LETTERS

Evidence for an ancient martian ocean in the topography of deformed shorelines

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A suite of observations suggests that the northern plains of Mars, which cover nearly one third of the planet's surface, may once have contained an ocean[1–7]. Perhaps the most provocative evidence for an ancient ocean is a set of surface features that ring the plains for thousands of kilometres and that have been interpreted as a series of palaeoshorelines of different age[1,7]. It has been shown, however, that topographic profiles along the putative shorelines contain long-wavelength trends with amplitudes of up to several kilometres[4,5,8], and these trends have been taken as an argument against the martian shoreline (and ocean) hypothesis[8]. Here we show that the long-wavelength topography of the shorelines is consistent with deformation caused by true polar wander—a change in the orientation of a planet with respect to its rotation pole—and that the inferred pole path has the geometry expected for a true polar wander event that postdates the formation of the massive Tharsis volcanic rise.

Parker *et al.*[1,3] and Clifford and Parker[7] used an array of geologic and topographic features to identify several possible palaeoshorelines near the margins of the northern plains of Mars. Two of these can be traced without major interruptions for thousands of kilometres (Fig. 1): the Arabia shoreline (contact 1 of refs 1 and 3), which coincides roughly with the dichotomy in crustal thickness between the northern and southern hemisphere, and the Deuteronilus shoreline (contact 2 of refs 1 and 3), which is inferred to be younger because it is encircled by the Arabia shoreline and is less degraded. However, subsequent studies have challenged the notion that these features are shorelines[9]. The most basic objection stems from the observation that topographic profiles along the contacts do not follow surfaces of equal gravitational potential (that is, sea level)[4,5,8], as the margins of a standing body of water should. In particular, the contacts contain significant long-wavelength trends, with amplitudes of ~2.5 km for Arabia and ~0.7 km for Deuteronilus (Fig. 1).

The antiquity of the putative shorelines (at least 2 billion years (Gyr), the age of most of the northern plains surface[10]) allows for the possibility that they have been subject to long-wavelength, large-amplitude deformation since their formation. On Earth, true polar wander—TPW, the reorientation of the planet relative to its rotation pole—has been implicated in very-long-wavelength sea-level variations with timescales exceeding 10^6–10^8 years (refs 11, 12). In the following, we investigate whether TPW also provides a plausible explanation for the observed deformation of the Arabia and Deuteronilus contacts on Mars. That is, we seek a TPW path that is consistent with the displacements of these contacts away from an ancient equipotential surface, and that is compatible with the basic physical principles governing the rotational dynamics of a terrestrial planet.

The present-day figure of Mars provides an important constraint on the expected geometry of any TPW event that postdates the

