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A History of Sea Ice in the Canadian Arctic Archipelago Based on Postglacial Remains of the Bowhead Whale (*Balaena mysticetus)*

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ABSTRACT. The bowhead whale (*Balaena mysticetus*) is a planktivore of the baleen group of whales adapted to live in the loose edges of the north polar sea ice. Its annual migrations roughly track the advance and retreat of the floe edge. The distribution and radiocarbon ages of bowhead subfossils in the Canadian Arctic Archipelago show that the range of the whale has expanded and contracted abruptly several times over the last 10.5 thousand years (ka). Each expansion or contraction was followed by nearly stable conditions that persisted for millennia.

These changes in the geographic range of the bowhead are defined by > 400 radiocarbon dates. The paleo-ranges are the basis for reconstructing summer sea-ice minima. Using this criterion, postglacial time is divided into four intervals: (1) 10.5–8.5 ka B.P.—A large bowhead population extended in the summer all the way to retreating glacier margins and ultimately from the Beaufort Sea to Baffin Bay; meltwater-driven outflows probably cleared the inter-island channels of sea ice; this interval terminated when the present interglacial circulation pattern was established; (2) 8.5–5 ka B.P.—Bowheads were excluded from most of the archipelago because the channels failed to clear of sea ice; summer sea-ice conditions for most of this time were more severe than during historical times; (3) 5–3 ka B.P.—Bowheads reoccupied the central channels of the Arctic Islands, and their range extended beyond historical limits; and (4) 3–0 ka B.P.—Sea ice excluded whales from the central channels, as it does today.

This paleoenvironmental record based on bowhead whale distributions is more complex than that revealed in the $\delta^{18}O$, conductivity or the percent-melt records of the Devon and Agassiz ice cores. A reconciliation of the two data sets may indicate the following general summer climatic conditions: 10–8 ka B.P.—warm summers with maximum postglacial warmth; 8–5 ka B.P.—cool, dry summers; 5–3 ka B.P.—cool, wet summers; 3–0 ka B.P.—cold, dry summers.

Key words: bowhead whale, sea ice, ocean currents, climate change

RÉSUMÉ. La baleine boréale (*Balaena mysticetus*) est un planctivore du groupe des baleines à fanons adapté à la vie dans les écotones fluctuants de la banquise polaire septentrionale. Ses migrations annuelles suivent approximativement l'avance et le retrait de la zone de dislocation. La distribution et la datation au radiocarbone de subfossiles de la baleine boréale dans l'archipel canadien Arctique montrent que l'aire de la baleine s'est plusieurs fois étendue et rétrécie soudainement au cours des derniers 10,5 milliers d'années (Ka). Chaque extension ou rétrécissement a été suivi de conditions relativement stables qui ont duré plusieurs millénaires.

Ces variations de l'aire géographique de la baleine boréale sont définies par la datation au radiocarbone > 400. Les paléo-aires constituent la base à partir de laquelle on reconstruit les minima de banquise estivale. En se servant de ce critère, on divise le temps postglaciaire en quatre intervalles: 1) de 10,5 à 8,5 Ka BP — En été, une vaste population de baleine boréale peuplait la mer jusqu'aux marges des glaciers en recul, et finalement de la mer de Beaufort à la baie de Baffin; des courants de décharge créés par les eaux de fonte dégageaient probablement la glace de mer des chenaux séparant les îles; cet intervalle s'est terminé quand le schéma actuel de circulation interglaciaire a pris place; 2) de 8,5 à 5 Ka BP — La baleine boréale était exclue de la plupart de l'archipel parce que les chenaux restaient bloqués par la glace de mer; durant presque tout ce temps-là, les conditions estivales en ce qui concerne la glace de mer étaient beaucoup plus extrêmes que durant la période historique; 3) de 5 à 3 Ka BP — La baleine boréale occupait de nouveau les chenaux centraux de l'archipel Arctique, et son aire s'étendait au-delà des limites historiques; et 4) de 3 à 0 Ka BP — La banquise excluait la baleine des chenaux centraux, comme c'est le cas de nos jours.

Ce relevé paléoenvironnemental fondé sur la distribution de la baleine boréale est plus complexe que celui révélé par $\delta^{18}O$, par la conductivité ou par les relevés de pourcentage de fonte des carottes de glace de Devon et d'Agassiz. Une réconciliation des deux ensembles de données pourrait indiquer les conditions climatiques estivales générales suivantes: de 10 à 8 Ka BP — étés chauds avec chaleur postglaciaire maximale; de 8 à 5 Ka BP — étés frais et secs; de 5 à 3 Ka BP — étés frais et humides; de 3 à 0 Ka BP — étés froids et secs.

Mots clés: baleine boréale, glace de mer, courants océaniques, changement climatique

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INTRODUCTION

The expansion and contraction of sea ice are important aspects of the environmental history of north polar areas. Here we are concerned not with the familiar seasonal expansion and contraction (14×10^6 km^2 in late winter to 7×10^6 km^2 in late summer), but with changes in ice extent over millennia. Sea-ice conditions affected the movements of marine and terrestrial species, including man; the history of sea ice provides a basis for inferring the climatological and oceanographic mechanisms involved in its changing extent. Sea-ice history, particularly changes in summer minima, is also important in modelling climate change because of its effect on summer albedo over large areas and because of its effect on stratification (hence deep water formation through thermohaline circulation) of the North Atlantic Ocean (Mysak and Power, 1992; Broecker, 1994). The volume of sea ice exported from the Arctic Ocean also significantly regulates Arctic Ocean and North Atlantic heat flux. Latent heat released on ice formation represents about one-third of the total advective heat budget of the Arctic Ocean (Barry, 1989), while the same amount of heat is exhausted in melting the exported ice farther south.

We show here that bowhead whale subfossils (hereafter fossils) yield the best available proxy of sea-ice history. Some diatoms are known to have sea-ice affinity, but far too few marine sediment cores have been analyzed from the Arctic Archipelago to reconstruct regional sea-ice history by this means (see e.g., Williams, 1990; Short et al., 1994). Otherwise sea ice—excepting icebergs, which contain appreciable sediment loads (e.g., Ruddiman, 1987)—is a geological agent that leaves little or no coherent, direct record of its changing extent through time. Our data allow a reconstruction of postglacial sea-ice history throughout the Canadian Arctic Archipelago. Furthermore, radiocarbon dates on whale bones from Svalbard display some patterns strikingly similar to those from Arctic Canada. This suggests that certain changes may have occurred extensively. Modest additional research could achieve similar results for the entire north polar region.

Early results, based on 53 radiocarbon-dated bowheads from the central part of the Canadian Arctic Archipelago, were presented by Dyke and Morris (1990). They showed that two major expansions in the range of the whale had occurred into areas beyond its historical range during postglacial time and inferred changes in sea-ice conditions and in ocean circulation patterns from these and other data. In this paper, we summarize a much-expanded database and present an interpretive series of paleogeographic reconstructions of summer sea-ice minima and of ocean surface circulation. Other papers will deal with the paleobiology of the bowhead whale (Savelle and Dyke, unpubl.) and with driftwood as an arctic paleoceanographic indicator (Dyke et al., unpubl.).

We have collected bone samples from the remains of 884 bowhead whales in postglacial raised marine sediments, mainly raised beaches; the remains of about 400 more whales were excavated but not collected. More than 400 of these samples from 69 sites have been radiocarbon-dated. Our surveys of whale bone abundance have extended well into areas that are barren of bones. Thus the largest range extensions of significance have been defined, barring extralimital excursions of stray individuals. Below we set out the ecological basis for interpreting sea-ice history from bowhead fossils. Then we present the chronological data that led to a synthesis of sea-ice extent through postglacial time. The numerous radiocarbon dates are not tabulated here, but details of both radiocarbon-dated and undated samples are filed in the National Radiocarbon Database, Radiocarbon Dating Laboratory, Geological Survey of Canada, and at the Canadian Museum of Nature (Paleobiology), where samples are archived and available for other research.

BOWHEAD DISTRIBUTION AND HABITAT: THE CENTRAL ARGUMENT

The bowhead (*Balaena mysticetus*), also known as the Greenland right whale, is an obligate north polar species. It often ranges nearer shore than its cousin, the pelagic northern right whale (*Eubalaena glacialis*), and was regarded as a littoral species by McLeod et al. (1993). It is the only large arctic whale. Prior to commercial whaling, the bowhead had a circumarctic distribution comprising five geographically distinct stocks: the Spitsbergen, Sea of Okhotsk, Bering Sea, Hudson Bay, and Davis Strait stocks, the last three in North American waters (Reeves, 1976; Burns et al., 1993; Moore and Reeves, 1993; see Fig. 1). The bowhead probably originated as a species during the Pliocene and has always inhabited high latitudes except during Pleistocene glaciations, when it was displaced southward (McLeod et al., 1993).

The bowhead is one of the few species of marine mammals that spend all or most of their lives in or near the loose edges of the northern pack ice. It is found only in waters seasonally covered by sea ice. Because the bowhead has the thickest blubber layer of any mammal (up to 50 cm), it can comfortably maintain homeostasis in waters that average < 0˚C. Bowheads can retreat under the ice when alarmed and reportedly can break ice 30–60 cm thick by lifting (Marquette, 1986; Montague, 1993; Würsig and Clark, 1993). They exploit leads through dense ice, but prefer areas of loose ice (30–50% cover) and open water just beyond, particularly in summer (Braham et al., 1980; Brueggeman, 1982; Reeves and Leatherwood, 1985; Marquette, 1986). Hence, bowheads are highly migratory, forced southward with the advance of the pack ice in the late fall and advancing northward with its retreat in the summer; their annual migrations roughly define the oscillation of the floe edge.

The other two arctic whales, the narwhal (*Monodon monoceros*) and the beluga (or white whale, *Delphinapterus leucas*), as well as the walrus (*Odobenus rosmarus),* have grossly similar ranges (in the eastern Canadian Arctic only for the narwhal), in that their annual migrations are largely dictated by patterns of ice clearance and formation. In comparison to the bowhead, these species have left a meager Holocene fossil record even though population levels were

