JOURNAL OF QUATERNARY SCIENCE (1998) **13** (3) 275–280 CCC 0267-8179/98/030275–06$17.50

Rapid Communication

Support for the Innuitian Ice Sheet in the Canadian High Arctic during the Last Glacial Maximum

JOHN ENGLAND*
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

England, J. 1998. Support for the Innuitian Ice Sheet in the Canadian High Arctic during the Last Glacial Maximum. *J. Quaternary Sci.,* **Vol. 13**, pp. 275–280. ISSN 0267–8179

Received 20 December 1997; revised 12 February 1998; accepted 14 February 1998

ABSTRACT: The extent of glacier ice in the Canadian High Arctic during the Last Glacial Maximum (LGM) has been debated for decades. One school proposed a regional Innuitian Ice Sheet whereas another proposed a smaller, non-contiguous Franklin Ice Complex. Research throughout western Nares Strait supports coalescent Innuitian and Greenland ice during the LGM, based on widespread glacial and marine deposits dated by ^{14}C and amino acid analyses. This coalescence likely promoted a vigorous regional ice flow westward across Ellesmere Island to Eureka Sound. Post-glacial emergence in Eureka Sound suggests a former ice thickness at least as great as that in Nares Strait ($\geq$ 1 km). Recently, independent field studies elsewhere in the High Arctic also support an Innuitian Ice Sheet during the LGM. Collectively, these studies resolve a long-standing debate, and initiate new opportunities concerning the reconstruction of high-latitude palaeoenvironmental and palaeoclimatic change. © 1998 John Wiley & Sons, Ltd.

Journal of Quaternary Science

KEYWORDS: Arctic; Canada; glaciation; Innuitian Ice Sheet.

Introduction

For the past two decades, the extent of ice during the Last Glacial Maximum (LGM) throughout the Queen Elizabeth Islands has been debated. Blake (1970) proposed a regional Innuitian Ice Sheet which coalesced with the Greenland Ice Sheet (Fig. 1) to the east, and with the Laurentide Ice Sheet to the south. England (1976) proposed a non-contiguous array of alpine ice-caps, termed the Franklin Ice Complex, which left many marine channels and some land ice-free (Dyke and Prest, 1987). Proponents of the Franklin Ice Complex, working along the northeast coast of Ellesmere Island, reported that Ellesmere Island and Greenland ice last coalesced > 35 000 yr BP, and that during the LGM these ice masses were separated by the sea (England 1974, 1996; England and Bradley, 1978; England *et al.*, 1978, 1981; Retelle, 1986). In contrast, fieldworkers on the Greenland side of Nares Strait, and along east-central Ellesmere Island, supported the filling of Nares Strait during the LGM (Weidick, 1975; Blake, 1977, 1992a, b; Bennike *et al.*, 1987; Funder, 1989; Blake *et al.*, 1996; Funder and Hansen, 1996).

To date, incomplete geological evidence has prevented resolution of these conflicting models. Support for an Innuitian Ice Sheet during the LGM emphasised the magnitude of post-glacial emergence, the freshness of glacially eroded bedrock, and radiocarbon dates (28–32 kyr BP) on shelly till (Blake, 1970, 1977, 1992a, b; Tushingham, 1991). A ridge of post-glacial emergence along Eureka Sound was termed the Innuitian uplift and attributed to the former axis of the Innuitian Ice Sheet (Walcott, 1972). Additional support for the Innuitian Ice Sheet was provided by radiocarbon dates on marine shells collected throughout the Queen Elizabeth Islands. These are oldest in the west and become progressively younger toward Eureka Sound, the direction of proposed ice retreat, initiated ca. 11 kyr BP (Blake, 1972). The principal weakness of the Innuitian Ice Sheet hypothesis has been the lack of stratigraphical evidence documenting this regional ice retreat in contact with the sea.

