In this case, the subduction of continental lithosphere would have started much later and the event of 55–50 Myr ago would have been caused by India's collision with an oceanic island arc, closing a major ocean basin and leaving only relatively young, buoyant back-arc basin crust to be subducted. The resulting diminished northward pull acting on India since 55–50 Myr ago would be an alternative explanation for India's deceleration at that time. There is ample geological evidence for the existence of intra-oceanic island-arc assemblages in the Himalayan mountains[2], implying the existence of a Cretaceous back-arc basin, which has also been inferred from the distribution of subducted slab material imaged beneath northern India and Tibet[3,4]. There is evidence[4] for a northward migration of subduction after 50 Myr ago (Fig. 1b). The migration of subduction could have been the consequence of the demise of subduction along an intra-oceanic island arc south of a back-arc basin bounding the margin of Eurasia. The system's response to continued convergence would have been subduction north of the back-arc basin. In this scenario, India's collision with Eurasia and the ensuing subduction of continental lithosphere would start about 20–25 Myr later than assumed in the model of Capitanio and colleagues[1], and cause the major slowdown of India–Eurasia convergence speed after 20 Myr ago[5], but without continental lithosphere reaching mid-mantle depths.

Whether or not Greater India had a thinned continental margin 600–1,000 km wide (the second assumption made by Capitanio and colleagues) will no doubt remain contested as well. A margin of these dimensions would be the widest known continental margin anywhere on the Earth, and the possibility seems unlikely: in the Palaeozoic era, two generations of continental slivers rifted away from the northern Gondwana margin, which included the precursor of the Greater Indian plate[6]. These events would have rifted away most of the previously existing thinned continental margin crust. To create an unusually wide margin it is necessary to stretch the continental lithosphere extremely during continental rifting. However, the stretching factor of the northern Indian margin has been estimated to be quite modest[7]. From this point of view, Greater India would not be the place to look for an unusually wide margin.

Capitanio and colleagues[1] have provided a fresh perspective on the long-standing problem of understanding the sequence of events before and after the collision of India and Eurasia, and its traces in today's mantle. However, whether prospecting for continental slabs deep in the Earth's mantle would be successful is likely to remain controversial for some time. ❐

R. Dietmar Müller is in the School of Geosciences, University of Sydney, New South Wales 2006, Australia.
e-mail: d.muller@usyd.edu.au

References

1. Capitanio, F. A. *et al. Nature Geosci.* **3,** 136–139 (2010).
2. Aitchison, J., Ali, J. R. & Davis, A. M. *J. Geophys. Res.* **112,** doi:10.1029/2006JB004706 (2007).
3. Hafkenscheid, E., Wortel, M. J. R. & Spakman, W. *J. Geophys. Res.* **111,** B08401 (2006).
4. Li, C., van der Hilst, R. D., Engdahl, E. R. & Burdick, S. *Geochem. Geophys. Geosyst.* **9,** Q05018 (2008).
5. Molnar, P. & Stock, J. M. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics. *Tectonics* **28,** doi:10.1029/2008TC002271 (2009).
6. Stampfli, G. M. & Borel, G. D. *Earth Planet. Sci. Lett.* **196,** 17–33 (2002).
7. Corfield, R. I., Watts, A. B. & Searle, M. P. *J. Geol. Soc. Lond.* **162,** 135–146 (2005).
8. Richards, S., Lister, G. & Kennett, B. *Geochem. Geophys. Geosyst.* **8,** Q12003 (2007).
9. Replumaz, A. & Tapponnier, P. *J. Geophys. Res.* **108,** 2285 (2003).
10. Lee, T.-Y. & Lawver, L. A. *Tectonophysics* **251,** 85–138 (1995).
11. Müller, R. D. *et al. Geochem. Geophys. Geosyst.* **9,** Q04006 (2008).

PALAEOCLIMATE

Extreme iceberg generation exposed

In the North Atlantic region, six massive iceberg discharge events marked the last glacial period. A numerical model now links these events to ocean temperatures and ice-shelf conditions.

Christina Hulbe

Earth's sedimentary materials, from terrestrial soils to seafloor sediments, contain a wealth of information about past climate states and events. However, these records are often incomplete and difficult to interpret. Widespread episodic deposits of ice-rafted debris that punctuate the sediment record of the glacial North Atlantic Ocean — known as Heinrich layers — have proven tricky to understand. They are attributed to massive iceberg discharge from Northern Hemisphere ice sheets, but the mechanisms leading to the development of the iceberg armadas remain controversial. Writing in *Nature Geoscience*, Alvarez-Solas and colleagues[1] describe a simple model that links ice-sheet and iceberg discharge to fluctuations in ocean temperature, through an ice shelf connected to a fast-flowing stream within the ice sheet.

