FORUM: Climate science

The history of Greenland's ice

Global sea levels would rise by several metres if the Greenland Ice Sheet melted completely. Two studies have examined its past behaviour in an effort to evaluate its vulnerability in a warming world — and have come to seemingly conflicting conclusions. Two geochemists and a glaciologist discuss the issues. SEE LETTERS P.252 & P.256

THE PAPERS IN BRIEF

- Knowledge of the ancient history of ice sheets is needed to inform predictions of their future response to climate change.
- On page 252, Schaefer *et al.*[1] present measurements of beryllium-10 (^{10}Be) and aluminium-26 (^{26}Al) from bedrock beneath the Greenland Ice Sheet.
- From their data, they propose that Greenland has undergone one or more episodes of deglaciation during the past 1.1 million years.
- On page 256, Bierman *et al.*[2] present ^{10}Be and ^{26}Al data from marine sediment cores collected off the coast of Greenland.
- They conclude that the East Greenland Ice Sheet remained present during the Pleistocene (the epoch that lasted from 2.6 million to 11,700 years ago), but grew and shrank dynamically in response to climate.

Cosmic signature

PIERRE-HENRI BLARD & GUILLAUME LEDUC

It is difficult to find evidence for past waxing and waning of the Greenland Ice Sheet (GrIS), because the glacial debris that can provide a record of ice-sheet dynamics (Fig. 1) is erased each time glaciers advance after a period of deglaciation. Schaefer *et al.* and Bierman *et al.* now report the presence of two rare nuclides (^{10}Be and ^{26}Al) in Greenland's geological archives. These 'cosmogenic' nuclides are produced by the interaction between atoms in minerals and high-energy cosmic neutrons that probably originated in supernovae, and they provide much-needed evidence about the GrIS's ancient past.

A key characteristic of these isotopes is that they are produced in detectable quantities in only the first few metres below Earth's surface. If they become buried below hundreds of metres of ice, their concentrations decrease through radioactive decay. The half-lives of ^{10}Be and ^{26}Al are 1.4 million and 0.7 million years, respectively, so the presence of these nuclides in bedrock under ice sheets is direct evidence that one or several ice-free episodes occurred in the recent past (less than 5 million years ago).

Bierman *et al.* report variations in ^{10}Be and ^{26}Al from marine sediments deposited near the eastern margin of today's GrIS over the past 7.5 million years. The low ^{10}Be concentrations suggest that the sedimentary material originates from locations that were efficiently shielded from cosmic rays. The authors therefore conclude that large ice caps probably existed continuously across East Greenland — the source of the sedimentary material — during the past 7.5 million years. They also observe an additional long-term decrease in ^{10}Be and ^{26}Al concentrations during this period, which indicates a gradual increase in the volume of the GrIS.

In parallel, Schaefer *et al.* analysed bedrock samples recovered from beneath several kilometres of ice in the centre of the present-day GrIS. These rocks cannot have been transported to their current position from elsewhere. The presence of ^{10}Be and ^{26}Al in these samples is therefore direct evidence for past deglaciation episodes at this location.

Schaefer and colleagues used the observed concentrations and ratios of ^{10}Be and ^{26}Al in a numerical model to explore plausible glaciation–deglaciation scenarios. They firmly conclude that the sampled bedrock must have been ice-free for at least one episode of about 280,000 years during the past 1.1 million years. Other glaciation–deglaciation scenarios are more plausible, however, such as several shorter disappearances (several thousand years) of the GrIS during the warmest interglacial periods of the Pleistocene[3].

The deglaciation proposed by Schaefer

NICK COBBING/GREENPEACE

Figure 1 | Ice-sheet dynamics. These icebergs calved from the Helheim Glacier, an outlet glacier at the periphery of the Greenland Ice Sheet. Such glaciers are responding rapidly to climate change.

et al. seems at odds with Bierman and colleagues' conclusions. But small ice caps might have persisted on the East Greenland highlands during such deglaciated episodes, and could be the origin of the ^{10}Be-poor material observed in Bierman and co-workers' marine sediments. Indeed, modelling experiments[4] estimate that ice caps 1,000 metres thick might persist on the south-eastern Greenland highlands in the future even if 95% of the GrIS disappears (Fig. 2).

Could the GrIS undergo similar deglaciations in the future? Average global warming of just 2 °C compared with preindustrial temperatures could be enough to melt more than 75% of the GrIS[3]. If this high sensitivity to warming is confirmed, then the current worst-case scenarios[5] for future sea-level rise associated with anthropogenic global warming will need to be revised.

Pierre-Henri Blard *is at the Centre de Recherches Pétrographiques et Géochimiques, CNRS, Université de Lorraine, 54500 Vandoeuvre-lès-Nancy, France.* **Guillaume Leduc** *is at the Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement, (Aix-Marseille University, CNRS, IRD), Europôle Méditérrannéen de l'Arbois, 13545 Aix en Provence, France.*
e-mails: blard@crpg.cnrs-nancy.fr; leduc@cerege.fr

