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Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum

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The areal extents of the Laurentide and Fennoscandian ice sheets during the Last Glacial Maximum (about 20,000 years ago) are well known[1], but thickness estimates range widely, from high-domed[2] to thin[3], with large implications for our reconstruction of the climate system regarding, for example, Northern Hemisphere atmospheric circulation and global sea levels. This uncertainty stems from difficulties in determining the basal temperatures of the ice sheets and the shear strength of subglacial materials[4], a knowledge of which would better constrain reconstructions of ice-sheet thickness. Here we show that, in the absence of direct data, the occurrence of ribbed moraines in modern landscapes can be used to determine the former spatial distribution of frozen- and thawed-bed conditions. We argue that ribbed moraines were formed by brittle fracture of subglacial sediments, induced by the excessive stress at the boundary between frozen- and thawed-bed conditions resulting from the across-boundary difference in basal ice velocity. Maps of glacial landforms from aerial photographs of Canada and Scandinavia reveal a concentration of ribbed moraines around the ice-sheet retreat centres of Quebec, Keewatin, Newfoundland and west-central Fennoscandia. Together with the evidence from relict landscapes that mark glacial areas with frozen-bed conditions, the distribution of ribbed moraines on both continents suggest that a large area of the Laurentide and Fennoscandian ice sheets was frozen-based—and therefore high-domed and stable—during the Last Glacial Maximum.

The glaciological factors controlling the location of thermal zones (surface temperature, ice thickness, geothermal flux, strain heating) under ice sheets are well understood[5], but because of the absence of direct subglacial palaeotemperature records, the actual basal thermal conditions under the Fennoscandian ice sheet (FIS) and Laurentide ice sheet (LIS) have remained elusive. Wide zones of subglacial till (glacially transported sediments) deformation have been invoked in modelling experiments predicting low ice-sheet profiles[3], but without data on the phase state (frozen or thawed) of the sediments in deformable bed areas under glacial conditions, the validity of these models has been difficult to verify. The problem is that the rheology of subglacial till is extremely sensitive to the phase state of the interstitial water; frozen subglacial till is much stronger than ice, whereas thawed till under high water pressures can be deformed by overriding ice[6]. We focus here on the landform record interpreted to result from the phase-state control on soil strength (and thereby landform-building processes) and perform an inversion of the record: that is, we use the spatial distribution of diagnostic landforms to gain insight into the former subglacial phase- and temperature-regime under the FIS and LIS.

The two main subglacial landform groups resulting from reshaping of subglacial sediments are: (1) drumlins and flutings (flow-parallel streamlined till ridges, 0.1–20 km in length), created by particle-by-particle entrainment and lodgement processes or plastic deformation of till masses[7], and (2) ribbed moraines or Rogen moraines (fields of till ridges, 0.1–1 km in length, formed transverse to ice flow), with a debated mode of formation[8]. Drumlins and flutings cover 90% of the terrestrial parts of the LIS[9,10] and FIS areas, but ribbed moraines less than 10%, with a spatial distribution that is extremely selective when compared to the lineation distribution. There is a third important group of subglacial landscapes: those which have been left essentially unmodified by the last ice sheet due to sustained frozen-bed conditions and absence of basal sliding[11].

Previous formation hypotheses for ribbed moraine suggested compressive flow (caused by topography, that is, by bedrock depressions)[12], or the type and amount of basal debris load[13] as the primary controls on its formation. As hilly topography and coarse-grained tills are widespread in areas of Precambrian basement rocks (shown yellow in Fig. 1a and b), these hypotheses imply that ribbed moraines would occur geographically dispersed, wherever local topographic or substratum conditions were favourable. The concentration of ribbed moraines in the four retreat centres of Quebec, Keewatin, Newfoundland and west-central Fennoscandia (Fig. 1a and b), and their absence in other areas of hilly relief and coarse-grained tills, indicates that some other type of primary control on their distribution exists.

