MODELLING OF THE THERMAL CONDITIONS AT THE GREENLAND ICE SHEET MARGIN DURING HOLOCENE DEGLACIATION: BOUNDARY CONDITIONS FOR MORAINE FORMATION

BY
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ABSTRACT. The specific geomorphological problem addressed in this paper is which thermal conditions determined moraine formation in west Greenland during Holocene deglaciation. Ice sheet modelling and geothermal research are used to delineate boundary conditions for landform formation and thereby improve and evaluate geomorphological hypotheses concerning moraine formation. Marginal thermal conditions are reconstructed from modelled basal temperature and estimates of Mean Annual ground Surface Temperature (MAST) contemporaneous to moraine formation. In mountainous areas with an altitude above 800 m, ice marginal morphology will be characterized by landforms typical for cold conditions owing to the combination of relatively thin ice throughout Holocene deglaciation and pronounced negative MAST values in the proglacial area. Low lying areas (0–250 m), with a sufficient areal extension in the direction of ice flow, have relatively thick ice throughout Holocene deglaciation. The combination of basal temperatures at the pressure melting point with positive MAST values in the proglacial area is postulated to produce deposits related to temperate beds and margins.

Introduction

In general, a genetic problem such as moraine formation can be treated as a forward or an inverse problem. The specific geomorphological problem we address in this paper is which thermal conditions determined moraine formation in west Greenland during Holocene deglaciation. A forward approach (how and under which thermal conditions are certain moraines created), is in this case difficult because moraines have been formed in west Greenland without being monitored by interested scientists.

Deducing thermal conditions at the margin of the ice sheet responsible for the formation of certain assemblages of ice marginal landforms, is the inverse approach of the genetical problem. The inverse approach requires many assumptions on the relationships between moraines and processes of moraine formation. Relationships which are poorly known for most of the moraine forms recognized. Despite the many efforts in the genetic interpretation of glacial sediments and landforms, the results are poor with respect to the distillation of quantitative estimates on the processes responsible for formation. The amount of information which can be deduced from landforms is limited as the processes involved in the formation of glacial landforms are in generally highly complex. At present the best possible conclusions which can be drawn from these sedimentological and geomorphological analysis are qualitative.

This paper will outline a strategy to incorporate results of geothermal research and ice sheet modelling to deal with the geomorphological problem of moraine formation. Geothermal research and ice sheet modelling are used to make some assumptions, used in an inverse approach, explicit. We use ice sheet models and geothermal research to delineate thermal boundary conditions for landform formation. These boundary conditions can be used to improve and evaluate geomorphological hypotheses concerning moraine formation during Holocene deglaciation in west Greenland.

The relevance of deducing thermal conditions from ice-marginal landforms is acknowledged by many workers. If one can relate landforms to thermal conditions, an important step can be made towards the reconstruction of glacial dynamics or climate during formation. This will be illustrated by two examples.

The thermal conditions required for the formation of ice-pushed ridges in North-western Europe are subject to debate over the last 50 years. The glaciotectonic transport of large volumes of sediment without disturbance of the primary sedimentary structures is explained by permafrost conditions by Moran (1971) and Schindler *et al.* (1978). On the other hand, geologists have argued that permafrost is not a prerequisite because displacement takes place at a décollement. This is the only zone where primary structures will be deformed. They assume temperate conditions, because these enable the development of high pore water pressures, thought to be essential to initiate and maintain displacement along the décollement (Van der Wateren 1985). Disagreement in paleoclimatological reconstructions is obvious depending on the 'thermal' interpretation of ice pushed-ridges.

An other example is the development of ice-cored moraines. These moraines are only found near present-day glaciers in areas with permafrost (Weertman 1961; Souchez 1971; Boulton 1972; Hooke 1973; Fitzsimons 1990) and are thought to be the result of thermally determined glacial debris transport mechanisms. It has been argued that the product, after disintegration of the ice core, is an irregular topography with many hills and hollows, 'hummocky moraine' (Boulton 1972). The existence of ice-cored moraines or hummocky moraine is therefore thought to give information on the control of the thermal regime on debris dispersal and glacial sedimentation. As illustrated by Fitzsimons (1990), the processes portrayed by ice-cored moraines may not be the debris transport mechanism, but rather the climate at the glacier terminus.

Landforms in relation to thermal regime

In general there seems to be more agreement on (subglacial or ice-marginal) features related to temperate then to cold conditions. Morphological features which are associated with temperate conditions are the products of glacial abrasion (striae, rouche moutonnées, U-shaped valleys), the products of subglacial fluviatile erosion (s-forms such as potholes, spindles and furrows) or deposition (eskers) and the products of subglacial deformation (flutes, drumlins, subglacial tills).

Basal sliding, generally related to temperatures at the pressure melting point, or temperate conditions (Paterson 1983), is needed to enable the glacier sole to abrade (Hallet 1979, 1981; Shoemaker 1988). Basal sliding can take place at sub-zero temperatures (Shreve 1984; Echelmeyer and Zhongxiang 1987), just like the formation of striae (Drewry 1986). As shown by Drewry (1986) the efficiency of abrasion under cold conditions is limited. Water pressure at the glacier bed largely controls subglacial deformation (Boulton and Hindmarsch 1987), and is a key parameter in subglacial till formation in general (Clarke 1987).

According to Maag (1969) thermal regime influences the glacial drainage patterns and the associated geomorphological products. Cold margins are characterized by absence of subglacial meltwater drainage (meltwater drains along the glacier) and a high preservation potential of frontal moraines, owing to the disperse meltwater drainage. The more likely existence of ice-dammed lakes in contrast to temperate margins will generate more floods.

Relics of periglacial landforms are thought to have survived glacial coverage in central Scandinavia and are used to indicate areas with cold basal temperatures (Lagerbäck 1988). The association of these relict surfaces and a specific moraine configuration was used for the same goal; delineating areas with frozen beds (Kleman 1992; Kleman and Borgström 1994). Kleman *et al.* (1992) presented a scheme of deglaciation based on glaciofluvial drainage systems. These systems partly survived post-formative ice sheet coverage, due to cold basal conditions. Especially the proposed indicators of cold conditions are problematic because it is difficult to evaluate all transient effects (see discussion).

Methods

To set boundary conditions for moraine formation at the margin of the Greenland ice sheet during the time period from about 12,000 cal yr B.P. to 5,500 cal yr B.P. we have to reconstruct the thermal regime near the margin in space and time. We have assumed that it is not possible to infer temperature conditions from the geological features which can be studied in the area outlined in Fig. 1. This is partly due to the general considerations given above, but also the present-day permafrost conditions, which inhibit the study of internal characteristics of ice-marginal landforms. The following

