SOLID EARTH

Heating glaciers from below

Climate change is affecting the cryosphere from above. Geothermal heat flux from below is also contributing to conditions at the base of Greenland's ice sheet, which sits atop a lithosphere of variable thickness.

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The heat that has been slowly escaping the Earth's interior since its formation 4.55 billion years ago is the motor that drives the tectonic plates[1]. But cooling the Earth's interior is a slow process; for the purposes of studying relatively fast processes at the Earth's surface, such as changes to the cryosphere over glacial cycles, the geothermal heat flux across the surface is often assumed to be unchanging. Thick ice sheets, however, are not only sensitive to temperature fluctuations from above, but also to heating from below, from the Earth's interior. Determining the geothermal heat flux manually — by drilling a hole into the Earth and measuring the local temperature gradient — is challenging beneath kilometres of ice. Thus, the heat flux beneath ice sheets remains poorly constrained[2]. Writing in *Nature Geoscience*, Petrunin and colleagues[3] use a coupled lithosphere–glacier model calibrated with temperature measurements from drill holes within the Greenland ice shield to show that the geothermal heat flux is strongly spatially variable across central Greenland.

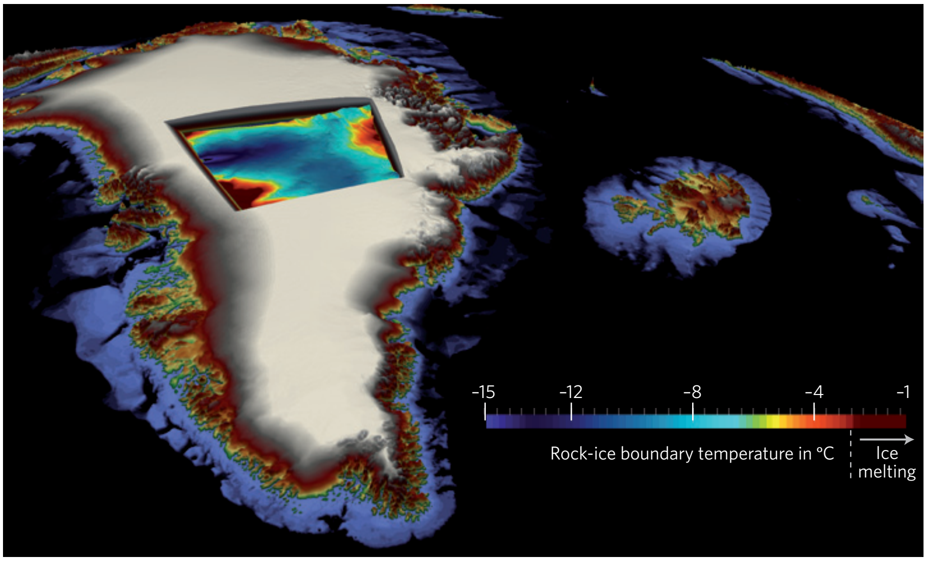

Figure 1 | Varying heat below glaciers. With the help of a coupled lithosphere–ice model, Petrunin *et al.*[3] predict that the temperature at the rock–ice interface beneath the Greenland ice sheet varies laterally, which may cause the ice to melt at certain locations where basal conditions are warm. The simulations suggest that the temperature variations are caused by glacial and intra-glacial periods, which cool and warm the lithosphere from above, in addition to variations in lithospheric thickness, which modify the geothermal heat flux from below. Figure courtesy of Tobias Baumann (Johannes-Gutenberg University), using data from ref. 11.

Anyone that has visited a deep mine knows that the Earth's interior is hotter than its surface. This heat is partly a leftover of the initial formation of the Earth, but is also produced by the ongoing decay of radioactive elements and the crystallization of the inner core[1]. The amount of thermal energy that leaves the Earth's surface every second — the heat flux — is largely proportional to the increase of temperature with depth. As the upper mantle beneath the lithosphere is thought to have an approximately constant temperature, the temperature increases most rapidly with depth — and most of the heat leaves the Earth — at locations where the lithosphere is thin[1].

Oceanic lithosphere has a predictable thermal structure due to steady cooling as newly formed oceanic crust drifts away from hot mid-ocean ridges[1]. Matters are more complicated for the continental lithosphere, which is thicker and much older than oceanic lithosphere. Continental rocks contain significantly more radioactive elements than oceanic rocks, which are an additional source of heat to the flux from the mantle. Moreover, the thermal structure of continental lithosphere is also modified by tectonics, topography, erosion and variations in the surface temperature[1]. Temperature differences between day and night only affect the upper few centimetres of the crust, whereas temperature variations that occur on a longer timescale are felt deeper.