Ribbed moraines are conspicuously lacking in the southern parts of both ice-sheet areas where thawed-bed conditions prevailed after the Last Glacial Maximum (LGM), and it thus appears unlikely that ribbed moraine formed under completely thawed-bed conditions. The concentric arrangement of ribbed moraines around late-glacial retreat centres, and their affinity to frozen-bed areas, indicates that the primary control is a time-dependent basal thermal evolution. The stratigraphical and structural composition of ribbed moraine is highly variable (from laminated silt to shattered bedrock), and generally follows local variations in the till composition[8,14]. Hence, ribbed moraines cannot be linked to any specific depositional facies. Rather, the deposition of the sediments in ribbed moraine ridges appears to be genetically unrelated to the actual landform-shaping process[8,15], predating it. Morphological evidence (Fig. 2a; detailed till block outline matching, grating patterns, strike-slip faulting of till slabs, rotation of discrete till blocks) indicate that individual ridges were once part of a coherent drift sheet, and we thus infer that formation of ribbed moraine occurred by brittle fracture of drift sheets. Such brittle behaviour cannot occur in unfrozen drift (due to its low cohesive strength), and we therefore argue for a primary thermal control on ribbed moraine formation, by fracturing of frozen drift sheets during the transition from frozen to thawed conditions in an extensional basal regime (Fig. 3). Extreme stress concentrations develop at frozen–thawed boundaries[16], because of the abrupt increase in basal ice flow velocity, and we infer brittle fracture of drift sheets to have occurred at migrating frozen–thawed boundaries. The often observed lack of material between ribbed moraine ridges[15] is not compatible with alternative formation processes of glaciotectonic stacking and sediment thickening[12]. The typical 150–600 m spacing of individual ribbed moraine ridges contrasts sharply with the observed tightly folded "wrinkled-carpet" morphology of subglacial compressional ridges[17].

Relict landscapes are defined by ground surfaces and landforms essentially unmodified during overriding by the last ice sheet[18] (Fig. 2b and c). In these landscapes glacial meltwater traces from the last deglaciation (that is, meltwater channels and ice dammed