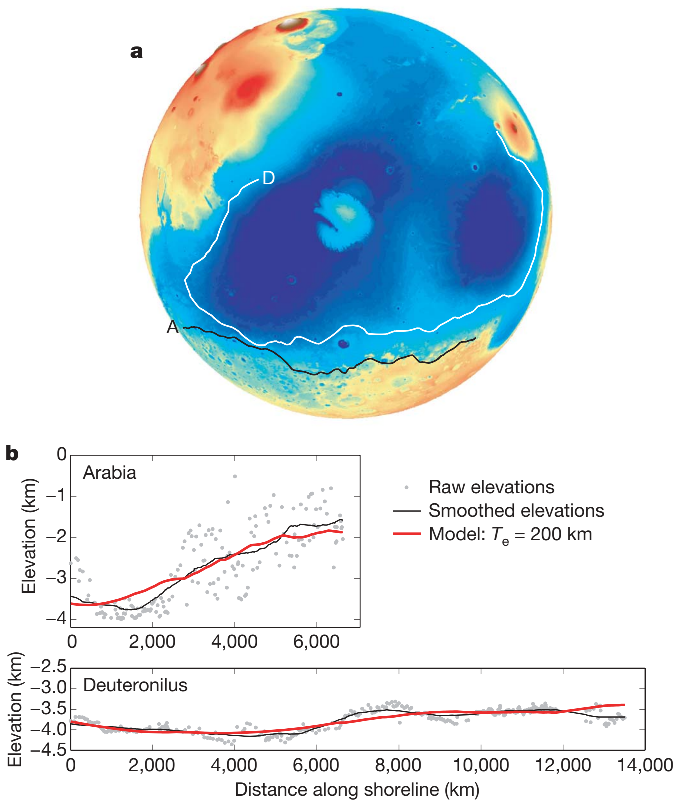

Figure 1 | Possible palaeoshorelines on Mars. a, Map of the northern hemisphere of Mars showing the portions of the hypothesized Arabia (black line A) and Deuteronilus (white line D) shorelines used in our analysis. Shoreline locations are from Carr and Head[8]. Orthographic spherical projection centred on the north pole. To avoid joining contacts that may have been formed at different times or by different processes, we used the longest section of each shoreline that can be traced continuously. This also avoids portions of the shorelines that may have been modified by more recent processes, such as erosion and sedimentation near the outflow channels in Chryse Planitia, crustal intrusion near Olympus Mons and west Tempe Terra, and sedimentary infilling in Isidis. **b**, Topographic profiles along the Arabia and Deuteronilus shorelines, beginning at locations A and D. The points are Mars Orbiter Laser Altimeter (MOLA) elevations reported by Carr and Head[8], and the black lines are 2,000 km moving averages. The short-wavelength scatter arises at least in part from generalization of the mapped shorelines in areas of complex topography[8], and detailed examination of these regions[30] suggests that the actual short-wavelength variations in elevation are small. Vertical and horizontal scales are the same for both profiles. Elevations are relative to the present-day 6 mbar geoid. Red lines are fits of equation (3) to the unsmoothed shoreline elevations for T_e = 200 km (see Methods and Table 1).

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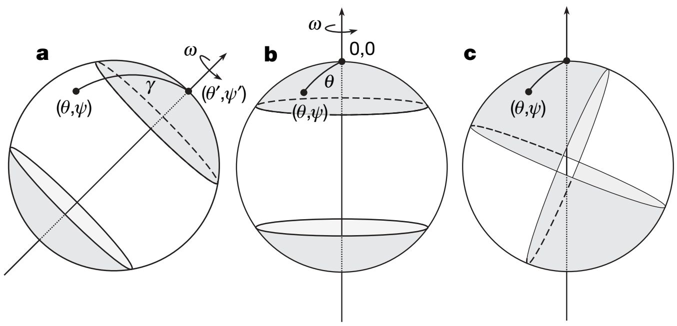

Figure 2 | Changes in topography due to TPW. a and b show the geographically variable component of the centrifugal potential for a TPW event that displaces the north pole of a planet with rotation rate ω from some original position (θ', ψ') (a) to the present orientation (b). In each state, the centrifugal potential is defined by a degree-two, order-zero spherical harmonic (that is, an oblateness term) plus a constant term, as illustrated by the shading. The change in the potential, and the associated change in topography, is characterized by a degree-two, order-one 'quadrential' geometry (c). These changes are zero along two great circles perpendicular to the pole path. The first great circle includes the point halfway along the (great circle) arc joining the initial and present pole position, and the second great circle is perpendicular to the first. The perturbation reaches a maximum value at four sites along the great circle that includes the pole path, 45° from the zeroes. The amplitude of the perturbation in the potential is a function of the displacement of the pole, while the topographic deflection associated with this perturbation is also a function of the thickness of the elastic lithosphere T_e (see Methods). The point (θ, ψ) represents an observation site fixed to the surface geography. All geographic coordinates are relative to the final pole location.

formation of the Arabia and Deuteronilus contacts. The long-term motion of a planet's rotation axis is controlled by the orientation of the non-hydrostatic geoid at spherical harmonic degree two[13,14]. On Mars, the degree-two, non-hydrostatic geoid is dominated by the Tharsis rise[15], an immense volcanic construct centred slightly north of the equator[16]. The emplacement of an excess mass such as Tharsis will drive TPW that brings it to a position closer to the equator[13], although this tendency may be inhibited by the presence of an elastic lithosphere[14,17] (see Supplementary Information). Equivalently, an excess mass near the equator will also resist a reorientation that would move it further from this position. Thus, any TPW of Mars occurring after the emplacement of Tharsis should, if driven by a load smaller than Tharsis, be constrained to follow a path that keeps Tharsis near the equator; such a path would be a great circle 90° from the centre of Tharsis[17].

