PLANETARY SCIENCE

Mars at the tipping point

Maria T. Zuber

There's a big problem with the idea of ancient oceans on Mars: if they were contained within the 'shoreline' visible today, sea level would not have been level. Could it be that Mars has since tipped over?

Despite spectacular *in situ* chemical and geological evidence for water on the surface of ancient Mars, courtesy of NASA's Opportunity and Spirit rovers[1,2], the temporal persistence and the spatial extent of surface water during the planet's early years remain unclear. Early studies raised the possibility that there was once an ocean in the lowlands of Mars's northern hemisphere[3,4] (Fig. 1), an idea based on the identification of 'palaeo-shorelines' in orbital images. Given the absence of preserved shorelines of a similar age — at least 2 billion years old — on Earth, their identification on Mars is necessarily a subjective endeavour[5]. Nevertheless, credible additional analyses do support the hypothesis[6,7]. On page 840 of this issue, Perron *et al.*[8] present a quantitative analysis that removes arguably the main objection to the shoreline interpretation.

This objection is that a shoreline must follow a line of constant gravitational potential: the 'geoid' on Earth, the 'areoid' on Mars. Mapped onto a topographic profile that indicates the level of fill, such an equipotential surface represents 'sea level'. Once Mars's topography and gravitational field had been accurately mapped[9–11] in the late 1990s, it became apparent that the traces of the previously hypothesized shoreline deviated from an equipotential surface. Unless these deviations could be explained, the observed features could not plausibly have originated as the edge of an ocean. Given the extent of the mapped shorelines, which extend over thousands of kilometres, any explanation for this deviation would have to reflect a process that was global in scale.

Perron *et al.*[8] demonstrate that the deviations of a couple of prominent palaeo-shorelines might be explained by a phenomenon known as 'true polar wander'. This is the reorientation of a planet with respect to its spin axis, and requires a significant mass redistribution on or within a planet[12]. In essence, the authors calculated how the topography of a planet deforms in response to a change in rotational potential as the planet reorients in response to a large load, and tested whether this could have been responsible for the modification of the mapped shorelines.

But why would a planet reorient itself at all? In general, a planet rotates stably around its axis of minimum inertia. The plane normal to that axis, approximately the equatorial plane, is often flattened owing to the centrifugal effect of rotation. The equatorial region of Mars has a huge excess mass associated with the vast Tharsis volcanic province (Fig. 1). Earth's largest volcano, Mauna Loa, which rises almost 10 kilometres above the Pacific Ocean floor to form a large part of the island of Hawaii, has an estimated volume of some 40,000 km^3. The volume of Tharsis is about 10,000 times greater. Such a bulging waistline would be impressive enough on Earth, but is even more so on Mars, which has only an eighth of Earth's volume.

Tharsis probably formed early in martian history[13], during the planet's Noachian era[14], some 3.8 billion years or more ago. Wherever on Mars Tharsis originally formed, its massive load would have reoriented to situate itself near the equator, and so form a stable rotational configuration. Structural superposition relationships indicate that the shorelines post-date the emplacement of Tharsis, and so its formation

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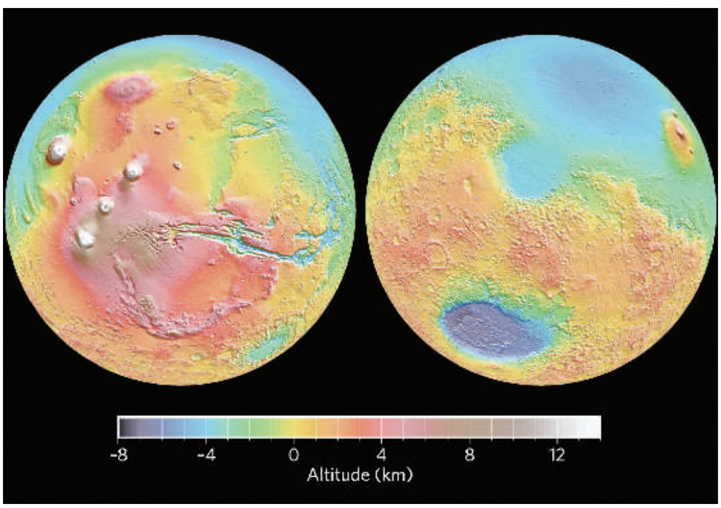

Figure 1 | Topographic maps of Mars. These maps show the Tharsis province (in red and yellow in the left-hand image), and the lowlands of the northern hemisphere (in blue in the upper parts of both images) that are the proposed site of an ancient ocean.

