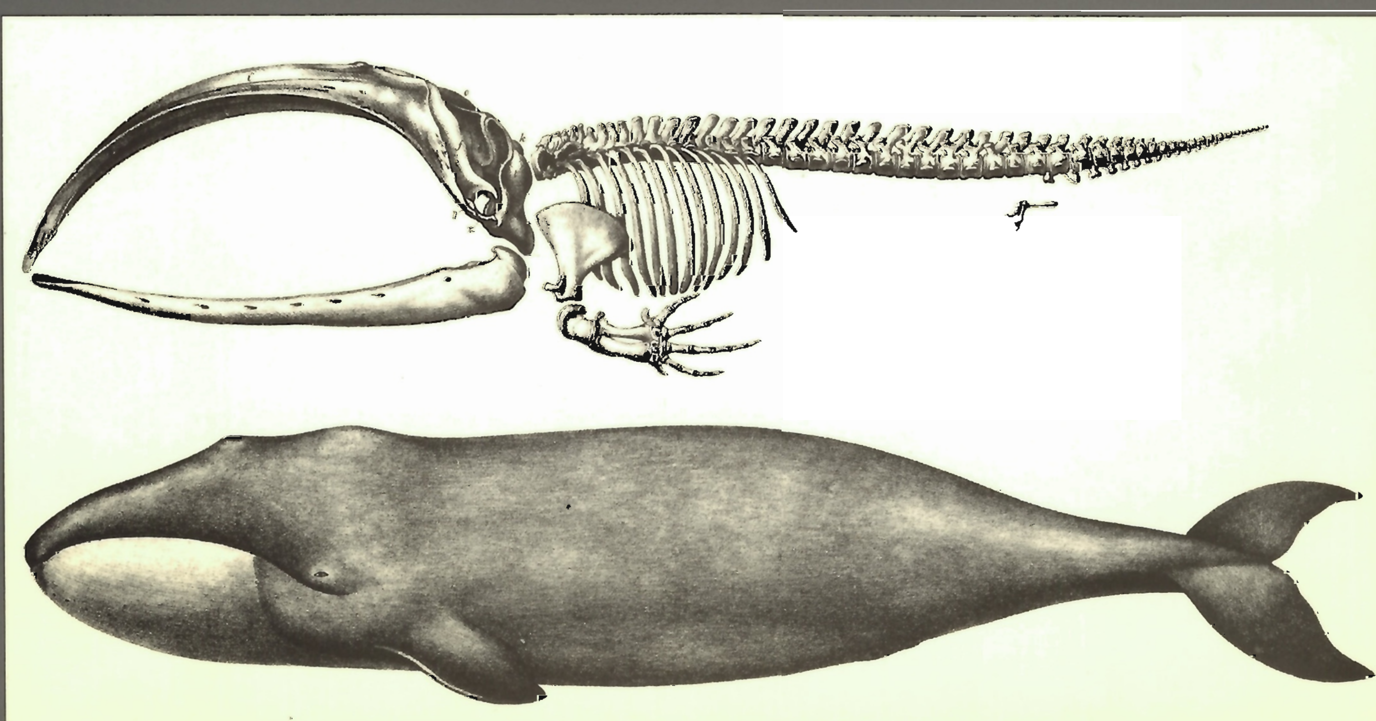
GEOLOGICAL SURVEY OF CANADA
PAPER 89-24

POSTGLACIAL HISTORY OF THE BOWHEAD WHALE AND OF DRIFTWOOD PENETRATION; IMPLICATIONS FOR PALEOCLIMATE, CENTRAL CANADIAN ARCTIC

Arthur S. Dyke and Thomas F. Morris

1990



Energy, Mines and Resources Canada
Energie, Mines et Ressources Canada

Canada

THE ENERGY OF OUR RESOURCES

THE POWER OF OUR IDEAS

GEOLOGICAL SURVEY OF CANADA
PAPER 89-24

POSTGLACIAL HISTORY OF THE BOWHEAD WHALE AND OF DRIFTWOOD PENETRATION; IMPLICATIONS FOR PALEOCLIMATE, CENTRAL CANADIAN ARCTIC

Arthur S. Dyke and Thomas F. Morris

1990

Available in Canada through authorized bookstore agents
and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa,Ontario K1A 0E8

3303-33rd Street N.W.
Calgary, Alberta T2L 2A7

A deposit copy of this publications is also available for reference in
public librairies across Canada

Cat. No. M44-89/24E
ISBN 0-660-13719-4

Price subject to change without notice

Critical Reader:

C.F.M. Lewis

Author's addresses:

A.S. Dyke
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario, K1A 0E8

T.F. Morris
Engineering and Terrain Geology Division
Ontario Geological Survey
77 Grenville Street
Toronto, Ontario, M5S 1B3

Cover description:

Drawing of a bowhead whale (from Eschricht and Reinhardt,1866).
Full grown bowhead whales reach 20m in length.

Manuscript submitted 07-06-89
Final version approved 25-08-89

CONTENTS

POSTGLACIAL HISTORY OF THE BOWHEAD WHALE AND OF DRIFTWOOD PENETRATION; IMPLICATIONS FOR PALEOCLIMATE, CENTRAL CANADIAN ARCTIC

Abstract

This report is the first to document changes in the summer range of the bowhead whale (Balaena mysticetus) *throughout postglacial time. These changes are documented for the central Canadian Arctic and are compared to changes in frequency of penetration of boreal driftwood during the same time interval in the same area. The current and former range of the whale is governed by sea ice conditions. The postglacial period is here divided into four parts. (1) 11000-8500 BP: a large bowhead population extended in the summer from Beaufort Sea to Baffin Bay with the first animals arriving in the central Arctic from Beaufort Sea while access from Baffin Bay likely was still blocked by glacier ice; no driftwood reached the central Arctic because meltwater driven currents created continuous outflow from the archipelago. (2) 8500-5000 BP: bowheads were excluded from the central Arctic channels but small amounts of driftwood arrived, which indicates congestion by moving pack ice rather than by landfast ice; arrival of wood and increased sea ice congestion indicate establishment of an oceanographic circulation pattern similar to that of today. (3) 5000-3000 BP: bowheads from Baffin Bay reoccupied the central Arctic channels either in lower numbers or less frequently than during the early Holocene; driftwood arrived in increased abundance. (4) 3000 BP-present: bowheads were excluded from the central Arctic channels during most summers but frequency of driftwood penetration reached its postglacial maximum.*

Major moraine deposition (Cockburn, Flint, and their age equivalents throughout the Arctic Islands) occurred during periods of more open water. Periods of aridity (8500-5000 BP) caused slow glacier retreat.

Résumé

Le présent rapport est le premier à décrire les changements survenus au sein de l'habitat estival de la baleine boréale (Balaena mysticetus) *au cours de la période postglaciaire. Ces changements sont décrits pour la partie centrale de l'Arctique canadien et sont comparés aux variations de la fréquence à laquelle du bois flotté boréal a pénétré dans cette région au cours de la même période. L'habitat de la baleine, tant par le passé qu'aujourd'hui, dépend des conditions de la glace de mer. La période postglaciaire est divisée en quatre parties aux fins du présent rapport. (1) De 11 000 à 8 5 00 B.P., une population considérable de baleines boréales a habité au cours de l'été les eaux s'étendant de la mer de Beaufort à la baie de Baffin; les premiers animaux qui sont arrivés dans la partie centrale de l'Arctique provenaient de la mer de Beaufort, les couloirs d'accès à partir de la mer de Baffin étant probablement encore bloqués par les glaciers. Il n'y avait pas de bois flotté dans la partie centrale de l'Arctique au cours de cette période, à cause des courants alimentés par l'eau de fonte qui faisaient en sorte que les eaux s'écoulaient continuellement de l'archipel. (2) De 8 500 à 5 000 B.P., les baleines boréales n'ont pu pénétrer dans les détroits du centre de l'Arctique, mais de petites quantités de bois flotté se sont rendues jusque là, ce qui indique que les détroits étaient encombrés par de la banquise à la dérive plutôt que par de la glace côtière fixée. La présence de bois flotté et la plus grande congestion due à la glace de mer témoignent de l'établissement d'une circulation océanique semblable à celle qu'on connaît aujourd'hui. (3) De 5 000 à 3 000 B.P., les baleines boréales de la baie de Baffin se sont de nouveau manifestées dans les détroits du centre de l'Arctique, mais en moins grand nombre ou moins fréquemment qu'au début de l'Holocène; le bois flotté, par contre, est devenu de plus en plus abondant. (4) Pour ce qui est de la période de 3 000 B.P. à aujourd'hui, on note que les baleines sont exclues des détroits du centre de l'Arctique la plupart des étés, mais que le bois flotté pénètre dans la région plus fréquemment que jamais depuis la déglaciation.*

D'importantes moraines (Cockburn, Flint et d'autres moraines contemporaines partout dans les îles de l'archipel Arctique) se sont formées lorsque la zone d'eau libre était plus vaste. Des périodes d'aridité (de 8 500 à 5 000 B.P.) ont ralenti le retrait des glaciers.

INTRODUCTION

The bowhead whale, *Balaena mysticetus,* is by far the largest of the three arctic whale species. Hence, its remains are readily distinguished from those of the narwhal *(Monodon monoceras)* or those of the beluga *(Delphinapterus leucas).* Remains of bowheads have been reported from raised marine deposits in Arctic Canada, Greenland, and Spitsbergen (e.g., Vibe, 1967) and a few have been radiocarbon dated. Radiocarbon dating has been done primarily for the purpose of establishing local histories of relative sea level change (e.g., Barr, 1971; Blake, 1975; Dyke, 1979a). Dates reported in the literature establish the fact that the bowhead has occupied Arctic Canada through postglacial time but until now no one has examined changes in bowhead abundance or range throughout the postglacial.

This report presents the frequency distribution of 53 radiocarbon dates on bowhead bones collected during four summer field seasons on Somerset and Prince of Wales islands in the central Arctic (Fig. 1, Appendix 1). We use these dates to document changes in the summer range of the whale during the last 10 500 years and to infer the sea ice conditions that have governed these changes.The information presented on bowhead ecology serves as a background for assessing its postglacial history.

Changes in frequency of boreal driftwood penetration into the Arctic Archipelago during postglacial time have been noted and interpreted in terms of changes in sea ice conditions (Blake, 1972; Stewart and England, 1983). We present the frequency distribution of 57 radiocarbon-dated postglacial driftwood samples from Somerset and Prince of Wales islands (Appendix 1) and compare them to the changes in bowhead abundance in the same areas to assess the utility of the driftwood record as a paleosea-ice indicator and to infer changes in oceanographic circulation patterns.

