Further work is required to understand whether the observed light oxygen isotope signature is an isolated phenomenon, related only to the three-billion-year-old komatiite magmatic event preserved in the Barberton greenstone belt, or whether any secular evolution in the oxygen isotope composition of Archaean komatiites globally can be ascertained. A question also remains as to why that anomalous portion of the mantle is apparently no longer sampled in modern magmas. It is either inaccessible to modern-day mantle plumes or it no longer exists because it has since been wiped out by homogenization.

Analysis of the secular evolution of the platinum content of komatiites globally could provide a hint to solving this conundrum. Komatiites erupted more than about 2.9 billion years ago display anomalously low platinum contents[7], which reflect derivation from a platinum-depleted source. Conversely, the composition of younger komatiites is consistent with derivation from a source that contains similar platinum levels to the modern mantle. The platinum-depleted signature of the mantle source supplying the older komatiites could have been caused by segregation of the proto-core about 4.4 billion years ago[7]. Then, as the platinum content of the Archaean mantle steadily increased following the Late Heavy Bombardment event[7], this anomalous signature was effectively homogenized away. This implies that the reservoir that fed the three-billion-year-old Weltevreden lavas may now be extinct[8].

Data from the Weltevreden komatiites could provide precious insights into the thermal evolution of the planet. Komatiites are thought to form from lavas erupted at very high temperatures of up to 1,600 °C, which implies even higher temperatures in their mantle source. However, these inferred temperatures only hold true if the komatiites were essentially dry and originated in mantle plumes[9]. If the magmas contained several per cent water, their eruption temperature would be drastically reduced[10]. It has recently been argued that a hydrous reservoir may have even existed in the deep mantle of early Earth[11], and that hydrous and CO_2-rich komatiites could have formed from carbonated wet spots in Archaean mantle plumes[12]. A fascinating question to ask then is whether the anomalously light oxygen composition of the Weltevreden komatiites may in fact reflect the presence in their mantle source of a non-terrestrial component derived from the proto-solar nebula[13].

Byerly and colleagues[1] show that the oxygen isotopic signature of lavas erupted above a mantle plume more than three-billion-years ago is anomalously light compared to the present-day mantle. This implies that Earth's early mantle was heterogeneous, made up of reservoirs with different compositions and has since been homogenized by millions of years of mantle convection. The source of the anomalously light oxygen has yet to be unravelled. ❒

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CRYOSPHERIC SCIENCE

Muddying Greenland's meltwaters

Satellite measurements indicate that Greenland's meltwater rivers are exporting one billion tons of sediment annually, a process that is controlled by the sliding rate of glaciers. This rate is nearly 10% of the fluvial sediment discharge to the ocean.

Matthew A. Charette

Each year, Greenland's glaciers lose enough water through surface melting to triple the volume of the Dead Sea[1]. Yet, the majority of this meltwater does not run off the top of the Greenland ice sheet; rather it is routed through crevasses and moulins to the base of the ice[2]. Once there, it mixes with water that has melted from below, and is transported by gravity to the fronts of outlet glaciers that line Greenland's coastline. Along the way, this subglacial meltwater entrains sediment ground from bedrock by the immense pressure created as kilometres of ice pass over[3]. However, despite the well-known importance of river runoff in supplying eroded material from the Earth's surface to the oceans, Greenland's contribution is not currently considered in global budgets of sediment transport, which ignore subglacial meltwater rivers. Writing in *Nature Geoscience*, Overeem and colleagues[4] provide — using a unique satellite remote sensing-based approach — an estimate of the sediment load carried by Greenland's meltwater that has tantalizing implications for ocean biogeochemistry in a changing climate.

Greenland's remoteness, vast size, lack of infrastructure and harsh working environment have greatly limited the number and geographical diversity of ground-based studies on meltwater biogeochemistry. Because most focus on a single glacial catchment, measured material fluxes are usually scaled to the entire Greenland ice-sheet margin, which relies on the assumption that meltwater concentrations of sediment or solutes are constant across the island's 45,000 km coastline (almost twice that of Australia). Furthermore, and perhaps most importantly, extrapolation based on isolated studies neglects the fact that accelerated melting may change the underlying process(es) that is (are) driving the fluxes.

Overeem and colleagues[4] overcame these limitations by using satellite observations to quantify suspended sediment concentrations for 160 of Greenland's meltwater rivers. By comparing satellite measurements of light reflectance of the rivers' surfaces (cloudier rivers suggest higher sediment loads; Fig. 1) to concurrent *in situ* suspended sediment measurements for a well-studied river in southwestern Greenland for the period 2007 to 2014, they estimate that the Greenland ice-sheet exports nearly one billion tons of sediment each year. To put this finding in a broader context, this estimate suggests Greenland is responsible for 8% of the world's suspended sediment flux to the ocean, despite contributing only 1% of discharge.

Moreover, Overeem and colleagues report that the vast majority of this sediment is carried by a small fraction (one-sixth) of Greenland's rivers. Interestingly, they found that although the catchment's meltwater volume was important, ice dynamics — namely the sliding rate of glacial ice at its base — was more important in controlling suspended sediment concentrations in meltwater, and therefore the rate of sediment delivery from the Greenland ice sheet. Thus, sediment export is dominated by the subset of rivers draining fast-moving glaciers.

Ice velocities in Greenland's outlet glaciers are, on average, speeding up[5]. Overeem and co-workers[4] estimate that the acceleration of glaciers could be responsible for up to a 12% increase in meltwater sediment concentrations from 2000 to 2012. They suggest that the sediment input today may be as much as 60% higher than the average from 1961–1990 because of significant changes in meltwater runoff due to a warming climate[6].

Although sediments of all shapes and sizes are eroded by Greenland's glaciers, much of what is carried by these subglacial rivers and streams is extremely fine-grained. Commonly known as 'glacial flour', this suspended sediment gives many Greenland rivers an intense greyish-brown colour (Fig. 1), with sediment concentrations that are often reported in grams per litre rather than milligrams per litre as commonly used for many lower-latitude rivers. Although some sediment may be deposited through flocculation in glacial fjords[7], into which the majority of the meltwater flows, this fine-grained material can be transported over substantial distances in the Arctic Ocean to the north and the Atlantic Ocean to the south.

Figure 1 | The author and former PhD student Maya Bhatia collecting samples of subglacial discharge from a land-terminating glacier of the Greenland ice sheet. The opaqueness of the meltwater is due to a high concentration of fine-grained suspended sediment. Overeem *et al.*[4] use satellite observations to quantify suspended sediment concentrations of Greenland's meltwater rivers and find that a disproportionately large part of the sediment delivered to the world's oceans is exported from Greenland. Image courtesy of the Woods Hole Oceanographic Institution.

Once in the ocean, the sediment can serve as a source of bioactive iron[8], an essential micronutrient for marine plants[9]. Also carrying dissolved nutrients such as iron and nitrate, runoff from the Greenland ice sheet may play an important role in high-latitude ocean productivity. In the North Atlantic Ocean, an intense spring phytoplankton bloom depletes the upper ocean's cache of nutrients, which can be restocked when Greenland's nutrient-laden meltwater arrives at the coast during summer. Furthermore, the ocean biological pump acts to sequester CO_2 from the atmosphere, so Greenland's meltwater may influence this feedback on the climate system.

At present, the precise impact of Greenland meltwater on the ocean carbon cycle is not fully known[10,11], and Overeem and colleagues[4] only quantify sediment export from Greenland, not what happens once it reaches the fjords and oceans. More work is needed to quantify the transport length-scales of the meltwater sediment and solutes and understand how the export of such materials might change with changing climate. ❐

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