



What do Holocene sediments in Petuniabukta, Spitsbergen reveal?

Alexandra BERNARDOVÁ and Jiří KOŠNAR

*Faculty of Science, University of South Bohemia,
Branišovská 31, CZ-37005 České Budějovice, Czech Republic
<alex.bernardova@gmail.com> <jiri.kosnar@prf.jcu.cz>*

Abstract: Studies of past vegetation from the inner fjords of the Svalbard archipelago have not previously been reported. This study assesses the potential of sediments retrieved from two sites in Petuniabukta, Billefjorden to track vegetation response to Quaternary climate change. The first sediment profile was retrieved from periodic lake on a 4 m a.s.l. marine terrace with a basal radiocarbon dated to $5\,080 \pm 30$ BP, the second was retrieved from a depression in wet tundra on a 24 m a.s.l. marine terrace, which upper part was dated to $9\,470 \pm 30$ BP. The study is primarily focused on macro- and micro-fossils. Pollen grains are present in very low concentrations. Macro-fossils were represented mostly by leaf and buds of *Salix* species and *Dryas octopetala* as well as the hybrid *Salix herbacea* x *polaris*. Fossil moss remains represent an important part of arctic ecosystems. Tardigrada remains were found in the sediments in high abundance whilst eggs and exuviae of at least six species were identified. The sediments are definitely suitable for the reconstruction of past conditions. However, it is necessary to take care not to focus at single type of analysis, as pollen analysis appeared uninformative and more information was obtained from plant macro-fossils (mosses, vascular plants). Little attention has been given to Tardigrada in the past, as they were overlooked and the preservation in sediments is usually very low.

Key words: Arctic, Svalbard, plant macro-fossils, Tardigrada, *Salix herbacea* x *polaris*.

Introduction

Pronounced environmental changes have been occurring in the Arctic over the past few centuries (Overpeck *et al.* 1997). This is evident by the rapid rate at which glaciers are retreating (Rachlewicz *et al.* 2007) and by enhanced sedimentation rates in fjords (Szczeniński *et al.* 2009). Changes in vegetation are recorded by plants (Moritz *et al.* 2002) that respond to changes in temperature or humidity through variations in biomass production, vegetative or sexual reproduction, species migration *etc.* (Callaghan *et al.* 2004). Palaeoecological research, which uses

the record of changes in fossil plant and animal assemblages together with sediment characteristics, provides valuable data for reconstructing past local climate and other environmental variables (Birks and Birks 2006). Sediment records from the Arctic provide a unique data-set of biotic changes especially due to the fact that this area has been protected from human impact until recent times (Birks 2007). This pilot study presents the results from two shallow lake sediment cores obtained during a summer expedition in 2009, which was primarily focused on a survey of Billefjorden, central Svalbard.

Background information

Paleoclimatic history of Svalbard. — The last glacial maximum on Svalbard was dated to 18 000–15 000 yr cal BP (Forman *et al.* 2004). According to geomorphological studies, Svalbard was largely covered with ice at this time (Landvik *et al.* 2003). The deglaciation of Svalbard had started by at least 13 000 cal yr BP (in the west and north), with the eastern part being deglaciated *ca* 10–10 500 yr ago (Birks *et al.* 1994; Forman *et al.* 2004). Deglaciation started shortly after the last glacial maximum in the south-west part of Bellsund (Landvik *et al.* 2005). The deglaciation of Isfjorden occurred about 12 300 cal yr BP and the whole archipelago became glaciated to the present extent by 10 000 cal yr BP (Mangerud *et al.* 1992).

Mean summer temperatures were probably below 0°C during the Late Weichselian. Sedimentary records from Svalbard, together with pollen and marine molluscan data, indicate that the climate was approximately 1 to 2°C warmer than today from 9 500 to 4 000 cal yr BP (Svendsen and Mangerud 1997). A warmer than present climate during the early and mid-Holocene enabled some thermophilous species (*e.g.* *Mytilus edulis*, *Salix herbacea*) to spread northwards and/or deeper in the inner part of the island respectively (Rozema *et al.* 2006; Salvigsen 1992). Gradual cooling accompanied by the advance of glaciers began around 2 800 cal yr BP and culminated in the Little Ice Age (LIA) dated to 700–100 cal yr BP (Elverhoi *et al.* 1995; Szczuciński *et al.* 2009). According to ice cores and marine sedimentary records, the LIA was probably the coolest period within the Holocene (Isaksson *et al.* 2003; Majewski *et al.* 2009).