THE BOWHEAD WHALE

The bowhead whale has been referred to as the Greenland whale, the right whale, the polar whale, and the common whale. It is a pan-arctic species that comprises a number of geographic stocks that have been depleted to the brink of extinction by commercial whaling, primarily between AD 1719 and 1915 (Ross, 1979). The largest remaining population winters in the Bering Sea and consists of about 7000 individuals, the remnant of an original stock of 18 000-36 000 (R. Reeves, personal communication, 1989). During spring and summer it advances through Bering Strait, whereafter most of it turns eastward to summer feeding grounds in the Beaufort Sea, currently penetrating as far eastward as eastern Amundsen Gulf and as far northward as Prince Patrick Island (Fig. 1). The population in eastern Canadian Arctic waters has been reduced to a few hundred individuals from an initial stock of more than 11 000 (Reeves et al., 1983). This population winters along the pack ice edge between northern Labrador and West Greenland and advances during the spring and summer months into Hudson Bay, Foxe Basin, northern Baffin Bay, Lancaster Sound, Prince Regent Inlet, and Barrow Strait (Fig. 1). The population summering in Hudson

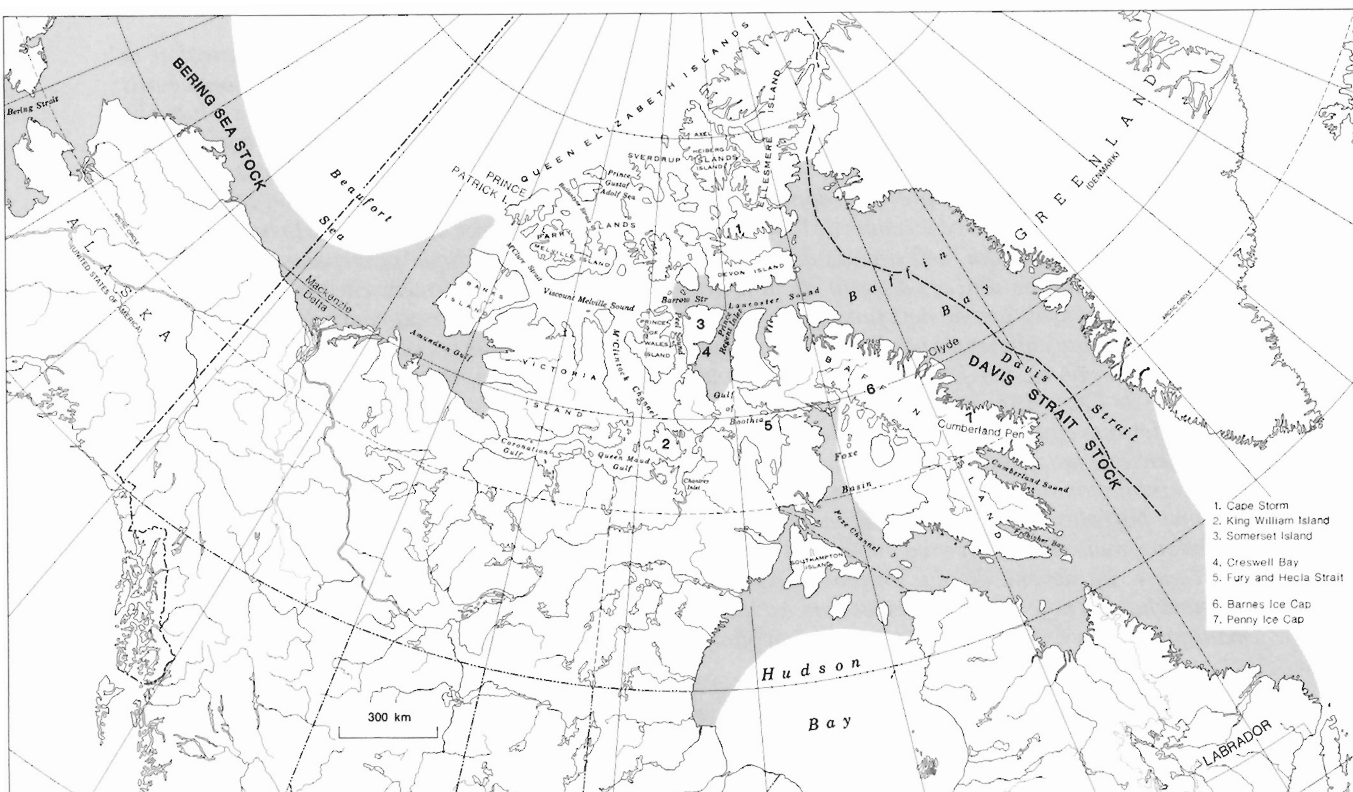


Figure 1. Current and historical distribution of bowhead whale stocks.

Bay and Foxe Basin had an initial size of only about 1000 or less and now numbers less than 100. Possibly the Foxe Basin-Hudson Bay group is a biologically distinct stock but there is no proof of this at present, and most of the group likely winters in the same area as the eastern Canadian Arctic (Davis Strait) group. Whether or not there is presently interchange between summer populations in Prince Regent Inlet and Foxe Basin via Fury and Hecla Strait is not known but was a favourite theory of European whalers (Reeves et al., 1983). The Spitsbergen-Greenland Sea stock, the earliest to be commercially exploited, is near extinction (Reeves, 1980).

The bowhead is adapted to an ice-edge habitat, wintering near the edge of the pack ice, following it northward in spring and summer, often exploiting leads well within the pack ice, and retreating from its summer feeding grounds as late as possible. Its "movements within a stock area are determined principally by ice conditions. The dynamic nature of the sea ice regime means that short and long term changes in the bowhead distribution might be expected ... and that fragmentation or integration in the aggregate population may occur..." (Reeves et al., 1983). This close linkage between the bowhead range and sea ice conditions provides the basis for inferring environmental history from changes in its range during postglacial time. There is evidence that the bowhead engages in some feeding during late winter and spring but the summer months result in a feeding binge, so summer conditions may be most critical to survival (R. Reeves, personal communication, 1989).

The only known predator of the bowhead is the killer whale *(Oricnus orca)*. Otherwise, natural mortality results from old age and ice entrapment although there is little information on the relative importance of these factors.

STUDY AREA IN RELATION TO BOWHEAD STOCKS

The Davis Strait bowhead stock was hunted extensively by British whalers using sailing ships in Lancaster Sound, and later using steam powered ships in Prince Regent Inlet and Barrow Strait. The western limit of abundant summer bowheads during the historical whaling period was near the north end of Peel Sound. Most of Prince of Wales Island lies beyond the historical limit of bowheads and beyond the apparent limit of Thule Eskimo bowhead whaling (McCartney and Savelle, 1985), whereas the north and east coasts of Somerset Island lie adjacent to its zone of abundance. Ice-choked M'Clintock Channel and Viscount Melville Sound, west of Prince of Wales Island, constitute the barrier that separates the summer ranges of the present and historical Davis Strait and Bering Sea stocks. This barrier also separates Pacific and Atlantic stocks of white whale, narwhal, and walrus and hampers interchange of various species of seal (Harington, 1966).

RADIOCARBON-DATED BOWHEADS

Bones of bowheads were been collected from raised mrine sediments and from colluvium below the postglacial marine limit at 112 sites on Prince of Wales, Somerset, and adjacent smaller islands. These collections were made in 25 camp or traverse areas. No more than 10% of the terrain below marine limit was searched and no single area was searched exhaustively, so the total number of postglacial bowhead skeletons, or parts thereof, present on these islands likely exceeds 1000. In addition, remains of hundreds of bowheads occur at low elevations near Thule Eskimo archeological sites and along associated flensing beaches. McCartney and Savelle (1985) estimate that between 1000 and 1500 Thule-killed bowheads are represented at archeological sites along the southeastern coast of Somerset Island.

Bowhead bones not associated with archeological sites most typically are found protruding from raised beach gravel or sand or from colluviated (soliflucted) till.There is no way of estimating the fraction of total bones present that are exposed as opposed to completely buried. All manner of bowhead bones have been encountered but among the most common are the large triangular cranial bases (occipital region) which typically measure 180-220 cm across, as measured from the ends of the processes (temporal bones) on either side of the spinal opening. A range of bone types has been utilized for radiocarbon dating but the ideal sample for this purpose is the ear bone, either the otic capsule or the periotic bones, because of its density, hence excellent preservation (see Dyke et al., in press, Fig. 7). During the course of this research, we made increasing efforts to recover ear bones for dating. If this was not possible, other bones were used after careful pretreatment by sectioning and selective subsampling in order to avoid spurious radiocarbon age determinations that can result from analyses of bones submitted in field condition for dating (eg. Dyke, 1980; Dyke et al., in press; Appendix 1).

The original purpose of the radiocarbon dating program was to establish emergence (relative sea level) curves for as many sites as possible; hence driftwood, marine shells, and other materials were also dated (Dyke et al., in press). The point of importance to this discussion is that bowhead bone samples were selected for dating on the basis of their elevations. For example, if samples of whale bone had been collected from elevations of 5, 20, 55, 56, 57, 60, and 90 m in any area, we likely would have submitted only the samples from 5, 20, 60, and 90 m for dating, excluding the samples from 55, 56, and 57 m. The hopeful assumption, as far as sea level history reconstruction is concerned, is that many of the bowhead bones represent animals that either floated ashore after dying or died at the beach, rather than animals that sank to the bottom some distance offshore. If this assumption were correct in all cases, the strategy for selecting samples for radiocarbon dating would tend to underrepresent elevation (hence age) clusters. In the Prince of Wales Island area, the assumption is not correct in more than half of the cases because we know that many of the bone elevations plot below the emergence curves (i.e., the animals sank some distance

