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Late Pleistocene–early Holocene polychaete borings in NE Spitsbergen and their palaeoecological and climatic implications: an example from the Basissletta area

NILS-MARTIN HANKEN, ALFRED UCHMAN AND STEN LENNART JAKOBSEN

Several marine invertebrates bore in rocks, mostly carbonates, producing characteristic microscopic and macroscopic bioerosion structures that have a high fossilization potential. In the fossil state, they are known as a major category of trace fossils, named borings. In common with other trace fossils, the Linnean taxonomy is applied for their classification, and ichnogenera and ichnospecies can be distinguished on the basis of their morphology (e.g. Ekdale et al. 1984; Bromley 1992, 1994; Wilson 2007). As most macroborings occur in intertidal to shallow-subtidal zones (e.g. Ekdale et al. 1984), they are a valuable tool for identifying fossil rocky coasts (e.g. Radwan´ ski 1969, 1970; Gibert et al. 1998; Johnson & Baarli 1999; Domenech et al. 2001).

Caulostrepsis is a widely distributed shallow-marine boring produced by polychaetes, but is rarely known from Polar Regions (e.g. Aitken & Risk 1988). Together with the related boring, Maeandropolydora, we discovered this characteristic bioerosion structure for the first time in Svalbard (the Basissletta area in NE Spitsbergen; Fig. 1). Our discoveries of Caulostrepsis and Maeandropolydora in Svalbard are the northernmost occurrences of these trace fossils. They help to improve our knowledge of the Late Pleistocene–early Holocene sealevel variations in this area, which was subject to glacio-isostatic uplift after the Weichselian glaciation. The main aims of this paper are to document Caulostrepsis and Maeandropolydora and to relate the finds to the sea surface temperature in the Late Pleistocene–early Holocene along the NE coast of Spitsbergen.

Geological setting and sites of the borings

The bedrock at Basissletta was originally assumed to consist of Upper Precambrian to Lower Ordovician marine sediments (Gobbett & Wilson 1960; Harland et al. 1966; Vallance & Fortey 1968; Fortey & Bruton 1973; Swett 1981; Harland 1997), but later biostratigraphic correlation indicates that the youngest part of the sequence is of Middle Ordovician age (cf. Fortey & Barnes 1977; Kosteva & Teben'kov 2006; Hansen & Holmer 2010). The Precambrian and lowermost Cambrian are dominated by clastic sediments overlain by thick Lower Cambrian dolomitic deposits. The Middle and Upper Cambrian are missing. The Ordovician sediments are characterized by limestones with subordinate shales and sandstones in some parts. The sequence at Basissletta was folded during the Caledonian Orogeny into a large syncline, with the oldest rocks exposed to the west and the youngest along the SE part of the present coastline (Fig. 1C).

A Late Weichselian icecap covered the Svalbard Archipelago during the Last Glacial Maximum; see review by Forman et al. (2004). The northern Barents Sea was deglaciated between 13.0 and 10.3 ka (Forman et al. 1995). After the ice sheet retreated, a net drop in sea
Fig. 1. Location maps. A. Section of the Arctic Ocean and North Atlantic showing the location of Svalbard. The present-day ocean circulation pattern is from Slubowska-Woldengen et al. (2008). Red arrows = warm Atlantic water; blue arrows = cold Polar water. NwAC = Norwegian Atlantic Current; NCaC = North Cape Current; WSC = West Spitsbergen Current; RAC = Return Atlantic Current; SB = Svalbard Branch; YB = Yermak Branch; ESC = East Spitsbergen Current; A = Archangel; BI = Bear Island; BS = Barents Sea.