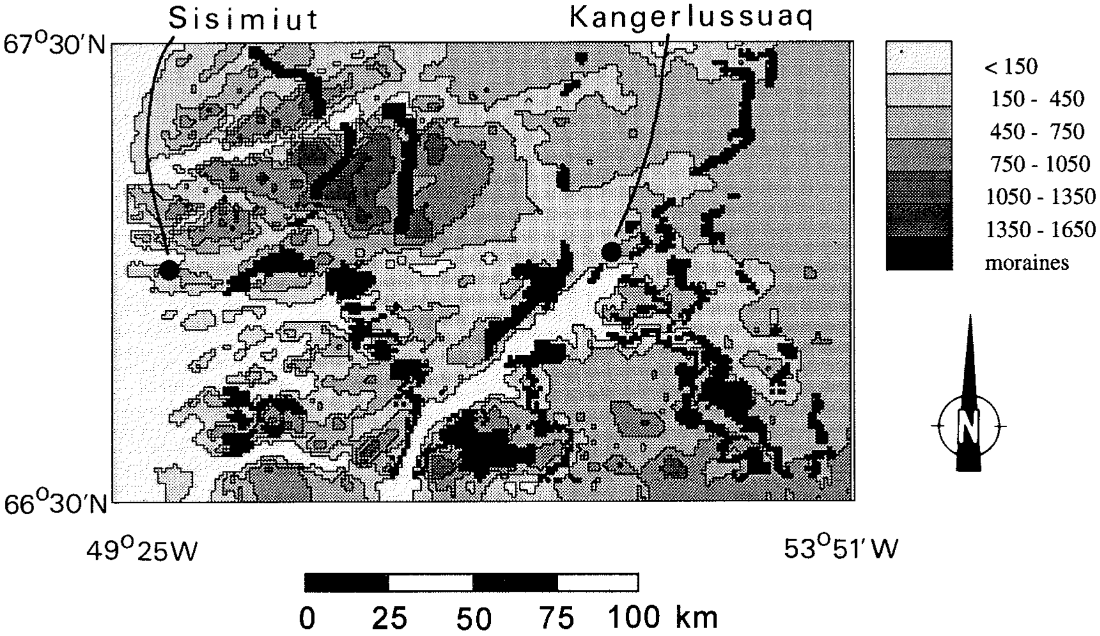


Fig. 1. Topographic map of the area. Grid spacing is 1 km. This map is compiled from digitized contour lines (0, 200, 500, 1000 m) and spot heights of the 1:250,000 topographical map of west Greenland. The map sheets used are 66V1, 66V2, 67V1 and 67V2. Cells with moraines are indicated in black and cover about 10% of the area.

assumptions are made to estimate thermal conditions near the margin of the ice sheet:

- the role of temperature during the formation of ice- marginal deposits can be described by the basal temperature of the ice sheet and the ground temperature in the proglacial area,
- ground temperatures after deglaciation are initially set by basal temperatures prior to deglaciation. The role of glaciation on ground temperature is recognized by many workers (Birch 1948; Lunardini 1981; Haeberli *et al.* 1984)
- there are a limited number of combinations of ground thermal conditions in the proglacial area (frozen or thawed) and at the base of the ice sheet (cold or temperate). How the ground temperature in the proglacial area and the thermal regime of the ice sheet interrelate and affect each others dynamic behaviour is outside the scope of this paper.

Present-day ground temperatures in the proglacial area were measured by Van Tatenhove and Olesen (1994). Air temperature changes for the period under consideration are estimated from recent progress in ice core analysis (Dansgaard *et al.* 1993; Cuffey *et al.* 1994; Kapsner *et al.* 1995; Alley and Anandakrishnan 1995).

Basal temperatures are derived from ice sheet modelling (Huybrechts 1994). Before the results of the analysis can be discussed, the following topics must be evaluated:

1. the required temporal and spatial scales,
2. spatial and temporal pattern of ground thermal conditions,
3. spatial and temporal pattern of modelled basal temperature.

Particular characteristic areas on the scale of the model, eg. areas with persistent cold, temperate or alternating basal temperatures can be combined with results of the ground temperature analysis. The combination of ground temperature and basal temperature may result in scenarios of the thermal regime at the ice sheet margin. Preferentially, such a combination should be uniquely defined.

Some explanatory notes on the used terminology

The margin of an ice sheet is divided into three zones; the proglacial zone, the ice margin itself and the subglacial zone. The thermal conditions in each zone are determined by complex, highly interactive and time-dependent processes. Basal ice sheet temperatures are determined by mass balance, horizontal and vertical velocity components, ice thickness, ice surface temperature and geothermal heat flow (Paterson 1983).

The ground temperature in the proglacial area reflects the major surface temperature events in the past. The basal temperature of the ice sheet which covered the area before deglaciation plays a major role in this respect. Other factors are the type of proglacial sedimentary environment (ocean, fjord, lake, land) and topoclimatological conditions in the proglacial zone. These topoclimatological conditions are superposed on the 'global' climate and the climatic gradient resulting from the distance of the ice sheet from the ocean. The term topoclimatological includes the effect of altitude, exposition and slope on temperature and precipitation. Near ice sheet margins a specific microclimate exists associated with the vicinity of the ice sheet. Conditions in the ice marginal zone are the result of all glaciological factors mentioned above and the ground temperature in the proglacial zone.

In relation to moraine formation, a major division is made between positive and negative ground temperatures. In case of an ice sheet, temperate conditions refer to basal temperatures at the pressure melting point, where cold conditions refer to temperatures below the pressure melting point. In the proglacial area ground temperature can be negative (permafrost) or positive.

Relative to the phase change temperature, four combinations exist between the proglacial area and the ice sheet margin.

Time and spatial scales

Time

Preceding a detailed description of each scenario and its origin, we need to consider the time scale of interest. We also need to consider the appropriate depth range. Because moraine formations is a geomorphological problem, the depth range must be related to processes of glacial erosion, transport and sedimentation. Although these processes act on material to near surface depths, ice sheets may even influence groundwater flow at km depth below surface in areas with thick aquifers. In Greenland sediment thickness of > 100 m are only found in valleys and fjords. Arbitrarily, we assume that the processes related to moraine formation reach to a depth of 30 m. Consequently, the time scale related to establish temperature changes in this depth range must be investigated. If conditions underneath the ice sheet margin are equal to conditions in the proglacial area the time scale is of less importance. Here only the magnitude of positive or negative temperatures will change in time.

The time required to reverse temperature from positive to negative or vice versa up to a depth of about 30 m is the time scale of interest. The length of this period depends on the preceding surface temperature, or initial surface temperature (T_o), the magnitude of the subsequent surface temperature change (δT_o) and material properties (water / ice-content). There are also geological constraints on the time period. It has been proposed that the formation of the major morainic systems in west Greenland was the result of ice sheet fluctuations with a duration of centuries (Ten Brink and Weidick 1974). Even more less time of moraine formation is derived from detailed studies of moraine sequences near the present ice margin, where individual moraines are thought to be the result of ice marginal fluctuations with a duration of only 1 to 30 years (Van Tatenhove 1995).

Analytic solutions of the propagation of a surface temperature disturbance can be used to estimate the time scale. We assume that heat is transferred by conduction only. If cold basal conditions are after deglaciation followed by positive MAST, the frozen ground will thaw. The time necessary to thaw 30 m depends on the initial temperature, the magnitude of the temperature change, the mode of temperature change (step wise or linear in time) and water content. The envelope which encompasses the range of possibilities has boundaries defined by analytic solutions of the heat transfer equation without including latent heat (Lachenbruch *et al.* 1982) or including latent heat (Haeberli *et al.* 1984) are expressed in Fig. 2. The first method is an estimate of the shortest possible period to thaw 30 m, the latter an estimate for the longest period. The potential influence of proglacial negative temperatures on moraine formation is mainly determined by the energy required to melt pore-ice, i.e. the latent heat effect. Without latent heat about 20 years are required to thaw 30 m (Figs 2C and 2D).