The last glacial period was characterized by millennial-scale climate oscillations between relatively mild and relatively cold conditions called Dansgaard–Oeschger cycles. These cycles are seen most prominently in Greenland ice cores, but are present in many palaeoclimate records, indicating that these climate swings are global in scale[2–4]. There is as yet no consensus regarding the forcing responsible for Dansgaard–Oeschger cycles, but similar transitions between cold and warm phases can be simulated in ocean models by varying the freshwater flux to the ocean surface.

Six Heinrich layers are apparent through the last glacial, between 70,000 and 14,000 years ago[5–7]. The ice-rafted debris events — known as Heinrich events — coincide with the culminations of sets of increasingly cold Dansgaard–Oeschger cycles. Heinrich events do not occur during every cool phase or with reliable freqency, but the timing of Heinrich-layer deposition is not entirely irregular either: they are always found at the cold extremes. It seems reasonable to conclude that the Dansgaard–Oeschger cycles and Heinrich layers are related, but more interpretive tools are required to understand how they are related.

The production of a Heinrich layer requires three conditions: a sediment source; a mechanism for moving that sediment up into the glacier ice and transporting it safely to the ocean; and a process that varies the rate of dirty iceberg production, or at least the persistence of the icebergs and their debris at sea. This third requirement may be met internally by processes in the ice sheet, or externally by forcing from other components of the climate system.

In the years since their discovery, Heinrich layers and the events responsible for their deposition have been explained in several ways. Cooling of the sea surface might simply have allowed icebergs to drift further afield during Heinrich events. Internally regulated cycles in the sliding of the ice sheet may have triggered the episodic purging of debris-charged ice, perhaps chilling the North Atlantic region by changing regional ocean and atmosphere circulations[8,9]. Or instead, the expansion of coastal ice-shelves during cold phases may have promoted debris storage until warming-induced collapse released armadas of icebergs to the sea[10]. Relatively large palaeotide heights have also been implicated as a forcing on either ice-stream or ice-shelf behaviour[11].

Alvarez-Solas and colleagues[1] offer a new interpretation of the record using a simple model designed to explore the interaction between ocean circulation and ice sheets. In their simulations, variable circulation in an ocean analogous to the glacial North Atlantic Ocean leads to oscillations in ice discharge from the adjacent ice sheet. The connection between the ocean and the ice sheet lies in the coastal ice-shelves into which fast-moving ice streams flow. The team uses the Laurentide ice sheet as their example, but the mechanism is equally viable elsewhere.

In this new model, climate cooling causes ice shelves to grow along the coast of the Labrador Sea. The floating ice impedes ice-stream discharge by modifying the force balance at the marine margin. Warming of the subsurface ocean waters, a result of altered ocean circulation, erodes the ice shelves and removes the impediment to ice-stream discharge. The resulting increase in ice-stream speed sends a flood of icebergs out to sea. The ice stream is essential to producing debris-rich icebergs. Basal meltwater, on which the ice stream slides, erodes the glacial bed upstream in debris-source regions and facilitates the entrainment of the debris downstream, where ice thinning and a shallowing bed both promote refreezing of the water. Sliding over a melted bed facilitates rapid propagation of the ocean forcing into the ice sheet.