The Franklin Ice Complex model emphasised the conspicuous occurrence of moraines and ice-contact deltas largely confined to fiord heads. Beyond these fiord-head ice margins, evidence for the preceding retreat of a regional ice sheet, following the glacial maximum, was unconfirmed. Instead, throughout many fiords, shell dates relating to local marine limits spanned a narrow interval (±200 yr), suggesting that the marine limit did not record ice retreat but simply trimmed a weathered (pre-dating the LGM) landscape. Furthermore, the same areas appear to be characterised by a relatively slow rate of initial emergence (ca. 1 m per 100

* Correspondence to: John England, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada, T6G 2E3.

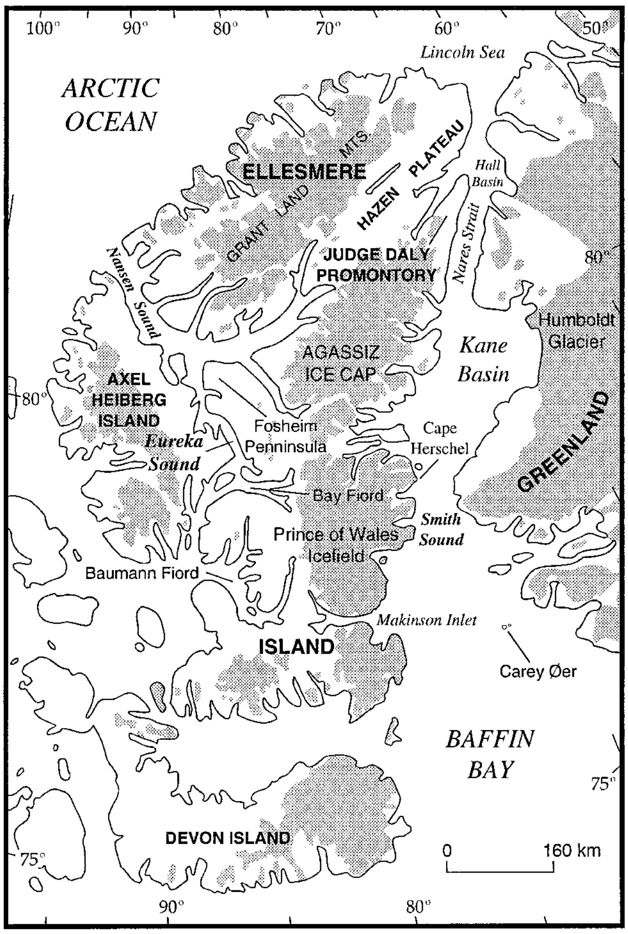

Figure 1 Map of the eastern Queen Elizabeth Islands showing regional place names used in the text. Nares Strait is the collective name applied to the channel separating Greenland and Ellesmere Island. Contemporary glaciers are shaded.

yr; England, 1983, 1992, 1997), unlike the rapid rates (7–30 m per 100 yr; Dyke *et al.*, 1991) reported from other parts of the Arctic where regional ice retreat was well documented. Hence, it was proposed that a 'full glacial sea' occupied fiords and channels beyond the Franklin Ice Complex (England, 1983, 1990). The principal weakness of the full glacial sea hypothesis was its failure to provide dates on marine shells between 10 and 20 kyr BP, when relative sea-level would have transgressed to marine limit ($\leq$ 120 m a.s.l. at ca. 8 kyr BP). Nonetheless, weathered terrain, and raised marine shorelines of pre-Holocene age ($>$ 35 kyr BP), were reported from northern Ellesmere Island, and were presumed to record unglaciated coastlines during the LGM (England *et al.*, 1978, 1981; Retelle, 1986, Lemmen, 1989, Lemmen and England, 1992).

Field area

This paper summarises a 500 km transect of late Quaternary deposits along western Nares Strait. Nares Strait is the regional name applied to the channel separating Ellesmere Island from Greenland, extending from Lincoln Sea in the north to Baffin Bay in the south (Fig. 1). During past glaciations of Nares Strait, Greenland ice advanced into Kane Basin, predominantly via the Humboldt Glacier (Fig. 2). From Kane Basin, ice diverged northward and southward along the axis of the strait while receiving tributary glaciers from both coastlines (Funder, 1989).

