

An invertebrate macrofauna from an early Holocene fjord-delta system, North Norway

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During early Holocene, the Breivikeidet Valley of Troms County was part of a fjord system. Prodelta and delta slope deposits were formed, overlain by fluvial deposits, and are presently exposed in river sections. The depositional setting was influenced by sediment suspension and traction processes. Our geochemical analyses, together with implications from macrofauna and sedimentology, indicate an overall change from occasionally oxygen deficiency in marine waters to an overall fall in salinity, these changes finally leading to brackish and freshwater conditions. Radiocarbon dates confirm an early Holocene age (Preboreal, Boreal and Atlantic) of the deposits. Shells reworked from older deposits indicate Allerød and Younger Dryas ages. Bivalves, gastropods and barnacles are common and well preserved in the muddy prodelta deposits, whereas they are uncommon and poorly preserved in the delta slope sands. Faunal composition of the delta slope sands is numerically characterised by suspension-feeding endobenthos that have moderate to fast burrowing ability. The fossil macrofauna of the muddy prodelta deposits, on the other hand, can be much more diverse, including mobile to stationary endobenthos and epibenthos. The prodelta muds were close to normal marine in their salinity. The delta slope sands were probably somewhat brackish, while the topsets were formed in fluvial freshwater. Faunal composition indicates water depth of the ancient habitat having been equivalent to nearshore shelf to fjord-deltaic setting. A fjord-deltaic setting is evident by the sedimentology and adjacent steep topography. We conclude that the fossil macrofauna is in composition comparable with modern marine communities of the high-boreal province. • Key words: molluscs, barnacles, radiocarbon, geochemistry, depositional conditions, benthic communities, bioprovinces.

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Fjord systems are abundant along the present coast of northern Norway, as confinements outlined by steep topography. Clastic sediments are formed by erosion of these mountains and transported by rivers into deltaic depositional systems within the fjords becoming redistributed by waves and tidal currents. The deltaic setting is characterised by varying environmental conditions in forms of river water charge, tide and waves. Such stressful conditions of short-term fluctuations in sedimentation, salinity and temperature affect the living animals (*e.g.* Hedgpeth 1957, Boesch & Rosenberg 1981) and their past variations are reflected in faunal remains from ancient deltaic successions. Early Holocene successions, exposed in river sections

along Breivikelva and Nakkeelva in the Troms County, North Norway (Fig. 1), have previously been investigated for sedimentology (*e.g.* Møller *et al.* 1986, Corner & Fjalstad 1993, Nielsen *et al.* 2004, Evison 2012). Previous faunal investigations from these deposits have focused only on the microstructural and incremental chronologies obtained from *Arctica islandica* shells unearthed from Preboreal section in one of the successions (Helama *et al.* 2014, 2015). A much broadened view is, however, required to understand the development of faunal communities through the early Holocene variations demonstrated for the physical environment of this setting (Nielsen *et al.* 2004, Evison 2012). To this end, the successions containing

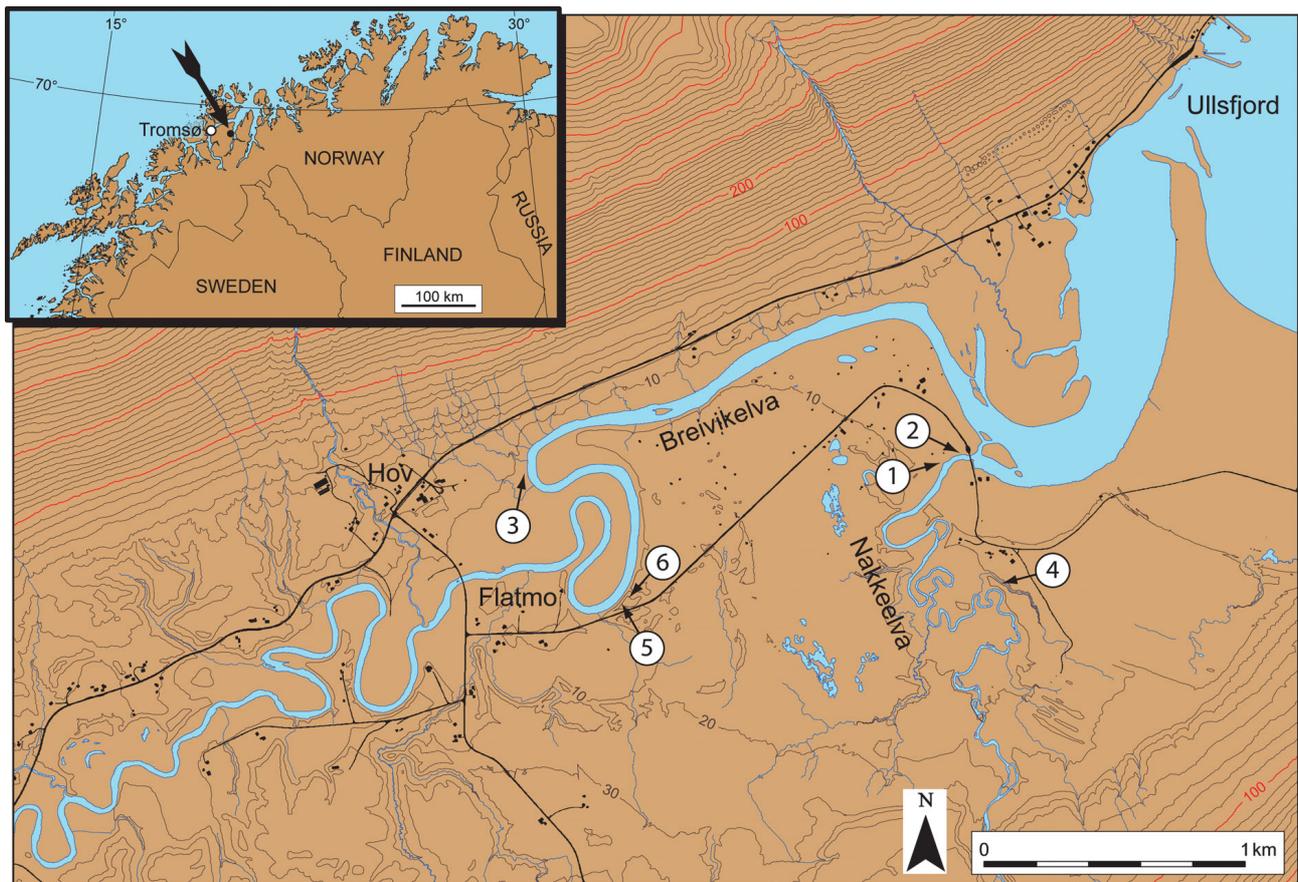


Figure 1. Topographical map of the study area in the Troms County, North Norway. The main river is Breivikelva, with its tributary Nakkeelva. Investigated localities in the Breivikeidet area are indicated by numbers. Contour lines 10 m. Modified from Helama *et al.* (2014). Numbers and arrows indicate positions of the six localities studied.

macrofaunal skeletal remains are investigated in detail for the first time herein. The remains are from species that still have modern representatives of which the living conditions are well known. Close comparisons with the modern communities can provide us new knowledge about the biotic and abiotic parameters of the early Holocene fjord-deltaic system in the Breivikeidet area of Troms County.

Geological setting

Previous studies

Breivikeidet is a valley extending from the Ramfjord in southwest to the Ullsfjord in northeast (Fig. 1). Steep mountains confine Breivikeidet to the northwest, while lower and less steep mountains are present to the southeast. A marginal moraine, Ramfjordmoen, is in the southwest end of the Breivikeidet Valley (Andersen 1968, Møller *et al.* 1986, Dagestad *et al.* 2006). The valley deposits comprise mainly late Quaternary outwash plain (valley train) and fluvial and marine deposits (Holmes & Andersen

1964, Andersen 1968). Aerial photographs of the delta plain show a mosaic of abundant distributary channels and interchannel environments dominated by flood plains and bogs. The presence of remains that represent terrestrial vegetation in these delta sediments indicates that the hinterland also was vegetated during early Holocene.

The Weichselian and Holocene sediments have been subjected to post-glacial isostatic uplift and are exposed in river sections along Breivikelva and its tributaries. Subsequent to the ice sheet had melted away from the area; the sea level was higher than its present level. Ancient shorelines and their displacement curves in Troms county have been constructed by Pettersen (1880), Marthinussen (1962), Andersen (1968), Corner (1980), Hald & Vorren (1983), Møller (1987, 1989) and Corner & Haugane (1993). The displacement curve nearest to Breivikeidet originates from the Lyngen area (Corner & Haugane 1993), 15 km northeast of the study area, the Lyngen being characterised by slightly lower isobases than the Breivikeidet. We estimate a need of an adjustment of approximately 1 m for the latter. A rapid pre-Tapes regression of about 10–15 mm/yr (before 8,500 ¹⁴C years BP)

was followed by the Tapes transgression (Corner & Haugane 1993). The transgression reached maximum at about 7,000 ¹⁴C years BP in the Lyngen area, where the sea-level rise was at least 2–3 m at the time. A slow post-Tapes regression, which occurred after 6,000 ¹⁴C years BP because of a glacio-isostatic rebound, had a rate of about 1.5–3 mm/yr (Corner & Haugane 1993). Because of the continued rebound, the rivers proceeded to erode into older fluvial and marine deposits.

At Breivikeidet, a river section through steep-faced fjord delta deposits were previously investigated ichnologically by Corner & Fjalstad (1993), about 750 m NNE from our locality 3 (Fig. 1). A radiocarbon date of 9,060±80 years BP (T-6027) was determined for *Macoma calcarea* in bottomset beds 1 m above river level. Making use of regional sea-level displacement curves and shoreline diagrams, Corner & Fjalstad (1993) interpreted the sea level to have been 30–35 m higher than its present level and, therefore, the depositional water depth of the bottomsets having been approximately 30 m.

Ground penetrating radar (GPR) profiles and two wells penetrating the sediments at the Hov waterworks (Hilmo 2011) are located approximately 500 m west from our locality 3 (Fig. 1). An upper unit of dipping layers comprises sand, gravel and stones was identified, overlaying the lower unit of horizontally layered mud, the unit transition found 5–12 m below the ground level (Hilmo 2011). The GPR measurements were unable to map the total sediment thickness that reach at least 70 m in the middle of the valley (Hilmo 2011). Building on Corner & Fjalstad's (1993) data, the coarse-grained unit is probably fjord-delta foresets and topsets, while the mud unit represents prodelta deposits.

Studied localities

The six localities of this study are all river sections along Breivikelva and its tributary Nakkeelva (Fig. 1), positioned at 69.65663° N, 19.62355° E (locality 1); 69.65664° N, 19.62430° E (locality 2); 69.65700° N, 19.58086° E (locality 3); 69.65204° N, 19.62648° E (locality 4); 69.65229° N, 19.58889° E (locality 5); and 69.65257° N, 19.58963° E (locality 6); based on the Norwegian Mapping Authority (<http://www.norgeskart.no>).

Sedimentological description

The sedimentary successions of these localities show a spatial complexity in their architecture of bottomsets, foresets and topsets (Figs 2–6). The bottomsets, which are gently inclined (less than 10°), are well exposed in our localities 1, 2 and 3. The bottomsets are characterised by massive, bioturbated or laminated mud, which may be interbedded by

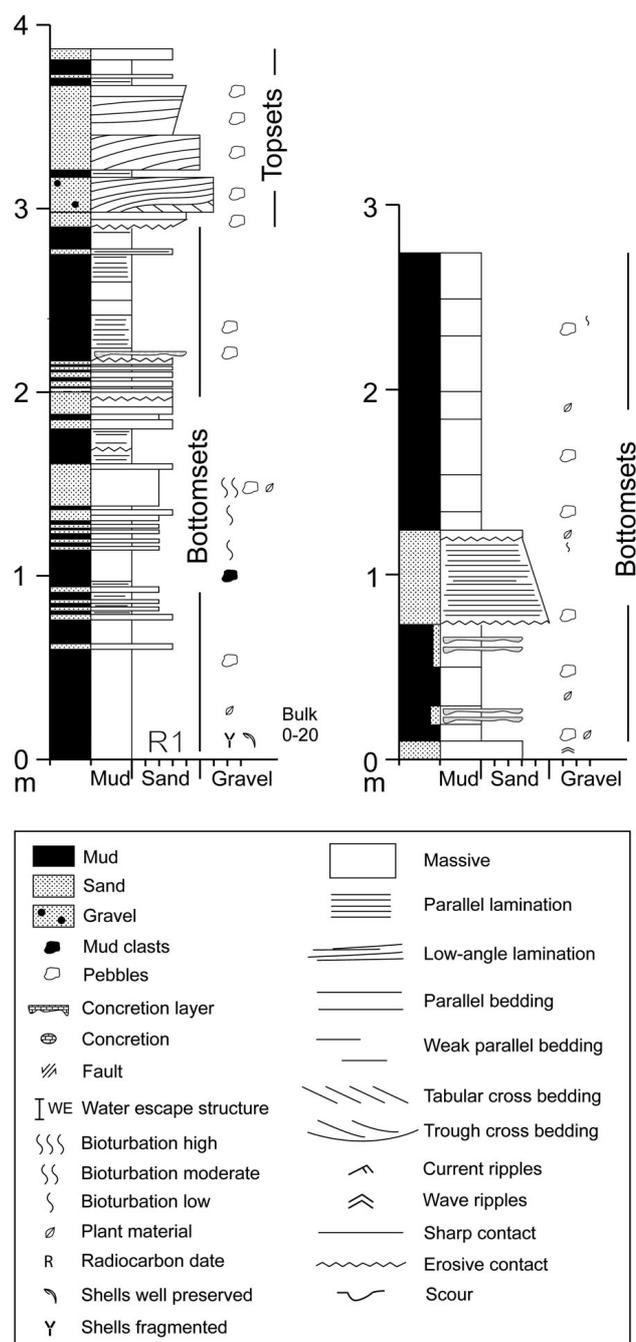


Figure 2. Sedimentological logs of the localities 1 and 2 showing the stratigraphical positions of bulk sediment samples and radiocarbon sample. Measured from 0.5 m above mean sea level.

thin sandy beds (e.g. locality 6). The sand is up to medium in grain size. The bottomsets are characterised by vertical transition into foresets (e.g. locality 5) or topsets (locality 3). The foresets are well exposed in our localities 4, 5 and 6. The foresets are dipping up to 15° and generally more coarse-grained than the bottomsets. Bed thickness in the foresets is up to more than 2 m. Massive beds are sandy

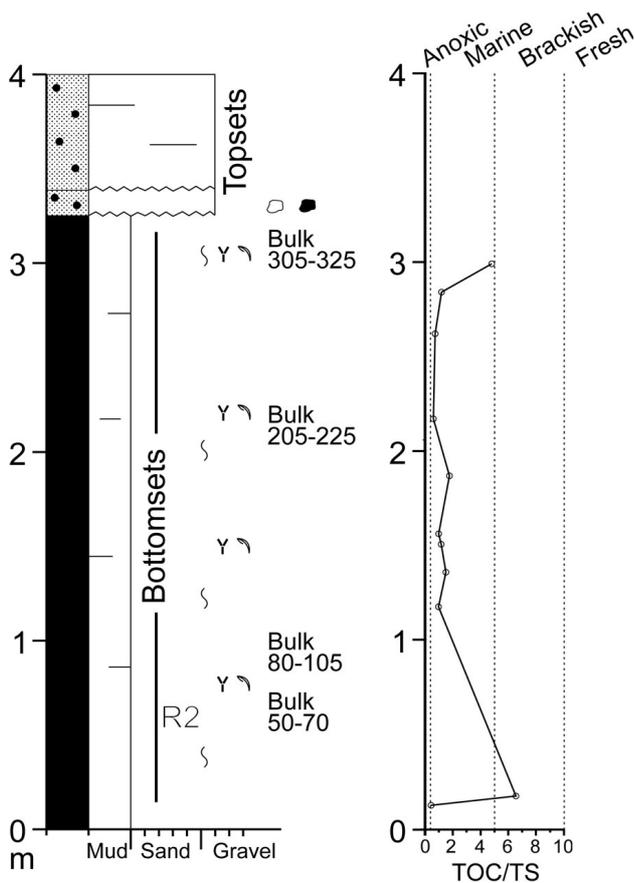


Figure 3. Sedimentological log of the locality 3 showing the stratigraphical positions of bulk sediment samples and radiocarbon sample. Measured from 1 m above mean sea level. Modified from Helama *et al.* (2014).

to gravely (*e.g.* localities 4 and 5). Parallel to low angle lamination in beds of silt to medium sand are characteristic to locality 5, in particular. Current ripples and scours are also present in the foresets. The foresets are unconformably truncated by nearly horizontal topsets characterised by coarse-grained sediment, typically sand to fine gravel. There are massive beds and beds with trough cross-bedding with garnet sand, parallel to low angle lamination and current ripples (*e.g.* localities 4, 5 and 6).

Sedimentary environment

The sediments make up bottomsets, foresets and topsets well known from deltas (*e.g.* Scruton 1960). The bottomset mud was deposited predominantly by suspension fallout on a low-angle prodelta. The thin sandy beds may have originated from high-energy sediment gravity flows. Gently dipping bottomsets and steeper foresets are known from steep-faced fjord deltas in North Norway (Corner *et al.* 1990, Corner & Fjalstad 1993, Eilertsen *et al.* 2011). Depositional processes of bottomsets on such fjord deltas may have been down into

44.5 m deep water and possibly deeper (Eilertsen *et al.* 2011). As an analogue for the deltaic setting, we have used the nearby locality of Corner & Fjalstad (1993).