B. Svalbard Archipelago showing the location of Basissletta and other places referred to in the text. G = Gråhukenv; I = Isfjord; L = Langnesodden; M = Murchisonfjord; PKF = Prins Karls Forland; R = Reinsdyrfylova. C. Simplified bedrock map of the Basissletta area (location in 1B) showing the locations of the borings given in Table 1 and the 14C-dated body fossils given in Table 2. Contour interval 25 m. Modified from Nielsen et al. (2010).
level took place as a result of the glacio-isostatic uplift of the landmass; see reviews regarding the Svalbard Archipelago by Landvik et al. (1998) and Forman et al. (2004). The emergence of the land relative to the sea is easy to recognize in well-preserved and extensive Late Weichselian and Holocene gravel beach ridges in northern Svalbard, but so far only a few localities in this area have been investigated. The raised-beach sequences in the Basissletta area have not been investigated yet, but Salvigsen & Østerholm (1982) determined the marine limit as 85 m a.s.l. at Mosselbukta, which is situated west of Basissletta (Fig. 1B). At the same locality, shells at 65 m a.s.l. were dated to 11.1 ka. Blake (1961) constructed a postglacial emergence curve from Lady Franklin Fjord (NE of Basissletta, see Fig. 1B) based on $^{14}C$ dating of driftwood, whalebone and bivalves. In the Murchisonfjord area (east of Basissletta), Olsson et al. (1969) demonstrated the presence of 10.7-ka-old skeletal material at 82 m a.s.l. Forman et al. (2004) showed that there was a rapid drop in the relative sea level (15–30 m ka$^{-1}$), which is in good agreement with the $^{14}C$ dating from Lady Franklin Fjord.

The Basissletta area forms a slightly undulating, lowland area whose surface dips to the east. During the Late Weichselian–Holocene regression the area was gradually covered by gravel beach ridges deposited in the supratidal zone as the former sea floor gradually became subaerially exposed. The beach deposits are parallel to the present shoreline, indicating that the wave direction was similar to that of the present. Most of the southern part of Basissletta is covered by outwash material from the slightly retreating Buldrebreen glacier. The extensive Quaternary overburden on Basissletta means that rock exposures are largely confined to the banks of meltwater streams, parts of the coast and minor topographical heights inland.

The surface of the fine-grained, well-cemented Lower Ordovician limestones has been only slightly affected by Holocene subaerial karstification processes and frost-shattering, and Caulostrepsis and Maeandropolydora are well preserved on these surfaces. However, as the Lower Cambrian dolomites have been less resistant to subaerial weathering, most borings on this bedrock surface have probably not been preserved. The Middle Ordovician deposits are dominated by shallow-water carbonate banks that are only partly cemented, resulting in the original bedrock surface having been subjected to a combination of karstification and frost-shattering, with the consequent loss of any original bioerosion sculpture. The differences in the response to Holocene subaerial weathering and karstification of the various lithologies may thus explain the selective preservation of bioerosion sculptures in certain parts of the geological sequence at Basissletta. The locations of sites with bioerosion are shown in Fig. 1C, and details of these occurrences are given in Table 1.

Body fossils and depositional environment

At Basissletta, we found only a single log of driftwood deposited higher than 3 m above present sea level. It was embedded in beach gravel about 30 m above present sea level (Fig. 5A). Driftwood has been used as a good indicator of the former sea level in arctic areas but, as Bondevik et al. (1995) pointed out, driftwood mainly strands during storms in summer when the coastal waters are ice-free. Storm waves may throw the wood above the high-tide level and either bury it in the beach ridge or leave it on the surface on or behind the ridge (Fig. 6). The ridge crest will normally be developed 1 to 2 m above high-tide level, the altitude being determined by the wave height during the storm (Reineck & Singh 1980). This implies that driftwood deposited at the storm surf limit may be several metres higher than the former mean tide level.

Whalebones are not common at Basissletta and were found only as scattered bones, not as more or less complete skeletons, indicating that they had been reworked.
before final deposition. Most of the bones were highly degraded by semi-recent weathering, but one well-preserved bulla (the inner ear of a whale) was fairly well preserved and was collected for \(^{14}\text{C}\) dating (Fig. 5B).

Reworked, individual whalebones may be thrown up together with driftwood on the beach during storms but, as Blake (1975) pointed out, the weight and size of whalebones make them more likely to be deposited in shallow water than to be thrown up onto the beach by storm waves. However, at Basissletta, the bulla was found in the upper part of a gravel beach ridge, indicating that it was deposited at the storm surf limit during a heavy storm.