In case of an initial positive ground temperature

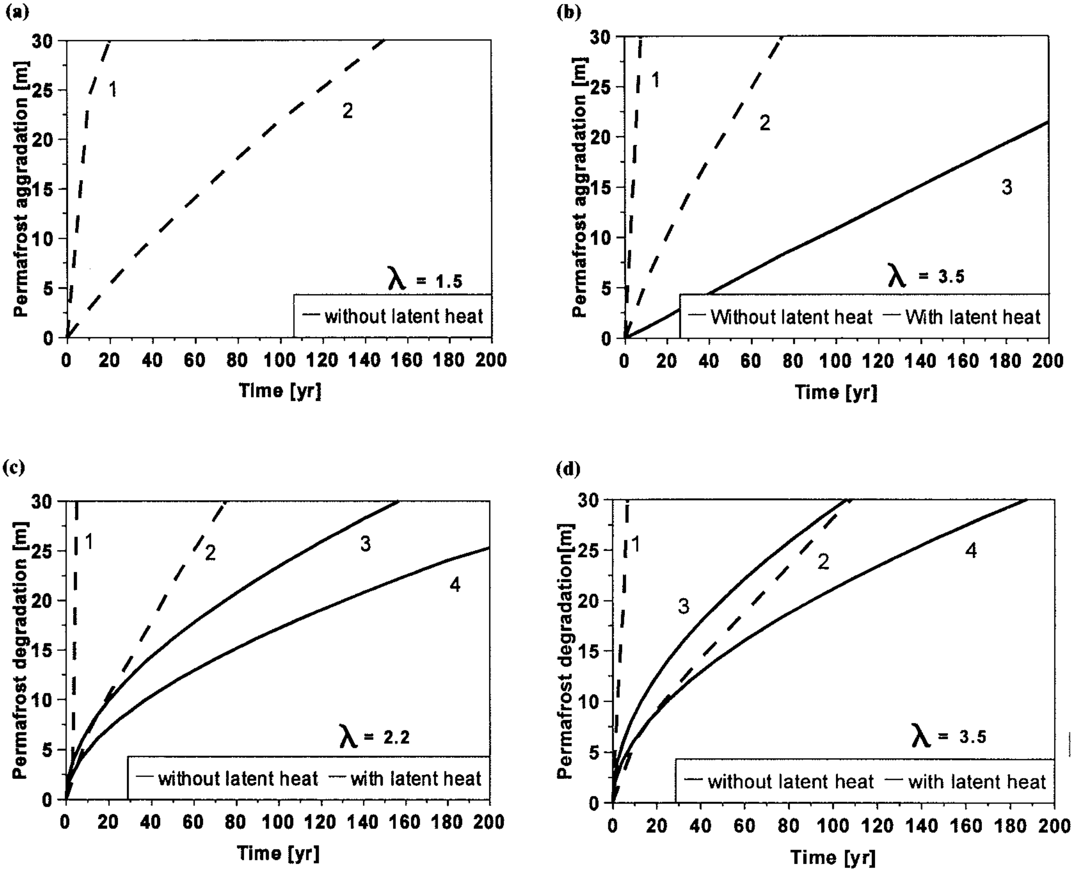


Fig. 2. *Upper panel*: Thickness of aggraded permafrost versus time, from analytic solutions of the heat equation without latent heat (Lachenbruch *et al.* 1982; Gold and Lachenbruch 1973) and with latent heat taking into account (after Kelly *et al.* 1990). Left panel with thermal conductivity (λ) of 1.5 and right panel 3.5 $Wm^{-1}°C^{-1}$. Limits of analytic solution are given by a step change in surface temperature from 0°C to -2°C (1) and a linear decrease in temperature with a rate of -0.946°C/100 yr (2). Model 3 from Kelly *et al.* (1990) with porosity = 0.2, λ = 3.5 $Wm^{-1}°C^{-1}$ and linear temperature change of -0.946°C/100 yr.
Lower panel: Thickness of degraded permafrost versus time, from analytic solutions of the heat equation without latent heat (Lachenbruch *et al.* 1982; Gold and Lachenbruch 1973) and with latent heat taking into account (after Haeberli *et al.* 1984). Left panel (C) with λ of 2.2 and right panel 3.5 $Wm^{-1}°C^{-1}$. Limits of analytic solution are given by a step change in surface temperature from -1°C to 0°C (1) and from -3°C to 0°C (2). Displayed is the depth of the -0.5°C isotherm. Model 3 and 4 from Haeberli *et al.* (1984) with the latent heat per unit volume of 80 10^6 Jm^{-3}.
For all cases, the geothermal gradient is taken as 41 mWm^{-2}. For the analytic solutions, the thermal diffusivity is $1 \cdot 10^{-6}$ m^2s^{-1}. The following step changes in surface temperature are within the limits of the hatched lines: -3 to +1°C, -3 to +2°C, -2 to 0°C, -2 to +1°C, -2 to +2°C, -1 to +1°C and -1 to +2°C.

followed by negative MAST (eg. temperate basal conditions are after deglaciation followed by negative MAST) frozen ground has to form and aggrade. Again, this process is very rapid when latent heat is neglected and slow when latent heat is taken into account. An estimate of the permafrost aggradation rate where latent heat is taken into account was taken from Kelly *et al.* (1990) and is displayed in Fig. 2B.

It may be concluded that volumetric latent heat plays a crucial role in the time required to change the sign of the thermal regime in the proglacial area. When proglacial thermal conditions have a different sign from basal temperature, the basal temperature of the ice sheet does not play a significant role in the temperature of the upper 30 m after approximately 100 years.

In case permafrost aggrades in the proglacial area, an advancing ice sheet will experience this frozen layer. If permafrost degrades, the thickness of the thawed layer can have significant dimensions in short periods of time (Figs 2C and 2D). Whether permafrost has effect on moraine formation is therefore time dependent, and relates to the frequency and distance of ice marginal fluctuations.

Space

Generally, depositional geological features related to former ice margins (i.e. moraines) are elongated. Their size perpendicular to the former margin is typically 10^0–10^2 m in west Greenland. The length of the features in our study area (parallel to the former ice margin) is within a range of 10^0–10^3 m. Moraine systems in west Greenland, such as defined by Ten Brink and Weidick (1974) can be traced over tens of kms. The distance between individual ice marginal features within a moraine system is about 10^1–10^2 m.

The scale of ice sheet models (gridsize 20 km), makes present-day models ineffective for the study of depositional conditions of existing moraine systems or single morainic ridges. The scale of ice sheet models drives us to work on the scale of the model. Ground temperatures must therefore be specified for grid cell areas of 400 km^2.

Ground temperature during the Holocene

The goal of this section is to define ground temperature for areas of 400 km^2 at present and during the period 11,500–5,500 cal yr B.P. years. Such an analysis can not provide more than an illustration of the major trends because important parameters affecting the ground temperature on a local scale have to be neglected. We will not consider the effects of topography on geothermal heat flux (Lee 1991), differences in surface characteristics (Luthin and Guymon 1974), local topoclimatological setting (aspect, slope) nor spatial and temporal differences in snow cover (Goodrich 1982). Further we assume that ground temperature can be related to the Mean Annual Air Temperature (MAAT). As pointed out in many studies, the relationship between MAAT and Mean Annual Surface Temperature (MAST) is highly variable (Williams and Smith 1989).