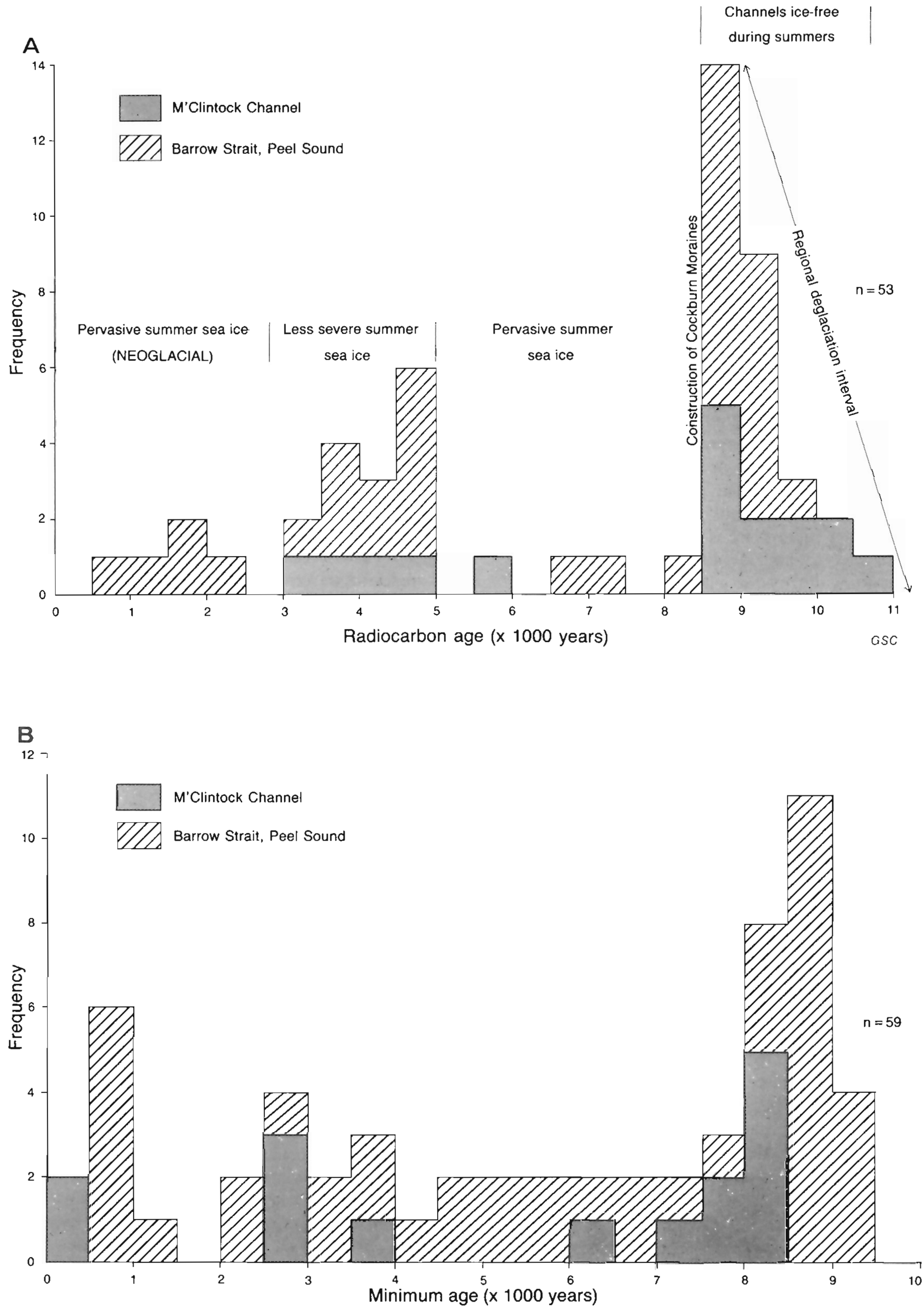


Figure 2. A. Frequency distribution of 53 radiocarbon-dated bowhead whale specimens with age, central Canadian Arctic, B. Minimum ages of 59 undated bowhead whale specimens, central Canadian Arctic.

offshore; Dyke et al., in press). The frequency distribution, despite the bias in selection of samples for dating, is strongly bimodally clustered.

The postglacial period in the central Arctic is here divided into four intervals based on the bimodal bowhead abundance (Fig. 2A). Of the 53 radiocarbon-dated specimens, 29 (55%) are older than 8500 years. Only 4 specimens (8%) date from the interval 8500 to 5000 years ago, but 15 specimens (28%) date from the interval 5000 to 3000 years ago. Lastly, only 5 specimens (9%) date from the last 3000 years.

The oldest dated specimen is from northwestern Prince of Wales Island. It yielded an age of 10 530 ± 145BP (S-2591), which is currently the oldest reliable radiocarbon date on a postglacial bowhead from Arctic Canada. Prince of Wales Island was deglaciated during the interval 11 000 to 9000 years ago, but only the northern and northwestern extremities were deglaciated before 9500 years ago. The oldest radiocarbon-dated postglacial material from Somerset Island is a bowhead bone dated at 9590 ± 115 BP (S-1381). It came from the northwest corner of the island, which was probably the first part to be deglaciated; the entire area below marine limit on Somerset Island was free of glacier ice by about 9000 years ago (Dyke, 1984; Dyke and Prest, 1987). The apparent increase in abundance of bowheads on Prince of Wales and Somerset islands (Fig. 2A) between 10 500 and 9000 years ago likely is an artifact of the steadily increasing extent of terrain, initially below sea level, since emerged, which became free of glacier ice during that interval. A survey of areas to the northwest that were deglaciated earlier, such as parts of northern Victoria Island, might reveal that bowhead bones dating between 9500 and 11 000 years ago are as abundant there as those on Prince of Wales Island dating between 8500 and 9500 years ago. Hence the data do not indicate improving conditions for bowheads between 11 000 and 9000 years ago. Instead, they indicate that summer conditions provided suitable bowhead habitat throughout the interval of regional deglaciation. The locations of bowhead bones that are more than 9000 radiocarbon years old, and independently dated ice marginal positions on Prince of Wales Island, indicate that these whales occupied marine waters right up to the retreating calving glacier front (Fig. 3). Numerous icebergs calving off the retreating ice front left fields of iceberg scours now visible on the emerged flat terrain of the Prince of Wales Lowland. But apart from these icebergs the marine channels must have been largely free of sea ice during the summers.

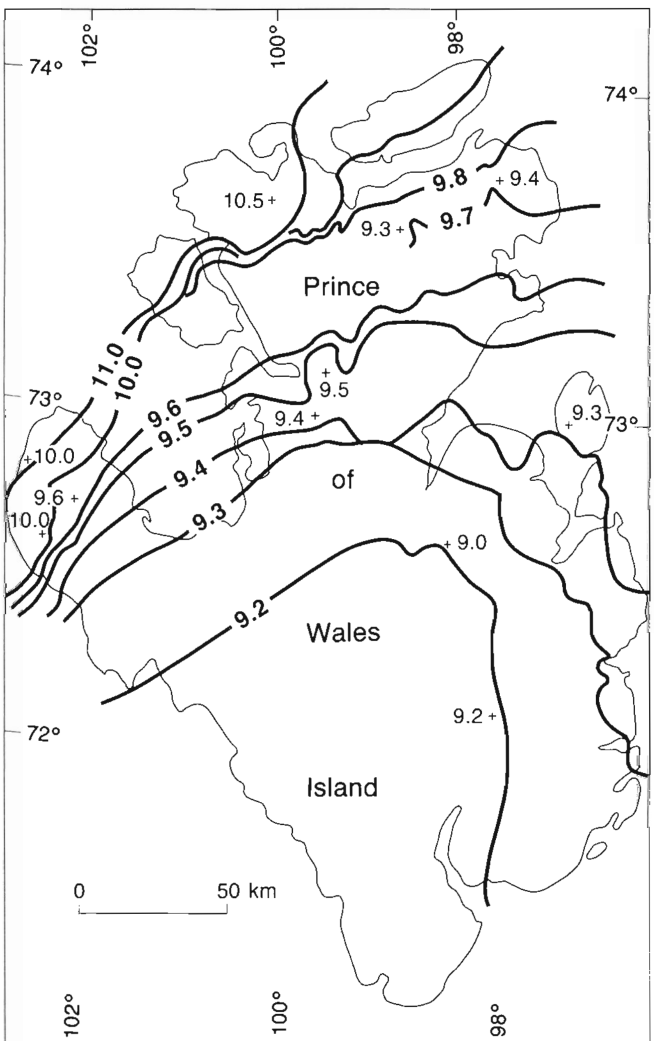


Figure 3. Location and ages of early Holocene bowhead whale specimens on Prince of Wales Island in relation to deglaciation isochrones.

From 8500 to 5000 years ago few bowheads seem to have entered the channels north and east of Prince of Wales Island and even fewer entered M'Clintock Channel. The Davis Strait and Bering Sea bowhead stocks likely were unable to mix then. The single dated specimen from this interval classified in the M'Clintock Channel group is from central King William Island and is the only bowhead bone sample yet recovered from that island. It could have gained access from Baffin Bay via either Peel Sound or M'Clintock Channel or conceivably even have come from the Beaufort Sea to the west via the straits south of Victoria Island. We interpret the period 8500-5000 years ago as one characterized by pervasive summer sea ice, sufficiently closed to discourage bowheads from entering the survey area. The change from large summer bowhead populations to no bowheads during most summers seems to have been remarkably abrupt. The change back to larger summer bowhead populations 5000 years ago seems to have been abrupt as well. There undoubtedly were exceptional summers between 8500 and 5000 years ago when the sea ice moved out of the central Arctic channels and some of these may be represented by the four radiocarbon-dated specimens. Although it could be argued alternatively that there was too little sea ice during this interval to provide the ice-edge habitat preferred by the bowhead, this would require an absence of sea ice even in the winter; if winter sea ice formed, as is likely, the bowheads would occupy the area during breakup.

During the period of renewed bowhead abundance from 5000 to about 3500 or 3000 years ago the average summer bowhead population in the central Arctic seems not to have reached its early Holocene levels. The animals reoccupied both M'Clintock Channel and the channels farther east but were relatively less frequent in M'Clintock Channel. This implies that there were many summers when the channels east of Prince of Wales Island provided attractive bowhead habitat while M'Clintock Channel remained too ice congested. During those summers when bowheads ranged into M'-Clintock Channel, the Davis Strait and Bering Sea bowhead stocks possibly had the opportunity to mix; surveys of Holocene bowheads on Victoria Island could clarify this.

The difference between apparent summer abundance of bowheads during the middle and early Holocene periods of relatively high abundance could be explained in different ways. For example, perhaps only 50% of summers were suitable for bowhead occupancy of the central Arctic channels during the period 5000 - 3000 years ago compared to all summers between the time of deglaciation and 8500 years ago. Alternatively, the eastern Arctic bowhead stock by 5000 years ago may have declined after 3500 years of reduced summer feeding range and perhaps higher mortality (in other areas) due to ice entrapment. Another possible explanation, again entertaining differences in absolute population size, could be that the central Arctic channels during the early Holocene regional deglaciation interval had much higher nutrient conditions than during any later periods because of water mass turbulence caused by meltwater, iceberg, and sediment flux. Hence, it is possible that for nonclimatic reasons the central Arctic channels were never able to support as large a summer population as they could during deglaciation. This does not mean that an equally large but more dispersed population did not exist. Possibly the importance of some of the factors in the future can be addressed by tracing the postglacial history of the bowhead throughout the Arctic. If the abrupt changes in abundance at 8500 and 5000 BP could be shown to have occurred synchronously throughout the North American Arctic, the case for a primarily climatic cause would be strengthened. But if bowheads were numerous in Foxe Basin 7000-6000 years ago, the interval of deglaciation of that area, other factors such as enhanced nutrient status would have to be considered.

At about 3000 years ago summer access of the bowhead to the central Arctic was again reduced. Animals continued to penetrate as far west as Peel Sound during some summers but M'Clintock Channel apparently remained beyond their range. Hence, the Bering Sea and Davis Strait stocks likely have been segregated for at least 3000 years, if not for 8500 years. The last 3000 years is globally recognized as a period of Neoglaciation, when arctic and alpine glaciers readvanced several times. The presence of a distinct Neoglacial signal in the central Arctic bowhead whale history suggests that the changes in abundance at other times (other than the depletion by commercial whaling during historical time) are climatically, or at least environmentally, controlled in large part. But again a decline in the Neoglacial (last 3000 years) summer population in the central Arctic does not mean that there was an overall reduction in the Davis Strait bowhead stock. Their range may simply have been displaced eastward and southward.

