Earth science

How continents gained their inner strength

Claire E. Bucholz

What stabilized and strengthened the oldest, most robust blocks of continental crust billions of years ago during the Archaean eon has long been a mystery. It seems that a surprise helping hand might have come from the air above. **See p.609**

Humans live on, and depend on the resources of, Earth's continental crust – a geological feature that is exclusive to Earth among the Solar System's rocky planets. The core regions of continental crust are called cratons, and they have remained stable and isolated from tectonic reworking for billions of years; the innermost nuclei of cratons date to the Archaean eon (4 billion to 2.5 billion years ago). How and why these ancient cores formed and stabilized remains unknown. On page 609, Reimink and Smye[1] propose an explanation that links the initial stabilization of cratons to the emergence of continents above sea level.

Crucial to the stability of cratons are strong roots. The deepest level of these foundations extends below the crust into mantle keels – distinctively thick layers of cold mantle that have been depleted of melted rock. These robust mantle keels have considerable strength, owing to their cold, melt-depleted nature, and they therefore protect the overlying crust from tectonic modification[2].

However, the lower crust of cratons must also remain strong. As with the mantle keels, the strength of the lower cratonic crust has been enhanced by the extraction of melt and by cooling[3]. Estimates of the vertical distribution of radioactive heat-producing elements (mainly uranium, thorium and potassium) in the continental crust indicate that the deep crust has lower concentrations of these elements than does the upper crust[4]. In particular, heat-producing elements are concentrated in granites, which are characteristic of the upper crust[5].

One potential mechanism for the formation of granites is the melting of rocks in the lower crust. Melting of the lower crust might sound straightforward, but it is not easy for the crust to reach temperatures that exceed the melting point of rocks. The specific melting temperature depends on several factors, including the depth, the type of rock and whether fluids are present, but temperatures higher than 700–800 °C are typically required to melt rocks in the lower crust to a substantial extent[6]. How can the required heat be generated?

Several answers to this question have been proposed, all of which emphasize the input of heat from the underlying mantle[7]. However, one issue with these models is that, for many cratons, the formation of the cold mantle keel predates the emplacement of granites in the upper crust[2]. Thus, in many locations, it seems that the mantle stabilized before the lower crust did.

Reimink and Smye suggest a mechanism for melting the lower crust that does not invoke heating from the mantle. Their hypothesis is simple: if heat-producing elements become concentrated in the lower crust, they could produce sufficient heat over geological timescales to increase temperatures past the melting point of rocks.

To address whether this theory is feasible, the authors first compiled existing data on heat-producing elements in rocks older than 2.5 billion years. They found that Archaean granites and basalts generally had low concentrations of these elements and thus low rates of heat production. By contrast, the heat-production rates of Archaean sedimentary rocks – which formed when the continents first began to emerge above sea level and were then weathered by the atmosphere – were twice as high. The authors' thermal modelling of thick crust composed of these different rock types demonstrates that only when sedimentary rocks are present in the mid- to lower crust can sufficient heat be generated through radioactive decay to induce melting.