From measurements of ground temperature in Kangerlussuaq, Sisimiut and other sites in west Greenland (Fig. 3) as reviewed by Van Tatenhove and Olesen (1994) the following relation was derived between MAST and MAAT

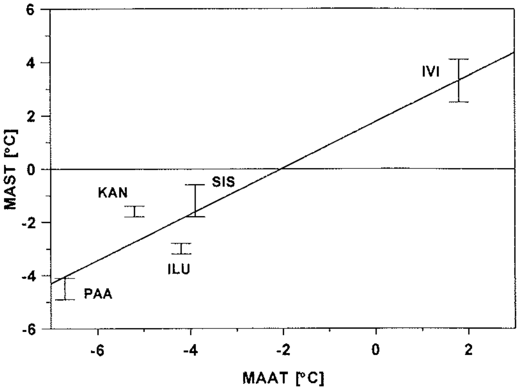


Fig. 3. MAAT against MAST. With KAN = Kangerlussuaq; IVI = Ivigtut; ILU = Ilulisiat; SIS = Sisimiut. The regression equation is MAST = 0.9MAAT+1.8 ($r^2 = 0.91$).

$$MAST(x,z) = 0.9 MAAT(x,z) + 1.8 \qquad (1)$$

To account for the large uncertainty in this relation an absolute error of + 4°C was introduced (MAAT is lower than MAST, Brown 1966). The MAAT is assumed to be a function of longitude and altitude. The relationship with altitude is determined from the air temperature data compiled by Ohmura (1987, Fig. 2a). MAAT-data of Sisimiut and Kangerlussuaq for the period 1961–1992 were used to estimate the effect of longitude (Fig. 4)

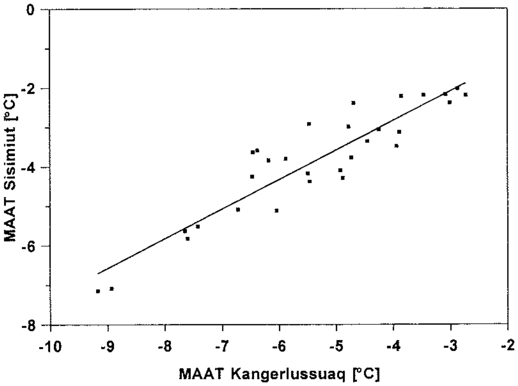


Fig. 4. Relationship of MAAT in Kangerlussuaq and MAAT in Sisimiut. The distance between Kangerlussuaq and Sisimiut is 125 km. The regression equation is $MAAT_{SIS} = 0.75MAAT_{KAN}+0.15$ ($r^2 = 0.85$, n=30, no data for 1972 and 1973 in Kangerlussuaq).

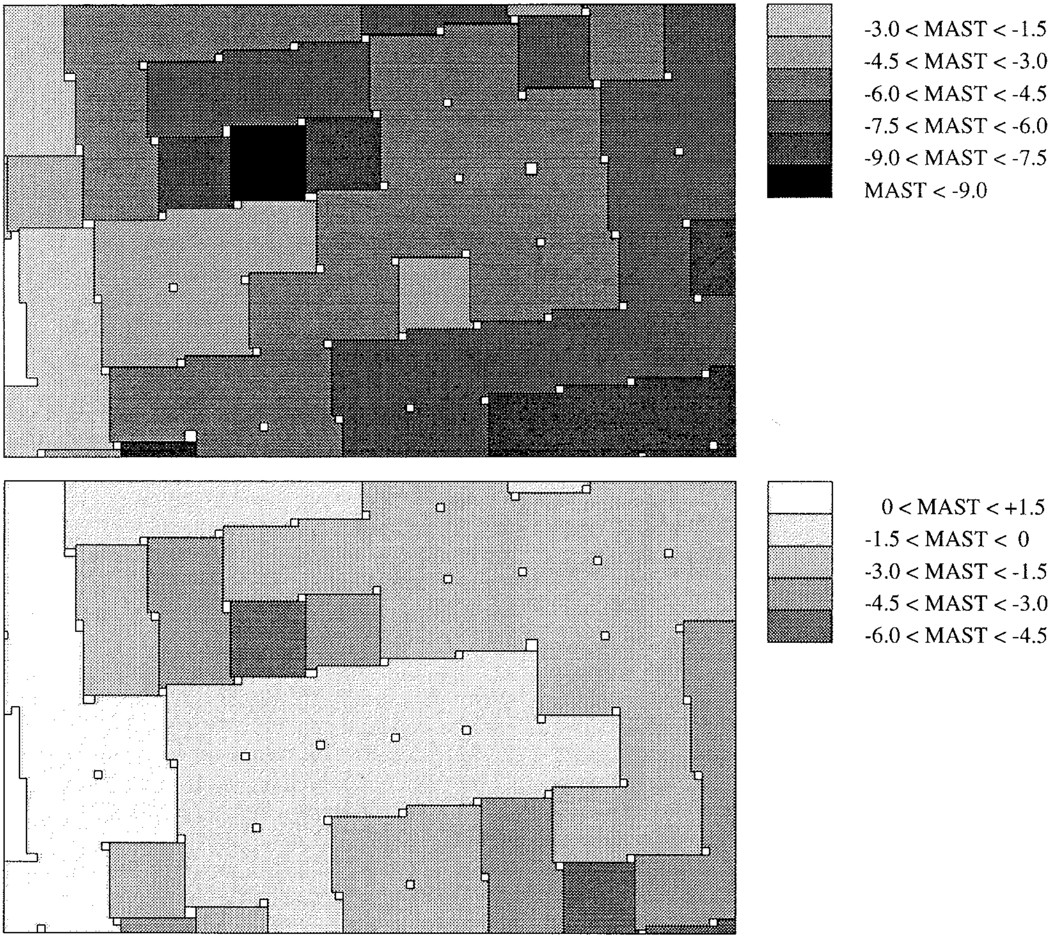


Fig. 5. (A) Estimated present-day MAST from eq. (1). (B) Estimated present-day MAST from eq. (1) + 4°C. Outline of area corresponds to Fig. 1.

$$MAAT\,(x,z) = -\frac{\delta T}{\delta z}z - \frac{\delta T}{\delta x}x + MAAT_{sis} \qquad (2)$$

With $\delta T/\delta z$, the lapse rate (0.769°C/100 m), $\delta T/\delta x$, the horizontal temperature gradient (0.0104°C/1000 m), $MAAT_{SIS}$, the MAAT in Sisimiut (-3.9°C), z, altitude and x, the distance from Sisimiut (positive to east). It is assumed that temperature for 67°N is representative for the area between 66°30'N and 67°30'N. No account was given to uncertainties in altitude on the available topographical maps or errors introduced by interpolation.

When applying Eq. (1), the entire area has MAST below -1°C (Fig. 5a). When taking into account the positively biased uncertainty in the relationship between MAAT and MAST, a more realistic scenario is obtained (Fig. 5b).

The mountainous areas still have MAST below -4°C, but the low lying areas and the coastal zone have a MAST close to 0°C. The area near the present ice margin has a MAST between -2 and -4°C.

The only independent control on these results are geophysical soundings in the area between Kangerlussuaq and the present ice sheet margin (Van Tatenhove 1995) and morphological observations near the coast (Kelly 1981). Frozen ground was proved to exist in all measured geoelectrical and seismic profiles, a conclusion confirmed by surficial temperature measurements in the same area (Van Tatenhove and Olesen 1994). Kelly (1981) studied ice-cored ridge fields and ice-cored

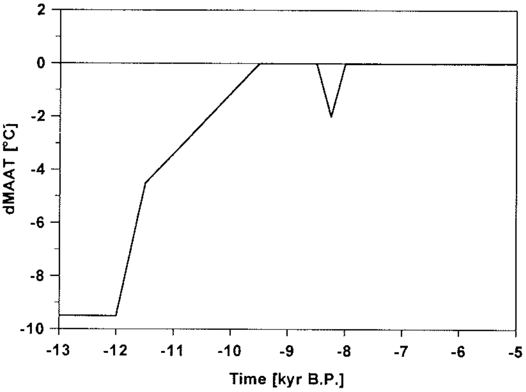


Fig. 6. Air temperature history expressed as deviation from present-day values derived form ice core records. See text for details and references.

domes north of Sisimiut. The existence of these features points to (at least) discontinuous permafrost in the coastal area.