The foresets were mainly formed by cohesion-less debris flows (grain flows). The current ripples and scours indicate traction currents. Depositional processes forming the foresets were most likely initiated by storms and tide causing mixing of the water column. Submarine channelized sand is recognised in locality 5 SW (710–1105 cm; Fig. 5), indicating genetic complexity of the foresets. Lateral shift away of a distributary channel can be represented by the fine-grained interval below (565–710 cm). Some beds within the foresets of locality 5 NE (Fig. 5) have been deformed by liquefaction and show related slumping and sliding. The topsets are characterised by coarse-grained sediment and trough to planar cross-bedding, related to fluvial bedload. The topsets unconformably truncating the foreset beds are also known from the locality of Corner & Fjalstad (1993).

Continued sediment supply from Breivikelva River has resulted in a shoreline progradation producing the fjord-head delta. The shoreline has prograded since early Holocene, with the coarser material being deposited near the river mouth while the finer sediments are transported further away and being deposited from suspension as bottomsets and offshore sediments.

Material and methods

Field observations and bulk samples form the basis for the present study of the fossil macrofauna (Tab. 1). Bulk samples of 10 litres were dried before being gently washed through a set of sieves of 1–2, 2–4, 4–8, 8–16, and > 16 mm. Where the sediment contained little shell material, additional 10 litres of sediment were taken and processed (bulk sample 0–25 cm in locality 4). Sediment retained on the sieve was dried, shell material was hand-picked and examined from each size fractions. The number of valves and fragments was counted. The following bulk samples did not contain identifiable shell material: 477–504 cm, 548–567, 625–645, 1103–1130, 1260–1278, 1380–1410, 1469–1487 (locality 4), 1000–1015 (locality 6). These were not processed further.

Well preserved valves were sent for accelerator mass spectrometry (AMS) radiocarbon dating. The dates R1, R3, R4, R5, R6 and R7 are based on single valves of *Macoma calcarea*, whereas R8 and R9 were derived from multiple valves of the same species (Tab. 2). The dates R2a–e represent single valves of *Arctica islandica* from locality 3 (Helama *et al.* 2014). A set of *Arctica islandica* shells from locality 3 was previously analysed for their concentration of uranium, but the levels were insufficient to be exploited in U-series dating (Helama *et al.* 2015). As

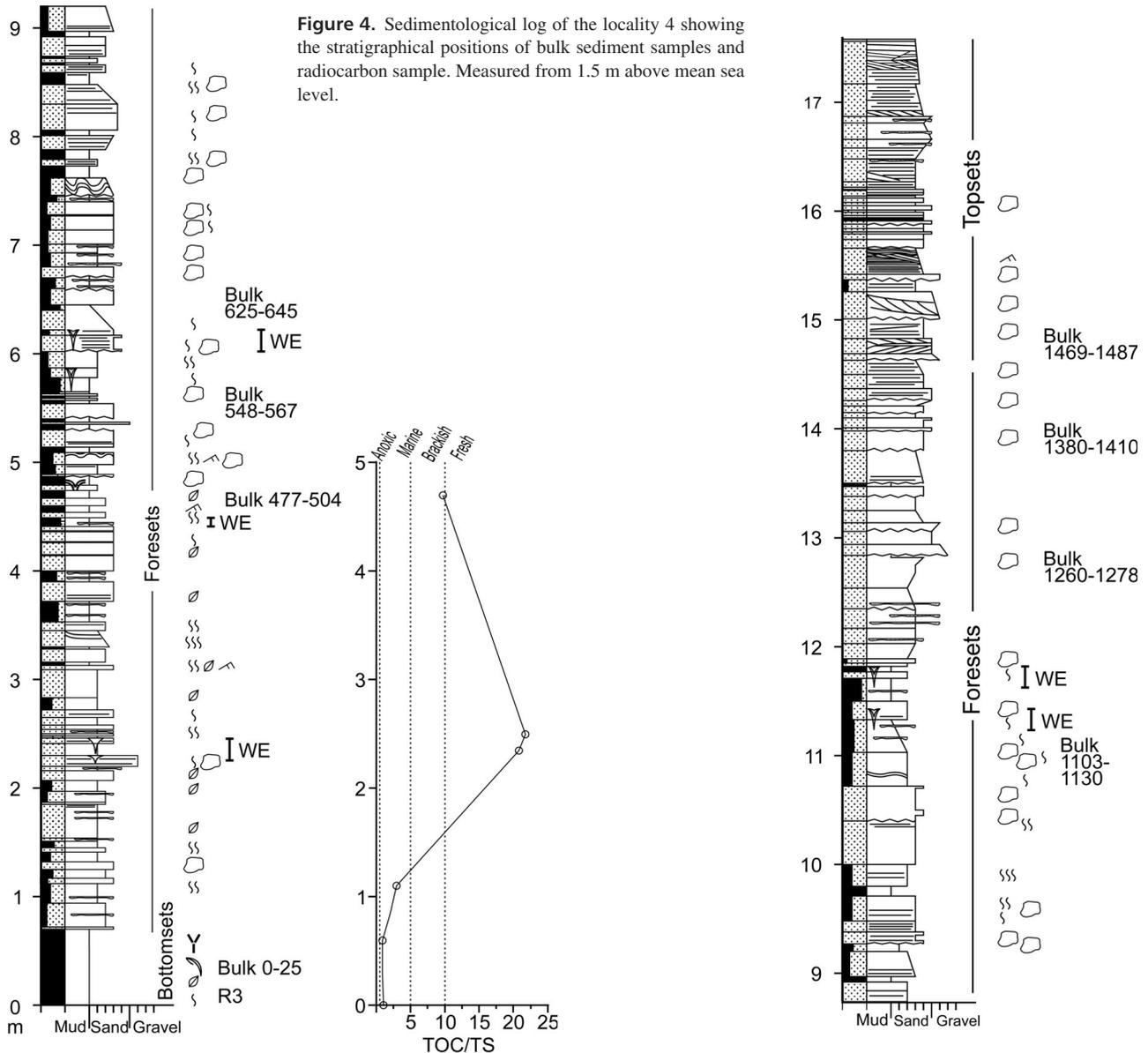


Figure 4. Sedimentological log of the locality 4 showing the stratigraphical positions of bulk sediment samples and radiocarbon sample. Measured from 1.5 m above mean sea level.

a result, the ^{14}C method appeared the most accurate method for dating this shell material. The calculation programme OxCal version 4.2 (2013) by Bronk Ramsey (2009) was applied together with the calibration curve Marine13 from Reimer *et al.* (2013). The radiocarbon dates were corrected for local reservoir effect by using the Marine Reservoir Correction Database (<http://radiocarbon.pa.qub.ac.uk/>), $\Delta R 65 \pm 37$ years based on the T-1534 date of the suspension-feeding bivalve *Chlamys islandica* (Mangerud & Gulliksen 1975; see Craig 1954, Mangerud 1972, Mangerud *et al.* 2006). The fjord delta succession locally contains terrestrial plant remains, which suggests that the waters during deposition contained some old carbon. Feeding bivalves may have incorporated old carbon into the shells and this could result in somewhat older dates

(Mangerud *et al.* 2006). Radiocarbon dates herein are from both suspension-feeders (*Arctica islandica*) and surface deposit-feeders (*Macoma calcaea*); the latter appears more likely to yield older ages of which we, however, have no evidence. Calendar ages are in Gregorian years before mid AD 1950.

Individual shell pieces were scored by visualising them for the taphonomical features of abrasion, bioerosion, disarticulation, dissolution, encrustation and fragmentation to assess their preservation. For this, the three-level scheme of taphonomical grades by Kowalewski *et al.* (1995) was used. The grades with 0, 1 and 2 levels refer to none, low and high alteration, respectively. Grade 2 means that more than 20% shell surface has been altered, with an exception of 50%, for fragmentation.

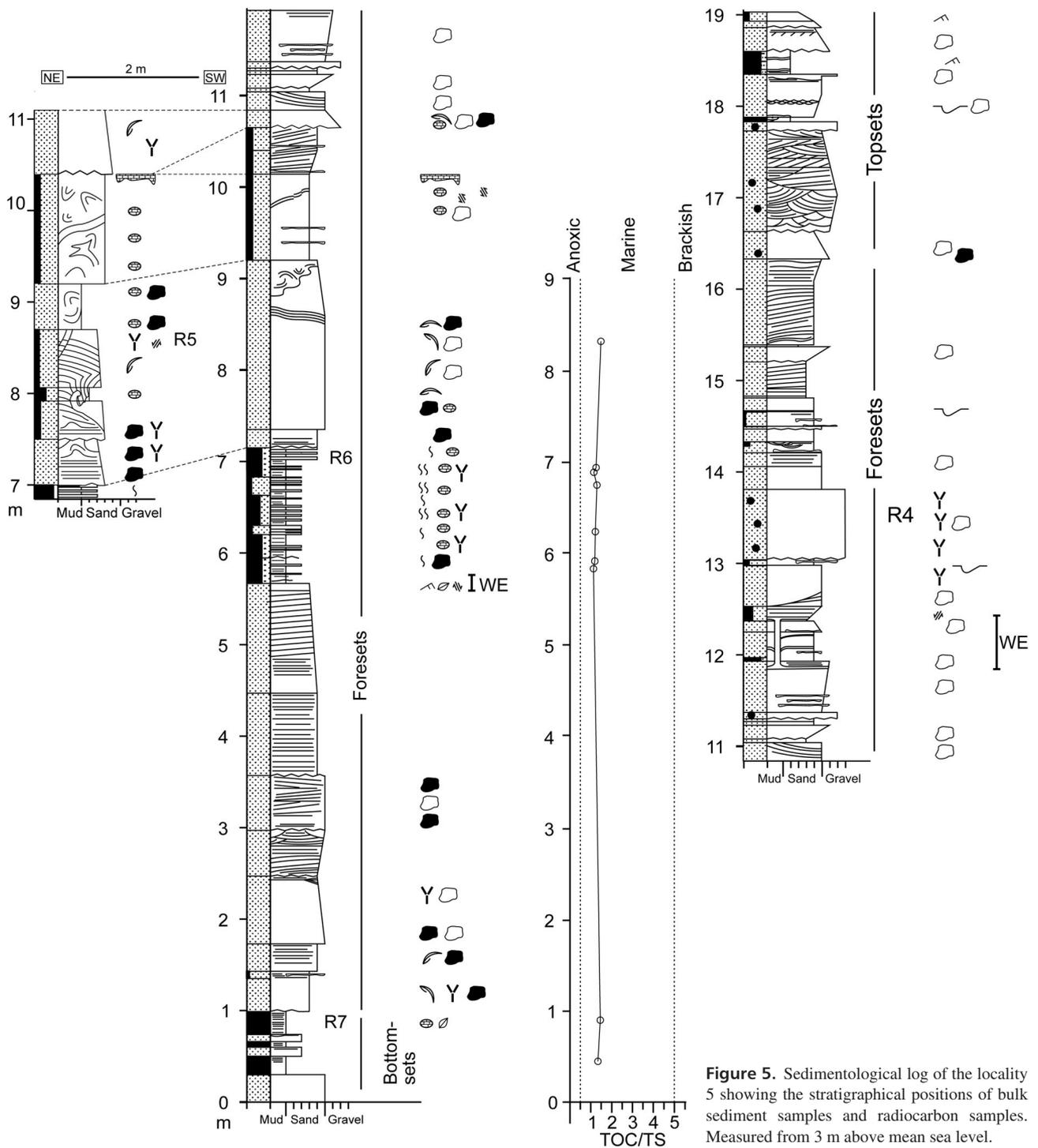


Figure 5. Sedimentological log of the locality 5 showing the stratigraphical positions of bulk sediment samples and radiocarbon samples. Measured from 3 m above mean sea level.

Twenty-eight samples from silty clay in the localities 3, 4 and 5 (Figs 3–5) were analysed for contents of total carbon (TC), total sulphur (TS) and total organic carbon (TOC), for indications of bottom water oxygenation and salinity during deposition (Bernier & Raiswell 1984, Leventhal 1995, Morse & Bernier 1995). The samples were dried at 40 °C, crushed to fine powder, and dried at 65 °C

for a minimum of 12 hours. An amount of 0.3–0.4 g of crushed sample was usually used, while the weight of shell-rich samples was increased to 0.6 g for TOC analyses, in order to compensate for weight lost during double acidic treatment with 3 ml warm 2 M HCl. Prior to analysis, the samples were rinsed repeatedly with distilled water to remove any acid remains and CaCl₂ formed during the acid

treatment. The instrument LECO CS-200 was calibrated against LECO standards, blank samples and the international standard 501–506 STD. Also the international standard LKSD-1 consisting of lake sediments from Joe Lake and Brady Lake, Ontario, USA, was used (Lynch 1990). The instrumental precision is 2 ppm or 0.5% standard deviation for carbon, and 2 ppm or 1.5% for sulphur, or what is largest.

Results

Fossil macrofauna

Molluscs and barnacles were determined after the literature cited elsewhere herein, in addition to Petersen (2001), Petersen (2004) and Darwin (1854b). The macrofauna comprises particularly shell remains of bivalves (Tab. 1). Barnacles and gastropods are less common, and remains of regular sea urchins are rare.

The shell abundance and diversity are moderate to high in the fine-grained intervals of the bottomsets (Tab. 1). Shells of *Macoma calcarea* are common or even abundant in the bottomsets and fine-grained foresets. *Mya truncata* is also present in the samples, albeit in smaller amount. We acknowledge the long-lasting discussion on *M. truncata* shell morphology, to distinguish possible forms and species (e.g. Jensen 1901, Jensen & Spärck 1934, Petersen 1999), and note that most of our shells are of similar form to recent specimens of *M. truncata*, characteristic of the European boreal province; for example, *M. truncata* forma typica and *M. truncata* as described by Jensen (1901) and Petersen (1999), respectively. Some of the large valves from locality 3 (80–105 cm) show a morphological continuum towards a shorter pallial sinus. We also note that the juvenile valves from the study area have a larger posterior end that is less truncated than observed in the adults (see Jensen 1901, Oliver et al. 2016).

Abra nitida and *Abra* sp. are common in samples from the fine-grained intervals of bottomsets (Tab. 1). We concur with Jensen & Spärck (1934) who found small specimens of *Abra nitida* to be hardly differentiated from another species, *Abra alba*. As a consequence, these specimens have here been assigned to *Abra* sp. *Arctica islandica*, cardiid indet. and *Mytilus edulis* are other major taxa to occur in our samples (Tab. 1). The shell preservation is generally good in the fine-grained sediments, where articulated shells and skeletal parts may be present with periostracum and ligament (Figs 7–9). Both small and large shells of bivalves are present.

At locality 3 (80–105 cm), the bottomsets contain several valves of *Arctica islandica*, *Astarte elliptica*, *Hiatella arctica*, *Mya truncata*, *Mytilus edulis* and *Panomya norvegica*, which are articulated and large in size. There are also incredibly well preserved, large valves of *Chlamys*

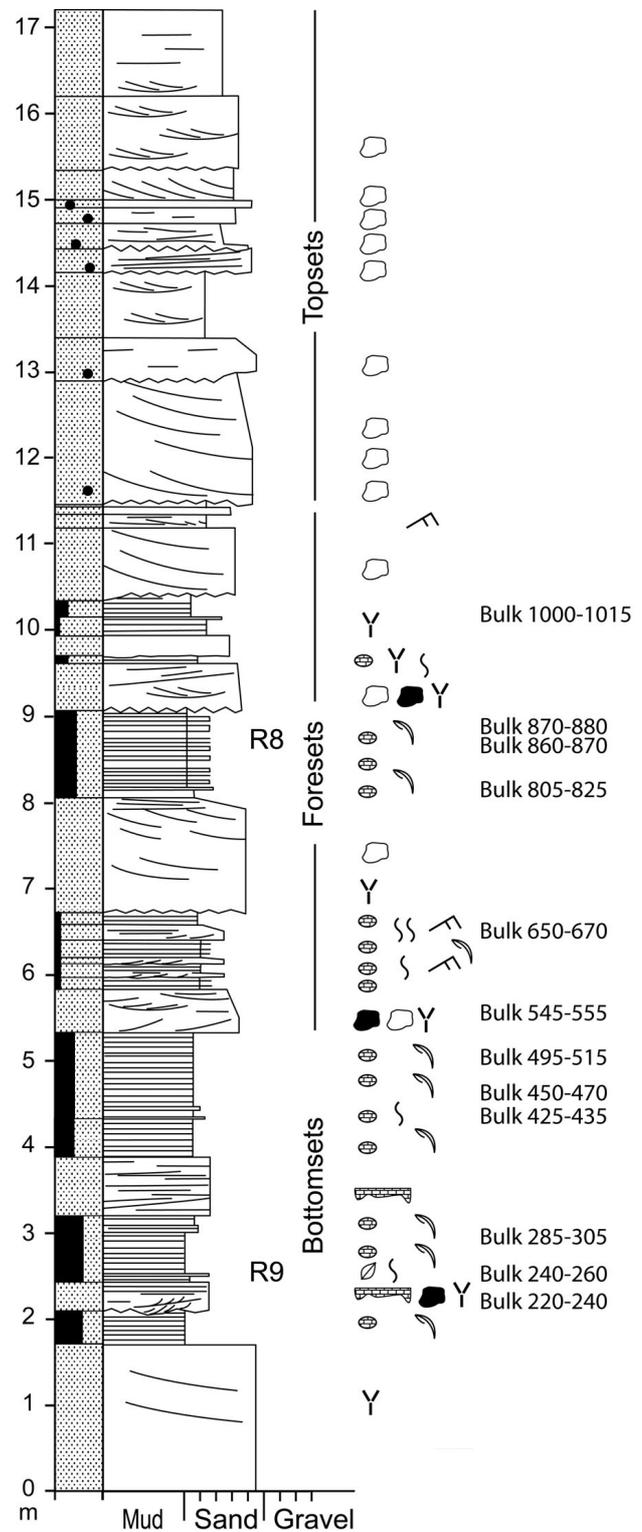


Figure 6. Sedimentological log of the locality 6 showing the stratigraphical positions of bulk sediment samples and radiocarbon samples. Measured from 1 m above mean sea level.

