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Unstable Behavior of the Laurentide Ice Sheet over Deforming Sediment and Its Implications for Climate Change

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Geologic records of fluctuations of the Laurentide ice sheet margin following the most recent glacial maximum (*ca.* 20,000 ^{14}C yr B.P.) identify fundamental differences in ice-sheet behavior depending on subglacial bed conditions. Rapid and irregular ice-margin fluctuations occurred only over areas of deforming sediment, indicating nonclimatic forcing controlled by the inherent instability of coupled ice sheet-deforming sediment dynamics. In contrast, largely uninterrupted ice-margin retreat with no evidence of significant readvance occurred over rigid-bed areas, indicating stable behavior. Unstable ice-sheet behavior was most pronounced from 15,000 until 10,000 ^{14}C yr B.P., by which time most of the ice margin had retreated onto a rigid bed. Unstable ice-sheet behavior would have been an integral component in controlling variable fluxes of icebergs and meltwater, as well as meltwater routing, to the North Atlantic, thus affecting thermohaline circulation. The abrupt climate oscillations in the North Atlantic region that ended at 10,000 ^{14}C yr B.P. may thus have their origin in the inherently unstable behavior of the Laurentide ice sheet overriding deforming sediment.

INTRODUCTION

Records of late Pleistocene climate change are dominated by cycles with periods of about 23,000, 41,000, and 100,000 yr, corresponding to orbital variations in insolation (Hays *et al.*, 1976; Imbrie *et al.*, 1984). Abrupt climatic oscillations identified from high-resolution paleoclimate records from the circum-North Atlantic region following the last glacial maximum (*ca.* 20,000 yr B.P.)[2] (Dansgaard *et al.*, 1982; Overpeck *et al.*, 1989; Lehman and Keigwin, 1992; Alley *et al.*, 1993) indicate additional causes of climate change that are attributed to equally sudden changes in North Atlantic thermohaline circulation resulting from ice-sheet meltwater and iceberg discharges (e.g., Rooth, 1982; Broecker *et al.*, 1985, 1989; Keigwin *et al.*, 1991; Charles and Fairbanks, 1992). Records that extend well into the last glaciation (>20,000 yr B.P.) identify similar high-frequency, aperiodic climate changes (Johnsen *et al.*, 1992; Taylor *et al.*, 1993), but their cause(s) remains unknown.

Studies of the Laurentide ice sheet since the last glacial maximum have long identified rapid and irregular readvances of the ice margin superimposed on overall retreat, and interpreted them as indicating unstable ice-sheet behavior (Prest, 1970; Dreimanis and Goldthwait, 1973; Wright, 1973; Clayton *et al.*, 1985). Marine records now identify unstable Laurentide ice sheet behavior through much of the last glacial cycle (Heinrich events) (Andrews and Tedesco, 1992; Bond *et al.*, 1992; Grousset *et al.*, 1993). Because of the important linkage between Northern Hemisphere ice sheets and climate change in the North Atlantic (e.g., Ruddiman and McIntyre, 1981; Manabe and Broccoli, 1985; Ruddiman, 1987), identifying the cause(s) of unstable ice-sheet behavior is of critical interest in evaluating the role of such behavior in the ice sheet–ocean–atmosphere system (Hughes, 1992; MacAyeal, in press).

In this paper, I propose that rapid oscillations of the Laurentide ice sheet margin are not climatic in origin but instead reflect inherent instability associated with deforming sediment dynamics. Such behavior would have played a critical role in affecting climate in the North Atlantic region by controlling variable fluxes of icebergs and meltwater, as well as meltwater routing.

SUBGLACIAL BED CONDITIONS

Distribution of areas of deforming beds beneath the Laurentide ice sheet is indicated by the strong relationship between bedrock lithology and the texture, thickness, and continuity of overlying till. Till overlying metamorphic, igneous, or sandstone bedrock is often coarser, thinner, and more discontinuous than till overlying carbonate, shale, and siltstone bedrock (e.g., Scott, 1976; Mickelson *et al.*, 1983). Sandy, discontinuous tills such as derived from underlying crystalline bedrock will have higher hydraulic permeability than clayey–silty tills overlying sedimentary bedrock (by up to several orders of magnitude) (Freeze and Cherry, 1979). Subglacial sediment deformation will occur when stress applied by the

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[2] All ages refer to the radiocarbon timescale unless otherwise noted.

