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APPLICATION OF ^{14}C AMS DATING TO THE CHRONOLOGY OF HOLOCENE GLACIER FLUCTUATIONS IN THE HIGH ARCTIC, WITH SPECIAL REFERENCE TO LEFFERT GLACIER, ELLESMERE ISLAND, CANADA*

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ABSTRACT. A series of radiocarbon age determinations obtained by Accelerator Mass Spectrometry (AMS) shows that the front of Leffert Glacier, a major outlet glacier from the Prince of Wales Icefield, Ellesmere Island, was 18+ km behind (west of) its present position for a period of at least 1500 radiocarbon years. A subsequent readvance occurred close to 2000 radiocarbon years ago, as a consequence of the climatic cooling that followed the warm Hypsithermal Interval. A number of other glaciers in the region appear to have behaved in similar fashion.

INTRODUCTION

The advent of ^{14}C dating by means of Accelerator Mass Spectrometry (AMS) has proved to be especially beneficial to a variety of investigations in the High Arctic. For example, many of the species of marine pelecypods that are available for dating in the far north are smaller in size than their counterparts in temperate latitudes. In addition, rates of sedimentation in lakes are apt to be much slower and woody materials derive from prostrate 'trees' that may only reach a few centimeters in height. AMS makes it possible to carry out ^{14}C age determinations on milligram - size samples that are undatable by conventional techniques. Examples are dating CO_2 in air bubbles in glacier ice (Andrée *et al,* 1986) and either extremely thin layers (< 5mm) or individual constituents from cores of lake sediments (Blake, 1985; Oeschger *et al,* 1985; MacDonald *et al,* 1987).

One important application of the AMS technique in the Arctic is in dating the fluctuations of tidewater glaciers during Holocene time. The example described in this paper is taken from the east coast of Ellesmere Island, Arctic Canada, where numerous outlet glaciers from the Prince of Wales Icefield reach the sea (Fig 1). Moraines of all such glaciers visited so far contain fragments, or even intact valves, of marine pelecypod shells. Less common are cirriped and gastropod shells as well as the occasional boulder with an encrusting layer of well-preserved crustose coralline algae. The presence of these marine organisms in moraines attests to the fact that the sea has extended much farther inland in the past, up valleys now occupied by glaciers, and in all probability, these transgressions have occurred on more than one occasion. Marine sediments have been: 1) incorporated by glaciers as they readvanced, or 2) pushed up from the sea floor by the ploughing action of certain glaciers.

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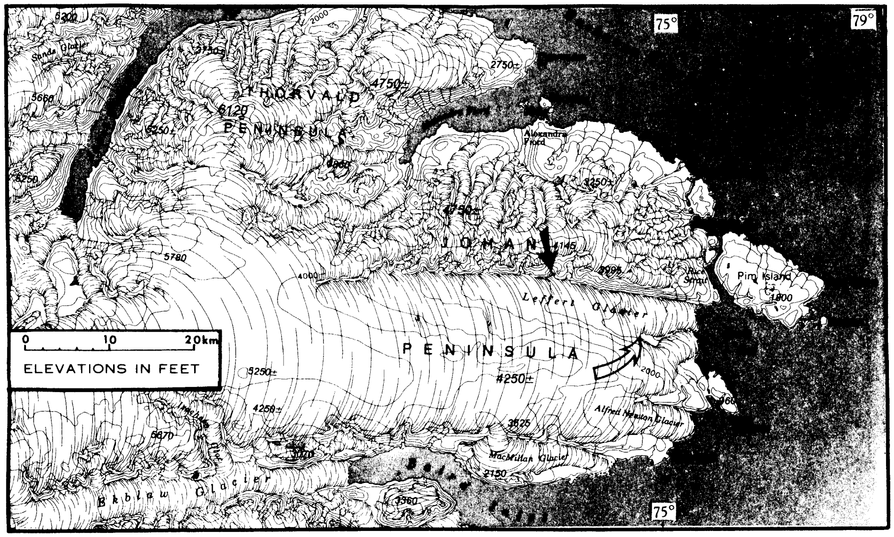

Fig 1. Location map for east-central Ellesmere Island, showing a small portion of the Prince of Wales Icefield. The map is adapted from the 1:500,000 map sheet, Bache Peninsula (NTS No. $49N^1/_2$ & $39N^1/_2$), Dept of Energy, Mines and Resources, Ottawa, 1978. 'Leffert Lake' is indicated by the black arrow, and 'Leffert Nunatak' is indicated by the open arrow. The contour interval is 500 ft.