At Basissletta, both the bivalves *Mytilus edulis* Linnaeus (Fig. 5C) and *Hiatella arctica* Linnaeus (Fig. 5D) were found together with gastropods at a few levels; see Hansen et al. (2011) for further details. The locations of the body fossils used for \(^{14}\text{C}\) dating are shown in Fig. 1C, and Table 2 gives the results.

In arctic areas, all molluscs live below the low-tide level because the shore is covered with sea ice for most of the year. For instance, *Mytilus edulis*, which is a common intertidal bivalve further south in Europe, lived at a water depth of about 10–20 m on Edgeøya during the Holocene climatic optimum (Hjort et al. 1995). During emergence, skeletal material from older sediments is commonly reworked and redeposited together with younger beach sediments. However, the biocoenosis at Basissletta consists of a mixture of *Mya truncata* in their burrows together with well-preserved molluscs in the ensuing fine-grained deposits lying below and with erosional contact with the overlying coarse-grained beach ridges. These observations indicate that the skeletal fauna consists of a mixture of *in situ* and autochthonous material that cannot have been reworked from older deposits (cf. De Francesco & Hassan 2008).

### Material and its preparation

The characteristic bioerosion structures were found both in carbonate blocks and *in situ* on some Lower Palaeozoic limestone and dolomite deposits exposed at various altitudes above present sea level. The loose, bioeroded blocks were found in multiple generations of Late Pleistocene–early Holocene beach ridges formed during heavy surf and storms, whereas the outcrops of underlying bedrock represent the rocky floor of the late Quaternary sea. The limited number of good exposures in the Basissletta area meant that it was possible to recognize the presence of bioerosion in only a limited number of outcrops. Their locations are shown in Fig. 1C, while Table 1 gives more information about the specific localities.

The borings were partly filled with a mixture of sand and silt partially consisting of a solid mass where it was

### Table 2. Radiocarbon ages of body fossils from Basissletta. The locality numbers are shown in Fig. 1C. The altitude is given in metres above present mean sea level. The level of the samples is based on GPS technology with an altitude uncertainty of about ±4 m.

<table>
<thead>
<tr>
<th>Loc.</th>
<th>GPS coordinates</th>
<th>Altitude (m a.s.l.)</th>
<th>Material</th>
<th>Calibrated age range 68%</th>
<th>Calibrated age range 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>N79 50.567; E017 43.820</td>
<td>6</td>
<td><em>Mytilus edulis</em></td>
<td>7100 ± 50 (68.2%)</td>
<td>12000 ± 50 (95.4%)</td>
</tr>
<tr>
<td>15</td>
<td>N79 50.560; E017 43.827</td>
<td>6</td>
<td><em>Hiatella arctica</em></td>
<td>7100 ± 50 (68.2%)</td>
<td>12000 ± 50 (95.4%)</td>
</tr>
<tr>
<td>16</td>
<td>N79 50.390; E017 40.978</td>
<td>33</td>
<td>Wood</td>
<td>9670 ± 45</td>
<td>9670 ± 45</td>
</tr>
</tbody>
</table>

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associated with living lichen and decaying organic matter. Most of the infill was removed by pretreatment with hydrogen peroxide (one part of 35% hydrogen peroxide mixed with two parts of water). This treatment oxidized the organic matter during the formation of carbon dioxide, which caused partial disaggregation of the infilled material. The chemical treatment was performed in short periods (about 10 min) before the samples were rinsed in water and the loosened material carefully removed using toothpicks without scraping the calcareous walls. It was possible to use toothpicks to remove matrix only from the outer parts of the borings; the inner parts had to be cleaned ultrasonically using the procedure described by Pojeta & Balanc (1989). Most borings were satisfactorily cleaned after two or three repetitions of H$_2$O$_2$ and ultrasonic treatment, but the deepest ones had to be cleaned with a hand-held water gun (Wagner Model W 400 SE). This gun generates a fine, high-powered jet of water adjustable up to 180 bars (10 mm from its orifice) that immediately removes particles and impurities from cavities of a very complex nature without harming the surface details (Nielsen & Jakobsen 2004).