The 59 undated samples of bowhead bones (Appendix 1) can be assigned minimum ages (Fig. 2B) on the basis of their elevations and relative sea level curves and isobase maps available for the sample areas (Dyke et al., in press). The true ages of many of these samples are considerably older than these minimum ages because we know from the radiocarbon-dated samples that many of the animals did not float ashore but sank in some depth of water. However, most of the group

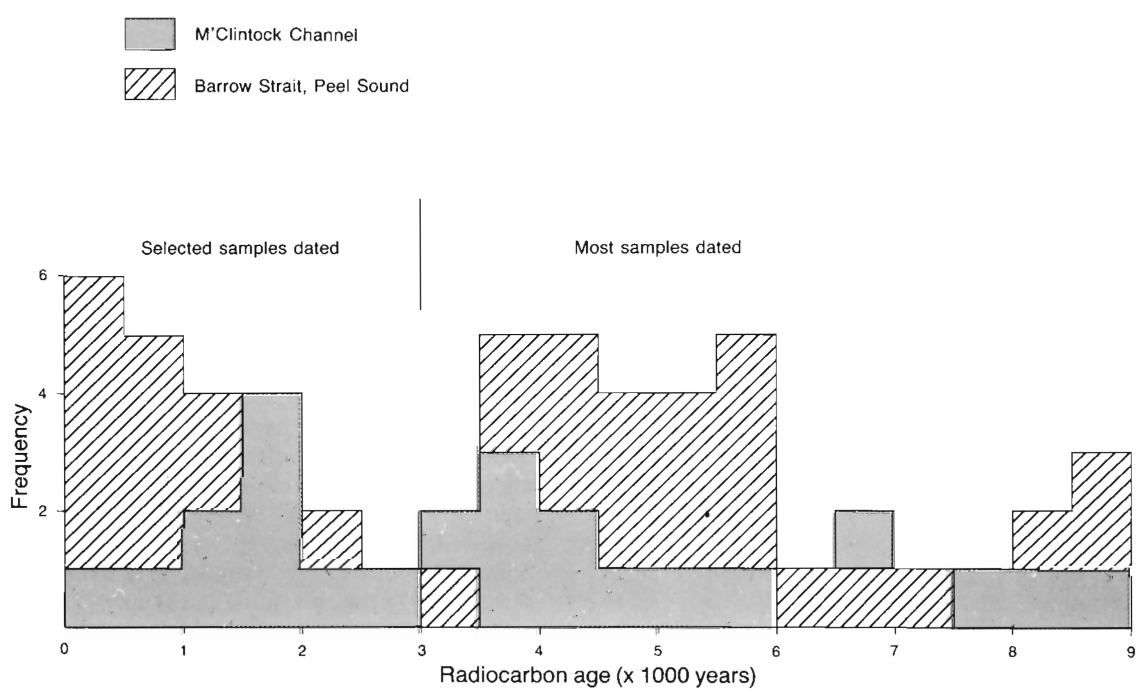


Figure 4. Frequency distribution of 57 radiocarbon-dated boreal driftwood (spruce, pine, larch) specimens, central Canadian Arctic.

that have minimum ages of 8000-9500 years cannot be older than 9500 years because these samples all come from sites that were deglaciated after 10 000 BP and mostly after 9500 BP. The only significant feature of the histogram of Figure 2B is the strong mode at 8000-9500 BP (40% of the undated specimens). Based on the experience of radiocarbon dating nearly half of all the samples collected, we suspect that nearly all of the samples with minimum ages of 8000-8500 years are actually older than 8500 years. This distribution illustrates that the early Holocene abundance of bowheads can be recognized in the field by the extraordinary abundance of bones at and above the elevation of the 8500 year old shoreline, which on Prince of Wales Island lies at 60-70 m (Dyke et al., in press). During field work we referred to this elevational interval as the "main bowhead level".

DRIFTWOOD AS AN INDICATOR OF POSTGLACIAL SEA ICE CONDITIONS

Changes in abundance of boreal driftwood penetrating the Canadian Arctic Archipelago have been used to suggest changes in postglacial climate and, in particular, in sea ice conditions (Blake, 1972; Stewart and England, 1983). Periods when driftwood arrived in abundance are thought to signify periods of more open water. Radiocarbon dates are now available on 57 samples of stranded driftwood from Prince of Wales and Somerset islands, from the same surveyed areas as the bowhead bone samples (Fig. 4). If both bowhead ranges and driftwood penetration are controlled by summer sea ice conditions, we should expect a positive correlation between the two records.

Virtually all driftwood samples that were collected from elevations that would indicate ages greater than about 3000 years were radiocarbon dated for the purpose of constructing relative sea level curves. Samples from lower elevations (younger than 3000 years) were selectively dated (about 1 out of 3 collected) and not all wood found in the lower 5 m or so (about 1000 years old and less) was sampled because of the considerable abundance of material there. Hence the histogram of Figure 4 under-represents the relative abundance of driftwood younger than 3000 years by a factor of at least 2.

The oldest driftwood arriving in the central Arctic during postglacial time dates just over 8500 years old (S-2720, 8660 ± 395 BP; GSC-4343, 8680 ± 90 BP; S-2702, 8695 ± 130 BP). Hence during the 2500-3000 years prior to 8500 BP when bowheads were abundant, hardly any, if any, driftwood arrived (the standard errors of the three oldest samples are such that the true ages could be very close to 8500 BP or slightly less), despite what must have been a prevalence of open water during the summers. Blake (1972) has noted almost precisely the same timing of initial driftwood arrival in the eastern Queen Elizabeth Islands. Currently, the oldest dates available on driftwood of postglacial age from the Arctic Archipelago are 8915 ± 115 BP (S-2211) and 8850 ± 50 BP (GSC-4559) (Stewart and England, 1983; Bedneaski, 1986; Lemmen, 1988), both from the northernmost coast of Ellesmere Island. The near absence of driftwood older than 8500 years is surprising because treeline was north of present in the Mackenzie Delta 11 500 years ago (Ritchie et al., 1983).

Frequency of driftwood penetration to the central Arctic remained low until 6000 years ago, when it increased and remained high until about 3500 years ago or possibly until present. Possibly the 6000-3500 BP peak or increase in frequency of driftwood penetration correlates with the 5000-3000 BP abundance of bowheads. Although the beginnings are offset by 1000 years, it could be argued that the sea ice conditions had improved sufficiently for driftwood penetration by 6000 BP but were not good enough for bowheads until 5000 BP. The increase in frequency of driftwood penetration about 6000 years ago seems to have occurred widely throughout the archipelago (Fig. 5; Blake, 1972; Williams and Bradley, 1985).

Clearly the highest frequency of driftwood penetration to the central Arctic was during Neoglacial time and possibly a more complete radiocarbon dating program to remove the underrepresentation of younger wood would yield a distribution approaching an exponential or linear increase in driftwood frequency throughout the middle and late Holocene. Hence, like the early Holocene but in contrast to the middle Holocene, the driftwood and bowhead records are negatively correlated during the Neoglacial. Wood continued to arrive via the central Arctic channels even during periods of bowhead exclusion. This means that the channels, including much of the shore zone, were occupied by moving pack ice rather than by landfast ice.

The fact that driftwood penetration to the central Arctic shores was at its maximum during the last 3000 years, when summers were colder (Neoglaciation) and when local summer bowhead abundance was low, indicates that driftwood abundance is not a reliable local paleoclimate indicator, or at least not a simple one. It is entirely possible that the long distance transport of driftwood to the Arctic Islands may depend on rafting of the wood (which usually is found as fragments of logs) on sea ice as this would prevent the wood from becoming saturated and sinking en route. Alternatively, changes in driftwood abundance in the Arctic may reflect distant causes such as changes in treeline or permafrost degradation within boreal forest areas, hence greater treefall into boreal rivers.

A marked reduction of driftwood arrival in the Queen Elizabeth Islands at about 4000-3500 years ago has been noted (e.g., Blake, 1972). This contrasts sharply with the central Arctic driftwood record and requires explanation. The dated driftwood from the Queen Elizabeth Islands is predominantly from two localities: from Cape Storm on southern Ellesmere Island (Fig. 5A) and from behind the large ice shelves in northern Ellesmere Island (Fig. 5B). The raised beaches at Cape Storm occupy a small cove. Today bays and coves are often occupied by landfast ice while adjacent channels are open or are occupied by moving pack ice. Possibly the cove at Cape Storm was occupied by landfast ice during most of the Neoglacial; driftwood arrival may have continued unabated elsewhere in Jones Sound. The wood behind the ice shelves of northern Ellesmere Island necessarily predates the ice shelves, which formed in early Neoglacial time. The absence of Neoglacial-age driftwood there does not signify that driftwood arrived less abundantly at the outer edge of the ice shelves during that time.

THE COCKBURN EVENT

The Baffin Sector of the Laurentide Ice Sheet built closely spaced sets of end moraines around most of its terrestrial perimeter between about 9000 and 8000 years ago. Many alpine glaciers east of the Laurentide margin also built moraines at that time (Andrews and Ives, 1978). The northern margin of the Keewatin Sector of the ice sheet constructed impressively continuous end moraines about 8600 to 8400 years ago (Dyke, 1984) and these can be traced eastward into the moraines of Cockburn age (9000-8000 years) of the Baffin Sector (Fig. 6). Early Holocene moraines also were built extensively by the ice caps of northern and western Ellesmere Island (England, 1978; Hodgson, 1985; Fig. 6). Hence, the Cockburn-age moraines of the Keewatin Sector coincide in time with the abrupt termination of summer bowhead occupation in the marine channels of the central Arctic while the Cockburn-age moraines of the Baffin Sector and of the local glaciers started to form shortly before and continued to form a little after the 8500 year central Arctic bowhead "termination". The central Arctic bowhead termination 8500 years ago also coincides closely with the initial penetration of driftwood to the same areas and apparently with initial driftwood penetration to a large part of the Queen Elizabeth Islands as well.

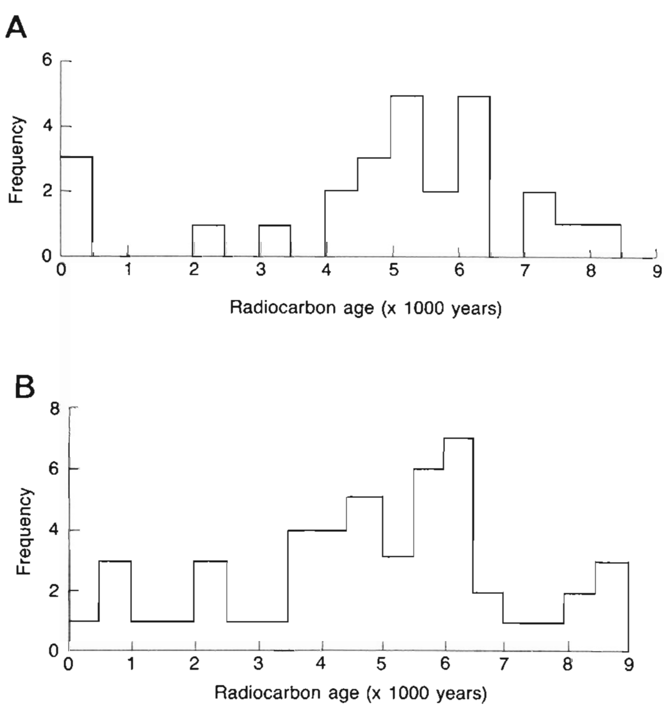


Figure 5. Frequency distribution of radiocarbon-dated driftwood from A. Cape Storm, Ellesmere Island and B. north coast of Ellesmere Island, predominantly behind ice shelves.

A key question is what climatic conditions caused the moraine-building during the Cockburn substage? The two likely answers are:

(1)the Cockburn-age moraines represent the glaciological response to the same summer conditions that led to the apparent exclusion of bowheads from the central Arctic; these conditions had set in by about 9000 years ago on eastern Baffin Island, or

(2)the Cockburn-age moraines represent the glaciological response to open water conditions, recorded in the central Arctic by abundant summer bowheads. The open water would have generated enhanced snowfall on the northern Laurentide Ice Sheet during autumn and possibly spring months while, as today, creating foggy and cool summers that would reduce ablation.