Table 1. Invertebrate macrofossils in the examined bulk samples. Numbers indicate the amount of individual valves. Numbers in brackets are for fragments.

Locality	Loc. 1	Loc. 3	Loc. 3	Loc. 3	Loc. 3	Loc. 3	Loc. 4	Loc. 6	Loc. 6
Level (cm)	0–20	50–70	80–105	H80–105	205–225	305–325	0–25	220–240	240–260
GASTROPODA									
<i>Boreotrophon clathratus</i> (Linnaeus, 1767)	–	–	2 (3)	1	–	–	–	–	–
<i>Buccinum undatum</i> Linnaeus, 1758	–	–	–	2	–	–	–	–	–
<i>Cylichna</i> sp.	2 (1)	–	2	–	3	–	–	–	–
<i>Lepeta caeca</i> (Müller, 1776)	–	–	1	–	–	–	–	–	–
<i>Littorina littorea</i> (Linnaeus, 1758)	–	–	–	–	–	–	(1)	(2)	–
Littorinid indet.	–	–	2	–	–	–	1 (1)	–	–
Nassariid indet.	–	–	(1)	–	–	–	–	–	–
Naticid indet.	1	–	(1)	2	–	–	1	–	–
<i>Neptunea despecta</i> (Linnaeus, 1758)	–	–	–	4	–	–	–	–	–
Turrid indet.	–	–	1	–	–	–	–	–	–
BIVALVIA									
<i>Abra nitida</i> (Müller, 1776)	–	–	12	2	29	2	–	2	2
<i>Abra</i> sp.	–	6	17 (3)	–	19 (3)	3	–	–	–
<i>Acanthocardia echinata</i> (Linnaeus, 1758)	–	–	1 (4)	–	? 1	–	–	–	3 (8)
Anomiid indet.	–	–	6	2	–	–	–	–	–
<i>Arctica islandica</i> (Linnaeus, 1767)	1	–	42 (31)	13 (2)	–	–	3 (1)	–	–
<i>Astarte borealis</i> (Schumacher, 1817)	–	–	4 (3)	–	–	–	–	–	–
<i>Astarte elliptica</i> (Brown, 1827)	–	–	16 (23)	2	–	–	–	–	–
<i>Astarte</i> sp.	(1)	–	3 (2)	–	–	–	–	–	–
<i>Axinopsida orbiculata</i> (Sars, 1878)	2	–	2	–	1	–	4 (2)	–	–
Cardiid indet.	3 (7)	2 (1)	16 (48)	–	1	–	4 (20)	–	1 (2)
<i>Cerastoderma edule</i> (Linnaeus, 1758)	3	–	11 (2)	1	1 (1)	–	–	–	2
<i>Chlamys islandica</i> (Müller, 1776)	–	–	1 (4)	29 (4)	–	–	–	–	–
<i>Crenella decussata</i> (Montagu, 1808)	2	–	138 (102)	4	–	1	9 (1)	–	–
<i>Hiatella arctica</i> (Linnaeus, 1758)	–	–	15 (16)	6	–	–	–	–	–
<i>Macoma balthica</i> (Linnaeus, 1758)	–	–	–	–	–	–	–	–	–
<i>Macoma calcarea</i> (Gmelin, 1791)	65 (25)	42 (13)	578 (259)	45 (7)	92 (20)	33 (12)	136 (83)	7 (6)	68 (84)
<i>Mya truncata</i> Linnaeus, 1758	7 (4)	3	52 (87)	36 (3)	9 (1)	1 (3)	42 (12)	–	5 (9)
<i>Mytilus edulis</i> Linnaeus, 1758	1 (2)	–	2 (78)	2	(10)	(3)	–	–	–
<i>Nucula</i> sp.	1	2	1	–	1 (1)	–	–	–	(1)
<i>Nuculana pernula</i> (Müller, 1779)	–	–	24 (23)	–	2	–	–	–	–
<i>Panomya norvegica</i> (Spengler, 1793)	–	–	–	3	–	–	–	–	–
<i>Parvicardium exiguum</i> (Gmelin, 1791)	–	–	–	–	–	–	–	–	2
<i>Parvicardium minimum</i> (Philippi, 1836)	–	–	–	–	–	–	–	–	–
Pectinid indet.	–	–	–	–	–	–	–	–	–
<i>Phaxas pellucidus</i> (Pennant, 1777)	–	–	–	–	–	–	–	–	–
<i>Similipecten greenlandicus</i> (Sowerby II, 1842)	–	–	–	–	–	–	–	1 (5)	–
<i>Thyasira sarsii</i> (Philippi, 1845)	2 (1)	2	–	–	1 (1)	1 (1)	11 (4)	–	–
<i>Yoldiella lenticula</i> (Möller, 1842)	11	3	12 (6)	–	–	2	3	1	–
CIRRIPEDIA									
<i>Balanus balanus</i> (Linnaeus, 1758)	–	–	16 (7)	54 (7)	–	–	–	–	–
<i>Balanus crenatus</i> Bruguière, 1789	–	–	6 (3)	–	–	–	–	(2)	–
<i>Balanus</i> sp.	–	–	3 (27)	–	–	–	–	(17)	–
<i>Verruca stroemia</i> (Müller, 1776)	–	–	–	–	–	–	–	–	–
ASSORTED									
Brown tubes indet.	–	–	–	–	–	–	–	–	–
Sea urchin skeletal parts indet.	–	–	2	–	–	–	–	–	–

Table 1. continued.

Locality	Loc. 6	Loc. 6	Loc. 6	Loc. 6	Loc. 6	Loc. 6	Loc. 6	Loc. 6	Loc. 6
Level (cm)	285–305	425–435	450–470	495–515	545–555	650–670	805–825	860–870	870–880
GASTROPODA									
<i>Boreotrophon clathratus</i> (Linnaeus, 1767)	–	–	–	–	–	–	–	–	–
<i>Buccinum undatum</i> Linnaeus, 1758	–	–	–	–	–	–	–	–	–
<i>Cylichna</i> sp.	–	–	–	–	–	–	–	–	–
<i>Lepeta caeca</i> (Müller, 1776)	–	–	–	–	–	–	–	–	–
<i>Littorina littorea</i> (Linnaeus, 1758)	–	2	–	–	–	7 (4)	3 (14)	(8)	–
Littorinid indet.	3 (8)	–	–	–	–	–	–	–	–
Nassariid indet.	–	–	–	–	–	–	–	–	–
Naticid indet.	–	–	–	–	–	–	–	–	–
<i>Neptunea despecta</i> (Linnaeus, 1758)	–	–	–	–	–	–	–	(1)	–
Turrid indet.	–	–	–	–	–	–	–	–	–
BIVALVIA									
<i>Abra nitida</i> (Müller, 1776)	3	1 (2)	(15)	–	–	–	–	–	–
<i>Abra</i> sp.	–	–	–	–	–	–	–	–	–
<i>Acanthocardia echinata</i> (Linnaeus, 1758)	–	1 (8)	1	–	–	–	–	–	–
Anomiid indet.	–	–	–	–	–	–	–	–	–
<i>Arctica islandica</i> (Linnaeus, 1767)	–	–	–	–	–	–	–	–	–
<i>Astarte borealis</i> (Schumacher, 1817)	–	–	–	–	–	–	–	–	–
<i>Astarte elliptica</i> (Brown, 1827)	–	–	–	–	–	–	–	–	–
<i>Astarte</i> sp.	–	–	–	–	–	–	–	–	–
<i>Axinopsida orbiculata</i> (Sars, 1878)	–	–	–	–	–	–	–	–	–
Cardiid indet.	–	4	5	–	1 (11)	–	–	2	1
<i>Cerastoderma edule</i> (Linnaeus, 1758)	–	3	–	–	1 (3)	–	–	(7)	3 (9)
<i>Chlamys islandica</i> (Müller, 1776)	–	–	–	–	–	–	–	–	–
<i>Crenella decussata</i> (Montagu, 1808)	–	–	–	–	–	–	–	–	–
<i>Hiatella arctica</i> (Linnaeus, 1758)	–	–	–	–	–	–	–	–	–
<i>Macoma balthica</i> (Linnaeus, 1758)	–	–	8 (1)	–	–	–	2	1 (1)	1 (2)
<i>Macoma calcarea</i> (Gmelin, 1791)	2 (4)	47 (102)	129 (101)	(2)	(11)	(1)	(10)	–	4 (20)
<i>Mya truncata</i> Linnaeus, 1758	1 (1)	26 (37)	42 (79)	2 (1)	2 (46)	–	(9)	–	1 (10)
<i>Mytilus edulis</i> Linnaeus, 1758	(3)	2 (12)	1	–	–	(33)	(148)	(12)	(2)
<i>Nucula</i> sp.	–	1?	–	–	–	–	–	–	–
<i>Nuculana pernula</i> (Müller, 1779)	–	–	2	–	–	–	–	–	–
<i>Panomya norvegica</i> (Spengler, 1793)	–	–	–	–	–	–	–	–	–
<i>Parvicardium exiguum</i> (Gmelin, 1791)	–	–	–	–	–	–	–	–	–
<i>Parvicardium minimum</i> (Philippi, 1836)	–	(2)	–	–	–	–	–	–	–
Pectinid indet.	–	–	–	–	–	–	2	–	1
<i>Phaxas pellucidus</i> (Pennant, 1777)	–	–	1	–	–	–	–	–	–
<i>Similipecten greenlandicus</i> (Sowerby II, 1842)	(4)	1	–	–	–	–	–	–	–
<i>Thyasira sarsii</i> (Philippi, 1845)	2?	–	–	–	–	–	–	–	–
<i>Yoldiella lenticula</i> (Möller, 1842)	4 (9)	1	–	–	–	–	–	–	–
CIRRIPEDIA									
<i>Balanus balanus</i> (Linnaeus, 1758)	–	–	–	–	–	1	–	1	–
<i>Balanus crenatus</i> Bruguière, 1789	(2)	–	1	–	–	7	4 (4)	2	–
<i>Balanus</i> sp.	2 (23)	2	2	(2)	3 (8)	4	2 (9)	(12)	2
<i>Verruca stroemia</i> (Müller, 1776)	–	–	1	–	–	–	–	(5)	–
ASSORTED									
Brown tubes indet.	1	–	–	–	–	4	2	–	–
Sea urchin skeletal parts indet.	–	–	2	–	–	–	–	–	–

islandica onto which *Balanus balanus*, an acorn barnacle, may occur abundantly. The presence of this barnacle is evident only on outer shell surfaces, indicating encrustation while the bivalves were alive. Specimens of *B. balanus* rarely contain *Hiatella arctica* that lived inside them. The same interval holds some large shells of *Buccinum undatum* and *Neptunea despecta*.

The coarse-grained intervals of the foresets are characterised by much lower quantity and diversity of shells. Shell fragments are scarce and most of them are unidentifiable. *Macoma calcarea*, *M. balthica* and cardiid indet. have been found. Field observations showed that the shell material in the coarse-grained foresets at the localities 5 and 6 is considerably more fragmented than in bottomsets and fine-grained foresets (Fig. 9). The shell material is characterised by various grades of dissolution. *Mytilus edulis* is particularly affected by fragmentation and dissolution, and the shells from the coarse-grained foresets are commonly preserved as loosely attached fibrous prisms from the calcite shell layer, purple in colour (see Nielsen 2004). Some of the prisms may originate from another mytilid, *Modiolus modiolus* (see Anwar *et al.* 1990); however, all identified fragments indicate *Mytilus edulis*. Irregular flakes of aragonitic nacre are rare and might derive from *Mytilus edulis*. Cardiid indet. and fragments of unidentifiable specimens occur sporadically and differ from those of *Mytilus edulis* by their chalky appearance that results from dissolution.

Contrary to the bottomsets and foresets, the topsets are barren of macrofaunal fossils.

Radiocarbon dates

Radiocarbon dating of shell material assigned to *Macoma calcarea* gave eight calibrated ages (Tab. 2). The youngest mean ages are 6,374 and 6,406 years cal BP in the lowermost part (bottomsets) of the localities 1 and 4, respectively (Figs 2, 4). The confidence ranges of these dates of Atlantic time overlap with each other. The other ages are at least 4,000 years older. Five valves of *Arctica islandica* from the bottomsets in the lower part of locality 3 gave a mean of 10,878 to 11,005 years cal BP, indicating Preboreal (Tab. 2; Helama *et al.* 2014).

Four dates are available for the locality 5. The date R7 is 10,440 years cal BP (Preboreal) for bottomsets in the lowest part of the succession. The dates R6, R5 and R4 are from different levels in the overlying foresets. R6 is 10,606 years cal BP (Preboreal). R5 and R4 are 13,167 and 11,779 years cal BP indicating Allerød and Younger Dryas, respectively. Considering their confidence ranges (Tab. 2), they are stratigraphically inconsistent with the dates R7 and R6 sampled from deeper levels. From locality 6, R9 and R8 show ages of 10,580 and 10,734 years cal BP.

The confidence ranges overlap partially each other with consistent indication of Preboreal time.

LECO values

At locality 3, the TOC values of 11 samples range from 0.092 to 0.172 weight % (Figs 3, 10A, Tab. 3). The TS values are between 0.014 and 0.606 weight %. The stratigraphical trends in the values are generally smooth. However, the TS value from the stratigraphical level 12 cm is much higher than at the other sampled levels. At locality 4, the eight geochemical samples were taken from the sparse occurrence of clay-rich layers suitable for LECO analysis (Fig. 10B, Tab. 3). The TOC values are between 0.109 and 0.702 weight %, while the TS values range from 0.008 to 0.766 weight %. Stratigraphically, the trends in TOC and TS values resemble each other, decreasing upwards in the succession (Figs 4, 10B). At locality 5 (Fig. 10C), the TOC values vary between 0.091 and 0.15 weight %, and the TS values between 0.068 and 0.126 weight %, the TOC and TS values thus following each other through the section (Figs 5, 10C, Tab. 3).

Discussion

Shell preservation

Overall, the succession is coarsening upwards due to shallowing during the delta progradation into the fjord. The higher hydrodynamical energy during the shallowing time can thus explain the parallel trend towards poorer shell preservation (Fig. 9). The transportation of shell material caused mechanical destruction depending on the mechanism and the hydrodynamical energy level, in relation to shell morphology and microstructural strength (*e.g.* Nielsen 2004). Seaward transport of shells, wrack (*Fucus*), gravel and pebbles away from the shore is a process evident for the recent fjord system of Troms County (Kiær 1902, 1908). Dredging the deep parts of the fjords reveals mud with shells derived from shallower waters (*e.g.* *Mytilus edulis*, *Cerastoderma edule*), and large quantities of wrack with shallow-water animals (Kiær 1908). This transport is by wave activity and the strong tidal current that regularly occurs through the fjords (Kiær 1908). This is also the case for the present Ullsfjord off Breivikeidet. Incorporation of material into ice flakes, which drift out onto the fjords and melt, is another transport mechanism (Kiær 1902). Similar transport processes plausibly existed in the study area during early Holocene.

