PLANETARY SCIENCE

Into thin martian air

A dense early atmosphere has been invoked to explain the strong greenhouse effect inferred for early Mars. Yet an analysis of the smallest impact craters suggests that the atmospheric pressure on Mars 3.6 billion years ago was surprisingly low.

Sanjoy M. Som

If you placed a glass of liquid water on the surface of Mars today, its contents would simultaneously freeze and sublime. Modern Mars is too cold and its air pressure too low for liquid water to be stable at the surface (Fig. 1). However, the red planet's ancient surface holds clues that water once flowed in abundance. Deep canyons presumably carved by catastrophic outflows, branching valleys interpreted as ancient river networks, and layered sedimentary sequences consistent with ancient lake deposits, are all evidence of abundant surface water early in the planet's history[1]. A wet early Mars is further corroborated by orbital and *in situ* detection of hydrous minerals formed by interaction with liquid water. To reconcile this seemingly warm and wet ancient world with today's cold and dry desert, a much thicker atmosphere containing sufficient greenhouse gases to allow stable liquid water to flow has been hypothesized for early Mars[2]. In contrast, writing in *Nature Geoscience*, Kite *et al.*[3] argue that atmospheric pressure on early Mars could not have been high throughout this interval of martian history because even relatively small impactors survived their journey through the atmosphere and left their mark as craters in ancient river deposits.

Meteoroids enter a planet's atmosphere at high speeds. Following entry, they slow down and heat up as a result of friction with air molecules. The heat and enormous stress on an object that penetrates an increasingly dense atmosphere causes it to break apart. Small meteoroids ablate and fragment, and do not survive passage through the atmosphere; only a sufficiently large object will survive atmospheric entry and make an impact crater. The size threshold above which bolides reach a planetary surface depends on the density of the atmosphere. The thicker the atmosphere, the larger the minimum size of meteorites that reach the surface and, therefore, the larger the minimum size of the impact craters that result.

Applying this concept to Mars, Kite and colleagues[3] extracted information about the pressure of the early martian atmosphere from the minimum sizes of impact craters in Aeolis Dorsa. This 3.6-billion-year-old region of Mars near the Curiosity rover landing site shows evidence of fluvial activity[4]. Ancient craters are preserved within river deposits. The craters must be at least as old as the river beds, and they presumably formed at about the same time as the rivers flowed. Kite *et al.* analysed high-resolution digital elevation maps from the Mars Reconnaissance Orbiter and measured the dimensions of 319 carefully selected craters.

Kite *et al.* then compared the measured population of small craters to those produced by numerical simulations over a range of martian atmospheric pressures. The best fit is achieved for an atmospheric pressure of up to 0.9 bar, which is 150 times greater than the current value. Even including only the best preserved craters and excluding more ambiguous circular features from the data set suggests a maximum atmospheric pressure of 1.9 bars. However, given that the early Sun was less luminous 3.6 billion years ago than it is today[5], atmospheric pressures of 5 bars and above have been proposed to keep the surface above the freezing point of water[6]. The atmospheric pressure estimates of Kite *et al.* fall short of these predictions. Furthermore, the estimates are upper limits and the actual atmospheric pressure could have been even lower, because the smallest craters may have been eroded away.

Kite and colleagues[3] effectively rule out a long-lasting thick atmosphere at a time when rivers flowed over hundreds of kilometres across the martian surface. But,

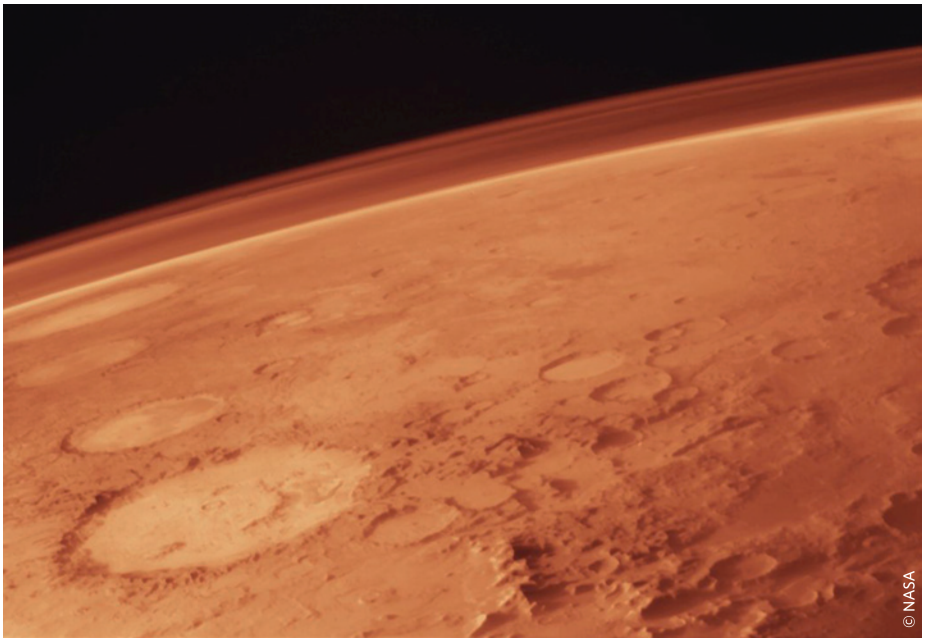

Figure 1 | The tenuous modern atmosphere of Mars seen from low-elevation orbit by NASA's Viking 1 spacecraft. Kite *et al.*[3] used the minimum size of craters in ancient martian river deposits — and thus the minimum size of the meteorites surviving atmospheric re-entry — to determine the palaeopressure of the martian atmosphere when ancient rivers flowed.

