

# Occurrence of the *Mytilus edulis* complex on Nordaustlandet, Svalbard: radiocarbon ages and climatic implications



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Fragments of the blue mussel (*Mytilus edulis* complex) are present on raised beaches in the vicinity of Langgrunnodden and Kinnvika, north-western Nordaustlandet, Svalbard. Both of these localities are north of 80°N. New radiocarbon age determinations, together with earlier results, show that *Mytilus* colonies were present in this area for much of the first half of Holocene time—from approximately 9000 to 5800 <sup>14</sup>C yr BP. *Mytilus* has also been recorded farther south in Nordaustlandet, at three localities in Wahlenbergfjorden. Age determinations of shells at two of these sites have yielded results in the range of 7400 to 6900 <sup>14</sup>C yr BP. The arrival of *Mytilus* to Nordaustlandet coincided with the early Holocene influx of warm North Atlantic Water off the west coast of Spitsbergen. The drastic warming in early Holocene time, which resulted in the rapid melt-off of glaciers and ice caps in Svalbard, also facilitated the establishment and perserverance of *Mytilus* colonies at this high latitude.

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The common blue mussel (*Mytilus edulis*) has featured in Arctic scientific literature for well over a century. Among the discoveries of the 1861 Swedish expedition to Spitsbergen, for example, were fragments of *M. edulis* at the westernmost point of Nordaustlandet (Figs. 1, 2), a locality then known as Shoal Point, now called Langgrunnodden (Chydenius 1865). Until recently the Arctic occurrences of this wide-ranging species have been referred to *M. edulis* L., but Feder et al. (2003) have shown that specimens collected alive at Barrow, on the northern coast of Alaska, are *M. trossulus* on the basis of DNA analysis (see also Norton & Feder 2006). For the purposes of the present paper, and following Feder et al. (2003), the *M. edulis* complex will be taken to include both species, should *M. trossulus* turn out to be present in Svalbard also.

Equally important as the species assignment, in terms of the discussion here, is the fact that *Mytilus* has long been regarded as an indicator of somewhat warmer sea conditions than those which have obtained throughout the past two centuries in Svalbard (Nathorst 1901a; Hoel 1909; Högbohm 1911, 1913; Elton & Baden-Powell 1931; Feyling-Hanssen & Jørstad 1950; Feyling-Hanssen 1955 [includes a detailed discussion and many references]; Feyling-Hanssen & Olsson 1960; Funder 1992; Hjort et al. 1992; Salvigsen et al. 1992; Hjort et al. 1995; Salvigsen 2002, 2005; Salvigsen & Høgvard 2005), in Greenland (Nathorst 1901b; Noe-Nygaard 1932; Hjort & Funder 1974; Funder 1978, 1990; Kelly 1985; Funder & Fredskild 1989; Funder & Weidick 1991) and elsewhere in the High Arctic, such as on Coburg Island in the northern tier of the islands of the

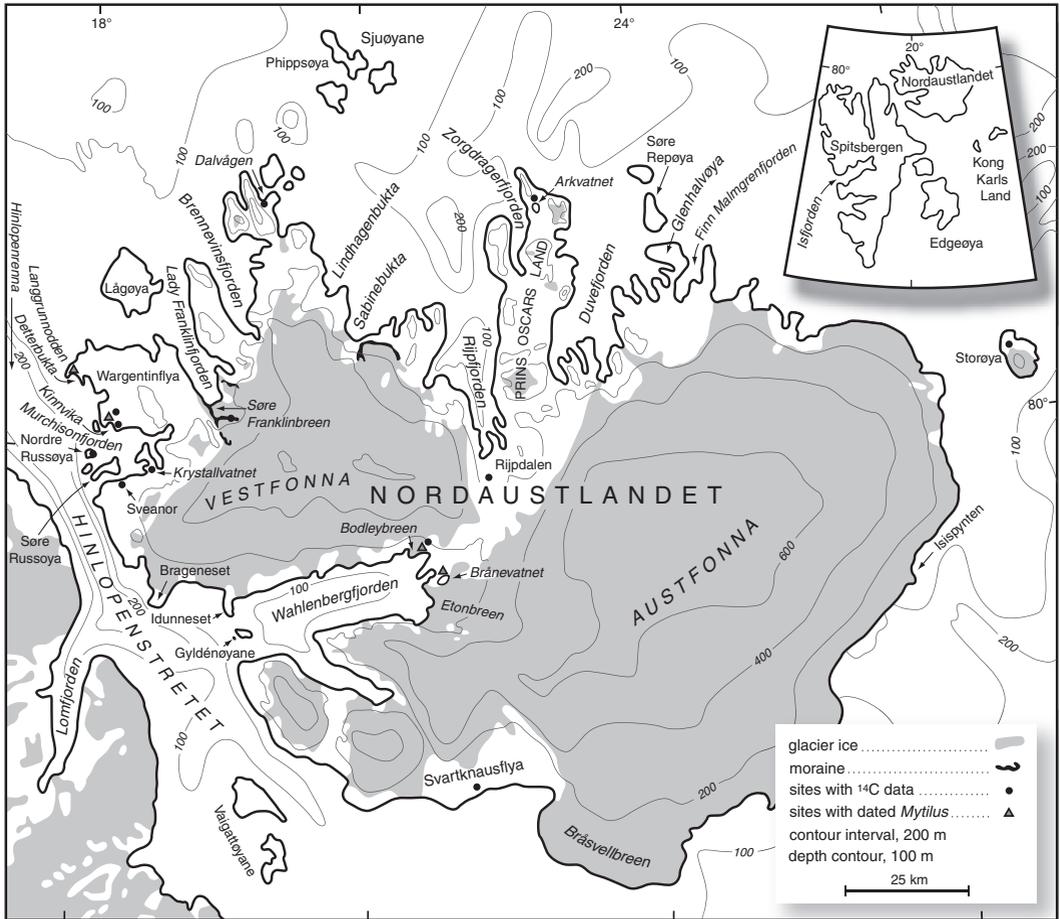


Fig. 1. Location map of Nordaustlandet, Svalbard, showing sites mentioned in the text. Illustration based on a 1:1 000 000 map of Svalbard by Kristiansen & Sollid (1986). Bjørnøya, at 74°30'N & 19°E, is ca. 225 km SSE of the southern tip of Spitsbergen.

Canadian Arctic Archipelago (Blake 1973).

Although *M. edulis* has occasionally been found alive on materials that have drifted to Svalbard waters with the West Spitsbergen Current (Heintz 1926; Christiansen 1965; Salvigsen 2002, 2005), until recently it has not been found living there. Now *Mytilus* has been reported from both Bjørnøya (Węśławski et al. 1997; although Berge et al. [2006] emphasize that the few individuals found there do not constitute a population) and from a group of skerries in outer Isfjorden, Spitsbergen (Berge et al. 2005). In the latter locality its appearance is attributed to the “unusually high northward mass transport of warm Atlantic water resulting in elevated sea-surface temperatures in the North Atlantic and along the west coast of Svalbard” (Berge et al. 2005: 167).