Reworking and associated time-averaging (*e.g.* Kidwell & Bosence 1991, Flessa & Kowalewski 1994) are evident from radiocarbon dates indicating older shells

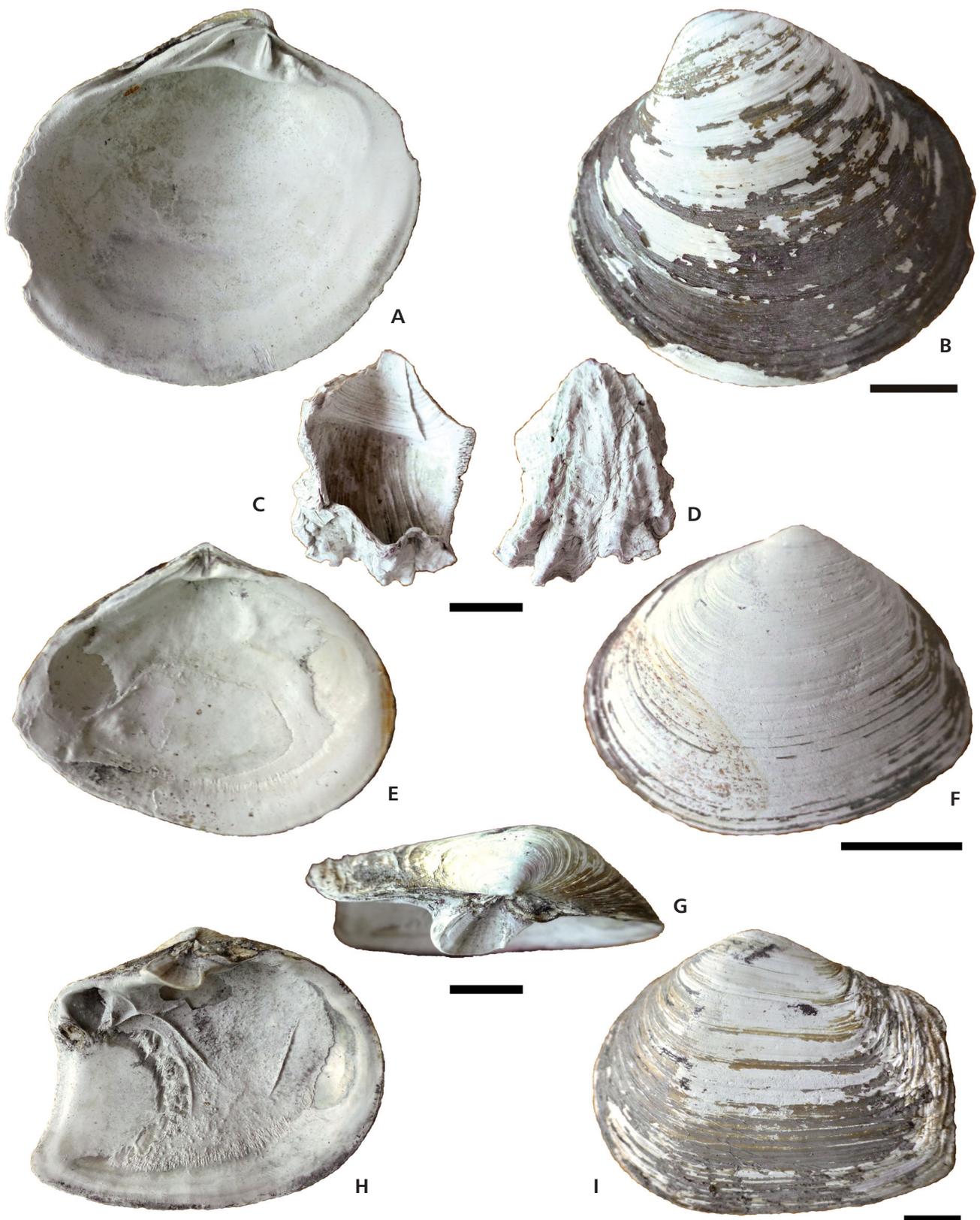


Figure 7. Common species of bivalves, barnacles and gastropods from locality 3 (sample H80–105 cm). Inner and outer shell surfaces of valves. • A, B – *Arctica islandica* (Linnaeus, 1767). • C, D – *Balanus balanus* (Linnaeus, 1758). • E, F – *Macoma calcarea* (Gmelin, 1791). • G–I – *Mya truncata*, Linnaeus, 1758. Scale bar 10 mm.

Table 2. Radiocarbon dates of shell material. Abbreviations: (1) = The Institute of Physics, Silesian University of Technology, Poland (laboratory report 18/2012); (2) = Poznań Radiocarbon Laboratory, Poland (laboratory report 4732/10); (3) = The ^{14}C Dating Centre, Department of Physics and Astronomy, University of Aarhus, Denmark (2001); (4) = Radiological Dating Laboratory, Norwegian Institute of Technology, Trondheim (Nydal 1960).

No.	Loc.	Sample level	Lab. No.	T ^{14}C BP	Calibrated age BP Range 68.2%	Calibrated age BP Range 95.4%	Cal BP Mean	Cal BP Median	Chronozone
R1	1	0–20 cm	GdA-2633 (1)	6,030±25	6,420–6,311	6,477–6,279	6,374	6,373	Atlantic
R2a	3	80–105 cm	Poz-37566 (2)	9,980±50	10,984–10,761	11,078–10,688	10,878	10,876	Preboreal
R2b	3	80–105 cm	Poz-37567 (2)	10,010±50	11,029–10,805	11,105–10,718	10,913	10,915	Preboreal
R2c	3	80–105 cm	Poz-37568 (2)	10,050±50	11,086–10,871	11,140–10,755	10,959	10,967	Preboreal
R2d	3	80–105 cm	Poz-37569 (2)	10,080±50	11,116–10,919	11,165–10,789	10,993	11,006	Preboreal
R2e	3	80–105 cm	Poz-37570 (2)	10,090±50	11,126–10,934	11,173–10,800	11,005	11,018	Preboreal
R3	4	0–25 cm	GdA-2635 (1)	6,060±25	6,463–6,345	6,517–6,293	6,406	6,406	Atlantic
R4	5 SW	1350 cm	GdA-2636 (1)	10,610±30	11,951–11,690	12,015–11,452	11,779	11,800	Younger Dryas
R5	5 NE	860 cm	GdA-2637 (1)	11,740±35	13,234–13,108	13,305–13,030	13,167	13,169	Allerød
R6	5 SW	705 cm	GdA-2638 (1)	9,770±30	10,666–10,545	10,741–10,482	10,606	10,605	Preboreal
R7	5 SW	90 cm	GdA-2639 (1)	9,640±30	10,529–10,379	10,574–10,277	10,440	10,446	Preboreal
R8	6	870 cm	AAR-6533 (3)	9,860±80	10,837–10,581	11,005–10,505	10,734	10,721	Preboreal
R9	6	250 cm	AAR-6534 (3)	9,750±75	10,690–10,479	10,821–10,327	10,580	10,580	Preboreal
–	Stormo	–	T-110 (4)	11,500±400	13,374–12,554	13,849–11,908	12,911	12,926	Allerød

stratigraphically above younger shells in locality 5. Evidence for any diagenetic mineral precipitation is absent. Also there are no barriers to vertical flow of porewater so that waters of different ages could not be kept separately. Reworking of dated shell material remains to be the simplest explanation.

Shells within the fine-grained intervals are generally better preserved than those in the coarse-grained intervals, where they are more severely deteriorated by being more fragmented and dissolved (Fig. 9). Shell disintegration into microscopic structural elements is evident in samples from these coarse-grained intervals. Lithological characteristics (Hilmo 2011) can explain the grade of shell preservation. The coarse-grained sediments allowed increased groundwater flow and, after additional glacio-isostatic uplift, meteoric water. The acidity of the meteoric pore water was probably crucial for shell dissolution.

Because the shells can have different mineralogy and microstructures, these factors are crucial for potential dissolution rate (*e.g.* Nielsen *et al.* 2004, 2008). The dissolution process may well have influenced the shell diversity and quantity so that a number of poorly preserving species is likely to be particularly underrepresented in the upper part of the succession.

Life position and sedimentary burial

Escaping capability during catastrophic burial is essential to the benthic invertebrates living in areas of variable sedimentation rates and erosion, that is, conditions typical to the deltaic fjord system. The macrofauna of this study is rich in burrowing bivalves (Tab. 1). These bivalves are

characteristic of habitats with softground to looseground, preferentially of sandy mud to muddy sand. For example, *Mya truncata* lives in vertical burrows within the substrate, where adults live deeply buried (Petersen 1999). Once catastrophically buried, the *Mya* juveniles turn the anterior upwards and attempt to pull themselves out; the adult specimens lose this ability (Schäfer 1962). Shells of both juveniles and adults of *M. truncata* are generally preserved within-habitat of the bottomset deposits of this study. This indicates a low sedimentation rate, interrupted by infrequent catastrophic burial events. The absence of large shells in the foresets may be related to (1) increased mortality of pre-mature individuals, or (2) hydrodynamic sorting before final deposition.

Arctica islandica, *Cerastoderma edule* and *Macoma calcaria* are other known burrowers (*e.g.* Petersen 1958, Tebble 1976). They commonly tolerate habitats with moderate water currents and recurring erosion and deposition pulses. *Cerastoderma edule* is capable of emergence after sudden burial with sediment during storms (Richardson *et al.* 1993), however, a major event of sedimentation would trap them (Schäfer 1962). *Macoma calcaria* burrows efficiently and its extensive mantle fusion protects the species against damaging even if sediment is entering the mantle cavity (Kranz 1974). This may explain why shells of *M. calcaria* can be found sporadically in situ within the fine-grained foresets. *Abra nitida* is a deeply burrowing bivalve in muddy sediments and fine sand, primarily surface deposit-feeding (*e.g.* Wikander 1980, Grémare *et al.* 2004).

Arctica islandica prefers muddy and sandy substrates and is highly resilient to abrupt sediment deposition (Powilleit *et al.* 2009). The species is common in the muddy bottomsets (Fig. 7, Tab. 1) but uncommon in the

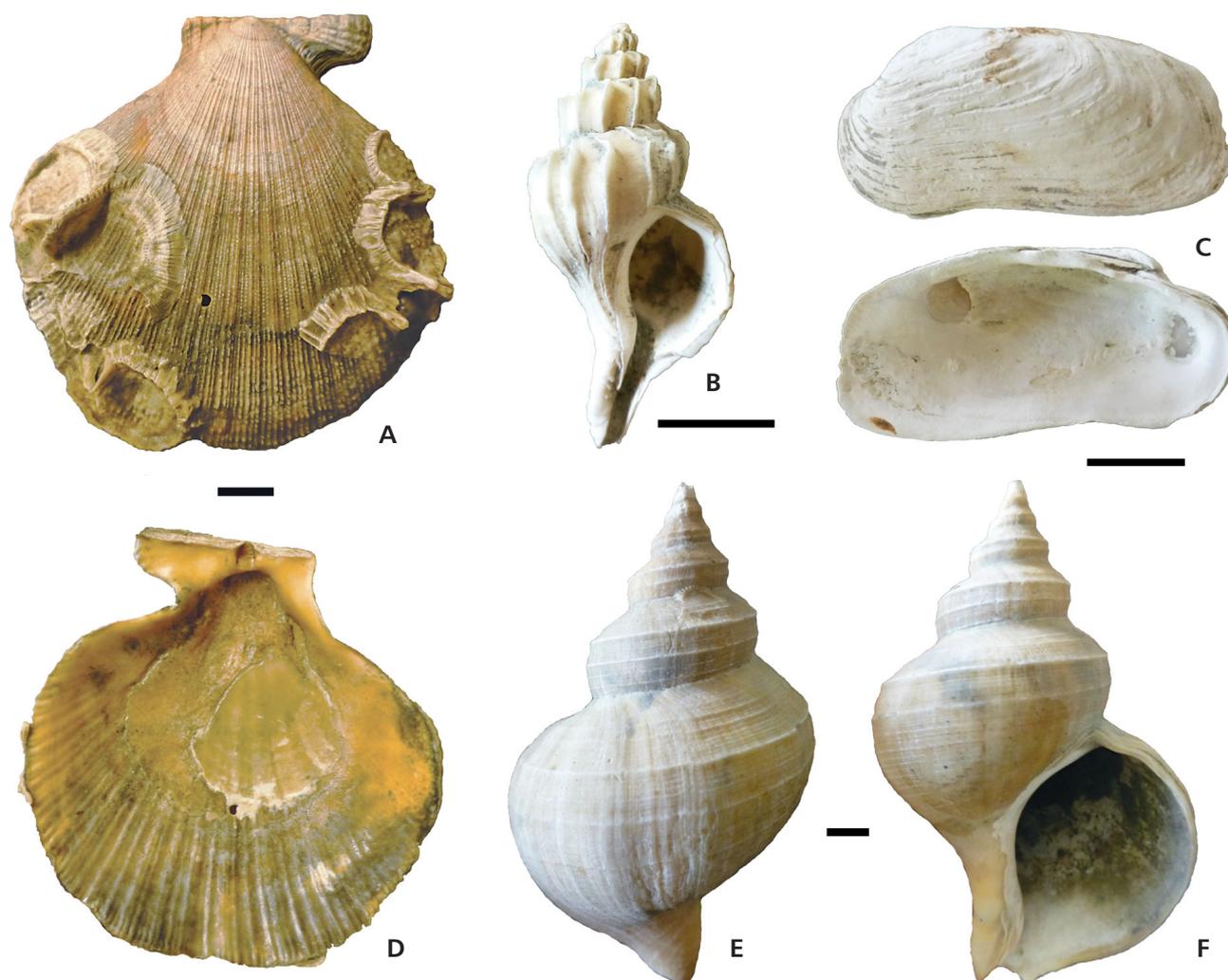


Figure 8. Common species of bivalves, barnacles and gastropods from locality 3 (sample H80–105 cm). Inner and outer shell surfaces of valves. • A, D – *Chlamys islandica* (Müller, 1776). • B – *Boreotrophon clathratus* (Linnaeus, 1767). • C – *Hiatella arctica* (Linnaeus, 1758). • E, F – *Neptunea despecta* (Linnaeus, 1758). Scale bar 10 mm.

sandy and gravely foresets, which can be explained by sporadically high hydrodynamic levels such as storms preventing population survival and recruitment in shallow waters (Rees *et al.* 1977). It is characterised by low recruitment rate (*e.g.* Witbaard & Bergman 2003) and adult growth (Helama *et al.* 2014). The life span of the species can be more than 100 years, with modal age for the Middle Atlantic Bight population at 65–105 years (Thompson *et al.* 1980). *Arctica islandica* shells of Preboreal age (mean ages 10,878–11,005 cal BP; Tab. 2) from our succession were previously found to contain between 35 and 169 annual increments, with an average lifespan of 105 years. The mean chronology of these increments (*i.e.* sclerochronology) was characterised by shell growth variability of 3.7- and 4.3-year periodicities (Helama *et al.* 2014). The demonstrated growth variations suggested that the North Atlantic Oscillation (Hurrell 1995, Hurrell & Deser 2010) may have

had a strong influence on this environmental setting during the Preboreal. This oscillation may have driven the phytoplankton production in fjords (Lindahl *et al.* 1998) and the supply of food to these bivalves (Helama *et al.* 2007), both the primary production and food supply belonging to most essential factors causing the variations in shell growth (Witbaard 1996). Also, the correlation statistics of annual increment data may be of value for interpreting the bivalve life conditions. The incremental series of our Preboreal *A. islandica* shells have an average correlation of 0.36 among the series (Helama *et al.* 2014). For modern live caught shell material, the mean correlation among the *A. islandica* shells from a site in northernmost Norway was seen to vary between 0.36 and 0.73 (Mette *et al.* 2015). The relatively low correlation found in shells from Breivikeidet muddy bottomsets likely results from growth disturbance that

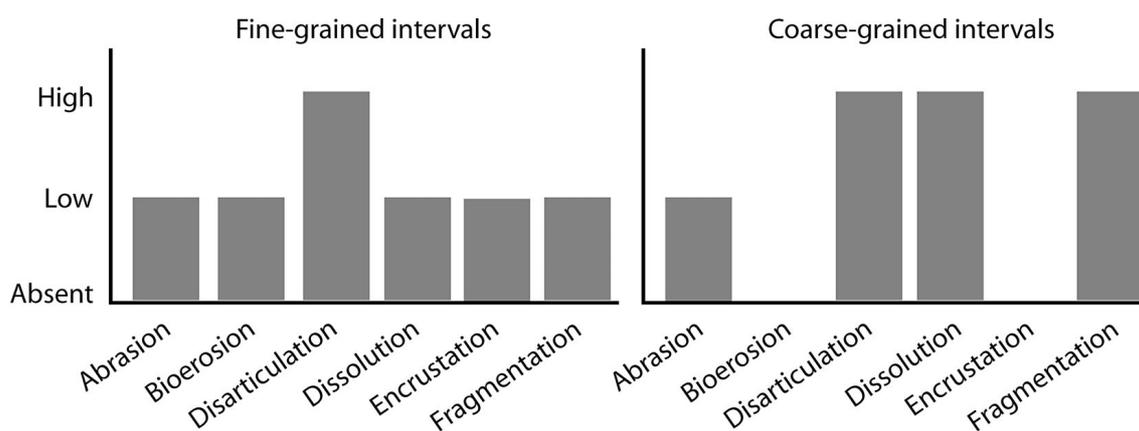


Figure 9. Overall shell preservation in the fine-grained and coarse-grained intervals of the stratigraphical succession.

Table 3. Geochemistry of sediment samples.

Locality 3			Locality 4			Locality 5		
Level (cm)	TOC (wt%)	TS (wt%)	Level (cm)	TOC (wt%)	TS (wt%)	Level (cm)	TOC (wt%)	TS (wt%)
12	0.172	0.606	0	0.596	0.56	15	0.0912	0.068
17	0.0923	0.0142	30	0.702	0.766	60	0.108	0.0742
118	0.117	0.145	60	0.463	0.505	584	0.123	0.109
137	0.124	0.0894	85	0.491	0.239	592	0.15	0.126
152	0.117	0.114	110	0.258	0.0869	624	0.119	0.0979
157	0.126	0.142	235	0.173	0.00832	675	0.0913	0.0705
187	0.112	0.0691	250	0.222	0.0102	689	0.139	0.121
217	0.103	0.25	470	0.109	0.0112	694	0.128	0.102
263	0.116	0.213				832	0.119	0.08
285	0.105	0.0988						
300	0.101	0.0216						

non-catastrophically has affected the bivalve population during shell formation. Such disturbance was likely present in the fjord prodelta.