To obtain information about the 3D structures of the borings, we made moulds of some of the best-preserved material in the following way. When the sample was dry after the cleaning procedure, plasticine ‘walls’ were built up around the areas of the borings in a ‘container’ large enough to hold the silicone rubber without the expanding rubber overflowing (normally 4–5 times its volume) during the vacuum degassing. For perfect impregnation we used low-viscosity, red, condensation-curing silicone rubber RTV (Elastosil M 4470 – Wacker Silicones), which becomes firm and flexible when cured. By adding a hardener of 3% (catalyst T 37), we achieved a working time of $\sim$90 min, depending on the room temperature. The catalyst was effectively dispersed by stirring, and care was taken not to whip large amounts of air into the mixture. The catalyzed rubber was placed in a vacuum chamber for degassing. A residual pressure of 10 to 20 mm of mercury sufficiently de-aired the material in 10 min. After polymerization (24 h), the silicone rubber was removed from the underside, thus exposing this part of the limestone sample. The limestone matrix between the borings was removed completely by soaking the samples with the remaining silicone rubber in a bath of 10% hydrochloric acid for several hours. The acid-prepared specimen offered excellent 3D moulds of the borings.

Although epoxy resins are commonly used for vacuum impregnation of such objects because of their low viscosity, the principal advantage of using silicone rubber is that small, individual specimens on a larger cast can easily be cut out using a scalpel. Individual moulds could thus be easily studied under a binocular microscope, revealing small details of the borings without any loss of material. Furthermore, the red colour of the cast makes a superb background colour prior to application of a light coating of sublimated ammonium chloride, which further enhances the contrast (e.g. Feldmann 1989).

The $^{14}$C dating of the body fossils from Basissletta was carried out at the Radiocarbon Laboratory at the Silesian University of Technology, Gliwice, Poland. The calibrated age ranges are according to the IntCal04 calibration curve for the wood material (Reimer et al. 2004) and to Marine04 for the marine material (Hughen et al. 2004). The OxCal v4.1.3. program (Bronk Ramsey 2009) was used for the calculation. Details of the Quaternary body fossils and their $^{14}$C dating are given in Hansen et al. (2011).

The illustrated material is housed at Tromsø University Museum, University of Tromsø, and has collection prefix TSGF.

Systematic description

_Ichnogenus Caulostrepsis_ Clarke, 1908; _Caulostrepsis taeniola_ Clarke, 1908; Figs 3A–E, 4A–D

_Description._ – U-shaped pouch-like borings, 1.5–4 mm, exceptionally up to 8 mm wide, mostly up to 10 mm, rarely up to 17 mm and exceptionally up to 22 mm long. Their width is even or they are slightly wider distally. The boring displays distinct or indistinct marginal tunnels (limbs+vertex; see Fig. 2 for terminology), which are 0.5–1.2 mm wide. The area between the tunnels, that is, vane _sensu_ Bromley & D’Alessandro (1983), is only slightly thinner than the limbs. In some borings, the surface of the vane is covered with linear corrugations forming arcs, which display concordance

Fig. 2. Morphological terminology concerning _Caulostrepsis_ (modified after Bromley & D’Alessandro 1983: fig. 2).
with the curvature of the vertex, or rarely with limbs of the marginal tunnel (Fig. 4B). Some borings are enlarged by weathering; their morphology is partly smeared. In some specimens, only the shallow, basal part is preserved (Fig. 3E). The remainder has been truncated by erosion. The entire boring is straight or slightly curved in most cases, but in some specimens it is strongly bent or even winds slightly in the horizontal plane. Their marginal tunnel is somewhat contorted. Such borings are transitional forms to *Caulostrepsis contorta*. In cross-section, the analysed *Caulostrepsis* appears dumbbell-shaped (lower part) or has figure-of-eight-shaped perforations (apertural part). The longer axis of the apertures of borings is differently oriented, perpendicular or oblique to the rock surface. The apertural part is commonly partly abraded.
The borings occur in calcarenitic limestones and rarely in calcite veins crossing the limestones (Fig. 3B). This trace fossil tends to occur in patches (Fig. 3C, D), which are mostly 2–3 cm across. In some cases, the surface of the patches is a little depressed, probably as a result of more intensive erosion of rock weakened by the borings in such a place. Intersections of neighbouring borings have not been encountered. The borings are crowded, up to 400 per 100 cm² (up to 4000 per m²).

