Reconstructing the temperature regime of the Weichselian ice sheet

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Studying the morphology of the deglaciated landscape of Sweden gives an indication of the temperature regime of the former ice sheet. The interior of northern Sweden contains few signs of the effects of glacial erosion, whilst the coast of the Gulf of Bothnia and the Baltic has clear signs (Holmlund and Fastook 1993). In the Västerbotten area there is a sharp line where drumlins change direction from south east in the inland partws to a more southern direction near the coast, indicating high ice velocities in the Gulf of Bothnia (Eklund 1988, Svedlund 1987). In Tornedalen (north easternmost part of Sweden) the survived traces of fragile landforms indicate cold based conditions (Lagerbäck 1988). Preserved tor formations in Tertiary sediments have been found in Sydsvenska Höglandet, indicating the near absence of glacial eroison during the entire Quaternary (Lidmar-Bergström *et al.* 1996). On the other hand, the closely located roche moutonées ("rundhällar") along the Swedish east coast are beautiful examples of both large and small scale glacial erosion. Thus from a glacial morphological viewpoint we may conclude that there has been a rather well defined pattern of frozen areas and basal melting areas; most parts of inland Sweden and, probably, also inland Finland were covered by cold based ice during the maximum phase of the Weichselian. During the phase of recession some areas may have experienced a change in thermal conditions from frozen base to thawed base as the frontal zone migrated backwards (Fastook and Holmlund 1994).

The thermal conditions outlined here compare well with the present day ice sheet of Greenland, for which we can describe the boundary conditions fairly satisfactorily. Thus, the question is; what was the climate like during the last glaciation? Greenland ice cores indicate a climate during the later phase of the Weichselian 10-15 degrees colder than present (Johnsson *et al.* 1992). Assuming these figures are correct, and that the period lasted long enough for an ice sheet to form and to expand from the mountains in northwestern Scandinavia towards the south, we will get a high polar ice sheet with a certain ice thickness and extent. Using an adiabatic lapse rate of 0.8 degrees per 100 m, we can assume annual temperatures of around -40°C at the top centre of the ice dome situated over the Gulf of Bothnia. If this estimation is reasonably correct we can conclude that the ice sheet over Scandinavia during the Weichselian was of a high polar type, similar to the present ice sheet over Greenland. Using these basic assumptions we can exclude temperate ice within most of the ice sheet, except for in the frontal region. According to such a model there were no water movements within the main ice body and the subglacial water flow was forced by glacier flow.

Conditions may have been different close to the margin. Because of ice flow induced internal heating, it is probable that englacial water existed which would have had an impact on the pattern of the local subglacial drainage system. The existence of an englacial drainage system allows the water-pressure at the bed to vary substantially and successive to floods caused by high rates of surface melting or rain, the subglacial tunnels become overdimensioned and thus at atmospheric pressure. Eskers may indicate close to atmospheric pressure if they formed above the marine limit. If they formed below the marine limit, other processes were active which slowed down the water flow and sedimentation occured.

As it is difficult to visualize future ice sheets we have to study the former ones and try to interpret how our present landscape will change as a consequence of a future ice sheet of a certain size. The last glaciation is often subdivided into three stages, based on the extent of the ice sheet which in turn is governed by climate.

The first phase was basically a mountain-centred glaciation, extending down to the inland of northern Sweden (Holmlund and Fastook 1995). Such an ice sheet is often referred to as an average Pleistocene ice sheet (Porter 1989). The best modern analogue is probably Vatnajökull on Iceland, though the climate was colder than at present on Iceland. Most of the glacial erosion in the mountain areas probably occurs during such phases. On the eastern rim of the Scandinavian mountain range there are remnants of preserved ancient landscapes, indicating local frozen bed conditions (Kleman 1992). Thus, though glacial erosion was active in the central and western parts of the mountains, inland Sweden may have been characterised by permafrost and frozen interface between ice and bed.

The next phase of tha last glaciation was when the ice sheet developed but was still smaller than during the glacial maximum. According to the Greenland ice cores, temperatures were only slightly warmer during this phase than during the last maximum phase (Dansgaard *et al.* 1993). Thus there is no reason to expect anything but a high polar ice sheet with frozen conditions under the entire ice sheet except for along the Norwegian west coast and perhaps some parts along the southern perimeter of the ice sheet.

The third and maximum phase is also characterized by a high polar ice sheet with below freezing point temperatures throughout the ice body. Wet based conditions may have occurred in the deepest areas, which according to different data sets was centred in the Gulf of Bothnia. The length of the flow line through the Baltic turning west towards Denmark, indicates high flowrates, and most likely an ice stream (Holmlund and Fastook 1993). In order to maintain a balanced flow along such a flow line with a low surface slope, high rates of basal sliding must have occurred beneath the ice stream (Boulton *et al.* 1985, Holmlund and Fastook 1993). This assumption is supported strongly by the beautiful glacially modified landscape which is slowly ascending by land uplift along the coastline of Gulf of Bothnia and the Baltic. However, basal melting is far from synonymous with temperate ice, it simply indicates that pressure melting temperature has been reached at the bed, not that there is any water flow within the ice. Water flow at the base is thus basically governed by the force of gravity and the weight of the overburden ice. In practice this means that basal meltwater will flow in the same direction as the ice. The reason for this is simply the fact that ice thins in the direction of ice flow. However, close to the front, external forcing by heavy rainfall and high ablation rates may have locally influenced the subglacial flow.

I have now tried to describe areas where the ice could have been at the pressure melting point during the last Ice Age. In order to transform into degree of glacial erosion, we must first estimate the time of ice coverage at a specific site, and then estimate the temperature distribution with time. Finally we need a reasonable figure for the erosion rate. It seems realistic to use the rate from Storglaciären which amounts to about 1 mm per year (Schneider and Bronge 1996). An estimation of the extent of ice cover can be made using the proxy temperature record from the Greenland ice cores and a model of the ice sheet (Holmlund 1993). Adding the estimations on climate and ice sheet shape outlined above to erosion figures we may conclude that the crucial areas for glacial erosion are within the mountains and where the present Baltic and the Gulf of Bothnia are situated. At these sites erosion rates of some tens of metres may have occurred. In inland northern Sweden and inland Southern Sweden (Sydsvenska Höglandet) the potential for glacial erosion seems to be small.

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