Mytilus edulis and barnacles live sessile on hard substrates such as rocks, shells and sea weed. Despite high mortality of the larval and post-settlement stages (Jørgensen 1981), specimens of *M. edulis* may become about twenty years old (Theisen 1973). The presence of large shells, which are preserved within-habitat in muddy bottomsets, indicates limited sedimentation over an interval of several years. Abrupt depositional event of mud may have led to final burial of the fauna, as indicated by weak parallel bedding (Fig. 3).

Abiotic living conditions

The fossil macrofauna comprises species that are still living today, and their ecology relevant for Quaternary deposits is shown in Table 4, and per sample in Table 5. Such information is used under the assumption that the fossil

macrofauna (Tab. 1) is preserved within the sediment that once represented its habitat.

Most of the species are typical of shallow waters of fjords and nearshore shelf setting (e.g. *Crenella decussata*, *Macoma balthica*, *Mya truncata*, *Mytilus edulis*) (Tab. 4), which match well with the present bathymetry of Ullsfjord and the present mountain topography enclosing the Breivikeidet valley (Fig. 1). The outer Ullsfjord is open outwards and about 80–280 m depth, without any sill at the entrance (Soot-Ryen 1934, Sælen 1950). Further into the fjord there is a shallow sill (10 m) as access to the inner parts of the fjord system. Tidal currents intensely mix and replace water in the outer Ullsfjord as well as its inner parts (Sælen 1950). The tide is in the mesotidal range (Kartverket 2015), and we assume tide of the same magnitude to have occurred during the early Holocene even though the study area represented depositional conditions in a shallower water and were more confined topographically. Nevertheless, the waters were probably well circulated by waves, tide and particularly river outlet with water discharge to the fjord at that time. Plotting the radiocarbon

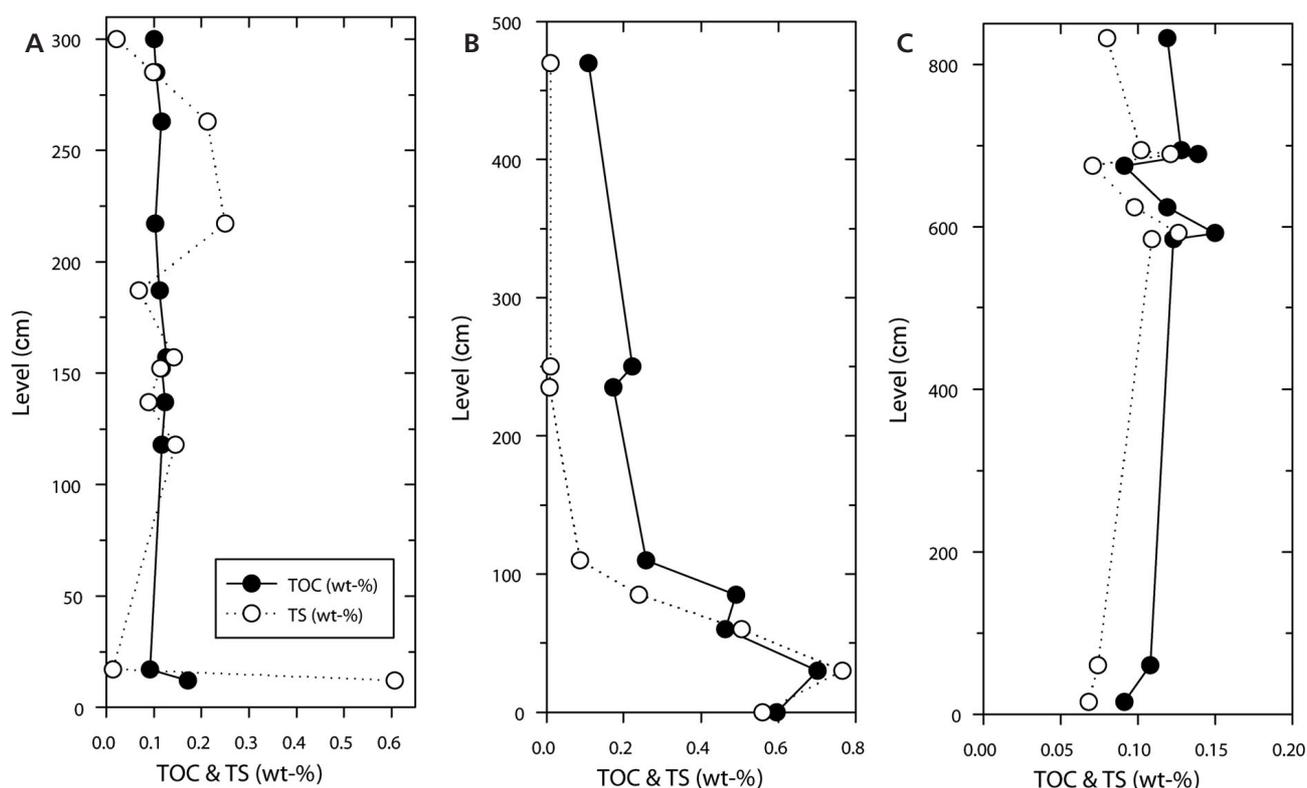


Figure 10. Total organic carbon (TOC) and total sulphur (TS) for A – locality 3, B – locality 4, and C – locality 5.

dates from the study area with the shoreline-displacement curve from the nearby Lyngen confirm the shallowness of the area during deposition (Fig. 11). Only one species, *Thyasira sarsii*, is atypical of shallow waters (Tab. 4), but it is also known from 50 m depth on the Norwegian shelf and fjords with detritus rich sediments to allow for bacterial symbiosis (Dufour 2005, Oliver *et al.* 2016). Plant detritus is visually present in the sediments of this study. Temporary plumes of brackish water may have occurred locally, bringing out the detritus. Most species have broad ranges of salinity tolerance (Tab. 4) and, therefore, normal marine to somewhat brackish conditions could have existed during deposition of the bottomsets and foresets. For comparison, salinity measurements from the present outer Ullsfjord are available from a station 1 (69° 40.7' N, 19° 43.3' E) off Breivikeidet (Aure *et al.* 1996). Averaged measurements from Nov./Dec. 1975–1994 were *c.* 32.5–34.2‰ in the upper 50 m of water, while the temperature was *c.* 4.3–8.0 °C. The nearby station U4 investigated by Soot-Ryen (1934) showed July 1930 measurements at *c.* 6.0–10.6 °C and 30.5(?)–33.5‰. Comparing with living conditions known for the identified species (Tabs 4, 5), these ranges would have upheld the faunal populations during early Holocene.

The macrofaunal diversity of the bottomsets indicates aerobic habitat conditions during deposition. Clearly, oxygenation was not a limiting factor, which is also supported by our geochemical results (see below). At present, the

outer Ullsfjord off Breivikeidet holds well oxygenated waters in the upper 50 m (Soot-Ryen 1934, Aure *et al.* 1996). During Nov./Dec. 1975–1994, the averages were *c.* 6.0–7.0 ml/l (Aure *et al.* 1996). The 1930 measurements from Soot-Ryen (1934) were in the same range at the nearby station U4, that is, July 6.6–7.0 ml/l and October 6.2–6.4 ml/l. Well circulated waters probably ensured that benthos continuously had aerobic conditions in our study area also during early Holocene.

Geochemical evidence

Our TOC and TS values (Tab. 3) are comparable with corresponding C/S ratios that commonly vary between 0.5 and 5.0 under normal marine conditions. The margin values for sediments deposited in freshwater usually has a higher C/S ratio above 10 (Bernier & Raiswell 1984). The relatively high ratio for freshwater deposits is related to a significantly lower concentration of dissolved sulphate than usually found in seawater. The C/S ratio is below 0.5 for deposits formed under euxinic bottom-water conditions (Leventhal 1995). Because of the high concentration of hydrogen sulphide, such conditions are commonly characterised by more pyrite relative to organic matter (Raiswell & Bernier 1986). Such large content of pyrite sulphur and the less good correlation between amounts of organic car-

Table 4. Living conditions recorded for molluscs from Northeast Atlantic. Brackets indicate maximum temperature under normal marine salinity only. Abbreviations: L – intertidal, SST – sea-surface temperature. Data for molluscs mainly extracted from Peacock (1993 and references therein). Additional data stated with references. Notes: **Ref. 1** = Thorson (1933); **Ref. 2** = Thorson (1934); **Ref. 3** = Ockelmann (1958); **Ref. 4** = Oliver *et al.* (2016); **Ref. 5** = Dufour (2005); **Ref. 6** = Jensen & Spärck (1934); **Ref. 7** = Russell & Petersen (1973); **Ref. 8** = Petersen & Russell (1973); **Ref. 9** = Wikander (1980); **Ref. 10** = Wiborg (1963); **Ref. 11** = Darwin (1854a); **Ref. 12** = Broch (1924); **Ref. 13** = Stephensen (1933); **Ref. 14** = Poulsen (1935); **Ref. 15** = Kerckhof (2002).

Species	Temperature (°C)		Salinity (‰)		Depth (m)		Notes		
	Range	Minimum summer SST	Normal minimum	Minimum (Baltic Sea)	Common range	Total range	Temperature (°C)	Salinity (‰)	Depth (m)
Gastropoda									
<i>Boreotrophon clathratus</i>	-1-8	5	25?	-	10-600	8-1000	-	-	-
<i>Buccinum undatum</i>	-1-19?	-	15	8	-	0-1200	-	-	-
<i>Lepeta caeca</i>	-	-	32	12	-	5-200	-	-	-
<i>Littorina littorea</i>	-2-20	9?	20	9	L	L-60	-	-	-
<i>Neptunea despecta</i>	-1-16	-	27	-	-	10-1200	-	-	-
Bivalvia									
<i>Abra nitida</i>	-	10	20	11	-	10-300	-	-	Just sublittoral to 4400 Ref. 9.
<i>Acanthocardia echinata</i>	0-12	9	25	12	0-75	0-100	-	-	-
<i>Arctica islandica</i>	0-20	8.5	10	-	-	0-100	Maximum winter temperature 10	-	-
<i>Astarte borealis</i>	-2-15	-	15	8	-	0-40	-	-	0-463 Ref. 1, 2, 3.
<i>Astarte elliptica</i>	-1-15	-	22	8	-	2-440	Maximum winter temperature 7.5	-	2-442 Ref. 1, 2.
<i>Axinopsida orbiculata</i>	-2-9	-	-	-	5-70	5-460	-	Euryhaline	2-944 Ref. 3, 30 Ref. 5.
<i>Cerastoderma edule</i>	-1- ?	9	15	5	L-2	L-46	3-25 Ref. 7. Larval development 15-25	15-35 Ref. 7, 8. Larval development 20-40	Prefer tidal habitat, amplitude 0.2-10 Ref. 7, 8. Common range 0-10 Ref. 8.
<i>Chlamys islandica</i>	-2-14 (6)	-	-	-	-	7-80	Bottom temperature 1-9.5 in fjords with sill at entrance in North Norway Ref. 10. Minimum for larvae 8; minimum for spawning 5	Euryhaline	2-356 Ref. 2, 3. 4-250 or even more, greatest concentrations most often at 10-60 in fjords with sill at entrance in North Norway Ref. 10.
<i>Crenella decussata</i>	-2-15	4	23	12	15-30	4-70	-	-	Typically 4-70, 2-1100 Ref. 3.
<i>Hiatella arctica</i>	-	-	20	11	L-75	L-120	-	-	0-2190? Ref. 3.
<i>Macoma balthica</i>	-2-22	7	2	-	0-25	L-45	-	-	Commonly as low as 2-3 in relative calm waters. > 50 in Baltic Sea Ref. 6.

bon and pyrite sulphur typically indicative of euxinic conditions (Raiswell & Berner 1986), however, have not been observed for the studied localities.

The TOC/TS ratio varies through the fine-grained terrigenous sediments in the locality 3. Overall the TOC/TS ratios in Fig. 3 indicate deposition under marine conditions that are confirmed by high content of shell material of marine origin. The amounts of organic matter and pyrite

sulphur follow each other to a lesser degree than observed at the localities 4 and 5 (Fig. 10A, Tab. 3). Somewhat larger TS values are recorded at the base of locality 3. The geochemical plot for the locality 4 indicates that the depositional conditions changed during the lower 5 m of the succession (Fig. 4). The TOC/TS ratio changes from normal marine conditions in the lowest part of the succession to freshwater for the upper three samples. Both the TOC and

Table 4. continued.

Species	Temperature (°C)		Salinity (‰)		Depth (m)		Notes		
	Range	Minimum summer SST	Normal minimum	Minimum (Baltic Sea)	Common range	Total range	Temperature (°C)	Salinity (‰)	Depth (m)
<i>Macoma calcarea</i>	-2-16 (11)	5	13	8	-	0-80	Larval development 5-6 at N and S limits	-	0-677 Ref. 3.
<i>Mya truncata sensu lato</i>	-2-17	4.5	17	8	L-50	L-70	Maximum winter temperature 8	-	0-625 Ref. 3.
<i>Mytilus edulis</i>	-10-30	4	7	-	L-10	L-25	-	Normally 15-40	L-180, uncommon below 50 Ref. 3. Mainly littoral
<i>Nuculana pernula</i>	-2-14 (8)	-	25	12	-	5-1275	Maximum winter temperature 6	-	3-1275 Ref. 2, 3.
<i>Panomya norvegica</i>	-	-	-	-	-	-	-	-	4-500 Ref. 6.
<i>Parvicardium exiguum</i>	-	10.5	10	-	0-20	0-55	3-25 Ref. 7	Brackish to normal marine Ref. 6. 25-35 Ref. 7, 8. Minimum for larvae 20	Shallow waters Ref. 6. Tidal amplitude 0-10 Ref. 7. Prefer tidal and lagoon, 0-55 Ref. 8.
<i>Parvicardium minimum</i>	4.5-?	8.5	25	12	100-150	9-400	-	-	30-2000 Ref. 6.
<i>Phaxas pellucidus</i>	-	12	20	9	4-40	4-150	-	-	-
<i>Similipecten greenlandicus</i>	-2-9	-	33	-	-	60-?	-	-	4-2000 Ref. 1, 3.
<i>Thyasira sarsii</i>	-	-	33.5	23	-	100-600	-	-	80-220, fjords Ref. 4. 50-340 Ref. 5.
<i>Yoldiella lenticula</i>	-1-8.5	-	33	-	-	10-300	Maximum winter temperature 4.5	-	0-1400 Ref. 2, 3.
Cirripedia									
<i>Balanus balanus</i>	-	-	-	14 Ref. 14	-	0-300 Ref. 12	-	-	5-50 fathoms Ref. 11. Few metres (in north)-300 Ref. 13. 5-130 in Danish waters Ref. 14.
<i>Balanus crenatus</i>	-	-	-	9 Ref. 14	-	0-320 Ref. 12	-	Prefers normal marine conditions Ref. 15	Down to 50 fathoms Ref. 11. 0-100 or more Ref. 13. 0-60 in Danish waters Ref. 14.
<i>Verruca stroemia</i>	-	-	20 Ref. 14	-	5-200 Ref. 14	0-548 Ref. 12	-	-	Tidal-50-90? fathoms Ref. 11. 0-200 Ref. 13.

TS values gradually change; however, the TS values decrease faster than those of TOC (Fig. 10B). This indicates a limitation in sulphur availability, causing higher TOC/TS values towards the top of the succession. All the TOC/TS ratios for the locality 5 are within the range for normal marine conditions (Fig. 5), where the amounts of carbon and sulphur vary only slightly throughout the section (Fig. 10C).

Benthic faunal communities

Taxa from our localities (Tab. 1) can be related to modern benthic communities in shallow-marine waters, defined in

the classical investigations by Petersen (1913, 1914, 1918, 1924). The communities were classified after recurring associations of certain animals and named after the most conspicuous species. The *Macoma calcarea* community comprises the characterising animals *Macoma calcarea*, *Mya truncata*, *Cardium ciliatum*, *Serripes groenlandicus*, *Ophiocten scriceum*, *Pectinaria granulata*, *Astarte borealis*, *A. elliptica*, and *A. montagui* (Thorson 1933, 1934, 1957). Some of these may be absent. The community is circumpolar on mixed bottoms from 4 to 50-60 m depth, even down to 100-130 m in the Barents Sea and at Spitsbergen (Thorson 1957). Many of the taxa (Tab. 1) are known from the *Macoma calcarea* community, which matches well with

Table 5. Minimum summer sea-surface temperature and normal minimum salinity (Tab. 4) and zoogeographical provinces (Tab. 6) compiled per sample, with the doubtful assumption that the shell material in every sample was preserved within habitat. Data from the Baltic Sea are excluded as they originate from a different oceanographic setting. Abbreviations: SST – sea-surface temperature; B – boreal; MB – mid boreal; HB – high boreal; LA – low arctic.