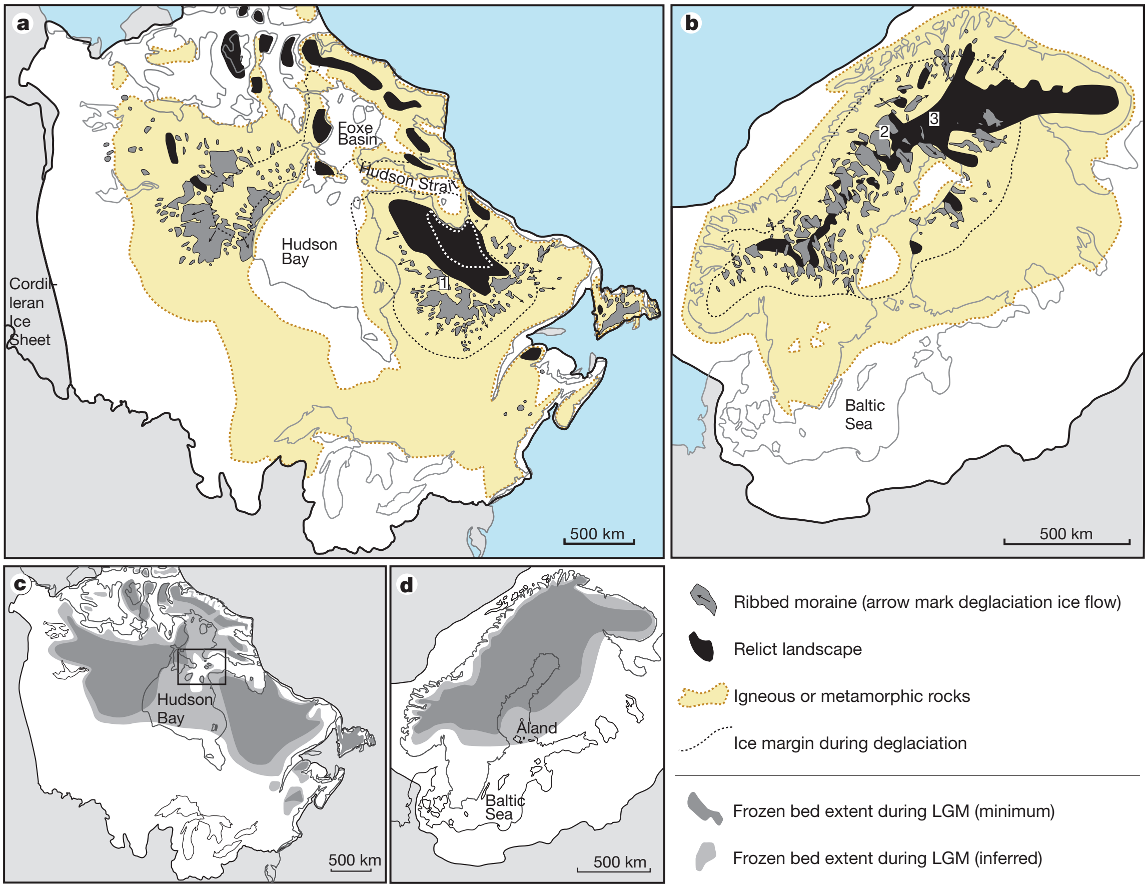

Figure 1 Frozen-bed extent reconstructed from ribbed moraines and relict landscapes. Ribbed moraines (grey) and relict landscapes (black) are shown in the LIS[10,13,19–22] (**a**) and FIS[11,15,23,24,28,31] (**b**) areas. Arrows mark deglacial (final) ice flow directions, the heavy black line shows the LGM ice-sheet margins, and the thin broken black line shows ice margins at 8,000 radiocarbon years before present (^{14}C yr BP; LIS) and 9,500 ^{14}C yr BP (FIS). Areas with exposed igneous or metamorphic rocks, commonly overlaid by discontinuous coarse-grained tills, are shown in yellow. Areas of sedimentary cover rocks, mostly overlain by fine-grained diamictons, are shown in white. Relict landscapes[18] mark the sites of sustained frozen-bed conditions, and ribbed moraine areas mark areas of frozen- to thawed-bed conversion[15]. Ribbed moraines exist also south of Ungava Bay (within white dashed line), but are considered to be unrelated to the last deglaciation[21]. The digit '1' shows location of Fig. 2a; '2' shows location of Fig. 2b; '3' shows location of Fig. 2c. **c, d,** Reconstruction of frozen-bed extent under the LIS and FIS during the LGM. Dark shading represents the minimum extent of zones dominated by frozen-bed conditions, directly based on geological evidence (ribbed moraine and relict landscapes). Lighter shading represents probable LGM frozen-bed extent, with allowance made for deglacial inward-transgression of thawed/frozen bed boundaries. Minor areas of thawed bed may have existed in frozen-bed zones but would have had negligible effect on overall ice-sheet dynamics because basal ice flow in a mosaic of frozen and thawed bed patches is largely controlled by the frozen patches[29]. The boxed area indicates an area critical for discharge of interior Laurentide ice. Frozen-bed sticky spots may have existed on islands at the western end of the Hudson Strait.

lake features) often overprint land surfaces with directionally unaligned glacial landforms, interstadial periglacial features, or pre-glacial weathering remnants. Relict landscapes are particularly well documented in Fennoscandia[11] but are also known from many smaller areas in the northern and eastern sectors of the Laurentide area[19,20]. We regard relict landscapes as frozen-bed markers because it is unlikely that delicate pre-existing landforms, such as metre-scale periglacial boulder polygons[17] (Fig. 2b) and tors (Fig. 2c) could survive thawed-bed conditions and basal sliding for any length of time.