Because the Cockburn-age moraines on eastern Baffin Island span a half millennium prior to the 8500 year bowhead termination in the central Arctic as well as a half millennium after, one could argue that the second answer is correct with the Cockburn moraines younger than 8500 years representing a lag in glaciological response of the Laurentide Ice Sheet to the change in climate at 8500 years ago. Retreat from the Cockburn-age moraines would then have to be explained as a response to increased aridity.

Palynological and macrofossil data from eastern Baffin Island and from Bathurst Island favour the "warm and wet Cockburn" over the "cold Cockburn" interpretation. For example, Short et al. (1985, p. 623) reported that on southern Cumberland Peninsula, at a site just beyond the Cockburn-age moraines, "exotic tree and shrub pollen (alder, spruce, and pine) influx was higher between 9200 and 8700 BP than at any time until 5800 BP, suggesting the importance of strong summer airflow from the boreal forest, at that time at least 2000 km to the south and or west... this climatic episode was warm and moist." Further evidence comes from an organic sample "dating 9950 ± 185 BP from the Qivitu region (northern Cumberland Peninsula) containing higher Betula and Alnus percentages than modern samples from the region" (Short et al., 1985, p. 628). Dwarf birch probably expanded as far north as Clyde on eastern Baffin Island during the early Holocene and was some 400 km north of its present limit 9000 years ago (Short et al., 1985, p. 632). Basal peat from central Bathurst Island dated at 9200 BP contained seeds and leaves of plants that are now restricted to areas farther south (Blake, 1972). Hence the warm and wet interpretation of the Cockburn substage followed by cold and arid conditions leading to slow glacier retreat brings the glacial geological record of Cumberland Peninsula, and of eastern Baffin Island in general, into substantial agreement with the paleoecological record and avoids the contradictions noted by Williams and Bradley (1985). The contradictions resulted from their assumption that glacier recession from the Cockburn-age moraines indicated warmer conditions.

Another key question pertinent to the nature of the Cockburn event is what excluded the entry of driftwood from at least the central Arctic channels and southeastern Queen

Figure 6. Paleogeography of the middle Cockburn substage, about 8500 years ago, the time of the most abrupt and largest change in climate. The Baffin Sector of the ice sheet is the part centred over Foxe Basin; the Keewatin Sector is the part flowing from the ice divide designated K. The bold segment of the ice margin shows the general distribution of Cockburn-age moraines.

Elizabeth Islands and possibly from all of Arctic Canada except for the northernmost coast of Ellesmere Island until about 8500 years ago ? Blake (1972) raised the same question and speculated that the initial arrival might signify an opening up of Davis Strait or a northward advance of the Siberian treeline among other possible causes. The abundance of bowheads in the central Arctic before 8500 years ago demonstrates that the wood was not excluded by perennial sea ice locally. Conceivably the early Holocene bowhead summer population in the central Arctic was an extension of the Bering Sea stock, and Baffin Bay, or at least northern Baffin Bay, may have remained sufficiently ice congested during the summers to block driftwood being brought in by the West Greenland Current from entering the interisland channels. The earliest bowheads to arrive in the central Arctic (oldest date 10 530 ± BP (S-2591) on Prince of Wales Island) likely did come from the Bering Sea stock to the west because Lancaster Sound evidently remained blocked by glacier ice until after 10 000 BP (Dyke and Prest, 1987). Deglaciation of the central south shore of Lancaster Sound has now been placed at 9780 ± 90 BP (GSC-4694) by an assay on marine mollusc shells from proximal glaciomarine sediment. But if northern Baffin Bay did remain sufficiently ice congested to exclude eastern bowheads until 8500 years ago, we still would be left with the question of why driftwood did not arrive in the central Arctic along with the whales from the west via the Beaufort Sea.

Clearly something happened at 8500 years ago that allowed driftwood to penetrate to the shores of the Canadian Arctic Islands. Possibly there was simply too little sea ice before that time in the Arctic channels or even in Baffin Bay and the Arctic Ocean margin to transport wood across large distances; wood that entered the Arctic Ocean and north Atlantic at that time may simply have sunk due to waterlogging. But that would require a High Arctic climate extremely different from that of today. More likely, the surface currents before 8500 BP were so dominated by glacial meltwater originating from the Laurentide Ice Sheet and from the ice caps in the Queen Elizabeth Islands that there was a persistent summer outflow from the archipelago as postulated in Figure 6, thus preventing driftwood from penetrating the archipelago. Subglacial melting by geothermal heat, capable of melting about 1 cm of basal ice per year, and continuous delivery of this meltwater to the subaqueous ice fronts may have extended this outflow into the winter months or even throughout the winter with diminished strength.

The widespread arrival of driftwood in the islands at about 8500 BP may indicate the establishment of a surface water circulation pattern similar to that of today (Fig. 7), which brings widespread driftwood to the modern beach. Certainly there is reason to suspect that such a change might have occurred at about 8500 years ago. Before then the northern Laurentide Ice Sheet had a rapidly retreating subaqueous margin; after that the margin was mostly terrestrial and well over 75% of the volume of Keewatin Ice had melted. Furthermore, iceberg and meltwater flux from the Laurentide Ice Sheet after 8500 BP was predominantly routed through Hudson Strait, presumably into the Labrador Current, and would not have affected circulation through the archipelago. The modern current pattern drives Arctic Ocean basin water southeastward through the archipelago, whereafter it converges at the head of Baffin Bay to provide the major cold water source for the Baffin and Labrador currents. It must be this southeastward flux of Arctic Ocean water that carries the

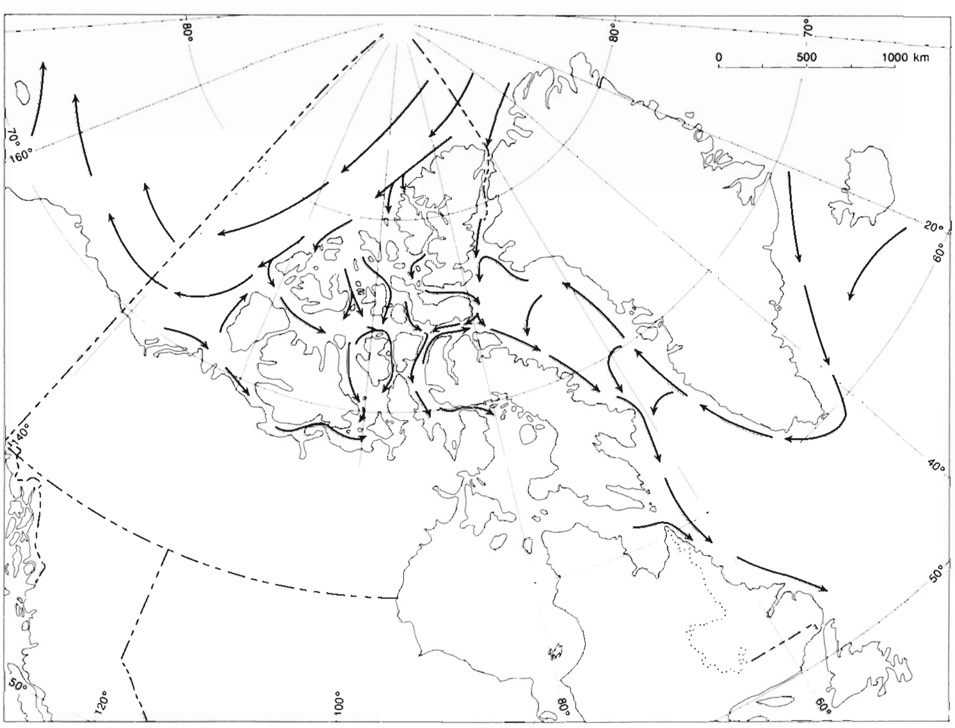


Figure 7. Modern oceanographic circulation in the Canadian Arctic Archipelago.

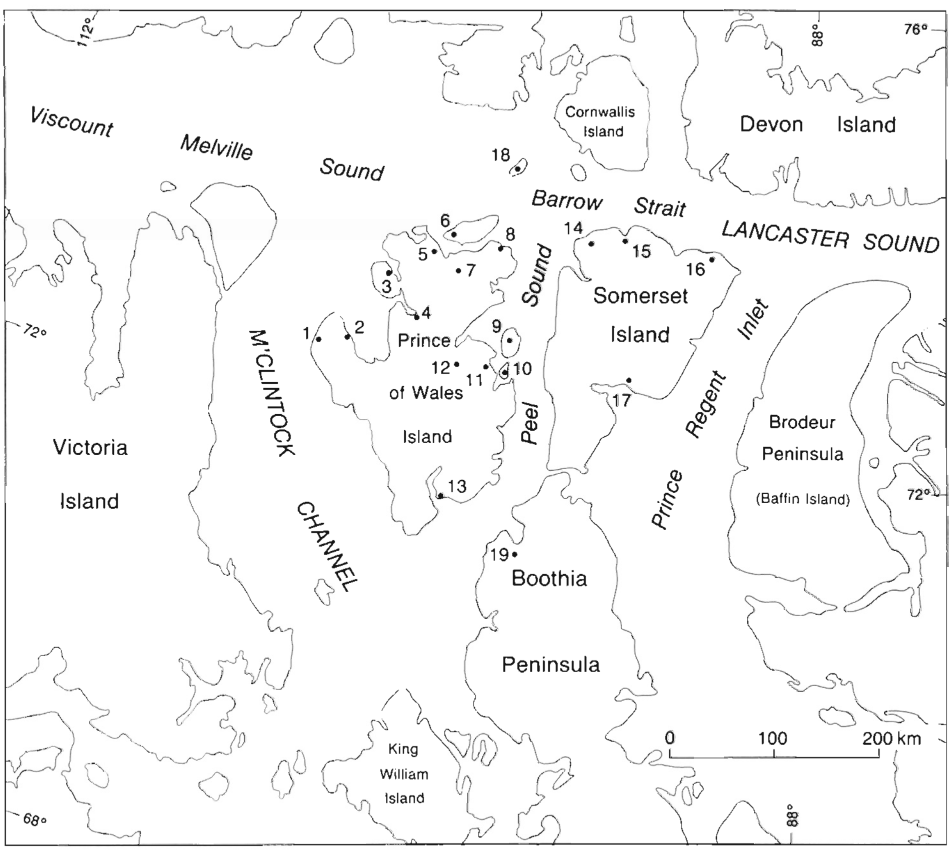
driftwood through the channels at present because there is no other source that can account for the widespread dispersal of wood.

The postulated oceanographic circulation pattern predating 8500 BP would tend to clear the central Arctic channels of sea ice during the summers by exporting it to both Baffin Bay and Beaufort Sea. Hence, the same mechanism, driven by glacial meltwater, can explain (1) the abundance of bowheads in the central Arctic prior to 8500 BP, (2) the absence of driftwood in the central Arctic prior to 8500 BP, and (3) the positive glacier mass balance during the Cockburn substage.