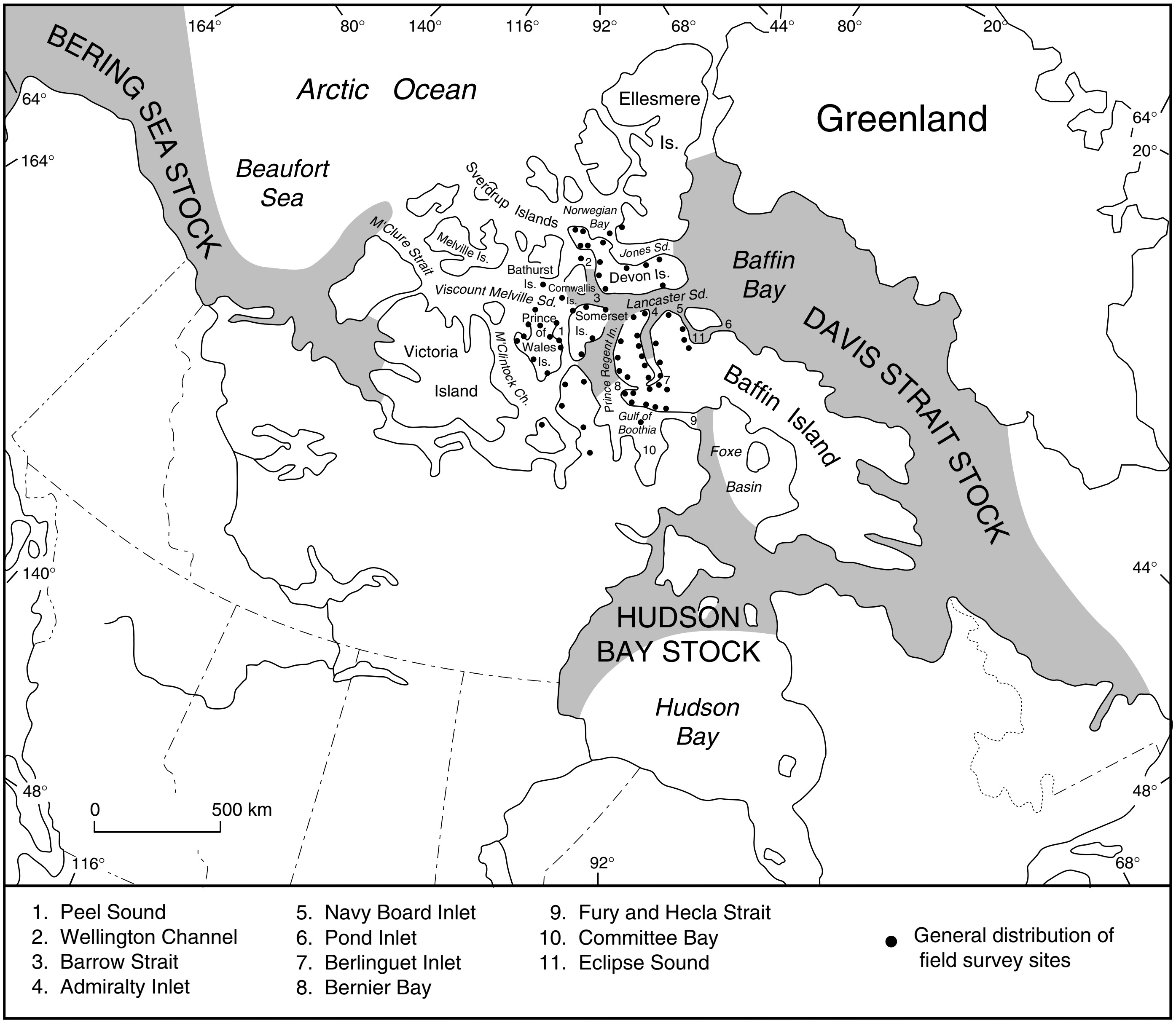

FIG 1. North American bowhead whale stocks. Distributions are those of the stocks before depletion by commercial hunting which probably resemble the distribution of the remnant stocks as well. The whales occupy the southern parts of these ranges in winter and the northern parts in summer. Study sites are shown schematically; a symbol (dot) may represent two or more survey areas.

comparable or larger (tens of thousands for bowheads; tens to hundreds of thousands for the others; see e.g., Haley, 1986). However, a radiocarbon database for these animals is slowly accumulating and eventually will allow extension of the interpretations presented below (Dyke, unpubl.).

The only predator of the bowhead, other than man, is the killer whale (*Orcinus orca*). In the study area, this species apparently visits at least Pond Inlet and Admiralty Inlet annually, and there are several historical and recent reports of predation on bowheads in these areas (Reeves and Mitchell, 1988). Otherwise, natural mortality of bowheads results presumably from old age, disease, and ice entrapment. However, virtually no information on the relative importance of these factors has been derived from studies of living bowheads (Philo et al., 1993). Our data are entirely from the summer-fall grounds of the bowhead, the northern parts of its present and former range. We have yet to find a single killer whale bone in our extensive searches, in contrast with thousands of bowhead bones and tens of narwhal/beluga and walrus bones. Therefore, if predation by the killer whale is an important cause of mortality in the northern parts of the bowhead range, the predator itself has left little or no trace.

The summer–fall feeding grounds may be critical in regulating the population (and health?) of bowhead whales. Bowheads feast in these areas on zooplankton, consisting mainly of copepods (brit) and euphausiids (krill), and eat little if anything for the rest of the year. These organisms have particularly high caloric value in contrast to other available organisms that are rarely and only incidentally eaten (Marquette, 1986; Lowry, 1993). The oceanographic conditions that promote availability of these foods are not well understood, but the bowhead is known to feed in the water column, at the sea surface, and at the bottom. Factors that could enhance production of foods include upwelling, water mass boundaries, ice-edge effects, and nutrient input from rivers. The bowhead's main competitors for food are arctic cod and ringed seals, which may now attain greater populations since commercial depletion of bowhead stocks. Food abundance apparently is not the only, or even the most important, control on migration patterns. For example, bowheads now abandon the highly productive Bering Sea during its spring plankton bloom to feed in the much less productive Beaufort Sea (Lowry, 1993). Perhaps the evolutionary preference for ice-edge habitat, predator avoidance, and lack of competition for food from other baleen whales are more significant than food abundance.

Eskimos of the Thule culture (1 ka B.P. to European contact) hunted bowheads extensively, as testified by the abundant bones at Thule archaeological sites (McCartney, 1979a, b; Savelle and McCartney, 1994). We avoided sampling animals near such sites. Pre-Thule Eskimo cultures in the Canadian Arctic (ca. 4.5–4.0 to 1 ka B.P.), collectively referred to as Paleoeskimo, lacked large whale hunting technology (Maxwell, 1985). Although Giddings (1961, 1967) suggested that the short-lived Old Whaling Culture in Alaska engaged in bowhead whaling around 3.8 ka B.P., a recent re-examination of the relevant data by Mason and Gerlach (1995) suggests that there is no clear evidence for whale hunting as opposed to whale carcass scavenging. Hence, the changing abundance of whale bones through time, as depicted below, was influenced little, if at all, by human cultural factors.

The close tie to the floe edge is the basis of our use of bowhead fossils as indicators of paleo-sea ice. Reeves et al. (1983:6) implicitly predicted this potential use when they stated: "The bowhead's 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 periodically."

Our specific central argument is that whale bones in the raised marine deposits represent natural mortality. We assume that the abundance of remains is proportional to the population and (or) to the seasonal length of occupation (or proportion of summers allowing access); a large population yields more deaths than a small one per unit of time. We have no means of distinguishing between an occupation by a population of a certain size every summer and an occupation by a population twice that size for half the summers. Because the bowhead floats when dead, it has a high stranding potential; it clearly leaves an excellent record of its occupation in the raised beaches. Conversely, an absence of fossils over large regions and for substantial intervals is taken as evidence that the area was not then occupied. Expansions and contractions of the bowhead range are thus identified. Because the whale seasonally migrates through the entire coastal zone from which the ice clears, changes in its range can be most reasonably explained by changes in patterns of summer ice clearance.

We prefer the hypothesis above, that bone-bearing deposits represent natural mortality during periods of occupation and bone-barren deposits represent intervals of inaccessibility, to three alternatives. The first alternative is that long intervals that are barren of bones over large regions represent occupations with very low or zero mortality rates. This is unattractive because we know of no reasonable mechanism to account for suddenly changing mortality rates. The second alternative is that the bone-barren deposits represent intervals of low plankton biomass (insufficient food) in regions with otherwise unimpeded access. This is unattractive because there is no obvious mechanism for abruptly switching regional plankton productivities and because there are no independent indications that this occurred. A third alternative is that the barren intervals here represent periods of regional abandonment by the whales because there was *too little* sea ice to provide the required pack-edge habitat at any time of year. We regard this as a much less conservative interpretation of the data. It requires us to assume that the High Arctic inter-island channels remained free of sea ice in the winters; i.e., that the whales did not retreat in the autumn to the Davis Strait region, but remained in the Arctic Ocean. The gross distribution of whale bones alone argues against this. No bone has been reported from the Arctic Ocean shores of the Canadian Arctic Archipelago north of Prince Patrick Island, and it is inconceivable that no carcasses would have washed ashore there if the whales had occupied the adjacent Arctic Ocean.

STUDY SITES, BOWHEAD STOCKS, AND PRESENT ICE CONDITIONS

Our study sites extend from areas well beyond the historic range of the whale in the west, south, and north to areas well within its range to the east (Fig. 1). Therefore, we can identify times of both expansion and contraction with respect to present limits.

The Davis Strait and Bering Sea bowhead stocks are separated today by a persistent summer sea-ice plug, the most resilient part of which fills M'Clure Strait, Viscount Melville Sound, and M'Clintock Channel (Fig. 2). We refer to this as the M'Clintock Channel sea-ice plug. This barrier normally separates Pacific and Atlantic stocks of belugas and walruses and limits movements of various species of seal (Harington, 1966). It was this barrier that defeated Sir John Franklin's expedition in 1848 (Alt et al., 1985). Furthermore, the M'Clintock Channel region apparently remained unattractive to Thule Eskimo bowhead whalers throughout the last thousand years (McCartney and Savelle, 1985). Hence, the ice plug has been a profound and nearly stable feature of the biogeography of North America for more than a thousand years. Our data suggest, however, that it was (and potentially is) not stable on longer time scales.

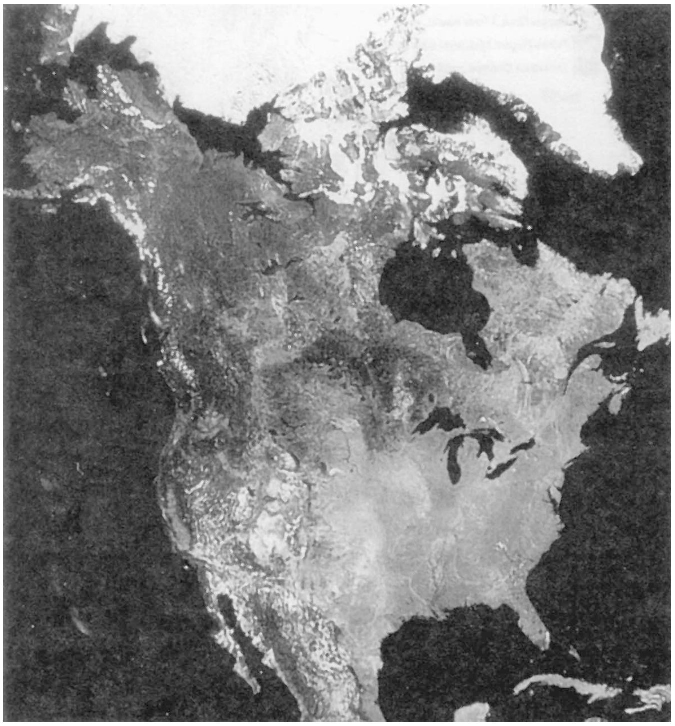

FIG. 2. Satellite image mosaic of North America showing summertime sea-ice extent. Note how the pack ice extends southward from the Arctic Ocean through the central Arctic Archipelago forming a barrier between the Beaufort Sea on the west and Baffin Bay on the east. The sea-ice plug as seen here is somewhat larger than its typical summer minimum during historical times.

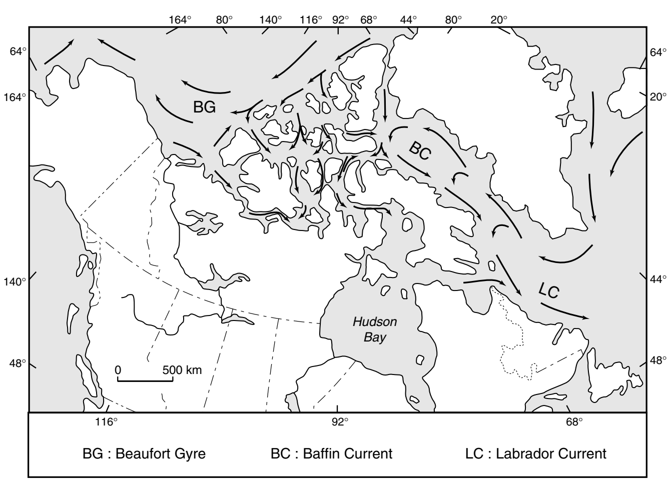

FIG. 3. The pattern of surface water circulation in the North American Arctic. Arctic Ocean surface water and its sea-ice load circulating anticyclonically in the Beaufort Gyre (BG) filter through the Arctic Archipelago to enter the Baffin Current (BC) at the head of Baffin Bay and the Labrador Current (LC) at the mouth of Hudson Strait.

The ice plug results largely from the pattern of surface water circulation in the archipelago. This involves a broad southeastward filtration of Arctic Ocean surface water through the archipelago to the Baffin and Labrador currents (Fig. 3). Channels that export sea ice to Baffin Bay via outflowing currents become ice-free in most summers. Other channels, such as M'Clintock Channel and southern Gulf of Boothia, form sea-ice cul-de-sacs. Ice in the cul-de-sacs may be replenished by pack ice from the Arctic Ocean at a rate that exceeds local ablation. Consequently they are rarely sufficiently ice-free to allow access by whales or walruses.

