Low-gradient outlet glaciers (ice streams?) drained the Laurentide ice sheet

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ABSTRACT

Observations of geomorphic features dated with cosmogenic nuclides are used to determine the configuration of glaciation in Cumberland Sound, Baffin Island, during the last glacial maximum. Cumberland Sound, which was a major drainage of the Laurentide Ice Sheet at its northeastern (Arctic Canada) margin, contained low-gradient ice with a surface slope of \( \approx 0.03^\circ \) and a driving stress between 2 and 7 kPa. These values are similar to those observed for the ice streams that dominate the dynamics of the West Antarctic ice sheet today. The presence of low-gradient ice in Cumberland Sound and other major outlets may similarly have influenced Laurentide ice sheet behavior and would account for the iceberg discharge episodes that produced the Heinrich-event debris layers observed in North Atlantic ocean sediments.

Keywords: Baffin Island, exposure age, Laurentide ice sheet, ice streams, glacial geology, last glacial maximum.

INTRODUCTION

Studies of the West Antarctic ice sheet show that the dynamics of ice streams (bounded by slow-moving ice) and outlet glaciers (bounded by rock), which are small in areal extent but account for the majority of total ice drainage, may strongly influence overall ice-sheet activity (Hughes, 1998). Low surface slopes (<0.3° or < 5 m/km), low driving stresses (<25 kPa), and rapid surface velocities characterize ice streams; these characteristics allow ice streams to be sensitive to changes in basal conditions and possibly to climate forcing (e.g., Alley and Whillians, 1991). Like the West Antarctic ice sheet today, the northeastern margin of the former Laurentide ice sheet may have been drained by regions of low-gradient, fast-moving ice, accounting for its apparent instability during the last glacial period, evidenced by repeated, rapid iceberg discharge episodes (Heinrich events) (e.g., Clark et al., 1999). However, the topography of the Laurentide ice sheet remains poorly known, and there is limited direct documentation of low-gradient ice streams or outlet glaciers. In contrast to ice-marginal positions that are demarcated by characteristic landform assemblages, former ice-sheet surfaces can be difficult or impossible to reconstruct. In this paper, we present glacial-geologic mapping and cosmogenic nuclide data from Cumberland Peninsula, Baffin Island (Fig. 1), where the high relief provides a unique opportunity to reconstruct the vertical extent of low-gradient ice in adjacent Cumberland Sound (Fig. 2) during the last glacial maximum.

BACKGROUND

The glacial history of the eastern Canadian Arctic, and of the Cumberland Sound region in particular, has been controversial for decades. Early reconstructions of the Late Foxe Glaciation (local term, ca. 25,000–8000 14C yr B.P. (Andrews and Ives, 1978)) or last glacial maximum, based on terrestrial investigations adjacent to inner Cumberland Sound, depicted Laurentide ice occupying only the head of the sound (Dyke, 1979). An alternative model for the last glacial maximum, originally based on conceptual arguments (Denton and Hughes, 1981), and more recently on marine geologic studies, depicts a grounded marine-based section of the Laurentide ice sheet (Jennings, 1993; Jennings et al., 1996) occupying Cumberland Sound, which served as an ice conduit between the Foxe Dome and the Labrador Sea. On nearby Cumberland Peninsula, paleolimnological data have been used to argue for last glacial maximum ice-free refugia (Wolfe et al., 2000, 2001). Marsella et al. (2000) used cosmogenic surface-exposure dating to demonstrate that during the last glacial maximum, ice was present in fiords and valleys of the southwestern Cumberland Peninsula that were previously mapped as outside the last glacial maximum ice limits (Dyke, 1979). The extent to which uplands on the southwestern Cumberland Peninsula were glaciated, however, remains controversial (Bierman et al., 1999; Wolfe et al., 2001). A field-based study of southeastern Cumberland Peninsula was undertaken in 1996 and 1997 (Fig. 1) to gather key observations that would resolve the apparent discrepancy between the minimum and maximum last glacial maximum ice reconstructions. A specific objective was to examine the terrestrial record in relation to the Cumberland Sound ice stream proposed by Jennings (1993).

GLACIAL GEOLOGY

Coastal southern Cumberland Peninsula (Fig. 2) exhibits geomorphic elements common to many other glaciated high-latitude, high-relief regions; glacially scoured lowlands are in stark juxtaposition to highly weathered uplands that lack evidence of glacial erosion. Micrelief on scoured bedrock surfaces is typically <1 cm. In contrast, adjacent uplands (above 300–400 m asl [above sea level]) are mantled by soliflucted and cryoturbated angular blocks through which protrude isolated bedrock residuals (i.e., felsenmeer and tors) that show advanced weathering characteristics, including grusformation and macropits to 15 cm deep.