We mapped glacial landforms in one of the two LIS core areas, Quebec-Labrador, in aerial photographs at a scale of 1:60,000, and established the approximate extent of relict landscapes and melt-water landforms (strictly marginal channels, but no eskers from the final glaciation) indicative of impermeable and cold ice during deglaciation[21]. For the more peripheral parts of this core area we used existing maps[10] and aerial-photograph interpretation. For the ribbed moraine distribution in the other LIS core area, Keewatin, we used existing map information[10,13]. For identifying relict landscapes in the northern and eastern part of the LIS area, we used regional descriptions of glacial geology and geomorphology[19,20,22]. To establish the spatial distribution of ribbed moraine in the FIS area, we mapped Sweden, which comprises most of the Fennoscandian occurrences, from high-altitude aerial photographs[14] at a scale of 1:150,000. For the more peripheral parts of the FIS area we used existing map data on the spatial distribution of ribbed moraine[23,24]. We mapped relict surfaces in the Swedish part of the Scandinavian mountain chain, using colour infrared aerial photographs at a scale of 1:60,000, and established the spatial extent of relict landscapes in other parts of Fennoscandia by analysis of existing map data on glacial geomorphology and surficial deposits. As to data quality: we regard the distribution of ribbed moraine as well established in both the LIS and FIS areas. The extent of relict landscapes in the FIS area is reasonably well known, but in the LIS area there is an uneven coverage, with research into identifying relict landscapes mainly having been focused at the northern and eastern parts.

In two regions, Quebec-Labrador and west-central Fennoscandia, ribbed moraine surrounds relict landscapes indicating frozen-bed conditions during deglaciation. The Keewatin area differs from Fennoscandia and Quebec-Labrador in that there is no surviving central area of relict landscape. Thus, lineation swarms[10] (which are superimposed on the ribbed moraine) extend all the way to the position of the former ice divide. In the Keewatin sector, therefore, ribbed moraine is the main indicator of the extent of the former frozen-bed core area.