Remarks. — The arcuate corrugations in concordance with the curvature of the vertex and the distal widening are evidence of onthogenic growth. The corrugations in concordance with the limbs suggest a lateral shift of the boring.

Bromley & D’Alessandro (1983) discussed the taxonomy of Caulostrepsis taeniola. This trace fossil is produced mainly by spionid polychaetes of the genus Polydora Bosc (Boekschoten 1966), particularly Polydora ciliata (Johnston), which is common on mid-latitude Atlantic coasts (Radwański 1969, and references therein), mostly no deeper than 25 m (Boekschoten 1966). This polychaete can live in loose sand, form tubes from mud, or can bore chemically and mechanically in mollusc shells, limestones, mudstones, peat and wood, and use sand-sized particles to line its borings.
and build low chimneys extending from the limb outlets above the substrate surface (Douville 1908; Söderström 1923; Prell 1926; Hempel 1957; Dorsett 1961; Boekschoten 1966; Blake & Evans 1973). Polydora ciliata feeds on fine detritus, small animals and diatoms (e.g. Daro & Polok 1973). It also lives in brackish water, for example in the Baltic Sea (D’Andrea et al. 1996) and the Black Sea (Murina 1997). The eunicid polychaete Lysidice ninetta Audouin & Milne-Edwards can also produce this trace fossil (Bromley 1978, 2004). This polychaete occurs in the Atlantic and Indo-Pacific, but its occurrence in Svalbard waters is unknown.

Caulostrepsis occurs mostly in infralittoral Plio-Pleistocene and recent Mediterranean environments (Bromley & D’Alessandro 1990). Ekdale et al. (1984: p. 127) placed the acme of the bathymetric range of Caulostrepsis in the lower intertidal and subtidal zones, decreasing in abundance on the shelf and with very rare occurrences on the continental slope and the abyssal zone. Caulostrepsis ranges from Devonian to Recent (Clarke 1908; Bromley 2004).

Caulostrepsis contorta Bromley & D’Alessandro, 1983; Fig. 4A, C–G

Description. – At least five specimens were discovered in the laboratory after moulding of borings whose entrance on the surface of blocks does not differ from the entrance of Caulostrepsis taeniola. Transitional forms from Caulostrepsis taeniola occur. The simplest forms display two short, almost symmetric or asymmetric galleries (Fig. 4D, E), 3–8 mm long, 4 mm wide, with a marginal tunnel and vane, which ramify obliquely or perpendicularly from the distal part of a Caulostrepsis taeniola-like boring. The galleries can be distally wider. In better-developed forms (Fig. 4F, G), the marginal tunnel and vane are contorted, and the overall length (up to 25 mm) and the degree and complications of contortion increase.

 Remarks. – It is difficult to distinguish between Caulostrepsis taeniola and Caulostrepsis contorta in the field because their entrances display the same morphology. Hence, the number of Caulostrepsis contorta is probably underestimated.

Bromley & D’Alessandro (1983), who discussed this ichnospecies, compared Caulostrepsis contorta with the borings of the living spionid polychaete Polydora concharum Verrill, illustrated by Evans (1969), and with borings of Polydora ciliata, illustrated by Bromley (1970). The initial ramified pouches can also be seen in borings of Polydora websteri Hartman, which bores chemically and mechanically in bivalve shells (Douville 1908; Blake & Evans 1973; Zottoli & Carriker 1974).
Borings of *Polydora concharum* also display the same features (Martin & Britayev 1998). The transitional forms between *Caulostrepsis taeniola* and *Caulostrepsis contorta* in the studied material strongly suggest that they were produced by the same tracemaker, probably *Polydora ciliata*.

