Their data allow ocean-based calculations of Greenland glacier melting. Perhaps their most notable finding is the marked variability of ocean properties between fjords sited within 30 km of each other. As a result, derived melt rates vary by a factor of five. For the glaciers Rignot and colleagues studied, ocean melting accounted for between 20% and 75% of frontal ice loss, with the remaining ice loss being through iceberg calving. Observed fjord currents reveal narrow jets near the surface, which could be glacial meltwater flowing away from the ice. Very fine sampling would be required to adequately measure these features.

Rignot and colleagues only observed the top 100 m or so of water, so melt-rate calculations partly rely on a conceptual model of fjord flow[11], rather than directly being based on conservation laws for mass and energy. In the model, the glacier face is melted by a rising plume that is initiated by fresh ice-sheet meltwater emerging from beneath the glacier. The plume incorporates warm fjord water at depth, and the heat of this water melts the glacier. Cooled water is then ejected at the surface[11]. This means that melt rates can be estimated by measuring the temperature decrease between deep and shallow waters near the calving front. However, Rignot and colleagues only sampled the full depth of the water column in one of the three fjords under investigation, Eqip Sermia (Fig. 1); for the others the source of heat for melting is obtained by extrapolation. Observed currents indicate that the fjord circulation is more complex than a simple rising plume, but for Eqip Sermia the results derived from the model agree with direct calculations. Obtaining melt rates from Greenland oceanographic data is a crucial advance, but future studies require fine sampling of the entire fjord cross-section.

The observed variability in water properties in the three adjacent fjords casts doubt on any extrapolation of conclusions drawn from a particular glacier outlet. However, the results from Sermilik Fjord on the east side of Greenland show that shallow waters are most variable[4], so deeper glaciers than those investigated by Rignot and colleagues might experience more uniform warm-water forcing. The Sermilik observations demonstrate that glacial meltwater plumes do not control circulation in the wider fjord, but they are not inconsistent with the existence of plumes or their control of glacier melting[11].

Important questions remain about the dynamics of ocean–glacier interactions. It is unclear how melting at the calving front accelerates Greenland glaciers — most glaciers terminate in a sheer vertical front rather than a floating tongue that can thin and disintegrate. Perhaps faster melting simply drives the ice front backwards, either directly or by undermining it. Undermining could increase iceberg calving or cause the glacier to float[5]. Alternative ocean-led explanations include a weakening of the fjords' mélange of sea ice and icebergs that is thought to resist glacier flow in winter[12].

The possibility remains that ice losses are driven entirely by increases in surface melting imposed by the atmosphere. Increased surface melting could thin the glaciers and cause them to float, increase iceberg calving through ice thinning or fracturing[12], or moderately accelerate glaciers by lubricating their base with meltwater. In an intriguing twist, increased surface melting would raise the flow of meltwater entering fjords from underneath the glacier. As this flow initiates the plumes that melt the glacier faces[11], its increase could raise oceanic melt rates by mixing more of the existing warm fjord water towards the glacier (refs 5, 11 and A. Jenkins, unpublished). In this way, ocean melting could be increased without any change in external ocean properties. None of the intricate processes linking glaciers and the ocean are included in current climate models.

The studies by Straneo and Rignot and their colleagues[4,5] are vital steps towards an understanding of Greenland's ice loss into fjords, but more needs to be learnt before fjord processes and their connections with glacier flow can be modelled to predict the fate of the Greenland ice sheet. Ongoing field studies promise to advance our understanding in this rapidly evolving field.

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References

1. Shepherd, A. & Wingham, D. *Science* **315,** 1529–1532 (2007).
2. Luckman, A., Murray, T., de Lange, R. & Hanna, E. *Geophys. Res. Lett.* **33**, L03503 (2006).
3. Holland, D. M., Thomas, R. H., de Young, B., Ribergaard, M. H. & Lyberth, B. *Nature Geosci.* **1,** 659–664 (2008).
4. Straneo, F. *et al. Nature Geosci.* **3,** 182–186 (2010).
5. Rignot, E., Koppes, M. & Velicogna, I. *Nature Geosci.* **3,** 187–191 (2010).
6. van den Broeke, M. *et al. Science* **326,** 984–986 (2009).
7. Sole, A., Payne, T., Bamber, J., Nienow, P. & Krabill, W. *Cryosphere* **2,** 205–218 (2008).
8. Moon, T. & Joughin, I. *J. Geophys. Res.* **113**, F02022 (2008).
9. Thomas, R. H. *J. Glaciol.* **50,** 57–66 (2004).
10. Howat, I. M., Joughin, I., Fahnestock, M., Smith, B. E. & Scambos, T. A. *J. Glaciol.* **54,** 646–660 (2008).
11. Motyka, R. J., Hunter, L., Echelmeyer, K. A. & Connor, C. *Ann. Glaciol.* **36,** 57–65 (2003).
12. Sohn, H., Jezek, K. C. & van der Veen, C. J. *Geophys. Res. Lett.* **25,** 2699–2702 (1998).

EARLY EARTH

Leftover lithosphere

The earliest evolution of our planet is difficult to reconstruct. Ancient rocks in Western Australia show an isotopic signature that links their formation with 4.3-billion-year-old crust.

Stephen J. Mojzsis

During the initial stages of Earth's evolution, the planet cooled and separated into core, mantle and crust. This process was a consequence of the different chemical and mechanical properties of the elements and compounds that went into its formation. A solid outer crust could have formed within ten million years of the formation of the Moon[1], but the precise timing of crustal differentiation and emplacement of basalt or more evolved rock types such as granite is unknown. Writing in *Nature Geoscience*, Tessalina *et al.*[2] report that a roughly 4.3-billion-year-old component of Hadean crust was later reworked into the Dresser Formation (Fig. 1) in Western Australia's Pilbara Craton, indicating that some geochemical fingerprints of primordial lithosphere survived to the Archaean. These venerable remnants could help us to understand better the thermal and geodynamic regimes operating on the earliest Earth, and whether they are common features within the cores of the oldest cratons.