Where there is ice, the story becomes even more complex. Ice sheets are cold and glacial–interglacial cycles cause temperature swings over long time periods. As a result, the temperature of the lithosphere is modified to a depth of a kilometre or more over timescales of about a hundred thousand years[4]. This influences the temperature gradient, and thus the upwards heat flux beneath the glacier. This heat flux in turn determines the temperature at the base of the glacier and the presence or lack of melt water, which affects glacier dynamics. Moreover, changes in the ice thickness — and hence the weight that presses down on the Earth's crust — might induce isostatic rebound of the lithosphere, which also influences ice-sheet dynamics.

Ice sheets are thus intimately coupled to the deformation and thermal structure of the solid Earth. Yet, most existing models of ice-sheet dynamics have focused on how they interact with climate, with only simplified representations of the solid Earth, for example by prescribing an unchanging basal heat flux or by modelling the lithosphere as a simple elastic plate. These models have failed to reproduce observed ice thicknesses, as well as temperature measurements of basal ice, in Greenland[5].

Petrunin and colleagues[3] treat the solid Earth more completely, and couple an ice–climate model with a three-dimensional visco-elasto-plastic model of the thermomechanical structure of the lithosphere. They ran their model simulation over the past 3 million years and compared predicted present-day ice thicknesses and temperatures at the base of the ice sheet to borehole measurements at two locations. The remarkable agreement is a significant improvement over previous glacier-only models, and the calculated geothermal heat fluxes constrain the amount of radioactive elements in the crust. Moreover, the model explains the puzzling observation that measured temperatures in two closely located boreholes are different: the thickness of Greenland's ancient lithosphere varies strongly over short distances in some places, and therefore geothermal heat flux varies as well.

Furthermore, the thermal ups and downs of glacial cycles amplify the geothermal signal. As a result, the temperature at the base of the ice sheet is expected to vary strongly in the lateral directions (Fig. 1). This fits well with observations that suggest that portions of the basal ice sheet are molten. Rather than requiring an additional heat source such as an active volcanic system[6], the nonlinear feedback between glacial dynamics and the solid Earth can potentially explain the regional patterns of melting beneath Greenland's ice.

Although the results from the coupled model are encouraging, the model focuses only on a small region of central Greenland. It is difficult to assess whether lithospheric thinning strongly affects basal ice conditions over the rest of the Greenland ice sheet too.

In Antarctica, borehole measurements also indicate substantial lateral variations in heat flux, but previous glacier-only models for Antarctica suggest that the influence of geothermal heating on large-scale ice-sheet dynamics is rather limited[7].

It also remains to be addressed how the considerable uncertainties in our understanding of the lithosphere[8] affect model outcome. The lithosphere beneath Greenland is thought to be ancient and geologically stable, so the cause of local thinning inferred by the model to be tens of kilometres in magnitude is enigmatic. High-resolution geophysical images of the base of the North American lithosphere reveal that such variations in lithospheric thickness are not uncommon in the continents[9]. Yet, the mechanisms that produce them remain elusive. In the case of Greenland, the nearby Iceland mantle plume may have played a role in thinning the lithosphere, as evidenced by basalts that outcrop along the shoreline of Greenland[10].

As Petrunin *et al.*[3] remind us, the solid Earth is not a force that can be ignored — it is an active player in surface processes. As we focus our attentions in a warming world on the atmosphere, oceans and glaciers, we must not forget the planet itself knocking on the surface from below. ❐

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References

1. Jaupart, C. & Mareschal, J-C. *Heat Generation and Transport in the Earth* (Cambridge Univ. Press, 2010).
2. Davies, J. H. & Davies D. R. *Solid Earth* **1,** 5–24 (2010).
3. Petrunin, A. G. *et al. Nature Geosci.* http://dx.doi.org/10.1038/ngeo1898 (2013).
4. Fowler, C. M. R. *The Solid Earth* 2nd edn (Cambridge Univ. Press, 2004).
5. Rogozhina. *et al. J. Geophys. Res.* **117,** F02025 (2012).
6. Fahnestock, M., Abdalati, W., Joughin, I., Brozena, J. & Gogineni, P. *Science* **294,** 2338–2342 (2001).
7. Pollard, D., DeConto, R. M. & Nyblade, A. A. *Glob. Planet. Change* ***49,*** 63–74 (2005).
8. Burov, E. B. in *Treatise on Geophysics—Crust and Lithosphere Dynamics* Vol. 6 (eds Schubert, G. & Watts, A. B.) 99–151 (2007).
9. Kerr, R. A. *Science* **340,** 1283–1285 (2013).
10. Lawver, L. A. & Müller, R. D. *Geology* **22,** 311 (1994).
11. Amante, C. & Eakins, B. W. *NOAA Technical Memorandum* NESDIS NGDC-24 (National Geophysical Data Center, 2009).

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