Present-day ground temperature is different from conditions in the proglacial area during deglaciation, owing to climate change and altitude change related to isostatic rebound. Maximum altitude change is 130 m and is experienced in the mountainous areas near the present-day coast (Weidick 1993). Therefore, present-day altitude underestimates MAST by about 1°C. This will not change the sign of the estimated ground temperature, because ground temperature in the mountainous areas is very low anyway. Detailed reconstructions of air temperature can be derived from the oxygen isotope records from central Greenland. Due to the uncertainty in the reconstructed timing of deglaciation in the order of 200–1900 years (see Van Tatenhove *et al. 1995), for this study only the general trends and magnitude of change is relevant. When converting* $\delta^{18}O$ as given by Dansgaard *et al.* (1993) to temperature using a calibration derived from comparison with borehole temperature (Cuffey *et al.* 1994), the following trends relative from the present MAAT at Summit can be identified (Fig. 6):

- From the middle part of the Younger Dryas (12,000 years ago) to the end of the Younger Dryas (≈ 11,500 years ago) temperature increased with 5°C from -9.5°C to -4.5°C relative to the present (Kapsner *et al.* 1995).
- From 11,500 to 9,500 cal yr B.P. temperature increased with another 4.5°C, reaching present day values.
- A cold event, with a temperature deviation of -2°C took place in the period 8,500 to 8000 cal yr B.P.
- From 9,500 to 5,500 cal yr B.P. temperature is not far from present-day. The range of temperature deviation is between -1°C and +2°C. At about 7,000 cal yr B.P. temperature was probably slightly higher than at present. Although Alley and Anandakrishnan (1995) estimated a cooling of about 1°C in summer temperature from 7,000 cal yr B.P. (based on variations in melt-layer frequency in the GISP2 ice core), this trend is not included in the reconstruction.

Based on the geological age of ice-marginal deposits (Fig. 7, Van Tatenhove *et al.* 1995; Van Tatenhove 1995), temperature deviations throughout the Holocene are superposed on present-day MAAT estimates to obtain the MAST contemporaneous to moraine formation. The reconstructed MAST will be different depending on the uncertainty in time of moraine formation (Fig. 8). Two extreme scenarios are given by the moraine age plus ('maximum') or minus ('minimum') the uncertainty in age (this uncertainty is displayed in Fig. 7b and is taken from Van Tatenhove *et al.* 1995). Between the scenarios, large differences exist in the coastal area, because moraine age is on the fringe of the Younger Dryas. In the central part a north-south belt of relative cold MAST, associated with the cold spell around 8,250 year ago, shifts to the east in case of the 'maximum' scenario and to the west in case of the 'minimum' scenario.

Basal temperature during the Holocene

The model output discussed in this paper originates from a model run presented in Huybrechts (1994). The horizontal resolution of the model is 20 km and there are 26 layers in the vertical. An overview of the fundamental mathematical equations governing the model has been given in Huybrechts *et al.* (1991). The temperature distribution within the ice sheet is calculated from the thermodynamic equation which includes conductive and convective heat transport. Temperature at the ice sheet surface is derived from oxygen isotope records of Pakitsoq, Camp Century and Dye 3 (Huybrechts 1994). At the base geothermal heat and dissipation due to sliding are incorporated within the basal temperature gradient. The geothermal heat flux is assumed to be constant in space and time. It is difficult to give an assessment

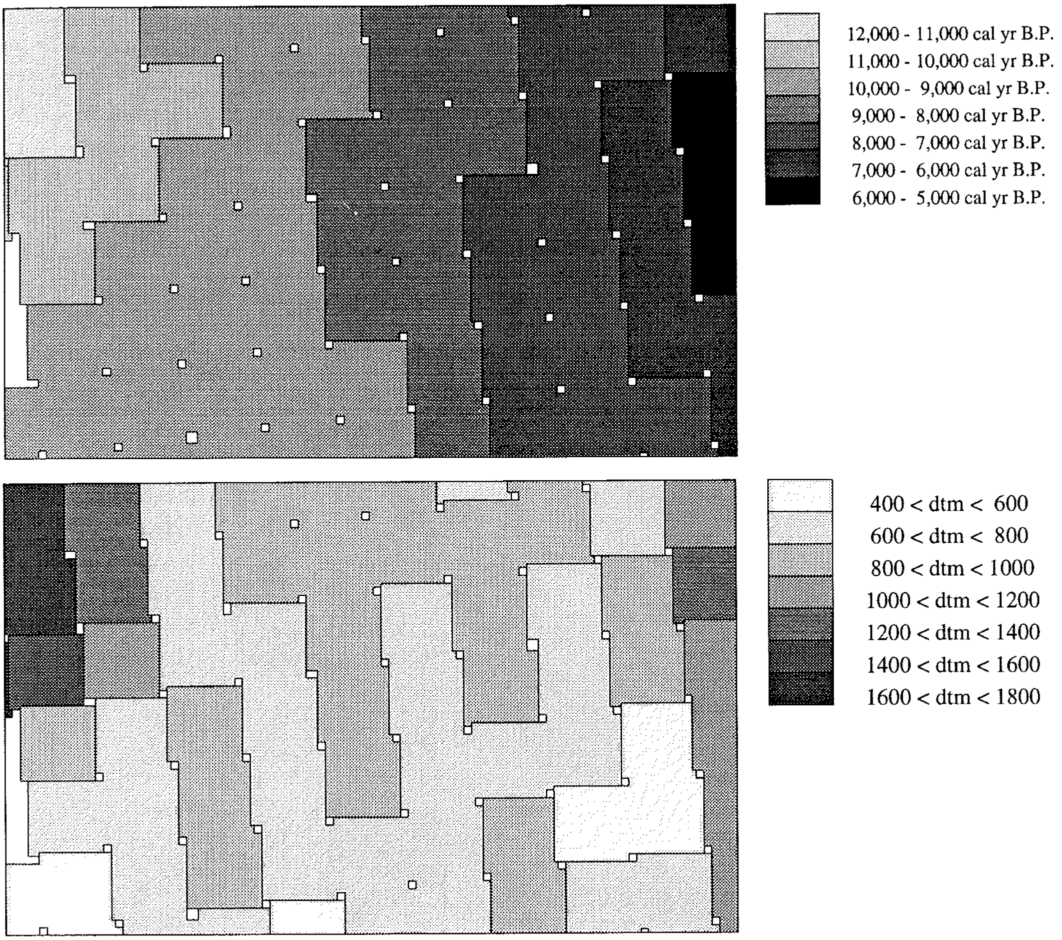


Fig. 7. (A) Age of ice marginal deposits with a 1000 year interval. (B) Absolute uncertainty in age of ice margin positions. The minimum scenario is the age of the marginal deposits minus the uncertainty given in the figure, while the maximum scenario is the uncertainty added to the age.

of the reliability of the calculated basal temperature. Besides uncertainties in the temperature forcing, calculated ice sheet geometry and geothermal heat flux, horizontal heat flow in bedrock (which is neglected) is of considerable influence on calculated basal temperatures (Waddington 1987).