In detail, the annual patterns of sea-ice breakup are more variable. The pattern in any year depends on complex variables of seasonal warming and of wind speed and direction (Dunbar and Greenaway, 1956; Stirling and Cleator, 1981; Alt et al., 1985). Hence, the duration of open water and loose ice varies from year to year. On average during the period 1959–1974, ice clearance exceeded 50% in the northernmost areas historically occupied by bowhead whales (Fig. 1) between August 20 and October 1. In comparison, Lancaster Sound typically has < 50% ice cover between August 6 and October 8 (Markham, 1981). The worst ice year in modern times was 1972, when only Lancaster Sound and its nearest approaches cleared. Weather conditions during that summer were controlled by an elongate low-pressure system that stretched from the Kara Sea across the Pole to a low centred in the Labrador Sea (Alt et al., 1985). This pressure system set up a northwesterly air flow across most of the Arctic Archipelago, driving ice into the channels and depressing summer temperatures by 1–4°C. Exceptional ice clearance occurred in 1962, when even M'Clintock Channel (but not Viscount Melville Sound) cleared. Persistent southwesterly winds driven by a high-pressure system over the central Arctic mainland aided exportation of ice to Baffin Bay and increased ablation in the M'Clintock Channel region (Alt et al., 1985).

RADIOCARBON DATING

Dating Strategy

We have outlined elsewhere our criteria for selection of samples for dating and sample preparation methods (Dyke and Morris, 1990; Dyke et al., 1991). Briefly, samples were selected for dating to address several questions, not all of which are relevant to this paper. We attempted to provide time series as complete as possible from individual sample areas, after culling on the basis of quality as radiocarbon targets. After some initial problems with sample quality (Dyke et al., 1991), we restricted our sampling of whale remains for radiocarbon dating to the ear bones (tympanic bullae and periotics collected from skulls), because they are much denser than any other whale bone and are resistant to internal contamination. However, they still require careful cleaning before submission for dating. This sampling strategy also ensures that no animal is sampled more than once, an essential constraint when assessing the number of animals represented in bone-rich deposits. We have confidence in the resulting radiocarbon age determinations because they form internally consistent (accordant) sets when plotted as relative sea-level curves and they compare well with dates on other materials, mainly driftwood. These latter results will be treated fully elsewhere.

Age Corrections

The radiocarbon results are presented as histograms in this paper in the form of both "corrected" and uncorrected ages in radiocarbon years. The uncorrected ages are the raw "machine ages" reported by the dating laboratory. That is, no correction is applied either for carbon isotopic fractionation or for the marine reservoir effect. Isotopic fractionation was measured for about half of the samples; most results fell between -15 and -17 per mil $\delta^{13}C$ with respect to the PDB standard. The ages can be approximately normalized to the terrestrial (wood) standard (-25 per mil $\delta^{13}C$ with respect to PDB) by adding 150 years.

The appropriate marine reservoir correction for the bowhead whale in this region has not been independently established. Long practice (e.g., Blake, 1975; see also Arundale, 1981) has been to subtract 400 years to correct for this effect on marine molluscs from this region. In the absence of a better criterion, this *may be* an appropriate correction to apply to the whale bone dates. A 400-year marine reservoir correction can be achieved by subtracting 250 years from the uncorrected ages (uncorrected age + 150 years - 400 years). Comparative dating of driftwood and whale bones from raised beaches will be reported elsewhere, but results suggest that a 400-year reservoir correction is sufficient, if not excessive. For simplicity in discussion below, we will refer to the uncorrected ages unless a specific circumstance warrants otherwise.

RESULTS AND INTERPRETATIONS

The discussion below proceeds from the central Arctic Archipelago eastward to Baffin Bay. Attention focuses initially on the history of the M'Clintock Channel sea-ice plug (Fig. 2), its apparent Holocene establishment and subsequent expansion and contraction. In general, the abundance of whale bones in raised marine deposits increases strongly from the central channels to the channels and inlets adjacent to the head of Baffin Bay—that is, toward the spring–early summer access points and in the general direction of increasingly reliable access. The postglacial sea-level history along this transect ranges from one of continuous emergence in the central islands to one of early Holocene emergence followed by middle and late Holocene submergence near to Baffin Bay (Andrews and Peltier, 1989; Dyke and Dredge, 1989; Dyke, unpubl.). Thus, the Holocene fossil record of the raised marine sediments is truncated in the east.

M'Clintock Channel and Approaches

The shores of Somerset and Prince of Wales Islands lie respectively close to and beyond the historic limit of the bowhead whale. Of 140 bowhead fossils collected from 28 areas searched on these and on small neighbouring islands, 67 fossils have been dated. The frequency distribution of bowheads through time in this area is strongly bimodal (Fig. 4). An earlier version of this graph (with 53 samples) was the basis of a four-fold subdivision of the Holocene in the region by Dyke and Morris (1990), and the present results are consistent with this original scheme.

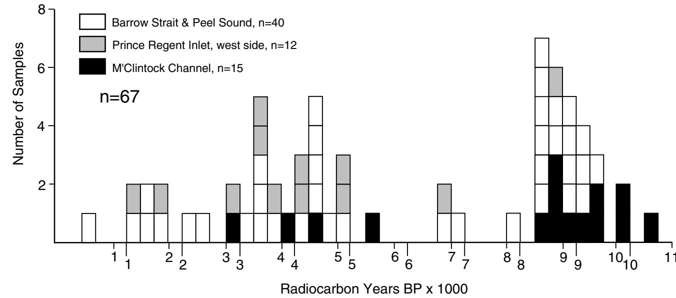

FIG. 4. Frequency distribution of radiocarbon dates on bowhead whales from the central Arctic channels — M'Clintock Channel to the west shore of Prince Regent Inlet. The x-axis shows uncorrected (upper) and "corrected" (lower) radiocarbon years B.P. Corrections are made for isotopic fractionation and for marine reservoir effect.

The region was deglaciated during the interval 11–9 ka B.P., mostly after 9.5 ka B.P. (Dyke and Prest, 1987; Dyke, 1984; Dyke et al., 1993). The radiocarbon-dated bowhead whales are among the oldest postglacial materials from the region. The whales thus occupied the newly deglaciated marine basins at the earliest opportunity and the increase in abundance of fossils dating from 10.5 to 8.5 ka B.P. reflects the increase in deglaciated area rather than otherwise improved conditions for whales. Thus, the data indicate suitable bowhead summer habitat throughout the interval 10.5–8.5 ka B.P. in all deglaciated areas within the region.

Two points are of particular interest with respect to the early Holocene part of the record. First, the bowheads ranged freely at that time in M'Clintock Channel, the core of the present sea-ice plug. Second, this occupation of M'Clintock Channel and adjacent Barrow Strait terminated abruptly at 8.5 ka B.P.

Few bowheads entered the central Arctic channels between 8.5 and 5.0 ka B.P. (Fig. 4). They failed to enter not just M'Clintock Channel but also adjacent straits that lie within the whale's historical range. The five animals that date from this interval possibly represent exceptional years of sea-ice reduction during a 3.5 ka period of otherwise pervasive summer sea ice when the M'Clintock Channel ice plug exceeded its historical size. Given that bowheads will enter areas of 90% ice cover, we infer that a sea-ice cover that excluded the whales must have been nearly continuous. Nevertheless, the ice must have been mobile at times, because some driftwood rafted into the area during this interval (Dyke and Morris, 1990).

Reoccupation of the central channels by bowheads seems to have started about 5.25 ka B.P. The animals ranged well into M'Clintock Channel until about 3 ka B.P., after which they failed to penetrate beyond Barrow Strait and Peel Sound. Thus, the M'Clintock Channel ice plug was greatly diminished or eliminated during some portion of the summers between 5 and 3 ka B.P., but seems to have been a nearly stable feature of approximately its present size for the last 3 ka.

During the middle Holocene period of renewed bowhead occupation, the population seems not to have reached its early Holocene levels. Although there are several possible explanations for this difference (Dyke and Morris, 1990), the simplest lies in the proportion of summers when occupation was possible. If we assume an equilibrium population density and mortality rates, and if we take the early Holocene fossils to represent conditions that allowed access to the area during all summers, then the relative height of peaks on the histogram (middle Holocene peak half as high as the early Holocene peak) (Fig. 4) suggests that the central channels as a group were accessible about 50% of summers in the middle Holocene, with M'Clintock Channel accessible about 10% of summers.

Lancaster Sound and Eastern Prince Regent Inlet

Lancaster Sound is the main approach for bowheads entering the central Arctic channels from Baffin Bay. Both Lancaster Sound and northern Prince Regent Inlet are well within the whale's historical range and were the centre of Scottish commercial whaling in the last century (Reeves et al., 1983). Prince Regent Inlet leads southward to the Gulf of Boothia, which resembles M'Clintock Channel in that the part south of Fury and Hecla Strait (Committee Bay) is a large sea-ice cul-de-sac that rarely clears today. The channel system was mostly free of glacier ice by 9.4 ka B.P. (Dyke, 1984).

We collected 162 bowhead samples from nine intensively searched small areas in this region and obtained radiocarbon dates on 73 of these. The resulting frequency distribution (Fig. 5) strikingly resembles that for the channels farther west, featuring a prominent early Holocene maximum and a middle Holocene recurrence, bracketed by barren intervals. Furthermore, here too the early Holocene termination of bowhead occupation seems to have been abrupt, and the following interval one of almost total exclusion. This similarity of bowhead chronology from sites as much as 600 km apart strongly suggests a single, broadly operating control mechanism. Either the M'Clintock sea-ice plug expanded eastward through Barrow Strait to envelop Prince Regent Inlet, or both the Gulf of Boothia and the M'Clintock ice plugs expanded and coalesced.

The subtle differences between the eastern and central chronologies also can be nicely explained by an expanding and contracting ice plug. Thus, the early Holocene termination in the east dates to about 8 ka B.P. as compared to 8.5 ka B.P. in the central area (plug expanding eastward), and the middle Holocene recurrence dates to about 5.5 ka B.P. in the east as compared to 5 ka B.P. in the centre (plug contracting westward).

The frequency distribution for Lancaster Sound and Prince Regent Inlet also resembles that for the M'Clintock region in the relative heights of its peaks; middle Holocene abundances of animals attain about 50% of early Holocene abundances. This similarity, however, may be fortuitous and perhaps is misleading. Note that all animals from the Lancaster Sound coast are of early Holocene age, whereas the animals from the Prince Regent Inlet coast are more evenly distributed between the early and middle Holocene groups. The Lancaster Sound coast has been submerging since the middle Holocene (Dyke, unpubl.) and the absence there of whales younger than 7 ka B.P. can be explained entirely by that fact: the whales lie offshore. Furthermore, the middle Holocene whales must have entered Prince Regent Inlet via Lancaster Sound.

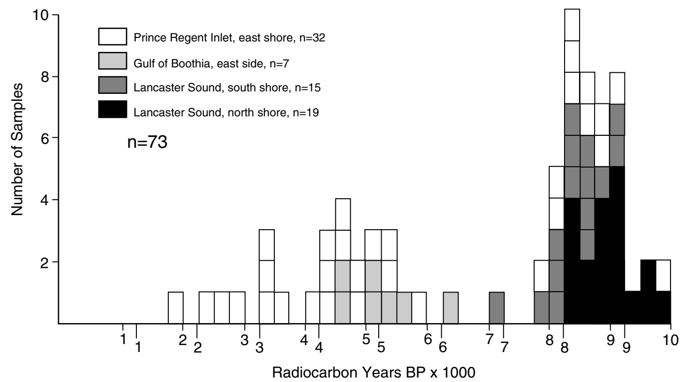

FIG. 5. Frequency distribution of radiocarbon dates on bowhead whales from the eastern Arctic channels.