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ice (τ_i) exceeds the sediment's shear strength (τ_s), where $\tau_s = c + \mu p_e$, where c is the cohesive strength, μ is the coefficient of internal friction, and p_e is the effective pressure, equal to the difference between ice overburden pressure p_i and pore-water pressure p_w. The pore pressure in a high-permeability sandy till will be lower than in a fine-grained till; thus, p_e will be greater and the sandy till will tend to be stronger.

Till continuity also plays an important role in controlling ice movement. Even where sediment deformation occurs, bedrock protuberances contribute a large basal resistance to ice motion (Humphrey *et al.*, 1993). Areas of crystalline bedrock tend to be largely exposed rock, whereas areas of sedimentary bedrock tend to have continuous till cover (e.g., Mickelson *et al.*, 1983; Dyke *et al.*, 1989).

These considerations of physical properties of tills indicate that subglacial sediment deformation is likely in regions of relatively low-permeability, fine-grained, continuous till, but much less likely where the till is discontinuous, coarse-grained, and has relatively high permeability. I thus infer subglacial sediment deformation beneath the Laurentide ice sheet where it was underlain by continuous, fine-grained till, generally corresponding to regions of sedimentary bedrock, and a rigid substrate where the ice sheet was underlain by discontinuous, coarse-grained till, or areas of crystalline bedrock (Fig. 1) (cf., Boulton *et al.*, 1985; Fisher *et al.*, 1985). This interpretation is supported by sediment and geomorphic records and ice-surface reconstructions of the Laurentide ice sheet (e.g., Alley, 1991; Clark, 1991, 1992; Hicock and Dreimanis, 1992; Clark and Walder, in press). By these criteria, roughly 50% of the area of the full-glacial Laurentide ice sheet rested on deforming sediment, although a much larger fraction (*ca.* 80–85%) of its margin was in contact with deforming sediment (Fig. 1).

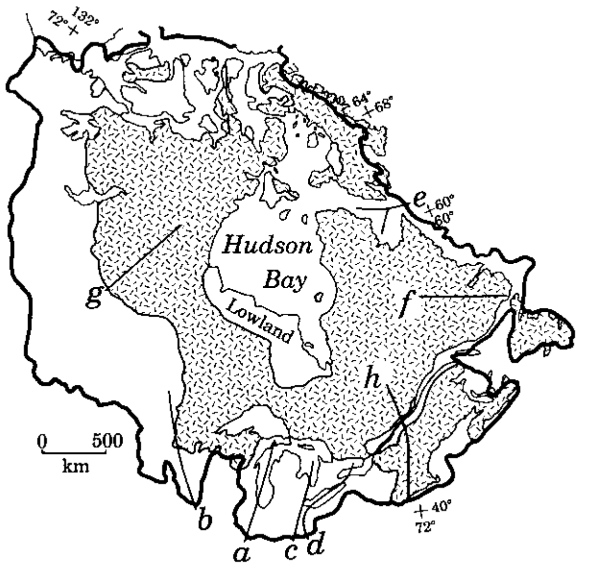

FIG. 1. Map showing locations of time–distance diagrams (*a–h*) in Fig. 2 and distribution of crystalline bedrock (igneous and metamorphic) (patterned area) and sedimentary bedrock (unpatterned area) that underlie the area covered by the Laurentide ice sheet. Extent of ice sheet at 18,000 yr B.P. shown by heavy line (from Dyke and Prest, 1987b). Distribution of former deforming beds is indicated by the strong relationship between bedrock lithology and the texture, thickness and continuity of overlying till (see discussion in text).

GEOLOGIC RECORDS OF ICE-SHEET BEHAVIOR

Well-dated (^{14}C) records of ice-margin retreat following the last glacial maximum (*ca.* 20,000 yr B.P.) (Fig. 2) identify significantly different ice-sheet behavior with respect to subglacial bed conditions. In general, ice resting on deforming sediment experienced large and rapid ice-margin oscillations; ice margins advanced at hundreds to thousands of meters per year over periods of hundreds of years (Figs. 2a–2e). By comparison, the geologic record indicates largely uninterrupted ice-margin retreat with no evidence of significant readvance where the margin rested on a rigid bed (Figs. 2f–2h).

Records from other areas where the Laurentide ice sheet advanced over fine-grained sediment also indicate irregular behavior, but there are insufficient data to illustrate their time–space relationships. Along the southwestern ice-sheet margin (Montana and Alberta), at least four significant readvances (up to 200 km) occurred following the last glacial maximum *ca.* 20,000 yr B.P. (Fullerton and Colton, 1986; Klassen, 1989). A complex history is also evident southwest of Hudson Bay. During the last stages of deglaciation, the Laurentide ice sheet margin retreated back from crystalline bedrock onto fine-grained sediment underlying the Hudson Bay and James Bay Lowlands. Between 8400 and 8000 yr B.P., when Hudson Bay and James Bay became ice free, the ice margin in the Lowlands advanced and retreated several times (Prest, 1970; Dyke and Prest, 1987a; Dredge and Cowan, 1989).

Differences in Laurentide ice sheet behavior with respect to subglacial bed conditions are also indicated by the outline of the retreating ice margin. Over areas of deforming sediment, the ice margin was strongly lobate; in contrast, the outline of the ice margin was much less lobate over areas of rigid beds (Fig. 3)

Several trends in the timing of advances of the Laurentide ice sheet margin over deforming sediment are apparent. The southern and southwestern ice-sheet margin advanced to or near its maximum extent at *ca.* 20,000 yr B.P. (Fig. 2). Following a major retreat that ended at 15,500–15,000 yr B.P. (Erie interstade; Dreimanis and Goldthwait, 1973), the southern margin readvanced 300 to 800 km between 15,000 and 14,000 yr B.P. to within ≤150 km of its maximum position. Correlative advances

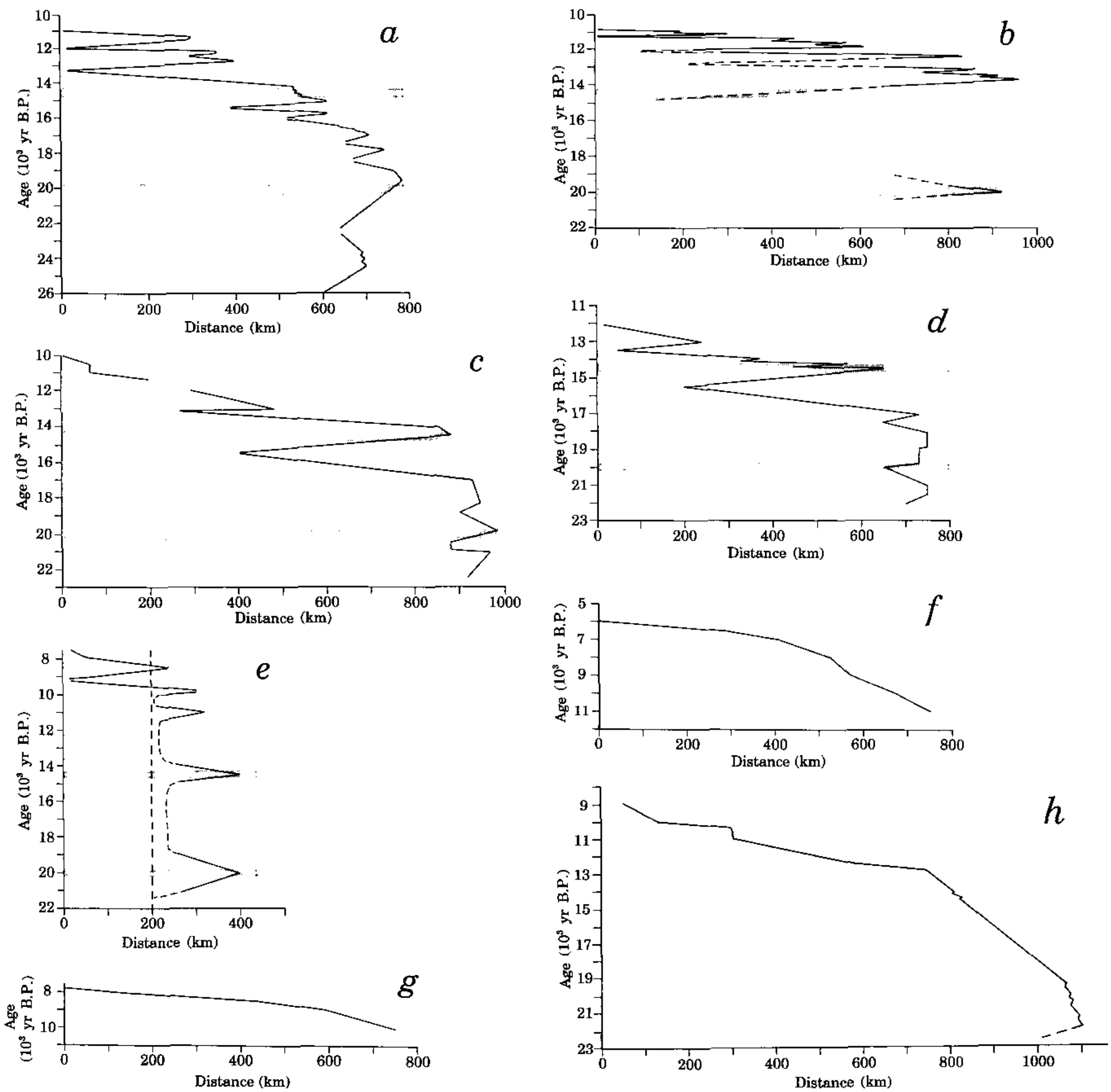

FIG. 2. Time-distance diagrams of the Laurentide ice sheet margin from: (*a*) the Lake Michigan Lobe (Hansel and Johnson, 1992); (*b*) the Des Moines Lobe (Clayton and Moran, 1982); (*c*) the Miami sublobe of the Huron–Erie Lobe (Dreimanis, 1977); (*d*) the Scioto sublobe of the Erie–Ontario Lobe (Dreimanis, 1977; Mickelson *et al.*, 1983; Calkin and Feenstra, 1985); (*e*) Hudson Strait (vertical dashed line represents entrance to Hudson Strait) (Miller and Kaufman, 1990; Andrews and Tedesco, 1992); (*f*) southeastern Labrador (King, 1985); (*g*) Keewatin (Dyke and Prest, 1987c); and (*h*) New England–southern Quebec (compiled from Larsen and Hartshorn, 1982; Sirkin, 1982; Dyke and Prest, 1987c; Ridge and Larsen, 1990; LaSalle and Shilts, 1993). Shaded lines centered at 20,000 and 14,500 yr B.P. on *a–e* represent timing of Heinrich events H2 and H1 recorded in North Atlantic sediments (Andrews and Tedesco, 1992; Bond *et al.*, 1992).

may have occurred along the southwestern margin (Dakotas, Montana, and Alberta) (Clayton and Moran, 1982).

Deep-sea records from the Labrador Sea (Andrews and Tedesco, 1992) and North Atlantic (Bond *et al.*, 1992; Grousset *et al.*, 1993) identify several episodes (Heinrich events) of massive discharges of icebergs derived from major advances of the Laurentide ice sheet through Hudson Strait into the North Atlantic during the last glacial cycle. Heinrich layers (HL) 2 and 1 are dated by radiocarbon at *ca.* 21,000–19,000 and 15,000–14,000 yr B.P., or at the same times as major advances along the south-

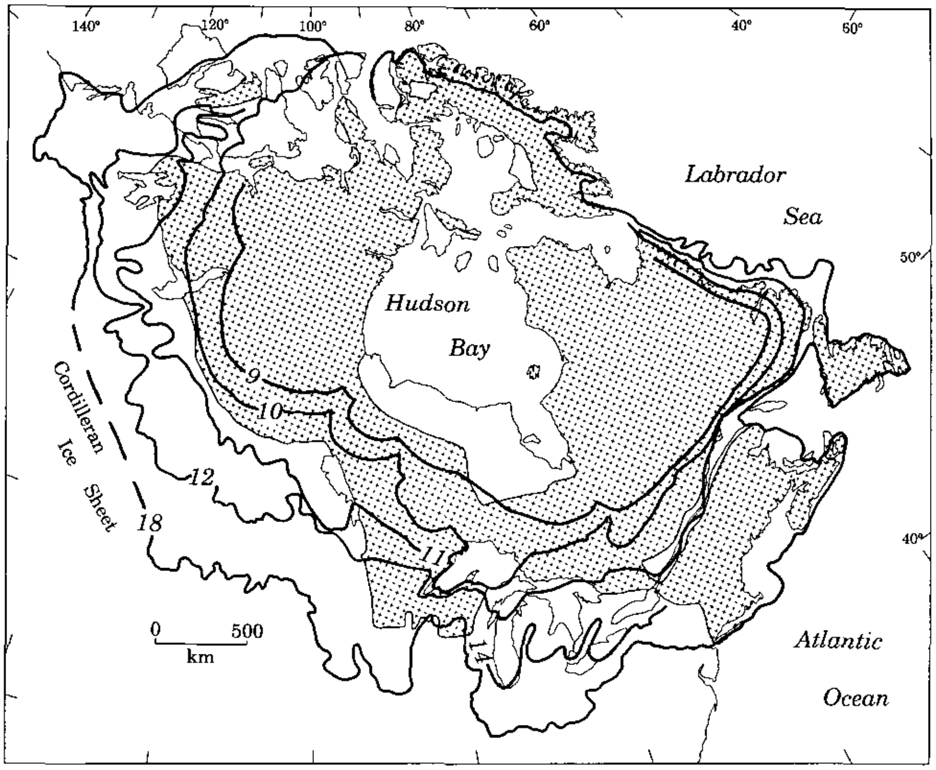

FIG. 3 Isochrones (in thousands of ^{14}C years B.P.) of recessional positions of the Laurentide ice sheet (after Dyke and Prest, 1987b). Full extent of all but the 18,000-yr-B.P. isochrone are not shown. Note different form of isochrones where the ice margin rested on a rigid bed (patterned area) versus their form where the ice margin rested on deforming sediment (nonpatterned area).

ern and southwestern margins (Fig. 2). These relationships suggest that the ice-margin advances through Hudson Strait that resulted in Heinrich events occurred elsewhere along the Laurentide ice sheet margin where it rested on deforming sediment, thus indicating ice-sheet scale events.

After 14,000 yr B.P., the Laurentide ice sheet margin experienced erratic behavior over deforming sediment on short time scales (10^2 yr), and fluctuations were asynchronous. By 10,000 yr B.P., all of the Laurentide ice sheet margin was on a rigid bed except in Hudson Strait and along part of its northwestern margin (Fig. 3). Other than readvances in Hudson Strait, and briefly in the Hudson Bay–James Bay Lowlands (8400–8000 yr B.P.), the ice margin after 10,000 yr B.P. was characterized by largely uninterrupted retreat.

CAUSES OF ICE-SHEET BEHAVIOR

Identifying the cause(s) of the rapid oscillations of the Laurentide ice sheet margin has important implications for understanding their role in ice sheet–ocean–atmosphere interactions. Calibration of the ^{14}C time scale to calendar years (Bard *et al.*, 1990) indicates that the advance of the Laurentide ice sheet margin at 21,000–19,000 yr B.P. occurred near the last minimum in Northern Hemisphere summer insolation (Berger, 1978). The rapidity and magnitude of this advance in producing a Heinrich event through Hudson Strait, however, points to ice-sheet instability rather than a linear response to insolation forcing (MacAyeal, in press). The major retreat of the southern ice margin ending at 15,500–15,000 yr B.P. (Erie interstade) apparently was in response to increasing hemispheric summer insolation (Berger, 1978). Warming during this interval (18,500–18,000 calendar yr B.P.) is recorded in cores from the Greenland ice sheet (depth in Summit core = *ca.* 1820–1830 m) (Johnsen *et al.*, 1992). The large fluctuations of the Laurentide ice sheet margin superimposed on overall retreat after 15,000 yr B.P., however, occurred during a period of steadily increasing hemispheric summer insolation (Berger, 1978), suggesting other forcing mechanisms for the fluctuations.

The rapid ice-margin fluctuations after 15,000 yr B.P. have been attributed to nonclimatic forcings, but none of the proposed mechanisms completely explains this irregular behavior. Wright (1973) and Clayton *et al.*, (1985) proposed surging over a rigid bed due to elevated subglacial water pressures over fine-grained till, but elevated water pressures could also be invoked for areas of crystalline bedrock where irregular behavior is not recorded. Dyke and Prest (1987a) suggested accelerated flow by oversteepening of the ice front by calving into an ice-contact lake. The fluctuating southern margin of the Laurentide ice sheet, however, terminated in glacial lakes for only part of its history. In some places where the Laurentide ice sheet did have an aquatic, calving margin, it did not experience any significant fluctuations (Dyke and Prest, 1987b). Mickelson *et al.* (1981) proposed a mechanism involving fluctuations in the position of the grounding line by changing levels of the ice-contact lake. Again, the retreating ice-sheet margin was not always in contact with lakes. Furthermore, calving dynamics can explain rapid retreat (hundreds of meters per year) of the ice margin, particularly in association with rising sea level, but the rate of advance following drastic retreat by calving is only on the order of tens of meters per year (Meier and Post, 1987), unlike reconstructed rates of advance for the Laurentide ice sheet margin (hundreds to thousands of meters per year) (Fig. 2).

Modern ice streams draining the West Antarctic ice sheet show evidence of rapid velocities (hundreds to thousands of meters per year) and life cycles (10^2–10^3 yr) (Clarke, 1987) that are comparable to fluctuations of the Laurentide ice sheet margin where it rested on deforming sediment (Fig. 2). Dynamics and inherent instability of these ice streams are controlled by properties of subglacial deforming sediment (e.g., water content, debris thickness, porosity, and viscosity) (Alley *et al.*, 1986, 1987; Alley and Whillans, 1991).

Several factors suggest that the inherent instability of coupled ice-sheet-deforming sediment dynamics that dictates unstable behavior of modern ice sheets also controlled behavior of the Laurentide ice sheet.

(1) Foremost is the observation that rapid and large fluctuations of the retreating ice-sheet margin occurred only over areas of deforming sediment, whereas the margin that rested on a rigid bed experienced largely unidirectional retreat (Fig. 2).

(2) The advances at 21,000–19,000 and 15,000–14,000 yr B.P. apparently occurred at the ice-sheet scale, but only over areas of deforming sediment (Hudson Strait margin, southern, and southwestern margins). Modeling results by MacAyeal (in press) suggest that advances through Hudson Strait at these times (Heinrich events H2 and H1) occurred in response to rapid collapse of an ice dome over Hudson Bay induced by warming at the ice-sheet base that initiated pervasive sediment deformation. Synchronous advances along the southern and southwestern ice-sheet margins indicate that they are also a product of this collapse.

(3) The asynchrony and rates of the ice-margin advances after 14,000 yr B.P. indicate nonclimatically forced ice-sheet behavior restricted to the scale of specific ice-drainage basins.

Control of ice-margin advances by the inherent instability of subglacial deforming sediment implies a nonclimatic origin for the unstable behavior of the Laurentide ice sheet margin following the last glacial maximum. By 10,000 yr B.P., most of the Laurentide ice-sheet margin had retreated onto a rigid bed (Fig. 3). Because the Eurasian ice-sheet margin had also retreated onto crystalline bedrock by 11,000–10,000 yr B.P. (Andersen, 1981), then 10,000 yr B.P. may mark a threshold in stability of Northern Hemisphere ice sheets.

IMPLICATIONS FOR CLIMATE CHANGE IN THE NORTH ATLANTIC REGION

High-resolution paleoclimatic records from the circum-North Atlantic region reveal a series of abrupt climatic oscillations between 15,000 and 10,000 yr B.P. (Keigwin *et al.*, 1991; Johnsen *et al.*, 1992; Lehman and Keigwin, 1992; Karpuz and Jansen, 1992). After 10,000 yr B.P., climate in this region stabilized except for one minor oscillation at *ca.* 9700 yr B.P. These events broadly correspond to behavior of the Laurentide ice sheet (*i.e.*, unstable ice-sheet behavior from 15,000 to 10,000 yr B.P., stable ice-sheet behavior after 10,000 yr B.P. except in Hudson Strait). Because the rapid oscillations of the Laurentide ice sheet during this period appear to be nonclimatic in origin, this relationship suggests that forcing of circum-North Atlantic events may have been by unstable ice-sheet behavior. Abrupt climatic oscillations have been previously tied to ice-sheet forcing by fluctuations in North Atlantic thermohaline circulation resulting from meltwater (Broecker *et al.*, 1989; Keigwin *et al.*, 1991) and iceberg discharges (Miller and Kaufman, 1990; Hughes, 1992; Kaufman *et al.*, in press). Instabilities associated with deforming beds would have been an integral component in directly controlling variable fluxes of icebergs (MacAyeal, in press). Nonclimatic forcing suggests that ice-margin advances were not a product of increases in ice volume. These advances would thus have increased the ratio of surface area to ice-sheet volume, leading to greater melting rates (Teller, 1987). Rapid advances also indirectly affected meltwater routing through the opening and closing of glacial lake outlets (Teller, 1987). Stable ice-sheet behavior that prevailed after 10,000 yr B.P. no longer strongly affected thermohaline circulation by varying meltwater and iceberg fluxes, thus offering an explanation for the abrupt end of the late-glacial climate oscillations *ca.* 10,000 yr B.P.

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