If a TPW event deformed the Arabia and Deuteronilus contacts, it would probably have been constrained to this geometry, because the contacts appear to be younger than Tharsis. The maps of Parker *et al.*[1] and Clifford and Parker[7] indicate that the Deuteronilus contact, and possibly a section of the Arabia contact, follows the outer margin of the Olympus Mons aureole, one of the youngest features on the Tharsis rise. The observation that the outflow channels in Chryse and Amazonis Planitiae, carved by floods that are the most likely source of ocean water[2,5,6], have eroded the outer margins of Tharsis further supports this ordering of ages.

With this physics in mind, we next turn to a direct estimate of palaeopole locations based on the assumption that the contacts are indeed shorelines and that their long-wavelength deformation (Fig. 1) is due to TPW. Polar motion leads to a geographically variable change in a planet's solid surface and geoid (sea surface). On a planet with an elastic lithosphere, these deflections will differ, even after all viscous stresses are relaxed, leading to a non-uniform change in sea level, and therefore also surface topography. The geometry of TPW-induced changes in topography[11,12] is illustrated schematically in Fig. 2. Our search for the palaeopoles followed the procedure described in the Methods. For each shoreline, we identified the palaeopole location that minimizes the misfit between the observed deformation along the contact and the predicted topographic response to the change in centrifugal potential. The topographic response was computed using fluid Love number theory. Table 1 lists the best-fit palaeopoles for various values of the lithospheric thickness T_e and Fig. 3 plots these locations for the specific case $T_e = 200$ km. The fits we obtained (Table 1; thick model line in Fig. 1a for $T_e = 200$ km) demonstrate that deformation associated with TPW can accurately reconcile the observed long-wavelength trends in both shorelines.

These palaeopoles are remarkable for three main reasons. First, the palaeopoles imply roughly 30–60° of net TPW since the formation of the Arabia shoreline and 5–25° since the formation of the Deuteronilus shoreline. These TPW angles are consistent with the relative ages of the shorelines, in the sense that the younger Deuteronilus shoreline corresponds to a pole location closer to the present-day pole. The location of the Arabia palaeopole implies that the oldest ocean was centred in the tropics rather than in the north polar region. Second, the best-fit palaeopoles for both shorelines lie within a few degrees of the same great circle (which passes through the present-day poles along the 335° E meridian), the expected path for TPW driven by an axisymmetric load[13]. This alignment is unlikely to occur by coincidence: the probability of randomly placed points falling this close to the same meridian, and in the appropriate age progression, is less than 0.0025. Nor is the alignment of the palaeopoles likely to be an artefact of background trends in Mars' large-scale topography, given the large difference in amplitude (Fig. 1) between shoreline features that are in close proximity to one another. Finally, the great circle path through the palaeopoles is approximately 90° from the centre of the Tharsis rise (6.7° N, 248.3° E; ref. 16, Fig. 3). As discussed above, this is the expected path of a post-Tharsis TPW event. The probability of randomly placed points falling this close to a great circle 90° from Tharsis is less than 0.0001.

What is the size and orientation of the post-Tharsis load necessary to drive our inferred TPW event? The answer to this question depends on the extent to which Tharsis itself perturbed the rotation pole (see Supplementary Information for a detailed discussion of this point, as summarized below). If the development of Tharsis moved the pole to a location near the great circle path inferred from the shorelines' deformation (Fig. 3), then the equations governing rotational stability suggest that the displacement of the pole was either very small or nearly 90° (refs 14, 17); that is, Tharsis originally formed in either a nearly equatorial or nearly polar location. The former, small Tharsis-driven TPW solution precludes the possibility that surface mass loads were responsible for the post-Tharsis TPW that deformed the shorelines (Fig. 3, Table 1), and in this case internal loads associated with mantle convection were the probable driving mechanism for the TPW. In contrast, if Tharsis drove a large excursion of the pole[18,19], a scenario less favoured in terms of the present-day figure of Mars (see Supplementary Information), then surface loads could have been sufficient to drive the subsequent TPW. In this

Table 1 | Fluid Love numbers and best-fit palaeopole locations

			Arabia			Deuteronilus		
T_e (km)	h_f	$(1 + k_f)$	Latitude, longitude	Z (km)	$\sigma_{r.m.s.}$ (km)	Latitude, longitude	Z (km)	$\sigma_{r.m.s.}$ (km)
100	1.928	2.053	30, 332	−2.55	0.725	66, 340	−3.70	0.155
200	1.663	1.899	40, 334	−2.25	0.619	79, 337	−3.70	0.159
300	1.517	1.817	49, 332	−2.15	0.595	82, 327	−3.75	0.160
400	1.330	1.714	58, 327	−2.15	0.582	84, 326	−3.75	0.160

scenario, physical considerations suggest that the mass load(s) would lie near the great circle that includes our inferred TPW path (Fig. 3), that is, a path that keeps the pole ~90° from Tharsis.