The change to an oceanographic circulation pattern similar to the modern one at 8500 years ago would have had a particularly large effect on summer sea ice conditions in the channels around and south of Prince of Wales Island. Today the currents bring ice southward into M'Clintock Channel and Peel Sound Sound, filling these cul-de-sacs from the mainland coast to Viscount Melville Sound. Once filled, the ablation of ice in these channels is restricted largely to in situ melting, and during most summers this process is not completed.

In the hypothesis presented above, there would not necessaily be any change in the surface ocean circulation pattern in Baffin Bay at 8500 BP. A Baffin Current was operating both before and after that time. But before 8500 BP the surface water of the Baffin Current carried a large glacial meltwater component and hence a reduced component from the Arctic Ocean basin. After 8500 BP, the Laurentide Ice Sheet still provided some meltwater to the Baffin Current, but much more of the surface water in the current would have come from the Arctic Ocean basin. Presumably this would have increased the salinity of the Baffin Current.

Today there are two major routes of egress of Arctic Ocean surface waters - through the Canadian Arctic Archipelago and through the Norwegian and Greenland seas. If



Cape Richard Collinson 1
Hollist Point 2
Drake Bay 3
Smith Bay 4
Arabella Bay 5
Russell Island 6
Allen Lake 7
Cape Hardy 8
Prescott Island 9
Pandora Island 10
Muskox Hill 11
Dolphin River 12
Guillemard Bay 13
Cape Anne 14
Cunningham Inlet 15
Rodd Bay 16
Creswell Bay 17
Lowther Island 18
Wrottesley Inlet 19

Figure 8. Locations of bone and wood samples, central Canadian Arctic.

the Canadian Arctic route was not being used before 8500 BP, most Arctic Ocean surface water and any driftwood carried by it had to exit via the route east of Greenland. Blake (1972) observed that driftwood was stranding on the Spitzbergen shores before 9000 BP, and Salvigsen (1977, 1981) reported seven radiocarbon dates on driftwood more than 8500 years old from two small sample areas in Spitzbergen, with the oldest being 9850 ± 80 BP (GSC-3039). This earlier arrival of driftwood in Spitzbergen than in Arctic Canada is entirely compatible with, and in a general way is required by, our hypothesis.

OTHER REGIONAL CORRELATIONS

To some extent the quest to reconcile all interpretations of Holocene paleoclimatic events through recognizing events that are regionally synchronous and in the same direction (eg., all records indicating warming at the same time) is a fool's errand. Climatic changes can be time transgressive, appearing earlier in one area than in another; different biological and physical systems (sea ice, glaciers, tundra plants) respond to a given climatic forcing at different thresholds; and changes in climate in opposite directions in different areas, and even at somewhat different times, may represent a response to a single event, such as the shift of a major atmospheric pressure system or ocean current. It is important, therefore, not to treat differences in local paleoclimate records as necessarily implying contradictions. We feel that there is no contradiction among data sets indicating abundant bowheads, absence of driftwood, northerly extended tundra plant ranges, and stable or advancing moraine-forming ice margins of both Laurentide and smaller glaciers prior to 8500 BP, although it reverses the traditional interpretation of the driftwood record (Blake, 1972; Williams and Bradley, 1985). It also reverses the interpretation of the Cockburn-age moraines applied by Williams and Bradley (1985, Fig. 26.9) but not by most other workers (eg., 1985; Andrews and Ives, 1972, 1978; Dyke, 1984;Short et al., Dyke and Prest, 1987). The Neoglacial driftwood record in the Arctic islands points to a further complexity. Whereas driftwood stranding in the central Arctic increased strongly in frequency during the Neoglacial, at Cape Storm on southern Ellesmere Island it decreased just as strongly. Regardless of the proper interpretation of these two driftwood records in terms of climatic or sea ice conditions, the records illustrate that a change in one system (sea ice, ocean current, or treeline?) can produce opposite responses in different areas.

A further potentially meaningful correlation may be between the recurrence of bowheads in the central Arctic and the Flint and Outer Penny end moraines on Baffin Island. The Flint Moraine was deposited by the Early Barnes Ice Cap and the Outer Penny Moraine by the Early Penny Ice Cap about 5000 years ago (Andrews, 1982). They are the oldest substantial moraines behind the belt of moraines of Cockburn age and are thought to represent a climatically induced change in glacier mass balance (Dyke and Prest, 1987; Andrews,1989). Although they have been generally taken to indicate a cooling following an earlier climatic optimum, and hence of having a climatic origin different from that of the Cockburn-age moraines, they might, like the Cockburn, be a response to increased precipitation attendant upon more open water in the central and eastern Arctic at 5000 years ago, as indicated by the sudden recurrence of bowheads at that time.

Retreat of the Laurentide ice and its successors, the Early Barnes and Early Penny ice caps, was slow between times of construction of the Cockburn-age and the Flint-Outer Penny moraines because of cold and arid conditions. A lake core from southern Cumberland Peninsula, near the Penny Ice Cap, displays low organic and pollen concentrations between 8700 and 5800 years ago, which suggests to Short et al. (1985, p. 623) cold and arid conditions, the lowest temperatures during the Holocene. After 5800 BP, exotic Alnus pollen percentages increased to a Holocene maximum about 5200 BP and continued high until 2700-2600 BP. Betula reached a Holocene maximum between 5200 and 4700 BP. These times and directions of environmental change are remarkably similar to those suggested by the bowhead history in the central Arctic and do not conflict with the glacial record of the middle Holocene as long as the advances that deposited Flint and Outer Penny moraines are interpreted, like the Cockburn, as precipitation controlled events.

The well documented Neoglacial glacier advances, in contrast to the earlier Holocene advances, appear to be summer temperature controlled events. This is not based on glaciological reasoning as much as it is on the constraint that the other proxy climate records, including the pollen and bowhead records, indicate change to generally colder conditions about 3500 to 2500 years ago. Neoglacial moraines are most conspicuous around the thousands of small alpine glaciers (Davis, 1985) in the eastern and high Arctic and more Neoglacial advances are recorded by cirque glacier moraines than by moraines around larger ice caps such as the Penny (Dyke, 1979b). Most margins of the larger ice caps are as advanced now as they have been at any time since formation of middle Holocene or even Cockburn-age moraines, although the more lobate margins and valley outlet glaciers have pulled back slightly from Little Ice Age positions. Hence there is a contrast between the Neoglacial responses of the larger and smaller arctic glaciers. There is also a contrast between behaviour of the larger ice caps during the Neoglacial (few moraines) and during the middle and early Holocene (many large moraines). These contrasts indicate that the larger glaciers (ice caps) are less sensitive to changes in temperature than they are to changes in moisture regime. This can be explained in part by the fact that cirque glaciers are compensated for a decrease in snowfall during colder intervals by accumulation of snow by drifting and avalanching from surrounding slopes. The ice caps have no such compensation mechanisms during more arid intervals.

INTEGRATED PALEOCLIMATE INTERPRETATION FOR THE CANADIAN ARCTIC ISLANDS

In the discussion of intraregional correlations of diverse data sets above, we have attempted to identify the types of changes in climate that could account for the "observed" changes in glacier margins, bowhead abundance, driftwood abundance, and the pollen record. We have avoided certain common assumptions, such as ice retreat equals warmer climate, or absence of driftwood equals severe sea ice conditions, because these assumptions lead to the conclusion that the various sources of proxy climate data are mutually contradictory and of little value at present (Williams and Bradley, 1985). Instead we suggest climatic conditions and changes that we feel can account for most current observations. Reiterated in summary form, these are as follows:

(1) During the latest Wisconsinan and early Holocene (≥ 11000-8500 BP), the interisland channels progressively became free of glacier ice, shelf ice, and/or sea ice. Bowhead whales occupied areas beyond their present range, and after deglaciation of Lancaster Sound (9.8 ka) likely extended during summers from Beaufort Sea to Baffin Bay. Driftwood was not able to penetrate these same channels during this interval. We speculate that this was due to a meltwater driven oceanographic circulation pattern that produced continuous summer outflow from the channels, preventing entry of driftwood while exporting sea ice. Dwarf birch extended well north of its present limit on eastern Baffin Island during this interval and boreal tree pollen influx from sources south of the still extant Laurentide Ice Sheet was high, which indicates a high frequency of incursion of moist southerly air masses so temperatures were probably higher than those of today. The Laurentide Ice Sheet, alpine glaciers beyond it on eastern Baffin Island, and ice caps in the eastern Queen Elizabeth Islands advanced and built end moraines. Because of heavy snowfall, the glaciers had a positive mass balance, despite warm summers.

(2) Starting abrubtly at 8500 BP in the central Arctic and extending to 5000 BP, bowheads were excluded from the channels but driftwood arrived in the same area and apparently throughout the Queen Elizabeth Islands as well. The cause of both these changes was establishment of an oceanographic circulation pattern similar to that at present. In the central Arctic this caused an increase in summer sea ice, sufficient to exclude the whales but moving sufficiently to carry driftwood. Organic and pollen accumulation in lakes on Baffin Island diminished to Holocene minimum levels and southerly air mass incursion was rare. The diminished extent of seasonally open water caused a decrease in nourishment of glaciers and an increase in clear weather during the summer. These cold and arid conditions led to slow retreat of Laurentide and local ice, except where mechanical disruption by calving was taking place (Hudson Bay, Foxe Basin). The eastern margin of Laurentide ice continued to build moraines until about 8 ka because of the time lag in response of a large ice mass to climate change or because of a later change to more arid conditions.

(3) At 5000 BP the bowheads again expanded their summer range into the central Arctic channels but apparently not in as great an abundance as during the early Holocene. Driftwood continued to arrive but with increased frequency, as it did in the Queen Elizabeth Islands. Because there is no reason to infer a change in oceanographic circulation pattern at 5000 BP, we infer that the more favourable sea ice conditons resulted from warmer summers. Increased in situ melting of sea ice in the central Arctic channels would have diminished the re-exportation of the ice rafted wood and increased its stranding potential. Exotic pollen of Alnus and local Betula pollen reached Holocene maxima on southeastern Baffin Island, and the Early Barnes and Early Penny ice caps readvanced and deposited end moraines because of a return to moister conditions.

(4) At about 3000 BP bowheads again apparently were prevented from entering the central Arctic channels during most summers. Driftwood continued to arrive there with still greater frequency. It arrived with much lower frequency at Cape Storm on southern Ellesmere Island, which possibly indicates a geographically complex pattern of change in sea ice or in driftwood source areas or transport routes. A strong Neoglacial cooling is recorded in pollen diagrams from eastern Baffin Island starting variably between about 3500 and 2000 years ago. Alpine cirque glaciers responded by advancing and retreating several times. The ice caps were less affected, which indicates that they were less sensitive to changes in temperature regime than they were to changes in moisture regime.

ACKNOWLEDGMENTS

This report is a contribution of Geological Survey of Canada Project 513-8144. Four summers of field work were expedited by the Polar Continental Shelf Project (GSC) from their Resolute Bay base. Several of the wood and bone samples within this study were contributed by David Green, then of the University of Alberta. C.R. Harington of the National Museums of Canada was very helpful in confirming some bone identifications and provided a review that stimulated some important reinterpretations. R. McNeely established a sample preparation laboratory which has allowed proper and efficient sample processing and quality assessment by users prior to submission of samples for radiocarbon dating. This facility was critical to the success of the present study. Comments on the manuscript by D.A. Hodgson and D.S. Lemmen (GSC), by R. Reeves, Arctic Biological Station, Department of Fisheries and Oceans, and by J.M. Savelle, Anthropology Department, McGill University were most helpful.C.F.M. Lewis provided a helpful formal review.