The colony at this site has been shown to be *M. edulis* on the basis of DNA analysis (Berge et al. 2006). It is interesting to note that *Mytilus* was not recorded in 1908 in the same general area by Odhner (1915), despite an extensive programme of dredging, and Berge et al. (2006) also observe that numerous surveys along the western coast of Spitsbergen over the last 30 years have failed to reveal the presence of *Mytilus*. However, Feder et al., as a result of extensive work along the northern and north-western coasts of Alaska, reached a very different conclusion with regard to the value of *Mytilus* as an indicator of warmer sea conditions:

“...water temperature cannot be the primary determinant of *Mytilus* persistence in the

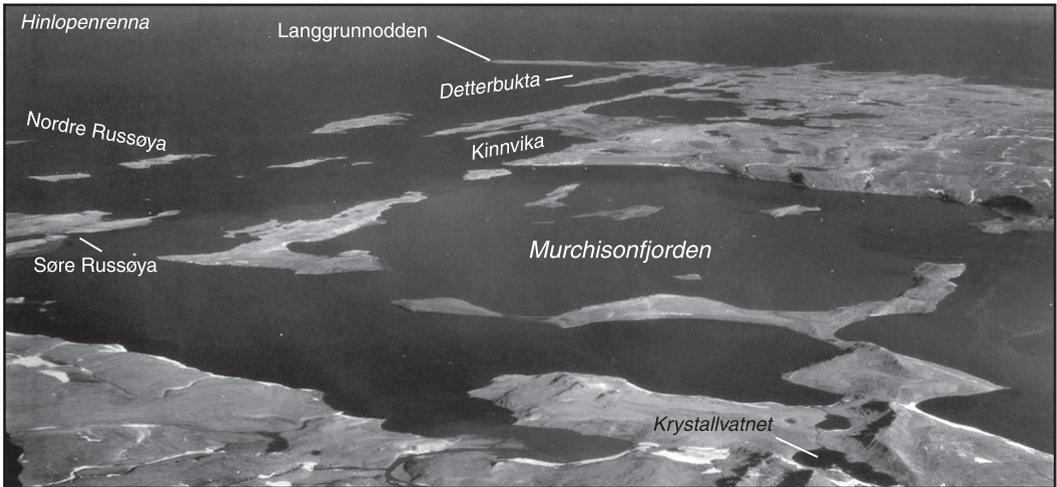


Fig. 2. Oblique aerial view north-west across Murchisonfjorden, showing the principal areas where *Mytilus* has been collected: Kinnvika and Langgrunnodden. This image is a portion of photograph S38-1247 taken by B. Luncke, 28 July 1938; between 0540 and 0615 hours. (Photograph courtesy of the Norwegian Polar Institute.)

Arctic. Low water temperature is known to prolong dispersive life-cycle stages and to slow later development and growth, but it has not been shown to limit *Mytilus* survival or reproduction. We suggest that the presence of this bivalve during periods of higher sea level during the early Holocene is a response to lower and more variable salinity of coastal waters rather than to increased temperature” (2003: 402).

Thirteen radiocarbon age determinations of *M. edulis* in raised beaches are now available from Nordaustlandet, the northernmost of the main islands in the Svalbard archipelago. All except two of these determinations are based on collections made by the writer north of the 80th parallel, and nine of the 13 age determinations are based on single valves or single shell fragments, thus eliminating the chance of mixing shell material of different ages. These occurrences are the most northerly known in which *M. edulis* is found in abundance on raised beaches. It thus seems appropriate to discuss the significance of these finds in light of the hypothesis advanced by Feder et al. (2003) and the 2004 discovery of a colony of living *M. edulis* near the entrance to Isfjorden, Spitsbergen (Berge et al. 2005; Berge et al. 2006), some 230 km to the south-west of Langgrunnodden.

## Materials and methods

### *Collections and radiocarbon ages of Mytilus shells from Nordaustlandet*

Following the 1861 discovery of *M. edulis* at Langgrunnodden, when numerous shells were collected by A. J. Malmgren at about 9 to 15 m a.s.l. in clay (Hägg 1950), the second find of this species in Nordaustlandet was made by K. S. Sandford, geologist on the 1924 Oxford University Expedition. He reported rare valves of the blue mussel in boulder clay at ca. 55 m a.s.l. at a site along the northern shore of inner Wahlenbergfjorden (Fig. 1 and Sandford 1929). Until recently the shells in this collection had not been dated, but the elevation reported is some 40 m higher than any of the previously dated Holocene collections of *Mytilus* from Nordaustlandet (Table 1). Thus, it seemed reasonable to surmise that Sandford’s collection might represent pre-last glaciation material, possibly transported upward by a southward advancing Bodleybreen, or possibly moved by an enlarged Etonbreen flowing westward out the fjord. Both glaciers have a history of surging (Dowdeswell 1986a, 1986b; Lefaconnier & Hagen 1991). Pelecypod shells of several other species which predate the last glaciation have been collected at numerous sites around Nordaustlandet and on Sjuøyane to the north (Blake 1961a, 1962, 1981, 1989, 1995; Olsson &

Blake 1962; Salvigsen & Nydal 1981; Forman & Ingólfsson 2000). Also, pre-Holocene *Mytilus* shells have been reported from one of the inner branches of Isfjorden, Spitsbergen (Mangerud & Svendsen 1992a, 1992b).

However, the single robust valve dated from Sandford's collection turned out to be Holocene, the lab-reported age being  $7370 \pm 20$   $^{14}\text{C}$  yr BP

(lab. no. UCIAMS-21868), or  $6930 \pm 20$   $^{14}\text{C}$  yr BP after the reservoir effect is taken into account (Table 1, Fig. 3). Because of its elevation, well above early Holocene shells collected by the writer at ca. 43 m a.s.l. (Table 2), it seems likely that both shells and the enclosing 'boulder clay' do indeed represent glacier-transported material, from a late Holocene readvance of Bodleybreen.