Given the challenge of identifying evidence of ancient internal loads that may no longer have an observable signature, we briefly review candidate surface loads for the large Tharsis-driven TPW scenario. The gravity signatures of most major impact basins—such as the Argyre basin (Fig. 3), which lies along the inferred great circle path—indicate that they are not significant mass anomalies[15,20], and are therefore unlikely to have influenced the location of Mars' rotation pole. In contrast, the Elysium volcanic province and the Utopia impact basin (Fig. 3) are characterized by significant gravity highs[15], the latter owing to infilling by a large volume of material[21], and both lie on or near the great circle path. It is also interesting to note that the centroids of the Arabia and Deuteronilus palaeobasins (Fig. 3), which we calculated by subtracting the modelled deformation from the present topography, lie very close to the great circle defined by our inferred TPW path. Thus, loading and unloading of these basins with water and sediment might also have influenced the pole's position along this path, although the magnitude of this effect would depend on the geometry of the load redistribution (see Supplementary Information).

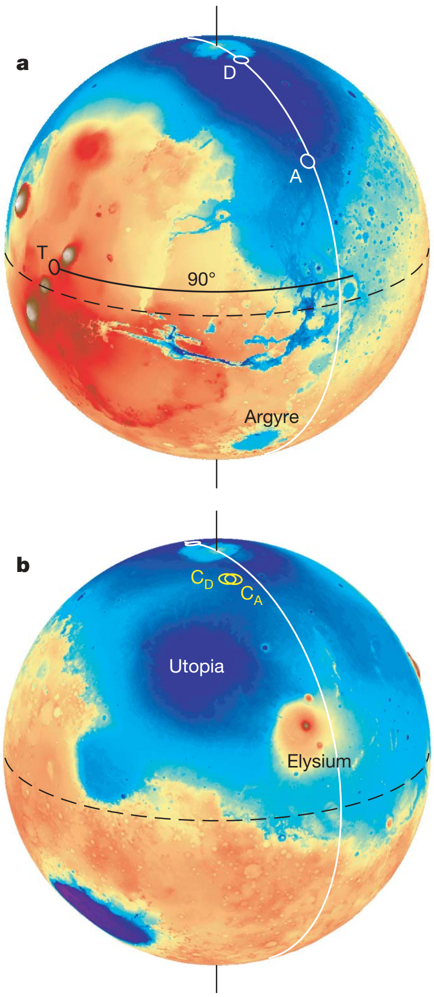

Figure 3 | TPW path that reconciles shoreline deformation. **a**, Best-fit palaeopoles inferred from the topography of the Arabia and Deuteronilus shorelines (small white circles labelled A and D) for $T_e = 200$ km (see Methods and Table 1), a value close to most recently published estimates for Mars' lithospheric thickness[25,28,29]. The palaeopoles fall along a great circle (white line) that follows the 335° E meridian. This great circle is nearly perpendicular to the Tharsis rise, as shown by the black line extending 90° east from the centre of Tharsis (black circle T). Palaeopoles for other values of T_e, which fall along the same great circle, are listed in the Methods. Orthographic spherical projection centred at 20° N, 30° E. **b**, View from the opposite side of Mars, showing the depth-weighted centroids of the Arabia (C_A) and Deuteronilus (C_D) palaeo-ocean basins. Orthographic spherical projection centred at 20° N, 210° E. Locations of the Argyre and Utopia impact basins and the Elysium volcanic rise are labelled. The present-day equator (dashed line) and rotation poles are shown in both panels.

Other processes may have contributed to the long-wavelength, large-amplitude topographic trends observed in the Arabia and Deuteronilus contacts. For example, the flexural response to the removal of the oceans would have altered the shoreline topography[22], but numerical calculations indicate that the amplitude of this response would be far too small to explain the observed trends or to affect the best-fit palaeopole locations significantly (see Supplementary Information). We also used similar numerical procedures to predict the flexural response to the development of the Tharsis rise. In this case, the amplitude can be significant[23], but the predicted trend, which diminishes with distance from Tharsis, does not match the elevation profile of either shoreline. Of course, this reasoning is also consistent with the conclusion that Tharsis was largely emplaced before the TPW episode we have invoked to explain the shoreline deformation.