Fig. 9 illustrates the modelled basal temperature (T_b) for two states. The upper panel displays the situation at the onset of deglaciation at 16 ka yr B.P. The lower panel gives the basal temperature just before a grid cell became ice free. Persistent features through time are a temperate zone in the central part, and cold areas in the northwest and southeast. The temperate zone relates to the zone of low altitude while the cold areas relate to mountainous zones. Another striking feature is the pressure melting point temperature of large areas when they occupy a marginal position (Fig. 9).

Thermal conditions at the ice sheet margin

To evaluate the relationship between MAST and basal temperature, 7 combinations of MAST and T_b are defined (Table 1). The combinations of MAST and T_b are reviewed in four scenarios. Three are based on the timing of deglaciation as derived from geological evidence ('average',

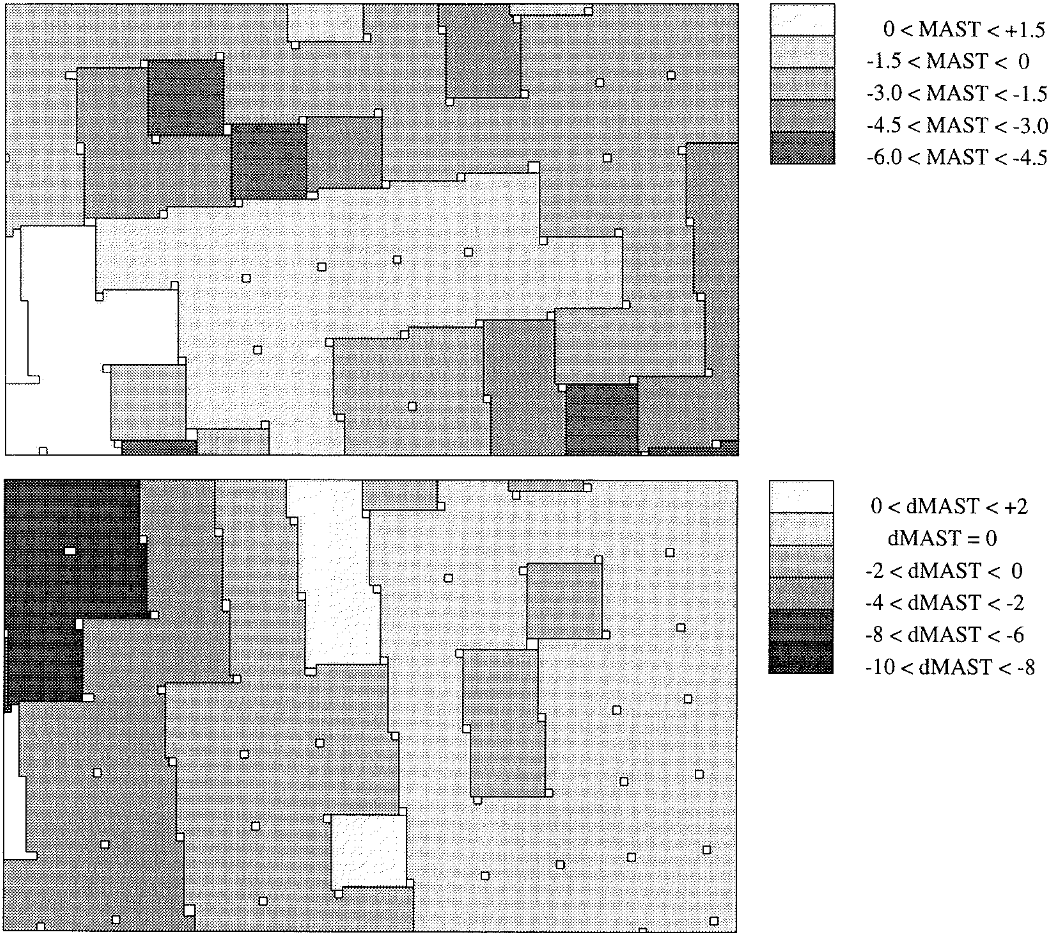


Fig. 8. (A) Estimated MAST at the time of moraine formation. MAST is calculated from present day MAAT with Holocene temperature change superposed. (B) The difference in MAST for the minimum and maximum scenarios for moraine age. Differences are large in the coastal area. Owing the uncertainty in moraine age the cold spell around 8,250 years ago causes a shift in relative cold MAST in the central part of the area.

'minimum' and 'maximum' scenario). The fourth scenario results from modelled ice margin positions ('model' scenario). Modelled positions are in general older than geological evidence suggests (Van Tatenhove *et al.* 1995) and therefore contemporaneous MAST is colder compared with the other three scenarios. Despite the scenario chosen, several features are robust, ie. the sign of temperature is not likely to change within about 50–100 years (Fig. 10):

1. The combination of cold T_b (< -2°C) and negative MAST (< -2.5°C) is found in mountainous area near the coast and in the southeast corner of the study area. In these areas, cold basal conditions are followed by topoclimatological conditions which sustain permafrost in the proglacial area. It is unlikely that the sign of ground temperature changes after or during deglaciation and therefore we postulate the formation of 'cold' ice-marginal features.
2. The combination of warm T_b (equal to pressure melting point) and negative MAST (< -2°C) is found in the inland area. The area is characterized by a hilly landscape with mountains up to 600 m and a gentle relief. Within this area the aggradation of permafrost follows deglaciation. A frozen toe will develop during periods

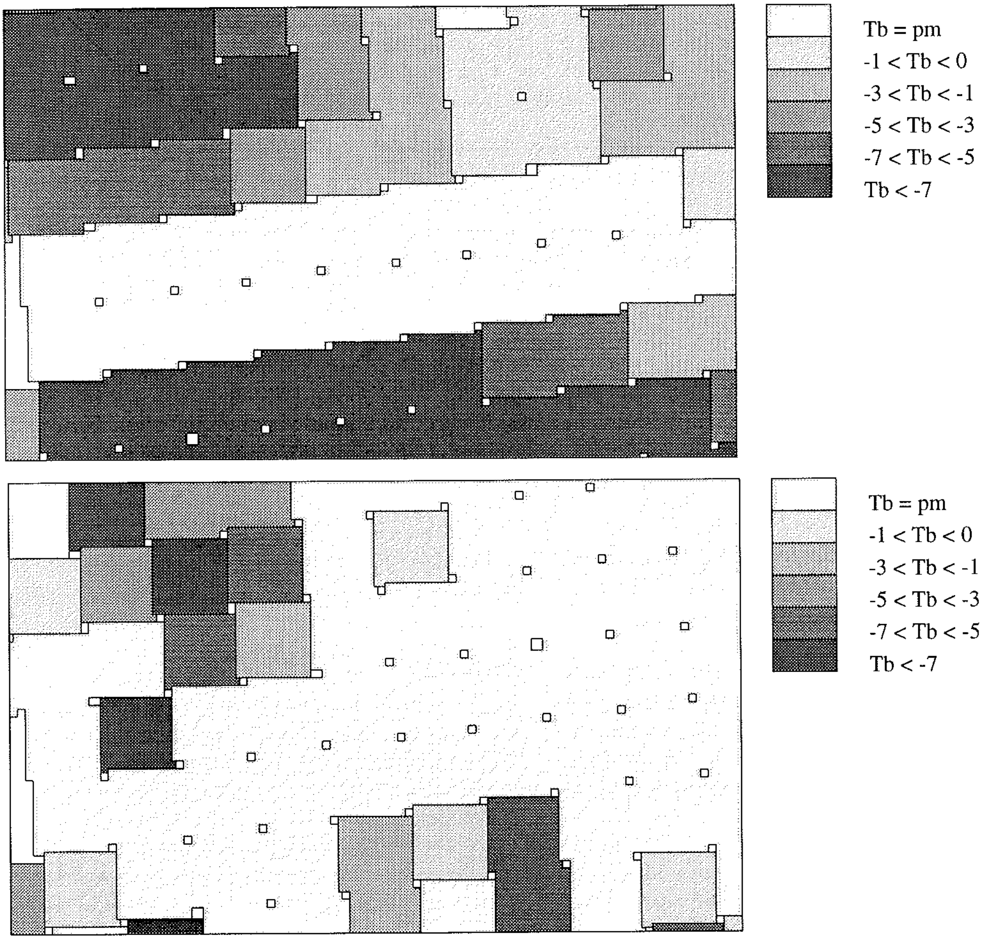


Fig. 9. (A) modelled basal temperature relative to the pressure melting point at 16,000 yr B.P. (B) Basal temperature prior to deglaciation.