**Ichnogenus Maeandropolydora Voigt, 1965; Maeandropolydora isp.; Fig. 3F**

**Description.** – Only one specimen was found in the field and documented by a photograph. It is a planar gallery composed of ramifying, curved tongues with pouches at the distal part. The pouches are 2.4–4 mm wide and 6–10 mm deep. They are encircled by a marginal tunnel, which is 1 mm wide. No twisting is observed.

**Remarks.** – Bromley & D’Alessandro (1983, 1987) discussed the taxonomy of *Maeandropolydora*. This trace fossil is produced by suspension-feeding spionid polychaetes (e.g. Barrier & D’Alessandro 1985) like recent *Polydora hoplura* (Claparède) (Mikulás & Pek 1996), in a similar way to *Caulostrepsis*. *Maeandropolydora* ranges from Triassic and maybe from Devonian to Recent (Bromley 2004).

**Discussion**

**Age**

*In situ* borings were found at only five localities between 28 and 50 m above present sea level (Table 1). In these cases, the bioeroded rock surfaces were limited to vertical to gently dipping surfaces of local heights, indicating that the bioerosion took place before these parts of the undulating, rocky sea floor were covered by marine sediments. The ensuing local depressions are filled with silty clay containing molluscs. The high concentration of well-preserved molluscs (including *in situ* *Mya truncata* in their burrows) in the fine-grained marine sediments indicates that the fauna is autochthonous and cannot have been reworked from older deposits (cf. De Francesco & Hassan 2008). This implies that radiocarbon dating of the skeletal material in the same level as the *in situ* borings can be utilized as a rough age estimate of these borings. However, all the bivalves collected were from somewhat lower levels than the borings and will therefore give only a minimum age for the *in situ* borings. The bivalves thus indicate that the *in situ* borings are about or slightly more than 10 ka, which also fits well with the $^{14}$C dating of a log and a bulla from a whale that were found higher above present sea level than the bivalves. Most
of the borings were found in loose carbonate blocks deposited in beach ridges between 9 and 78 m above present sea level. All the blocks were well rounded, indicating some transportation and mechanical abrasion before final deposition. However, most of the bioerosion fabric is fairly well preserved, perhaps indicating that most bioerosion took place on loose limestone blocks lying exposed on the sea floor. Bioeroded blocks were found down to about 9 m above present sea level, but these blocks may represent older material transported down the dipping surface. Thus, the radiocarbon ages of the bivalve fauna in excess of 7 ka at the same height above present sea level as the lowermost blocks give only an indication of a minimum age of these borings. Bioeroded blocks were found in beach ridges up to 78 m above sea level. We have no radiocarbon dating from Basissletta so far above present sea level, but correlation with the $^{14}$C dating of bivalves at about the same height above present sea level from Mosselbukta (west of Basissletta) indicates that this bioerosion may be somewhat older than 11.1 ka. However, the age of the borings from localities higher than 33 m above sea level can be estimated by adjustment to the postglacial emergence curve constructed for the studied area (Fig. 7). Judging from the curve, they are not older than 11 ka and most of them are related to the time of rapid sea-level rise from 10 to 7 ka.

**Northern range of polychaete borings**

The trace fossils, *Caulostrepsis taeniola*, *C. contorta* and *Maeandropolydora* isp., described here are the northernmost occurrences of these ichnotaxa (N79°49’–52’, see Table 1). Data from the literature on these borings in Svalbard are not clear. Andersson et al. (2000: p. 463) listed *Polydora ciliata* from the Late Weichselian on the island of Prins Karls Forland (78°30’N), probably in the form of borings (?), but no details are provided. *Polydora ciliata* occurs in Kongsfjord in west Spitsbergen (Jørgensen & Gulliksen 2001), where Kaczmarek et al. (2005) list *Polydora* sp. *Polydora ciliata* is also known from Iceland (Ingolfsson 1996), and pelagic *Polydora* larvae are known from the Barents Sea (Mileikovsky 1968). We searched in vain for recent borings in limestone substrate in the intertidal zone of the study area.