Ice thickness and configuration

The upper limit of meltwater channels and erratics along eastern Ellesmere Island record the filling of Nares Strait by coalescent Greenland and Ellesmere Island ice. The contact of these two ice masses displays Greenland dominance at the north end of the strait. There, granite erratics of Greenland provenance extend 5–10 km inland from the Ellesmere Island coast, reaching $>$ 600 and $>$ 800 m above sea level (a.s.l.) on Hazen Plateau and Judge Daly Promontory, respectively (Fig. 2). South of Judge Daly Promontory, the upper limit of granite erratics reaches ca. 725 m a.s.l., but is limited to within a few kilometres of the coastline. In this sector, granite erratics are precluded from the larger Ellesmere Island valleys, indicating the displacement of Greenland ice by Ellesmere Island ice, which entered the northward-flowing trunk glacier in Nares Strait. Farther south, just north of Kane Basin, Greenland erratics are replaced by Ellesmere Island erratics, indicating that the contact was offshore.

During the last filling of Nares Strait, northward-flowing trunk ice from Kane Basin coalesced with additional Greenland ice, debouching from Petermann Fiord (Fig. 2). Based on the elevation of erratics, the surface of the Petermann ice was higher ($\geq$ 840 m a.s.l.), and had already extended on to Hazen Plateau and Judge Daly Promontory (Christie, 1965; England and Bradley, 1978; Retelle, 1986). Blockage of northern Nares Strait by Petermann ice may have enhanced southward flow from Kane Basin, favouring the establishment of the 'Smith Sound Ice Stream' (Blake, 1992b), which extended south of Carey Oer (Fig. 1), into northern Baffin Bay (Blake *et al.*, 1996).

Chronology

The chronology of ice advance and retreat along Nares Strait is provided by 40 radiocarbon dates of pre-Holocene age collected from shelly till and outwash; and 70 amino acid ratios (Alle/Ile) on both Holocene and pre-Holocene shells from all representative stratigraphical settings (from till to undisturbed marine sediments). Both of these chronologies support a Late Wisconsinan age. Indeed, several accelerator mass spectrometer (AMS) dates obtained on samples collected from shelly till range from 19 to 24 kyr BP. Furthermore, throughout eastern Ellesmere Island, geomorphological evidence links the retreat of trunk ice from Nares Strait to $>$ 50 radiocarbon dates on ice-contact deltas (Fig. 3). These record a progressive Holocene invasion of the sea into Nares Strait from both its northern and southern ends. The pattern of ice retreat is shown on three palaeogeographical maps spanning 10 kyr BP to 7 kyr BP (Fig. 4a–c). The earliest entry of the sea at the northeastern end of Nares Strait is dated at 10.1 kyr BP, whereas the oldest dates available at the southern end are ca. 9 kyr BP (Blake, 1992a). The marine embayments at the northern and southern ends of Nares Strait finally merged by ca. 7.5 kyr BP, reconnecting Baffin Bay to the Arctic Ocean (England, in press).