of standstill or readvance. Basal sliding will be less important near the margin and basal shear stresses will increase. The boundary between temperate and cold basal ice is important with respect to sediment entrainment by basal freezing (Weertman 1961) and shearing or folding of debris along fault planes, shear zones or fold axes. Features associated with a cold ice margin can develop, especially ice-cored moraines. Because this scenario has a transient character (basal temperature is different from proglacial temperature) time is crucial with regard to the resulting geological products. If readvances succeed deglaciation fast or if stable periods capable of producing ice-marginal sedimentation last shortly, morphology and sediments associated with a temperate ice margin are possible as well.

3. The combination of warm T_b (at pressure melting point) and positive MAST (> 0°C) or slightly negative MAST (> -0.7°C) is found in the centre of the area. In case of the geological scenarios this area ranges from the present-day coast to 20–40 km east of the present-day ice sheet margin. In the 'model' scenario this combination is limited to 4 cells inland (Fig. 10). This scenario allows the development of all geological products associated with a temper-

Table 1. Definition of the combinations of MAST and modelled basal temperature. 'Undefined' refers to all other combinations not listed. Columns 1, 2, 3 and 4 express the surface area occupied by a combination given as percentage of total area, for the average geological scenario (1, Figure 7), the minimum (2), the maximum (3) scenario and the modelled deglaciation scenario from ice sheet modelling (4).

Combinations	MAST [°C]	Basal T [°C]	1	2	3	4
warm	≥ 0	pm	5	8	0	0
near warm	> -1	≥ -0.5	14	17	9	7
warm -> cold	< -2	pm	31	25	39	52
cold -> warm	> -0.5	< -2.5	2	2	1	0
near cold	< -2	< -2.5	7	3	4	4
cold	< -3	< -4	7	7	11	14
undefined			34	38	36	23

Note: 1 cell is 1.75 % of total area.

ate bed. The 'warm' corridor is associated with low altitudes due to the incision of fjords in areas with moderate altitudes.

Only in case of the combinations 'warm' and 'cold', thermal conditions with respect to marginal sedimentary processes are uniquely defined, because transient effects are likely to be unimportant. These uniquely defined conditions apply to about 10% of the area (Table 1).

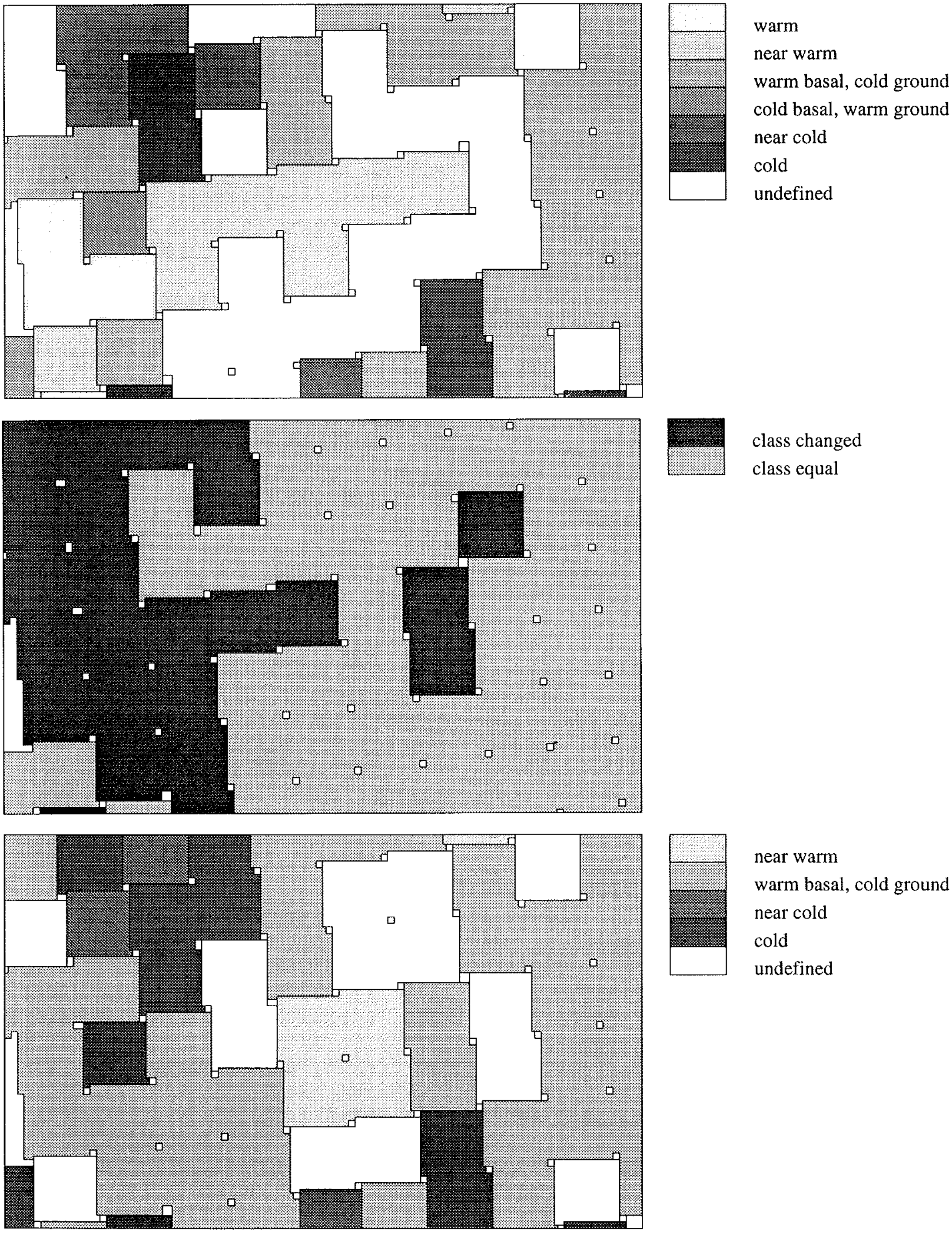
The combination warm T_b and negative MAST is possibly exemplified near the present-day ice sheet margin in the Kangerlussuaq area. From geoelectrical measurements on recently deglaciated surfaces in front of the Leverett glacier, it is plausible that the advance of the ice sheet margin after the Hypsithermal took place over permafrost (Van Tatenhove 1995). Modelled basal temperature in this area is consequently at the pressure melting point from 6,000 cal yr B.P. to the present-day. The horizontal surface velocities of the Russell glacier (73–180 m/yr, Sugden *et al.* 1987) are difficult to explain by the internal deformation of ice alone. Basal sliding could take place as indicated by the isotopic signature of basal ice (Knight 1987). The ice-cored moraines found at present at the flanks of the ice sheet are therefore regarded as the expression of the advance over a frozen bed.