alternatively, it is possible that transient intervals of dense atmosphere periodically permitted liquid water flow.

The tilt of the spin axis of Mars changes over long timescales of 120,000 years[7], which leads to cyclical changes in the amount of solar energy reaching the poles, and hence the extent of polar ice. The smaller craters observed in Aeolis Dorsa may be recording periods of lower air pressure during periods of atmospheric deflation when gases condensed to form extended ice sheets at the poles. In contrast, the river deposits may have formed during periods when the tilt changed to warm the poles and reinflate the atmosphere. The amount of time needed to deposit the sediments and make the craters in Aeolis Dorsa could overlap with many such collapse and reinflation cycles[3], so it is currently only possible to rule out long-term stability of a dense ancient atmosphere from the impact crater data.

If the air on ancient Mars was indeed thin, alternative scenarios have been proposed that allow liquid water under lower air pressure, and thus colder surface temperatures. Briny water, for example, has a lower freezing point. Dense acid-brine flows may be consistent with a subset of the martian sedimentary record[8]. Additionally, large impacts would have been more frequent 3.6 billion years ago and could have temporarily injected sufficient quantities of volatiles and greenhouse gases into the atmosphere to permit liquid water to flow[9].

Kite *et al.*[3] use the size of the smallest preserved impact craters as a proxy for the palaeopressure of the ancient martian atmosphere. Likewise, depressions on the martian surface formed by the impact of chunks of rock flung from volcanoes have been used to extract information about the air pressure of early Mars[10], as have the sizes of raindrop imprints preserved in stone for information about early Earth[11]. This nascent field of atmospheric geology is adding much-needed constraints to our understanding of planetary atmospheres, climates and, by extension, habitability. Indeed, the longevity of stable liquid water on the ancient martian surface may prove to be a key factor in considering whether life could have taken hold early in the planet's history. Applying the impact crater proxy to more ancient and diverse martian deposits may help to further unravel the history of Mars's water. ❐

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GEODYNAMICS

Mantle plume chemical diversity

Ocean island lavas have complex geochemical signatures. Numerical simulations suggest that these signatures may reflect the entrainment and transport to Earth's surface of both primordial material and recycled oceanic crust by deeply rooted mantle plumes.

Frédéric Deschamps

Mantle plumes are thought to be generated from Earth's deepest mantle. They well up through the Earth and drive volcanism at the surface, often in the form of lavas erupted at ocean islands. Such plumes therefore provide a precious probe of Earth's deep mantle, potentially to depths of up to 2,890 km, and are used to infer its chemistry. However, ocean island lavas have complex compositions that cannot be explained by a single source reservoir in the mantle[1]. Furthermore, seismic images reveal a strongly heterogeneous deep mantle, supporting the idea of distinct reservoirs with different compositions[2]. Writing in *Nature Geoscience*, Li *et al.*[3] report the use of numerical simulations of mantle convection to show that plumes generated in the deep Earth can entrain different types of material, including recycled oceanic crust and primordial mantle, and transport it to the surface to generate the heterogeneity observed in ocean island lavas.

Ocean island basalts typically have scattered helium isotopic ratios that hint at a source in at least two distinct reservoirs (Fig. 1). Low helium-4 to helium-3 isotopic ratios (typically 3.0×10^4 and less) are thought to characterize primordial material that became trapped in the deep mantle shortly after Earth formed and has remained isolated ever since[4]. This primordial material probably forms large pools of chemically distinct lower mantle. Seismic images[2] identify two such reservoirs in the lowermost mantle beneath Africa and the Pacific Ocean. Because seismic shear waves pass slowly through these reservoirs, they are termed large low shear-wave velocity provinces — with a possible reason for the seismic slow-down being that these regions are enriched in iron. A second source of chemical heterogeneity in the deep mantle is thought to come from subducting slabs of oceanic lithosphere that penetrate the lower mantle[5]. Where ocean island lavas sample recycled oceanic crust, they have high helium isotopic ratios. However, ocean island basalts may also sample recycled oceanic crust with vastly different ages[6,7].

Li *et al.*[3] use high-resolution numerical simulations of mantle convection, driven by both thermal and compositional contrasts, to study the interactions between recycled oceanic crust, primordial material and mantle plumes that rise from the top of the primordial reservoirs. They model