Table 1. Radiocarbon ages on shells of the *Mytilus edulis* complex, Nordaustlandet, Svalbard.

| Field no. <sup>a</sup>     | Elev. (m) | Weight used (g) | Lab. no. <sup>b</sup> | Age, reported by lab. | Age, corrected for apparent age of seawater <sup>c</sup> | $\delta^{13}\text{C}$ (PDB) ‰ | Comments  |
|----------------------------|-----------|-----------------|-----------------------|-----------------------|--|-------------------------------|---|
| Langgrunnodden/Detterbukta |           |                 |                       |                       |  |                               |   |
| WB-58-303                  | ~14.0     | 0.16            | UCIAMS-19833          | $9470 \pm 25$         | $9030 \pm 25$  | $0.1 \pm 0.1$                 | Single fragment.  |
| WB-58-303                  | ~14.0     | 0.27            | UCIAMS-21867          | $9490 \pm 20$         | $9050 \pm 20$  | $-0.65 \pm 0.1$               | Single fragment.  |
| WB-58-312                  | 9.0       | 90.0            | { U-173               | $9200 \pm 190$        | $8760 \pm 190$   | -2.0                          | Numerous fragments—innermost 13% of shell material. Next 14% of shell material. Outermost 73% removed by HCl leach. |
| WB-58-312                  | 9.0       |                 |                       | { U-174               | $8530 \pm 190$   | $8090 \pm 190$                |   |
| WB-58-312                  | 9.0       | 0.23            | UCIAMS-20526          | $8790 \pm 15$         | $8350 \pm 15$  | $-0.4 \pm 0.1$                | Single fragment.  |
| Kinnvika, Murchisonfjorden |           |                 |                       |                       |  |                               |   |
| WB-90-28                   | 14.5      | 0.23            | Ua-2102               | $9060 \pm 90$         | $8620 \pm 90$  | —                             | Single fragment of blue-violet shell only.  |
| WB-90-28                   | 14.5      | 0.16            | UCIAMS-20527          | $8960 \pm 20$         | $8520 \pm 20$  | $0.6 \pm 0.1$                 | Single fragment of blue shell.  |
| WB-66-178                  | 7.5       | —               | GaK-1916 <sup>d</sup> | $7530 \pm 130$        | $7530 \pm 130$   | —                             | Numerous fragments.   |
| WB-66-178                  | 7.5       | 0.76            | UCIAMS-16174          | $7095 \pm 20$         | $6655 \pm 20$  | $-0.27 \pm 0.1$               | Single fragment.  |
| WB-90-25                   | 5.1       | 0.14            | Ua-11158              | $6435 \pm 105$        | $5995 \pm 105$   | 0.5                           | Single fragment. Inner fraction dated.  |
| WB-90-25                   | 5.1       | 0.11            | UCIAMS-19834          | $6335 \pm 25$         | $5895 \pm 25$  | $0.2 \pm 0.1$                 | Single fragment.  |
| Wahlenbergfjorden          |           |                 |                       |                       |  |                               |   |
| Sa-97-100                  | ~10       | 5.0             | T-13426               | $7260 \pm 105$        | $7260 \pm 105$ <sup>e</sup>                              | —                             | 1 whole valve plus several large fragments, all of good quality. Coll. A. M. Tebenkov.                              |
| OUM QX. 1639               | ~55       | 0.40            | UCIAMS-21868          | $7370 \pm 20$         | $6930 \pm 20$  | $-0.74 \pm 0.1$               | Single left valve, 6 cm long, 2.5 cm high, shell 2-3 mm thick; periostracum partly intact. Coll. K. S. Sandford.    |

<sup>a</sup> All samples with field designation WB were collected by W. Blake, Jr.; R. Bergström helped make the 1958 collections.

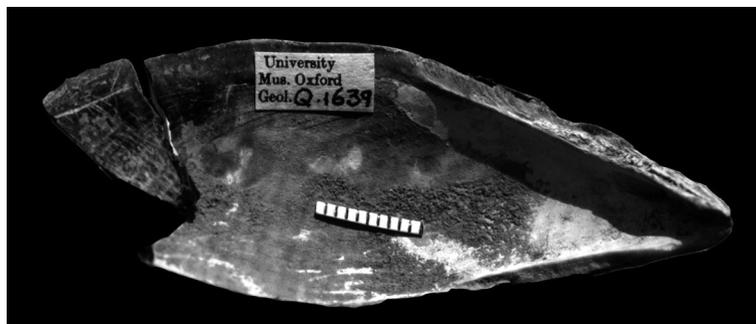
<sup>b</sup> Laboratory designations: U = Uppsala; Ua = Tandem Accelerator Laboratory, Uppsala; UCIAMS = University of California, Irvine (AMS); GaK = Gakushuin University, Japan; T = Trondheim.

<sup>c</sup> Following Mangerud & Gulliksen (1975) a reservoir effect of -440 years is applied to samples with designations UCIAMS, U and Ua.

<sup>d</sup> Doubts about the accuracy of some Gakushuin  $^{14}\text{C}$  ages have been expressed earlier (Blake 1980, 1989); the Gakushuin determination on marine shells is corrected to  $\delta^{13}\text{C} = 0.0$  ‰, so no additional correction is applied (Kigoshi et al. 1962).

<sup>e</sup> As reported by Salvigsen (2002) with a built-in correction of -440 years.

Fig. 3. Inner left valve of *Mytilus edulis* from the north side of Wahlenbergfjorden, following sampling for  $^{14}\text{C}$  age determination. Scale is 1 cm in length. Collected 1924 by K. S. Sandford, Oxford University Expedition. Identified by D. F. W. Baden-Powell (OUM QX 1639). (Photograph by W. Blake, Jr., 26 March 2006.)



Following Sandford's find in Wahlenbergfjorden the next discovery of *M. edulis* in Nordaustlandet was made in 1931, from two sites on the southern side of Murchisonfjorden (Figs. 1, 2): at 14.5 m a.s.l. near Sveanor, the base of the Swedish–Norwegian Arctic Expedition, and on nearby Søre Russøya, where occasional shells were found in the raised beaches at an approximate elevation of 16 to 19 m (Kulling 1936). Although several later visits have been made to these general locations, unfortunately no additional finds of *Mytilus* have been recorded.

Next, J. J. Donner and R. G. West, members of the 1955 Oxford University Expedition, collected two valves of *M. edulis* at 4.5 m a.s.l. near the top of a disturbed section at Idunneset, on the north side of Wahlenbergfjorden, near the mouth of the fjord (Donner & West 1957). These shells have not been dated. *Mytilus edulis* shells were not found on the nearby Gyldenøyane at the mouth of Wahlenbergfjorden (Elton & Baden-Powell 1931), nor were any discovered in the vicinity of the 1955 expedition's base, Brageneset, at the northern entrance to the fjord (Donner & West 1957, 1995). More recently, in 1997, A. M. Tebenkov collected *M. edulis* shells at Brånevatnet in innermost Wahlenbergfjorden (actually east of the present-day head of the fjord) at ca. 10 m a.s.l., and these shells yielded an age of  $7260 \pm 105$   $^{14}\text{C}$  yr BP (T-13426; Salvigsen 2002). So far Wahlenbergfjorden is the only fjord-head locality in Nordaustlandet where *Mytilus* has been collected. Its occurrence there is not surprising, however, in view of the more favourable environments characteristic of fjord-head localities in Svalbard (Summerhayes & Elton 1928), coupled with the southward set of the current with the falling tide in Hinlopenstretet (Binney 1926; Mosby 1938; Ślubowska et al. 2005). In particular, the

area north of Etonbreen in innermost Wahlenbergfjorden is known to have the richest terrestrial flora in Nordaustlandet (Neilson 1968).