Locality	Level (cm)	Temperature (°C)		Zoogeography
		Minimum summer SST	Normal minimum	
1	0–20	8.5	23	HB
3	50–70	5	33	MB, HB
3	80–105	10	12	HB
3	H80–105	10	27	MB, HB
3	205–225	10	23	HB
3	305–325	10	23	MB, HB
4	0–25	8.5 (9?)	33.5	HB
6	220–240	10	33	HB
6	240–260	10.5	25	B
6	285–305	10	33	HB
6	425–435	10	33	HB
6	450–470	12	25	B
6	495–515	5	17	B
6	545–555	9	17	B
6	650–670	5 (9?)	20	B, LA
6	805–825	5 (9?)	20	B
6	860–870	9	27	B
6	870–880	9	17	B
6	1000–1015	Indet.	Indet.	Indet.

the grain size and sorting of the associated sediments. For example, *Macoma calcarea* lives in clayey or muddy bottoms that may be mixed with sand, gravel and stones on shallow depth in the inner Kejser Franz Joseph Fjord, East Greenland (Ockelmann 1958). In the Ramfjord of Troms County, the *Macoma calcarea* community occurs especially at 2–15 m water depth in the inner parts of the fjord (Soot-Ryen 1924, 1932). The inner basin of the fjord showed yearly temperature range of about 0–10 °C and salinity at 27.7–33.4‰, measured at 2–20 m water depth (Soot-Ryen 1932).

The common occurrence of *Abra nitida* may be due to ecological as well as preservational favouring. Its ability to both surface deposit-feeding and suspension-feeding indicates that the species is somewhat adapted to rely on an abundant food source available for short periods (Grémare *et al.* 2004). This would be an advantage for the variable habitat conditions and food availability in a fjord delta. *Abra nitida* is one of the characterising species in the *Amphiura filiformis*-*A. chiajei* community present on clayey to silty soft bottoms at about 15–100 m depth (Thorson 1957). It is also known from the circumpolar

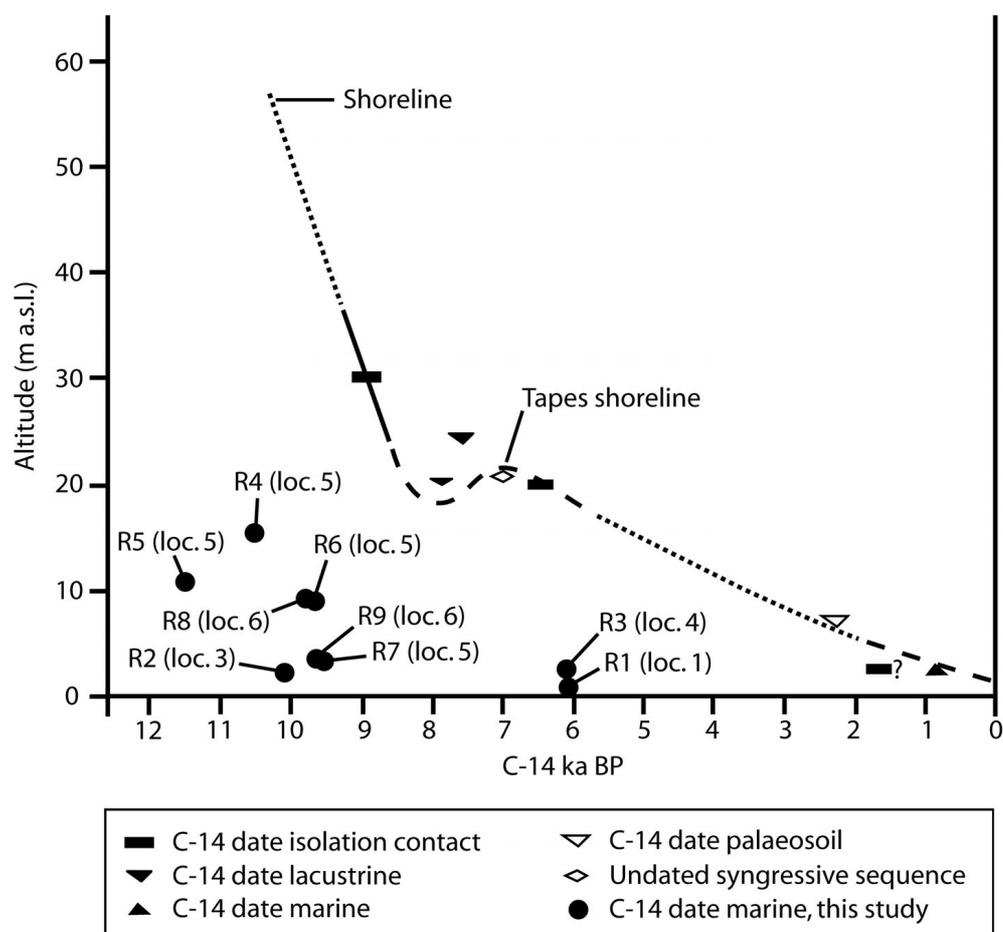
Maldane sarsi-*Ophiura sarsi* community in fine mud bottoms of shallow estuaries and at 100–300 m in the open sea (Thorson 1957; see Petersen 1918).

Similar feeding modes are known for *Macoma balthica*. Surface suspension feeding predominates in exposed sandy sites, and deposit feeding in sheltered muddy sand (Ólafsson 1986), dependent upon food availability in the water column (Hummel 1985). *Macoma balthica*, *Mya arenaria* and *Cerastoderma edule* are characterising bivalves of the boreal *Macoma balthica* community, particularly present in estuarine conditions from the tidal zone to depths of 8–10 m (Thorson 1957; see Petersen 1913, 1918). The rareness of *Macoma balthica* in the fjord deltaic foresets suggests that the community was scarcely developed or of low preservation potential (Tab. 1). More sandy bottoms may hold a larger quantity of *C. edule* (Thorson 1957), explaining its presence in the foresets (Tab. 1).

Nuculana pernula lives in similar sediments and has greatest abundance in the *Macoma calcarea* community (Thorson 1934, Ockelmann 1958). *Astarte borealis* may occur in clay, sand, gravel and mixed bottom, abundant in the *Gomphina fluctuosa* and *Macoma calcarea* communities (Thorson 1933, 1934; Madsen 1949; Ockelmann 1958). *Astarte elliptica* can be abundant in the *Macoma calcarea* community, where the substrate mainly is clay, mud, sand and mixed bottom (Thorson 1933, Ockelmann 1958). *Axinopsida orbiculata* occurs preferentially in silt of the *Macoma calcarea*, *Gomphina fluctuosa* and *Yoldia hyperborea* communities (Ockelmann 1958). *Yoldiella lenticula* lives in mud and clay, which may contain sand and gravel, with greatest abundance in the *Astarte crenata* community (Thorson 1934, Ockelmann 1958). *Panomya norvegica* occurs deeply buried in mud, muddy and sandy gravel bottoms (Tebble 1976). *Mya truncata* lives in various substrates of clay, mud, sand, gravel and stones. Juveniles commonly attach to algae in large numbers, whereas adults are endobenthos in the *Macoma calcarea* community (Ockelmann 1958). Juveniles of *Hiatella arctica* also belong to the epifauna, commonly on algae in shallow waters. The adults are mainly byssally attached to stones and other hard substrates, in irregularities of the sea bottom, or numerously lumped to each other (Ockelmann 1958). Larvae are able to settle and bore into solid but soft substrates (Hunter 1949); however, no such borings were found in the study area.

Mytilus edulis belongs to the algal epifauna and hard substrates, as byssate suspension feeder on rocks, stones and seaweed preferably where currents are strong (Ockelmann 1958). It is mainly found in the tidal zone and a few metres down (*e.g.* Sars 1878, Ockelmann 1958). Another mytilid, *Crenella decussata*, is known from both sandy and muddy bottom, mixed with sand or gravel, in mainly shallow waters (Ockelmann 1958). It is very common in shallow waters at Finnmark (Sars 1878).

Figure 11. Radiocarbon dates from this study shown in comparison with the Lyngen dates and shoreline-displacement curve by Corner & Haugane (1993), who emphasized that the curve represents high-tide level (threshold isolation level of lake).



Chlamys islandica is associated with the algal epifauna; juveniles mostly live with *Fucus* in shallow water. *Chlamys islandica* can swim or lives attached by byssus to substrate or to each other (Wiborg 1962, 1963). Adults migrate to greater depths to the zone with red algae (Thorson 1934, Ockelmann 1958); the migration appears to be seasonal, into deeper water during summer and back to shallow waters during winter (Soot-Ryen 1924). This may well explain why only large shells of *C. islandica* are in the interval 80–105 cm of locality 3 (Fig. 3). *Chlamys islandica* usually lives in the North Norwegian fjords at 10–60 m where the shells typically are heavily encrusted by other organisms (Wiborg 1962, 1963). The preferred bottom is sand, gravel, shells, stones and sometimes clay, in fjords with shallow sill of 10–15 m depth or less at the entrance (Wiborg 1962, 1963). *Chlamys islandica* thrives in waters characterised by strong currents (Wiborg 1963). Its presence is in good agreement with the overall deltaic fjord setting during early Holocene.

Similipecten greenlandicum prefers a bottom of clay with gravel, stones and shells; it is especially abundant in lower *Ophioceten* zone of the *Macoma calcarea* community (Thorson 1933, Ockelmann 1958).

The barnacles belong to the algal epifauna and those preferring hard substrates. They live sessile with basis cemented on hard substrates, and cannot live on sand, mud or moving shingle (Darwin 1854a). *Balanus balanus*, *B. crenatus* and *Verruca stroemia* are usually found on molluscan shells (e.g. large pectinids, gastropods), crustaceans and rocks (Darwin 1854a, Stephensen 1933, Poulsen 1935, Kerckhof 2002). *Balanus balanus* prefers habitats with comparatively strong current (Rasmussen 1973). *Balanus balanus*, which also can be on the holdfasts of larger sea-weeds and imbedded in sponges, is commonly associated with *B. crenatus* and sometimes with *B. hammeri* and *V. stroemia* (Darwin 1854a). *Balanus crenatus* and *V. stroemia* also attaches themselves to pebbles and floating wood (Darwin 1854a). *Balanus balanus*, *B. crenatus* and *V. stroemia* are more or less euryhaline species (Poulsen 1935; Tab. 4).

Preservation bias probably favoured certain species and modified the community structure (e.g. Kidwell & Bosence 1991). Still, the investigated samples primarily point towards the *Macoma calcarea* community. Many of the species are well known from this soft bottom community. There is also an indication of transition with other

Table 6. Zoogeographical provinces for modern specimens of the species in the investigated fossil macrofauna. The provinces where the species are commonly living are shaded in grey. Province data compiled from biogeographical information by Darwin (1854a), Sars (1878), Stephensen (1933), Jensen & Spärck (1934), Grønlie (1945), Feyling-Hanssen (1955), Ockelmann (1958), Wiborg (1962), Petersen & Russell (1973), Tebble (1976), Petersen (1977, 1999) and GBIF (2014a, b, c). Sectoral distribution along the northern Norway extracted from Høisæter *et al.* (2001a, b) and Sneli & Brattegard (2001). Abbreviations: * = Zoogeographical division after Feyling-Hanssen (1955); ** = Sectoral distribution in northern Norway: 13 = Trondheimsfjorden; 14 = northwestern Sør Trøndelag; 15 = Nord Trøndelag; 16 = southern Nordland; 17 = mid Nordland; 18 = northern Nordland (Lofoten); 19 = southern Troms; 20 = mid Troms; 21 = northern Troms; 22 = western Finnmark (northeast to Tarhalsen); 23 = northwestern Finnmark (northeast to North Cape); 24 = northern Finnmark (Porsangerfjorden – Nordkinnhalvøya); 25 = northeastern Finnmark (Slettnes light – Harbaken); 26 = eastern Finnmark (Harbaken – border to Russia); N = northern species; S = southern species; X = pan-sectoral distribution (known south and north of Norway).

Species	Zoogeographical provinces *						Sectoral distribution in northern Norway **													
	Lusitanian		Boreal		Arctic		13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Low	Mid	High	Low	Mid	High														
GASTROPODA																				
<i>Littorina littorea</i>	+	+	+	+	+		X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Buccinum undatum</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Boreotrophon clathratus</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Lepeta caeca</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Neptunea despecta</i>		+	+	+	+	+	N	N	N	N	N	N	N	N	N	N	N	N	N	N
BIVALVIA																				
<i>Abra nitida</i>	+	+	+	+			S	S	S	S	S	S	S	S	S					
<i>Acanthocardia echinata</i>	+	+	+	+			S	S	S	S	S	S	S	S	S	S	S	S		
<i>Cerastoderma edule</i>	+	+	+	+			S	S	S	S	S	S	S	S	S	S	S	S	S	
<i>Parvicardium exiguum</i>	+	+	+	+			S	S	S	S	S	S	S	S	S					
<i>Phaxas pellucidus</i>	+	+	+	+			S	S	S	S	S	S	S	S	S	S				
<i>Panomya norvegica</i>	+	+	+	+			N	N	N	N	N	N	N	N	N	N	N	N	N	N
<i>Parvicardium minimum</i>	+	+	+	+			S	S	S	S	S	S	S	S	S	S	S	S	S	
<i>Arctica islandica</i>	+	+	+	+	+		X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Macoma balthica</i>	+	+	+	+	+		X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Mytilus edulis</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Hiatella arctica</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Crenella decussata</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Mya truncata</i>		+	+	+			X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Astarte elliptica</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Nuculana pernula</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Thyasira sarsii</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Macoma calcarea</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Astarte borealis</i>			+	+	+	+	N	N	N	N	N	N	N	N	N	N	N	N	N	N
<i>Chlamys islandica</i>			+	+	+	+	N	N	N	N	N	N	N	N	N	N	N	N	N	N
<i>Yoldiella lenticula</i>			+	+	+	+		N	N	N	N	N	N	N	N	N	N	N	N	N
<i>Axinopsida orbiculata</i>				+	+	+					N	N	N	N	N	N	N	N	N	N
<i>Similipecten greenlandicus</i>				+	+	+							N	N	N	N	N	N	N	N
CIRRIPEDIA																				
<i>Verruca stroemia</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Balanus crenatus</i>	+	+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Balanus balanus</i>		+	+	+	+	+	X	X	X	X	X	X	X	X	X	X	X	X	X	X

communities (e.g. *Amphiura filiformis*-*A. chiajei* community) in the bottomsets at locality 3. Additional species in-

dicating the community of the algal epifauna and hard substrates.

Zoogeography

The zoogeographical province division by Feyling-Hanssen (1955) for shelf areas has commonly been used for interpretation of Quaternary faunas. Troms County is presently in the high-boreal province affected by the warm surface water of the Norwegian current (see Feyling-Hanssen 1955). Still, the cold waters of the fjords in north-west Norway are known to support arctic species that otherwise only live further north and east (Sars 1878). Living location in a fjord of Troms County also affects the composition (Soot-Ryen 1932). A zoogeographical overview of the obtained species is given in Table 6. The macrofauna probably originated in the high-boreal province. For instance, *Acanthocardia echinata* and *Cerastoderma edule* are typical boreal species (e.g. Sars 1878). Species distinctive of the arctic province are also present. For instance, *Crenella decussata* is most common in the northern parts of its geographical range, particularly in shallow waters (Jensen & Spärck 1934). This range includes the arctic, boreal and lusitanian provinces (Feyling-Hanssen 1955 and references therein). Traditionally, *Mya truncata* (Fig. 7G–I) has been considered to be widespread from arctic to boreal seas, and into the northern lusitanian province (e.g. Feyling-Hanssen 1955). Ockelmann (1958), who followed the terminology of Ekman (1953), summarised a pan-arctic-boreal and circumpolar main distribution as the major occurrence. Later, Petersen (1999) revised the Greenlandic material of the genus *Mya* and emphasized that *M. truncata* is a boreal North Atlantic species. This can be critical for assigning some of the investigated samples to a certain province; only few other species are available to specify the exact province (Tab. 6).

The modern fauna at Tromsø was estimated by Grønlie (1945) to have about 50% species of arctic element, co-occurring with boreal species. Ockelmann (1958) summarised the area north of Lofoten (North Norway) to have about 31% arctic species and 66% southern species of total 109 bivalves. This owes to the hydrographical currents bridging the boreal coast of west Norway and the low-arctic areas to the north and east (Ockelmann 1958). Living location of the modern fauna in a fjord of Troms County also affects the composition (Soot-Ryen 1932). Biogeographical sector distribution of Norwegian marine prosobranch gastropods, bivalves and barnacles was reviewed by Høisæter *et al.* (2001a, b) and Sneli & Brattegard (2001). The distribution indicates that our fossil macrofauna comprises species still living in Troms County and westernmost Finnmark County (Tab. 6). These are within the recent high-boreal province. Only few species are available in each individual sample to specify a certain part of the province. Generally, the samples contain species limiting them to the boreal province; a number of samples even to the high boreal (Tab. 5). Other samples are indica-

tive of mid/high-boreal or boreal/low-arctic provinces (Tab. 5). There is consequently no indication of zoogeographical changes during the Holocene (Tab. 2). Investigating gravity cores from the shelf off Troms and west Finnmark, Vorren *et al.* (1978) concluded that high-boreal conditions had prevailed during the Holocene. This view is supported by our macrofaunal findings from the fjord delta successions (Tabs 5, 6). Mid-boreal conditions might have occurred in a part of Holocene (Vorren *et al.* 1978), for which we do not have any direct evidence. A major faunal change offshore North Norway was probably caused by the intrusion of warm, saline, nutrient-rich Atlantic water masses into the Norwegian Current for about 10,000 years BP, with the change from a low-arctic to high-boreal fauna at that time, based on core samples from Andfjorden and Malangsdjupet, North Norway (Thomsen & Vorren 1986). Further south, the Atlantic Current entered the Norwegian Sea 13,000–13,700 years BP (Ruddiman & McIntyre 1973), and it swept along western Norway prior to 12,600 years BP (Mangerud 1977). Our radiocarbon dated shells of *Macoma calcarea* from locality 5 indicate Allerød and Younger Dryas (Tab. 2). Previously, the Stormo area in the midst of the Breivikeidet Valley has yielded *Portlandia arctica* and *Macoma calcarea* of Allerød age, in laminated bluish-grey clay of glaciomarine origin (Holmes & Andersen 1964, Andersen 1968; Tab. 2). *Macoma calcarea* has a broad distribution in the present boreal and arctic provinces. As stated by Vorren *et al.* (1978), high/mid arctic conditions might have occurred during Younger Dryas.