Bowheads apparently were not able to penetrate to the southern Gulf of Boothia during the early Holocene. That area was deglaciated by 9 ka B.P. (Dyke, 1984; Dredge, 1990; Hooper, 1995). The exclusion of the whales must therefore indicate strong, persistent, sea-ice congestion of that region, as there is today. Seven samples from the northern Gulf of Boothia (none south of Fury and Hecla Strait) date generally from the middle Holocene and none younger than 4.5 ka B.P. have been found (Hooper, 1995). Surveys along Fury and Hecla Strait itself, deglaciated during the interval 7–6 ka B.P., yielded no bowhead bones of any age. It appears, therefore, that if the Hudson Bay–Foxe Basin bowhead stock became established during regional deglaciation, as might be expected from the radiocarbon records of adjacent regions, it remained separate during summers from the population to the northwest. This conclusion increases the probability that the Hudson Bay–Foxe Basin stock may be biologically (not just geographically) distinct from the other eastern Canadian Arctic bowheads; it also lessens the viability of Southwell's (1898; cf. Moore and Reeves, 1993) hypothesis of annual fall circumnavigation of Baffin Island by females and young whales via Fury and Hecla Strait.

Admiralty Inlet and Environs

Admiralty Inlet extends south from Lancaster Sound, and its mouth lies en route to Prince Regent Inlet. The southern and central shores of the inlet have experienced continuous Holocene emergence, but the northern part has been submerging for the last several thousand years. Berlinguet Inlet is an arm of Admiralty Inlet that was connected to Bernier Bay to the west until about 2 ka B.P. (Hooper, 1995). Hence, whales could have entered the channel system during most of the postglacial period either from the north (most directly) or from the west. The northern half of Admiralty Inlet was free of glacier ice by 9.1 ka B.P.; the southern half was deglaciated between 9.1 ka and 6.6 ka B.P. (Dyke in McNeely and Jorgensen, 1992; 1993; McNeely and Atkinson, 1996). Bernier Bay and Berlinguet Inlet were deglaciated mostly between 8.8 ka and 6.6 ka B.P. (Hooper, 1995).

We have collected 387 bowhead samples from 17 intensively searched areas in the region and have radiocarbon dated 181 of these samples (Fig. 6). The frequency distribution of animals through time approximates a normal distribution. The subset of dates from Bernier Bay and Berlinguet Inlet is not significantly different from that for Admiralty Inlet. Although the occupation of the latter may have been somewhat longer and perhaps was more continuous, this apparent difference may result from the different sample sizes. Clearly this general area was first occupied consistently by bowheads starting about 7.5 ka B.P. The early Holocene population (> 8 ka B.P.)—so prominent in the records from Lancaster Sound to M'Clintock Channel, including those from sites on either side of the mouth of Admiralty Inlet—is absent from the inlet and environs. The Admiralty Inlet summer population rose to a sharp, well-defined maximum between 4 ka and 3.5 ka B.P., after which it declined to minimal levels by 0.25 ka B.P., with possible resurgences at 2.5–2 ka and at 1.5–1 ka B.P.

The middle Holocene peak occupation of Admiralty Inlet and vicinity is broadly synchronous with the middle Holocene recurrences recorded in the two regions farther west. Thus its explanation lies in the same underlying paleoclimatic (or paleoceanographic) mechanism, which we have not yet defined. But beyond this simple correlation lie more interesting differences that we can explain only speculatively.

First, the population in Admiralty Inlet, which began a steep rise at 7.5 ka B.P., fell in the early part of the period when bowheads were excluded from Prince Regent Inlet westward (cf. Figs. 6 and 5). Second, the strong peak of fossil abundance in Admiralty Inlet (3.5–4 ka B.P.) lagged behind the peak of the middle Holocene recurrence in adjacent Prince Regent Inlet (4.25–5.5 ka B.P.). Possibly this signals an eastward propagation of summer-persistent sea-ice conditions.

The decline of fossil abundance after 3.5 ka B.P. in Admiralty Inlet was as sharp as the preceding rise. Unlike the channels farther west, however, the Admiralty Inlet area had no recognizable intervals of total bowhead exclusion between 7.5 and 0.25 ka B.P. except possibly in Bernier Bay and Berlinguet Inlet.

If the peak abundance represents an interval when the inlet was occupied during all summers, then the lower relative abundances before and after that peak represent the proportion of summers when access was possible. Peak abundances of bones in Admiralty Inlet are an order of magnitude or more greater than in the M'Clintock Channel region (compare sample sizes recovered from the 17 areas surveyed around Admiralty Inlet with those recovered from the 28 areas surveyed in the central region). This greater eastern abundance could represent 1) a higher proportion of summers allowing access, 2) a longer duration of occupation each

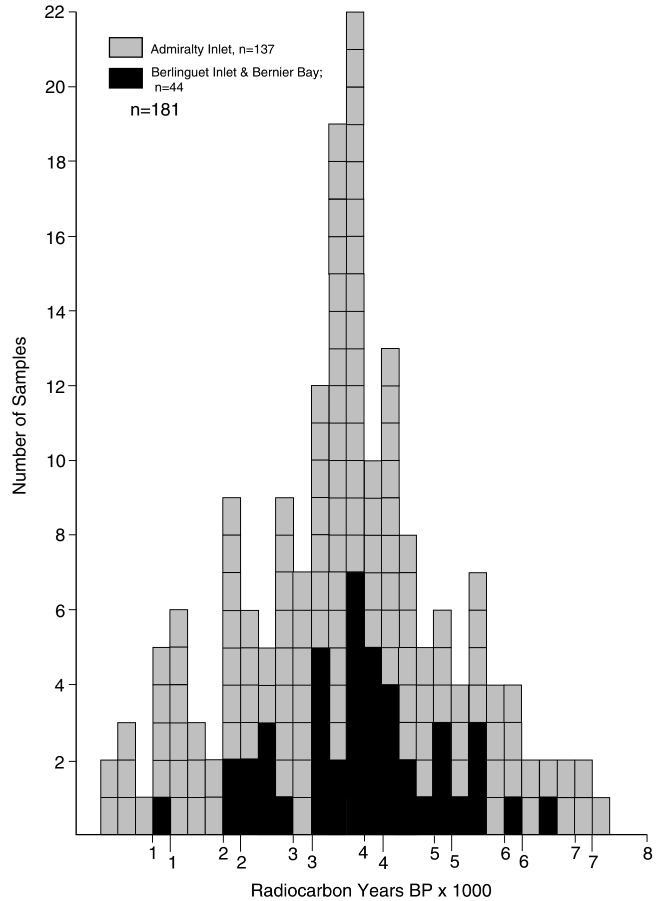

FIG. 6. Frequency distribution of radiocarbon dates on bowhead whales from Admiralty Inlet and environs.

summer, or 3) a higher population density. We have no objective basis for preferring one of these possibilities over the others.

More reliable access may have affected the behaviour of the whales through the characteristic of site fidelity: the tendency, common among some whales and other sea mammals, to follow closely similar annual migration patterns. Bowheads in general apparently exhibit site fidelity (see e.g., Ross and MacIver, 1982; Reeves et al., 1983; Moore and Reeves, 1993); but destination sites may change for individual animals during their lifetime according to state of maturity or, for adult females, according to whether they are oestrous or anoestrous (see e.g., Finley, 1990). Clearly, however, site fidelity is not an entirely slavish behaviour as evidenced by the whales' ready exploitation of vast, newly deglaciated territories.

The secondary mode between 1 and 1.5 ka B.P. (0.75–1.25 ka B.P., corrected age) in Admiralty Inlet is unique among the frequency distributions available to date. It possibly represents the 'Medieval Warm Period' when the Norse settled in southwest Greenland and the bowhead-hunting Thule expanded across Arctic Canada (see e.g., Williams and Bradley, 1985). This episode may be recognizable in the Admiralty Inlet bowhead time-series because of the boosted signal strength that results from large sample size.

However, this Thule-aged peak probably does not represent Thule-killed animals. We distinguish between naturally stranded and Thule-derived animals on the young raised beaches on the basis of two criteria. First, any bones located within or near Thule villages or camping sites, either as structural material or as refuse, were avoided as samples. Second, larger whale bones such as crania and mandibles at Thule 'flensing beaches,' which may be several kilometres from associated residential sites, are invariably found directly on the surface or only slightly embedded; similar bones of naturally stranded whales, on the other hand, tend to be mostly or completely embedded. Using these criteria, we are confident that the animals dated 0.75–1.25 ka B.P. (corrected) are not cultural "contamination" of the signal, but represent a resurgence of the summer bowhead population.

These findings provide a perspective on critical conditions during the arrival of the Thule people. As a group whose economy was ostensibly based on bowhead harvesting in the central and eastern Canadian Arctic, the Thule people appear to have arrived (1 ka B.P.) during a brief favourable phase within a long period of otherwise declining bowhead resources.

Navy Board Inlet and Eclipse Sound

Navy Board Inlet and Eclipse Sound open southward from Lancaster Sound and are also accessible from Baffin Bay via Pond Inlet. This coastline was deglaciated between 9.3 and 6 ka B.P., most of it before 8 ka B.P. (Dyke in McNeely and Atkinson, 1996). The highest density of fossil whale bone encountered in this study (or known to us) was at the site on Navy Board Inlet, where about 120 skulls were excavated from a surveyed area of about 6 km^2. We collected 98 bowhead samples from three sites, the easternmost in our survey, and have obtained dates on 36 of these (Fig. 7).

From its geographic position with respect to bowhead stocks and migration routes, and from the likely controls on sea-ice conditions discussed above, one expects a frequency distribution of bowhead remains in Navy Board Inlet similar to that in Admiralty Inlet. Indeed, several aspects are grossly similar: the absence of early Holocene bowheads, the middle Holocene abundance, and the late Holocene decline.

The two distributions differ, however, in the timing of modal abundances: 3.5–4 ka B.P. in Admiralty Inlet; 2.5–2.75 ka B.P. in Navy Board Inlet. This difference may be due to an inadequate sample size in the latter region, where most data are from only two sites. Individual sites are not generally representative of the aggregate frequency distributions for entire inlets, because each site records a unique set of mortality events probably due to localized ice entrapment (Savelle and Dyke, unpubl. data).

Should the tentative Navy Board Inlet ^{14}C date distribution prove stable with the addition of dates from more sites, it would be tempting to invoke the site fidelity characteristic to explain the differences between the two adjacent inlets. The specific hypothesis to be explored would be that Admiralty Inlet had become established as the "inlet of choice" for bowheads, who abandoned it in favour of Navy Board Inlet only after significant deterioration in the former; i.e., that site fidelity is not easily broken.

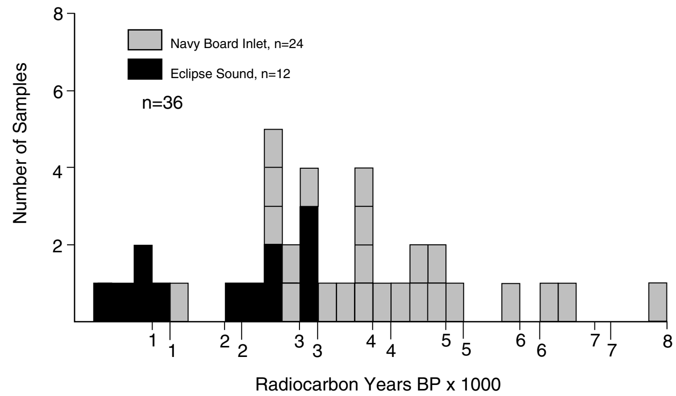

FIG. 7. Frequency distribution of radiocarbon dates on bowhead whales from Navy Board Inlet and environs.

Wellington Channel

Wellington Channel connects the waters of the Sverdrup Islands region to inner Lancaster Sound and carries outflow from the former to the latter. Because it is an ice exporter, it tends to clear even in poor ice years such as 1972 (Alt et al., 1985). During the Late Wisconsinan, the channel was entirely filled by a glacier ice stream fed by confluent ice, from Bathurst and Cornwallis Islands on the one side and from Devon Island on the other. The retreat of this ice stream left the adjacent coast of Devon Island ice-free between 8.7 ka and 8.2 ka B.P. (cf. Dyke and Prest, 1987; Dyke, unpubl.).