In 1958 abundant fragments of *Mytilus* shells were discovered by the writer and R. Bergström, members of the Swedish Glaciological Expedition to Nordaustlandet, on the ground surface (in raised beach gravels and sorted circles) inland from Detterbukta and north-east of Langgrunnodden, the westernmost point of Nordaustlandet. This is the same site that had been visited by the 1861 Swedish expedition. One collection was dated at the then newly-opened laboratory in Uppsala. Following a fairly heavy HCl leach to remove any surface contamination such as secondary calcite crusts, these shells (the innermost 13% of shell material) yielded a lab-reported age of  $9200 \pm 190$   $^{14}\text{C}$  years (U-173; Table 1). This is the age converted to the NBS oxalic acid standard—the original published laboratory age of  $9070 \pm 190$   $^{14}\text{C}$  yr BP was based on the Swedish elm standard (Olsson 1960; Olsson et al. 1961; I. U. Olsson, pers. comm. 1961, 1966). The  $9070 \pm 190$   $^{14}\text{C}$  yr BP value also was used in the original papers dealing with postglacial emergence (Blake 1961a, 1962; Olsson & Blake 1962), and it is often cited in the literature (e.g. Salvigsen et al. 1992; Salvigsen 2002), but the 9200 year-value is the correct one that should be used for the lab-reported age in radiocarbon years (see also Deevey et al. 1967). The next 14% of shell material yielded a lab-reported age of  $8530 \pm 190$  (U-174). The age difference between U-173 and U-174 suggests that this large sample (90 g), collected over a significant area of beaches, was made up of shells of varying age and varying thickness, hence the discrepancy between the two dated fractions.

With the advent of radiocarbon dating by means of accelerator mass spectrometry (AMS) in the

late 1970s, several age determinations have been made on individual fragments of *Mytilus*, collected by the writer in 1966 on the Stockholm University Svalbard Expedition and in 1990 on the Nordaustlandet-90 Expedition. These shells came from the raised beaches in the vicinity of Kinnvika, at the northern entrance to Murchisonfjorden (Figs. 2, 4). They range in age from  $8620 \pm 90$   $^{14}\text{C}$  yr BP (Ua-2102; cf. Blake 1995, where the lab-reported age of  $9060 \pm 90$  was used) to  $5895 \pm 25$   $^{14}\text{C}$  yr BP (UCIAMS-19834; Table 1). In addition, new analyses of the original collections from the vicinity of Langgrunnodden have been made and these results are reported here as well.

As mentioned earlier in this section, and following the approach taken by several others in reporting radiocarbon age determinations from Svalbard (Salvigsen et al. 1992; Hjort et al. 1992; Hjort et al. 1995; Koç et al. 2002; Salvigsen 2002; Salvigsen & Høgvard 2005; Ślubowska et al. 2005; all of whom cite Mangerud & Gulliksen 1975), a reservoir effect of  $-440$  years to compensate for the apparent age of seawater has been applied to the  $^{14}\text{C}$  ages in Tables 1 and 2 (see footnotes to tables). This value corresponds closely to the 410-year difference if radiocarbon ages on shells are corrected to a  $\delta^{13}\text{C}$  value of  $0.0\text{‰}$ , which was the practice at the Geological Survey of Canada at the time that shells from Nordaustlandet were dated (Table 2; see Lowdon 1985; Blake 1987). In addition, it is also worth noting that a single intact *Buccinum glaciale* shell, collected in 1958 amidst the debris of an abandoned Russian trapping hut on Nordre Russøya, Murchisonfjorden (Blake 1961b), yielded an age of  $295 \pm 70$  years (U-122; Olsson 1960). When converted to the NBS oxalic acid standard this age becomes  $420 \pm 80$   $^{14}\text{C}$  years (I. U. Olsson pers. comm. 1966), also close to the 440-year value cited above. However, Forman & Polyak (1997), in a sophisticated analysis of pre-bomb molluscs from the Kola Peninsula, Franz Josef Land and Novaya Zemlya, derived reservoir ages for Franz Josef Land of only  $159 \pm 50$  (GX-19024) and  $263 \pm 48$  years (GX-19026), so the radiocarbon ages from Nordaustlandet eventually may have to be adjusted as well.

### Deglaciation chronology

At Kinnvika the oldest radiocarbon dated Holocene material is a partial shaft of the left humerus of a polar bear (*Ursus maritimus*) collected at 72 m a.s.l. and dated at  $10030 \pm 110$   $^{14}\text{C}$  yr

BP (Ua-2207). Next oldest, and from the raised beaches proper, a partial right pelvic bone from a bearded seal (*Erignathus barbatus*) (both identified by C. R. Harington, Canadian Museum of Nature, Ottawa, pers. comm. 1990) at 62 m a.s.l. is  $9930 \pm 100$   $^{14}\text{C}$  yr BP (Ua-2099; both in Blake 1996). Applying the same marine correction of  $-440$  years (see Olsson 1980) to these bones yields ages of  $9590 \pm 110$  and  $9490 \pm 100$   $^{14}\text{C}$  yr BP for bear and seal, respectively (Table 2). On the opposite, south side of Murchisonfjorden, *Mya truncata* shells at 82 m have yielded lab-reported ages of  $11180 \pm 190$   $^{14}\text{C}$  yr BP (U-2095) and  $11150 \pm 110$   $^{14}\text{C}$  yr BP (U-660; both in Olsson et al. 1969; Blake 1981; Hoppe 1987), but note that Karlén (1994) places the highest marine limit in this area at 67 m a.s.l. These results become  $10740 \pm 190$  and  $10710 \pm 110$ , respectively, when the  $-440$  year correction is applied. Also, a driftwood log (*Larix* sp.) at 36.5 m elevation near Sveanor (Kulling 1936), in the vicinity, has provided age determinations from two laboratories:  $9400 \pm 140$  (U-70; converted to the NBS oxalic acid standard; Olsson 1959; Deevey et al. 1967) and  $9420 \pm 100$  (GSC-3490; Blake 1987). These results from wood reinforce the  $^{14}\text{C}$  ages of bones and shells as well as the age of the basal organic sediments in Krystallvatnet,  $10000 \pm 600$   $^{14}\text{C}$  yr BP (U-92; converted to the NBS oxalic acid standard), some 8 km to the east-north-east of Sveanor (Olsson 1960; Häggblom 1963). Individuals of the *Mytilus edulis* complex thus appeared some 900 to 1000  $^{14}\text{C}$  years after the earliest mammals were recorded at Kinnvika or, assuming that the early ages of shells are correct, roughly 2000  $^{14}\text{C}$  years after the sea first entered Murchisonfjorden some 10 km to the south of Kinnvika.