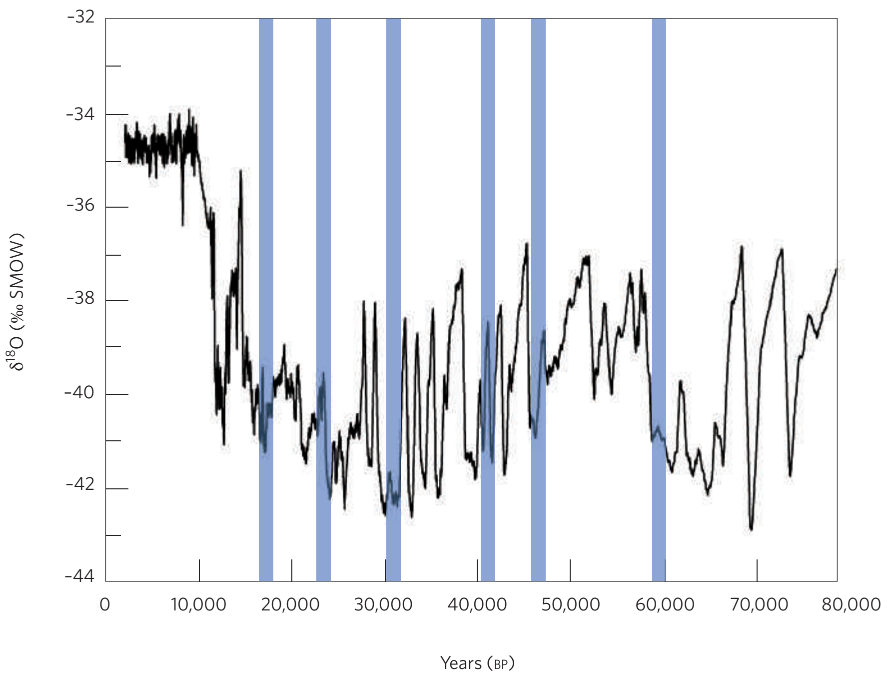

Figure 1 | Heinrich events during the last glacial. The glacial North Atlantic cycle of warming and cooling, shown here in the oxygen isotopic record (referenced against standard mean ocean water) from Greenland ice cores[13], is punctuated by massive iceberg discharge events (blue bars) lasting 500±250 years (ref. 14). A simple numerical model from Alvarez-Solas and colleagues[1] links these events to interplay between ocean temperatures, ice shelves and snow accumulation.

Modern evidence for regulation of grounded ice discharge by peripheral floating ice comes from the Antarctic Peninsula, where relatively large outlet glaciers increased in speed following collapse of the Larsen B ice shelf. In Greenland, changes to fjord-filling ice jams are associated with at least some outlet glacier speed-up events. Ice shelves have previously been implicated in Heinrich events, with rapid ice-shelf disintegration attributed to rising air temperature at the end of a Dansgaard–Oeschger cold extreme. Alvarez-Solas and colleagues instead invoke warming of the ocean subsurface, caused by weakening of the Atlantic meridional overturning circulation[12]. The subsurface warming would precede the atmospheric warming, providing an arguably better fit for the sequence of events inferred from the palaeoclimate record (Fig. 1).

The coupled ocean, ice-shelf and ice-sheet mechanism neatly links millennial-scale variations in the ocean and atmosphere to the adjacent ice sheet. It also allows for pacing of Heinrich events that is different from the oceanic pacing. Mass flows through components of the system in a straightforward way: snow accumulates on the ice sheet, the resulting glacial ice flows into the ice shelf via the ice stream, and is lost through melting and iceberg calving from the floating shelf. The size of the ice shelf, and in turn its effect on the grounded ice, depends on the balance of ice coming in via the ice stream and going out through melting and calving. When ice-shelf melting is forced to vary with an ocean-driven periodicity, the ice sheet responds with oscillatory iceberg discharge. The frequency of the response is modulated by both snow accumulation and ice-stream sliding. If the snow accumulation rate varies over time, as it surely does, irregular Heinrich events may also be produced.

This new reading of the Heinrich-layer record by Alvarez-Solas and colleagues[1] embraces the best elements of previous interpretations and incorporates modern observations of ice sheets in transition. They plant their flag on the side of climate forcing of Heinrich events, nevertheless maintaining that the ice-sheet response is not a passive one, but is instead closely related to interactions between components of the ice-sheet system, even accounting for the irregular frequency. ❐

Christina Hulbe is in the Department of Geology, Portland State University, PO Box 751, Portland, Oregon 97207-0751, USA.
e-mail: chulbe@pdx.edu

References

1. Alvarez-Solas, J. *et al. Nature Geosci.* **3,** 122–126 (2010).
2. Bond, G. *et al. Nature* **365,** 143–147 (1993).
3. Bond, G. *et al. Science* **278,** 1257–1266 (1997).
4. Voelker, A. H. L. *Quat. Sci. Rev.* **21,** 1185–1214 (2002).
5. Heinrich, H. *et al. Quat. Res.* **29,** 142–152 (1988).
6. Bond, G. C. *et al. Nature* **360,** 245–249 (1992).
7. Bond, G. C. & Lotti, R. *Science* **267,** 1005–1010 (1995).
8. MacAyeal, D. R. *Paleoceanography* **8,** 775–784 (1993).
9. Jackson, C. J. *Geophys. Res.* **105,** 24443–24454 (2000).
10. Hulbe, C. L. *Paleoceanography* **12,** 711–717 (1997).
11. Arbic, B. K., MacAyeal, D. R., Mitrovica, J. X. & Milne, G. A. *Nature* **432,** 460 (2004).
12. Mignot, J., Ganopolski, A. & Levermann, A. *J. Clim.* **20,** 4884–4898 (2007).
13. Stuiver, M. & Grootes, P. M. *Quat Res.* **53,** 277–284 (2000).
14. Hemming, S. R. *Rev. Geophys.* **42,** RG1005 (2004).