its maximum extension during the Late Noachian. Furthermore, the distribution and outlet elevation of the 210 known martian palaeolakes within open basins is also consistent with the elevation of the **S** enclosure: a negligible number of lake outlets show terminations below this level[20].

At the **S** level, the volume of the putative ocean could have reached 1.24×10^8 km^3 (Table 1). Approximately one-third (∼36%) of the planet's surface should have been covered by water ponding and saturating the crust in hydrostatic equilibrium (equivalent to a ∼550-m-deep global layer of water). These estimates are broadly compatible with the amount of water independently predicted for the Noachian[4,26], providing geomorphic and topographic support for theoretical calculations based on thermal-hydraulic considerations. Collectively, these results support the existing theories regarding extent and formation time of an ancient ocean on Mars and imply that surface conditions during that time probably allowed the occurrence of a global and active hydrosphere integrating valley networks, deltas and a vast ocean as main components of an Earth-like hydrological cycle.

Methods

The 52 candidate deltas reported in Supplementary Table S1 were analysed in combination with global topography from MOLA (ref. 13) and all available imagery (Supplementary Fig. S1). We distinguished deltaic features from sub-aerial alluvial fans for the presence of clearly defined depositional fronts suggesting a formation in a body of standing water and the adjustment of the sedimentary deposition to its main stationary level. By using both the global MOLA gridded data set and the individual altimetry profiles (∼75 m spot size along orbital tracks every 300 m), the elevation values of the apex (maximum water level), delta front (mean highstand) and of the distal part (minimum water level) were extracted for each delta (Fig. 1). These values were used as proxies for the maximum water level excursion (apex elevation − distal part elevation) and of the main highstands during the formation of the sedimentary deposits. These morphometric indicators have been plotted as a function of longitude (Fig. 1) to detect possible equipotential surfaces indicative of ancient ocean coastlines. This plot should also reflect the elevation of any emergent groundwater table saturating the planet's crust and ponding on the surface across the planet[4]. Furthermore, we extracted the elevations of all of the vertices (both the upper—the initiations, and the lower—the termini) of all of the fluvial segments mapped for a global database of martian valley networks[8], to compare them with the distribution of deltas. In fact, if an ocean was present during the formation of the deltas, valleys opening into the site occupied by the water should show abrupt terminations approximately at the same elevation indicated by the analysis of the deltas. The present test is not sensitive for the detection of possible isostastic, tectonic and subsidence movements that may have occurred after the disappearance of the putative oceans and displaced the contacts from their original positions. Nevertheless, the obtained variation ($\sigma = 177$ m) for the elevation values of the 17 open deltas is compatible with the variation range (up to some hundreds of metres) that would be expected after the modification of the ancient shorelines resulting from post-Noachian isostasy processes and rebound of the lithosphere resulting from the dissipation of the putative water body[27,28]. Finally, it has been suggested that the putative ocean shorelines were deformed by true polar wander[29]. However, if this was the case, the position/elevation of the deltas would have been also modified to reflect the deformation of the corresponding shoreline. Thus, the topographic distribution of the deltas should also show the same long-wavelength trends visible in the topography of shorelines[29]. Figure 2c shows that the distribution of deltas does not contain such a long-wavelength trend. Therefore, our results seem to rule out the possibility that the ocean contacts were displaced by true polar wander. Ocean volume estimate was obtained by considering water within the enclosure determined by **S** along the northern plains in addition to bodies of standing water in other low-lying basins such as Hellas and Argyre, as well as other palaeolakes ponding at the same base levels across the planet (Table 1). The distribution of possible palaeolakes and thus the resultant volume estimate could be overestimated because of the possibility that some of the craters formed later.

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Author contributions

G.D.A. conceived this research study, implemented the deltas' catalogue and the topographic analyses, and wrote the paper. B.M.H. compiled the valley networks database, discussed the results and contributed to the manuscript.

Additional information

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