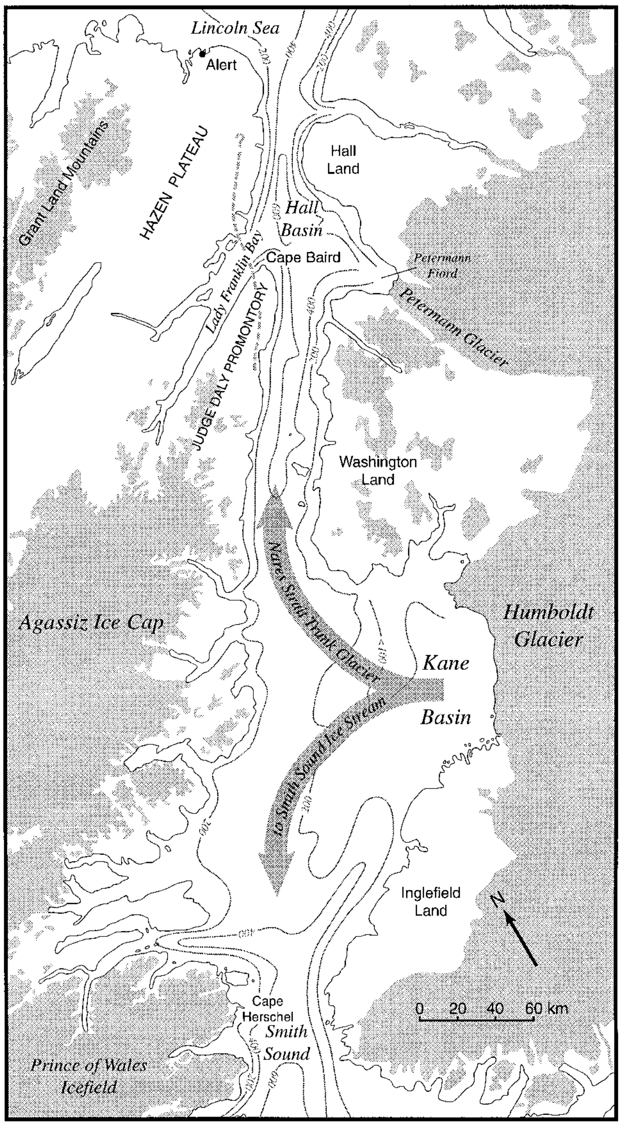

Figure 2 Map of Nares Strait showing place names used in text and generalised bathymetry (in metres). Dark arrows schematically portray the divergence of ice from Kane Basin, which would have been supplemented by convergent Ellesmere island and Greenland ice along the length of the strait. The dashed, shaded line west of Hall Basin shows the mapped limit of Greenland erratics transported by Petermann ice. South of this line, Greenland erratics are confined to within ca. 1 km of the Ellesmere Island coast until they are displaced offshore just north of Kane Basin. Contemporary glaciers are shaded.

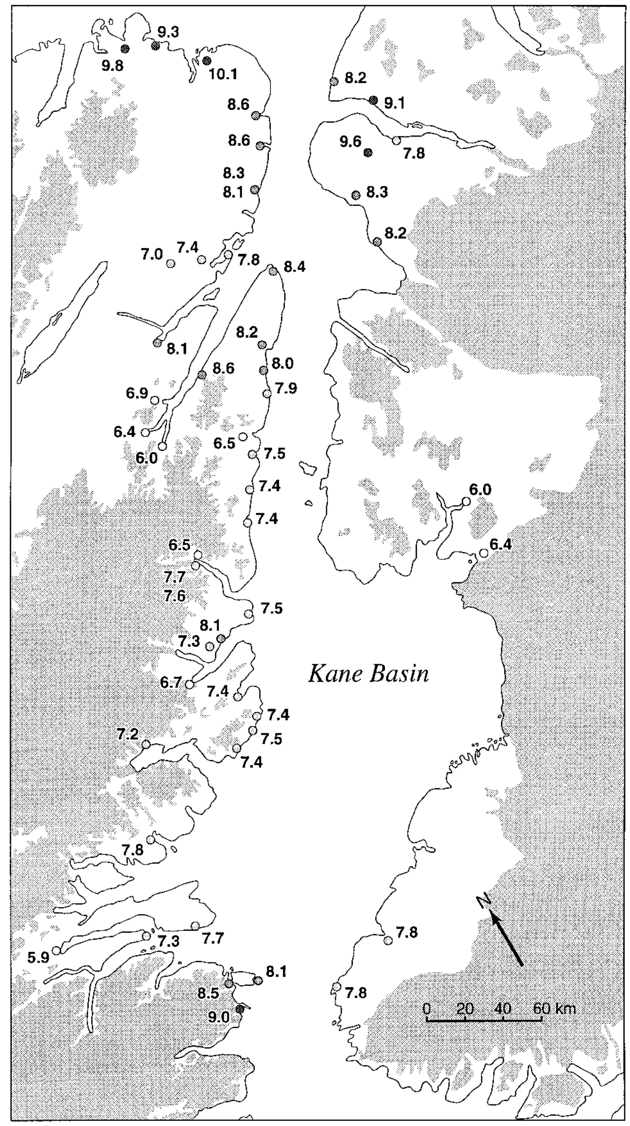

Figure 3 Distribution of oldest available Holocene radiocarbon dates on marine shells collected along Nares Strait. Dates are given in thousands of years (kyr BP). Dates are assumed to provide minimum age-estimates on the entry of the sea following deglaciation. The distribution of these dates shows a progressive entry of the sea from the northern and southern ends of Nares Strait.