Discussion

Because of the scale adopted in this study, important topographical features are not represented. Topographically determined proglacial environments controlling ice marginal sedimentary processes (ice marginal lakes, fjords) are not noticed. These features have a typical scale of several km's. At a more detailed scale, the position of meltwater outlets may locally produce anomalous thermal conditions. For that reason, the presented analysis is thought to represent the area outside the termini of outlet glaciers.

The time period in which ground temperature can reverse sign in the upper 30 m is short (say about 100 yr). We are not able to date any moraine in the time period under consideration with an uncertainty less than about 100 to 200 year. This error is related to the measuring error of dating techniques (for AMS-dated organic material at least 50 yr), the calibration of ^{14}C-years to calender years and the often indirect dating of moraines (not the moraines are dated directly, but marine

Fig. 10. (A) The combined conditions of basal temperature and MAST during Holocene deglaciation based on geological model in Fig. 7 and modelled T_b (Fig. 9B). For the definition of combinations see Table 1. (B:) Grid cells which changed class when comparing the 'minimum' and 'maximum' geological scenarios. 36 % of the area changed, which is equal to the area changed when comparing the scenario based on modelled ice margin positions with the average geological scenario. **(C)** The combined conditions of basal temperature and MAST during Holocene deglaciation based on modelled timing of deglaciation and modelled T_b (Fig. 9B).


warm
near warm
warm basal, cold ground
cold basal, warm ground
near cold
cold
undefined
class changed
class equal
near warm
warm basal, cold ground
near cold
cold
undefined

shells related to moraines or organic material in between moraines). A detailed reconstruction of site specific topoclimatological conditions from high resolution paleoclimatological records will always have some uncertainty because the exact age of the moraine can not be given.

The approach followed in this paper cannot give unique sets of basal and/or ground temperature for specific moraines found in the study area in west Greenland. The scale of the ice sheet model which provides an estimate of the basal temperature is to far from the scale of the morphology. Of course more refined modelling on the scale of the morphology would be a better option. Unfortunately this possibility is not yet at hand. We lack the knowledge of the processes taking place at the margins of ice sheets, because very few studies have actually measured processes which could be used to calibrate or test models. This not only involves the processes of erosion and deposition, but also the glaciological dynamics of marginal areas.

In the literature on reconstructed thermal conditions of the ice sheet base or margin, manifest differences can be found in the interpretation of identical features. Liszkowski (1987) uses the displacement of large nappes into pushed moraines as evidence for cold basal conditions. According to Van der Wateren (1992) periglacial conditions are not a prerequisite and some of the largest push moraines appear to have formed in areas where the ice sheet advanced into large lakes. The danger of mis-interpretation of glacial geomorphological features or glacial deposits lies permanently in ambush.

According Lagerbäck (1988) and Kleman and Borgström (1994), periglacial features have survived Weichselian ice sheet coverage in Scandinavia. If so, these surfaces are indicative of low rates of geomorphological work at the base of the Weichselian ice sheet, associated with cold basal temperatures. Based on requirements to form the periglacial features, Lagerbäck (1988) assumes an interstadial age for relics of frost-shattering and ventifaction. Holocene climatic conditions are considered to be incompatible with the observed periglacial phenomena. In general, the studies in central Scandinavia do not explicitly consider transient effects. If these reconstructions are true, permafrost conditions were inherited from cold basal ice sheet temperature. Following deglaciation, only moderate cold topoclimatological conditions are required to maintain permafrost. Combined with relatively high precipitation (compared with central west Greenland) this may lead to intensive periglacial activity, including frost shattering and the formation of patterned ground. In the area described by Kleman and Borgström (1994), the erosional contact between relict surfaces and glacially sculptured terrain is a strong argument for the preservation of relict peri-glacial surfaces. However, paleoglaciological conclusions from relict periglacial surfaces would increase in strength when accompanied with a temporal evaluation of ground thermal conditions, prior and after deglaciation.

Combining information from different sources is useful in formulating new perspectives. This point of view was already raised by Payne and Sugden (1987) but has never been worked out explicitly. From ice sheet modelling and estimates of possible ground temperature conditions, envelopes of potential conditions at the margin in northwestern Europe may shed some light on the thermal dynamics involved in push moraine formation.

Careful studies of landforms and sediments will still provide essential information on their genesis, especially if landforms can be put within a time framework. The opportunities to use geomorphology for ice sheet modelling will increase if studies aim to extract physical parameters related to erosion or deposition. Because the amount of information held in sediments and landforms is in essence limited, studies on ice marginal processes in present-day glacierized areas must be an integral part to provide data for physical models of ice marginal sedimentation.

Conclusions

We have shown that it is possible to define unique boundary conditions for landform formation at the scale of an ice sheet model in the area we have chosen for this study. However, because model scale is not equal to the scale of ice-marginal morphology, we can not select a landform from the field and simply apply our analysis. Furthermore it must be realized that our results are only valid for marginal areas outside the termini of outlet glacier. If the result of this study are used to set boundary conditions for moraine genesis at a specific locality, a careful evaluation of the local setting is essential. Our 'model-scale' boundary conditions may be flawed from such a local study. However, we think that ice sheet models can be used to delineate boundary conditions for landform formation. Our results must be viewed as hypotheses, rather than firm statements, because of:

- the scale adopted in this study, which is not the scale of moraines,
- the discrepancy in age of ice margin positions from geological evidence and ice sheet modelling and,
- the lack of field data.

The following hypotheses are formulated:

1. In mountainous areas with an altitude above 800 m, ice-marginal morphology (i.e. remnants of ice-cored moraines) will be characterized by landforms typical for cold conditions owing to the combination of relatively thin ice throughout Holocene deglaciation and pronounced negative MAST in the proglacial area.
2. Low-lying areas (0–250 m), with a sufficient areal extension in the direction of ice flow, have relatively thick ice throughout Holocene deglaciation. The combination of basal temperatures at the pressure melting point with positive MAST in the proglacial area produces deposits related to temperate beds and margins.

Detailed sedimentological and micromorphological inventories of moraines and surrounding surfaces in combination with ice-sheet modelling on the scale of landforms must be used for testing the first hypothesis. Unfortunately, detailed sedimentological and morphological inventories are time-consuming and therefore these studies will be limited in spatial extent. Modelling on the scale of landforms may provide understanding in the physical processes of moraine formation. When landforms at a specific site are addressed, accurate dating of moraines to enable correct paleoclimatological reconstructions, is vital for modelling.

With respect to the second hypothesis, we expect concentrations of basal tills and the frontal styles of the continuation of subglacial deformation in low-lying areas. Morphological features related to temperate conditions could be ice-pushed ridges or till deltas in a subaquatic setting. The 'warm' areas implied in hypothesis 2 could also have experienced higher glacial erosion rates than neighbouring areas. Comparative studies could derive differences in the intensity of erosional features, although dating of bedrock surfaces will be problematic.

The combination of temperate basal temperatures with negative MAST in the proglacial area, has probably occurred frequently during Holocene deglaciation in the inland part of central west Greenland. Depending on the time between deglaciation and moraine formation at a certain location and ice margin dynamics, the resulting morphology will be influenced by the presence or absence of a frozen bed.

In such a setting, we are not able to define clear criteria for ice-marginal conditions because of the marked transient effects. Systematic, comparative studies of landform assemblages along sectors of the present-day ice sheet margin in Greenland experiencing different combinations of thermal conditions, may provide criteria to distinguish ice-marginal landforms related to different thermal conditions.

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