NATURE

50 & 100 YEARS AGO

50 YEARS AGO

When reindeer were introduced into Scotland some ten years ago, a significant factor was that the various ground, rock and tree lichens eaten by reindeer play little part in the diet of red deer, roe deer, sheep, or other indigenous animals... In northern Scandinavia there are more than 600,000 domesticated reindeer and in the northern USSR approximately two million, valued for their meat, skins, milk and hair, and for transport. These benefits have led to imports of reindeer in Alaska, Canada and South Georgia... There were many reindeer in Scotland in prehistoric times, and these were probably hunted with red deer. Why the wild reindeer died out while the red deer remained is unknown... reindeer meat was probably more popular, and the pre-firearm techniques of the chase were not adequate to eliminate the fleeter red deer.

From *Nature* 15 June 1957.

100 YEARS AGO

The closing months of 1906 and the opening months of 1907 are likely to be long remembered by electrical engineers as a period of a remarkable recrudescence of interest in the subject of incandescent electric lamps. For many years the familiar carbon filament lamp has been the only commercial incandescent electric lamp, in spite of its threatened extinction by the invention of the Nernst lamp in 1897–1898. The feeling of uncertainty caused by this discovery was short-lived... the electrical world settled down with the conviction that the threatened revolution was not destined to be achieved. But in the meantime inventors were busy... The tungsten lamp appears to have a brilliant future before it. A lamp working at a little more than 1 watt per candle brings electric lighting almost to the level of gas for cheapness... a radical improvement has long been wanting, and there seems every reason to believe that it has at last been made.

From *Nature* 13 June 1907.

is ruled out as the source of shoreline deformation. Any subsequent mass redistributions would have been considerably less than that associated with the formation of Tharsis, and would almost certainly have left Tharsis close to Mars's equatorial plane. But might Mars have reordered itself less comprehensively in more recent times, in the Hesperian epoch — middle martian history — roughly 2.8–3.7 billion years ago?

Perron *et al.*[8] believe so. The first question they address successfully is whether there is a path of true polar wander that can explain the deviation of the putative shorelines from equipotential surfaces. The supplementary question is whether plausible candidates exist that could have driven such a reorientation during middle martian history. The Elysium volcanic province, which is in the opposite hemisphere to Tharsis, is a possibility, as is the massive Utopia basin that is buried beneath the northern plains, or a redistribution of mass associated with large-scale convection in the interior of Mars. Other, arguably less likely, possibilities include the addition of even more volcanic material during the late-stage accretion of the Tharsis volcanic pile, or the mass associated with the putative ocean itself.

Evidence for recently discovered sedimentary depositional features on Mars[15] and models that support the possibility of sustained groundwater upwelling at Meridiani Planum, the landing site of the Opportunity rover[16], have, for the time being, focused attention away from the idea of an ancient ocean or oceans to explain Mars's watery past. Perron and colleagues now resuscitate that possibility. Their result[8] hints that, despite dramatic recent advances made possible by various rovers and orbiters, the understanding of the 'blue' history of the red planet is far from complete. ■

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PALAEOBOTANY

Forests frozen in time

Kirk R. Johnson

Just over 300 million years ago, a forest was dropped below sea level by an earthquake and swiftly buried. Such rapid events provide snapshots of lost ecosystems, sometimes on a huge spatial scale.

Fossil plants preserve a vast amount of information about ancient ecosystems and climates. But much of this information is difficult to retrieve because plants fall apart both during life and after death, and many extinct groups are still poorly described because not all of their organs are known. However, the rooted nature of plants means that vegetation can be buried in place, preserving spatial and ecological information that could never be retrieved for mobile organisms.

Writing in *Geology*, DiMichele *et al.*[1] report an extraordinary occurrence of a catastrophically buried forest, now exposed on the roofs of tunnels and chambers of a coal mine in Vermillion County, Illinois. By surveying the mine, they have documented the vegetation of an Upper Carboniferous forest covering an area greater than 1,000 hectares. Such extensive data allow them to map both the small-scale and large-scale spatial patterns of the 307-million-year-old forest, and statistically to resolve ecological gradients.

Dispersed plant parts are rapidly recycled by soil organisms and reduced to their organic constituents within months. Well-preserved palaeobotanical remains are therefore direct evidence of rapid burial below the level of destructive processes occurring in soils. For this reason, fossil plants represent the least time-averaged of any terrestrial fossils, and present opportunities to capture precise data about ancient ecosystems and climates. Rapid burial can result from various mechanisms. In the case of the Illinois forest, which grew in a coastal mire, local tectonic subsidence dropped the forest floor to sea level quickly enough for the plants to be preserved in place. The rate of this type of subsidence is difficult to measure, but DiMichele *et al.*[1] argue that it must have

Figure 1 | In the mire. A reconstruction of a lycopsid forest similar to that preserved intact in a coal mine in Vermillion County, Illinois, and described by DiMichele *et al.*[1]. These forest giants (which sometimes exceeded 40 metres in height) were characterized by sparse canopies and photosynthetic bark, properties that suggest that sunlight penetrated to the forest floor. (Painting by J. Vriesen and K. Johnson. Reprinted with permission from the Denver Office of Cultural Affairs.)