REFERENCES

Andrews, J.T.
1982: Holocene glacier variations in the eastern Canadian Arctic: a review; Striae, v. 18, p. 9-14.
1989: Quaternary geology of the northeastern Canadian Shield; in Quaternary Geology of Canada and Greenland; R.J. Fulton (ed.); Geological Survey of Canada, Geology of Canada, no. 1 (also Geological Society of America, The Geology of North America, v. K-1).

Andrews, J.T. and Ives, J.D.
1972: Late- and post-glacial events (<10,000 B.P.) in the eastern Canadian Arctic with particular reference to the Cockburn Moraine and break-up of the Laurentide Ice Sheet; in Climatic Changes in Arctic Areas During the Last 10,000 years; Y. Vasari, H. Hyvarinen, and S. Hicks (ed.); Acta Universitatis Ouluensis, Series A, Geologica No. 1, p. 149-176.
1978: "Cockburn" nomenclature and the Late Quaternary history of the eastern Canadian Arctic; Arctic and Alpine Research, v. 10, p. 617-633.

Barr, W.
1971: Postglacial isostatic movement in northeastern Devon Island: a reappraisal; Arctic, v. 24, p. 249-268.
Bednarski, J.
1986: Late Quaternary glacial and sea-level events, Clements Markham Inlet, northern Ellesmere Island, Arctic Canada; Canadian Journal of Earth Sciences, v. 23, p. 1343-1355.
Blake, W., Jr.
1972: Climatic implication of radiocarbon-dated driftwood in the Queen Elizabeth Islands, Arctic Canada; in Climatic Changes in Arctic Areas During the Last 10,000 years, Y. Vasari, H. Hyvarinen, and S. Hicks (ed.); Acta Universitatis Ouluensis, Series A, Geologica No. 1, p. 77-104.
1975: Radiocarbon age determinations and postglacial emergence at Cape Storm, southern Ellesmere Island, Arctic Canada; Geografiska Annaler, v. 57, Series A, p. 1-71.
Davis, P.T.
1985: Neoglacial moraines on Baffin Island; in Quaternary Environments: Eastern Canadian Arctic, Baffin Bay, and Western Greenland, J.T. Andrews (ed.); Allen and Unwin, Boston, p. 682-718.
Dyke, A.S.
1979a: Radiocarbon-dated Holocene emergence of Somerset Island, central Canadian Arctic; in Current Research, Part B, Geological Survey of Canada, Paper 79-1B, p. 307-318.
1979b: Glacial and sea-level history of southwestern Cumberland Peninsula, Baffin Island, N.W.T., Canada; Arctic and Alpine Research, v. 11, p. 179-202.
1980: Redated Holocene whale bones from Somerset Island, District of Franklin; in Current Research, Part B, Geological Survey of Canada, Paper 80-1B, p. 269-270.
1984: Quaternary geology of Boothia Peninsula, District of Franklin and northern District of Keewatin, central Canadian Arctic; Geological Survey of Canada, Memoir 407, 26 p.
Dyke, A.S. and Prest, V.K.
1987: Late Wisconsinan and Holocene history of the Laurentide Ice Sheet; Géographie physique et Quaternaire, v. 41, p. 237-264.
Dyke, A.S., Morris, T.F., and Green, D.E.C.
- Postglacial tectonic and sea level history of the central Canadian Arctic; Geological Survey of Canada, Bulletin 397 (in press)
England, J.
1978: The glacial geology of northeastern Ellesmere Island, N.W.T., Canada; Canadian Journal of Earth Sciences, v. 15, p. 603-617.
Eschricht, D.F. and Reinhardt, J.
1866: On the Greenland Right-Whale (Balaena mysticetus, Linn.), with special reference to its geographic distribution and migrations in times past and present, and to its external and internal characteristics; in Recent Memoirs on the Cetacea by Professors Eshricht, Reinhardt, and Lilljeborg, W.H. Flower (ed.) published for the Ray Society by Robert Hardwicke, London, p. 1-150.
Harington, C.R.
1966: Extralimital occurrences of walruses in the Canadian Arctic; Journal of Mammalogy, v. 47, p. 506-513.
Hodgson, D.A.
1985: The last glaciation of west-central Ellesmere Island, Arctic Archipelago, Canada; Canadian Journal of Earth Sciences, v. 22, p. 347-368.
Lemmen, D.S.
1988: The glacial history of Marvin Peninsula, northern Ellesmere Island, and Ward Hunt Island, High Arctic Canada; unpublished PhD thesis, University of Alberta, Edmonton, 174 p.
McCartney, A.P. and Savelle, J.M.
1985: Thule Eskimo whaling in the central Canadian Arctic; Arctic Anthropology, v. 22, p. 37-58.
Reeves, R.R.
1980: Spitsbergen bowhead stock: a short review; Marine Fisheries Review, Sept.-Oct., p. 65-69.
Reeves, R., Mitchell, E., Mansfield, A., and McLaughlin, M.
1983: Distribution and migration of the bowhead whale, Balaena mysticetus, in the eastern North American Arctic; Arctic, v. 36, p. 5-64.
Ritchie, J.C., Cwynar, L.C., and Spear, R.W.
1983: Evidence from northwest Canada for an early Holocene Milankovitch thermal maximum; Nature, v. 305, p. 126-128.
Ross, W.G.
1979: The annual catch of Greenland (bowhead) whales in waters north of Canada, 1719-1915: a preliminary compilation; Arctic, v. 32, p. 91-121.
Salvigsen, O.
1977: Holocene emergence and finds of pumice, whalebones, and driftwood at Svartknausflya, Nordaustlandet; Norsk Polarinstitutt, Arbok 1977, p. 217-228.
1981: Radiocarbon dated raised beaches in Kong Karls Land, Svalbard, and their consequences for the glacial history of the Barents Sea area; Geografiska Annaler, v. 63A, p. 283-291.
Short, S.K., Mode, W.N., and Davis, P.T.
1985: The Holocene record from Baffin Island: modern and fossil pollen studies; in Quaternary Environments: Eastern Canadian Arctic, Baffin Bay and Western Greenland, J.T. Andrews (ed.); Allen and Unwin, Boston, p. 608-642.
Stewart, T.G. and England, J.
1983: Holocene sea-ice variations and paleoenvironmental change, northernmost Ellesmere Island, N.W.T., Canada; Arctic and Alpine Research, v. 15, p. 1-17.
Vibe, C.
1967: Arctic animals in relation to climatic fluctuations; Meddelelser om Gronland, v. 170, no. 5, 227 p.
Williams, L.D. and Bradley, R.S.
1985: Paleoclimatology of the Baffin Bay region; in Quaternary Environments: Eastern Canadian Arctic, Baffin Bay and Western Greenland, J.T. Andrews (ed.); Allen and Unwin, Boston, p. 741-772.

APPENDIX 1

Table 1. Radiocarbon-dated bowhead whales, central Canadian Arctic (cf. Fig. 8 for locations)

Laboratory No.	^{14}C Date (years BP)	Material	Elevation (m)	Location
Cape Richard Collinson area, Prince of Wales Island				
S-2919	4550 ± 90	Ear bone	16.5	72°50'N, 102°44'W
S-2964	8555 ± 165	Ear bone	57	72°51'N, 102°35'W
S-2922	10 000 ± 145	Skull	66.5	72°56'N, 102°28'W
S-2916	10 005 ± 120	Skull	62	72°42'N, 102°22'W
Hollist Point area, Prince of Wales Island				
S-2589	4155 ± 100	Vertebra	12	72°50.0'N, 101°32'W
S-2588	8875 ± 135	Rib	58	73°2'N, 101°54'W
S-2590	9605 ± 140	Rib	66	72°49.5'N, 101°58'W
Drake Bay area, Prince of Wales Island				
S-2910	9000 ± 130	Ear bone	59	73°19'N, 100°36'W
Smith Bay area, Prince of Wales Island				
S-2917	8875 ± 120	Jawbone	65	73°18'N, 100°8'W
S-2923	8990 ± 130	Skull	61.5	73°14'N, 99°27'W
S-2912	9440 ± 135	Ear bone	70	73°13'N, 99°26'W
S-2918	9505 ± 120	Ear bone	74.5	73°4'N, 99°28'W
Arabella Bay area, Prince of Wales Island				
S-2592	3025 ± 90	Rib	7	73°46'N, 100°2'W
S-2591	10 530 ± 145	Skull	54	73°43'N, 100°0'W
Northwestern Russell Island				
S-2662	3675 ± 110	Rib	14.6	74°2.5'N, 98°36'W
Eastern Russell Island				
S-2671	3685 ± 155	?	10.8	74°0.5'N, 97°39'W
S-2664	4510 ± 165	?	15.6	74°7.5'N, 97°44'W
Allen Lake area, Prince of Wales Island				
S-2593	9285 ± 135	Skull	71	73°37'N, 98°38'N
Cape Hardy area, Prince of Wales Island				
S-2711	3500 ± 80	Vertebra	11.5	73°47'N, 97°5'W
S-2707	8645 ± 135	Jaw	51.5	73°50.5'N, 97°17'W
S-2706	9375 ± 140	Skull	69-71	73°44.5'N, 97°41'W
Prescott Island				
S-2920	1585 ± 70	Ear bone	3.5	73°3'N, 97°7'W
S-2921	3315 ± 75	Ear bone	9	73°6'N, 97°7'W
S-2915	4635 ± 80	Ear bone	14	73°9.5'N, 96°43'W
S-2965	8765 ± 160	Ear bone	50.5	73°8'N, 97°3'W
S-2913	9335 ± 145	Ear bone	57.5	73°1'N, 97°3'W

Laboratory No.	^{14}C Date (years BP)	Material	Elevation (m)	Location
Muskox Hill - Pendora Island area, Prince of Wales Island				
S-2715	2270 ± 230	?	10	72°52'N, 97°17'W
S-2835	8565 ± 125	?	66	72°53'N, 96°47'W
S-2864	8655 ± 130	?	68	72°53'N, 97°30'W
S-2716	8905 ± 405	?	100	72°49'N, 97°18'W
Dolphin River area, Prince of Wales Island				
S-2836	9040 ± 130	Rib	79.5	72°40'N, 98°17'W
Guillemard Bay area and other sites on southern Prince of Wales Island				
S-2861	4505 ± 85		18	71°40'N, 98°24'W
S-2600	4870 ± 95	Rib	17	71°40'N, 97°15.5'W
S-2601	6940 ± 155		48	71°41'N, 97°15.5'W
S-2604	8520 ± 190	Rib	84	71°36'N, 97°21'W
S-2603	8675 ± 135	Rib	75	71°35.5'N, 97°21'W
S-2598	8630 ± 195		81.5	72°10'N, 97°51'N
S-2597	9225 ± 215	Skull	99	72°10.5'N, 97°51'W
S-2599	8645 ± 205		87	72°0.5'N, 96°30.5'W
Cape Anne, Somerset Island				
S-1391	635 ± 50	Vertebra	4	74°5'N, 94°47'W
S-1383	1455 ± 80	Vertebra	7.5	74°4'N, 94°48.5'W
S-1389	4265 ± 65	Skull	18	74°3.3'N, 94°48.5'W
S-1386	7105 ± 90	Rib	28	74°3.5'N, 94°48'W
S-1384	8005 ± 155	?	50	74°1.3'N, 94°53'W
S-1381	9590 ± 115	Vertebra	69	74°1.8'N, 94°48'W
Cunningham Inlet, Somerset Island				
GSC-450	8990 ± 140	Vertebra	66	73°59'N, 93°40'W
Rodd Bay, Somerset Island				
S-1405	1860 ± 80	?	4.5	73°57.7'N, 90°38'W
S-1393	3825 ± 75	?	10	73°57.5'N, 90°38'W
S-1387	4570 ± 85	?	14	73°57.3'N, 90°38'N
S-1390	9210 ± 120	Fin	76	73°55.6'N, 90°37.5'W
Southern Somerset Island				
S-1382	4310 ± 90	Skull	22	72°52.3'N, 93°32'W
S-1388	8805 ± 95		73	72°51.6'N, 93°34'W
King William Island				
S-2681	5620 ± 95	Fin	37	69°28.7'N, 97°57.5'W