Ages between 9500 and 9000  $^{14}\text{C}$  years BP on marine pelecypod shells are recorded for the initial incursion of the sea into the heads of nearby fjords such as Wahlenbergfjorden and Lady Franklinfjorden, slightly earlier at Dalvågen (where *Chlamys islandica* and *Balanus balanoides* were dated as well as *Hiatella arctica*) near the northern tip of Nordaustlandet (Table 2; also Blake 1987, 1989). Elsewhere on Nordaustlandet, driftwood at 22 m a.s.l. near the northern tip of Prins Oscars Land dates from  $9465 \pm 120$   $^{14}\text{C}$  yr BP (St-7989; Karlén 1987), and *Mya truncata* shells from a river section south of the head of Rippfjorden are  $9100 \pm 140$   $^{14}\text{C}$  yr BP (GSC-2669; Blake 1981, 1987). Further east, the earliest radiocarbon age for the raised beaches on Storøya, an

Table 2. Selected early Holocene radiocarbon ages, Nordaustlandet, Svalbard. (Table continues next page.)

| Field no.                                   | Elev. (m) | Lab. no. <sup>a</sup> | Age, reported by lab. | Age, corrected for apparent age of seawater | $\gamma^{13}\text{C}$ (PDB) ‰ | Comments and collector <sup>b</sup>   |
|---|-----------|-----------------------|-----------------------|---|-------------------------------|---|
| Kinnvika, Murchisonfjorden                  |           |                       |                       |   |                               |   |
| WB-90-21A                                   | 72        | Ua-2207               | 10 030 ± 110          | 9590 ± 110 <sup>c</sup>                     | -21.0 (assumed)               | Partial shaft of left humerus of a polar bear ( <i>Ursus maritimus</i> ). 9.3 g. W. Blake, Jr.  |
| WB-90-11                                    | 62        | Ua-2099               | 9930 ± 100            | 9490 ± 100 <sup>c</sup>                     | -21.0 (assumed)               | A right pelvic bone from a bearded seal ( <i>Erignathus barbatus</i> ). 12.6 g. W. Blake, Jr.   |
| South side of Murchisonfjorden              |           |                       |                       |   |                               |   |
| H/131-135                                   | 62        | U-92                  | 10 000 ± 600          | —   | -32.0                         | Krystallvatnet—limnic peat at 131 - 134 (or 118 - 122) cm depth in core. Water depth 19 m. A. Häggblom.   |
| WB-58-27                                    | 36.5      | U-70                  | 9400 ± 140            | —   | -24.0                         | <i>Larix</i> sp. log near Sveanor. W. Blake, Jr.  |
| WB-58-27                                    | 36.5      | GSC-3490              | 9420 ± 100            | —   | -25.7                         | Same log, 11.7 g dry wood. One 4-day count in 5-L counter.  |
| —   | 82        | U-2095                | 11 180 ± 190          | 10 740 ± 190                                | 0.3                           | Numerous <i>Mya truncata</i> shells, partly buried in beach material. Innermost 35 % of shell material. M. G. Grosswald.                          |
| —   | 82        | U-660                 | 11 150 ± 110          | 10 710 ± 110                                | 0.3 (assumed)                 | Shell layer surrounding U-2095 corresponds to 40 % of shell material. Outermost 25 % removed by HCl leach.  |
| Lady Franklinfjorden—Søre Franklinbreen     |           |                       |                       |   |                               |   |
| WB-167-66                                   | 125-130   | Ua-905                | 9525 ± 130            | 9085 ± 130                                  | —                             | Pelecypod shell fragment, probably <i>Chlamys islandica</i> . Calcite. 0.008 g. No leach. W. Blake, Jr.   |
| WB-167-66                                   | 125-130   | Ua-1058               | 9675 ± 140            | 9235 ± 140                                  | —                             | Unidentified pelecypod shell fragment. Aragonite. 0.16 g. Outermost 50 % removed by HCl leach.  |
| Dalvågen                                    |           |                       |                       |   |                               |   |
| WB-41-66                                    | 18        | GSC-2729              | 9670 ± 200            | 9670 ± 200                                  | 2.6                           | <i>Chlamys islandica</i> (intact pair), same site. Outermost 10 % of shell removed by HCl leach. Calcite, aragonite and rhodocrosite 10.25 g.     |
| WB-41-66                                    | 18        | Ua-341                | 9950 ± 200            | 9510 ± 200                                  | —                             | <i>Chlamys islandica</i> (single fragment), same site. Calcite. 0.04 g. Innermost 5 % of shell used for dating.                                   |
| WB-64-66                                    | 23        | Ua-902                | 9720 ± 115            | 9280 ± 115                                  | —                             | <i>Balanus balanus</i> Calcite. 0.07 g. Inner 50 % of shell used for dating. W. Blake, Jr.  |
| North end Prins Oscars Land, near Arkvatnet |           |                       |                       |   |                               |   |
| —   | 22        | St-7989               | 9465 ± 120            | —   | -26.8                         | Driftwood log. H. Österholm & V. Schytt.  |
| Rijpdalen                                   |           |                       |                       |   |                               |   |
| WB-120-66                                   | 32-36     | GaK-1915              | 9200 ± 180            | 9200 ± 180                                  | —                             | <i>Mya truncata</i> shells in river section, south of the head of Rijpfjorden. 47.0 g. W. Blake, Jr.  |
| WB-120-66                                   | 32-36     | GSC-2669              | 9100 ± 140            | 9100 ± 140                                  | 0.3                           | <i>Mya truncata</i> shells in river section, same site. Outermost 20 % of shell removed by HCl leach. 26.9 g.                                     |
| Wahlenbergfjorden                           |           |                       |                       |   |                               |   |
| WB-187-66                                   | ~43       | GSC-2736              | 9670 ± 140            | 9670 ± 140                                  | 3.6                           | Single right valve of <i>Mya truncata</i> . Outermost 10 % of shell removed by HCl leach. Aragonite. 12.0 g. Marine limit at ~66 m. W. Blake, Jr. |