When shell-bearing moraines are examined, it is difficult or impossible to distinguish between Holocene-aged shells and shells with ages beyond the limit of radiocarbon dating. In order to avoid dating assemblages that may contain shells of mixed ages, as proved to be the case with the first determinations on collections from moraines using conventional gas counters (Blake, 1985, 1986, 1987), it is preferable to determine the ages of individual shells. Because of the small size of many Arctic pelecypods, especially after they have been fragmented by transport within a glacier, much of this dating has to be carried out on an accelerator rather than in a conventional counter.

SITE DESCRIPTION

Leffert Glacier, a major outlet glacier draining eastward from the Prince of Wales Icefield in the central part of Ellesmere Island (Fig 1), can be traced inland for ca 50km. It occupies a topographic depression that bisects Johan Peninsula, with ice-covered terrain to the south and a mountain wall rising to over 1300m along the north side. Throughout most of its length, Leffert Glacier is at least 5km wide, except close to the sea where another lobe of ice impinges on it from the south. Echo-sounding in 1988 across Rosse Bay in front of Leffert Glacier revealed water depths in excess of 120m (the limit of the Raytheon Model DE-719C fathometer) along much of the glacier front. This sounding profile was in a zone entirely covered by glacier ice in 1959, the year that the aerial photographs were taken on which Figure 1 is based.

The first 'up-glacier' pelecypod shells were discovered in an ice-cored lateral moraine along the edge of 'Leffert Nunatak' (78°40.0′N, 75°06.0′W), an exposed rock knob on the south side of Leffert Glacier some 6 to 7km behind (west of) the present position of the glacier front (Fig 1). Shells, many of them intact valves, were abundant locally on the surface of this moraine. Boulders with encrusting coralline algae were also present. Five samples were dated from collections made between 165 and 180m asl (540 to 590ft; altimeter determinations; Blake, 1984a, b). These elevations are well above the highest evidence for Holocene marine submergence around Rosse Bay (Fig 1), provided by *Hiatella arctica* shells at 108m, which are 8470±70 yr old (GSC–3314). A second determination, on a single fragment of the same species, gave 8230±70 BP (TO-230; Blake, 1987). The results of ^{14}C age determinations for the five 'Leffert Nunatak' samples are summarized in Table 1.

TABLE 1

^{14}C age determinations on marine materials from 'Leffert Nunatak'

Sample no.	Species*	Weight (g)	Lab no.**	Age (yr BP)†	$\delta^{13}C$ (‰)	XRD mineralogy	Pre-leach
BS–82–145	Coralline algae	58.0	GSC-3472	2540± 50	−2.4	Calcite+ Aragonite (~10%)	20%
BS-81-205	*Astarte borealis* var *arctica*	8.5	GSC-3515	2280±140	+0.5	Aragonite	5%
BS-82-143	*Mya truncata*	48.5	GSC-3793	2880± 70	+1.4	Aragonite	20%
84-BS-228	Coralline algae	30.0	GSC-3932	2410± 60	−2.2	Calcite	20%
83-BS-144+ 84-BS-231	*Hiatella arctica*	0.2	TO-231	4800± 80	–	Aragonite	20%

*The two samples of crustose coralline algae are presumably some species of *Lithothamnion*. Identification of pelecypods by W Blake, Jr and I Lubinsky.

**GSC = Geological Survey of Canada, Ottawa; TO = IsoTrace Laboratory, University of Toronto.

†All age determinations from the Radiocarbon Dating Laboratory, GSC, are based on a ^{14}C half-life of 5568±30 yr and 0.95 of the activity of the NBS oxalic acid standard. Ages are quoted in conventional ^{14}C years BP (1950). All finite age determinations from this laboratory are based on the 2σ criterion, and ages on marine invertebrates are normalized to $\delta^{13}C = 0‰$ (Lowdon & Blake, 1970). $^{13}C/^{12}C$ ratios were determined, under contract, at the University of Waterloo.