Aitken & Risk (1988) described *Caulostrepsis* from Holocene–Pleistocene shells and limestone clasts at 70°N in the Canadian Arctic. They also illustrated ramified *Caulostrepsis*-like borings in shells, which may be ascribed to *Caulostrepsis contorta* (their fig. 6). *Polydora ciliata* is known from this area (Dale et al. 1989). Bennike et al. (1994) noted *Caulostrepsis* isp. in the Holocene of West Greenland at N71°30’. Jensen et al. (2006) reported *Polydora ciliata* borings in Middle Weichselian shells from the Archangel area in Russia (N65°–68’) and noted that this polychaete is unknown from the recent coast of northern Russia.

The *Caulostrepsis taeniola* described from Svalbard are narrower (mostly 1.5–4 mm) than those described from various substrates on the North Sea island of Helgoland, which mostly range from 3 to 7 mm (Van der Pers 1978). The smaller size of borings from Svalbard may be caused by environmental stress at the boundary of their range, which may be related to the low temperature.

**Climate**

The present climate of the northern North Atlantic region is 5°–10°C warmer than the zonal mean, partly because of the huge amount of heat transported northwards by the warm Atlantic Water in the Norwegian Atlantic Current (Hopkins 1991). The relatively warm climate is more or less characteristic for the Holocene, but, as shown by Hald et al. (2007), there have also been considerable variations in the climate throughout this period. Studies of planctonic foraminifera from the western margin of Svalbard (Ebbesen et al. 2007) indicate a marked increase in surface summer temperature from 4° to 10°C between 10 800 and 9700 cal. a BP. The warmest interval was dated to 9700 to 8800 cal. a BP, with temperatures reaching almost 10°C. This is in good agreement with Rahmstorf (2002) and Sarnthein et al. (2003), who recognized enhanced northward heat transportation by the Gulf Stream system peaking about 9000 a BP. At 8800 cal. a BP the sea surface was exposed to an abrupt cooling, and from 8800 to 3500 cal. a BP the average temperature was around 3°C (Ebbesen et al. 2007). The recent summer surface water temperature along the northern coast of Spitsbergen is up to about 4°C (Normann & Pettersen 1984). Based on the known temperature tolerances of *Polydora ciliata*, it is possible to estimate the minimum temperature during the Holocene temperature optimum in NE Spitsbergen. In the Baltic Sea, *Polydora ciliata* tolerates a drop in temperature from 11.5° to 7.5°C (Gulliksen 1977) and can survive several weeks of cold, wintry weather with temperatures below freezing (Crisp 1964). *Polydora ciliata* is also common along the Norwegian coast, and Holte & Oug (1996) reported that it constitutes a significant part of the soft-bottom macrofauna in subarctic waters off Tromsø (N Norway). The surface temperature of the sea in this area usually ranges from 1–3°C in January–February to 7–9°C in August–September. *Polydora ciliata* is also known from Kongsfjord in W Spitsbergen, where temperatures up to 7°C have been recorded near the surface (Jørgensen & Gulliksen 2001). These investigations indicate that *Polydora ciliata* is restricted to areas where the water temperature attains at least 7°C in summer. It is also possible to use the presence or absence of molluscs to estimate the minimum seawater temperatures,
because many species in cold-water areas are very susceptible to minor changes in the surface water temperature; see Peacock (1989) for a review of the potential of late Quaternary marine molluscs from NW Europe for environmental studies. In Svalbard, about 100 mollusc species have been described from Holocene raised beaches (Feyling-Hanssen & Jørstad 1950; Feyling-Hanssen 1955). The majority of these are still living along the coast and in the fjords of Spitsbergen, but nine species are now extinct according to Feyling-Hanssen (1955). Salvigsen et al. (1992) showed that five of the extinct species in Svalbard had lived there under warmer conditions, for example the thermophilous blue mussel Mytilus edulis, which has been found at Reinsdyrflya (Forman 1990) and Gråhukken west of Basissletta (Salvigsen & Österholm 1982), at Langgrummodden, NE of Basissletta (Blake 1961), and in E Svalbard (Hort et al. 1995). 14C dating, summarized by Salvigsen (2002), indicates that these occurrences from N Svalbard date from about 9000 a BP or slightly earlier. There is thus good agreement with the Holocene temperature optimum and the distribution of M. edulis in this area. The surface water temperature at this time must have been at least 8°C, because the spawning of M. edulis is highly temperature-dependent and typically occurs at temperatures around 8 to 10°C (Bayne 1965, 1976; Thorarinsdóttir & Gunnarson 2003). The presence of both Mytilus edulis (Hansen et al. 2011) and borings at the same height above present sea level thus indicates that the bioeroding organisms were dependent on a surface water temperature of at least 8°C.