Table 2. Undated bowhead whale collections, central Canadian Arctic (cf. Fig. 8 for locations)

Sample no.	Elevation (m)	Location	Minimum age (years)
Cape Richard Collinson area, Prince of Wales Island			
86 DCA 407	55	72°54'N, 102°32'W	8200
86 DCA 409	49	72°55.5'N, 102°31'W	7800
86 DCA 429	58	72°54'N, 102°31'W	8300
86 DCA 437	11	73°26'N, 100°30'N	2700
Drake Bay area, Prince of Wales Island			
86 DCA 451	11	73°26'N, 100°25'W	2800
86 DCA 452	15	73°24'N, 100°20'W	3700
86 DCA 453	11	73°24'N, 100°27'W	2800
Arabella Bay area, Prince of Wales Island			
84 DCA 749	2	73°44'N, 100°3'W	400
Western Russell Island			
84 DCA 468	2	73°57'N, 98°58'N	400
Eastern Russell Island			
84 DCA 483*	25	74°6'N, 97°59.5'W	5600
84 DCA 509*	61	74°0.5'N, 98°3.5'W	8600
84 DCA 510*	4	74°6.5'N, 97°50'W	900
84 DCA 516	27	74°2'N, 97°40'W	6000
84 DCA 517*	37	74°1.5'N, 97°37.5'W	6600
84 DCA 524	3	73°58'N, 97°52'W	700
84 DCA 525*	16	74°N, 97°42'W	3900
84 DCA 526	44	74°1'N, 97°42'W	7400
Prescott Island			
86 DCA 529	50	73°1.5'N, 97°4'W	7700
86 DCA 549	14	73°6.5', 97°5'W	4400
86 DCA 558	16	73°9.5'N, 96°57'W	4700
86 DCA 563	3	73°10'N, 96°42'W	1100
86 DCA 566	9	73°7.5'N, 97°44'W	2200
Pandora Island – Muskox Hill area, Prince of Wales Island			
86 DCA 97B	4	72°53'N, 96°47'W	1000
86 DCA 98B	12	72°53'N, 96°49'W	2900
86 DCA 102B	10	72°51'N, 96°49'W	2400
86 DCA 105B	15	72°49'N, 96°54'W	3600
86 DCA 107B	9	72°52'N, 96°51'W	2200
85 DCA 35B	88		9000
85 DCA 117B*	104	72°27'M, 97°19'W	9300
Dolphin River area, Prince of Wales Island			
86 DCA 55B	67	72°47'N, 98°31'W	8400
86 DCA 80B	77	72°40'N, 98°16'W	8600
Guillimard Bay area and other sites on southern Prince of Wales Island			
84 DCA 50B*	81	71°50.5'N, 98°10'W	8700
84 DCA 65B	94	71°51'N, 98°7'W	9000
84 DCA 73B*	103	71°51'N, 98°5.5'W	9200
84 DCA 131B	85	72°15'N, 97°30'W	9000
84 DCA 132B	84	72°15'N, 97°30'W	9000
84 DCA 229B	84	71°39'N, 97°22'W	9000
84 DCA 230B*	98	71°36'N, 97°21'W	9200
84 DCA 231B	86	71°38'N, 97°25'W	9000
84 DCA 244B	84	71°40'N, 97°23'W	9000
85 DCA 51B	32	71°36'N, 98°56'W	6400
85 DCA 52B	44	71°38'N, 98°56'W	7300
85 DCA 75B*	56	71°41'N, 98°56'W	8100
86 DCA 1B	60	71°51'N, 99°34'W	8300
86 DCA 8B	61	71°50'N, 99°31'W	8300
86 DCA 9B	52	71°49'N, 99°30'W	7900
86 DCA 42B	95	71°50'N, 98°35'W	9200
Cape Anne area, Somerset Island			
75 NJ 97B	3	73°45'N, 95°8'N	700
77 DCA B11	21	74°5'N, 94°47'W	4900
77 DCA B14	57	74°3'N, 94°47'W	8100
77 DCA B23	22	74°4'N, 94°47'W	5100
Rodd Bay area, Somerset Island			
77 DCA B18	3	73°59.5'N, 90°38'N	700
77 DCA B20	9	73°57.5'N, 90°38'W	3100
Creswell Bay area, southern Somerset Island			
75 NJ 66	96	72°57'N, 93°20'W	9000
77 DCA B3	64	72°55'N, 93°34'W	8300
77 DCA B4	27	72°53'N, 93°34'W	6300
77 DCA B5	3	72°51'N, 93°34'W	700
77 DCA B7	22	72°52'N, 93°34'W	5100
77 DCA B8	28	72°53'N, 93°34'W	6600

Samples that yielded unacceptable radiocarbon ages (see Dyke et al., in press) are treated here as undated samples. These unacceptable ages were obtained on samples submitted for dating in field condition early in this project. Generally they were samples heavily contaminated by plant material.

Table 3. Radiocarbon-dated driftwood, central Canadian Arctic (cf. Fig. 8 for locations)

Laboratory No.	^{14}C Date (years BP)	Elevation (m)	Location
Cape Richard Collinson area, Prince of Wales Island			
GSC-4398	1400 ± 50	5	72°54.5°N, 102°38'W
GSC-4478	1860 ± 70	6.5-7.0	72°53'N, 102°37'W
GSC-4387	4070 ± 60	17.0-17.5	72°55'N, 102°37'W
GSC-4479	4630 ± 60	22	72°57'N, 102°32'W
GSC-4361	5270 ± 70	24	72°53'N, 102°33'W
GSC-4343	8680 ± 90	59	72°54'N, 102°34'W
Hollist Point area, Prince of Wales Island			
GSC-3977	920 ± 60	2.0-2.3	72°52'N, 101°30'W
GSC-3945	1060 ± 50	3.5-4.0	72°53'N, 101°33'W
GSC-3962	3660 ± 60	12	72°51'N, 101°33'W
GSC-3936	8230 ± 110	58.5	73°2'N, 101°54'W
Smith Bay area, Prince of Wales Island			
GSC-4412	130 ± 70	32	73°14'N, 99°59'N
GSC-4428	2350 ± 60	10	73°11'N, 99°59'W
GSC-4427	4020 ± 70	15	73°12'N, 99°57'W
GSC-4417	5910 ± 80	25.5	73°11.5'N, 100°2'W
Northwestern Russell Island			
GSC-2300	1800 ± 50	5.7	73°57.5'N, 98°58'W
GSC-3978	2930 ± 60	12.1	73°56.5'N, 99°11'W
GSC-2240	3630 ± 60	14.3	73°57'N, 98°59'W
GSC-4002	3820 ± 70	14.7	74°2'N, 98°34'W
Eastern Russell Island			
GSC-4001	2250 ± 60	8.23	74°6.5'N, 97°45'W
Lowther Island			
GSC-224	4410 ± 70	21.5	74°34'N, 97°35.5'W
Cape Hardy area, Prince of Wales Island			
S-2704	765 ± 65	6.0-6.5	73°52'N, 97°21'W
S-2703	4945 ± 95	18.0-18.5	73°44'N, 97°00'W
S-2705	5595 ± 100	25	73°51.5'N, 97°30'W
S-2702	8695 ± 130	64.5	73°49.5',97°26'W
Prescott Island			
GSC-4447	70 ± 50	32	72°58'N, 97.2°2'W
GSC-4457	560 ± 60	12.5	73°7'N, 97°6'W
GSC-4458	1380 ± 60	8	73°8'N, 96°42'W
GSC-4503	3470 ± 70	11	73°9'N, 96°43'N
GSC-4456	5070 ± 90	23.5	73°7'N, 96°43'N
GSC-4459	5300 ± 80	21.0-21.5	73°9'N, 96°44'W

Laboratory No.	^{14}C Date (years BP)	Elevation (m)	Location
Muskox Hill – Pandora Island areas. Prince of Wales Island			
S-2714	275 ± 105	4	72°52'N, 97°23'W
S-2833	315 ± 60	2	72°53'N, 96°49'W
S-2834	845 ± 60	7	72°51'N, 96°54'W
S-2829	5795 ± 90	23	72°46'N, 96°53'W
S-2832	8265 ± 120	10	72°51'N, 96°52'W
S-2720	8660 ± 395	54	72°36'N, 97°00'W
Dolphin River area, Prince of Wales Island			
S-2859	605 ± 65	6	72°55'N, 98°22'W
S-2837	3765 ± 80	12	72°49'N, 98°29'W
S-2839	4890 ± 90	19	72°50'N, 98°27'W
S-2831	5965 ± 95	25	72°46'N, 98°35'W
S-2838	7100 ± 110	30	72°46'N, 98°34'W
Guillemard Bay area and other sites on southern Prince of Wales Island			
GSC-3989	4400 ± 70	16	71°41'N, 98°08'W
GSC-3985	6100 ± 80	31.5	71°39.5'N, 97°21'W
GSC-3967	6910 ± 80	39	71°39.5'N, 97°22'W
S-2718	1620 ± 220	6	71°22'N, 98°54'W
S-2717	1900 ± 325	2	71°29'N, 99°24'W
S-2860	3170 ± 75	9	72°51'N, 99°52'W
S-2830	6630 ± 100	26	71°51'N, 99°38'W
S-2719	7620 ± 345	46	71°57'N, 98°56'W
S-2862	360 ± 65	2.5	72°33'N, 96°26'W
S-2863	4370 ± 85	4	72°19'N, 96°51'W
Wrottesley Inlet, Northwestern Boothia Peninsula			
GSC-2782	150 ± 50	2	71°17'N, 95°35.5'W
Cunningham Inlet, Somerset Island			
GSC-2704	1420 ± 50	5	74°4'N, 93°34'W
GSC-2233	3580 ± 60	12.6	74°6.6'N, 94°15.5'W
GSC-2081	4930 ± 70	17	74°7.9'N, 93°53.8'W
GSC-2080	5300 ± 70	21	74°8.9'N, 93°55'W
Rodd Bay, Somerset Island			
S-1374	5965 ± 75	18	74°0.5'N, 91°19.5'W