cause increased disruption to the surface waters of the Arctic Ocean as sea ice is progressively lost[9]. According to the findings of Shakhova *et al.*, this rise in surface water disturbance is likely to exacerbate marine methane emissions in the Arctic[6]. The focus of this paper is on the under-recognized impact of storms, which will be increasingly felt as sea ice recedes. In a disturbing coincidence, the authors dedicate their paper to the crew of the rescue ship that died trying to save them during a severe storm. ❐

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EARLY EARTH

# Archaean drips

The Archaean Earth was much hotter than today. Numerical modelling shows that the base of thickened crust that formed at the time would have been so dense that it dripped back into the mantle.

Claude Herzberg

Earth is continuously being heated up by the radioactive decay of elements in its interior. Yet, at the same time, it is cooling down by mantle convection, and the cooling process is dominant at present. Mantle convection is sometimes referred to as Earth's heat engine because it is the driver of modern plate tectonics — the movement and interaction of the lithospheric plates that make up Earth's strong outermost crust and mantle. However, it is unclear how much hotter Earth was in the past and how long ago modern plate tectonic processes were operating. Writing in *Nature Geoscience*, Johnson and colleagues[1] use thermodynamic and geodynamic numerical models to explore the tectonics of crust production and destruction in the context of a hot Archaean mantle. They show that the base of thick crust dripped into the mantle, rather than being drawn down in slabs as observed today.

In the modern Earth, plate collision and the subduction of cold slabs below hotter lithosphere can produce metamorphic belts with contrasting rock types. These are seen as far back as the Neoarchaean era, about 2.8 to 2.5 billion years ago, but the rocks differ because the belts formed in settings that were much hotter than modern subduction zones[2]. A hotter Archaean mantle would have had weaker lithospheric plates compared with today. It has therefore been unclear whether subduction zones existed, and whether the crust was recycled back into the mantle as coherent slabs or delaminated drips[3]. During the Archaean eon, thick sequences of basaltic lavas erupted below sea level, but on top of continental crust[4] — and the flat

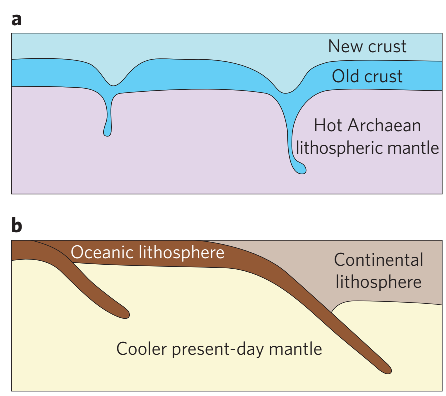


**Figure 1 |** Schematic comparison of Archaean and present-day mechanisms for recycling. During the Archaean, the mantle was much hotter than today. **a**, Johnson and colleagues[1] use numerical models to show that an early formed crust (blue) would have been more dense than the underlying hot lithospheric mantle, causing the crust to delaminate and sink as vertical drips. **b**, In contrast, present-day recycling occurs at subduction zones, where transport of both crust and mantle in cold oceanic lithosphere occurs with a significant horizontal component.

Earth hypothesis was invoked to interpret this and other geological evidence that point to shallow subaqueous topography over much of Earth's surface[5]. Although some variation in topography is expected, the landscape could have been largely flat because the lithosphere was too hot and weak to maintain high, heavy crustal loads[5]. However, cooling and strengthening of the lithosphere in the Neoarchean could have given rise to mountain ranges, which would have fostered weathering of the continents, changes in the chemistry of sediments and sea water, and possibly an increase in atmospheric oxygen[5–7]. Every aspect of our planet was affected by its internal heat engine.

The hot, ambient Archaean mantle is thought to have melted extensively in its uppermost region, creating a primary basaltic crust that was rich in magnesium oxide and about 25 to 45 km thick[8]. Most of this crust was oceanic, but the magma probably flooded the continents as well. A complementary residue must have remained in the mantle when this crust formed, and mantle fragments in kimberlites provide evidence for such residues. Owing to their low water contents, these residues today form the strong mantle lithosphere that makes up the nuclei of Earth's continents. However, when they formed, these rocks were weak because of their higher temperatures.

Johnson *et al.*[1] build on this understanding[8] using a thermodynamic model to simulate the formation of minerals in a primary Archaean crust. They calculated the densities and mineral assemblages that would have been likely to occur at the base of a thick, primary basaltic crust, and compared these with the complementary residual mantle. They found that a range of dry and hydrous rock types would form and that these would have higher densities than the mantle below, causing them to be gravitationally unstable. By integrating these results with a geodynamic model, Johnson *et al.* confirm that the bottom of the over-thickened primary crust could have peeled off into



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the mantle, a process called delamination. However, the primary crust would probably have sunk vertically into the mantle as drips, rather than sliding in a more horizontal direction as a coherent slab, as is observed in modern subduction zones (Fig. 1).