'Leffert Lake' is an ice-dammed lake on the north side of Leffert Glacier (78°43.7′N, 75°35.5′W), 18km west of the front of the glacier in Rosse Bay (Fig 1). The lake is now at an elevation of ca 405m (1325ft; altimeter determinations), but a well-defined trimline, marked by a change in the lichen cover, shows that the lake has been some 45m higher in the past. It is worth noting here that the earliest detailed map of the area, from 1899 (Sverdrup, 1903), depicts the front of Leffert Glacier close to 3km east of its present position. If the glacier was thicker throughout its length at the turn of the century, 'Leffert Lake' was probably deeper at that time also.

During the summer, a river flows into 'Leffert Lake' from an englacial tunnel at the southwestern corner of the lake (Fig 2A). This tunnel can be entered in the spring before melting commences and traced up-glacier for several hundred meters. It is actually a series of tunnels close to the ice margin; in places, the river flows between the glacier and the rock wall; elsewhere, it flows in tunnels. Sand, gravel, cobbles and boulders are flushed through the tunnel system by the river and deposited on a ramp of fairly inactive glacier ice that extends out into the lake (Fig 2A). This veneer of sediment not only shifts from year to year as the river discharge fluctuates and the lake changes in level, but it is also subject to slumping as the underlying ice melts. This relatively coarse material contains occasional fragments of marine pelecypod shells. Shell fragments also were found in stringers of sandy/bouldery debris, representing former positions of the river, which are preserved along the walls of the tunnels (Fig 2B). Four shell fragments from the delta have now been dated (Table 2).

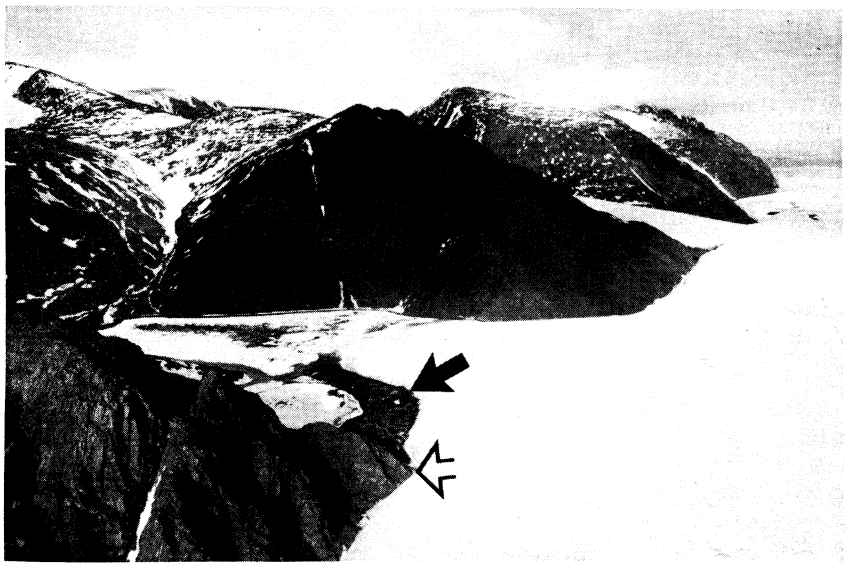

Fig 2A. View eastward along the north side of Leffert Glacier, with 'Leffert Lake' (405m asl) in the foreground. The debris-covered ice is indicated by the black arrow, and the tunnel from which the river emerges is at the site marked by the open arrow. June 24, 1983. GSC-204622-A.

Fig 2B: View from inside one of the tunnel segments leading to 'Leffert Lake'. The stringers of coarse debris along the tunnel wall, representing earlier levels of the englacial river, were found to contain marine shell fragments also. June 9, 1986. GSC-204622.

