

## GEOMORPHOLOGY

## Where glaciers cut deep

Stunning images of fjords are familiar to geologists, but their origins are less well known. A simple model suggests that topographic steering of ice and erosion proportional to ice discharge are sufficient to explain fjord formation during the Quaternary period.

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Of all elevated continental margins, only those repeatedly covered by Quaternary ice sheets display fjords (Fig. 1). These dramatic features include steep-sided and ocean-terminating valleys with basins that extend kilometres below sea level. The process of selective linear erosion<sup>1</sup>, in which local variations in basal temperature and presence of water lead to distinct corridors of erosion, is well established. It is also widely understood that strong feedback mechanisms must be in operation to allow highly localized erosion to grind into resistant rock types at such great depths. However, the precise nature of these feedbacks has remained elusive, and the complexity of glacial erosion processes has greatly discouraged serious attempts to numerically model fjord formation. On the *Nature Geoscience* website today, Kessler and co-authors<sup>2</sup> come up with a surprisingly elegant concept for fjord formation by avoiding this complexity through the use of a relatively simple model.

Fjords are the most extreme manifestations of Quaternary glacial erosion. They are the linear conduits for erosion products from continental interiors and margins, and are also features where the research issues of tectonic uplift<sup>3</sup>, climate evolution<sup>4</sup>, glacial erosion processes<sup>5</sup> and denudation rates<sup>6</sup> all come together. In some areas, fjords developed through extreme deepening of pre-existing fluvial valleys<sup>7</sup>, but such part-inheritance of relief is not universal for all fjords, and hence, not the key factor in their formation. Neither can such inheritance from fluvial valley precursors explain erosion deep below sea level.

Kessler and co-authors shed new light on fjord formation, showing that just two factors — topographic steering of ice and erosion proportional to ice discharge — can explain how fjords can be cut to realistic depths in the timeframes available during



**Figure 1** Fjorded coastline on Meta Incognita Peninsula, Baffin Island. This landscape clearly displays the essence of Kessler and co-authors' object of study. Deep glacially eroded fjords coexist side-by-side with uplands that are almost untouched by glacial erosion despite having been overridden by ice.

the Quaternary period. To do this, they use a simplified two-dimensional model that runs on a cleverly designed initial topography. In their simulation, an ice sheet overruns a low mountain range with four saddles of differing depths on its way to the continental shelf and ocean. Over time, erosion lowers the saddles, and this in turn influences the ice surface topography, which is the driving force for ice flow. In the erosion race, the saddle that is initially deepest is the clear winner. Its catchment area grows faster because ice discharge increases nonlinearly with ice thickness. The model clearly shows that the glacial system is extremely relief-enhancing and capable of greatly magnifying subtle height differences in the initial relief. This is in line with previous empirical observations and qualitative models<sup>1,8</sup> but has not previously been shown numerically.

Kessler and co-authors justify the use of a very simple model because "basal sliding and erosion are driven by the same variables

that govern the ice discharge: ice thickness, slope and basal temperature". Hence, they encompass the challenging complexity that a precise description of the subglacial processes would entail within the much simpler variable of ice discharge. There are good reasons for doing this: on the scale of an ice-sheet, the glacier bed is a forbidding environment to study directly. This leaves laboratory-scale simulations, radio-echo data and rare borehole data as the only means to make inferences about the highly complex processes at the basal interface. There are simply not enough good data to drive a complex model.

The simulations by Kessler and co-authors add fjords to the list of reasonably well-understood glacial phenomena, but many questions remain unanswered. A particularly intriguing one is why different ice drainage systems in coastal British Columbia, Labrador, Greenland and Norway all appear to have evolved so that

it takes, on average, the ice discharge from ten mountain-crossing fjords to feed one shelf-crossing ice-stream trough. This implies a strong scale-dependency for ice streaming and erosion processes. The implications of fjord formation for interactions between climate and ice sheets may also be less clear than Kessler and co-authors suggest. With its relatively few variables, their highly simplified model is unlikely to capture a reasonable range of potential feedback mechanisms.

The findings presented by Kessler and co-authors also help to resolve the hundred-year-old controversy surrounding nunataks — postulated ice-free areas on formerly glaciated coastal mountain ranges — and their identification in the geologic record. When considering the new simulations and recent geomorphological and cosmogenic dating evidence for preservation of relict surfaces on uplands<sup>8–10</sup>, it becomes clear that glacial erosion on the highpoints in a high-relief landscape will

be minimal in any case, and especially so if the ice is frozen to its base. Kessler and co-authors give a figure of 5 m of summit erosion for the long timespan of 1.2 Myr. Hence, a single and much shorter phase of glaciation can not be expected to produce a clear glacial imprint on such summits. An absence of glacial landforms therefore does not conclusively demonstrate lack of ice cover. These summit areas only tell us something about former ice cover and ice elevations if they contain glacial erratics that can be cosmogenically dated<sup>9</sup>. Without glacial erratics, we are simply left in the dark regarding the presence or absence of former ice cover.

The time may have come to stop regarding the glacial system as one system. At least in terms of erosion, there appear to be two systems: a non-erosive thin-ice system on high points, often with divergent flow and frozen-bed conditions, and a highly erosive thick-ice system over low

points, with parallel or convergent flow and dominantly thawed-bed conditions. In terms of denudation rates, the thick-ice system is likely to have a much stronger affinity to the fluvial system than to the almost powerless thin-ice system. In any case, it is this binary division that makes ice-sheets so splendidly relief-enhancing.

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## CLIMATE SCIENCE

# Globalized carbon emissions



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An index that both climate scientists and policy makers anxiously keep track of is national emission rates of carbon dioxide, particularly for China, which has quickly been catching up with the US, hitherto the world's largest emitter of carbon dioxide. Despite all efforts to the contrary, the rates for both China and the world are rapidly going up, rather than down. Jay Gregg of the University of Maryland, US, and colleagues suggest that paying attention to China is justified as 54% of the growth of

global carbon dioxide emissions between the years 2001 and 2006 has come from increases in Chinese emissions (*Geophys. Res. Lett.* **35**, L08806; 2008).

However, the researchers also estimate large uncertainties, on the order of 15–20%, in the Chinese annual trends. Discrepancies between some of the changes announced in the official Chinese statistics are hard to reconcile with current understanding. For example, between 1996 and 2000 a decrease in carbon dioxide emissions was reported,

whereas electricity generation, industrial output and gross domestic product were all reported to have increased. In addition, official numbers for emissions in the year 2000 were recently revised upwards by 23%.

Whether China has already overtaken the US in terms of national carbon dioxide emissions in 2004, or will not do so before 2010, is therefore uncertain. But what does an answer to this particular question mean? A comparison of carbon emissions by country is not necessarily informative, when the populations differ by a factor of four. In addition, an estimated fraction of 7–14% of China's carbon dioxide emissions is ultimately outsourced from the US, in the sense that many energy-intensive products that are manufactured in China are eventually consumed in North America. And other western countries import goods from China, too.

China's sizable and growing contribution to global carbon emissions cannot be ignored: countries are still political units where legislation can steer development, at least to some degree. But part of this contribution is due to demand from developed countries for energy-intensive goods. In today's globally entangled economies it is not entirely straightforward to attribute carbon emissions.

**Heike Langenberg**