island east of Nordaustlandet, is  $9685 \pm 125$   $^{14}\text{C}$  yr BP (St-7825, Jonsson 1983; also reported uncorrected for  $\delta^{13}\text{C}$  in Häggblom 1982a, 1982b). This result was obtained on a driftwood log at 53.3 m a.s.l. The beach at this level, as with all other raised beaches on Storøya, disappears under the ice cap that occupies the southern half of the island, showing that the ice cap has developed, again, in latest Holocene time (Schytt 1981). At Svartknausflya, south-western Nordaustlandet, willow wood at 65.5 m a.s.l. dates from  $9550 \pm 80$   $^{14}\text{C}$  yr BP (T-2503; Salvigsen 1978, 1979). It is thus clear that by 9500 to 9000  $^{14}\text{C}$  yr BP, coasts all around Nordaustlandet had become free of glacier ice. However, with the exception of innermost Wahlenbergfjorden, *M. edulis* has not been found at any of these locations. Nor was any trace of *Mytilus* found at the other north coast sites visited in the wide-ranging 1966 surveys carried out by the writer, namely at Lady Franklinfjorden, Lindhagenbukta, Sabinebukta, Rijpfjorden, Zorgdragerfjorden, Finn Malmgrenfjorden, Søre Repøya, and Sjuøyane (Fig. 1).

Data from Hinlopenrenna, the trough across the continental shelf to the north of Hinlopenstretet and north-west of Nordaustlandet, are as follows: 1) shells of *Chlamys islandica* ca. 1.2 m below the seabed and above coarse sediments interpreted as glaciomarine in core PO 78-17 ( $80^\circ 11' \text{N}$ ,  $16^\circ 40' \text{E}$ ; 205 m water depth), some

17.5 km north-west of Langgrunnodden, are  $9010 \pm 140$   $^{14}\text{C}$  yr BP (T-3103; Salvigsen & Nydal 1981); and 2) where Hinlopenrenna intersects the edge of the continental shelf, ca. 36.5 km north-west of Langgrunnodden, benthic foraminifera at 690-699 cm in core NP 94-51SC2 ( $80^\circ 21.35' \text{N}$ ,  $16^\circ 17.970' \text{E}$ , 400 m water depth) are  $13\,725 \pm 135$   $^{14}\text{C}$  yr BP (TUa-3587; Koç et al. 2002; this age is listed in uncorrected form as  $14\,162 \pm 135$   $^{14}\text{C}$  yr BP in Ślubowska et al. 2005).

## Discussion

### *Oceanographic conditions and glacier recession*

With regard to the question of lower and more variable salinity in coastal waters, proposed by Feder et al. (2003) as important to the distribution of *Mytilus* in northern Alaska, a few observations are pertinent. As shown in Fig. 2, the north-west corner of Nordaustlandet, between Kinnvika and Langgrunnodden, has an intricate and low-lying coastline, developed in carbonate rocks of the Roaldtoppen Group (Flood et al. 1969; Sandelin et al. 2001). This gently shelving coast, characterized by the presence of numerous shoals (Binney 1926), lagoons and both bay-head and bay-mouth bars, is the area where all of the writer's col-

Table 2, continued from previous page.

| Field no.      | Elev. (m) | Lab. no. <sup>a</sup> | Age, reported by lab. | Age, corrected for apparent age of seawater | $\delta^{13}\text{C}$ (PDB) ‰ | Comments and collector <sup>b</sup>                             |
|----------------|-----------|-----------------------|-----------------------|---|-------------------------------|---|
| Storøya        |           |                       |                       |   |                               |   |
| 7              | 53.3      | St-7825               | $9685 \pm 125$        | —   | -26.4                         | Driftwood log. A Häggblom.                                      |
| Svartknausflya |           |                       |                       |   |                               |   |
| 30             | 65.5      | T-2503                | $9550 \pm 80$         | —   | —                             | <i>Salix</i> sp. wood 1 m long on ground surface. O. Salvigsen. |

<sup>a</sup> Laboratory designations: U = Uppsala; Ua = Tandem Accelerator Laboratory, Uppsala; St = Natural History Museum, Stockholm; GaK = Gakushuin University, Japan; GSC = Geological Survey of Canada, Ottawa; T = Trondheim. See footnote d, Table 1, with regard to Gakushuin results. Laboratory reported ages from U, Ua, St and T are normalized to a base of  $\delta^{13}\text{C} = -25.0\text{‰}$ . Marine shell samples processed at GSC and GaK are corrected to  $\delta^{13}\text{C} = 0.0\text{‰}$ , so no additional correction is applied (Lowdon 1985; Blake 1987; Kigoshi et al. 1963).

<sup>b</sup> Identifications of bones: C. R. Harington, Canadian Museum of Nature, Ottawa; shells: W. Blake, Jr., Geological Survey of Canada, Ottawa (except for U-2095); driftwood from Sveanor: G. W. Burns, Ohio Wesleyan University, Delaware, OH

<sup>c</sup> Here the same correction (-440 years) is used as for marine molluscs. Håkansson (1974) reports an apparent age of  $480 \pm 70$  years (Lu-715) for the cranium of a young polar bear collected in 1989 in inner Isfjorden, but time of death is estimated at  $50 \pm 50$  years. Thus the "apparent age" for mammals whose diet is marine organisms may have to be modified when additional data become available.

lections of *Mytilus* have been made. No significant rivers reach this part of the coast. Early in Holocene time, when the peninsulas now exposed because of glacial rebound would have been beneath the sea, conditions closer to full marine might have prevailed, as they do offshore today under the influence of North Atlantic Water of the Atlantic Current (Loeng 1991). This Atlantic Layer is conveyed northward and then eastward by a strong boundary current, the West Spitsbergen Current. North of Hinlopenstretet the core of the Atlantic Layer occurs at 100 to 400 m depth, with temperatures of 3 to 4.5 °C and salinities of 34.4 to 35.0‰ (Koç et al. 2002; Ślubowska et al. 2005; see also Fig. 2 in Peacock 1989). Furthermore, under early Holocene conditions of rapid rebound, there would have been little time available for lagoons and bars to develop.

Some 9200 to 8700 <sup>14</sup>C yr BP and perhaps until ca. 1000 <sup>14</sup>C yr BP (Blake 1987, 1989), the front of Søre Franklinbreen at the head of Lady Franklinfjorden is known to have been several kilometres behind (south-east of) the various positions that it has occupied since 1899 (De Geer 1923; Moss & Glen 1939; Blake 1962, 1989). That is, at the time that *Mytilus* reached the north-west coast of Nordaustlandet, this major source of freshwater would have been even more distant from Langgrunnodden and Kinnvika than it is today, if in fact this outlet glacier continued to exist at all. In this connection Koerner concluded that the Svalbard ice caps, among others, “consist entirely of Holocene ice indicating that their re-growth began during some part of the Holocene, as the climate cooled” (1999: 81).