Discussion

Stratigraphical and chronological evidence for Holocene ice retreat is now available along the length of western Nares Strait and parts of adjacent Greenland. Combined with various dating techniques on glacial landforms and sediments, this fieldwork confirms coalescent Ellesmere Island and Greenland ice during the LGM, as proposed by Blake (1970, 1977, 1992b) and others (Funder, 1989, Funder and Hansen, 1996). Greenland ice reached at least 725 m a.s.l. throughout western Nares Strait, hence it buttressed the eastern Ellesmere Island ice margin to an elevation of at least 1 km above the floor of Nares Strait. This would have lowered the surface profile on the eastern side of the central Ellesmere Island ice divide, diminishing outflow along its eastern flank. This would have promoted thickening and westward migration of the central Ellesmere Island ice divide, causing a strengthening of westward ice flow toward Eureka Sound.

Westward ice flow was proposed earlier by Bell (1992) who mapped granite erratics on Fosheim Peninsula, northern Eureka Sound (Fig. 1). Bell (1992, p. 106) attributed the provenance of these erratics to the Shield of southeast Ellesmere Island, where they were transported by glaciers to Fosheim Peninsula via Bay Fiord (Fig. 1). Bell further proposed that this granite erratic train dated at least 0.4 Ma. However, their deposition on Fosheim Peninsula during the LGM is considered likely, given the glacial configuration reported here for Nares Strait. Furthermore, thick ice in Eureka Sound during the LGM would harmonise the interpretation of post-glacial emergence on both the east and west coasts of Ellesmere Island. Post-glacial emergence in Eureka Sound reaches 150 m and this is higher than the emergence recorded along Nares Strait, where LGM ice thickness exceeded 1 km (England, in press). Northward-flowing ice from Eureka Sound during the LGM has been