The effect of internal loading on the observed shoreline deformation, either through the direct effect of dynamic topography[24,25] or via TPW-driven deformation, is difficult to assess. The greatest possible age difference between the Arabia shoreline, which may be as old as ~4 Gyr (ref. 7), and the Deuteronilus shoreline, which encircles the Hesperian age[10] Vastitas Borealis Formation and is therefore at least ~2 Gyr old, is ~2 Gyr, and the diminution with time of the observed long-wavelength trends is roughly a factor of four (Fig. 1). Thus, dynamic topography would have had to diminish in amplitude by a factor of four over a period of at most 2 Gyr, and subsequently a much smaller amount over a period of at least 2 Gyr. However, a transient convective event, such as wholesale overturn of the mantle due to thermochemical instability[26], might well attenuate in intensity on the timescale separating the Arabia and Deuteronilus shorelines, and thus contribute to the observed shoreline topography either directly through dynamic topography or indirectly by inducing TPW. As noted above, internal loading would be required to explain the inferred TPW path in Fig. 3 in the event that the growth of Tharsis drove relatively little TPW.

The long-wavelength deformation of the Arabia and Deuteronilus contacts has been used as a primary argument against their interpretation as shorelines, and has cast doubt on the idea that large standing bodies of water once existed on Mars. Our results support the hypothesis that the present topography of Mars, as sampled by the contacts, may not be representative of the topography at the time these features were formed. In particular, the difference is consistent with a TPW path that matches the expected rotational dynamics of Mars. The plausibility of an ancient northern ocean suggests several possible features that should serve as a focus for current and future Mars exploration, including the preservation of coastal and submarine sedimentary features such as transgressive–regressive sequences and turbidites, and the presence of relict ice in the sediments of the northern lowlands.

METHODS

We use fluid Love number theory to calculate the topographic response to a TPW event. Consider the initial rotational state shown in Fig. 2a, where (θ', ψ') are the colatitude and east longitude of the ancient north rotation pole. The centrifugal potential in this configuration at an arbitrary observation site (θ, ψ) is given by[27]:

$$\phi(\theta,\psi) = \frac{1}{3}\omega^2 a^2 - \frac{1}{3}\omega^2 a^2 P_{2,0}(\cos\gamma) \qquad (1)$$

where ω and a are the rotation rate and mean radius, and γ is the angular distance between the observation site and the rotation pole (Fig. 2a). The function $P_{2,0}$ is the unnormalized degree-two, order-zero Legendre polynomial: $P_{2,0}(\cos\eta) = \frac{1}{2}(3\cos^2\eta - 1)$.

Assuming no change in ω, the perturbation in the centrifugal potential at (θ, ψ) as the rotation vector wanders from the initial orientation to the present one (Fig. 2b) is:

$$\Lambda(\theta,\psi) = \frac{1}{3}\omega^2 a^2 [P_{2,0}(\cos\gamma) - P_{2,0}(\cos\theta)] \quad (2)$$

Equation (2), represented graphically in Fig. 2c, describes the geometry of the topographic response to TPW. The amplitude of the response is[12]:

$$\Delta T(\theta,\psi) = \frac{\Lambda(\theta,\psi)}{g}\left[h_f - (1+k_f)\right] + Z \quad (3)$$

where g is the surface gravitational acceleration, the parameters h_f and k_f are the degree-two fluid h and k tidal Love numbers, and Z is a constant included because the sea surface potential at the time of shoreline formation is not necessarily the same as the potential that defines the present geoid. The fluid Love numbers are functions of Mars' density structure[28] and lithospheric thickness. Table 1 lists calculated values of h_f, which governs the solid surface displacement, and $(1 + k_f)$, which governs the geoid or sea surface displacement, as a function of the elastic thickness of the lithosphere T_e.

For each shoreline, we identified the palaeopole location and the value of Z that minimize the root-mean-square deviation ($\sigma_{r.m.s.}$) between equation (3) and the unsmoothed shoreline topography in Fig. 1. Best-fit palaeopoles and $\sigma_{r.m.s.}$ values for $100\,km \leq T_e \leq 400\,km$ (a range that encompasses most estimates for Mars[25,28,29]) are listed in Table 1.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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