

## GEOCHEMISTRY

## Rise of the continents

The continents are archives of Earth's evolution. Analysis of the isotopic signature of continental crust globally suggests that buoyant, silicic continents began to form 3 billion years ago, possibly linked to the onset of plate tectonics.

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Earth is the only known planet in the solar system with continents and ocean basins. The continents ride high, about four kilometres above the seafloor. They are composed of thick, silicic crust that is more buoyant than the thin, dense crust that floors the oceans. Oceanic crust is thin — only about 7 km on average — because the addition of new crust via magmatism at spreading ridges is compensated by tectonic extension that stretches out the crust. In contrast, continental crust forms from magmatism in zones of tectonic plate convergence — subduction and continental collision zones. As a result, the continental crust has grown to an average thickness of about 35 km. The combination of low density and thick crust makes the continents more difficult to subduct than oceanic crust, so the continents survive longer at the surface of the Earth. Nevertheless, our understanding of how and when the continents formed is incomplete. Writing in *Nature Geoscience*, Dhuime *et al.*<sup>1</sup> analyse geochemical and isotopic data from over 13,000 samples of continental crustal rocks to suggest that the continents, as we know them today, first began to form about 3 billion years ago (Ga).

The first two billion years of Earth's history are thought to have been dominated by basaltic magmatism that created oceanic-like crust. More silica-rich, continent-like crust became important, in terms of volume, only in the last two billion years<sup>2,3</sup>. Such estimates are based on the compositions of magmatic rocks and sediments, but it is unclear whether these approaches truly constrain the composition of the protocrust. Earth's crust can remelt again and again, and magmatic rocks often reflect compositions imparted during the last crustal remelting event and not that of the proto- or juvenile crust at the time of first extraction from the mantle. Furthermore, sediments represent mixtures of different sources and their compositions have been modified by weathering processes.

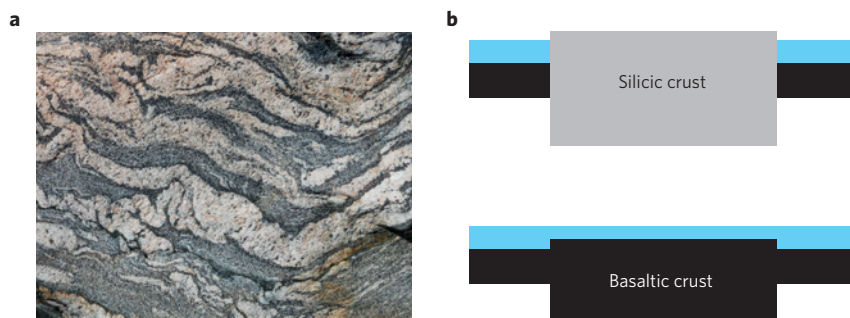
To filter out the effects of crustal reworking and re-melting, Dhuime and colleagues<sup>1</sup> turn to two radioactive decay

systems, that of <sup>87</sup>Rb to <sup>87</sup>Sr and <sup>147</sup>Sm to <sup>143</sup>Nd. Specifically, they show that the parent-to-daughter ratios of these isotopes can be used to constrain the composition of the continental crust at specific times. When the crust remelts or when magmas cool and crystallize, the remaining residual melt becomes enriched in silica and rubidium (Rb), but less so in strontium (Sr), which partitions into both the crystals and residual melt<sup>4</sup>. The Rb/Sr ratio therefore correlates with the silica content of a rock and can be used as a proxy for magma differentiation process. The samarium/neodymium (Sm/Nd) ratio, however, is only affected during melting of the mantle — the first stage of crust formation — and less so by magmatic differentiation or remelting in later stages of crustal reworking.

Using these concepts, Dhuime and colleagues extrapolate the measured Sr isotopic signatures of continental crustal rocks back to the time of last crystallization or reworking. They then determine the time at which the juvenile crust was extracted from the mantle using the Sm/Nd isotopic systematics. This allows them to determine the time-integrated Rb/Sr ratio of the juvenile crust, which in many cases

predates the time of crustal reworking. From the Rb/Sr ratio of the juvenile crust, they are able to infer the juvenile crust's silica content. It turns out that the Rb/Sr ratio of juvenile crust increased around 3 Ga. This change implies a transition from basaltic to more silicic crust and points to the emergence of silica-rich continents at that time. Such a change in the composition of juvenile crust had been suggested previously<sup>2,3</sup>, but the current analysis provides independent and robust confirmation of this transition.