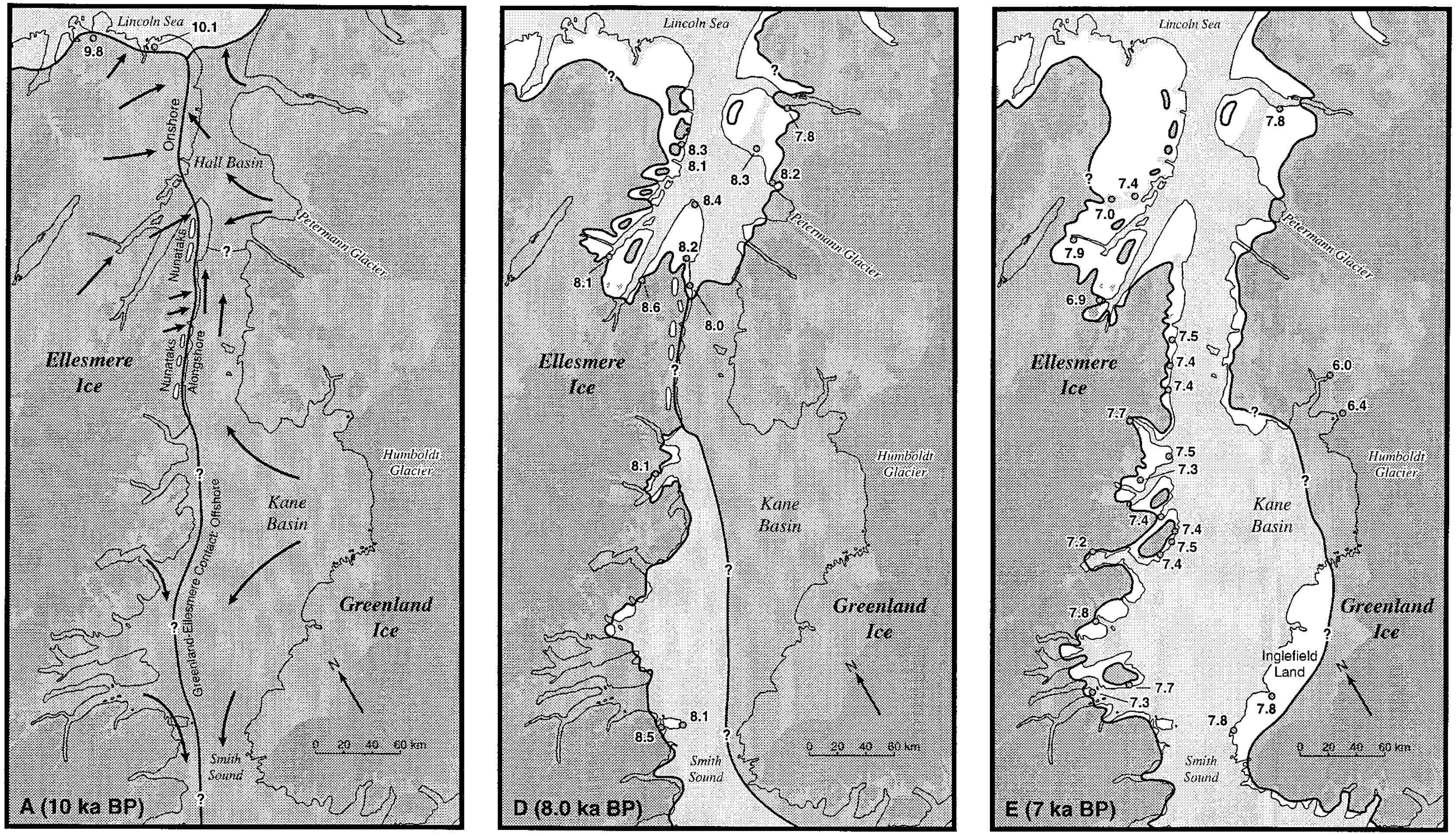

Figure 4 Palaeogeographical maps showing the proposed retreat of Greenland and Ellesmere Island ice from Nares Strait for 10 kyr BP (A), 8 kyr BP (B), and 7 kyr BP (C). Black arrows on map A show assumed direction of ice flow. Key radiocarbon dates on each map are shown in thousands of years (kyr BP) and correspond to those shown on Fig. 3.

proposed recently by Bednarski (in press), based on adjoining fieldwork along Nansen Sound, which was filled by glaciers (Fig. 1). Similarly, evidence for the Innuitian Ice Sheet in the central arctic islands during the LGM has been demonstrated by Dyke (in press), who reports southward flowing ice through Wellington Channel, bordering western Devon Island (Fig. 1). Hence, clarification of the Innuitian Ice Sheet's configuration, geometry, and retreat is well underway.

Radiocarbon (AMS) dates as young as 19 kyr BP on shelly till along Nares Strait raise questions concerning the rapidity of ice growth during the last glaciation, an interval widely assumed to be constrained by severe aridity (England and Bradley, 1978, Kapsner *et al.*, 1995). Blake (1992b) also cites evidence for ice advance after 20.2 kyr BP, based on the youngest AMS date on subtill organic detritus west of Makinson Inlet (Fig. 1). Vigorous outflow of ice from the southern end of Nares Strait during the LGM is relevant to the interpretation of detrital carbonate in Baffin Bay (Andrews *et al.*, in press). The reconnection of the Arctic Ocean to Baffin Bay via Nares Strait, around 7.5 kyr BP, may have triggered the temporary retraction of subarctic molluscs noted in Baffin Bay at this time (Dyke *et al.*, 1996).

