OCEANOGRAPHY
Siberian salt in the cellar

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The Lomonosov ridge, a mountain range under the Arctic Ocean, gained unusual notoriety in August, when a Russian submarine expedition planted a rust-proof titanium flag there to reinforce the country's Arctic territorial claims.

Now Brian Haley and colleagues report in *Nature Geoscience* that the ridge furnishes evidence of Russia's past influence on the region — at least, on its ocean circulation (B. A. Haley *et al. Nature Geosci.* doi:10.1038/ngeo.2007.5; 2007). They study neodymium (Nd) isotopic ratios in marine sediments in a core of sediments drilled from the Lomonosov ridge near the North Pole, at a sea depth of 1,250 metres.

The core represents a historical sketch of Arctic oceanography over the past 65 million years. The authors' big news is that the ratio $^{143}Nd/^{144}Nd$ of deep Arctic water that is preserved in the sediments was consistently far higher in the Neogene period between 15 million and 2 million years ago than it is now,

indicating the influence of young, mantle-derived rock. In the past 2 million years, similarly high ratios are found only during short ice ages.

Haley *et al.* argue that the only credible source for such a signal is material from the Putorana basalts of the Central Siberian Plateau. But how did a surface-water signal from the Siberian coastal shelf sink to the great depths of the Lomonosov ridge?

The authors see the answer in the wider global climate, and the opening up of the Fram Strait 17.5 million years ago. This strait is the only deep passage for water to and from the Arctic, and runs roughly along the Greenwich meridian between Greenland and the Norwegian island of Spitsbergen. Its breaching allowed warm, saline waters to flow into the Arctic from the Atlantic. As these waters entered colder climes, evaporation increased, causing more precipitation and the growth of extensive floating ice shelves at northerly latitudes —

including along the Siberian coast.

As sea water freezes, it rejects salt. Haley *et al.* propose that the resulting denser, briny water that sank beneath the developing ice sheet carried Russian sediment to the Lomonosov ridge during the Neogene, as it similarly does off Antarctica today.

Waters from the North Atlantic drift have low neodymium ratios. The authors estimate that, to maintain the ratios of the Neogene core record after the initial influx following the Fram breach, the flow of warm water from the Atlantic into the Arctic could have been no more than half of that today. They suggest that the Atlantic conveyor belt must

at that time have stopped at a more southerly point than it does today. This is a well-established prediction for recent ice ages, which indeed also produce high neodymium ratios in the Arctic cores. But how it would have been maintained as an equilibrium state during the entire Neogene is unclear.

The model of an Arctic circulation dominated by seawater subduction off the Russian coast contrasts with today's picture, in which the Arctic is under a steady North Atlantic influence. In sketching the Arctic's sensitivity to past climate change, Haley *et al.* underscore its vulnerability to further change today.

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the ice age. As iron-bearing minerals such as haematite (Fe_2O_3) are remarkably insoluble in the presence of oxygen, large regions of the ocean must have been largely anoxic during the glacial periods — at odds with the authors' suggestion of progressive oxygenation. A whiff of oxygen would have caused an iron-rich sea to rust, potentially consuming much of the oxidant needed to convert dissolved organic carbon to CO_2. Other potential sinks for oxygen, including weathering of the continents and the oxidation of volcanic gases, were similarly overlooked in the model exercise.

The cap carbonates are testament to the extreme build-up of carbonate anions (alkalinity) in sea water during the Neoproterozoic glacial episodes, and to their wholesale accumulation as carbonate minerals in the glacial aftermath. The oxidative respiration of organic matter produces CO_2 and also creates alkalinity, so Peltier and colleagues' open-ocean solution might also explain the ubiquitous presence of the cap carbonates. But as the authors acknowledge[3], there are other possible oxidants that would work in an anoxic glacial ocean — sulphate, for example[13]. In the absence of free oxygen, sulphate-reducing bacteria could have occupied the water column, as they do in the Black Sea today, and could have fed on the standing pool of organic carbon, progressively raising the concentrations of inorganic carbon. At the same time, their metabolic activity would have released hydrogen sulphide

that, when combined with iron, would form the highly insoluble mineral pyrite (FeS_2). The resultant rain of pyrite to the sea floor might help to explain extreme sulphur-isotope variations that are notably present in the post-glacial cap carbonates[14].

These texturally and isotopically distinct carbonates figure prominently in Neoproterozoic palaeoclimate interpretations. In Peltier and colleagues' model, the ^{12}C-rich cap carbonates reflect one stable state of the carbon cycle. But notably, isotopically similar carbonates also accumulated immediately before the ice ages[7,15]. Depending on the timing of CO_2 release, the presence of these deposits can effectively neutralize the authors' proposed solubility hypothesis for the Neoproterozoic ice ages. Not only is more oxygen dissolved when the oceans get colder, so too is more CO_2, which makes water acidic. Acidification of the oceans would have a profound effect on the preservation of carbonate deposited before or after the ice ages.

The variable accumulation of carbonate and iron-oxide-rich deposits across the glacial cycles is not necessarily incompatible with Peltier and colleagues' slushball model[3]. It could well reflect regional differences in seawater salinity and pH, as well as levels of soluble oxygen, sulphate, iron and dissolved organic and inorganic carbon in sea water. The idea of a self-limiting climate as expressed in their model is a tantalizing prospect, and an

important contribution to the debate. But our poor understanding of Neoproterozoic ocean dynamics and oxidation add great uncertainty to such mathematical models of Neoproterozoic climate and carbon cycling. ∎

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