**Transportation of Polydora larvae**

It is reasonable to assume that the Polydora larvae, together with other temperate species, have been brought to Spitsbergen by surface-layer transport in the warm Norwegian Atlantic Current (Fig. 1A). Around Andøya, at 69°N, the Norwegian Atlantic Current divides into the West Spitsbergen Current and the North Cape Current, leading to W Spitsbergen and the Barents Sea, respectively (Orvik & Niller 2002; Saloranta & Haugan 2004). The shortest transport route for the Polydora larvae from warmer water would entail a seeding-stock area for larvae in coastal waters on a limestone coast in Norway south of 69°N, because larvae originating further north would be transported into the Barents Sea by the North Cape Current.

Polydora larvae have a vertical range distribution of 0 to 75 m, but the majority are found in the surface layers (Murina 1997). The distance between Andøya and the southern part of Spitsbergen is nearly 1000 km, and estimations of the transport time for passively drifting organisms in surface layers from Andøya to W Spitsbergen have been simulated by Berge et al. (2005). These estimations indicate that surface-layer transport is slow and could require up to about 3–4 months. Larvae of Polydora ciliata metamorphose within 10 days to a month in temperatures exceeding 10°C, but below 6°C their metamorphosis takes approximately 3 months (Anger et al. 1986). The long metamorphosis of Polydora ciliata larvae at low temperatures indicates that they could survive the long transport from Norwegian coastal waters to Spitsbergen. The first Polydora larvae arriving in Spitsbergen probably settled along the SW coast. The species then spread gradually, following the West Spitsbergen Current northwards and then the Svalbard branch to the east where the West Spitsbergen Current divides NW of Spitsbergen. No finds of Caulostrepsis have so far been reported along the west coast of Spitsbergen, but Quaternary geologists have probably overlooked them because small bioerosion traces are an uncommon object of research.

**Conclusions**

- Late Pleistocene–early Holocene settlement of polychaete Polydora larvae along the coast of Spitsbergen may have been episodically induced by larvae transported from a limestone coast south of Andøya in N Norway. Judging by the limited finds at different heights above present sea level at Basissletta (NE Spitsbergen), these events have probably been rare, depending on the co-occurrence of favourable warmer conditions with increased transport of warm Atlantic Water by the West Spitsbergen Current, higher sea surface temperatures and local wind directions.

- Comparisons with sea-level curves and 14C dating from neighbouring localities indicate that the oldest Caulostrepsis and Mæandropolydora borings are about 10 ka to slightly more than 11 ka. However, loose bioeroded blocks indicate that the youngest borings in the Basissletta area may be only slightly more than 7 ka old.

- The presence of Caulostrepsis and Mæandropolydora fits fairly well with the subfossil occurrence of thermophilous marine molluscs in Svalbard, and can thus be used as an indicator of warmer water (at least 8°C) in arctic areas.
• The presumed age of in situ Caulostrepsis and Meandropolydora fits fairly well with the distribution of ‘warm water’ planktonic foraminifera.

• The loose bioeroded blocks found close to recent sea level probably represent older material transported down the dipping surface because the radiocarbon age of the bivalve fauna is in excess of 7 ka at the same height above present sea level, which according to the distribution of the planktonic foraminifera indicates a cool period.

• The presence of bioerosion structures on subaerially exposed, shallow-water Pleistocene–Holocene bedrock surfaces may be a valuable tool with which to evaluate climatic oscillations and postglacial emergence in arctic areas.

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