Acknowledgements Logistical support for this research was provided throughout by Polar Continental Shelf Project, Natural Resources Canada. Financial support was provided by the Natural Sciences and Engineering Research Council of Canada (grant A-1660 to J. England). The paper has benefited from discussions with numerous colleagues: A. S. Dyke, J. Bednarski, and D. S. Lemmen of the Geological Survey of Canada; M. Sharp, R. Smith, S. Lamoureux, C. O'Cofaigh, and J. Hooper (University of Alberta). M. Fisher, University of Alberta, drafted the figures. D. J. A. Evans (University of Glasgow) and D. I. Benn (University of Aberdeen) provided helpful formal reviews.

References

ANDREWS, J. T., KIRBY, M., AKSU, A., BARBER, D. C. and MEESE, D. in press. Late Quaternary detrital carbonate (DC-) layers in Baffin Bay marine sediments (67–74°N): correlation to Hienrich events in the North Atlantic? *Quaternary Science Reviews.*

BELL, T. 1992. *Glacial and sea level history of western Fosheim Peninsula, Ellesmere Island, Arctic Canada.* PhD thesis, University of Alberta, Edmonton.

BEDNARSKI, J. in press. Quaternary history of northeastern Axel Heiberg Island, Arctic Canada. *Canadian Journal of Earth Sciences.*

BENNIKE, P. R., DAWES, S., FUNDER, S., KELLY, M. and WEIDICK, A. 1987. The late Quaternary history of Hall Land, northwest Greenland: discussion. *Canadian Journal of Earth Sciences,* **24**, 370–374.

BLAKE, W., JR. 1970. Studies of glacial history in arctic Canada. I. Pumice, radiocarbon dates, and differential postglacial uplift in the eastern Queen Elizabeth Islands. *Canadian Journal of Earth Sciences,* **7**, 634–664.

BLAKE, W., JR. 1972. Climatic implications of radiocarbon-dated driftwood in the Queen Elizabeth Islands, arctic Canada. *IN:* Hyvärinen, Y. and Hicks, S. (eds), *Climatic Changes in Arctic Areas during the Past Ten-thousand Years,* 77–104. Acta Universitatis Ouluensis, Ser. A. Scientifiae Rerum Naturalium, No. 3, Geologica No. 1.

BLAKE, W., JR. 1977. Glacial sculpture along the east-central coast of Ellesmere Island, Arctic Archipelago. *Geological Survey of Canada Paper,* **77–1A**, 107–115.

BLAKE, W., JR. 1992a. Holocene emergence at Cape Herschel, east-central Ellesmere Island, Arctic Canada: implications for ice sheet configuration. *Canadian Journal of Earth Sciences,* **29**, 1958–1980.

BLAKE, W., JR. 1992b. Shell-bearing till along Smith Sound, Ellesmere Island – Greenland: age and significance. *Sveriges Geologiska Undersökning,* **81**, 51–58.

BLAKE, W., JR., JACKSON, H. R. and CURRIE, C. G. 1996. Seafloor evidence for glaciation, northernmost Baffin Bay. *Bulletin of the Geological Society of Denmark,* **23**, 157–168.

CHRISTIE, R. L. 1967. Reconnaissance of the surficial geology of northeastern Ellesmere Island, arctic archipelago. *Geological Survey of Canada Bulletin,* **138**.

DE FREITAS, T. A. 1990. Implications of glacial striae on Hans Island, between Greenland and Ellesmere island (Nares Strait). *Journal of Glaciology,* **36**, 129–130.

DYKE, A. S. in press. The last glacial maximum and deglaciation of Devon Island: Support for an Innuitian Ice Sheet. *Quaternary Science Reviews.*

DYKE, A. S. and PREST, V. K. 1987. Late Wisconsinan and Holocene history of the Laurentide Ice Sheet. *Géographie Physique et Quaternaire,* **41**, 237–263

DYKE, A. S., MORRIS, T. F. and GREEN, D. E. 1991. Postglacial tectonic and sea level history of the central Canadian Arctic. *Geological Survey of Canada, Bulletin,* **397**.

DYKE, A. S., DALE, J. E. and McNEELY, R. N. 1996. Marine molluscs as indicators of environmental change in glaciated North America and Greenland during the last 18,000 years. *Géographie Physique et Quaternaire,* **50**, 125–184.