We have collected 38 bowhead samples from five intensively searched areas along the Devon Island coast of Wellington Channel and have dated 22 of these. Although the sample is small, the relatively large number of sites represented means that distribution is not dominated by any single massive mortality event at one site. The abundance of bowhead remains here is intermediate between the great abundances of north Baffin Island (and eastern Devon Island, below) and the relatively scarce remains along M'Clintock Channel.

The frequency distribution of bowhead ages for this area (Fig. 8) has several features of note. With one exception, the early Holocene bowhead remains are limited to the south end of the channel. This group is merely an extension of the contemporaneous Lancaster Sound population. Most of that coast of Devon Island was deglaciated very close to the time of the early Holocene bowhead termination, so beaches older than 5 ka B.P., except at the south end, are entirely devoid of bowhead fossils. This indicates pervasive summer sea ice between 8 and 5 ka B.P. just as in adjacent Barrow Strait (and westward) and in Prince Regent Inlet. The middle Holocene recurrence is clearly recorded in Wellington Channel, but either populations remained low, or only a small proportion of summers offered access (about 10% of the Admiralty Inlet population density or accessibility). Wellington Channel lacks a convincing Neoglacial decline of bowheads, which makes this distribution unique.

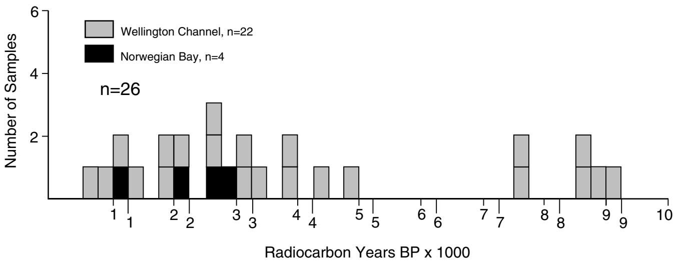

FIG. 8. Frequency distribution of radiocarbon dates on bowhead whales from Wellington Channel and Norwegian Bay.

Norwegian Bay

Drifting sea ice piles against the Norwegian Bay coast of Devon and Ellesmere Islands en route to Wellington Channel and Jones Sound. The coast lies well beyond the historical range of the bowhead whale, and Thule whaling sites are unknown from the region. Glacier ice had retreated to the vicinity of the coast by 9–8.8 ka B.P., before deglaciation of Wellington Channel but probably after deglaciation of Jones Sound (Dyke, unpubl.). We have extensively searched the Norwegian Bay coast from five field camps and have found only seven bowheads, four of which have been dated (Fig. 8). We can confidently conclude that whales rarely reached this region. Oddly, the few that did penetrate this far did so only in the last 3 ka, a time of restricted access in most other channels, except perhaps in Wellington Channel.

The Norwegian Bay area was deglaciated early enough to have been occupied by the early Holocene bowheads that were abundant to the south and east. Wellington Channel, however, remained blocked by glacier ice, and the straits at the head of Jones Sound probably were not deglaciated until after 9 ka B.P. The Bathurst Island area was mostly or entirely deglaciated by 9 ka B.P. (Dyke et al., 1991), so access from that direction must have been blocked by sea ice. Even in the best recorded sea-ice years, ice did not clear from the north coasts of Bathurst and Melville Islands (Alt et al., 1985:84, see their Fig. 8). Animals of the Spitsbergen stock apparently never penetrated to the Canadian Arctic Islands via North Greenland; bowhead remains are not known from the Arctic Ocean coasts of Ellesmere Island, Axel Heiberg Island, or western North Greenland.

Bednarski (1990) reported an isolated bowhead occurrence from the Nansen Sound coast of northwestern Ellesmere Island which has been dated 7475 ± 220 B.P. (S-3035). Not only is this the northernmost location recorded in the archipelago for a bowhead fossil, but the whale made its way there during what now appears to have been one of the most inhospitable times for bowheads throughout the archipelago. This fact cautions against attaching much paleoenvironmental significance to isolated occurrences. It is remotely possible that such anomalous outliers result from strandings of rare, far-drifted corpses locked in ice. If so, the most likely source of an animal stranded in Eureka Sound would be the Spitsbergen stock.

Jones Sound

Jones Sound opens directly into Baffin Bay. It carries surface outflow from the Arctic Ocean via narrow straits that connect to Norwegian Bay. The North Water polynya adjacent to the mouth of the sound (Stirling and Cleator, 1981) serves as a staging area for sea mammals, including walrus, narwhal, and beluga awaiting regional ice breakup (Stirling et al., 1981). Bowhead sightings and commercial whale kills were infrequent in the sound during the historic period (Ross and MacIver, 1982; Reeves et al., 1983), and prehistoric Thule whaling sites, although present on both the eastern north and south shores, are nevertheless rare compared with 'core' bowhead areas (see Fig. 19).

It is not clear at present that this large sound was filled by Late Wisconsinan glacier ice. If it was, it was deglaciated by 9.4 ka B.P., because fossils of that age, including a bowhead whale, have been dated near its head (Blake, 1975).

Blake (1975) reported dates on nine bowheads from the inner Ellesmere Island coast of Jones Sound, and five dated bowheads have been reported from Truelove Lowland on northeast Devon Island (Barr, 1971; King, 1991). We have collected an additional 52 animals from two other sites on northeast Devon Island, 23 of which have been dated. All 37 dates are compiled in Fig. 9.

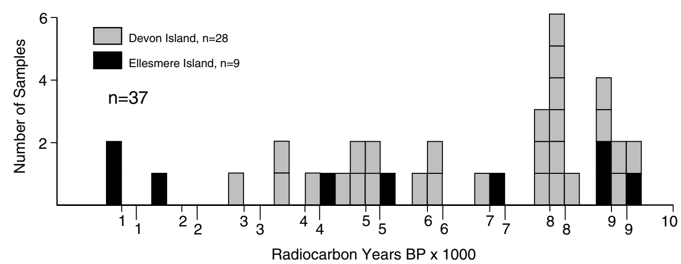

FIG. 9. Frequency distribution of radiocarbon dates on bowhead whales from Jones Sound.

The sample size for this large region is too small, and too dominated by data from only two sites, to allow establishment of a satisfactory chronology of bowhead occupation. Nevertheless, there are definite similarities to the record from Lancaster Sound. Whales were most abundant in the early Holocene, decreasing about 8 ka B.P.; there is also a suggestion of a middle Holocene recurrence, followed, less convincingly, by a Neoglacial decline. During the Neoglacial, whales may have penetrated along the Ellesmere coast, but not the Devon coast, of the sound.

Summary of Frequency Distributions

The frequency distributions of whale radiocarbon ages define three fundamental patterns for areas that were deglaciated in the early Holocene:

1. Large early Holocene populations that were abruptly terminated, followed in succession by a long interval of

whale exclusion, a middle Holocene recurrence, and a late Holocene (Neoglacial) exclusion. This pattern occurs in all large channels from the centre of the archipelago to Baffin Bay: M'Clintock Channel, Peel Sound, Barrow Strait, Prince Regent Inlet, Lancaster Sound, and probably Jones Sound. Wellington Channel records a variant of this pattern, in that glacier ice largely excluded the early Holocene whales.

2. Exclusion of early Holocene whales followed by a rapid rise of local summer populations, narrowly peaking in the middle Holocene, then sharply declining to minimal levels through the Neoglacial. This pattern characterizes the smaller eastern inlets: Admiralty Inlet, Bernier Bay, Berlinguet Inlet, Eclipse Sound, and Navy Board Inlet.

3. All but total exclusion of whales throughout the Holocene. This pattern characterizes the southern portion of the Gulf of Boothia, Fury and Hecla Strait, and Norwegian Bay. We infer that it also characterizes the entire Sverdrup Islands region, because that region lies upcurrent of Norwegian Bay, and whale bones have not been reported from there despite extensive field work.

Because we have defined the areas for which the third pattern holds, we can reconstruct the extent of sea ice for postglacial time throughout most of the archipelago. The unfortunate gap is the lack of a comparable data set for the Bering Sea bowhead stock in the approaches to the Beaufort Sea. A few animals have been dated from that area (Dyck et al., 1966; McNeely, 1989; J.-S. Vincent and D.R. Sharpe, pers. comm., 1995) and these results, along with scattered other dates from the archipelago (Lowdon and Blake, 1968; Lowdon et al., 1971; Blake, 1987; Hodgson, 1993), are considered in the following paleogeographic reconstructions, which constitute our conclusions.

PALEOGEOGRAPHY OF SEA ICE

In the following set of paleogeographic reconstructions, the paleoshorelines and glacier ice reconstructions are taken or modified from Dyke and Prest (1987). Modifications of glacier ice margins are based mainly on Blake (1992), who indicated a confluence of Ellesmere and Greenland ice during the last glaciation; on Dyke and Hooper's unpublished work on deglaciation of north Baffin Island, which generally indicates later deglaciation than that shown by Dyke and Prest (1987); and on unpublished work on the glacial geology of Devon Island by Dyke, general results of which have been alluded to above.

Paleogeography at 10 ka B.P.

Our oldest bowhead remains, three samples dating 10–10.5 ka B.P., are all from the M'Clintock Channel area (Fig. 10). That area was not then accessible from Baffin Bay.

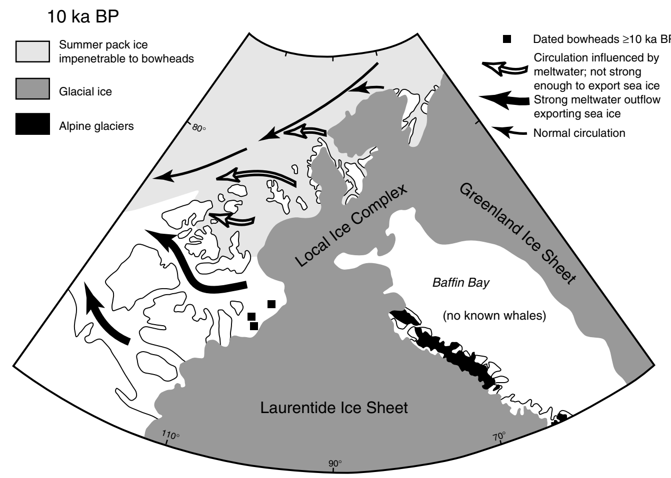

FIG. 10. Paleogeography of 10 ka B.P. showing inferred summer sea-ice extent and ocean circulation patterns. In the sequence of paleogeographic maps (Figs. 10–19), a symbol for "dated bowheads" may represent one or several animals; see Figures 4–9 for regional abundances. Extent of glacier ice between northern Ellesmere Island and Greenland (cf. Kelly and Bennike, 1992; England, 1985) is uncertain.

Hence the whales must have entered the area either from the Spitsbergen stock via the Arctic Ocean or from the Bering Sea stock via the Beaufort Sea. The latter is more probable in light of the apparent absence of early Holocene whales in the Sverdrup Islands region (none reported despite extensive field work; Hodgson, 1982, 1992). The Bering Sea bowheads probably entered the Arctic Ocean as soon as Bering Strait submerged, but our dates are the only indication of this so far. Dyke et al. (1996) place the opening of Bering Strait at 10.5–10.3 ka B.P. on the basis of the initial entry of molluscs of Pacific origin into the western Canadian Arctic; this dating agrees with the earliest bowhead dates.

By 10 ka B.P., the northwestern Laurentide Ice Sheet was ablating rapidly (Dyke and Prest, 1987). We propose that westward meltwater flow during the summer exported sea ice and allowed the whales to range right up to the calving glacier fronts. The apparent absence of whales around the Sverdrup Islands at this time is the basis for depicting impenetrable summer sea-ice conditions there. Glacier ablation in the far North was probably too slow to produce a meltwater outflow strong enough to clear the channels of sea ice.

Throughout the paleogeographic sequence, summer sea-ice minima and summer circulation patterns are illustrated. Clearly the meltwater discharge was much less in the winter, so seasonal changes of circulation in the periglacial zone can also be inferred. The "local ice complex" was largely cold-based and generated little basal meltwater (Dyke, 1993); so the weak summer outflow through the Sverdrup Islands may have been replaced by winter through-flow from the Arctic Ocean. In contrast, the northwestern Laurentide ice sheet had a wide, warm-based peripheral zone, which may have continuously yielded basal meltwater to the marine-based ice fronts and maintained weak outflows even in winter.