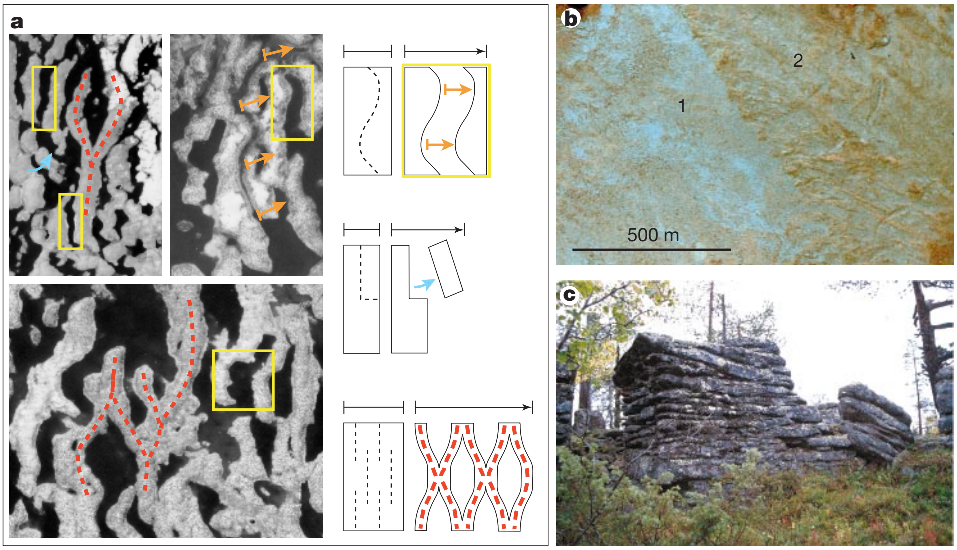

Figure 2 Landforms indicating former frozen-bed conditions. **a,** Vertical aerial photographs of ribbed moraines in central Quebec-Labrador. Ice flow direction in all photographs is from left to right. Three types of dislocation features show that the till sheet underwent extension and fracturing; grating splays (broken red lines), slab detachment and rotation (curved blue arrow), and detailed ridge outline matching (yellow boxes). An embryonic split between two till slabs is shown by orange arrows. Grating splays can only occur in material with considerable tensile strength and thus indicate that fracturing occurred when the till was in a frozen state. **b,** Relict surface of interstadial patterned ground (sorted boulder polygons), labelled '1', truncated by glacial fluting ('2') formed by basal sliding or till deformation in a thawed-bed zone during deglaciation. This image is a colour infrared photo of Sjuva Hill (800 m elevation) at 66° 37' N, 18° 03' E, northern Sweden. **c,** Granite tor (weathering remnant) at Paljaslaki (390 m elevation), northeastern Sweden. The height of the tor is 2 m. Tors are typical landforms in unglaciated regions, indicating long exposure to subaerial weathering and erosion processes, and where found in previously glaciated areas, such as in northern Sweden, they are indicative of negligible glacial erosion due to frozen-bed conditions[20]. The locations of these photographs are shown in Fig. 1.

Our evidence suggests that the LIS had wide terrestrial frozen-bed zones (Fig. 1c), similar to the one in Fennoscandia (Fig. 1d), implying high and stable domes over Keewatin and Labrador. The morphological evidence for frozen-bed core areas provides convergence with glaciological theory[5] that predicts terrestrial core areas, especially at higher elevation, as likely sites for frozen-bed conditions. The results also converge with thermal modelling experiments suggesting frozen-bed conditions in central ice sheet areas, possibly slowly consumed by basal melting late in the glacial cycle[25], and time-dependent three-dimensional modelling of Northern Hemisphere ice sheets which suggests frozen-bed core areas[26]. Oxygen-isotope analyses[27] of Pleistocene ice in the Penny ice cap, Baffin island, indicate that the ice is not of local origin, but originated at a high-elevation source over Hudson Bay and/or Foxe basin. Frozen bed conditions in Hudson Bay during the LGM were inferred[27].

Because of the cumulative nature of subglacial reshaping, the present extent of ribbed moraines and relict landscapes most probably represents only a part of the area that at any given time had a frozen bed. Hence, we have shown (Fig. 1c and d) two alternative frozen-bed extents during the LGM; the smallest we consider the data to allow, and a more tentative extent where allowance has been made for the likely destruction of morphological evidence in peripheral sliding zones that transgressed inwards over former frozen-bed areas during final deglaciation. As shown in Fig. 4, the duration of (final) wet-based flow was longer in the more peripheral parts of the ice sheet, and major (possibly complete), reshaping and destruction is therefore likely to have affected the oldest and most peripheral ribbed moraines. The shrinkage of the frozen-bed zone mainly occurred by slow retreat of the boundary between the frozen and the thawed bed (Fig. 4), but was locally enhanced by rapid headward propagation of discrete radial wet-bed zones during development of late glacial ice streams[28].

For the overall ice sheet geometry in the LIS area, conditions at the junction between Hudson Bay, the Hudson Strait and Foxe basin must have been crucial. These areas are mainly underlain by