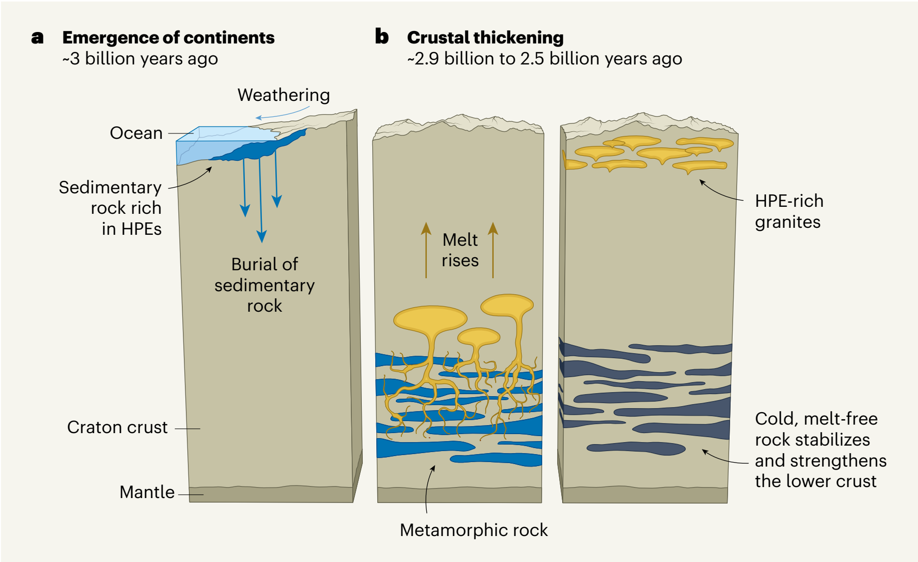

Figure 1 | Proposed model for the stabilization of the lower crust in cratons. Reimink and Smye[1] modelled the evolution of Earth's crust at cratons – the strong and ancient cores of continents. **a**, The authors suggest that when continents first emerged above sea level about three billion years ago, atmospheric weathering of the land masses resulted in the formation of sedimentary rocks in which radioactive heat-producing elements (HPEs) were highly concentrated. These rocks were then buried and incorporated into the lower crust. **b**, The concentration of HPEs in the lower crust generated temperatures that resulted in metamorphism (processes that change the mineral content and structure of rocks) and melting. The melt rose to the upper crust, forming granites rich in HPEs, and leaving behind a lower crust that was cold and melt-free. These characteristics stabilized and strengthened the lower crust, thereby helping to protect the craton from modification by tectonic forces.

Although this study is based mainly on geochemistry and thermal modelling, the proposed model is consistent with the ages and types of rocks observed in cratons. The geological record of every Archaean craton reveals a typical sequence of rock formation. First, beginning between about three billion and four billion years ago, the record is dominated by mafic (rich in magnesium and iron) volcanic rocks and sodium-rich granites[8]. Then, about three billion years ago, mantle keels began to stabilize[2], continental masses emerged above sea level and thick sequences of sedimentary rocks derived from the uplift and erosion of older continental crust were deposited[9]. Finally, between 2.5 billion and 2.9 billion years ago, depending on the craton, high-temperature metamorphism – transformation of the minerals and textures of rock under conditions different from those of their original formation – in the lower crust occurred at the same time as the intrusion into the upper crust of granites characterized by high concentrations of heat-producing elements.

This last event is the one modelled by Reimink and Smye: the amalgamation of the Archaean cores of cratons, which resulted in a cool, strong lower crust and an upper crust cemented together by late-Archaean granites. Putting the authors' findings into context with the geological history of cratons, the story that emerges is that the earliest continental masses ensured their own survival by rising above the oceans, shedding the detritus of atmospheric weathering to sedimentary basins and then reincorporating those sediments into the crust (Fig. 1). In essence, this is the first clear evidence for a full circuit of the rock cycle – the continual sequence of transitions in which rock is converted from igneous to sedimentary to metamorphic rock, and back to igneous.

Reimink and Smye's model opens up questions for future discussion. For example, why did the concentrations of heat-producing elements in sedimentary rocks increase in the late Archaean and peak between 2.5 billion and 2.0 billion years ago? Notably, Earth was dynamic during this period: not only were the continents stabilizing, but also the first major increase in the levels of atmospheric oxygen occurred, which would certainly have influenced how rocks were weathered. Among the heat-producing elements, uranium is especially sensitive to atmospheric oxygen levels, and becomes mobile in fluids when it is oxidized. The onset of oxidative rock weathering by the atmosphere would therefore have released uranium to marine sedimentary basins[10].

Moreover, the redistribution of heat-producing elements during melt extraction is controlled by the behaviour of an array of minerals during melting[5]. Further detailed studies of late-Archaean high-temperature metamorphic rocks and their derivative granites are required to understand the details of how heat-producing elements were distributed between these rocks[11].

In the meantime, these findings add considerably to Earth scientists' understanding of continent formation. More broadly, they contribute to an ever increasing, transdisciplinary dialogue that aims to construct a holistic understanding of our planet, thereby revealing how changes at the surface affect the dynamics of deep Earth, and vice versa.