TABLE 2

AMS age determinations on marine shells from 'Leffert Lake'

Sample	Species*	Weight (mg)	Lab no.**	Age (yr BP)**	XRD mineralogy	Pre-leach
83-BS-169	*Mya truncata*	181	TO-229	3930±60	Aragonite	~20%
86-BS-5	*Hiatella arctica*	365	TO-387	2390±70	Aragonite	~28%
86-BS-5	*Mya* sp	369	TO-713	3040±50	Aragonite	32%
86-BS-5	*Mya* sp	199	TO-968	3600±60	Aragonite	40-50%

*Identification of pelecypods by W Blake, Jr. As no other *Mya* species inhabits these far northern waters, TO-713 and -968 undoubtedly represent *M truncata* as well.

**TO dates are "the average of at least two machine-ready targets, measured on different occasions. All results are corrected for natural, preparation and sputtering fractionation to a base of $\delta^{13}C$ = 0‰. The ages are quoted in uncalibrated radiocarbon years using the Libby ^{14}C meanlife of 8033 years. The errors represent 68% "confidence limits" (comment by R P Beukens, Radiocarbon Analyst, with each of the above four age determinations).

RESULTS AND DISCUSSION

The age determinations in both tables are listed simply in the order in which the samples were processed. Because of 1) the ephemeral nature of any deposit overlying glacier ice, 2) the lack of knowledge of the original position of the living invertebrates with respect to each other and to sea level, and 3) the uncertainty of their route through the glacier to reach the surface, no conclusions can be drawn with regard to the stratigraphy of the original marine deposits.

The pelecypods collected from the surface of the moraine along 'Leffert Nunatak' were whole in many cases, but no valves of *Astarte borealis,* which frequently exhibit intact periostracum, were found at 'Leffert Lake'. This may be a function of the longer englacial route required to reach the higher level site, although *Astarte borealis* is equally as robust a pelecypod as *Mya truncata* and *Hiatella arctica.* Another explanation for its absence from the collections at 'Leffert Lake' may simply be that this pelecypod did not colonize the innermost part of the former fiord, now occupied by Leffert Glacier, to the same degree as *Mya truncata* and *Hiatella arctica*. However, a single hinge fragment of *Astarte* sp, as well as one tiny fragment of a barnacle *(Balanus sp,* probably *Balanus crenatus*) and one of the fragile pelecypod *Chlamys islandica,* were found in 1988 at a second ice-dammed lake 1.3km east of 'Leffert Lake'. As additional collections are made, other species undoubtedly will turn up also.

The two age determinations on crustose coralline algae (probably a species of *Lithothamnion*) at 'Leffert Nunatak' were carried out, in each case, on material recovered from a single boulder, and the determination on *Mya truncata* was done on a sub-sample comprising 50 fragments, all of which exhibited the truncated posterior end, which is typical of the species. Perhaps most unusual at 'Leffert Nunatak' was the discovery of several erratic limestone boulders that had been bored by *Hiatella arctica.* This is the first site at which I have found evidence of boring pelecypods in the High Arctic (*cf* Ockelmann, 1958), and in numerous cases, the paired valves remained intact in the holes. The dated sample, TO-231, was a single shell from one such pair (Table 1).

The shells in the collection from 'Leffert Lake' were all worn fragments of *Hiatella arctica* and *Mya truncata* (in all likelihood, the fragments identifiable only as *Mya* sp were also *M truncata,* as it is the only species of *Mya* found at such high latitudes). For the reasons given in the previous section, it seems unlikely that the shell fragments have been exposed at the surface for more than a few years, and thus, there is every reason to believe that they have been less subject to contamination than many other surface collections of Arctic pelecypods. The shells on the moraine at 'Leffert Nunatak', for instance, have been exposed longer, as the surface there is stable enough to allow the development of a sparse cover of vascular plants on the till comprising the moraine. Yet there is no reason to doubt the validity of the determinations from 'Leffert Nunatak' either.

