SHORT NOTES

GLACIERS AND ICE-SHEETS: MODERN PROBLEMS AND TECTONIC ASSOCIATIONS

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Abstract: Glaciers, and rocks of the Earth's crust, have a brittle zone (which breaks) above a plastic zone (which flows). The brittle zone is distinguished by crevasses (glaciers) and faults (rocks); the plastic zone by flow structures. Glaciers and ice-sheets such as Greenland and Antarctica flow essentially by creep, and are governed by laws of creep. The surface temperature has negligible effect on flow. Global warming cannot cause a "collapse" of the ice-caps. The basins of Greenland and Antarctica are, if created by isostatic response to the load of the ice pile, a result of creep in the lower crust or mantle.

Keywords: *glaciers, creep, melting, tectonic basins*

Introduction

In a recent article I wrote about the spreading of a former Tibetan Plateau to form the Himalayas and Kunlun Mountains (Ollier, 2006). The proposed mechanism involved flow in the solid state known to metallurgists and crystallographers as 'creep', a topic far from the forefront of most geologists' reasoning. The topic has re-emerged, thanks to a claim by Jim Hansen that global warming will cause "collapse" of the ice-sheets, and cause a huge rise in sea level.

To understand the relationship between global warming and the breakdown of ice-sheets it is really necessary to know how ice-sheets work. Ice-sheets do not simply grow and melt in response to average global temperature. Anyone with this naïve view would have difficulty in explaining why glaciation has been present in the southern hemisphere for about 30 million years, and in the northern hemisphere for only 3 million years.

A glacier budget

In general glaciers grow, flow and melt continuously. There is a budget of gains and losses. Snow falls on high ground in the glacier's accumulation area. It becomes more and more compact with time, air is extruded, and it turns into solid ice. A few bubbles of air might be trapped, and may be used by scientists later to examine the air composition at the time of deposition. More precipitation of snow forms another layer on the top, which goes through the same process, so the ice grows thicker by the addition of new layers at the surface. The existence of such layers, youngest at the top, enables the glacial ice to be studied through time, as in the Vostok cores of Antarctica, a basic source of data on temperature and carbon dioxide over about 400,000 years.

When the ice is thick enough it starts to flow under the force of gravity. In a mountain glacier it flows downhill, in an ice-sheet from the depositional high centre towards the edges of the ice-sheet. The flow is generally slow, as expressed in the common metaphor "glacially slow". The Upernivek Glacier in Greenland flows at about 40 metres per day, which is as much as a smaller Alpine glacier covers in a year. When the ice reaches a lower altitude or lower latitude where temperature is warmer it starts to melt and evaporate. (Evaporation and melting together are called ablation, but for simplicity I shall use 'melting' from now on.)

If growth and melting balance the glacier appears to be 'stationary'. If precipitation (snowfall) exceeds melting the glacier grows. If melting exceeds precipitation the glacier appears to recede.

How glaciers move

Flow is by a process called creep, essentially the movement of atoms from one crystal to another, and the size of crystals grows by a thousand times from the tiny crystals deposited as snow to the large crystals found at the glacier snout.

There are three laws of creep:

1. Creep is directly proportional to temperature.
2. Creep is directly proportional to stress (essentially proportional to the weight of overlying ice)
3. There is a minimum stress, called the threshold stress, below which creep does not operate.

All these laws have significant effects on glacier movement, and on how glacial behaviour might be interpreted.

Creep is directly proportional to temperature
In valley glaciers the ice is almost everywhere at the prevailing melting point of ice, so it is not an important feature. In ice-sheets the temperature gets very much below freezing point, so flow is very limited in most of the very cold ice. At the base of the glacier the ice is warmed by the Earth's heat, and the flow is concentrated at and near the base of the glacier. This is why the stratified layers of ice are preserved in the upper ice, and can be recovered in cores like the Vostok cores. Stratified ice has been found to a depth of about 3300m, below which the ice is deformed.

Creep is directly proportional to stress
Stress is essentially proportional to the weight of overlying ice. This means that the thicker the ice, the greater the stress at depth, and the faster the flow. In a valley glacier there is frictional drag at the base, and no flow at the top because it is below threshold stress (explained below), so the maximum flow is somewhere in the middle. In an ice-sheet the greatest stress will be at the base under the thickest ice. Again we see that the upper ice will be preserved, which we already know from the many cores.

There is a minimum stress, the threshold, below which creep does not operate.
At the surface there is no stress, so the ice does not flow: at a certain depth the weight of ice is sufficient to cause flow. Between these two limits the ice is a brittle solid being carried along on plastic ice beneath. Since the flow is uneven (greatest in the middle in valley glaciers) the solid, brittle ice is broken up by a series of cracks called crevasses.

Some results of the laws of glacier flow

These simple rules allow us to understand some observations on glaciers. The speed of valley glaciers has been measured for a long time, and is rather variable. Sometimes a valley will flow several times faster than it did earlier. Suppose we had a period of a thousand years of heavy precipitation. This would cause a thickening of the ice, and more rapid glacial flow. The pulse of more rapid flow would eventually pass down the valley. It is important to understand that *the increase in flow rate is not related to present day air temperature, but to increased precipitation long ago.*

Melting and climate
In the case of ice-sheets it may take many thousands of years for ice to flow from the accumulation area to the melting area. The balance between movement and melting therefore does not relate simply to today's climate, but to the climate thousands of years ago.

Glaciers and precipitation
We have seen that glaciers and ice-sheets are in a state of quasi-equilibrium, governed by rates of melting and rates of accumulation.

