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

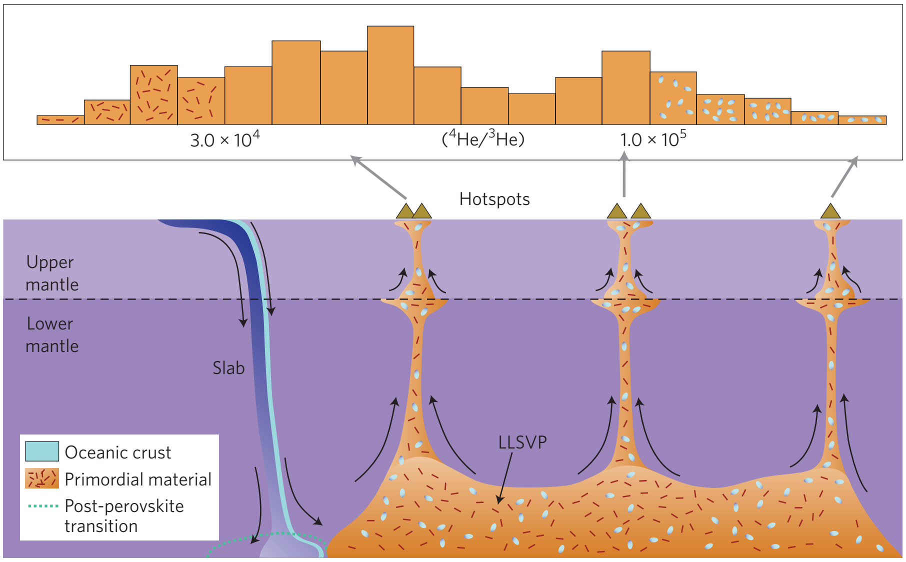

Figure 1 | Deep-mantle mixing. When oceanic crust (light blue) is transported to the deep mantle as part of sinking slabs (dark blue), it probably mixes with pools of primordial material that are thought to form provinces of low shear-wave velocity (orange). Mantle plumes, generated from the edges of the large low shear-wave velocity provinces (LLSVPs), upwell through the mantle and generate ocean island basalts at Earth's surface (bottom panel). The ocean island lavas typically have variable helium isotopic ratios (top panel). High helium isotopic ratios are typical of recycled oceanic crust of different ages (small light blue shapes) and low helium isotopic ratios (3.0 × 10^4 and less) are typical of primordial material (red dashes). Li *et al.*[3] use numerical simulations to show that these characteristics of ocean island lavas can result from the entrainment into rising mantle plumes of small quantities of both relatively young recycled oceanic crust (derived directly from the subducting slabs) and older oceanic crust that has spent time mixing within the primordial reservoir, as well as primordial and ambient mantle. The post-perovskite phase may be present around LLSVPs and affect the amount of oceanic crust that can be incorporated into LLSVPs, depending on its viscosity.

the chemical heterogeneities in three components: oceanic crust initially created at Earth's surface but recycled into the deep mantle by subduction; primordial material distributed in piles at the bottom of the mantle; and ambient mantle. The simulations reveal that when subducted slabs reach the lower mantle, some of the oceanic crust is incorporated directly into the rising mantle plumes, but a substantial portion of any slab is incorporated into and mixed with the primordial reservoirs, irrespective of density contrasts. Small fractions of relatively young oceanic crust, primordial material mixed with older oceanic crust, and ambient mantle, are then entrained upwards by plumes. The model can therefore explain the varied chemistry and ages of oceanic crustal components observed in ocean island lavas.

The simulations may also provide insight into the composition of the large low shear-wave velocity provinces, the detailed nature of which is still debated. These reservoirs may represent purely thermal anomalies[8], but a thermo-chemical origin, with the material enriched in iron and silicate[2], remains a more convincing hypothesis. Early differentiation of Earth's mantle could have led to the formation of reservoirs enriched in iron[9]. The 'basal mélange' scenario[10] further assumes that these primordial reservoirs are periodically blended with recycled oceanic crust entrained in the deep mantle throughout Earth's history. Li and colleagues' simulations support this scenario because their results imply that the primordial reservoirs also contain oceanic crust.

Several observations suggest that the large low shear-wave velocity provinces have remained stable for the past 300 million years, and that mantle plumes are generated along their sharp edges[11,12]. Interestingly, Li and colleagues' simulations replicate these observations. However, treatment of mineral phase transitions in the model is quite simplified. The model accounts for the possibility that the viscosity of the post-perovskite mineral phase, which may be present outside the primordial reservoirs, is different from that of the reservoirs, showing that smaller amounts of recycled crust are incorporated into the primordial reservoirs with decreasing post-perovskite viscosity. However, other subtle effects of these phase transitions could affect, for instance, the volume of different materials entrained into a rising plume[13], and yet are not simulated explicitly. Furthermore, the model provides only a qualitative explanation of ocean island lava geochemistry. In the future, such models could attempt to quantify the entrainment of primordial and recycled oceanic crustal material. The lowest known values of helium ratios observed in ocean island lavas, combined with mass–balance calculations, suggest that about 10% of material entrained into a rising plume is primordial — a value that is well explained by simulations of convection with a two-component chemical field[14]. Detailed quantitative comparison with observations from Earth's mantle will require numerical simulations in three-dimensional spherical space. Such a step requires large amounts of computational time because of the high resolution needed to properly model the dynamics of mantle plumes and the evolution of the thermo-chemical reservoirs.

Li *et al.*[3] qualitatively explain the complex geochemistry of ocean island lavas as the result of mantle-plume entrainment of subducted oceanic crust of varying age and primordial material, with the help of numerical simulations. That recycled oceanic crust can follow several pathways through the mantle — direct entrainment into rising plumes, mixing with ambient mantle or mingling with primordial reservoirs — highlights the complexity of Earth's mantle geodynamics and the heterogeneity of its thermo-chemical structure. ❐

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