The elevation of the erosional boundary (trimline) that separates the glacially scoured lowlands from the weathered-upland landscape was measured along the coastline (to ~5 km inland) of the study area (Fig. 3). Some field measurements of the trimline may provide a minimum elevation, because it is possible that mass movement has disrupted the original trimline since deglaciation. To evaluate the inferred trend of the field-based...
measurements, the elevations of the lowest weathered summits, which provide maximum trimline elevations, were also measured (Fig. 3). Both lines of evidence indicate a similar decrease in trimline elevation over ~100 km between Kingnait Fiord and Cape Mercy, sloping ~1.0 m/km (~0.06°).

Associated with the scoured landscape are striae and lateral moraines, which are directed southwest, south, and southeast (Fig. 2), meltwater channels, and marine limits. There is no evidence for ice flowing from Cumberland Sound onto Cumberland Peninsula. On two islands near Kingnait Fiord, striae parallel the axis of the sound. The field evidence also indicates that ice flowed around the uplands fringing the coastline (Fig. 2, inset). Marine limit elevations, typically indicated by wave-washed shorelines, are >100 m asl near Kingnait Fiord and decrease to ~25 m asl by Cape Mercy (slope of ~0.05°).

**COSMOGENIC DATING**

Cosmogenic surface-exposure dating provides the only available chronometer for constraining the glacial history of southeastern Cumberland Peninsula. Samples were acquired from glacially scoured bedrock surfaces, weathered bedrock tors, and boulders from moraines and on the upland terrain. All sampled sites are above the local marine limit; thus, no age correction for water shielding is needed. Samples were prepared at the University of Colorado following standard procedures (Kohl and Nishiizumi, 1992) and analyzed at the Center of Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory.

Exposure ages provide both temporal and spatial data on the glacial history of Cumberland Sound (Table 1; Fig. 4). Below or at the trimline, all exposure ages from glacially scoured bedrock and morainal boulders are between ca. 23 and 8 ka. Samples CM24 and CM66, from areas that are below the nominal trimline but that lack evidence of recent glacial erosion (Kaplan, 1999), yield ages older than 43 ka. Above the trimline, weathered upland surfaces produce exposure ages that are older and more scattered compared to those from the lower scoured areas (Fig. 4). Tors, all from the outer sound area, produce ages older than 42 ka. Three of four boulders above the trimline produce ages older than 31 ka. Below the trimline, both 10Be and 26Al were measured on 14 samples; 11 pairs contain concordant 10Be and 26Al ages (within 1σ). We measured 26Al on two tors, CM13 and CM40; the 10Be and 26Al ages are significantly different at 1σ for CM13.

**LAST GLACIAL MAXIMUM RECONSTRUCTION**

The combination of geomorphic evidence (Fig. 2) and exposure ages (Table 1) allows reconstruction of the glacial configuration on southeastern Cumberland Peninsula and in Cumberland Sound during the last glacial maximum. While there is abundant evidence of ice flowing from Cumberland Peninsula into Cumberland Sound, there is no evidence of the reverse; thus, the paleo-ice surface on the peninsula dipped seaward. The highly weathered plateaus fringing the coastline contain no evidence of former ice movement. Evidently, erosive ice in coastal fiords and valleys, the source of which must have been one or more interior ice divides on Cumberland Peninsula (see Dyke and Prest, 1987), flowed around the upland plateaus and converged with Laurentide ice in Cumberland Sound.

The trimline along the coastal southern Cumberland Peninsula, which separates an older weathered upland from a younger scoured landscape, must represent either an ice surface or an englacial thermal boundary that separated cold-based from warm-based ice. Ratios of 26Al/10Be that are significantly lower than the production ratio, as for one of our upland samples (CM13), indicate a complex history of burial and exposure that could be attributed to the presence of cold-based ice, as Bierman et al. (1999) suggested for southwestern Cumberland Peninsula. However, the presence of permanent snowfields, and/or the prior history of the sampled surface, could ac-
count for low 26Al/10Be ratios, which do not require the presence of glacial ice during the last glacial maximum (Wolfe et al., 2001). In any case, if last glacial maximum ice was present above the trimline adjacent to Cumberland Sound, the evidence shows (Fig. 2) that it was cold based, essentially nonerosive, and dynamically decoupled from eroding ice in the valleys and fiords. Plateau ice must therefore have been quite thin. Almost all of the plateaus adjacent to Cumberland Sound are <100 km² in area (Fig. 2); if plastic flow with a yield stress of 100 kPa is assumed (e.g., Paterson, 1994), any ice confined to these plateaus would have had a maximum thickness of ~200 m (Kaplan, 1999).