The cause of this geochemical transition is unclear. It could reflect the onset of plate tectonics. Initially, Earth's upper thermal boundary layer was probably an immobile lid, with small-scale convective instabilities at its base. This lid could have become mobile when the upper thermal boundary layer sunk back into the mantle as focused downwellings, like subducting slabs in today's plate tectonic regime<sup>5,6</sup>. Subduction, broadly defined, may be the only mechanism to introduce water back into Earth's interior, causing dehydration melting of the subducted materials or hydrous melting of the mantle to produce hydrous magmas. Only hydrous magmas



**Figure 1** | Continental evolution. **a**, A rock sampled from the 2.5 to 3 billion-year-old Farmington complex in Utah, USA, preserves a record of silica-rich (light coloured) magmas that are beginning to segregate from a more iron and magnesium-rich parent. **b**, A change in the crustal composition (from basaltic to silicic) and an increase in crustal thickness could have caused the average elevation of Earth's juvenile continental crust to increase, causing the crust to emerge from below sea level (blue represents the ocean), assuming the volume of the oceans has not changed significantly. Dhuime *et al.*<sup>1</sup> suggest that such a change in composition and thickness may have occurred about 3 billion years ago and could be linked to the onset of modern-style plate tectonics.

can fractionate and cool to form significant amounts of silicic magmas that make up much of Earth's continental crust. This supports the idea that the onset of plate tectonics (or more generally, a mobile-lid regime) and continental crust formation could be linked. Alternatively, plate tectonics may have always operated, but Earth's interior was initially too hot to form and preserve thick hydrated layers in oceanic lithosphere, minimizing the transport of water into the mantle and the generation of hydrous magmas.

The most provocative observation from the study by Dhuime *et al.* is that the Rb/Sr ratio and silica content of the rocks empirically correlate with crustal thickness in active magmatic belts, such as the modern Andes Mountains in South America. This correlation suggests that magmas that have traversed through thick, cold crust will have cooled and crystallized more by the time they reach the surface, giving rise to more evolved crusts. Complex feedbacks between magmatic flux, upper plate stress state, erosion, magma rheology and thermal state of the crust will also affect magma differentiation, making the observation of this simple empirical relationship between silica and crustal thickness even more remarkable.

Importantly, if these empirical observations can be applied to the past, the implication is that the transition in juvenile crust composition from 3 Ga was accompanied by an increase in juvenile crustal thickness. Dhuime and colleagues

suggest that the juvenile crust was rich in iron and magnesium and thin, at less than 20 km thick, prior to about 3 Ga. After that, it became increasingly more silica-rich and thick, peaking at 40 km thickness about 1 Ga and declining in thickness since then to about 30 km.

Boldly assuming that crustal thickness is a proxy for crustal volume, Dhuime and colleagues go on to argue that the rise in crustal thickness signifies net growth of continents, whereas the decline in crustal thickness since about 1 Ga suggests net destruction of continental crust in subduction zones. However, the data only constrain thickness during juvenile crust formation and cannot be applied to the crust that remains millions or billions of years later, after the original crust has collapsed or eroded. In addition, there is no clear relationship between crustal thickness and net crustal growth because processes such as surface erosion, lower crustal foundering and crustal remelting obscure the contribution of juvenile magmatism to crustal thickening<sup>7</sup>.

If there was a temporal change in juvenile crustal thickness, the average elevation of juvenile crust must have also changed, because thick crusts isostatically support high elevations. Assuming ocean volume and continental area have not changed significantly, the 20-km-thick crusts before 3 Ga would have been near or below sea level. Only after about 2.5 Ga would juvenile continental crusts have thickened enough to emerge significantly above sea level (Fig. 1).

The emergence of high elevations would have subjected these juvenile continents to rain, rivers, glaciers and even life, which erode the rocks and transport sediments to the ocean.

If the change in composition of Earth's juvenile crust about 3 billion years ago, as documented by Dhuime and colleagues<sup>1</sup>, does indeed signify the onset of plate tectonics, then the emergence of a more efficient physical and chemical weathering regime is likely to have followed in its footsteps. The significance of this change is substantial: the feedbacks between climate, magmatism and weathering were probably altered for good. □

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