As yet, there is no direct evidence that a Davis Strait bowhead stock existed this early or therefore, that Baffin Bay was penetrable during the summer. The diatom record of a core (HU82-031-MC83.6) off McBeth Fiord, east central Baffin coast shows a generally high productivity for the interval 12.3–8 ka B.P., interpreted as indicating seasonally open pack ice; however, the dating of this core (and others) is suspect, in that it utilized fine-grained total organic carbon (Williams, 1990). Williams reported other western Baffin Bay cores that penetrate 10 ka B.P. sediment; these show low diatom productivity and presumably summer-persistent sea ice. Thus, from the diatom record, parts of Baffin Bay may have been penetrable by bowheads at 10 ka B.P., but much of it may not have been. On the basis of benthic foraminiferal assemblages, Osterman and Nelson (1989) recognize distal glaciomarine conditions prior to 8.5 ka B.P. in four widely spaced cores (three also analyzed by Williams) from the east Baffin continental shelf; the same dating uncertainties pertain.

The Spitsbergen stock may have been established by about 13.1 ka B.P. (Forman, 1990a; see below), but there is no evidence that animals from that stock were ever able to extend into Canadian waters.

Paleogeography at 9 ka B.P.

By 9 ka B.P., most of the large channels were deglaciated, and bowheads ranged freely during the summer from the Beaufort Sea to Baffin Bay (Fig. 11). The Davis Strait bowhead stock had become established before 9.5 ka B.P. and was commonly able to penetrate to the head of Baffin Bay and beyond and even to intermix with the Bering Sea stock. Farther north, the whales still failed to penetrate the Sverdrup Islands, and in the south, they failed to penetrate the southern part of the Gulf of Boothia, Admiralty Inlet, and Navy Board Inlet. Severe summer sea-ice conditions in Admiralty Inlet from 9–6.3 ka B.P. are also indicated by the lack of diatoms in a core (HU76-025-35) from Strathcona Sound, which opens off the inlet (Short et al., 1994). However, a core from Jones Sound (HU83-023-053), where bowheads clearly were able to enter during the interval 10–9 ka B.P., is entirely barren of diatoms in all sediment older than 2.8 ka B.P. (questionably extending back to 17 ka B.P.; Williams, 1990). Hence, the diatom and bowhead records do not consistently agree where we have both sets of data from the same channels. However, the established presence of bowheads during times when zones in the same channel were diatom-barren requires an explanation of the lack of diatoms other than summer-persistent sea ice.

We suggest that the still rapidly melting northwestern Laurentide ice exported meltwater and summer sea ice to both Beaufort Sea and Baffin Bay, whereas the much more stable glacier ice masses farther east and north produced too little meltwater to break up the adjacent sea ice. The feedback between summer open water conditions and glacier mass balance is discussed further below.

Paleogeography at 8.5 ka B.P.

The northwestern Laurentide ice continued to melt rapidly between 9 and 8.5 ka B.P., sustaining a meltwater-driven

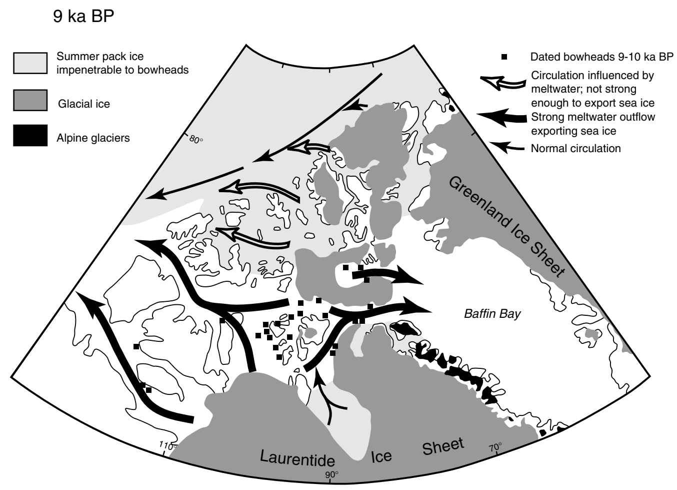

FIG. 11. Paleogeography of 9 ka B.P.

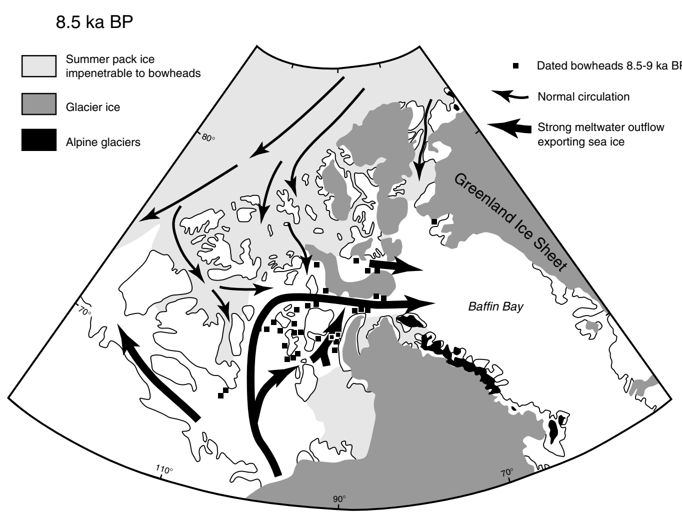

FIG. 12. Paleogeography of 8.5 ka B.P.

outflow that weakened as the source became more distant. Whales continued to range right into M'Clintock Channel, probably from both east and west, until 8.5 ka B.P. (Fig. 12). However, this accessibility then ended, because by 8.5 ka B.P., the glacier ice mass over Keewatin had been critically reduced, and little of its meltwater reached the Arctic seas.

We attempted to test the "meltwater drive" hypothesis by examining the isotopic composition of fossil marine molluscs from the region of bowhead fossil collection (Andrews et al., 1993). The results indicate that the upper seawater column was much fresher before about 8.5 ka B.P. than after, and that the freshening of the surface water extended to tens of metres in depth and to hundreds of kilometres beyond the retreating glacier front. The results, therefore, are compatible with the hypothesis.

The failure of bowheads to penetrate the Gulf of Boothia and Admiralty and Navy Board Inlets in the early Holocene (Fig. 12) must indicate, if we are to be consistent, that there was much less meltwater discharge from the retreating ice fronts in this region than farther west, too little to disrupt the proglacial sea-ice cover. This is consistent with the fact that early Holocene glacier retreat on Baffin Island was far slower and more intermittent than in areas at similar latitude farther west (Dyke and Prest, 1987). The Cockburn end moraines were constructed during this interval on Baffin Island; this fact indicates that the part of the ice sheet there had a positive mass balance. Dyke and Morris (1990) proposed that the climatic force behind this end moraine construction was enhanced precipitation from the new open seas to the west combined with downwind (eastward) summer fogs generated by the open water, which reduced both glacier and sea-ice ablation.

Paleogeography at 8 ka B.P.

Dyke and Morris (1990) noted that the 8.5 ka B.P. bowhead termination in the M'Clintock Channel area coincided with the earliest boreal driftwood incursion, not only to this region but to the Arctic Archipelago in general. They postulated that the glacial meltwater-driven surface water outflow from the archipelago, invoked to explain entry of the whales, also diverted driftwood from the region until about 8.5 ka B.P.

The coincidence at 8.5 ka B.P. of 1) widespread arrival of driftwood; 2) bowhead termination; and 3) the increased surface water salinity recorded in the mollusc isotopic composition (Andrews et al., 1993) can be explained by establishment of the modern oceanographic circulation pattern in the archipelago at that time. This pattern brought with it the M'Clintock Channel sea-ice plug (Fig. 13). This pack ice from the Arctic Ocean probably consisted mostly of multiyear ice, which would have been much thicker than the first-year ice that had formed in these channels before 8.5 ka B.P. First-year ice grows to be about 2 m thick. Multiyear ice has drafts ranging from 4 to 16 m (Koerner, 1973; Barry, 1989), the thicker parts resulting from pressure ridge and hummock formation. Multiyear ice in the central Arctic Ocean is 2–4 m thick today but it is 6 m thick off the Queen Elizabeth Islands because of convergence of ice in this area (Hibler, 1989). This is much thicker than can melt in situ during a High Arctic summer.

In that 8.5 ka B.P. marks the initial flux of Arctic Ocean surface water through to Baffin Bay according to the interpretation above, it also dates the first transport of that water mass by the Baffin Current, which replaced meltwater from the High Arctic and essentially established the modern characteristics of that current. On the other hand, Osterman and Nelson (1989) proposed, on benthic foraminiferal evidence, that northern Baffin Bay became warmer and more saline than it is at present at 8.5 ka B.P., and that the end of this warm event at 6 ka B.P. marked the onset of flow from the Arctic Ocean and establishment of the modern Baffin Current. In light of the insecure dating of the Baffin Bay cores, as discussed by Osterman and Nelson, we suggest the possibility that the warm, saline *Melonis zaandamae* foraminiferal zone dates from about 10–8.5 ka B.P. By adjusting the chronology, we can independently support Osterman and Nelson's interpretation of the cause of the foraminiferal assemblage change.

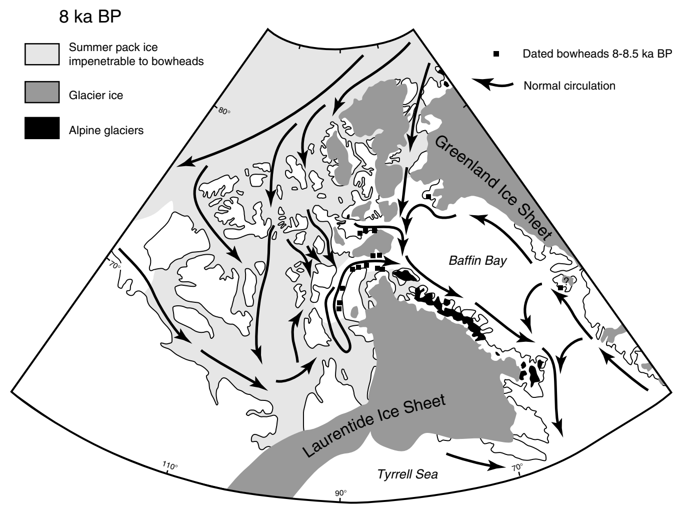

FIG. 13. Paleogeography of 8 ka B.P.

These authors entertained an essentially identical alternative chronology (Osterman and Nelson, 1989:2246). They also noted that this would bring their interpretation in line with that of Aksu (1983) for central Baffin Bay (deep water) cores. Aksu proposed onset of Arctic Ocean water flux through to Baffin Bay at 8 ka B.P., the start of a foraminiferal dissolution (cold, CO_2-rich water) event. Recently Rahman and De Vernal (1994) concluded that the West Greenland Current became suddenly warmer at 8.4 ka B.P. and that the Labrador Current became much stronger at that time; they based their conclusions on nannofossil records of two deep-sea cores from the Labrador Sea.

By all indications, environmental change in the Arctic between 8.5 and 8 ka B.P. was profound. The bowhead summer range shrank to the easternmost large channels, and sea ice blocked the rest of the archipelago. If the Cockburn end moraine construction had been driven by precipitation from the newly open seas to the west, by 8 ka B.P. the glacier masses in the east should have been suffering from aridity. Retreat from the moraines may indicate this aridity as well as the less foggy summer weather to be expected from the persistent sea-ice cover.

In apparent contradiction of the conditions described above, surface water temperatures in some coastal areas of Baffin Bay were warmer by 8 ka B.P. than today (Williams et al., 1995; Funder and Weidick, 1991; Dyke et al., 1996). Boreal molluscs extended to the head of Baffin Bay on both sides throughout the period of most extensive summer ice in the archipelago, whereas today on the Canadian side they do not extend north of Cumberland Peninsula. Funder and Weidick (1991) concluded that the West Greenland Current carried warmer water into Baffin Bay at that time. Williams et al. (1995) suggested that the then-deeper channels of the Queen Elizabeth Islands allowed a flow of deeper water (> 200 m) of Atlantic origin into Baffin Bay from the Arctic Ocean, which has since ceased because of uplift. Dyke et al. (1996) suggested that the failure of ice to clear from the Arctic Archipelago would have lessened the sea-ice load of the Baffin Current, allowing for a longer ice-free period and thus greater solar warming of shallow water along the Baffin coast. All three of these mechanisms probably operated.