Even allowing for the presence of cold-based ice on the uplands, the mapped trimline still represents the surface elevation of the former actively eroding ice in Cumberland Sound. The former gradient of this ice surface can be estimated after correcting for postglacial isostatic uplift (Fig. 5) on the basis of mapped marine limit elevations. The reconstructed last glacial maximum ice surface elevations are ~300 m asl in middle Cumberland Sound (near Kingnait Fiord) and 245 m asl in the outer sound (near Cape Mercy), indicating a surface slope of ~0.5 m/km or ~0.03° (Fig. 5). The surface elevations are maximum values, because it is likely that some uplift occurred before deglaciation and a eustatic correction is not applied while adjusting for isostatic uplift. If the same amount of isostatic uplift occurred before deglaciation as after, our approximated surface slope could change by ±0.03°; an additional approximate eustatic correction (the timing of deglaciation was between ca. 10 500 to 9400 14 C yr B.P.; Jennings et al., 1996; Kaplan, 1999) could result in an estimated former ice surface slope to 0.06°. Maximum driving stresses of 2–7 kPa are determined (τd = ρgh · σ0; where τd = driving stress, ρ = ice density, g = gravitational acceleration, h = ice thickness, and σ0 = surface slope) for the grounded Laurentide outlet glacier, on the basis of an ice surface slope of 0.03° and a range of maximum ice thickness from ~1500 to 500 m (5–14 kPa with a surface slope of 0.06°). This range of maximum ice thickness is obtained by totaling the height of the corrected trimline and the depth of Cumberland Sound, which is 1200 m in the deepest part (middle part of sound near Kingnait Fiord), and 250 m at the sill near Cape Mercy (MacLean et al., 1986).

**DISCUSSION**

On the basis of the evidence presented above, Cumberland Sound is inferred to have contained a low-gradient outlet glacier (or ice stream, if we accept the presence of cold-based ice on the uplands and interpretation of the trimline as an englacial thermal boundary; cf. Bierman et al., 1999) during the last glacial maximum. On southeastern Cumberland Peninsula, smaller tributary fiords and valleys drained inland ice that flowed around the coastal upland areas that were either ice free or covered with thin, cold-based ice to 200 m.
thick. Our reconstruction is essentially intermediate between minimum (e.g., Dyke and Prest, 1987) and maximum extent (e.g., Denton and Hughes, 1981) glacial scenarios. This study is not only consistent with but defines the surface morphology of the extensive marine-based ice proposed by Jennings (1993). Our findings are in line with those of Marsella et al. (2000), who documented glacial ice in the fiords and valleys of the southwestern Cumberland Peninsula during the last glacial maximum. At the same time, our conclusions accommodate evidence on the southwestern Cumberland Peninsula indicating that upland plateaus were either ice free (Wolfe et al., 2001) or at least remained glacially unmodified during this period (Bierman et al., 1999). Our last glacial maximum scenario is also harmonious with the intermediate ice configuration proposed for the northern Cumberland Peninsula, where ice-free refugia are inferred to have coexisted with extensive low-gradient outlet glaciation of the fiords (Steig et al., 1998; Wolfe et al., 2000). Our findings, however, are incompatible with the presence of a thick last glacial maximum ice sheet over this area (Fig. 5).

Kaplan et al. (1999) used a finite element model to test whether our intermediate (field-based) glacial reconstruction is consistent with reasonable glaciological boundary conditions. They invoked high ice velocities and basal sliding (e.g., on a deforming till bed) to simulate advance of a low-gradient ice stream through Cumberland Sound. The simulated ice sheet is only slightly higher and steeper than the observation-based surface (Fig. 5). This modeling exercise clearly confirms that the inferred low-gradient outlet glacier in Cumberland Sound can be accommodated by glaciological theory.

Our findings indicate that during the cold, dry last glacial maximum, basal conditions favorable for fast-moving, low-gradient ice flow existed in Cumberland Sound, and presumably in other large marine embayments such as Hudson Strait. Ice surface slopes and driving stresses determined for the Cumberland Sound outlet glacier are equal to or lower than those estimated for lobes of the southern Laurentide ice sheet (1–5 m/km and 0.7–22 kPa, respectively; Clark, 1992) and the modern West Antarctic ice streams where they are lowest near the Ross Ice Shelf (<5 m/km and 2–7 kPa; Bentley, 1987). In the cold, dry Arctic regime, fast-moving, low-gradient marine-based ice is dominant in regulating overall ice-sheet activity (Hughes, 1998). We infer that similar ice conduits would have promoted rapid flow within discrete segments of the northeastern Laurentide ice sheet. These conduits, which may have behaved independently of climate forcing, facilitated dynamic interaction between the ice sheet and the adjacent ocean. The presence of low-gradient outlet glaciers or ice streams explains how sectors of the northeastern Laurentide ice sheet could have undergone the major reorganizations (perhaps including collapse) needed to produce the Heinrich events observed in the North Atlantic Ocean. These events may have altered thermohaline circulation, with global climatic consequences (e.g., Clark et al., 1999). Cumberland Sound has been independently identified as one of the sources for Heinrich events, as evidenced by sediment deposits on the adjacent Labrador Sea slope (Andrews et al., 1998).

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