ENGLAND, J. 1974. Advance of the Greenland Ice Sheet on to north-eastern Ellesmere Island. *Nature* (London), 252, 373–375.

ENGLAND, J. 1976. Late Quaternary glaciation of the eastern Queen Elizabeth Islands, Northwest Territories, Canada: alternative models. *Quaternary Research,* **6**, 185–202.

ENGLAND, J. 1983. Isostatic adjustments in a full glacial sea. *Canadian Journal of Earth Sciences,* **20**, 895–917.

ENGLAND, J. 1990. The late Quaternary history of Greely Fiord and its tributaries, west-central Ellesmere Island. *Canadian Journal of Earth Sciences,* **27**, 255–270.

ENGLAND, J. 1992. Postglacial emergence in the Canadian High Arctic: integrating glacioisostasy, eustasy, and late deglaciation. *Canadian Journal of Earth Sciences,* **29**, 984–999.

ENGLAND, J. 1996. Glacier dynamics and paleoclimatic change during the last glaciation of eastern Ellesmere island, Canada. *Canadian Journal of Earth Sciences,* **33**, 779–799.

ENGLAND, J. 1997. Unusual rates and patterns of Holocene emergence, Arctic Canada. *Journal of the Geological Society of London,* **154**, 781–792.

ENGLAND, J. in press. Coalescent Greenland and Innuitian ice during the last glacial maximum: revising the Quaternary of the Canadian High Arctic. *Quaternary Science Reviews.*

ENGLAND, J. and BRADLEY, R. S. 1978. Past glacial activity in the Canadian high arctic. *Science,* **200**, 265–270.

ENGLAND, J., BRADLEY, R. S. and MILLER, G. H. 1978. Former ice shelves in the Canadian High Arctic. *Journal of Glaciology,* **20**, 393–404.

ENGLAND, J., BRADLEY, R. S. and STUCKENRATH, R. 1981. Multiple glaciations and marine transgressions, western Kennedy, Northwest Territories, Canada. *Boreas,* **10**, 71–89.

FUNDER, S. 1989. Quaternary geology of the ice-free areas and adjacent shelves of Greenland. *IN:* Fulton, R. J. (ed), *Quaternary Geology of Canada and Greenland,* 743–792. Geological Survey of Canada, Geology of Canada, no. 1, Calgary.

FUNDER, S. and HANSEN, L. 1996. The Greenland ice sheet — a model for its culmination and decay during and after the last glacial maximum. *Geological Society of Denmark Bulletin,* **42**, 137–152.

KAPSNER, W. R., ALLEY, R. B., SHAMAN, C. A., ANANDAKRISHNAN, S. and GROOTES, P. M. 1995. Dominant influence of atmospheric circulation on snow accumulation in Greenland over the past 18,000 years. *Nature* (London), **373**, 52–54.

LEMMEN, D. S. 1989. The last glaciation of Marvin Peninsula, northern Ellesmere Island, High Arctic, Canada. *Canadian Journal of Earth Sciences,* **26**, 2758–2590.

LEMMEN, D. S. and ENGLAND, J. 1992. Multiple glaciations and sea level changes, northern Ellesmere Island, high arctic Canada. *Boreas,* **21**, 137–152.

RETELLE, M. J. 1986. Glacial geology and Quaternary marine stratigraphy of the Robeson Channel area, northeastern Ellesmere Island, Northwest Territories. *Canadian Journal of Earth Sciences,* **23**, 1001–1012.

TUSHINGHAM, A. M. 1991. On the extent and thickness of the Innuitian Ice Sheet: a postglacial-adjustment approach. *Canadian Journal of Earth Sciences,* **28**, 231–238.

WALCOTT, R. I. 1972. Late Quaternary vertical movements in eastern North America: quantitative evidence of glacio-isostatic rebound. *Reviews of Geophysics and Space Physics,* **10**, 849–884.

WEIDICK, H. P. 1975. *A review of Quaternary investigations in Greenland*. Institute of Polar Studies, Ohio State University, Columbus, OH, Report No. 55.