Paleogeography at 7 and 6 ka B.P.

Bowhead access, hence summer sea-ice conditions, in general continued to decline between 8 and 7 ka B.P. By 7 ka B.P. (Fig. 14), few bowheads penetrated beyond Baffin Bay. The rare remains dating 7–8 ka B.P. are mostly in Admiralty and Navy Board Inlets and probably represent access during a few exceptional summers or rare long-distance rafting of carcasses in dense, but mobile, sea ice (Marquette [1986] reported that carcasses without wounds have been observed floating in ice). By 6 ka B.P. (Fig. 15), access to inlets nearest Baffin Bay was improving, but was probably not reliable. The diatom record from Strathcona Sound fully supports these inferences and indicates lessening of summer sea-ice extent beginning only at 6.3 ka B.P. locally (Short et al., 1994).

Regionally, the bowhead data indicate that summer sea ice during the interval 7–6 ka B.P. was at its most extensive for the postglacial period in the Arctic Archipelago, considerably more than during the worst year of recorded sea-ice history (A.D. 1972, Alt et al., 1985). That such conditions persisted for millennia suggests that this is one of the stable environmental modes for the region during interglacial times. Williams (1990) concluded that similar summer ice conditions extended along much of the east Baffin coast, but this conclusion is difficult to reconcile with the well-established and well-dated mollusc record.

Unfortunately, we presently have little basis to select from among the several possible causes of such bad summer conditions in the High Arctic. Among the possibilities are 1) more vigorous supply of sea ice from the Arctic Ocean, potential supply exceeding transport through the archipelago (persistent northerly winds during the summer; generally increased surface water outflow from the Arctic Ocean); 2) diminished evacuation of ice from Baffin Bay (weakened Baffin Current or greater closure of circulation in Baffin Bay); 3) prevalent summer winds from the east or northeast in the Lancaster Sound region, as might be caused by a Labrador Sea or Baffin Bay-centred atmospheric low-pressure system; and 4) cooler summers leading to less sea-ice ablation.

Independent paleoenvironmental data are needed in order to assess these possible causes of the changes in summer sea-ice minima. The only continuous and well-dated proxy environmental records for the whole Holocene in the region are those of the Devon and Agassiz (Ellesmere Island) glacier ice cores (Paterson et al., 1977; Fisher et al., 1983; Koerner, 1989). However, strong differences between the two main cores complicate interpretation and correlation. Neither core shows patterns that correlate strongly or consistently with each other or in total with the bowhead records. For example the $\delta^{18}O$ record of the Devon ice core suggests early Holocene temperatures similar to present temperatures, whereas the record for the Agassiz ice core suggests maximum Holocene warmth at that time. The Devon record is the odd one, in that the Agassiz record more fully agrees with the Greenland records (D.A. Fisher, pers. comm. 1995). The percent-melt record for the Agassiz Ice Cap also indicates that the warmest summers occurred prior to 8 ka B.P., before the early Holocene bowhead termination (Koerner, 1989; Koerner and Fisher, 1990; Fisher et al., 1995). Therefore, the poor sea-ice years thereafter may be due in part to colder summers, although we feel that the primary mechanism was the change in ocean circulation.

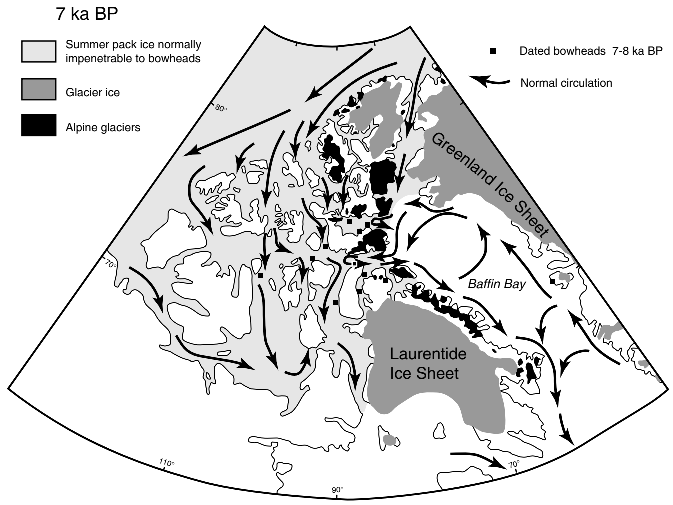

FIG. 14. Paleogeography of 7 ka B.P. Rare occurrences of bowheads within the area shown as "impenetrable" pack ice probably represent exceptional summers during the interval 7–8 ka B.P.

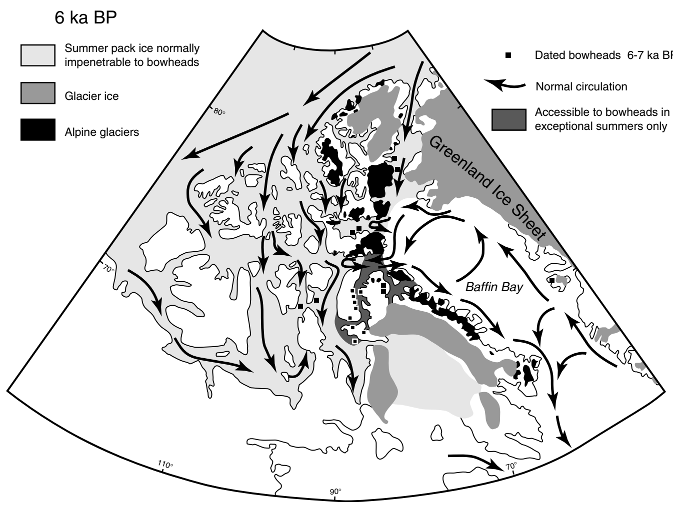

FIG. 15. Paleogeography of 6 ka B.P. Bowhead remains dated 6–7 ka B.P. are moderately abundant in areas shown as "accessible in exceptional summers," but far below peak abundance; they are much more rare in "pack ice normally impenetrable to bowheads."

Paleogeography at 5 and 4 ka B.P.

Between 6 and 5 ka B.P., bowhead access increased, so that by 5 ka B.P., the range of the whale closely resembled its historical range (Fig. 16). The cause of this and subsequent range expansions cannot be understood until the cause of the preceding range retraction is known. By 4 ka B.P., the whale range had extended back into Wellington and M'Clintock Channels, well beyond its known historical range. On Figure 17 we have shown a conservative range limit in southern M'Clintock Channel. Future surveys on Victoria Island may reveal an open connection with the Beaufort Sea at this time and hence an opportunity for whale and other sea mammal stocks to intermix.

The earliest Paleoeskimo inhabitants migrated east from Alaska into the arctic islands and northern Greenland at least as early as 4.0 ka B.P. (Knuth, 1983; McGhee, 1976; Maxwell, 1985) and possibly as early as 4.5 ka B.P. (Helmer, 1991). Their occupation thus started during the middle Holocene bowhead recurrence. Although these people were not bowhead whale hunters, the wave of occupation may signal that increasing marine mammal resources during an interval of greater seasonal ice clearance increased the attractiveness of the region.

There is no sign of a correlative middle Holocene warming in the Agassiz percent-melt record. Therefore, it seems improbable that the middle Holocene recurrence of bowheads can be attributed to increased summer sea-ice ablation. However, the Devon oxygen isotope record indicates that the least negative $\delta^{18}O$ values for the whole Holocene centred on 4.5 ka B.P. This core also displays maximum electrolytic conductivity of ice accumulated between 5 ka and 3.5 ka B.P., thus correlating with the bowhead recurrence. Koerner (1989) interpreted the $\delta^{18}O$ record as indicating maximum winter or mean annual warmth and attributed the conductivity maximum to increased concentrations of marine salts deposited on the ice cap during longer periods of open water in Baffin Bay, specifically the North Water polynya.

Alt's (1985) climatological analysis provides the basis for a probable unified interpretation of the middle Holocene bowhead and ice-core data. The bowhead record indicates that the inter-island channels north, south, and west of the Devon Ice Cap, in addition to Baffin Bay, were widely available as sources of salt aerosols. This source would have been at annual maxima during late summer and fall (August to October) if present patterns of ice breakup are representative. Theoretically, $\delta^{18}O$ values become less negative with either increasing winter warmth, with increasing proximity of a precipitation (snow) source, or with an increasing proportion of snow falling during warmer parts of the year (Alt, 1985; Fisher and Alt, 1985; Fisher, 1992). We suggest that both the $\delta^{18}O$ maximum (least negative) and the salt maximum of the Devon ice core can be explained by local inter-island channel autumn sources. The low percent-melt record of Agassiz for the same time interval indicates relatively cool summers, possibly even cool enough to allow summer accumulation at the top of the ice caps. Such conditions occurred in A.D. 1964, when local moisture sources generated unusually heavy warm-season snowfall that resulted in less negative $\delta^{18}O$ ratios and low percent melt (Alt, 1985). The absence of a correlative $\delta^{18}O$ response in the Agassiz ice core supports interpretation of these features of the Devon $\delta^{18}O$ record as regional effects. If these inferences are generally correct, prevalent surface winds were generally from west to east, a pattern that aids clearing of sea ice from the inter-island channels.

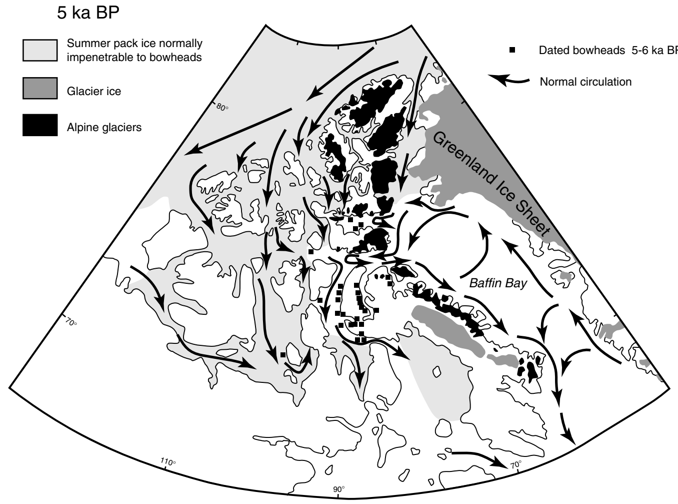

FIG. 16. Paleogeography of 5 ka B.P. A single animal is recorded from the area "normally impenetrable" to bowheads.

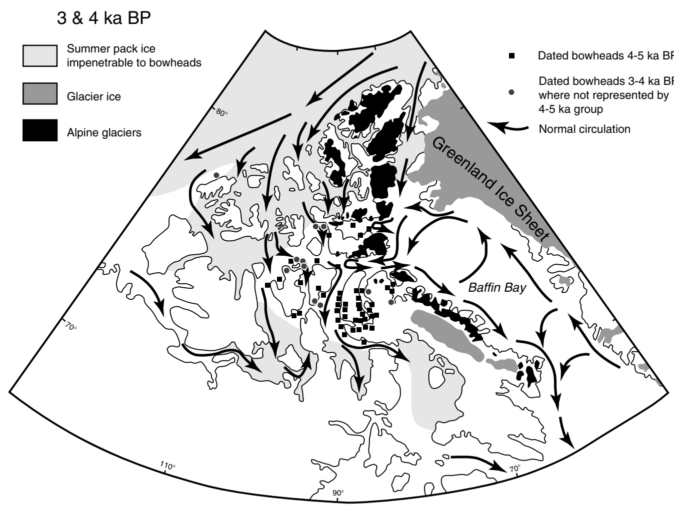

FIG. 17. Paleogeography was similar at 3 ka B.P. and 4 ka B.P. with regard to sea-ice conditions.