As indicated in footnotes to both tables, the age determinations on marine shells have been normalized to $\delta^{13}C = 0‰$, as is the practice at both the IsoTrace Laboratory and the GSC. In order to adjust the results for the 'apparent age' of sea water, a further correction (subtraction) of 330 years must be made, based on two determinations on pre-1950 shell collections from the area. Paired aragonitic valves of *Astarte borealis,* collected alive (Aug 1898) in Rice Strait a few kilometers north of Leffert Glacier by the Second Norwegian Expedition in the *Fram,* 1898-1902 (Grieg, 1909), gave an age of 380 ± 50 years (GSC-1916; Blake, 1975, 1987). A second determination on *Astarte borealis* valves from the same collection was made at Laboratoriet for Radiologisk Datering, Trondheim, Norway, and their result was 690 ± 70 years (T-1554; normalized to $\delta^{13}C$ = -25‰ PDB; Mangerud & Gulliksen, 1975). If this value is normalized to $\delta^{13}C$ = 0‰, as is GSC-1916, 280 years remain to be subtracted in order to correct for the 'apparent age' of sea water. Thus, an average of the GSC and Trondheim determinations would be 330 years (*cf* Blake, 1975).

CONCLUSIONS

The age determinations on marine invertebrates from 'Leffert Nunatak' and 'Leffert Lake' are internally consistent, but the series from the latter locality provide the most striking evidence with regard to glacier fluctuations during Holocene time. The dates show that the front of Leffert Glacier was *at least* 18km west of its present position for an interval of the order of 1500 radiocarbon years. The youngest date, which is critical for pinpointing the time of readvance, is in close agreement with conventional dates from 'Leffert Nunatak', some 12km nearer the sea, especially those based on a single valve of *Astarte borealis* and crustose coralline algae from single boulders.

The dated samples from 'Leffert Lake' are nearly 300m above the limit of Holocene marine submergence around nearby Rosse Bay. In their travel eastward, the shells have moved upward more than 400m, as sea level has been close to its present position during the last 2500 years. This statement can be made because a piece of driftwood at only 4m asl at the south end of Rosse Bay (Fig 1) is 2440 ± 50 yr old (GSC-3293; Blake, 1987). In addition, data for latitudes 60° to 75°N, published by Newman *et al* (1980), show that sea level has been within 5m of its present position over the last 3000 years.

Because the subglacial topography has not been determined, except near the calving front of Leffert Glacier in 1972 (G Holdsworth, Environment Canada, pers commun, 1983) we do not know how far west of 'Leffert Lake' the 'fiord' extends, but it seems safe to assume that the shells could easily have been transported a few kilometers toward the east. At Cadogan Glacier, an outlet glacier 70km to the southwest along the east coast of Ellesmere Island (outside the area covered by Fig 1) and the only one where extensive echo-sounding has been carried out, Koerner (1977) determined that the subglacial bed was below sea level for most of the final 30km of the glacier, as was another section between 40 and 45km behind (west of) the calving front.

The advance of Leffert Glacier some 2000 radiocarbon years ago, or shortly thereafter, can be interpreted as a result of the climatic cooling following the Hypsithermal maximum. This cooling has been estimated at 2° to 3°C over the last 5000 years, based on changes in the oxygen isotope ratios from the Devon Island Ice Cap (Fisher & Koerner, 1981; *cf* also Paterson *et al*, 1977). Evidence is widespread, in southern and east-central Ellesmere Island, that ice caps and glaciers were much reduced in size during the mid-Holocene warm interval (Blake, 1981). In fact, at a number of sites, the drastic recession and melting following the late Wisconsin maximum resulted, in early Holocene time, in smaller ice caps and outlet glaciers than at present (Blake, 1975). Reduced size continued, apparently, until the advances of the last two millennia, such as has occurred at Leffert Glacier.

Additional collecting is planned for the region around Leffert Glacier in future field seasons, and the moraines of as many tidewater glaciers as possible will be visited to search for datable materials. Obviously, another need is for radio echo-sounding of all the tidewater glaciers along the east coast of Ellesmere Island. If the details of the subglacial topography were known, the dynamics of the outlet glaciers would be better understood, and localities where marine fauna in moraines could be expected would be more readily identifiable.

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Note added in proof: A determination on a single right-valve fragment of *Mya truncata* (on which traces of the periostracum remained), from an elevation of 385m beside a second ice-dammed lake located 1.3km east of 'Leffert Lake', gave 2840±50 yr (TO-1227). This result is in accordance with the dates listed in Table 2.

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