The amounts of primary crust inferred to have been produced in the Archaean greatly outweigh that preserved today. Rather, most preserved Archaean rocks are continental crust composed of tonalities, trondhjemites and granodiorites (TTGs)[3,9]. These rocks formed from hydrated basalt that was low in magnesium oxide[9] — a source that is very different to the magnesium-oxide-rich primary crust. It is therefore unclear where the primary crust has gone and how it relates to the preserved Archaean TTGs. Building on an earlier study[10], Johnson *et al.*[1] show that some of the primary crust could have been recycled back into the mantle in the form of delaminated drips. The remainder could have been transformed through fractional crystallization, hydration and partial melting to form continental crust. Thus, by integrating models of equilibrium mineral assemblages and densities with a geodynamic model, Johnson and colleagues help to deepen our understanding of the origin of continents. Future studies are needed to determine how exactly thick primary crust could have transformed to TTG continental crust, and how this was linked to the emergence of land masses in the Neoarchaean.

Tighter constraints on Earth's present-day convective Urey ratio — a measure of the balance between heat gain by radioactive decay and heat loss by mantle convection — could help falsify or support the delamination model. The production of thick, primary high-magnesium-oxide crust in the Archaean is consistent with a Urey ratio[8,11] of 0.23 ± 0.15. Yet, estimates of the present-day Urey ratio are controversial because they depend critically on understanding the U, Th and K abundances in Earth, and all estimates are model dependent. Some reports[12] suggest the present-day Urey ratio could be as high as 0.8, in which case it would be difficult to produce thick primary crust in the Archaean. However, independent measurements[13] using geoneutrinos emitted from the mantle during U and Th decay indicate the Urey ratio is between 0.18 and 0.67, implying that thick primary crust formation in the Archaean could be plausible. Tighter constraints on Earth's present-day Urey ratio will provide a more secure understanding of the thermal history of the Earth, and how it was expressed by changes in the tectonics of crust production and destruction.

Johnson and colleagues[1] use numerical models to show that thick primary crust that formed in a hotter Earth during the Archaean would have delaminated into the mantle as drips, explaining, in part, why such crust is rarely preserved at Earth's surface today. Future work using similar computational methods will help to clarify how the remaining primary basaltic crust could have transformed to Archaean TTG continental crust. ❐

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PLANETARY SCIENCE

# Flow of an alien ocean

Liquid water may lurk beneath the frozen surfaces of Jupiter's moon Europa and other icy worlds. Extending ocean science beyond Earth, planetary oceanographers are linking Europa's ocean dynamics to its enigmatic surface geology.

Jason Goodman

When the Voyager spacecraft flew past Jupiter in 1979, it imaged the icy surface of the moon Europa, cracked and creased and showing few craters. The geologically active surface led scientists to speculate that Europa might have a liquid water ocean beneath its ice[1], maintained in part by tidal heating such as that driving volcanism on the neighbouring moon Io. The Galileo spacecraft's detection of induced magnetic fields on Europa and Jupiter's other icy satellites provided strong evidence for subsurface oceans[2]. But unlike on the older, cratered surfaces of Callisto and Ganymede, Europa's relatively high heat flow and relatively thin ice shell suggest that interactions between the ocean and ice influence Europa's surface geology. Writing in *Nature Geoscience*, Soderlund *et al.*[3] present a detailed global-scale simulation of Europa's internal ocean dynamics that suggests that Europa's ocean circulation could be intensely turbulent and, through uneven heat delivery to the icy crust, explain the spatial distribution of disrupted crust.

Europa's ice crust is almost as enigmatic as its liquid interior. The surface is geologically very young, and is covered with cracks and violently disrupted regions termed chaos terrains, where the surface has been deformed, pulverized and often cracked into mobile ice blocks, on scales ranging from a few to hundreds of kilometres. Chaos terrain is probably formed by heating from below, which either melts away the ice shell or drives convection within it. However, the exact mechanism remains a mystery[4].

Although evidence for an ocean beneath Europa's surface ice is strong, observational constraints on its properties are almost non-existent. Planetary oceanographers have thus turned to computer simulations for insight. The behaviour of Europa's tidal flows[5] and small-scale hydrothermal plumes[6] have been examined, but Europa's global thermally driven circulation has not yet been modelled. The computational challenges are tremendous: Europa's ocean has a volume similar to the Earth's, but simplifying assumptions that apply to the shallower Earth oceans (for example, hydrostatic



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