Paleogeography at 3 ka B.P. and later

Summer bowhead access was reduced significantly between 3 and 2 ka B.P. (Fig. 18). Remains of this age are moderately abundant in Navy Board and Admiralty Inlets, but in Prince Regent Inlet they are rare and known only on its east coast. Barrow Strait and Wellington Channel were occupied occasionally. Two dated remains on Prince Patrick Island suggest that the shore lead along the edge of the Beaufort Gyre offered access to animals from the Beaufort Sea. The oldest dated bowhead remains from that area date just over 3 ka B.P. (GSC-361; Fig. 17).

At 1 ka B.P., the bowhead range was similar to that at 2 ka B.P.; the range appears to have expanded in places and to have retracted in others (Fig 19). The pattern of occupation of

Prince Regent Inlet seems to have switched: earlier, whales seem to have occupied the east side but not the west; later, the west side but not the east. This switch may be related to changes of access and perhaps also to patterns of ice breakup brought on by land uplift (glacial rebound). Until about 2 ka B.P., Prince Regent Inlet was accessible from Admiralty Inlet via Bernier Bay; after the uplift of the isthmus between Bernier Bay and Berlinguet Inlet, the whales could enter only from Lancaster Sound (Hooper, 1995).

The difference between the two sides of Prince Regent Inlet about 1 ka B.P. is brought out strongly by the distribution of Thule culture whaling sites (Fig. 19). Such sites are exceedingly abundant on the west side (Savelle and McCartney, 1994), and McCartney (1979b) has estimated that they contain about 40% of all archaeological whale bone in the entire Canadian Arctic. On the east side, in contrast, only one site (Cape Kater) has been reported. This site was described by Mathiassen (1927:204) as consisting of "houses of whalebone and stone," but he did not personally visit it; thus the nature and amount of whale bone has not been determined.

At the scale of the archipelago, a clearer definition of bowhead ranges than is possible for earlier times derives from archaeological information (Fig. 19). The distribution of (a) early Thule winter occupations that are characterized by great abundances of bowhead bones, and (b) contemporaneous Thule winter sites with little or no whale bone generally agrees with the distribution of naturally stranded whales, but the site distribution data are from a much broader area than the stranded whale data. The distribution of Thule culture whaling sites provides the only present evidence of the prehistoric range of the Hudson Bay–Foxe Basin stock of bowheads, which apparently was similar to the present range.

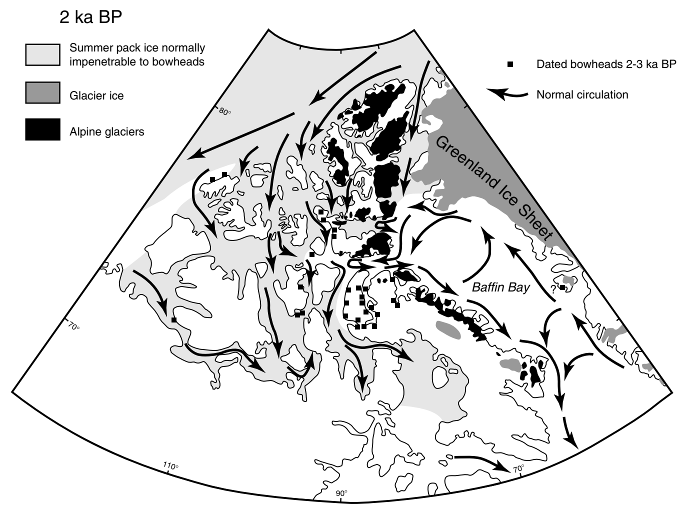

FIG. 18. Paleogeography of 2 ka B.P.

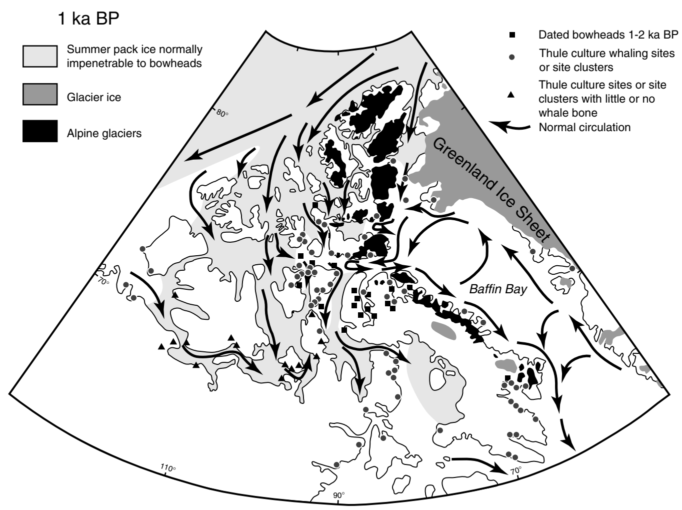

FIG. 19. Paleogeography of 1 ka B.P. Note that the Thule site data for Greenland are not as comprehensive as those for the Canadian Arctic, and sites or site clusters in Greenland indicate those interpreted as major whaling centres only.

SUMMARY AND DISCUSSION

The interpretations presented above rest entirely on a premise based on bowhead whale ecology: the whale exploits a floe-edge habitat, and its annual migratory sweep follows the oscillation of the floe edge. Large-scale changes of the dynamic sea-ice regime are inferred just as they were implicitly predicted by Reeves et al. (1983). These changes are large enough to affect regional radiation balance via albedo and to otherwise affect regional cloud (fog) cover and precipitation, and thus glacier mass balance.

The changes in summer sea-ice minima during regional deglaciation were caused mainly by changing meltwater flux, essentially by the switch from a glacial to an interglacial mode of regional oceanographic circulation, possibly assisted by coincidental changes in summer temperature. But large changes also have occurred since deglaciation between contrasting environmental modes that are apparently each stable on a time scale of centuries to millennia. The most likely causes of these more recent changes have not been isolated, but likely involve changes in average summer positions of the Icelandic Low and Mackenzie High pressure systems.

The use of bowhead fossils to derive sea-ice history has been successful in the Canadian Arctic, although several extensions, including data from the Beaufort Sea region, from Hudson Bay and Foxe Basin, and from the wintering regions of all stocks are needed to satisfyingly complete the interpretations. Data from wintering regions would be most informative in that they should lead to reconstructions of winter ice maxima, the ultimate complement of the summer minima reconstructions presented above. The new datings of bowhead bones from Disko Island, West Greenland, which lies adjacent to the winter–spring range of the whale (Figs. 12–15), offer encouragement that this will be possible (Bennike et al., 1994; Bennike, pers. comm. 1996). Similarly, Basque whalers operating from shore stations in the Strait of Belle Isle in the sixteenth century (Barkham, 1984) harvested nearly even numbers of bowheads and North Atlantic right whales (Cumbaa, 1986). This region is south of the present winter range of the bowhead (Fig. 1), and these archaeological findings indicate a southward shift during the Little Ice Age (0.4–0.1 ka B.P.).

When viewed at the scale of the entire North Polar region, the polar pack ice has greatest potential for areal fluctuation on millennial time scales in the Canadian Arctic and in the Greenland Sea–Barents Sea region. Elsewhere the Arctic Ocean is landlocked, and the summer coastal leads are narrow.

Radiocarbon dates on bones of large whales have been reported from Svalbard and East Greenland. A survey of the journal *Radiocarbon* and reports on the Quaternary history of Svalbard (Blake, 1961; Hoppe et al., 1969; Salvigsen, 1977, 1978, 1981; Salvigsen and Österholm, 1982; Forman et al., 1987; Landvik et al., 1987; Forman, 1990a, b; Österholm, 1990; Salvigsen et al., 1990; Salvigsen and Mangerud, 1991; Gulliksen et al., 1992) revealed 121 dated whale bones (Fig. 20). Accompanying photographs, although rarely identified, illustrate large bone elements that could be from bowheads or, perhaps less likely, one of the large balaenopterine whales (blue, *Balaenoptera musculus*, or fin, *B. physalus*), the humpback (*Megaptera novaeangliae*), the northern right whale (*Eubalaena glacialis*), or the now-extinct North Atlantic population of the gray whale (*Eschrichtius robustus*). All of these species, as well as the sperm whale (*Physeter catodon)*, occur in the northeast Atlantic. Blue whales were often seen in the pack ice in the Svalbard latitudes by bowhead hunters. Depending on ice and oceanographic conditions, any of these whales could have contributed to the remains at Svalbard (R. Reeves, pers. comm. 1995).

There may be some danger in interpreting this frequency distribution because of uncertain species identity and because, as far as we know, no surveys have attempted to establish fully the changing abundance of bones through time. Furthermore, the general tendency among Quaternary geologists to date the oldest remains and ignore younger occurrences may have strongly biased the distribution.

Nevertheless, the resemblance of the Svalbard distribution to "Pattern 1" of Arctic Canada is strong: it features a prominent early Holocene abundance ending in a sudden decline or termination, possibly a middle Holocene recurrence, and late Holocene (Neoglacial) decline or termination around 3 ka B.P. Given the large size (113) of the radiocarbon whale bone sample from Svalbard, it is improbable that these similarities are entirely fortuitous. The similarities clearly show a need for further survey and dating to fully document the changing abundance of animals through time in Svalbard. Should it be shown that the summer range of the Spitsbergen bowhead stock expanded and contracted in synchrony with that of the Davis Strait stock, panarctic mechanisms would be required to explain the correlations.

In Arctic Canada, the early Holocene termination of bowheads coincided with the initial incursion of driftwood; in Svalbard, some driftwood arrived during the early Holocene period of abundant large whales, but an increase in wood abundance dated about 9.5–8.75 ka B.P. coincides closely enough with the whale decline to suggest that both events have a common cause. The most likely cause is a change in ocean currents, especially in the Transpolar Drift (Dyke et al., unpubl.).

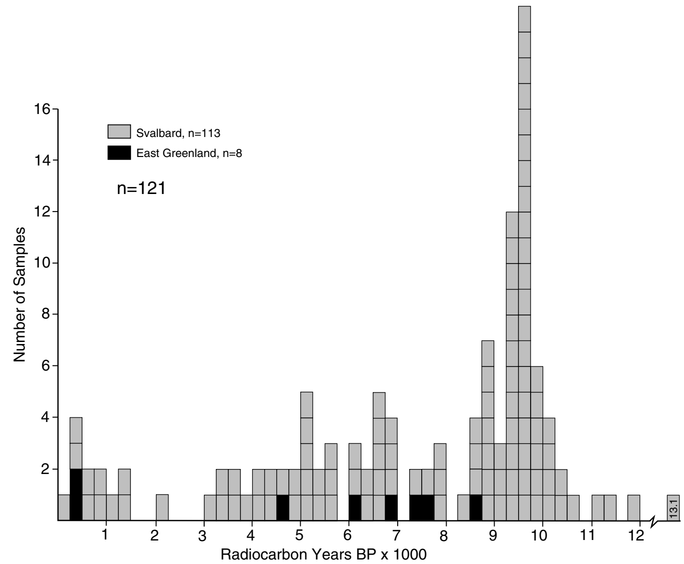

FIG. 20. Frequency distribution of radiocarbon dates on large whales from Svalbard and East Greenland. Dates are corrected for the marine reservoir effect.

In addition to the need for further dating of bowhead fossils in more broadly interpreting sea-ice history, there is the opportunity of clarifying the ancestry of the various stocks. On present evidence, for example, the Davis Strait stock may owe its ancestry to either the Bering Sea stock just after 10 ka B.P., to the Spitsbergen stock which may have been established by at least 13.1 ka B.P. (Forman et al., 1987), or to the stock retreating northward from its last glacial maximum position off the southeast Laurentide Ice Sheet. This latter paleo-stock of bowheads is all but unknown. Its animals occupied the Gulf of St. Lawrence region from at least 13.3 ka B.P. (Grant, 1991) until 11.5 ka B.P. or later (Harington, 1988), as did other arctic sea mammals. These bowheads may have given rise to both the Davis Strait and the Hudson Bay-Foxe Basin stocks. The Spitsbergen stock presumably arose from a bowhead refugium in the eastern North Atlantic (e.g., Fredén, 1975).

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