Conclusions

Early Holocene fjord deltaic successions in the Breivikeidet Valley, Troms County were represented by shell materials of 27, 10 and 4 taxa of identified bivalves, gastropods and barnacles, respectively. The most common species are *Macoma calcarea*, *Mya truncata* and *Mytilus edulis*, in descending order. The shells have higher preservation potential in the muddy prodelta deposits than in the delta slope sand.

The macrofauna is a useful proxy for inferring the abiotic conditions of the depositional setting. Bathymetric ranges of the species indicate shallow water. The recent counterparts to the prevalent benthic communities live in shallow waters, in a depth of 10–60 m. Our findings agreed with the previous sclerochronological deductions implying that the bivalves have inhabited the shallow fjord delta receiving North Atlantic influence. Salinity was near normal marine during the deposition of the muddy bottomsets. The deltaic sandy foresets developed under normal marine to brackish conditions and are dominated by euryhaline species. The sandy and gravely topsets are river deposits

formed under a strong influence of fluvial waters. This change in salinity is also expressed in TOC/TS ratios indicating a progradation from marine, brackish to freshwater depositional conditions. The overall fauna indicates the high-boreal province, which is supported individually by a number of samples. This is consistent with observations of modern marine populations in this part of Norway, and with prior shelf investigations offshore west and north of our study area.

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References

- ANDERSEN, B.G. 1968. Glacial geology of western Troms, North Norway. *Norges Geologiske Undersøkelse* 256, 1–160.
- ANWAR, N.A., RICHARDSON, C.A. & SEED, R. 1990. Age determination, growth rate and population structure of the horse mussel (*Modiolus modiolus*). *Journal of the Marine Biological Association of the United Kingdom* 70, 441–457. DOI 10.1017/S0025315400035529
- AURE, J., FØYN, L. & PETTERSEN, R. 1996. Miljøundersøkelser i norske fjorder 1975–1994. 3. Nord-Troms: Tromsundet, Ullsfjord, Lyngenfjord og Kvæningen [Environmental monitoring of Norwegian fjords 1975–1994. 3. Nord-Troms: Tromsundet, Ullsfjord, Lyngenfjord and Kvæningen]. *Fisken og Havet* 28, 1–69.
- BERNER, R.A. & RAISWELL, R. 1984. C/S method for distinguishing fresh-water from marine sedimentary rocks. *Geology* 12, 365–368. DOI 10.1130/0091-7613(1984)12<365:CMFDFD>2.0.CO;2
- BOESCH, D.F. & ROSENBERG, R. 1981. Response to stress in marine benthic communities, 179–200. In BARRETT, G.W. & ROSENBERG, R. (eds) *Stress Effects on Natural Ecosystems*. John Wiley, Chichester.
- BROCH, H. 1924. Cirripedia Thoracica von Norwegen und dem norwegischen Nordmeere. Eine Systematische und Biologisch-Tiergeographische Studie. *Videnskapselskapets Skrifter. I, Matematisk-naturvidenskabelig klasse*, 17, 1–121.
- BRONK RAMSEY, C. 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360. DOI 10.1017/S0033822200033865
- BROWN, T. 1827. *Illustrations of the recent conchology of Great Britain and Ireland*. 125 pp. D. Lizars, Edinburgh.
- BRUGUIÈRE, J.G. 1789. *Encyclopédie méthodique. Histoire naturelle des vers. 1*, 757 pp. Panckoucke, Paris.
- CORNER, G.D. 1980. Preboreal deglaciation chronology and marine limits of the Lyngen-Storfjord area, Troms, North Norway. *Boreas* 9, 239–249. DOI 10.1111/j.1502-3885.1980.tb00700.x
- CORNER, G.D. & FJALSTAD, A. 1993. Spreite trace fossils (*Teichichnus*) in a raised Holocene fjord-delta, Breidvikeidet, Norway. *Ichnos* 2, 155–164. DOI 10.1080/10420949309380085
- CORNER, G.D. & HAUGANE, E. 1993. Marine-lacustrine stratigraphy of raised costal basins and postglacial sea-level change at Lyngen and Vanna, Troms, northern Norway. *Norsk Geologisk Tidsskrift* 73, 175–197.
- CORNER, G.D., NORDAHL, E., MUNCH-ELLINGSEN, K. & ROBERTSEN, K.R. 1990. Morphology and sedimentology of an emergent fjord-head Gilbert-type delta: Alta delta, Norway, 155–168. In COLELLA, A. & PRIOR, D.B. (eds) *Coarse-Grained Deltas. International Association of Sedimentologists, Special Publication 10*. DOI 10.1002/9781444303858.ch8
- CRAIG, H. 1954. Carbon 13 in plants and the relationships between Carbon 13 and Carbon 14 variations in nature. *The Journal of Geology* 62, 115–149. DOI 10.1086/626141
- DAGESTAD, A., TØNNESEN, J.F. & DALSEGG, E. 2006. Hydrogeologiske undersøkelser ved Ramfjordmoen, Tromsø kommune [Hydrogeological investigations at Ramfjordmoen, Tromsø municipality]. *Norges Geologiske Undersøkelse, Rapport 2005.079*, 1–34.
- DARWIN, C. 1854a. *A Monograph on the sub-class Cirripedia with Figures of all the Species. The Balanidae, (or sessile cirripedes); The Verrucidae, etc.* 684 pp. The Ray Society, London.
- DARWIN, C. 1854b. *A Monograph on the fossil Balanidae and Verrucidae of Great Britain*. 44 pp. The Palaeontographical Society, London.
- DUFUR, S.C. 2005. Gill anatomy and the evolution of symbiosis in the bivalve family Thyasiridae. *Biological Bulletin* 208, 200–212. DOI 10.2307/3593152
- EILERTSEN, R.S., CORNER, G.D., AASHEIM, O. & HANSEN, L. 2011. Facies characteristics and architecture related to palaeodepth of Holocene fjord-delta sediments. *Sedimentology* 58, 1784–1809. DOI 10.1111/j.1365-3091.2011.01239.x
- EKMANN, S. 1953. *Zoogeography of the Sea*. 417 pp. Sidgwick and Jackson, London.
- EVISON, K. 2012. *Sedimentologiske, Paleøkologiske og Diagenetiske Undersøkelser av Holocene Deltaavleiringer ved Breivikeidet, Troms* [Sedimentological, Palaeoecological and Diagenetic Investigations of Holocene Delta Deposits at

- Breivikeidet, Troms]. GEO-3900, 93 pp. Master thesis, University of Tromsø, Tromsø, Norway.
- FEYLING-HANSEN, R.W. 1955. Stratigraphy of the marine late Pleistocene of Billefjorden, Vestspitsbergen. *Skrifter Norsk Polarinstitut* 107, 1–186.
- FLESSA, K.W. & KOWALEWSKI, M. 1994. Shell survival and time-averaging in nearshore and shelf environments: estimates from the radiocarbon literature. *Lethaia* 27, 153–165. DOI 10.1111/j.1502-3931.1994.tb01570.x
- GBIF 2014a. *The Global Biodiversity Information Facility: GBIF Backbone Taxonomy, 2013-07-01. Delectopecten greenlandicus (Sowerby, 1842)*. Norwegian Biodiversity Information Centre, Natural History Museum, University of Oslo. <http://www.gbif.org/species/2285988> on 2014-07-27
- GBIF 2014b. *The Global Biodiversity Information Facility: GBIF Backbone Taxonomy, 2013-07-01. Phaxas pellucidus (Pennant, 1777)*. Norwegian Biodiversity Information Centre, Natural History Museum, University of Oslo. Invertebrates (GBIF-SE:SMNH), GBIF-Sweden. <http://www.gbif.org/species/2287245> on 2014-07-30
- GBIF 2014c. *The Global Biodiversity Information Facility: GBIF Backbone Taxonomy, 2013-07-01. Neptunea despecta (Linnaeus, 1758)*. Bergen Museum (Gastropoda), Norwegian Biodiversity Information Centre, Natural History Museum, University of Oslo. Invertebrates (GBIF-SE:SMNH), GBIF-Sweden. <http://www.gbif.org/species/2304684> on 2014-07-30
- GMELIN, J.F. 1791. *Caroli a Linné. Systema naturae per regna tria naturae, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis. 13th edition, 1(6)*, 3021–3910. G.E. Beer, Lipsiae.
- GRÉMARE, A., DUCHÈNE, J.C., ROSENBERG, R., DAVID, E. & DESMALADES, M. 2004. Feeding behaviour and functional response of *Abra ovata* and *A. nitida* compared by image analysis. *Marine Ecology Progress Series* 267, 195–208. DOI 10.3354/meps267195
- GRØNLIE, O.T. 1945. Postglaciale skjellbanker på Langnes ved Tromsø [Postglacial shell banks on Langnes at Tromsø]. *Norsk Geologisk Tidsskrift* 25, 159–167.
- HALD, M. & VORREN, T.O. 1983. A shoreline displacement curve from the Tromsø district, North Norway. *Norsk Geologisk Tidsskrift* 63, 103–110.
- HEDGPETH, J.W. 1957. Estuaries and lagoons. II. Biological aspects. 693–729. In HEDGPETH, J.W. (ed.) *Treatise on Marine Ecology and Paleocology, Volume 1 Ecology, The Geological Society of America, Memoir 67*.
- HELAMA, S., HEIKKILÄ, P., RINNE, K., NIELSEN, J.K. & NIELSEN, J.K. 2015. LA-ICP-MS-derived U-concentrations and microstructural domains within biogenic aragonite of *Arctica islandica* shell. *Environmental Monitoring and Assessment* 187, article 260. DOI 10.1007/s10661-015-4495-5
- HELAMA, S., NIELSEN, J.K., NIELSEN, J.K., HANKEN, N.M. & EIVISON, K. 2014. Preboreal oscillations within the North Atlantic inferred from *Arctica islandica* sclerochronology. *Geobios* 47, 305–313. DOI 10.1016/j.geobios.2014.07.003
- HELAMA, S., SCHÖNE, B.R., KIRCHHEFER, A.J., NIELSEN, J.K., RODLAND, D.L. & JANSSEN, R. 2007. Compound response of marine and terrestrial ecosystems to varying climate: pre-anthropogenic perspective from bivalve shell growth increments and tree-rings. *Marine Environmental Research* 63, 185–199. DOI 10.1016/j.marenvres.2006.08.003
- HILMO, B.O. 2011. *Grunnvannskartlegging i Tromsø Kommune [Groundwater Mapping in Tromsø Municipality]*. 18 pp. Asplan Viak AS, Report VRL46-2011-001.
- HOLMES, G.W. & ANDERSEN, B.G. 1964. Glacial chronology of Ullsfjord, northern Norway. *U.S. Geological Survey Professional Paper* 475, D159–D163.
- HUMMEL, H. 1985. Food-in take of *Macoma balthica* (Mollusca) in relation to seasonal changes in its potential food on a tidal flat in the Dutch Wadden Sea. *Netherlands Journal of Sea Research* 19, 52–76. DOI 10.1016/0077-7579(85)90043-2
- HUNTER, W.R. 1949. The structure and behaviour of *Hiatella gallicana* (Lamarck) and *H. arctica* (L.), with special reference to the boring habit. *Proceedings of the Royal Society of Edinburgh. Section B. Biology* 63, 271–289. DOI 10.1017/S0080455X00011930
- HURRELL, J.W., 1995. Decadal trends in the North Atlantic oscillation, regional temperatures and precipitation. *Science* 269, 676–679. DOI 10.1126/science.269.5224.676
- HURRELL, J.W. & DESER, C. 2010. North Atlantic climate variability: the role of the North Atlantic oscillation. *Journal of Marine Systems* 79, 231–244. DOI 10.1016/j.jmarsys.2009.11.002
- HØISÆTER, T., SNELI, J.A., WIKANDER, P.B. & BRATTEGARD, T. 2001a. Bivalvia, 264–278. In BRATTEGARD, T. & HOLTHE, T. (eds) *Distribution of Marine, Benthic Macroorganisms in Norway. A Tabulated Catalogue. Directorate for Nature Management, Research Report 2001-3*.
- HØISÆTER, T., SNELI, J.A., WIKANDER, P.B. & BRATTEGARD, T. 2001b. Prosobranchia, 230–247. In BRATTEGARD, T. & HOLTHE, T. (eds) *Distribution of Marine, Benthic Macroorganisms in Norway. A Tabulated Catalogue. Directorate for Nature Management, Research Report 2001-3*.
- JENSEN, A.S. 1901. Studier over nordiske Mollusker [Studies on Nordic molluscs]. *Videnskabelige Meddelelser fra den Naturhistoriske Forening i Kjøbenhavn 1900*, 133–158.
- JENSEN, A.S. & SPÆRCK, R. 1934. *Bløddyr II. Saltvandsmuslinger [Molluscs II. Saltwater Bivalves]*. 280 pp. Dansk Naturhistorisk Forening, G.E.C. Gads Forlag, København. *Danmarks Fauna* 40.
- JØRGENSEN, C.B. 1981. Mortality, growth, and grazing impact on a cohort of bivalve larvae, *Mytilus edulis* L. *Ophelia* 20, 185–192. DOI 10.1080/00785236.1981.10426570
- KARTVERKET 2015. *Tidevannstabeller. For den Norske Kyst med Svalbard samt Dover, England [Tidal Tables. For the Norwegian Coast with Svalbard and Dover, England]*. 89 pp. 79. Årgang 2016.
- KERCKHOF, F. 2002. Barnacles (Cirripedia, Balanomorpha) in Belgian waters, an overview of the species and recent evolutions, with emphasis on exotic species. *Bulletin de l'Institut*