For a glacier to maintain its present size it must have precipitation as snowfall at its source. This leads to a slightly complex relationship with temperature. If the regional climate becomes too dry, there will be no precipitation, so the glacier will diminish. This could happen if the region became cold enough to reduce evaporation from the ocean. If temperatures rise, evaporation is enhanced and so therefore is snowfall. *Paradoxically a rise of temperature may lead to increased growth of glaciers and ice-sheets.* Today, for example, the ice-sheets of both Antarctica (Davis et al., 2005) and Greenland (Johannessen et al., 2005) are growing by accumulation of snow.

Icebergs
Where ice-sheets or individual glaciers reach the sea, the ice floats and eventually breaks off to form icebergs. This is inevitable so long as glaciers reach the sea. In the southern hemisphere Captain Cook saw icebergs on his search for the great south land. Icebergs have long been familiar to sailors in the northern hemisphere, and the *Titanic* struck one that had drifted farther south than usual in 1912. The actual break is a sudden, one-off event, but can be built into a typical greenhouse-horror scenario. Some weeks ago, when a piece of the Greenland ice shelf broke away, the scientists interviewed all said they were surprised at how suddenly it happened. But how else but suddenly would a piece of ice shelf break off! And this was an area that was ice free before the Little Ice Age. Arctic explorers used to get their ships a lot closer to northern Greenland than you can now.

Hansen's view of glacier collapse

In a television interview in Australia on March 13, 2007, Jim Hansen claimed that a rise in temperature of a few degrees in the next few years would cause 'collapse' of the ice-sheets and a rise of sea level of many metres.

Hansen's view of ice-sheet 'collapse' is untenable. Ice-sheets do not melt from the surface down – only at the edges. Once the edges are lost, further loss depends on the rate of flow of the ice. The rate of flow of ice does not depend on the present climate, but on the amount of ice already accumulated, and that will keep it flowing for a very long time. It is possible that any increase in temperature will cause increased snowfall thereby nourishing the growth of the ice-sheet, not diminishing it. While Hansen concentrates on ice-sheets, evidence of glacier recession is more obvious in alpine glaciers. In many parts of the world glaciers have been receding since 1895 and with increasing pace since

1930. This is the wrong time scale to be associated with Hansen's hypothesis, and the dates have no counterpart in carbon dioxide records.

The origin of the great ice-sheet basins

The simple problem is this: did the ice fill a pre-existing basin, or did the weight of the ice create the basin?

It is generally assumed that the increasing weight as an ice-cap grows will cause an isostatic sinking of the underlying rocks, and ever-increasing thickness of ice-cap will cause ever more subsidence.

Alternatively, Ollier and Pain (2004) when studying mountains on passive margins noted that since many continents have central depressions and mountains round the rim (Fig. 1) Antarctica and Greenland may have had a similar depression even before ice accumulation started. Such basins would provide ideal conditions for the collection of ice if the climate was right. Isostasy would enhance the effect, but does not have the problem of initiating it. This idea may be relevant to the problem of why the Canadian and Scandinavian ice-sheets apparently melt frequently the Greenland and Antarctic ones do not. The latter do not have a deep basin in which ice can accumulate and to gain sufficient thickness to casuse isostatic feed-back.

The reverse scenario is that melting of an ice-cap will cause uplift of the land. This appears to be true in places like Hudson's Bay and Scandinavia. Uplift at Stockholm is at present at a rate of about 1 cm per year. The isostatic response, without faulting, shows there is flow in the mantle, by creep. Creep in the mantle takes time, so Stockholm is only slowly moving to its old elevation. In the same way the flow of the ice-caps is responding to ancient build-up of potential energy, despite current melting at the ice front.

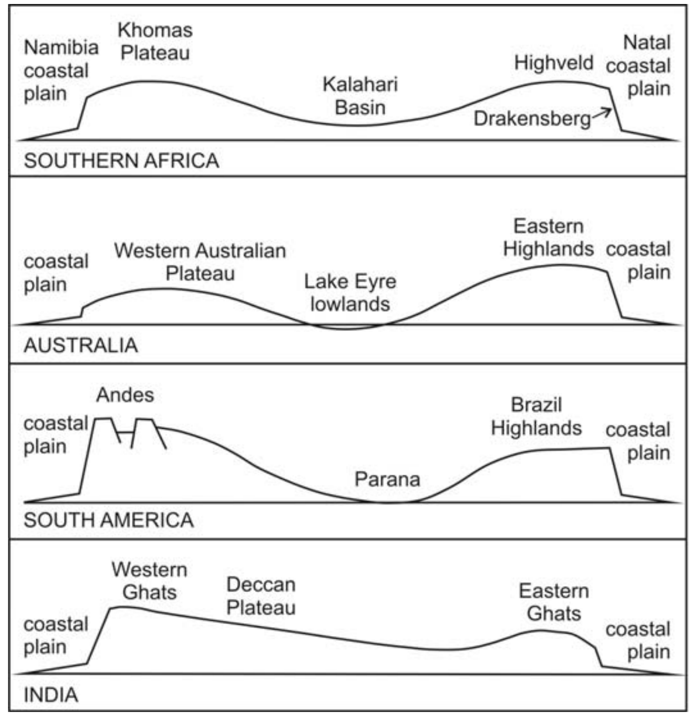

Figure.1. Diagrammatic cross sections of continents (after Ollier and Pain, 2001), showing possible morphotectonic similarities. Cross sections of Greenland or East Antarctica show similar profiles, so they may have had an initial depression even before ice accumulation.

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