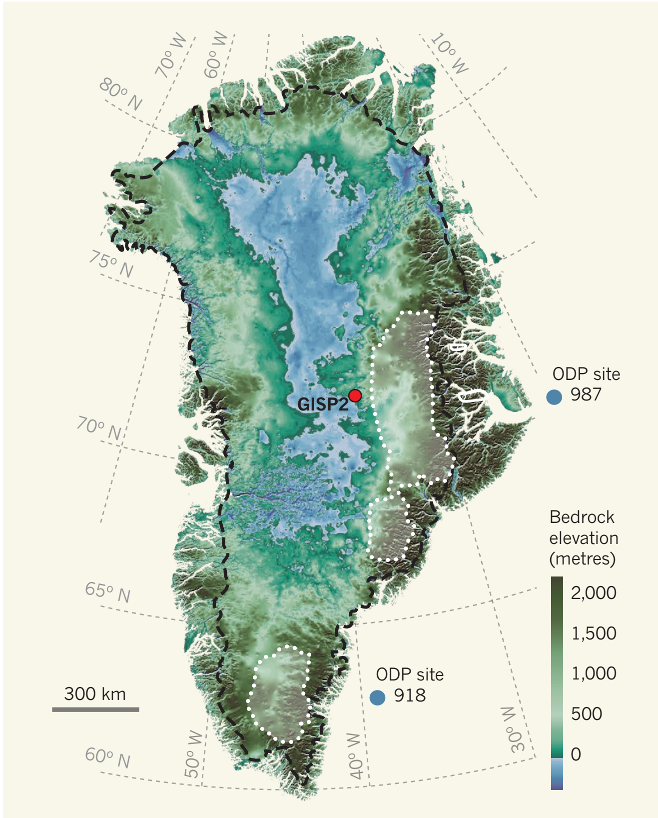

Figure 2 | Subglacial topography of Greenland and deglaciation of its ice sheet. The map shows the bedrock core of Greenland and its elevation above or below sea level. Schaefer *et al.*[1] analysed bedrock samples taken from a site at Greenland's centre (GISP2), and conclude that Greenland was ice-free for long periods during the Pleistocene epoch (2.6 million to 11,700 years ago). Bierman *et al.*[2] analysed marine sedimentary cores taken from two sites off the east coast of Greenland (ODP sites 918 and 987), and deduce that the East Greenland Ice Sheet remained intact during the Pleistocene. Although seemingly contradictory, the results could be reconciled if a small ice cap remained during major deglaciations — previous simulations[4] suggest that remnants of the ice sheet (enclosed by dotted white lines) would persist in the eastern highlands even if 95% of the Greenland Ice Sheet melted. The broken black line indicates the approximate extent of the current ice sheet. (Adapted from refs 4 and 7.)

Glaciological puzzle

NEIL GLASSER

One of the most powerful methods for predicting future behaviour is to look for clues from the past. But interpreting the past is rarely straightforward, as illustrated by the seemingly contradictory conclusions of Schaefer *et al.* and Bierman and colleagues. The findings can perhaps be reconciled, but that would require glaciologists to have a major rethink about current theories of ice-sheet behaviour.

Schaefer and colleagues' analysis of the terrestrial bedrock beneath the GrIS leads them to conclude that the ice sheet was sometimes reduced to less than 10% of its current volume, so that the only ice to be found in Greenland was in the peripheral mountain ranges. By contrast, Bierman and co-workers' study of the marine record indicates that warming was short-lived, and that it seldom caused substantial and lengthy reductions in the extent of the East Greenland Ice Sheet. So how do these conclusions fit in with what is known about ice-sheet dynamics?

One source of information is numerical modelling of ice sheets. Simulations[6] based on such models tend to predict that the GrIS existed continuously throughout the Pleistocene. The models rarely predict extended periods during which Greenland was nearly ice-free.

Glaciologists also know from observations that the GrIS is dynamic, and that its peripheral outlet glaciers are responding rapidly to climate change (Fig. 1). But most of these observations come from areas around the periphery of the ice sheet; the central areas are considered to be relatively stable. The conclusion that the GrIS shrank to less than 10% of its current volume, leaving ice-free areas at its centre, is therefore particularly difficult to explain glaciologically because it requires the entire ice sheet to have been removed and completely 'rebuilt', possibly on several occasions.

Perhaps part of the explanation lies in Greenland's subglacial topography[7]. Earth's crust is depressed at the centre of Greenland because of the great weight of the ice sheet, whereas the periphery is surrounded by mountain ranges (Fig. 2). Deglaciation right to the centre of the GrIS — rather than just changes in the peripheral outlet glaciers — would therefore require massive, rapid changes of ice dynamics. This calls for glaciologists to rethink how the ice sheet interacts with subglacial topography and sea level. Could the same deep valleys that give the central GrIS its great thickness also open up the underside of the ice sheet and make it vulnerable to warming oceans as sea levels rise?

These new papers throw down three immediate challenges. First, we must seek ways to reconcile the two seemingly contradictory records of the ice sheet's past behaviour. Second, we must try to understand the dynamical processes of the ice sheet that make possible the required huge and rapid variations in the size and volume of the GrIS. And third, we need to assess whether such variations could happen again in the near future, with all the attendant social and economic consequences that would accompany a rapid rise in global sea level. ■

Neil Glasser *is in the Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, UK.*
e-mail: nfg@aber.ac.uk

1. Schaefer, J. M. *et al. Nature* **540,** 252–255 (2016).
2. Bierman, P. R., Shakun, J. D., Corbett, L. B., Zimmerman, S. R. & Rood, D. H. *Nature* **540,** 256–260 (2016).
3. Dutton, A. *et al. Science* **349,** aaa4019 (2015).
4. Fyke, J., Eby, M., Mackintosh, A. & Weaver, A. *Clim. Dyn.* **43,** 2249–2260 (2014).
5. Ridley, J., Gregory, J. M., Huybrechts, P & Lowe, J. *Clim. Dyn.* **35,** 1049–1057 (2010).
6. Calov, R., Robinson, A., Perrette, M. & Ganopolski, A. *Cryosphere* **9,** 179–196 (2015).
7. Morlighem, M., Rignot, E., Mouginot, J., Seroussi, H. & Larour, E. *Nature Geosci.* **7,** 418–422 (2014).