- Royal des Sciences Naturelles de Belgique, *Biologie* 72 (Supplement), 93–104.
- KIDWELL, S.M. & BOSENCE, D.W.J., 1991. Taphonomy and time-averaging of marine shelly faunas, 115–209. In ALLISON, P.A. & BRIGGS, D.E.G. (eds) *Taphonomy. Releasing the Data Locked in the Fossil Record*. Plenum, New York.
- KLÆR, H. 1902. Niveauforandring eller transport ved drivis [Level changes or transport by drift ice]. *Naturen, Bergens Museum*, 1902 (12), 364–367.
- KLÆR, H. 1908. Om kvartærtidens marine afleiringer ved Tromsø [About Quaternary marine deposits at Tromsø]. *Tromsø Museum Aarshefter* 25(1902), 17–44.
- KOWALEWSKI, M., FLESSA, K.W. & HALLMAN, D.P. 1995. Ternary taphograms: triangular diagrams applied to taphonomic analysis. *Palaios* 10, 478–483. DOI 10.2307/3515049
- KRANZ, P.M. 1974. The anastrophic burial of bivalves and its paleoecological significance. *Journal of Geology* 82, 237–265. DOI 10.1086/627961
- LEVENTHAL, J.S. 1995. Carbon-sulfur plots to show diagenetic and epigenetic sulfidation in sediments. *Geochimica et Cosmochimica Acta* 59, 1207–1211. DOI 10.1016/0016-7037(95)00036-Y
- LINDAHL, O., BELGRANO, A., DAVIDSSON, L. & HERNROTH, B. 1998. Primary production, climatic oscillations, and physico-chemical processes: the Gullmar Fjord time-series data set (1985–1996). *ICES Journal of Marine Science* 55, 723–729. DOI 10.1006/jmsc.1998.0379
- LINNAEUS, C. 1758. *Systema naturæ per regna tria naturæ, secundum classes, ordines, genera, species, cum characteribus, differentiis, synonymis, locis*. 10th edition, 1. 824 pp. Laurentii Salvii, Holmiæ.
- LINNAEUS, C. 1767. *Systema naturæ per regna tria naturæ, secundum classes, ordines, genera, species cum characteribus, differentiis, synonymis, locis*. 12th edition, 2. 533–1327 pp. Laurentii Salvii, Holmiæ.
- LYNCH, J. 1990. Provisional elemental values for eight new geochemical lake sediment and stream sediment reference materials LKSD-1, LKSD-2, LKSD-3, LKSD-4, STSD-1, STSD-2, STSD-3 and STSD-4. *Geostandards Newsletter* 14, 153–167. DOI 10.1111/j.1751-908X.1990.tb00070.x
- MADSEN, F.J. 1949. Marine Bivalvia. *The Zoology of Iceland* 4(63), 1–116.
- MANGERUD, J. 1972. Radiocarbon dating of marine shells, including a discussion of apparent age of recent shells from Norway. *Boreas* 1, 143–172. DOI 10.1111/j.1502-3885.1972.tb00147.x
- MANGERUD, J. 1977. Late Weichselian sediments containing shells, foraminifera, and pollen, at Ågotnes, western Norway. *Norsk Geologisk Tidsskrift* 57, 23–54.
- MANGERUD, J., BONDEVIK, S., GULLIKSEN, S., HUFTHAMMER, A.K. & HØISETER, T. 2006. Marine ¹⁴C reservoir ages for 19th century whales and molluscs from the North Atlantic. *Quaternary Science Reviews* 25, 3228–3245. DOI 10.1016/j.quascirev.2006.03.010
- MANGERUD, J. & GULLIKSEN, S. 1975. Apparent radiocarbon ages of Recent marine shells from Norway, Spitsbergen, and Arctic Canada. *Quaternary Research* 5, 263–273. DOI 10.1016/0033-5894(75)90028-9
- MARTHINUSSEN, M. 1962. ¹⁴C-datings referring to shore lines, transgressions, and glacial substages in northern Norway. *Norges Geologiske Undersøkelse, Årbok* 215, 37–67.
- METTE, M.J., WANAMAKER, A.D. JR., CARROLL, M.L., AMBROSE, W.G. JR. & RETELLE, M.J. 2015. Linking large-scale climate variability with *Arctica islandica* shell growth and geochemistry in northern Norway. *Limnology and Oceanography* 61, 2016, 748–764. DOI 10.1002/lno.10252
- MONTAGU, G. 1808. *Supplement to Testacea Britannica*. 183 pp. S. Woolmer, Exeter.
- MÖLLER, H.P.C. 1842. *Index molluscorum Groenlandiæ*. 24 pp. I.G. Salomon, Hafniæ. DOI 10.5962/bhl.title.10433
- MORSE, J.W. & BERNER, R.A. 1995. What determines sedimentary C-S ratios? *Geochimica et Cosmochimica Acta* 59, 1073–1077. DOI 10.1016/0016-7037(95)00024-T
- MØLLER, J.J. 1987. Shoreline relation and prehistoric settlement in northern Norway. *Norsk Geografisk Tidsskrift* 41, 45–60. DOI 10.1080/00291958708552171
- MØLLER, J.J. 1989. Geometric simulation and mapping of Holocene relative sea-level changes in northern Norway. *Journal of Coastal Research* 5, 403–417.
- MØLLER, J.J., FJALSTAD, A., HAUGANE, E., JOHANSEN, K.B. & LARSEN, V. 1986. Kvartærgeologisk verneværdige områder i Troms [Quaternary geologically worth preserving areas in Troms]. *Tromsø, Naturvitenskap* 49, 1–302.
- MÜLLER, O.F. 1776. *Zoologiae Danicæ prodromus, seu Animalium Danicæ et Norvegiæ indigenarum characteres, nomina, et synonyma imprimis popularium*. 274 pp. Typiis Hallageriis, Havnæ. DOI 10.5962/bhl.title.63795
- MÜLLER, O.F. 1779. Von zwoen wenig bekannten Muscheln, der Schinkenarche und der gerunzelten Mahlermuschel. *Beschäftigungen der Berlinischen Gesellschaft naturforschender Freunde* 4, 55–59.
- NIELSEN, J.K. 2004. Taphonomy in the light of intrinsic shell properties and life habits: Marine bivalves from the Eemian of northern Russia. *Paläontologische Zeitschrift* 78, 53–72. DOI 10.1007/BF03009130
- NIELSEN, J.K., HANKEN, N.-M. & NIELSEN, J.K. 2004. The relationships between early diagenetic calcite concretions and shell dissolution in subaerially exposed Holocene marine sediments, North Norway. *Abstracts, Scientific Sessions, 32nd International Geological Congress* 32(1), p. 166.
- NIELSEN, J.K., HELAMA, S. & NIELSEN, J.K. 2008. Taphonomy of freshwater molluscs in carbonate-poor deposits: a case study of the river pearl mussel in northeastern Finnish Lapland. *Norwegian Journal of Geology* 88, 103–116.
- NYDAL, R. 1960. Trondheim natural radiocarbon measurements II. *American Journal of Science Radiocarbon Supplement* 2, 82–96. DOI 10.1017/S1061592X00020627
- OCKELMANN, W.K. 1958. The zoology of East Greenland. *Meddelelser om Grønland* 122, 1–256.
- ÓLAFSSON, E.B. 1986. Density dependence in suspension-feeding and deposit-feeding populations of the bivalve *Macoma*

- balthica*: a field experiment. *Journal of Animal Ecology* 55, 517–526. DOI 10.2307/4735
- OLIVER, P.G., HOLMES, A.M., KILLEEN, I.J. & TURNER, J.A. 2016. Marine bivalve shells of the British Isles. Amgueddfa Cymru – National Museum Wales. <http://naturalhistory.museumwales.ac.uk/britishbivalves>
- PEACOCK, J.D. 1993. Late Quaternary marine mollusca as palaeoenvironmental proxies: a compilation and assessment of basic numerical data for NE Atlantic species found in shallow water. *Quaternary Science Reviews* 12, 263–275. DOI 10.1016/0277-3791(93)90082-W
- PENNANT, T. 1777. *British Zoology. Vol. IV. Crustacea. Mollusca. Testacea*. 154 pp. Benj. White, London.
- PETERSEN, C.G.J. 1913. Valuation of the sea. II. The animal communities of the sea bottom and their importance for marine zoogeography. *Reports of the Danish Biological Station* 21, 1–44.
- PETERSEN, C.G.J. 1914. Appendix to report 21. On the distribution of the animal communities of the sea bottom. *Reports of the Danish Biological Station* 22, 1–7.
- PETERSEN, C.G.J. 1918. The sea bottom and its production of fish-food. A survey of the work done in connection with valuation of the Danish waters from 1883–1917. *Reports of the Danish Biological Station* 25, 1–62.
- PETERSEN, C.G.J. 1924. A brief survey of the animal communities in Danish waters, based upon quantitative samples taken with the bottom sampler. *American Journal of Science, Series 5*, 7, 343–354. DOI 10.2475/ajs.s5-7.41.343
- PETERSEN, G.H. 1958. Notes on the growth and biology of the different *Cardium* species in Danish brackish water areas. *Meddelelser fra Danmarks Fiskeri- og Havundersøgelser, New Series* 2(22), 1–31.
- PETERSEN, G.H. 1977. The density, biomass and origin of the bivalves of the Central North Sea. *Meddelelser fra Danmarks Fiskeri- og Havundersøgelser* 7, 221–273.
- PETERSEN, G.H. 1999. Five Recent *Mya* species, including three new species and their fossil connections. *Polar Biology* 22, 322–328. DOI 10.1007/s003000050425
- PETERSEN, G.H. 2001. Studies on some Arctic and Baltic *Astarte* species (Bivalvia, Mollusca). *Meddelelser om Grønland, Bioscience* 52, 1–71.
- PETERSEN, G.H. & RUSSELL, P.J.C. 1973. The nomenclature and classification of some European shallow-water *Cardium* species. *Malacologia* 14, 233–234.
- PETERSEN, K.S. 2004. Late Quaternary environmental changes recorded in the Danish marine molluscan faunas. *Geological Survey of Denmark and Greenland Bulletin* 3, 1–196.
- PETTERSEN, K. 1880. Terrasser og gamle strandlinjer [Terraces and old shorelines]. *Tromsø Museums Aarshefter* 3, 1–52.
- PHILIPPI, R.A. 1836. *Enumeratio molluscorum Siciliae cum viventium tum in tellure tertiaria fossilium, quae in itinere suo observavit. I.* 267 pp. Schropp, Berolini. DOI 10.5962/bhl.title.100735
- PHILIPPI, R.A. 1845. Kritische Bemerkungen über einige *Trochus*-Arten und die Gattung *Axinus*. *Zeitschrift für Malakozoologie* 1845(June), 87–91.
- POULSEN, E.M. 1935. De danske farvandes rurer (Balanomorpha og Verrucomorpha) [The Danish waters' barnacles (Balanomorpha and Verrucomorpha)]. *Videnskabelige Meddelelser fra Dansk Naturhistorisk Forening* 99, 5–27.
- POWILLEIT, M., GRAF, G., KLEINE, J., RIETHMULLER, R., STOCKMANN, K., WETZEL, M.A. & KOOP, J.H.E. 2009. Experiments on the survival of six brackish macro-invertebrates from the Baltic Sea after dredged spoil coverage and its implications for the field. *Journal of Marine Systems* 75, 441–451. DOI 10.1016/j.jmarsys.2007.06.011
- RAISWELL, R. & BERNER, R.A. 1986. Pyrite and organic matter in Phanerozoic normal marine shales. *Geochimica et Cosmochimica Acta* 50, 1967–1976. DOI 10.1016/0016-7037(86)90252-8
- RASMUSSEN, E. 1973. Systematics and ecology of the Isefjord marine fauna (Denmark). *Ophelia* 11, 1–507. DOI 10.1080/00785326.1973.10430115
- REES, E.I.S., NICHOLAIDOU, A. & LASKARIDOU, P. 1977. The effects of storms on the dynamics of shallow water benthic associations, 465–474. In KEEGAN, B.F., O'CEIDIGH, P. & BOADEN, P.J.S. (eds) *Biology of Benthic Organisms. 11th European Symposium on Marine Biology*.
- RICHARDSON, C.A., IBARROLA, I. & INGHAM, R.J. 1993. Emergence pattern and spatial distribution of the common cockle *Cerastoderma edule*. *Marine Ecology Progress Series* 99, 71–81. DOI 10.3354/meps099071
- REIMER, P.J., BARD, E., BAYLISS, A., BECK, J.W., BLACKWELL, P.G., BRONK RAMSEY, C., GROOTES, P.M., GUILDERSON, T.P., HAFLIDASON, H., HAJDAS, I., HATTÉ, C., HEATON, T.J., HOFFMANN, D.L., HOGG, A.G., HUGHEN, K.A., KAISER, K.F., KROMER, B., MANNING, S.W., NIU, M., REIMER, R.W., RICHARDS, D.A., SCOTT, E.M., SOUTHON, J.R., STAFF, R.A., TURNER, C.S.M. & PLICHT, J. VAN DER 2013. IntCal13 and Marine13 Radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869–1887. DOI 10.2458/azu_js_rc.55.16947
- RUDDIMAN, W.F. & MCINTYRE, A. 1973. Time-transgressive deglacial retreat of polar waters from the North Atlantic. *Quaternary Research* 3, 117–130. DOI 10.1016/0033-5894(73)90058-6
- RUSSELL, P.J.C. & PETERSEN, G.H. 1973. The use of ecological data in the elucidation of some shallow water European *Cardium* species. *Malacologia* 14, 223–232.
- SÆLEN, O.H. 1950. The hydrography of some fjords in northern Norway. Balsfjord, Ulfsfjord, Grøtsund, Vengsøyfjord and Malangen. *Tromsø Museums Årshefter, Naturhistorisk Avdeling Nr. 38, 70 (1947, No. 1)*, 1–102.
- SARS, G.O. 1878. *Bidrag til Kundskaben om Norges arktiske Fauna. I. Mollusca Regionis Arcticae Norvegiae. Oversigt over de i Norges arktiske Region forekommende Bløddyr [Contribution to the Knowledge about Norway's Arctic Fauna. I. Mollusca Regionis Arcticae Norvegiae. Overview over Molluscs occurring in Norway's Arctic Region]*. 466 pp. A.W. Brøgger, Christiania. DOI 10.5962/bhl.title.42224
- SCHÄFER, W. 1962. *Aktuo-paläontologie nach Studien in der Nordsee*. 666 pp. Verlag Waldemar Kramer, Frankfurt am Main.

- SCHUMACHER, C.F. 1817. *Essai d'un nouveau système des habitations des vers testacés*. 287 pp. Schultz, Copenhagen.
- SCRUTON, P.C. 1960. Delta building and the deltaic sequence, 82–102. In SHEPARD, F.P., PHLEGER, F.B. & VAN ANDEL, T.H. (eds) *Recent Sediments, Northwest Gulf of Mexico*. American Association of Petroleum Geologists, Special Publication 21.
- SNELI, J.A. & BRATTEGARD, T. 2001. Cirripedia, 152–155. In BRATTEGARD, T. & HOLTHE, T. (eds) *Distribution of Marine, Benthic Macroorganisms in Norway. A Tabulated Catalogue*. Directorate for Nature Management, Research Report 2001-3.
- SOOT-RYEN, T. 1924. Faunistische Untersuchungen im Ramfjorde. *Tromsø Museums Aarshefter* 45 (1922, No. 6), 1–106.
- SOOT-RYEN, T. 1932. Hydrographical investigations in the Ramfiord 1924–25. *Tromsø Museums Årshefter, Naturhistorisk Avdeling Nr. 2*, 51 (1928, No. 4), 1–21.
- SOOT-RYEN, T. 1934. Hydrographical investigations in the Tromsø District 1930. *Tromsø Museums Årshefter, Naturhistorisk Avdeling Nr. 3*, 52 (1929, No. 1), 1–78.
- SOWERBY, G.B. II 1842. *Thesaurus conchyliorum, or monographs of genera of shells. 1*, 438 pp. G.B. Sowerby, junior (ed.), Sowerby, London.
- SPENGLER, L. 1793. Beskrivelse over et nyt Slægt af de toskallede Konkylier, forhen af mig kaldet Chæna, saa og over det Linnéiske Slægt Mya, hvilket nøiere bestemmes, og inddeles i tvende Slægter [Description of a new genus of the bivalved conchs, previously by me called Chæna, also of the Linnean genus Mya, which is determined in more details, and divided into two genera]. *Skrivter af Naturhistorie-Selskabet* 3(1), 16–69.
- STEPHENSEN, K. 1933. Havedderkopper (Pycnogonida) og Rankefødder (Cirripedia) [Sea Spiders (Pycnogonida) and Barnacles (Cirripedia)]. *Dansk Naturhistorisk Forening, G.E.C. Gads Forlag, København. Danmarks Fauna* 38, 1–158.
- TEBBLE, N. 1976. *British Bivalve Seashells. A Handbook for Identification*. 212 pp. British Museum (Natural History), Her Majesty's Stationary Office, Edinburgh, 2nd edition.
- THEISEN, B.F. 1973. The growth of *Mytilus edulis* L. (Bivalvia) from Disko and Thule district, Greenland. *Ophelia* 12, 59–77. DOI 10.1080/00785326.1973.10430120
- THOMPSON, I., JONES, D.S. & DREIBELBIS, D. 1980. Annual internal growth banding and life history of the ocean quahog *Arctica islandica* (Mollusca: Bivalvia). *Marine Biology* 57, 25–34. DOI 10.1007/BF00420964
- THOMSEN, E. & VORREN, T.O. 1986. Macrofaunal palaeoecology and stratigraphy in Late Quaternary shelf sediments off northern Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology* 56, 103–150. DOI 10.1016/0031-0182(86)90110-0
- THORSON, G. 1933. Investigations on shallow water animal communities in the Franz Joseph Fjord (East Greenland) and adjacent waters. *Meddelelser om Grønland* 100(2), 1–68.
- THORSON, G. 1934. Contributions to the animal ecology of the Scoresby Sound fjord complex (East Greenland). *Meddelelser om Grønland* 100(3), 1–67.
- THORSON, G. 1957. Bottom communities (sublittoral or shallow shelf), 461–534. In HEDGPETH, J.W. (ed.) *Treatise on Marine Ecology and Paleocology Vol. I. Geological Society of America Memoir* 67. DOI 10.1130/MEM67V1-p461
- VORREN, T.O., STRASS, I.F. & LIND-HANSEN, O.W. 1978. Late Quaternary sediments and stratigraphy on the continental shelf off Troms and West Finnmark, northern Norway. *Quaternary Research* 10, 340–365. DOI 10.1016/0033-5894(78)90026-1
- WIBORG, K.F. 1962. Haneskjellet, *Chlamys islandica* (O. F. Müller) og dets utbredelse i noen nordnorske fjorder [The Iceland scallop, *Chlamys islandica* (O. F. Müller) and its distribution in some northern Norwegian fjords]. *Fisken og Havet, Rapporter og Meldinger fra Fiskeridirektoratets Havforskningsinstitutt Bergen*, 1963(3), 17–23.
- WIBORG, K.F. 1963. Some observations on the Iceland scallop *Chlamys islandica* (O.F. Müller) in Norwegian waters. *Fiskeridirektoratets Skrifter Serie Havundersøkelser* 13, 38–53.
- WIKANDER, P.B. 1980. Biometry and behaviour in *Abra nitida* (Müller) and *A. longicallus* (Scacchi) (Bivalvia, Tellinacea). *Sarsia* 65, 255–268. DOI 10.1080/00364827.1980.10431488
- WITBAARD, R. 1996. Growth variations in *Arctica islandica* L. (Mollusca): a reflection of hydrography-related food supply. *ICES Journal of Marine Science* 53, 981–987. DOI 10.1006/jmsc.1996.0122
- WITBAARD, R. & BERGMAN, M.J.N. 2003. The distribution and population structure of the bivalve *Arctica islandica* L. in the North Sea: what possible factors are involved? *Journal of Sea Research* 50, 11–25. DOI 10.1016/S1385-1101(03)00039-X