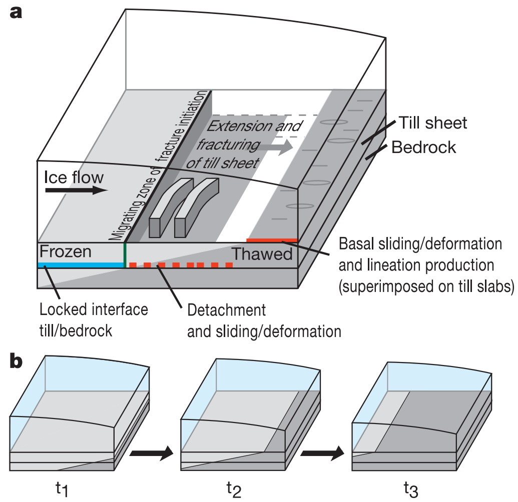

Figure 3 Formative conditions for ribbed moraine. **a**, Block diagram of the three-layer sandwich ice–till–bedrock, where the two interfaces can be either locked (frozen), or unlocked (thawed). During thawing of a glacier bed from underneath, a phase-change surface (separating frozen and thawed material) intersects the glacier bed at low angle, sloping upward in the ice-flow direction. Where the phase-change surface intersects the till–bedrock interface, the basal ice flow velocity will increase as the bed thaws, causing a zone of strong longitudinal tensile stresses. Fracturing of the still frozen till sheet is likely to occur immediately above the detachment zone (broken red line), down-ice of the locked till–bedrock interface (blue line), creating ribbed moraine. Further downglacier, where the thawing front reaches the till–ice interface (red line), basal sliding, till deformation and lineation production can take place. **b,** The sequence $\mathbf{t}_1$–$\mathbf{t}_3$ shows ice sheet thinning and retreat of the frozen/thawed bed boundary during deglaciation. We interpret the thawed/frozen bed boundary to have transgressed inwards during final decay of mid-latitude ice sheets, causing a narrow fracture-inducing zone of tensile stresses to transgress over till sheets and creating ribbed moraine successively up-ice. Ribbed moraine probably formed as a consequence of non-equilibrium conditions unique to ice-sheet decay phases (ice-marginal retreat and slow subglacial thawing).

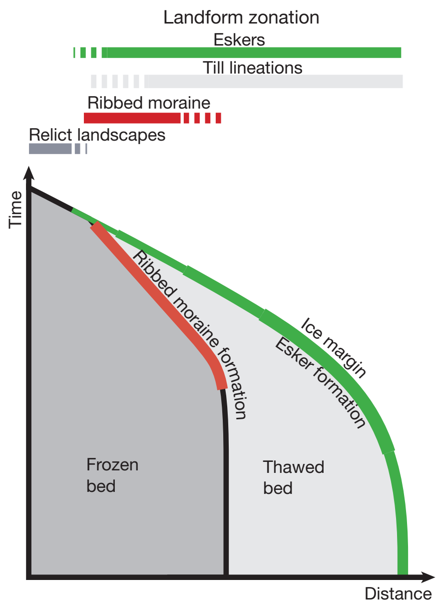

Figure 4 Time–space domains of glacial landform formation**.** Distance is shown along a transect from dispersal centre to ice margin. Time is shown from the LGM to the time of deglaciation at the final dispersal centre. Bars at the top of the figure show along-transect location of landform types and relict landscapes.

sedimentary cover rocks, the main source of fine-grained sea-floor diamictons in the region. Whether or not these diamictons were deformable (and therefore conductive to low ice-sheet profiles) was a function of ice-sheet basal temperatures in this region, and cannot be assumed *a priori*. Horsts of Precambrian rock (Nottingham, Salisbury and Mill islands, and the northern part of Southampton island) stand 200–600 m above the adjacent sea floor and may have acted as frozen-bed ‘sticky spots’[29] in a region elsewhere characterized by thawed-bed conditions, thereby substantially retarding ice outflow through the Hudson Strait and raising the surface elevations over Hudson Bay. This is a situation analogous to the Åland islands in the FIS area, which modelling experiments indicate to have been frozen-bed sticky spots hindering headward propagation of the Baltic ice stream into the central Fennoscandian ice sheet area[30].

Our results show that a time-dependent basal thermal evolution was the primary control on bed traction in each of the FIS and LIS areas. Large fractions of the LIS and FIS beds were frozen, but thawed during the post-LGM stages. This created the conspicuous landform ribbed moraine, and efficiently lowered ice-sheet profiles by allowing basal sliding and deformation of formerly frozen and undeformable till. □

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Limits on differential rotation of the inner core from an analysis of the Earth’s free oscillations

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Differential rotation of the Earth’s inner core has been inferred by several seismic ‘body-wave’ studies[1–6] which indicate that the inner core is rotating at a rate between 0.2° and 3° per year faster than the Earth’s crust and mantle. The wide range in inferred rotation rate is thought to be caused by the sensitivity of body-wave studies to local complexities in inner-core structure[3,7]. Free-oscillation ‘splitting functions’, on the other hand, are insensitive to local structure and therefore have the potential to estimate differential rotation more accurately. A previous free-oscillation study[8], however, was equivocal in its conclusions because of the relatively poor quality and coverage of the long-period digital data available 20 years ago. Here we use a method for analysing free oscillations[9] which is insensitive to