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1. Reimink, J. R. & Smye, A. J. *Nature* **629**, 609–615 (2024).
2. Pearson, D. G. *et al*. *Nature* **596**, 199–210 (2021).
3. Mareschal, J. C. & Jaupart, C. in *Archean Geodynamics and Environments* (eds Benn, K. *et al*.) 61–73 (American Geophysical Union, 2006).
4. Rudnick, R. L. & Gao, S. in *Treatise on Geochemistry* 2nd edn, Vol. 4 (eds Holland, H. D. & Turekian, K. K.) 1–51 (Elsevier, 2014).
5. Bea, F. *Lithos* **153**, 278–291 (2012).
6. Weinberg, R. F. & Hasalová, P. *Lithos* **212–215**, 158–188 (2015).
7. Laurent, O., Martin, H., Moyen, J. F. & Doucelance, R. *Lithos* **205**, 208–235 (2014).
8. Moyen, J.-F. *Geol. Soc. Spec. Publ.* **489**, 15–49 (2020).
9. Reimink, J. R., Davies, J. H. F. L. & Ielpi, A. *Earth Planet. Sci. Lett.* **554**, 116654 (2021).
10. Partin, C. A. *et al*. *Earth Planet. Sci. Lett.* **369–370**, 284–293 (2013).
11. Kinney, C., Kendrick, J., Duguet, M. & Yakymchuk, C. *J. Metamorph. Geol.* **42**, 197–224 (2024).

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Cell biology

Donated mitochondria help to build blood vessels

Chantell S. Evans

Organelles called mitochondria are transferred to blood-vessel-forming cells by support cells. Unexpectedly, these mitochondria are degraded, kick-starting the production of new ones and boosting vessel formation. **See p.660**

Blood vessels deliver oxygen and nutrients to tissues and remove waste products from them. When these vessels become narrow or blocked, the blood supply and waste clearance are prevented, resulting in what is called ischaemia, which in turn leads to conditions such as coronary heart disease and heart attack[1]. On page 660, Lin *et al.*[2] report an innovative transplantation strategy to aid the repair of ischaemic tissue; it relies on energy-generating organelles called mitochondria being transferred from one cell to another.

Blood vessels are lined with endothelial cells, which are essential for the formation of vessels and the flow of blood. To treat ischaemic conditions, endothelial cells are transplanted near the site of a vessel blockage to promote the formation of blood vessels and restore blood flow to the tissue[3]. However, a considerable limitation of this therapy is that endothelial cells must be co-transplanted with undifferentiated stem cells called mesenchymal stromal cells, which support tissue repair and regeneration[4]. Until now, the mechanism by which stromal cells promote endothelial-cell engraftment was poorly understood.

> **"The mechanisms that stabilize and destabilize nanotubes remain to be established."**

Lin and colleagues reveal that stromal cells transfer mitochondria to endothelial cells. Unexpectedly, these mitochondria are degraded after transfer, prompting endothelial cells to produce new mitochondria of their own. The authors show that artificially transplanting mitochondria into endothelial cells to mimic this natural transfer can stimulate blood-vessel formation by transplanted endothelial cells, paving the way for a treatment for ischaemic disease that requires only one cell type to be transplanted (Fig. 1).

First, Lin *et al.* transplanted human endothelial cells beneath the skin of mice in the presence or absence of supporting stromal cells, and confirmed that only co-transplanted grafts had viable endothelial cells that formed functional blood vessels. In the past decade, stromal cells have been shown to naturally transfer mitochondria to other cell types, and mitochondrial transfer has been shown to promote the regeneration of tissue that has been damaged by ischaemia[5]. To investigate whether this is how stromal cells enable successful endothelial-cell engraftment, the authors labelled mitochondria in stromal cells with a fluorescent protein called DsRed.

The authors observed DsRed-labelled mitochondria in long protrusions, called nanotubes, that extended from stromal cells and made direct contact with endothelial cells. After 24 hours, DsRed-labelled mitochondria could be seen inside the endothelial cells that lined new blood vessels. However, the mitochondrial transfer was surprisingly temporary: