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Applications of cosmogenic nuclides to Laurentide Ice Sheet history and dynamics

Jason P. Briner[†]
Department of Geology, University at Buffalo, Buffalo, New York 14260, USA

John C. Gosse[‡]
Department of Earth Sciences, Dalhousie University, Halifax, Nova Scotia B3H-4R2, Canada

Paul R. Bierman[§]
Geology Department and School Natural Resources, University of Vermont, Burlington, Vermont 05405, USA

ABSTRACT

Ice sheets play a fundamental role within Earth's climate system and in shaping landscapes. Despite extensive research, the maximum extent and basal dynamics of the Laurentide Ice Sheet (LIS) during the last glacial cycle remain elusive and debated in many areas. Recently, cosmogenic nuclides (e.g., ^{36}Cl, ^{26}Al, ^{10}Be) have played an important role in improving our understanding of LIS extent and behavior. Applications of cosmogenic nuclides to LIS research include surface exposure dating of glacial features, constraining magnitudes of glacial erosion, addressing long-term subaerial exposure and ice sheet burial histories, and burial dating of glacial sediments. These techniques have contributed to the depiction of a more extensive LIS than previously reconstructed for the Last Glacial Maximum. In addition, cosmogenic nuclide research has definitively shown that the LIS covered intensely weathered terrain along its deeply dissected eastern margin, where there were steep gradients in the effectiveness of basal erosion related to basal thermal regime. Cosmogenic nuclide applications, those already employed as well as those yet to be discovered, will undoubtedly continue to contribute to our ever-improving understanding of ice sheet history and dynamics.

Keywords: Laurentide Ice Sheet, cosmogenic nuclide, ice sheet history, ice sheet dynamics, Last Glacial Maximum.

INTRODUCTION

The history and dynamics of the Laurentide Ice Sheet (LIS) have been the focus of research for over a century (e.g., Tyrrell, 1898; Coleman, 1920; Flint, 1943). However, the maximum extent, basal ice dynamics, and pattern of retreat of the LIS during the last glacial cycle have been debated along many of its sectors, in particular in the eastern Arctic (e.g., Miller et al., 2002). The use of in situ–produced cosmogenic nuclides, in conjunction with radiocarbon dating, marine and lake coring efforts, and ice sheet modeling, has led to recent advances in understanding the history and dynamics of glaciers in general (e.g., Phillips et al., 1986; Gosse et al., 1995a) and the LIS in particular (e.g., Gosse

[†]E-mail: jbriner@buffalo.edu.
[‡]E-mail: john.gosse@dal.ca.
[§]E-mail: paul.bierman@uvm.edu.

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et al., 1995b; Bierman et al., 1999; Balco et al., 2002; Briner et al., 2003).

Progress toward understanding the history of the LIS is hampered by limited geochronological tools. Although many different and innovative dating techniques have been applied, radiocarbon dating traditionally has been the most useful and is the basis for much of our current understanding of LIS history during the Last Glacial Maximum (LGM) and deglaciation (Dyke et al., 2002). However, the general scarcity of organic materials associated with glacial deposits, as well as the lag time for vegetation to become established after deglaciation, has limited the application of radiocarbon dating in many areas. An added complication in many sectors of the LIS is the realization that cold-based ice can lead to the preservation of preglacial organic-rich surficial sediments (Davis et al., in press). It is becoming increasingly clear that while some areas beneath the LIS experienced intense erosion, some landscapes were only slightly modified during the last glacial cycle (e.g., Kleman and Hättestrand, 1999; Bierman et al., 2000; Dredge, 2000; Colgan et al., 2002; Jansson et al., 2003; Briner et al., 2003; Marquette et al., 2004; Staiger et al., 2005), complicating the interpretation of stratigraphic and geomorphic records of the last glaciation.

Cosmogenic exposure dating, based on the buildup of nuclides produced at and near Earth's surface by cosmic-ray bombardment, has recently been added to the geochronological toolbox. Over the past 20 yr, cosmogenic nuclides have filled a niche by making it possible to date directly glacial landforms (Phillips et al., 1986; Nishiizumi et al., 1989; Lal, 1991; Gosse et al., 1995a; Bierman et al., 1999; Briner et al., 2005). Over the last decade, cosmogenic exposure dating has contributed to updated reconstructions of the LIS during the LGM (Dyke et al., 2002; Miller et al., 2002), especially in regions where LGM ice extents have been debated, and contributed to the most recent overall LIS reconstruction (Dyke et al., 2002) (Fig. 1). Dating earlier advances and retreats of the LIS is hampered by the overriding of older deposits by younger ice and the limit of radiocarbon dating to <40 ka. In some cases, marine records distal to the ice sheet record evidence of earlier advances (e.g., Andrews et al., 1998). Recently, cosmogenic nuclide analysis of multiple till sheets (Balco et al., 2005a, 2005b, 2005c), as well as sampling of areas not covered by younger glacial advances (Steig et al., 1998; Kaplan and Miller, 2003), have yielded important chronologic data. In addition, applications that focus on cosmogenic nuclide inheritance (the carryover of cosmogenically produced nuclides from periods of exposure prior to the most recent period of exposure) have been used to address LIS dynamics. Such studies have improved our understanding of ice sheet behavior both in low-relief mid-continent settings (e.g., Colgan et al., 2002) and in the differentially weathered mountain landscapes that fringe eastern Canada (e.g., Bierman et al., 1999; Davis et al., 1999; Briner et al., in press).

In this paper, we review applications of cosmogenic nuclides that further the understanding of the history and dynamics of the LIS. Whereas Dyke et al. (2002) provide an up-to-date synthesis of the areal extent of the LIS during the LGM, we focus on how our understanding of both the process and history of the LIS has improved from cosmogenic nuclide studies. Although we do not provide a review of the extensive studies of marine records from the continental shelves and slopes, we show how cosmogenic

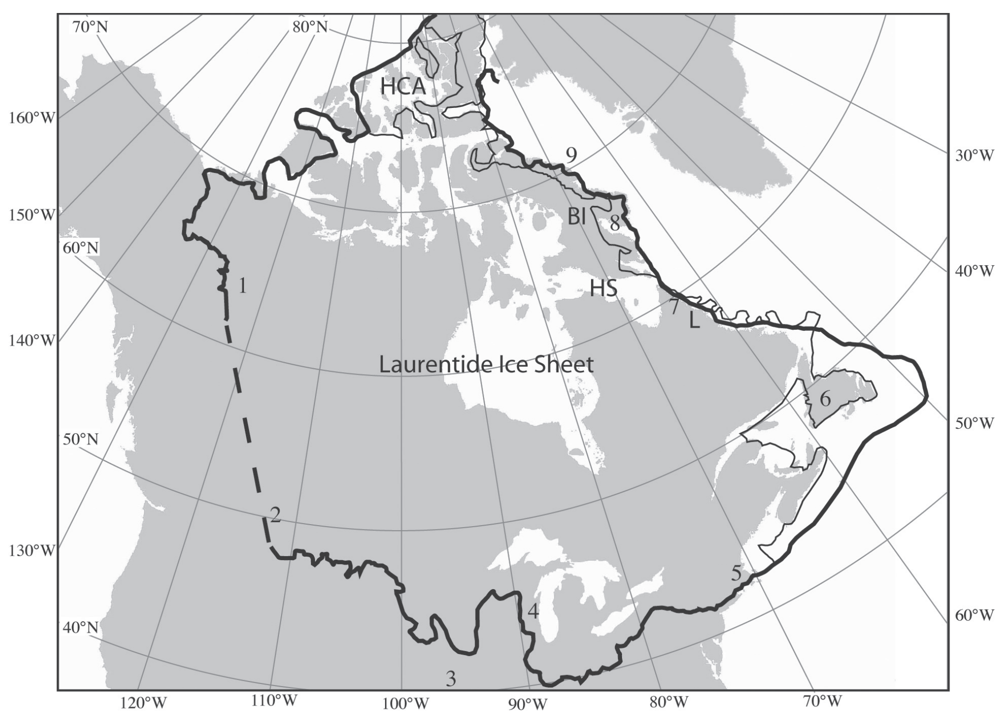


Figure 1. Last Glacial Maximum reconstruction of the Laurentide Ice Sheet (LIS) by Dyke and Prest (1987; thin line) and Dyke et al. (2002; thick line). BI—Baffin Island; HCA—high Canadian Arctic; HS—Hudson Strait; L—Labrador. Numbers refer to sites of cosmogenic nuclide applications on LIS studies. 1—Duk-Rodkin et al. (1996); 2—Jackson et al. (1997, 1999); 3—Balco et al. (2005b); 4—Colgan et al. (2002); 5—Balco et al. (2002); 6— Gosse et al. (1995b, 2006); 7—Clark et al. (2003), Marquette et al. (2004), Staiger et al. (2005); 8—Steig et al. (1998), Bierman et al. (1999), Marsella et al. (2000), Kaplan et al. (2001), Miller et al. (2002), Kaplan and Miller (2003); 9—Briner et al. (2003, 2005, in press), Davis et al. (in press).

nuclide research has complemented those studies and linked offshore and onshore deglacial chronologies. Following an overview of past and ongoing cosmogenic nuclide applications, we highlight the emerging strengths and challenges of using cosmogenic nuclides to understand ice sheets.

LAURENTIDE ICE SHEET BACKGROUND

The LIS played a dominant role in the climate system during the last glaciation (ca. 120–8 ka; Martinson et al., 1987). Gradually growing to the size of the present-day Antarctic Ice Sheet, perhaps in rapid spurts, and disappearing over a period of ~10 k.y., the LIS increased Earth's albedo, altered atmospheric circulation, sequestered 70–80 m of sea-level equivalent, and significantly altered ocean circulation on millennial timescales (e.g., Imbrie and Imbrie, 1980). Our most complete understanding of the LIS configuration is for the time period of the LGM (22–18 ka) and the subsequent deglaciation (e.g., Dyke et al., 2002).

Reconstructions of the LIS over the past 100 yr have ranged significantly, and often have been cast as minimum versus maximum paradigms. A paradigm shift occurred when Flint (1943) popularized an extensive LIS covering North America during the LGM. Flint's reconstruction had ice extending from the continental shelves in the north to the continental United States in the south. Flint's mode was conceptual, included a single ice dome over Hudson Bay during its maximum phase, and overlooked previous field-based work that depicted relatively restricted ice extent at high latitudes (e.g., Tyrrell, 1898; Coleman, 1920).

The next paradigm shift occurred in the 1960s and 1970s, when the first intensive field-based research was carried out along LIS margins in the north (e.g., Ives and Andrews, 1963; Løken, 1966; Andrews et al., 1970; Grant, 1977). These investigations supported a thinner and less extensive LIS than proposed in Flint's model (Fig. 2), and suggested that the LIS contained multiple domes (Prest et al., 1968; Bryson et al., 1969; Miller and Dyke, 1974; Grant, 1977). These conclusions were based on old radiocarbon ages and the assumption that weathered bedrock terrain indicated ice-free conditions during the LGM. Well into the minimum ice paradigm, some researchers continued to favor a maximum ice model, relying on theoretical ideas based on lessons from Antarctica and the assumption that weathered bedrock terrain could have been covered by ice during the LGM (Fig. 2) (Hughes et al., 1977; Sugden and Watts, 1977; Denton and Hughes, 1981).

Throughout the 1980s, the majority of field evidence continued to point toward relatively restricted ice margins (e.g., ice terminating at the heads of fiords and sounds; Dyke and Prest, 1987), and the controversy regarding the existence of an ice-free corridor between the LIS and the Cordilleran Ice Sheet (CIS) remained unresolved (e.g., Jackson, 1980; Liverman et al., 1989). In the eastern sector of the LIS, field observations and the radiocarbon chronology revealed a far more complicated history of ice cover than could be explained with LIS cover flowing solely from the west (Brookes, 1977; Grant, 1977). With the addition of subsequent offshore data (Stea et al., 1998; Piper and MacDonald, 2001), it seemed clear that a multidomal LIS covered the entire Atlantic provinces and Maine, or that there were peripheral ice caps over the Atlantic provinces.

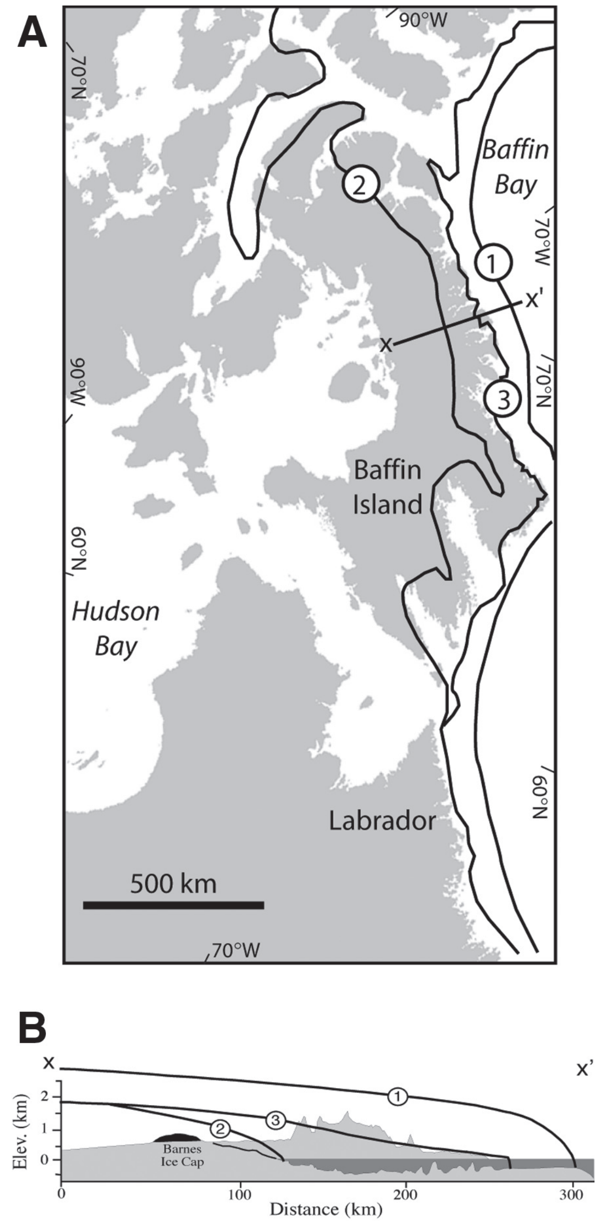


Figure 2. A: Map of eastern Canadian Arctic showing three Last Glacial Maximum reconstructions of the Laurentide Ice Sheet. 1—maximum extent representative of the Flint (1943) paradigm; 2—minimal extent from Dyke and Prest (1987); 3—most recent reconstruction of Dyke et al. (2002). B: Schematic cross section showing ice sheet profiles superposed on topographic profile for the landscape near x–x′ line in A.

Meanwhile, evidence was increasing for a highly dynamic LIS (Andrews and Miller, 1979; Andrews et al., 1985). Research on the Antarctic ice streams revealed that high domes at the center of ice sheets could be drained through low-gradient (~1–2 m/km), very fast-moving (~500 km/yr) ice streams that account for most of an ice sheet's discharge into adjacent seas (Bentley, 1987). Based on the Antarctic Ice Sheet as an analogue (Hughes et al., 1985), research was carried out along the former bed of the LIS, and indicated that it also had low-gradient outlet glaciers and ice streams where it flowed over soft sediments on land (e.g., Clark, 1994; Patterson, 1998) and in marine troughs (e.g., Alley and MacAyeal, 1994). In the North Atlantic deep sea, widespread layers of ice-rafted detritus (Heinrich layers) were found periodically throughout cores of marine sediments deposited during the last glacial cycle (Heinrich, 1988; Bond et al., 1992, 1993). Heinrich-type layers of detrital carbonate were also found in the Labrador Sea and in Baffin Bay (e.g., Andrews et al., 1998), and were traced to Hudson Strait (Andrews and Tedesco, 1992; Andrews et al., 1998; Grousset et al., 2000; Andrews and MacLean, 2003; Hemming and Hajdas, 2003). The combination of terrestrial, marine, and ice sheet modeling studies led to a new understanding of LIS behavior that was far more dynamic than previously envisioned (e.g., Alley and MacAyeal, 1994; Kaplan et al., 1999).

Continued examination of ice extent using new approaches and techniques gradually challenged the minimum LIS model and improved our understanding of ice dynamics (Fig. 2) (Jennings, 1993; Bierman et al., 1999; Marsella et al., 2000; Kaplan et al., 2001; Miller et al., 2002; Marquette et al., 2004). Between earlier (Dyke and Prest, 1987) and more recent compilations of LIS limits during the LGM (Dyke et al., 2002), reconstructed ice margins were expanded in several regions in eastern Canada as a result of both terrestrial (lake sediment and cosmogenic nuclide exposure dating) and marine (coring, imaging) research (e.g., Josenhans et al., 1986; Clark and Josenhans, 1990; Jennings, 1993). Analysis of remotely sensed data revealed mega-scale bedforms across the former footprint of the LIS, and indicated remarkable variation in past ice flow patterns (Boulton and Clark, 1990; Clark, 1997; Veillette et al., 1999; Stokes and Clark, 2002). In Labrador, Klassen's (1994) interpretation of till geochemistry and clast provenance data revealed more than ten large-scale (>200 km) crosscutting flow directions, indicating complex paleoglacier dynamics over the region.

Much of the variation in the LIS ice flow record was thought to have occurred during the last glacial cycle, and its discovery led to three important conclusions: (1) LIS domes that persisted throughout the last glacial cycle were not only deglacial phenomena, but existed and shifted their location throughout the last glacial cycle, (2) the shifting of domes was likely related to ice stream activity (e.g., Stokes and Clark, 2001; Jansson et al., 2003), and (3) in some places erosion was not substantial enough to remove prior bedforms, indicating minimal glacial erosion and landscape preservation near ice sheet centers (Kleman and Hättestrand, 1999). Several studies showed that large portions of former ice sheets were frozen to the bed and preserved ancient (preglacial) terrain upon deglaciation (e.g., Shilts et al., 1979; Dyke, 1993; Kleman, 1994; Dredge, 2000).

COSMOGENIC NUCLIDE BACKGROUND

Isotopes produced in situ at Earth's surface (e.g., the radionuclides ^{36}Cl, ^{26}Al, ^{14}C, ^{10}Be, and the noble gases ^{21}Ne and ^{3}He) via bombardment by cosmic rays are now used routinely in geomorphic studies, including ice sheet research. Because these isotopes are mostly produced in the upper several meters of Earth's surface (Lal and Peters, 1967), a thickness that is readily influenced by glacial erosion, ice sheet processes and their timing can be constrained. Readers are referred to recent comprehensive review papers on cosmogenic nuclide systematics and applications for information on the method (Gosse and Phillips, 2001; Cockburn and Summerfield, 2004).

Cosmogenic nuclides have been used to address LIS history and dynamics in three main ways. First, cosmogenic nuclide exposure dating (Gosse and Phillips, 2001, and references therein) is used to constrain the timing of deglaciation by dating the deposition of erratics and moraine boulders and the exposure of ice-sculpted bedrock surfaces. A second application involves comparing measured nuclide concentrations to independent ages. In this approach, the presence or absence of inheritance (e.g., Briner and Swanson, 1998) is used to address the efficiency of glacial erosion and to elucidate the spatial patterns of erosive versus nonerosive ice. A third application is based on measuring pairs of cosmogenic nuclides with different half-lives in shielded bedrock surfaces or buried sediments on long (>100 k.y.) timescales. This multiple-nuclide approach allows nonunique inferences about surface exposure, burial, and erosion histories over time.

APPLICATIONS

Chronology: Western and Southern LIS Margins

Several cosmogenic nuclide studies over the last decade have dated the timing of LIS deglaciation (Fig. 1). Most of these studies provide age information in areas with previously scant chronology and have made substantial contributions toward solving historical debates concerning the extent of the LIS during the LGM. At the northwestern margin of the LIS (Fig. 1), Duk-Rodkin et al. (1996) report four ^{36}Cl ages that constrain the timing of deglaciation from the LGM advance to 20–28 ka, and two ^{36}Cl ages from a recessional limit to ca. 19 ka. Along the southwestern sector (Fig. 1), Jackson et al. (1997, 1999) provided 19 ^{36}Cl ages from erratics and moraine boulders in an area where the age of the most recent LIS and CIS convergence had remained controversial. All but one of the samples yielded ages between ca. 12 and ca. 18 ka (one anomalously old age is suspected to have resulted from inheritance), indicating an absence of an ice-free corridor between the LIS and CIS during the LGM (Jackson et al., 1997, 1999). At the southeastern margin, where the LIS terminated along the present coast of the northeastern United States (Fig. 1), Balco et al. (2002) provide boulder ^{10}Be and ^{26}Al ages from a terminal moraine and a stratigraphically younger end moraine, respectively. The age of the terminal moraine is 23.2

± 0.5 ka (n = 13); the younger moraine is 18.8 ± 0.4 ka (n = 10). Farther north, Gosse et al. (2006) dated boulders to constrain the timing of deglaciation at 13.5 ± 0.4 ka (n = 4) on the Saint John's Highlands, Great Northern Peninsula of Newfoundland, and 20.9 ± 3.0 ka on a boulder on the summit of Big Level. Both localities were previously believed to be ice-free "nunataks" during at least the last and penultimate glaciations, if not the entire Quaternary (Grant, 1977). These ages helped spawn new interpretations from other regions in western Newfoundland that were also thought to have been ice-free (Brookes, 1977).

Chronology: Northeastern Margins

Several studies have taken place along the northeastern sector of the LIS, an area with historically controversial LGM reconstructions. The glacial history of the Torngat Mountains, Labrador (Fig. 1) was intermittently studied over the past century (e.g., Daly, 1902; Coleman, 1920; Odell, 1933; Ives, 1957, 1978; Clark, 1988; Bell et al., 1989). Owing to the difficulty of access and scale of the range, most studies concentrated in areas with the best-preserved record or where coastal inlets provided access. Most of this mountain range (and the Arctic regions discussed next) is above the tree line, and radiocarbon chronologies are mostly limited to sediments below the marine limit. The principal contributions in Labrador from cosmogenic nuclide studies are the dating of LGM and recessional moraines that could never be dated previously (Clark et al., 2003; Marquette et al., 2004). The prominent Saglek moraine system was shown to consist of two or more components, with an outer ridge dating in the range of 25–18 ka (Marquette et al., 2004), and an inner ridge dating from 13.5 to 11 ka (Clark et al., 2003; Marquette et al., 2004). This new dating built on the only previous age on the Saglek moraine, which was a basal lake sediment date at Square Pond along the outermost and highest moraine ridge (Clark et al., 1989). Younger moraines higher in the fiord and in cirques have been dated to trace the deglacial history through the Holocene (Marquette et al., 2004). However, it was the ubiquitous lack of moraines (with some exceptions in the Nachvak Fiord region) (Bell et al., 1989) for the older glaciations that caused earlier workers to interpret the coastal highlands of the Torngat Mountains to be ice-free (e.g., Koroksoak Zone of Ives, 1957, 1978) and to interpret altitudinally separable zones of differential weathering as trimlines indicating the vertical limit of penultimate glaciations. In lieu of moraines, Marquette et al. (2004) dated boulders exposed on local promontories. The selected boulders were often only subtly different from the underlying bedrock (e.g., in color, grain size, or mineralogy); however, in most instances the boulders were from the Archean gneisses of the Torngat Mountains, which led previous authors to preclude them as erratics. The majority of boulders dated to ca. 11.7 ka (n = 14; Marquette et al., 2004) and were interpreted to indicate that ice persisted through the Younger Dryas chronozone even on the broad summits that were previously interpreted as nunataks. The lack of boulders on the highest steep peaks may indicate they projected through the LIS as nunataks.

Several cosmogenic nuclide studies have shown that glacial features on Cumberland Peninsula, Baffin Island (Fig. 1), previously believed to be pre-LGM in age are in fact LGM features (Steig et al., 1998; Marsella et al., 2000; Kaplan et al., 2001; Miller et al., 2002; Kaplan and Miller, 2003). These studies favor a larger LGM ice extent than previously depicted in the minimum ice model, supporting marine core findings (e.g., Jennings, 1993). On northern Cumberland Peninsula, Steig et al. (1998) provided six exposure ages from surface clasts from three lateral moraine segments. The ages increase on morphostratigraphically older moraines, from 13.4 ± 3.0 ka (n = 3) to 20.6 ± 0.6 ka (n = 1) to ca. 35.7 ± 1.1 ka (n = 2). In the uplands above the highest moraine, bedrock tors have ages of >50 and >65 ka, and lake basins have sediment preserved from prior to the LGM (Steig et al., 1998; Wolfe et al., 2001).

On southern Cumberland Peninsula, the prominent Duval moraines, previously ascribed to pre-LGM based on radiocarbon ages and relative weathering criteria (Dyke, 1979), were part of a comprehensive exposure dating campaign (n = 47) that revealed their LGM age (Marsella et al., 2000). The age interpretation is not without complications, however, even considering the large sample set (n = 17) that was obtained on the Duval and associated recessional moraines. There is a clear bimodal distribution of the ages centered at ca. 22 and ca. 10 ka, which also exists outside of the Duval limit, suggesting that the outer LGM ice margin does not correspond to a moraine. In addition, the 25 ages that Kaplan et al. (2001) reported from scoured bedrock in adjacent Cumberland Sound support LGM ice occupation of the sound to the continental shelf with deglaciation occurring ca. 11–12 ka. However, many of the bedrock samples contain inheritance (Kaplan and Miller, 2003) indicating limited glacial erosion. Finally, six exposure ages from eastern Cumberland Peninsula were reported for the first time in Miller et al.'s (2002) synthesis of the LIS on Baffin Island. Similar to the Steig et al. (1998) study, five of the ages come from a flight of three lateral moraine segments bordering Sunneshine Fiord, with ages of 7.6 ± 0.7 ka (n = 2) to 22.0 ± 2.3 ka (n = 1) to 35.4 ± 3.5 ka (n = 2). An upland bedrock sample is older than 77 ka. The youngest ages are in contradiction with an ocean sediment core taken within the moraines that has a basal age of ca. 14 ka, but appear to be generally compatible with the northern Cumberland Peninsula ages (Miller et al., 2002).

Briner et al. (2005) obtained exposure ages from 103 erratics on the Clyde Foreland to determine the LGM ice limit on northeastern Baffin Island. The foreland was subdivided into zones covered by erosive ice (dominated by moraines and an overall scoured appearance) and nonerosive ice (dominated by lateral meltwater channels and nonglacial topography). Exposure ages from both zones are consistent with LGM ice cover of the foreland, but only a subset of the ages from the unscoured zone fall within the LGM/deglacial period, indicating an overall high amount of inheritance. Davis et al. (in press) obtained 13 exposure ages on erratics on and beyond the raised Aston Delta (Løken, 1966), ~50 km to the south of the Clyde Foreland. Because the intact delta is radiocarbon dated (>54 ka) to prior to the LGM, the Aston Delta became a cornerstone for limiting LGM ice to fiord and sound heads. The 14.1 ± 0.8 ka average exposure age based on seven erratics that constitute the youngest age cluster reveals that a nonerosive LIS overran the delta during the LGM (Davis et al., in press). These studies on northeastern Baffin Island, together with the exposure ages from Cumberland Peninsula, clearly illustrate the complicated nature of exposure dating in terrains covered by minimally erosive ice.

Cosmogenic nuclides have been used in other applications aimed at understanding the LIS with mixed success. Erratics from northernmost Baffin Island have ^{10}Be and ^{26}Al ages consistent with restricted LGM ice, contradicting a growing body of evidence from elsewhere; however, the ages are difficult to place in context or evaluate as they have only appeared in one abstract (McCuaig et al., 1994). Raised shorelines provide important indications of the history of ice thickness and rate of deglaciation (Walcott, 1970). Emergence curves reveal the half response time of different regions, and provide insights into mantle rheology (Peltier, 1996). In arctic Canada, shoreline emergence curves have been reconstructed from radiocarbon-dated driftwood and marine and land fauna (Dyke et al., 1992). Uncertainty in the marine radiocarbon reservoir effects and reworking of wood and shell material often limit the accuracy and precision of emergence curves. Cosmogenic nuclide dating of shorelines was done first on Prescott Island in the central Arctic (Gosse et al., 1998). Ages on boulders (n = 6) that arose from the reworking of LIS till on beaches from modern to 120 masl allowed the construction of emergence curves indistinguishable from the radiocarbon-dated (n = 41) emergence history of Dyke et al. (1992) (Fig. 3). However, shoreline cosmogenic nuclide ages from cobbles, pebbles, and plucked bedrock surfaces (n = 16) typically yielded ages older than the radiocarbon data, probably due to nuclide inheritance.

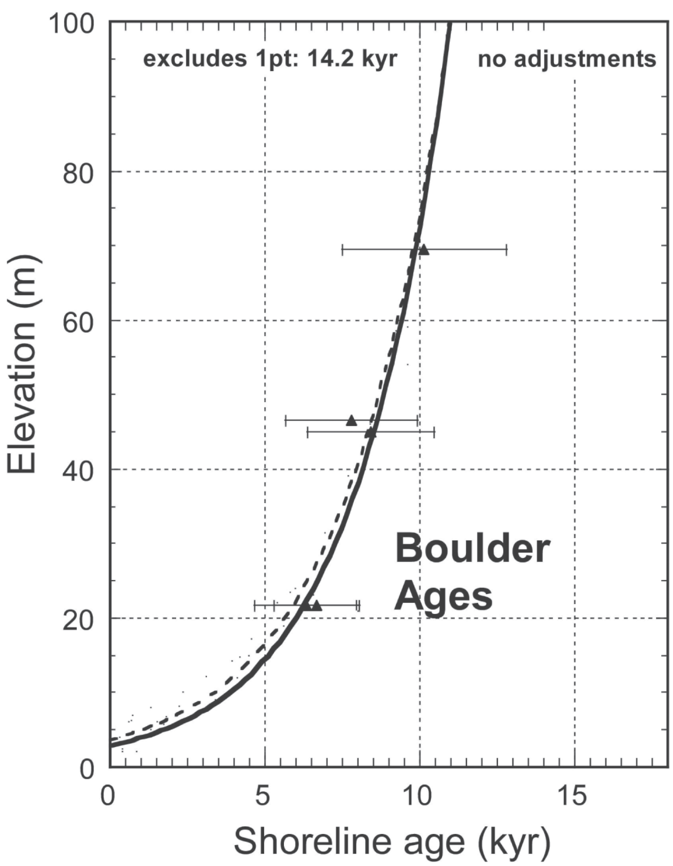


Figure 3. ^{10}Be ages on boulders on beaches of Prescott Island, central Arctic. Ages are not corrected for small effects of snow cover, erosion, or changes in production rate due to uplift. One age (14.2 ka) is not plotted and is considered an outlier based on the regional deglacial history according to Dyke et al. (1992). Errors are 1σ on AMS precisions. Solid curve is exponential fit to ^{10}Be ages. Dashed curve is driftwood-based radiocarbon-dated shoreline emergence curve for adjacent Prince of Wales Island (Dyke et al., 1992).

Ice Sheet Dynamics

Cosmogenic nuclides are also used to reconstruct spatial patterns of glacial erosion by the LIS. The origin of differentially weathered mountain landscapes has led to historically contrasting views on ice sheet extent across the Northern Hemisphere. While some workers have argued that highly weathered uplands persisted as nunataks during the last glaciation (e.g., Ives, 1957, 1978; Grant, 1977; Nesje and Dahl, 1990; Steig et al., 1998; Ballantyne, 1998; Rae et al., 2004), others have suggested that different “weathering zones” (Pheasant and Andrews, 1973; Boyer and Pheasant, 1974; Ives, 1978) represent different basal thermal regimes, hence differential glacial erosion by an overriding LGM ice sheet (Sugden, 1977; Sugden and Watts, 1977; Hall and Sugden, 1987; Bierman et al., 2001; Briner et al., 2003; Hall and Glasser, 2003; André, 2004; Marquette et al., 2004; Staiger et al., 2005; Gosse et al., 2006). Until the application of cosmogenic nuclides to these landscapes, their history and relation to ice sheet extent remained enigmatic. Cosmogenic nuclide data from differentially weathered mountain landscapes have several important implications for interpreting nunataks, trimlines, perched erratics, ice sheet thickness, ice sheet extent, spatial patterns of basal thermal regimes and glacial erosion, and ultimately ice sheet dynamics. Thus, all of these topics are covered in this section.

Differentially weathered mountain landscapes have been examined in several areas along the eastern LIS. Several samples from the Marsella et al. (2000) study address differentially weathered landscapes. For example, the exposure ages of erratics both above and below the prominent trimline at the Duval moraines yield the same age distribution, suggesting that the trimline does not represent the LGM ice limit. In addition, Bierman et al. (2001) report a ca. 9 ka upland erratic resting adjacent to >100 ka highly weathered bedrock, indicating the emplacement of the erratic by cold-based ice that did not erode the bedrock. Since the investigations on Cumberland Peninsula and in Newfoundland, more samples have been collected and analyzed both from Baffin Island and from Labrador. On northeastern Baffin Island, Briner et al. (2003) reported three deglacial-aged erratics perched on bedrock surfaces (Fig. 4) that have much older exposure ages (older than 60 ka); these data mandate cold-based LIS ice cover on highly weathered interfiord uplands during the LGM. Following their initial study, Briner et al. (in press) obtained cosmogenic nuclide measurements from 27 erratics perched in upland weathered terrain and 33 bedrock samples from three different weathering zones across four fiords on northeastern Baffin Island. These data confirm earlier hypotheses of upland glacierization during the LGM (e.g., Sugden and Watts, 1977; Sugden, 1977), and provide new information on patterns of glacial erosion of a fiord landscape. For example, ^{10}Be and ^{26}Al concentrations increase and their ratios decrease with elevation from fiords to interfiord uplands (Briner et al., in press). The data indicate that significant glacial erosion (>2 m) occurred in fiords and valleys, between one and two meters of erosion occurred at intermediate elevations, and negligible erosion occurred at the highest elevations during the last glaciation. This pattern of erosion also existed prior to the LGM, as revealed by ^{26}Al/^{10}Be ratios, which provide information on long-term exposure, burial, and glacial erosion histories (see below).

Cosmogenic nuclide measurements on bedrock in the Torngat Mountains, Labrador (Fig. 1), show an increasing trend in concentration with increasing elevation (Staiger et al., 2005). Bedrock in the valleys has cosmogenic nuclide concentrations equivalent to adjacent boulders, whereas bedrock ages are ca. 20–90 ka in the intermediate weathering zone and ca. 80–300 ka in the highly weathered zone. Because ice covered all but the highest peaks, as recently as 11 ka, Staiger et al. (2005) proposed that the ice eroded bedrock more deeply at low elevations than on higher summit plateaus, in accordance with changes in basal thermal regime. The interpretation that erosion rates vary beneath polythermal ice is supported by soils (Marquette et al., 2004) and numerical model simulations of basal sliding and hydrology of the LIS and local ice caps in Labrador (Staiger et al., 2005). Measurements of ^{10}Be inventories in middle Holocene glaciolacustrine deltaic sediment in north-central Baffin Island also reveal a large inheritance component (Gosse et al., 2005). If the deltaic sand ^{10}Be concentrations were interpreted as ages, they would correspond to exposures older than 30 ka. This indicates that even in the glaciofluvial system that fed the delta, most of the sediment is not sourced from meters below the surface, but instead from till and bedrock that has not been significantly eroded by the last ice cover.

A study from the southern margin of the LIS also indicates the spatial variability of glacial erosion. Colgan et al. (2002) provide cosmogenic nuclide measurements on 16 LIS-sculpted bedrock samples near the margin of the Green Bay lobe. A significant amount of inheritance and sample-to-sample variability was found in samples (n = 7) that were collected from erosion-resistant lithologies in low-lying areas close to the LGM margin. In contrast, samples collected farther from the ice margin gave tightly clustered model ages consistent with extensive, preexisting radiocarbon estimates for the age of deglaciation. Combined with studies from arctic terrains (e.g., Bierman et al., 1999; Briner et al., 2003, 2005, in press; Marquette et al., 2004; Davis et al., in press), these data highlight the spatial variability of glacial erosion.

Cosmogenic Nuclide Ratios

In some cases, cosmogenic nuclides have been used to reconstruct the long-term history of the LIS by exploiting the faster decay of ^{26}Al ($t_{1/2}$ = 700 k.y.) with respect to ^{10}Be ($t_{1/2}$ = 1.5 m.y.; Lal, 1991; Bierman et al., 1999; Fabel and Harbor, 1999). This isotopic disequilibrium can be used to detect periods of prolonged shielding from cosmic rays following initial exposure. Prolonged burial is implied when the measured ratio of ^{26}Al/^{10}Be is lower than that expected from the measured concentration of ^{10}Be.

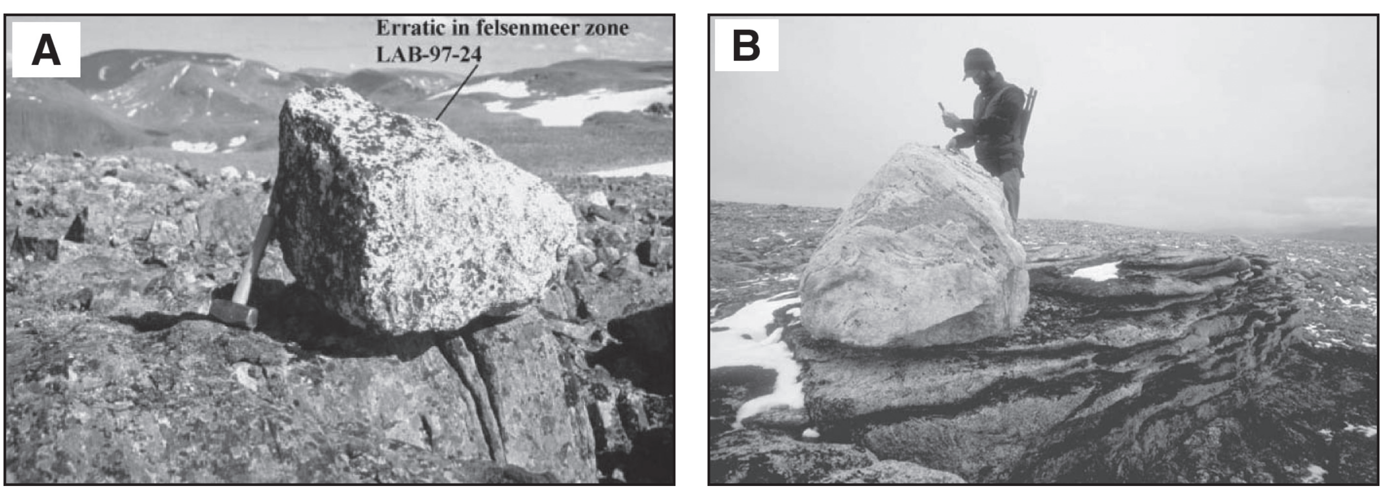


Figure 4. Erratics perched on weathered bedrock from Labrador (A) and Baffin Island (B).

Gosse et al. (1993, 1995b) and Bierman et al. (1999) first applied $^{26}Al/^{10}Be$ data in glacial terrains by sampling upland tors along the eastern margin of the LIS. In Newfoundland, tor samples recorded a minimum of ~100 k.y. of burial, indicating that they had been covered by glacier ice, perhaps intermittently, but not significantly eroded, for that duration (Gosse et al., 1993, 1995b, 2006). The $^{26}Al/^{10}Be$ ratio for the least weathered (lowest) zone is 5.9 ± 0.5 (n = 1), which is the same as the ratio expected for a continuously exposed surface in the late Pleistocene (~6.0 ± 0.1; Gosse and Phillips, 2001). On the other hand, the ratios of tor-like bedrock knobs in the most weathered (highest) zone are substantially lower at 4.4 ± 0.4 and 5.1 ± 0.2. These ratios show that at least some of the bedrock surfaces within the highest weathering zone have an exposure history that was substantially interrupted by prolonged shielding. Seven tor samples from Cumberland Peninsula on Baffin Island have ^{26}Al and ^{10}Be values consistent with at least 550 k.y. of surface history, including at least 420 k.y. of burial (Bierman et al., 1999). These were some of the first data demonstrating nonerosive cold-based ice cover of weathered uplands, and were suggestive of LGM ice cover, a hypothesis supported by later data from a nearby erratic (Bierman et al., 2001).

Marquette et al. (2004) and Briner et al. (in press) provide additional ratio data for Labrador and northeastern Baffin Island, respectively. In Labrador, $^{26}Al/^{10}Be$ data from four bedrock samples representing all three weathering zones reveal a lack of long-term burial in the recently eroded zone (n = 1), and increasing burial with elevation from the intermediately weathered (~80 k.y.; n = 1) to highly weathered (~175 k.y.; n = 2) zones. Briner et al. (in press) found similar results, showing no long-term burial in recently sculpted (n = 6) or intermediately weathered (n = 7) bedrock, but an average of ~300 k.y. of burial in upland tors (n = 10).

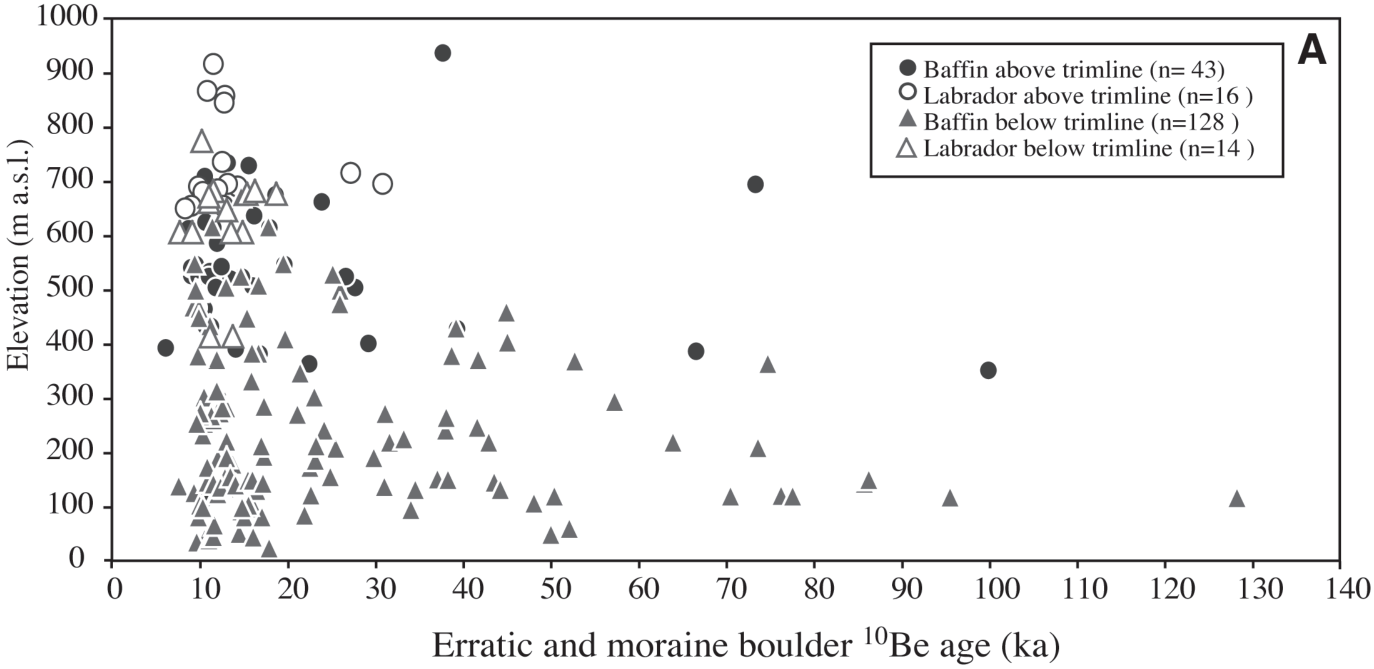
In midwestern North America, Bierman et al. (1999) used the discordance of $^{26}Al/^{10}Be$ ratios to place limits of the age of four Sioux Quartzite outcrops exposed outside the LGM margin. The exceptionally hard, striated bedrock had $^{26}Al/^{10}Be$ ratios varying from 4.3 to 5.2. Although there is no unique interpretation for these data, they allowed Bierman et al. (1999) to set limits on the exposure history and suggest that the bedrock was last covered by ice at least half a million years ago. Balco et al. (2005a, 2005b) have made recent progress toward extending the use of cosmogenic nuclides to LIS deposits farther back in time by developing a technique that utilizes ^{10}Be and ^{26}Al concentrations and ratios in buried tills in the midwestern United States. The ages of several early and middle Pleistocene tills have been constrained (e.g., Balco et al., 2005b), and relatively abundant inheritance in some tills allowed Balco et al. (2005c) to constrain the timing of the oldest maximum ice sheet advances (ca. 2.4 Ma) that overran and reworked pre-Quaternary regolith that had high cosmogenic nuclide concentrations.

EMERGING STRENGTHS AND CHALLENGES

After a decade of cosmogenic nuclide applications to LIS research, we have an improved understanding of LIS chronology, LGM ice extent, and ice sheet dynamics. At the same time, we have a much better appreciation of the complexities associated with cosmogenic nuclide applications, especially those involved with using exposure dating in landscapes formerly covered by cold-based ice.

Because exposure dating studies are complicated by landform instability and inheritance, a relatively large number of samples has the potential to provide a more precise chronology and a more robust means by which to identify outliers. In landscapes covered by cold-based ice, inheritance is prevalent and spatially complicated (Fig. 5). Davis et al. (1999) and Colgan et al. (2002) explicitly deal with inheritance, and together provide some guidelines on minimizing its effects. Of 16 samples dated in the glacially scoured terrain at Cumberland Sound by Kaplan and Miller (2003), at least seven contain nuclides inherited from previous periods of surface or near-surface exposure. Both Marsella et al. (2000) and Briner et al. (2005) report large numbers of moraine and erratic boulders that appear to contain inherited nuclides (50% of Duval moraine boulders, 60% of Clyde Foreland erratics); these studies took place in terrains partially covered by cold-based ice. Boulders with inherited nuclides were either deposited during the most recent ice sheet advance already carrying that inheritance, or deposited on the landscape during a prior advance, then received exposure that was subsequently preserved beneath cold-based ice of the youngest advance. Although it is difficult to separate these scenarios, a cluster of samples with similar inheritance has been interpreted to indicate that boulders can survive beneath younger advances (Marsella et al., 2000; Briner et al., 2005). Davis et al. (in press) report the preservation of a pre-LGM delta (the Aston Delta), along with associated beaches and meltwater channels, beneath cold-based LGM ice on Baffin Island. This finding supports the notion that cold-based ice can overrun preexisting moraines, erratics, and unconsolidated deposits with minimal disturbance. Similarly, clasts isolated from tills in interior Baffin Island contain abundant inheritance, supporting minimal glacial erosion there (Staiger et al., 2004). Inheritance is clearly present and even prevalent within the LGM extent of the LIS (Fig. 5).

Cosmogenic nuclide studies that have taken place in differentially weathered mountain landscapes explicitly address historically debated LGM ice sheet reconstructions. Nuclide concentrations measured in bedrock confirm that weathering zones represent different surface exposure durations, supporting relative weathering studies. The interpretation that differential ice sheet erosion (Fig. 6) gave rise to differentially weathered mountain landscapes is supported by the abundance of bedrock surfaces within the LGM ice limit that have pre-LGM cosmogenic nuclide concentrations and the presence of perched erratics on weathered uplands (Fig. 4). Because ^{10}Be and ^{26}Al half-lives are too long to detect recent burial, $^{26}Al/^{10}Be$ data only provide information on long-term ice sheet burial history. On the other hand, exposure ages from perched erratics can constrain the age of the most recent period of upland glacierization. Dating upland erratics has the highest potential to address LGM ice sheet reconstructions



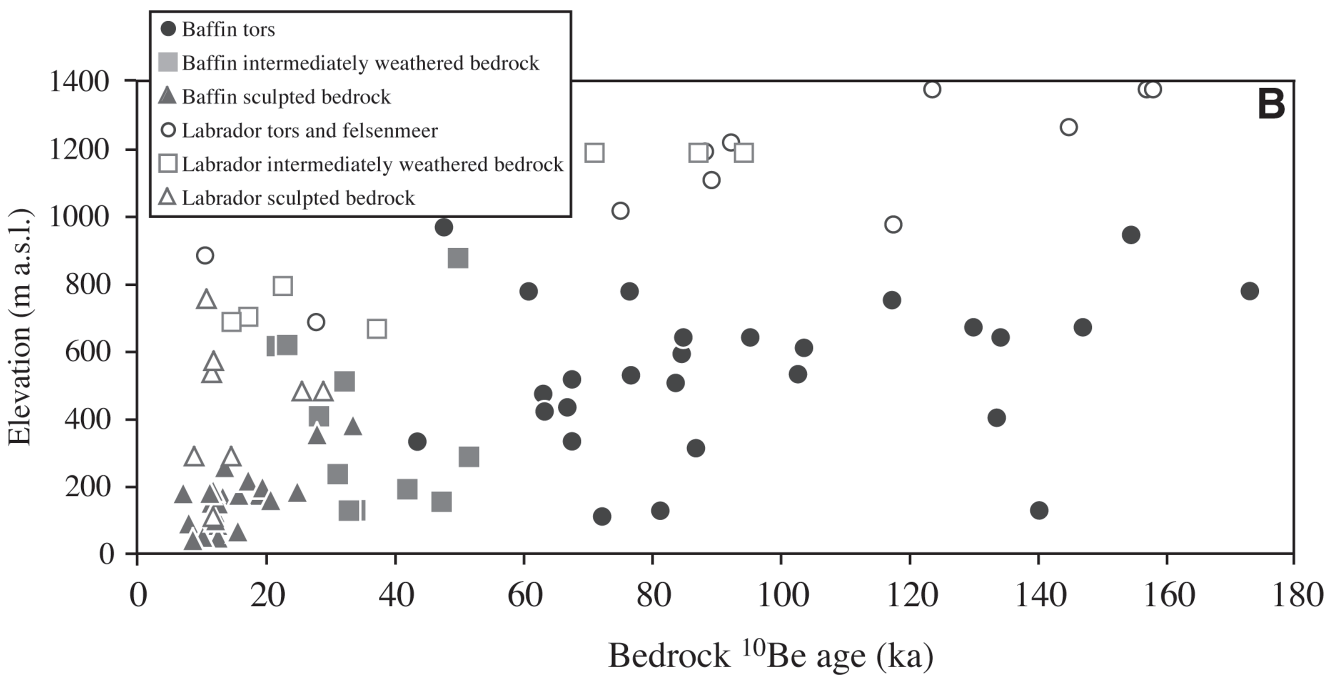


Figure 5. Erratic and moraine boulder (A) and bedrock (B) cosmogenic nuclide ages from the published literature from Labrador and Baffin Island. All ages have been recalculated using the same production rate (5.1 g atoms^{-1} yr^{-1}). A: All samples are interpreted to be from within the LGM ice limit. Samples from above and below regional trimlines have pre-LGM cosmogenic nuclide ages, indicating the abundance of inheritance. B: Cosmogenic nuclide ages are subdivided into sculpted, intermediately weathered, and tor samples, revealing increasing inheritance with surface type/elevation. Because the boundaries (trimlines) between surface type dip seaward, absolute elevation has only a moderate correlation with cosmogenic nuclide age.

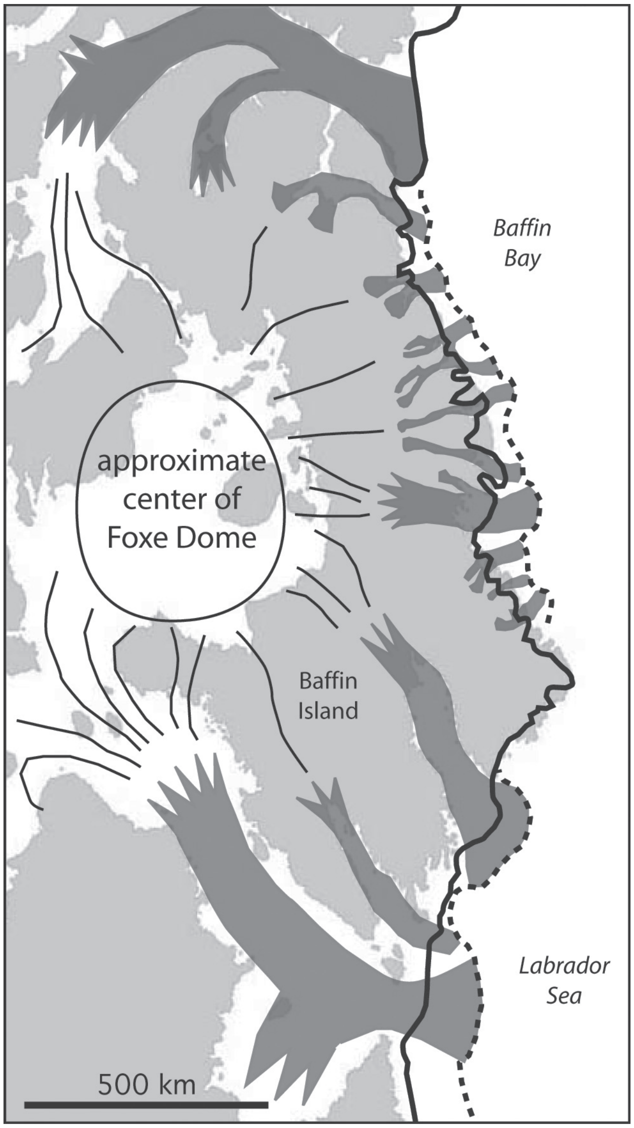


Figure 6. Northeastern sector (Foxe Dome) of the Laurentide Ice Sheet showing the most recently reconstructed Last Glacial Maximum ice limit (thick black line) from Dyke et al. (2002) and hypothesized Last Glacial Maximum ice limit (dashed lines) from Briner et al. (in press). The thin black lines represent ice flow, and the gray areas represent the hypothesized locations of ice streams, whose flow pattern gave rise to differentially weathered mountain landscapes.

in differentially weathered mountain landscapes, but because nuclides from prior exposure periods remain in many of these boulders, reliably identifying LGM ice presence requires dating many upland erratics.

In most cases, it has been the combination of cosmogenic nuclide data with other information that has provided new information on LIS history and dynamics. For example, relative weathering parameters (soils and bedrock characteristics) from different elevations in mountain landscapes provide an essential context for interpreting the complex pattern of cosmogenic nuclide concentrations. In other cases, the preservation of pre-LGM lake sediments in lake basins (e.g., Wolfe et al., 2000) or lateral meltwater channels has provided independent evidence for cold-based ice (e.g., Briner et al., 2005; Davis et al., in press). Studies in other parts of the world have documented the glacial modification of highly weathered features (e.g., Hall and Glasser, 2003; André, 2004) and glacial erosion by cold-based ice (e.g., Cuffey et al., 2000; Atkins et al., 2002). Combining this type of detailed research with cosmogenic nuclide measurements will add to our growing understanding of ice sheet dynamics.

CONCLUSIONS

The application of cosmogenic nuclides has made substantial contributions toward LIS extent and dynamics. Exposure dating has constrained the age of LIS marginal deposits that previously lacked chronologic control, and has contributed to the resolution of long-standing debates in the Cordillera, eastern Canadian Arctic, and the Maritime provinces. Sediment burial dating has allowed us to date ice sheet deposits much farther back in time than surface exposure techniques. Cosmogenic nuclide studies have proven to be useful in studying LIS dynamics, leading to reinterpretations of trimlines, weathering zones, and enigmatic perched erratics, as well as the subsequent reconstruction of spatial patterns of basal thermal regimes and subglacial erosion. However, many questions remain. For example, although there is now general understanding of LIS dynamics in fiord landscapes, studies have taken place in relatively few regions and it is uncertain whether cosmogenic nuclide results to date can be extrapolated to less-studied regions. Our understanding of glacial erosion processes will likely improve as cosmogenic nuclide concentrations are measured in more samples. In particular, more data should help constrain the frequency and spatial distribution of inheritance from prior exposure periods, at both the local and regional scales. Cosmogenic nuclides also have potential to add to our understanding of ice sheet dynamics in interior regions of the LIS. With the future application of cosmogenic ^{14}C in quartz, difficulties associated with inheritance will be minimized. Continuing improvements in reducing the effect of other sources of error (e.g., snow cover, production rates, moraine erosion) should result in a significantly improved history of the LIS over the past half million years.

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REFERENCES CITED

Alley, R.B., and MacAyeal, D.R., 1994, Ice-rafted debris associated with binge purge oscillations of the Laurentide Ice Sheet: Paleoceanography, v. 9, p. 503–511, doi: 10.1029/94PA01008.

André, M.F., 2004, The geomorphic impact of glaciers as indicated by tors in North Sweden (Aurivaara, 68 degrees N): Geomorphology, v. 57, p. 403–421, doi: 10.1016/S0169-555X(03)00182-X.

Andrews, J.T., and MacLean, B., 2003, Hudson Strait ice streams: A review of stratigraphy, chronology and links with North Atlantic Heinrich events: Boreas, v. 32, p. 4–17, doi: 10.1080/03009480310001010.

Andrews, J.T., and Miller, G.H., 1979, Glacial erosion and ice sheet divides, northeastern Laurentide Ice Sheet, on the basis of the distribution of limestone erratics: Geology, v. 7, p. 592–596, doi: 10.1130/0091-7613(1979)7<592:GEAISD>2.0.CO;2.

Andrews, J.T., and Tedesco, K., 1992, Detrital carbonate rich sediments, northwestern Labrador Sea—Implications for ice-sheet dynamics and iceberg rafting (Heinrich) events in the North Atlantic: Geology, v. 20, p. 1087–1090, doi: 10.1130/0091-7613(1992)020<1087:DCRSNL>2.3.CO;2.

Andrews, J.T., Buckley, J.T., and England, J.H., 1970, Late-glacial chronology and glacio-isostatic recovery, Home Bay, East Baffin Island, Canada: Geological Society of America Bulletin, v. 81, p. 1123–1148.

Andrews, J.T., Clark, P.U., and Stravers, J.A., 1985, The pattern of glacial erosion across the eastern Canadian Arctic, *in* Andrews, J.T., ed., Quaternary environments: Eastern Canadian Arctic, Baffin Bay, and West Greenland: Winchester, Allen and Unwin, p. 62–92.

Andrews, J.T., Kirby, M.E., Aksu, A., Barber, D.C., and Meese, D., 1998, Late Quaternary detrital carbonate (DC-) layers in Baffin Bay marine sediments (67 degrees-74 degrees N): Correlation with Heinrich events in the North Atlantic?: Quaternary Science Reviews, v. 17, p. 1125–1137, doi: 10.1016/S0277-3791(97)00064-4.

Atkins, C.B., Barrett, P.J., and Hicock, S.R., 2002, Cold glaciers erode and deposit: Evidence from Alan Hills, Antarctica: Geology, v. 30, p. 659–662, doi: 10.1130/0091-7613(2002)030<0659:CGEADE>2.0.CO;2.

Balco, G., Stone, J.O.H., Porter, S.C., and Caffee, M.W., 2002, Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: Quaternary Science Reviews, v. 21, no. 20-22, p. 2127–2135, doi: 10.1016/S0277-3791(02)00085-9.

Balco, G., Stone, J., Jennings, C., 2005a, Dating Plio-Pleistocene glacial sediments using the cosmic-ray-produced radionuclides ^{10}Be and ^{26}Al: American Journal of Science, v. 305, no. 1, p. 1–41.

Balco, G., Stone, J.O.H., and Mason, J.A., 2005b, Numerical ages for Plio-Pleistocene glacial sediment sequences by ^{26}Al/^{10}Be dating of quartz in buried paleosols: Earth and Planetary Science Letters, v. 232, p. 179–191, doi: 10.1016/j.epsl.2004.12.013.

Balco, G., Rovey, C.W., and Stone, J.O.H., 2005c, The first glacial maximum in North America: Science, v. 307, p. 222, doi: 10.1126/science.1103406.

Ballantyne, C.K., 1998, Age and significance of mountain-top detritus: Permafrost and Periglacial Processes, v. 9, no. 4, p. 327–345, doi: 10.1002/(SICI)1099-1530(199810/12)9:4<327::AID-PPP298>3.0.CO;2-9.

Bell, T., Rogerson, R.J., and Mengel, F., 1989, Reconstructed ice-flow patterns and ice limits using drift pebble lithology, Outer Nachvak Fiord, northern Labrador: Canadian Journal of Earth Sciences, v. 26, p. 577–590.

Bentley, C.R., 1987, Antarctic ice streams: A review: Journal of Geophysical Research, v. 92, p. 8843–8858.

Bierman, P.R., Marsella, K.A., Patterson, C., Davis, P.T., and Caffee, M., 1999, Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsinan glacial surfaces in southwestern Minnesota and southern Baffin Island: A multiple nuclide approach: Geomorphology, v. 27, p. 25–39, doi: 10.1016/S0169-555X(98)00088-9.

Bierman, P.R., Davis, P.T., and Caffee, M.W., 2000, Old surfaces on New England summits imply thin Laurentide ice: Geological Society of America Abstracts with Programs, v. 31, no. 7, p. A-330.

Bierman, P.R., Marsella, K.A., Davis, P.T., and Caffee, M.W., 2001, Response to discussion by Wolfe et al. on Bierman et al. (Geomorphology 25 (1999) 25–39): Geomorphology, v. 39, p. 255–260.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S., 1992, Evidence for massive discharges of icebergs into the North Atlantic Ocean during the Last Glacial Period: Nature, v. 360, p. 245–249, doi: 10.1038/360245a0.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G., 1993, Correlations between climate records from North Atlantic sediments and Greenland ice: Nature, v. 365, p. 143–147, doi: 10.1038/365143a0.

Boulton, G.S., and Clark, C.D., 1990, A highly mobile Laurentide Ice Sheet revealed by satellite images of glacial lineations: Nature, v. 346, p. 813–817, doi: 10.1038/346813a0.

Boyer, S.J., and Pheasant, D.R., 1974, Delimitation of weathering zones in the fiord area of eastern Baffin Island, Canada: Geological Society of America Bulletin, v. 85, p. 805–810, doi: 10.1130/0016-7606(1974)85<805:DOWZIT>2.0.CO;2.

Briner, J.P., and Swanson, T.W., 1998, Using inherited cosmogenic Cl-36 to constrain glacial erosion rates of the Cordilleran ice sheet: Geology, v. 26, p. 3–6, doi: 10.1130/0091-7613(1998)026<0003:UICCTC>2.3.CO;2.

Briner, J.P., Miller, G.H., Davis, P.T., Bierman, P.R., and Caffee, M., 2003, Last Glacial Maximum ice sheet dynamics in Arctic Canada inferred from young erratics perched on ancient tors: Quaternary Science Reviews, v. 22, p. 437–444, doi: 10.1016/S0277-3791(03)00003-9.

Briner, J.P., Miller, G.H., Davis, P.T., and Finkel, R., 2005, Cosmogenic exposure dating in Arctic glacial landscapes: Implications for the glacial history of northeastern Baffin Island, Canada: Canadian Journal of Earth Sciences, v. 42, no. 1, p. 67–84.

Briner, J.P., Miller, G.H., Davis, P.T., and Finkel, R.C., Cosmogenic radionuclides from differentially weathered fiord landscapes support differential erosion by overriding ice sheets: Geological Society of America Bulletin (in press).

Brookes, I.A., 1977, Geomorphology and Quaternary geology of Codroy Lowland and adjacent plateaus, southwest Newfoundland: Canadian Journal of Earth Sciences, v. 14, p. 2101–2120.

Bryson, R.A., Wendland, W.M., Ives, J.D., and Andrews, J.T., 1969, Radiocarbon isochrones on the disintegration of the Laurentide ice sheet: Arctic and Alpine Research, v. 1, p. 1–14, doi: 10.2307/1550356.

Clark, C.D., 1997, Reconstructing the evolutionary dynamics of former ice sheets using multi-temporal evidence, remote sensing and GIS: Quaternary Science Reviews, v. 16, no. 9, p. 1067–1092, doi: 10.1016/S0277-3791(97)00037-1.

Clark, P.U., 1988, Glacial geology of the Torngat Mountains, Labrador: Canadian Journal of Earth Sciences, v. 25, p. 1184–1198.

Clark, P.U., 1994, Unstable behavior of the Laurentide Ice Sheet over deforming sediment and its implications for climate change: Quaternary Research, v. 41, p. 19–25, doi: 10.1006/qres.1994.1002.

Clark, P.U., and Josenhans, H.W., 1990, Reconstructed ice-flow patterns and ice limits using drift pebble lithology, Outer Nachvak Fjord, northern Labrador—Discussion: Canadian Journal of Earth Sciences, v. 27, p. 1002–1006.

Clark, P.U., Short, S.K., Williams, K.M., and Andrews, J.T., 1989, Late Quaternary chronology and environments of Square Lake, Torngat Mountains, Labrador: Canadian Journal of Earth Sciences, v. 26, p. 2130–2144.

Clark, P.U., Brook, E.J., Raisbeck, G.M., Yiou, F., and Clark, J., 2003, Cosmogenic Be-10 ages of the Saglek moraines, Torngat Mountains, Labrador: Geology, v. 31, p. 617–620, doi: 10.1130/0091-7613(2003)031<0617:CBAOTS>2.0.CO;2.

Cockburn, H.A.P., and Summerfield, M.A., 2004, Geomorphological applications of cosmogenic isotope analysis: Progress in Physical Geography, v. 28, p. 1–42, doi: 10.1191/0309133304pp395oa.

Coleman, A.P., 1920, Extent and thickness of the Labrador ice sheet: Geological Society of America Bulletin, v. 31, p. 819–828.

Colgan, P.M., Bierman, P.R., Mickelson, D.M., and Caffee, M., 2002, Variation in glacial erosion near the southern margin of the Laurentide Ice Sheet, south-central Wisconsin, USA: Implications for cosmogenic dating of glacial terrains: Geological Society of America Bulletin, v. 114, p. 1581–1591, doi: 10.1130/0016-7606(2002)114<1581:VIGENT>2.0.CO;2.

Cuffey, K.M., Conway, H., Gades, A.M., Hallet, B., Lorrain, R., Severinghaus, J.P., Steig, E.J., Vaughn, B., and White, J.W.C., 2000, Entrainment at cold glacier beds: Geology, v. 28, p. 351–354, doi: 10.1130/0091-7613(2000)028<0351:EACGB>2.3.CO;2.

Daly, R.A., 1902, The geology of the northeast coast of Labrador: Harbard University Museum of Comparative Zoology Bulletin, v. 38, p. 205–270.

Davis, P.T., Bierman, P.R., Marsella, K.A., Caffee, M.W., and Southon, J.R., 1999, Cosmogenic analysis of glacial terrains in the eastern Canadian Arctic: A test for inherited nuclides and the effectiveness of glacial erosion: Annals of Glaciology, v. 28, p. 181–188.

Davis, P.T., Briner, J.P., Coulthard, R.C., Finkel, R.W., and Miller, G.H., Preservation of arctic landscapes overridden by cold-based ice sheets: Quaternary Research (in press).

Denton, G.H., and Hughes, T., 1981, The last great ice sheets: New York, Wiley and Sons, 484 p.

Dredge, L.A., 2000, Age and origin of upland block fields on Melville Peninsula, eastern Canadian Arctic: Geografiska Annaler, ser. A, Physical Geography, v. 82A, p. 443–454.

Duk-Rodkin, A., Barendregt, R.W., Tarnocai, C., and Phillips, F.M., 1996, Late Tertiary to late Quaternary record in the Mackenzie Mountains, Northwest Territories, Canada: Stratigraphy, paleosols, paleomagnetism, and chlorine-36: Canadian Journal of Earth Sciences, v. 33, p. 875–895.

Dyke, A.S., 1979, Glacial and sea-level history of southwestern Cumberland Peninsula, Baffin Island, N.W.T., Canada: Arctic and Alpine Research, v. 11, p. 179–202, doi: 10.2307/1550644.

Dyke, A.S., 1993, Landscapes of cold-centered Late Wisconsinan ice caps, arctic Canada: Progress in Physical Geography, v. 17, p. 223–247.

Dyke, A.S., and Prest, V.K., 1987, Late Wisconsin and Holocene history of the Laurentide Ice Sheet: Geographie Physique et Quaternaire, v. 41, p. 237–263.

Dyke, A.S., Morris, T.F., Green, D.E.C., and England, J., 1992, Quaternary geology of Prince of Wales Island, Arctic Canada: Geological Survey of Canada Memoir 433, 142 p.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J., and Veillette, J.J., 2002, The Laurentide and Innuitian ice sheets during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, p. 9–31, doi: 10.1016/S0277-3791(01)00095-6.

Fabel, D., and Harbor, J., 1999, The use of in situ produced cosmogenic radionuclides in glaciology and glacial geomorphology: Annals of Glaciology, v. 28, p. 103–110.

Flint, R.F., 1943, Growth of the North American ice sheet during the Wisconsin age: Geological Society of America Bulletin, v. 54, p. 325–362.

Gosse, J.C., and Phillips, F.M., 2001, Terrestrial in situ cosmogenic nuclides: Theory and application: Quaternary Science Reviews, v. 20, p. 1475–1560, doi: 10.1016/S0277-3791(00)00171-2.

Gosse, J.C., Grant, D.R., Klein, J., Klassen, R.A., Evenson, E.B., Lawn, B., and Middleton, R., 1993, Significance of altitudinal weathering zones in Atlantic Canada, inferred from in situ produced cosmogenic radionuclides: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A394.

Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., and Middleton, R., 1995a, Precise cosmogenic ^{10}Be measurements in western North America: Support for a global Younger Dryas cooling event: Geology, v. 23, p. 877–880, doi: 10.1130/0091-7613(1995)023<0877:PCBMIW>2.3.CO;2.

Gosse, J.C., Grant, D.R., Klein, J., and Lawn, B., 1995b, Cosmogenic ^{10}Be and ^{26}Al constraints on weathering zone genesis, ice cap basal conditions, and Long Range Mountains (Newfoundland) glacial history, *in* Proceedings of the Canadian Quaternary Association–Canadian Geomorphology Research Group (CANQUA-CGRC) Conference: Memorial University, Saint Johns, Newfoundland, p. CA19.

Gosse, J., Hecht, G., Mehring, N., Klein, J., Lawn, B., and Dyke, A., 1998, Comparison of radiocarbon and in situ cosmogenic nuclide-derived postglacial emergence curves for Prescott Island, central Canadian Arctic: Geological Society of America Abstracts with Programs, v. 30, no. 7, p. 298.

Gosse, J.C., Staiger, J.W., Fastook, J., Johnson, J., Utting, D., and Little, E., 2005, Tagging glacial erosion and till production for drift prospecting: Geological Society of America Abstracts with Programs, v. 37, no. 7, p. 398.

Gosse, J.C., Bell, T., and Gray, J., 2006, Using cosmogenic isotopes to interpret the landscape record of glaciation: Nunataks in Newfoundland? *in* Knight, P., ed., Glacier science and environmental change: Blackwell Publishing, p. **XXX–XXX**.

Grant, D.R., 1977, Altitudinal weathering zones and glacial limits in western Newfoundland, with particular reference to Gros Morne National Park: Geological Survey of Canada Paper 77-1A, p. 455–463.

Grousset, F.E., Pujol, C., Labeyrie, L., Auffret, G., and Boelaert, A., 2000, Were the North Atlantic Heinrich events triggered by the behavior of the European ice sheets?: Geology, v. 28, p. 123–126, doi: 10.1130/0091-7613(2000)028<0123:WTNAHE>2.3.CO;2.

Hall, A.M., and Glasser, N.F., 2003, Reconstructing the basal thermal regime of an ice stream in a landscape of selective linear erosion: Glen Avon, Cairngorm Mountains, Scotland: Boreas, v. 32, p. 191–207, doi: 10.1080/03009480310001100.

Hall, A.M., and Sugden, D.E., 1987, Limited modification of midlatitude landscapes by ice sheets—The case of northeast Scotland: Earth Surface Processes and Landforms, v. 12, no. 5, p. 531–542.

Heinrich, H., 1988, Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 Years: Quaternary Research, v. 29, p. 142–152, doi: 10.1016/0033-5894(88)90057-9.

Hemming, S.R., and Hajdas, I., 2003, Ice-rafted detritus evidence from Ar-40/Ar-39 ages of individual hornblende grains for evolution of the eastern margin of the Laurentide ice sheet since 43 C-14 ky: Quaternary International, v. 99, p. 29–43, doi: 10.1016/S1040-6182(02)00110-6.

Hughes, T., Denton, G.H., and Grosswald, M.G., 1977, Was there a Late Würm arctic ice sheet?: Nature, v. 266, p. 596–602, doi: 10.1038/266596a0.

Hughes, T.J., Denton, G.H., and Fastook, J.L., 1985, The Antarctic Ice Sheet: An analog for Northern Hemisphere paleo-ice sheets?, *in* Woldenburk, M.J., ed., Models in Geomorphology: London, Allen and Unwin, p. 25–72.

Imbrie, J., and Imbrie, J.Z., 1980, Modeling the climatic response to orbital variations: Science, v. 207, p. 943–953.

Ives, J.D., 1957, Glaciation of the Torngat Mountains, northern Labrador: Journal of the Arctic Institute of North America, v. 10, p. 67–87.

Ives, J.D., 1978, Maximum extent of Laurentide Ice Sheet along east coast of North America during last glaciation: Arctic, v. 311, p. 24–53.

Ives, J.D., and Andrews, J.T., 1963, Studies in the physical geography of north-central Baffin Island, N.W.T.: Geographical Bulletin, v. 5, p. 5–48.

Jackson, L.E., 1980, Glacial history and stratigraphy of the Alberta portion of the Kananaskis Lakes map area: Canadian Journal of Earth Sciences, v. 17, p. 459–477.

Jackson, L.E., Phillips, F.M., Shimamura, K., and Little, E.C., 1997, Cosmogenic Cl-36 dating of the Foothills erratics train, Alberta, Canada: Geology, v. 25, p. 195–198, doi: 10.1130/0091-7613(1997)025<0195:CCDOTF>2.3.CO;2.

Jackson, L.E., Phillips, F.M., and Little, E.C., 1999, Cosmogenic Cl-36 dating of the maximum limit of the Laurentide Ice Sheet in southwestern Alberta: Canadian Journal of Earth Sciences, v. 36, p. 1347–1356, doi: 10.1139/cjes-36-8-1347.

Jansson, K.N., Stroeven, A.P., and Kleman, J., 2003, Configuration and timing of Ungava Bay ice streams, Labrador-Ungava, Canada: Boreas, v. 32, p. 256–262, doi: 10.1080/03009480310001146.

Jennings, A.E., 1993, The Quaternary history of Cumberland Sound, southeastern Baffin Island: The marine evidence: Geographie physique et Quaternaire, v. 47, p. 21–42.

Josenhans, H.W., Zevenhuizen, J., and Klassen, R.A., 1986, The Quaternary Geology of the Labrador Shelf: Canadian Journal of Earth Sciences, v. 23, p. 1190–1213.

Kaplan, M.R., and Miller, G.H., 2003, Early Holocene delevelling and deglaciation of the Cumberland Sound region, Baffin Island, Arctic Canada: Geological Society of America Bulletin, v. 115, p. 445–462, doi: 10.1130/0016-7606(2003)115<0445:EHDADO>2.0.CO;2.

Kaplan, M.R., Pfeffer, W.T., Sassolas, C., and Miller, G.H., 1999, Numerical modelling of the Laurentide Ice Sheet in the Baffin Island region: The role of a Cumberland Sound ice stream: Canadian Journal of Earth Sciences, v. 36, p. 1315–1326, doi: 10.1139/cjes-36-8-1315.

Kaplan, M.R., Miller, G.H., and Steig, E.J., 2001, Low-gradient outlet glaciers (ice streams?) drained the Laurentide ice sheet: Geology, v. 29, p. 343–346, doi: 10.1130/0091-7613(2001)029<0343:LGOGIS>2.0.CO;2.

Klassen, R.W., 1994, Late Wisconsinan and Holocene history of southwestern Saskatchewan: Canadian Journal of Earth Sciences, v. 31, p. 1822–1837.

Kleman, J., 1994, Preservation of landforms under ice sheets and ice caps: Geomorphology, v. 9, p. 19–32, doi: 10.1016/0169-555X(94)90028-0.

Kleman, J., and Hättestrand, C., 1999, Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum: Nature, v. 402, p. 63–66, doi: 10.1038/47005.

Lal, D., 1991, Cosmic-ray labeling of erosion surfaces—In situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, p. 424–439, doi: 10.1016/0012-821X(91)90220-C.

Lal, D., and Peters, B., 1967, Cosmic ray produced radioactivity on the earth, *in* Sitte, K., ed., Handbuch der Physik, v. XLVI/2: Berlin, Springer, p. 551–612.

Liverman, D.G.E., Catto, N.R., and Rutter, N.W., 1989, Laurentide glaciation in west-central Alberta: A single (Late Wisconsinan) event: Canadian Journal of Earth Sciences, v. 26, p. 266–274.

Løken, O.H., 1966, Baffin Island refugia older than 54,000 years: Science, v. 153, p. 1378–1380.

Marquette, G.C., Gray, J.T., Gosse, J.C., Courchesne, F., Stockli, L., Macpherson, G., and Finkel, R., 2004, Felsenmeer persistence under non-erosive ice in the Torngat and Kaumajet Mountains, Quebec and Labrador, as determined by soil weathering and cosmogenic nuclide exposure dating: Canadian Journal of Earth Sciences, v. 41, p. 19–38, doi: 10.1139/e03-072.
Marsella, K.A., Bierman, P.R., Davis, P.T., and Caffee, M.W., 2000, Cosmogenic Be-10 and Al-26 ages for the Last Glacial Maximum, eastern Baffin Island, Arctic Canada: Geological Society of America Bulletin, v. 112, p. 1296–1312, doi: 10.1130/0016-7606(2000)112<1296:CBAAAF>2.3.CO;2.
Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Jr., and Shackleton, N.J., 1987, Age dating and orbital theory of the ice ages: Development of a high-resolution 0 to 300,000-year chronostratigraphy: Quaternary Research, v. 27, p. 1–29, doi: 10.1016/0033-5894(87)90046-9.
McCuaig, S.J., Shilts, W.W., Evenson, E.B., and Klein, J., 1994, Use of cosmogenic ^{10}Be and ^{26}Al for determining glacial history of the South Bylot Island and Salmon River Lowlands, N.W.T., Canada: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A127.
Miller, G.H., and Dyke, A.S., 1974, Proposed extent of Late Wisconsin Laurentide ice on eastern Baffin Island: Geology, v. 2, p. 125–130, doi: 10.1130/0091-7613(1974)2<125:PEOLWL>2.0.CO;2.
Miller, G.H., Wolfe, A.P., Steig, E.J., Sauer, P.E., Kaplan, M.R., and Briner, J.P., 2002, The Goldilocks dilemma: Big ice, little ice, or "just-right" ice in the eastern Canadian Arctic: Quaternary Science Reviews, v. 21, p. 33–48, doi: 10.1016/S0277-3791(01)00085-3.
Nesje, A., and Dahl, S.O., 1990, Autochthonous block fields in southern Norway—Implications for the geometry, thickness, and isostatic loading of the Late Weichselian Scandinavian Ice Sheet: Journal of Quaternary Science, v. 5, p. 225–234.
Nishiizumi, K., Winterer, E.L., Kohl, C.P., Klein, J., Middleton, R., Lal, D., and Arnold, J.R., 1989, Cosmic-ray production rates of Be-10 and Al-26 in quartz from glacially polished rocks: Journal of Geophysical Research, B, Solid Earth and Planets, v. 94, p. 17,907–17,915.
Odell, N.E., 1933, The mountains of northern Labrador: Geographical Journal, v. 82, p. 193–210.
Patterson, C.J., 1998, Laurentide glacial landscapes: The role of ice streams: Geology, v. 26, p. 643–646, doi: 10.1130/0091-7613(1998)026<0643:LGLTRO>2.3.CO;2.
Peltier, W.R., 1996, Mantle viscosity and ice-age ice sheet topography: Science, v. 273, p. 1359–1364.
Pheasant, D.R., and Andrews, J.T., 1973, Wisconsin glacial chronology and relative sea level movements, Narpaing Fjord / Broughton Island area, eastern Baffin Island: Canadian Journal of Earth Sciences, v. 10, p. 1621–1641.
Phillips, F.M., Leavy, B.D., Jannik, N.O., Elmore, D., and Kubik, P.W., 1986, The accumulation of cosmogenic chlorine-36 in rocks: A method for surface exposure dating: Science, v. 231, p. 41–43.
Piper, D.J.W., and Macdonald, A., 2001, Timing and position of Late Wisconsinan ice margins on the upper slope seaward of Laurentian Channel: Geographie Physique et Quaternaire, v. 55, p. 131–140.
Prest, V.K., Grant, D.R., and Rampton, V.N., 1968, Glacial map of Canada: Geological Survey of Canada Map 1253A, scale 1:5,000,000.
Rae, A.C., Harrison, S., Mighall, T., and Dawson, A.G., 2004, Periglacial trimlines and nunataks of the Last Glacial Maximum: The Gap of Dunloe, southwest Ireland: Journal of Quaternary Science, v. 19, p. 87–97, doi: 10.1002/jqs.807.
Shilts, W.W., Cunningham, C.M., and Kaszycki, C.A., 1979, Keewatin Ice Sheet—Re-evaluation of the traditional concept of the Laurentide Ice Sheet: Geology, v. 7, p. 537–541, doi: 10.1130/0091-7613(1979)7<537:KISOTT>2.0.CO;2.
Staiger, J.K.W., Gosse, J.C., Johnson, J., Fastook, J., Gray, J., Little, E.C., Hilchey, A., and Finkel, R., 2004, Long-term (10^4-10^5 yr) differential glacial erosion beneath polythermal glacier ice in the Atlantic and Arctic Canadian highlands: Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 70.
Staiger, J.K.W., Gosse, J.C., Johnson, J.H., Fastook, J., Gray, J.T., Stockli, D.F., Stockli, L., and Finkel, R., 2005, Quaternary relief generation by polythermal glacier ice: Earth Surface Processes and Landforms, v. 30, p. 1145–1159, doi: 10.1002/esp.1267.
Stea, R.R., Piper, D.J.W., Fader, G.B.J., and Boyd, R., 1998, Wisconsinan glacial and sea-level history of Maritime Canada and the adjacent continental shelf: A correlation of land and sea events: Geological Society of America Bulletin, v. 110, p. 821–845, doi: 10.1130/0016-7606(1998)110<0821:WGASLH>2.3.CO;2.
Steig, E.J., Wolfe, A.P., and Miller, G.H., 1998, Wisconsinan refugia and the glacial history of eastern Baffin Island, Arctic Canada: Coupled evidence from cosmogenic isotopes and lake sediments: Geology, v. 26, p. 835–838, doi: 10.1130/0091-7613(1998)026<0835:WRATGH>2.3.CO;2.
Stokes, C.R., and Clark, C.D., 2001, Palaeo-ice streams: Quaternary Science Reviews, v. 20, p. 1437–1457, doi: 10.1016/S0277-3791(01)00003-8.
Stokes, C.R., and Clark, C.D., 2002, Are long subglacial bedforms indicative of fast ice flow?: Boreas, v. 31, p. 239–249, doi: 10.1080/030094802760260355.
Sugden, D.E., 1977, Reconstruction of morphology, dynamics, and thermal characteristics of Laurentide Ice Sheet at its maximum: Arctic and Alpine Research, v. 9, p. 21–47, doi: 10.2307/1550407.
Sugden, D.E., and Watts, S.H., 1977, Tors, felsenmeer, and glaciation in northern Cumberland Peninsula, Baffin Island: Canadian Journal of Earth Sciences, v. 14, p. 2817–2823.
Tyrrell, J.B., 1898, The glaciation of north-central Canada: Journal of Geology, v. 6, p. 147–160.
Veillette, J.J., Dyke, A.S., and Roy, M., 1999, Ice-flow evolution of the Labrador Sector of the Laurentide Ice Sheet: A review with new data from northern Quebec: Quaternary Science Reviews, v. 18, p. 993–1019, doi: 10.1016/S0277-3791(98)00076-6.
Walcott, R.I., 1970, Isostatic response to loading of the crust in Canada: Canadian Journal of Earth Sciences, v. 7, p. 716–726.
Wolfe, A.P., Steig, E.J., and Kaplan, M.R., 2001, An alternative model for the geomorphic history of pre-Wisconsinan surfaces on eastern Baffin Island: A comment on Bierman et al. (Geomorphology 25 (1999) 25–39): Geomorphology, v. 39, p. 251–254.
Wolfe, A.P., Fréchette, B., Richard, P.J.H., Miller, G.H., and Forman, S.L., 2000, Paleoecology of a >90,000-year lacustrine sequence from Fog Lake, Baffin Island, Arctic Canada: Quaternary Science Reviews, v. 19, p. 1677–1699.

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