The ages of the oldest terrestrial rocks can be determined using the isotopic system[3] of samarium (Sm) and neodymium (Nd). The Sm–Nd system is considered robust because these parent and daughter elements are near neighbours in the periodic table. However, the signature can be sensitive to resetting by later metamorphisms, and such changes often affect the oldest terranes. Fortunately the Pilbara rocks are only mildly metamorphosed, and this gentle history has preserved the earliest probable morphological evidence for life[4].

The Dresser Formation consists of cherty sediments rich in the mineral barium sulphate (barite). Although the ages for this formation as a whole are well constrained[5], debate lingers over its tectonic setting and origin. The presence of barite could represent the post-depositional replacement of calcium with barium in evaporitic deposits of calcium sulphate (gypsum)[6]. Alternatively, barite could have formed syn-depositionally through volcanogenic hydrothermal circulation associated with exhalative cooling of sub-seafloor magma chambers[7]. A direct absolute-age determination on the Dresser barites would put to rest this debate.

Tessalina and colleagues[2] performed Sm–Nd geochronology in whole rocks from the barite-rich layers of the Dresser Formation collected from fresh drill cores. They found the rocks and the barites to be about 3.49 billion years old, in line with earlier work[5,8,9]. The data show that the Sm/Nd ratio was modified little or not at all, implying syn-deposition of the chert–barite unit through hydrothermal deposition, without significant subsequent alteration. They also demonstrate that the Dresser rocks are depleted in radiogenic $^{143}\mathrm{Nd}$ relative to the bulk Earth. This depletion is expressed as negative $\varepsilon_{\mathrm{Nd}}$ values or the deviation towards lower $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ ratios expressed in parts per ten thousand versus bulk Earth. This indicates that the Dresser Formation was either derived from, or assimilated, some much older crust at the time of emplacement. To determine the type and age of this component of old rock, Tessalina and colleagues[2] used geochemical modelling of probable end-member compositions. The models show that the old assimilated crust separated from the mantle 4.3 billion years ago, indicating contamination from a Hadean crustal component. If this material was granitic in composition, the crust must already have been significantly differentiated by that time. If this crust was basaltic (as it probably was), differentiation must have happened even earlier.


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Figure 1 | The Dresser Formation in Western Australia's Pilbara Craton consists of volcanics and chert–barite units. Tessalina and colleagues[2] show that the Dresser rocks were contaminated by a roughly 4.3-billion-year-old crustal component at the time they formed. This implies that a differentiated and enriched crust was established during the Hadean eon.

In the 1980s, remnants of crust that were more than 4 billion years old were revealed by U–Pb zircon analyses in the Narryer Gneiss Complex, south of the Pilbara Craton[10], and in the Acasta locality of northern Canada[11]. Since then, evidence has accumulated for an hospitable Hadean Earth with granite crust, liquid water and a full-blown rock cycle that may have also witnessed plate-boundary interactions in its first 700 million years[12]. However, even taking into account more vigorous crust recycling and postulated crust-busting impact bombardments[13] early on, it seems unlikely that such a scenario would leave behind the present-day rock record of only a few meagre rock and mineral scraps. Indeed, over time, more old rocks and detrital zircons are being discovered, and new techniques are being brought to task in their analysis. Collectively, these results lend further credibility to the view that, instead of a primordial Earth with a primitive rocky rind that superficially resembled the Moon in most of its early history, the Hadean eon saw the quick establishment of differentiated and enriched crust.

The study by Tessalina *et al.*[2] cannot define the origin of the proposed Hadean lithosphere involved in the genesis of the Pilbara units. Whether this material was basaltic or a composite of granitoids in small fledgling continental nuclei, and whether rocks from this crust still exist, remain as unknowns. Around the world, vast areas of the oldest continental cores await more detailed analysis. Hidden Hadean histories may be preserved in these places; an obvious target for investigation would be other well-preserved early Archaean blocks such as the Barberton Greenstone Belt in South Africa. ❐

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References

1. Sleep, N. H., Zahnle, K. & Neuhoff, P. S. *Proc. Natl Acad. Sci. USA* **98,** 3666–3672 (2001).
2. Tessalina, S. G., Bourdon, B., Van Kranendonk, M., Birck, J.-L. & Philippot, P. *Nature Geosci.* **3,** 214–217 (2010).
3. DePaolo, D. J. *Rev. Geophys.* **21,** 1347–1358 (1983).
4. Van Kranendonk, M. J. *Earth Sci. Rev.* **74,** 197–240 (2006).
5. Thorpe, R. I. *et al. Precamb. Res.* **56,** 169–189 (1992).
6. Buick, R. & Dunlop, J. S. R. *Sedimentology* **37,** 247–277 (1990).
7. Van Kranendonk, M. J. & Pirajno, F. *Geochem. Explor. Env. Anal.* **4,** 253–278 (2004).
8. Van Kranendonk, M. J. *et al. Precamb. Res.* **167,** 93–124 (2008).
9. Pujol, M. *et al. Geochim. Cosmochim. Acta* **73,** 6834–6846 (2009).
10. Froude, C. F. *et al. Nature* **304,** 616–618 (1983).
11. Bowring, S. A., Williams, I. S. & Compston, W. *Geology* **17,** 971–975 (1989).
12. Harrison, T. M. *Ann. Rev. Earth Planet. Sci.* **37,** 479–505 (2009).
13. Abramov, O. & Mojzsis, S. J. *Nature* **459,** 419–422 (2009).