Nonetheless, the yearly melting of sea ice, plus runoff from the land, clearly must have resulted in at least some temporary reduction in salinity in the shallow water along the outermost coasts where *Mytilus* has been found in considerable abundance on the raised beaches. But were the waters any less saline at that time than they are today, and what effect did any changes in salinity have on the abundance of predators (cf. Feder et al. 2003)? As an example of conditions during the International Geophysical Year (1957–58), on 18 July 1957, the Finnish ship RV *Aranda* occupied Hydrographic Station No. 35 in Kinnvika, Murchisonfjorden (80° 03' N, 18° 15' E). Salinities and water temperature were as follows: surface (33.96‰; 2.67 °C); 10 m depth (34.39‰; 2.01 °C), 15 m depth (34.44‰; 1.88 °C) and 20 m depth (34.48‰; 1.78 °C; Hela & Koroleff 1958).



Fig. 4. Typical occurrence of *Mytilus* fragment (arrow) in beach gravel at Kinnvika; part of sample WB-90-25 at 5.1 m a.s.l. (Table 1). Knife for scale is 9 cm in length. (Photograph by W. Blake, Jr., 27 July 1990.)

Yet no evidence has been found by the writer that Kinnvika harbours *Mytilus edulis* today, either as living colonies or individuals cast up on the modern beaches attached to marine algae. The same is true for the Langgrunnodden–Detterbukta area. Also, the *Mytilus* collections from the raised beaches in these areas showed no evidence of drilling by naticid or other predatory snails.

The configuration of Wahlenbergfjorden is very different from the topography of the outer coast between Kinnvika and Langgrunnodden. The 40 to 45 km long Wahlenbergfjorden extends deeply into Nordaustlandet, reaching close to the geographical centre of the island (Fig. 1). Glaciers enter the head of the fjord from high land to the north, east and south, and rivers draining the southern half of Rijpdalen, as well as the adjacent ice caps, provide additional freshwater. Some 7400 to 6900 <sup>14</sup>C yr BP, when *Mytilus* lived at the head of the fjord, that area still would have received significant runoff from the land even though the ice caps and glaciers were much reduced in size, or perhaps absent.

Basic oceanographic data for Hinlopenstretet and Wahlenbergfjorden, plus some information for Murchisonfjorden, were provided by Mosby (1938), as a result of his work aboard *Quest* during the course of the Swedish–Norwegian Arctic Expedition in the summer of 1931. Hydrographic stations on both the north and south sides of Søre Russøya (24 and 30 June, respectively), yielded salinities in the 33.84 to 34.29‰ range with most temperatures slightly negative at depths between 0 and 25 m (Mosby 1938, Table 1). Mosby noted with regard to Murchisonfjorden, “It thus appears that these waters are extensively diluted by melting water from land, from the glaciers” (p. 61).

Data for 10 hydrographic stations spread over the length of Hinlopenstretet were also presented: at Station 94, west of Langgrunnodden, the surface water had a salinity of 33.57‰ on 17 August 1931, and the values increased progressively with depth to a maximum of 34.98‰ at 200 m; temperatures ranged between 3.45 and 5.13 °C. Mosby (1938) also stressed the fact that salinities at the most easterly stations (6 and 7) in Wahlenbergfjorden were lower (all <34.0‰ at 0 to 10 m depth, with negative temperatures throughout) than at Station 13 in Hinlopenstretet outside the mouth of the fjord (due south of Brageneset; see Fig. 1), where all salinity values were above 34.0‰ and temperatures ranged between -0.89 and 0.71 °C (0 to 250 m depth, 3–4 July 1931). Although Mosby does not comment with regard to the salinities in inner Wahlenbergfjorden, presumably the same conclusion can be reached that he did for Murchisonfjorden. According to Peacock (1993), *M. edulis*, in open sea conditions at the northern limit of its distribution, requires a minimum summer sea surface temperature of 4 °C.

#### *Palaeoceanographic implications*

The age determinations on *Mytilus* shells from north-western Nordaustlandet show that this pelecypod lived north of the 80th parallel for much of the first half of Holocene time. The arrival of *Mytilus* to Nordaustlandet coincided with the first influx of subpolar North Atlantic Water recorded in core PCM7 (78° 37' N, 7° 54' E) at 1073 m depth off the west coast of Spitsbergen (Lloyd et al. 1996). These authors state: "This initial period of subpolar water influence along the Spitsbergen margin lasted until approximately 9 ka..." (p. 297). The information gleaned from this core agrees with the earlier conclusion by Svendsen & Mangerud (1992) that a phase of rapid glacial retreat in the inner fjords of Spitsbergen and in eastern Svalbard occurred at the beginning of the Holocene. Farther south, off the western Barents shelf at 75° N, Sarnthein et al. (2003) calculated that the major postglacial warming of the West Spitsbergen Current, by 4 to 5 °C, occurred in early Holocene time.

Salvigsen (2002) has suggested that *Mytilus* was most widespread in Svalbard at ca. 7250 <sup>14</sup>C yr BP, a conclusion based in part on the one age determination available to him from Wahlenbergfjorden. Had more extensive and more detailed collections been made in north-western

Nordaustlandet, with a whole series of sub-collections selected across the altitudinal range at which the shells occur at each site, and if a significantly greater number of age determinations had been carried out, it might have been possible to determine with certainty whether *Mytilus* lived along Hinlopenstretet continuously for some 3000 years or whether it colonized the island on more than one occasion. The series of 14 radiocarbon ages on *Mytilus* shells from the Hiorthfjellet fan delta, on Spitsbergen, ranging from 6175 ± 90 (T-13345) to 4350 ± 110 (T-13358) <sup>14</sup>C yr BP (Lønne & Nemeč 2004), for example, clearly shows the continuous presence of *Mytilus* at this site on the south side of Isfjorden.

On the northern coast of Spitsbergen *Mytilus* had appeared by ca. 9300 <sup>14</sup>C years BP (Salvigsen & Österholm 1982; Brückner & Halfar 1994; Salvigsen 2002), that is, slightly earlier than on Nordaustlandet. Then *Mytilus* persisted in northern Spitsbergen for another 500 years—until ca. 5300 <sup>14</sup>C yr BP (Salvigsen 2002)—in the innermost, southern part of one of the main, north coast fjords. Nearly all of the ages on *Mytilus* from Nordaustlandet fall within the interval of ca. 8800 to 5000 <sup>14</sup>C yr BP when this species also was present on Edgeøya, in south-eastern Svalbard (Hjort et al. 1992; Hjort et al. 1995). The interval from ca. 8000 to 4000 <sup>14</sup>C yr BP is the time when the mean July temperatures in outer Isfjorden, based on the analysis of macrofossils in lake sediments, may have been at least 1.5 °C higher than today (Birks 1991). In addition, the interval from 8400 to 4900 <sup>14</sup>C yr BP corresponds to the time when six Boreal mollusc species colonized a section of the West Greenland coast between 65° 30' N and 68° 30' N (Funder & Fredskild 1989; Funder & Weidick 1991), and a similar interval of roughly 8000 to 5500 <sup>14</sup>C yr BP for colonization by *Mytilus* was reported from the central East Greenland coast by Hjort & Funder (1974). These authors suggested that *Mytilus* may have reached central East Greenland via a branch of the West Spitsbergen Current, which brought warm Atlantic water to the coast at a time when the cold polar East Greenland Current was diminished in strength. This hypothesis is supported by an analysis of stable isotope composition of water samples and bivalve shells in East Greenland. Israelson & Buchardt concluded that:

"A higher salinity in Scoresby Sund and in the coastal waters of Germania Land in

the early Holocene has been demonstrated. This is in agreement with the studies of Hjort & Funder (1974) who postulated that the immigration of *Mytilus edulis* to the East Greenland fjords during this time was connected with an influence of Atlantic Water, more saline than the present coastal waters of East Greenland” (1991: 121–122).

Further, Dyke et al. (1996) note that a shift westward in the Transpolar Drift may result in both the East and West Greenland Currents becoming warmer.

### *Comparison with Baffin Bay*

An analogous situation to Nordaustlandet exists in northernmost Baffin Bay. In 1940 *M. edulis* was found living intertidally at North Star Bugt in the Thule District, North-west Greenland (ca. 76° 30' N; Vibe 1950). Later, in 1968, living individuals of *Mytilus* were collected at several additional sites in the Thule District and, in 1973, farther north at Siorapaluk in Robertson Fjord (ca. 77° 46' N), where these pelecypods were used by the local population as food (Theisen 1973). By contrast, no living *Mytilus* or fossil shells have been found on the Ellesmere Island side of northernmost Baffin Bay at similar latitudes (Dale 1985; Blake 1992, 1993). However, near the southern end of Coburg Island (75° 52.5' N), at the entrance to Jones Sound and some 40 km from Devon Island, *Mytilus* was collected from a coastal section by the writer in 1970 and 1972. Two radiocarbon age determinations were made on these shells: the blue, outer prismatic layer (calcite) yielded an age of >38000 <sup>14</sup>C yr BP (GSC-1425; Blake 1973), whereas the inner nacreous material (aragonite) from the same shells, dated later by AMS, yielded an age of 46070 ± 830 <sup>14</sup>C yr BP (TO-3991). No *Mytilus* shells were discovered in the richly fossiliferous Holocene strata overlying the “old” shells, nor were any modern shells of this species found along the present-day shores of Coburg Island or along the southern coast of Ellesmere Island. On the Greenland side, by contrast, both pre-Holocene and Holocene occurrences of *Mytilus* are known from the North Star Bugt area, Thule District (Davies et al. 1963; Blake 1975; Funder & Fredskild 1989; Funder 1990). These northern occurrences of *Mytilus* along the Baffin Bay coast of Greenland are a consequence of the northward flowing warm

water of the West Greenland Current which, like the West Spitsbergen Current in Svalbard, carries the pelagic *Mytilus* larvae northward. In the case of Greenland, the pelagic larvae originate in southern West Greenland, where *Mytilus* is widespread (Madsen 1936; Funder & Simonarson 1984), whereas in Svalbard, the larvae presumably originate in northern Norway (Berge et al. 2005; Berge et al. 2006).

On the Canadian side of Baffin Bay, cooled by the southward flowing Baffin Current (Funder 1990), recent *Mytilus* has not been found north of the Pond Inlet area, northern Baffin Island, at approximately 72° 41' N, some 500 km south-west of the Thule District and 350 km south of Coburg Island (Nichols 1936; Laursen 1946; Ellis 1955; Lubinsky 1980). Radiocarbon age determinations of *Mytilus* collected from the modern beach near the hamlet of Pond Inlet in 1963 by B. G. Craig were 80 ± 220 and 340 ± 90 <sup>14</sup>C yr BP (GSC-1570 and -1898, respectively); another sample collected in roughly the same area in 1923 yielded an age of 1210 ± 330 <sup>14</sup>C yr BP (GSC-1583; all in Blake 1987). The occurrence of *Mytilus* at this latitude results from the counter-clockwise circulation which brings the warmer waters of the West Greenland Current to the west side of northern Baffin Bay (Kiilerich 1939; Dunbar 1972; Funder 1990; Funder & Weidick 1991). *Mytilus* shells of Holocene age, based on stratigraphy, also have been found in the vicinity of Pond Inlet. To the west shells were found in a river-cut section at about 15 m a.s.l. (Klassen 1993), and to the east shell fragments were found among rounded pebbles on a raised beach at about 26 m a.s.l. (D. A. Hodgson pers. comm. 2006).

### Conclusions

The timing of the arrival of *Mytilus* in north-western Nordaustlandet agrees with the proposal by Lloyd et al. (1996) that the first penetration of subpolar North Atlantic waters occurred off the western margin of Spitsbergen at the beginning of the Holocene. According to their results, based on a study of two cores, “the faunal data suggest this period, until approximately 9 ka BP, was as warm if not warmer than the present day along the Spitsbergen margin” (p. 299). The drastic warming in early Holocene time, well documented from ice caps as far afield from Svalbard as Arctic Canada (Koerner & Fisher 1990, 1995,

2002), resulted in rapid recession of glaciers all around Nordaustlandet and probably caused the disappearance, or near disappearance, of the ice caps on this island. This same warming allowed mussels of the *M. edulis* complex to colonize the coasts of Spitsbergen via the West Spitsbergen Current, reaching north-western Nordaustlandet by 9000 <sup>14</sup>C yr BP. The lower salinities which resulted from the massive melt-off of glaciers may have played a role in the spread of *Mytilus* along the coasts of Svalbard in early Holocene time, but the warming and intensity of the West Spitsbergen Current itself must be regarded as the driving force.

On the basis of their study of core NP94-51SC2 in Hinlopenrenna, only 36.5 km north-west of Langgrunnodden, the northernmost site where *Mytilus* was collected, Ślubowska et al. (2005) conclude that:

“During the late Holocene the inflow of warm water masses carried by the West Spitsbergen Current decreased to a very low level. Conditions at the surface and bottom water were polar with low salinity and extensive sea ice cover and marked by the readvance of glaciers on Svalbard” (2005: 13).

This statement is consistent with the evidence presented here for the disappearance of *Mytilus* from Nordaustlandet after ca. 5800 <sup>14</sup>C yr BP.

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