The contemporary climate of Svalbard is influenced by the West Spitsbergen Current and thus is relatively mild, being considered as arctic-oceanic. Mean annual temperature is -5.3°C for Svalbard with an annual precipitation of about 400 (western coast) to 200 mm (inner fjord) (Birks *et al.* 2004).

Pollen and macrofossil analysis in the arctic. — Pollen analysis is one of the basic methods employed in palaeoecology. The obtained data usually enable reconstruction of terrestrial vegetation based on the composition of the pollen spectra (Bennett and Willis 2002). In contrast to pollen analysis, the macrofossil con-

ment in sediment reflects the development of the local area and does not necessarily represent average plant cover of the surrounding landscape as these remnants are generally not dispersed far from the parent plant (Birks 2002). Macrofossils can often be identified to a higher taxonomic level, which allows for the tracking of taxa that produce a low amount or no pollen, *e.g.* mosses (Birks *et al.* 2000; Birks and Birks 2000). Mosses play an important role in the plant communities. They have specific habitat requirements and may indicate conditions and interspecific relationships in the community (Dickson 1986; Jonsgard and Birks 1995).

In the Arctic, local pollen production is sparse and the pollen signal is often mixed up by pollen that has been transported from large distances (van der Knaap 1987a). However, the dispersal of macrofossils in treeless conditions can be also effective. The remains can be transported long distances from their source by melting snow or rivers, while winter winds can disperse seeds and fruits many kilometers over a smooth winter snow-surface (Birks 1991). It seems that plant macrofossils should be a better tool for reconstructing past events under arctic conditions although the combination of both methods is optimal.

Vegetation history of Svalbard. — The past vegetation on the Svalbard archipelago has previously been studied predominantly using pollen analysis. For a schematic map indicating the position of studied localities see Fig. 1. The first studies were undertaken during the 1960's (Häggblom 1963; Blake *et al.* 1965). Hyvärinen (1968, 1970) continued in pollen studies and found a similar flora as nowadays at 11000 BP. The studies of van der Knaap from 1985–1991 described changes in the past vegetation and documented the stability of vegetation at bird manured sites (van der Knaap 1988a, b). A comprehensive study of the history of past vegetation investigations on Svalbard was compiled by Jankovská (1995). In contrast, macrofossil analysis had been conducted only in a few cases (Birks 1991; van der Knaap 1985). There have been only a few palaeoecological studies from Svalbard published in the last decade, which is surprising given the interest in Arctic climate change and palaeoenvironmental change (Isaksson *et al.* 2003; Birks *et al.* 2004; Rozema *et al.* 2006).

Van der Knaap (1988c, 1989) suggest that the vegetation of Svalbard was moderately rich in species before *ca* 4000 BP, supporting a similar observation made by Birks (1991). Species richness at the lower part of a sediment core collected from Skadjørna lake (dated to *ca* to 8 000 to 4 000 cal yr BP) was higher than in the upper parts (Birks 1991). Vegetation, dominated mostly by Brassicaceae and Cyperaceae pollen, was found on nutrient-rich sites such as bird cliffs or skua mounds, accompanied with *Salix polaris* pollen during warmer and wetter climate and with pollen of *Saxifraga oppositifolia* during colder and drier periods (Rozema *et al.* 2006; van der Knaap 1988a, b). Van der Knaap (1985) found nutrient-enriched soils in the area of Smeerenburg inhabited by Dutch whalers. The presence of settlement was proven by the replacement of dense grass mats of *Phippisia* by open moss vegetation dominated by *Drepanocladus* species and allochthonous pollen types, such as *Erica* or

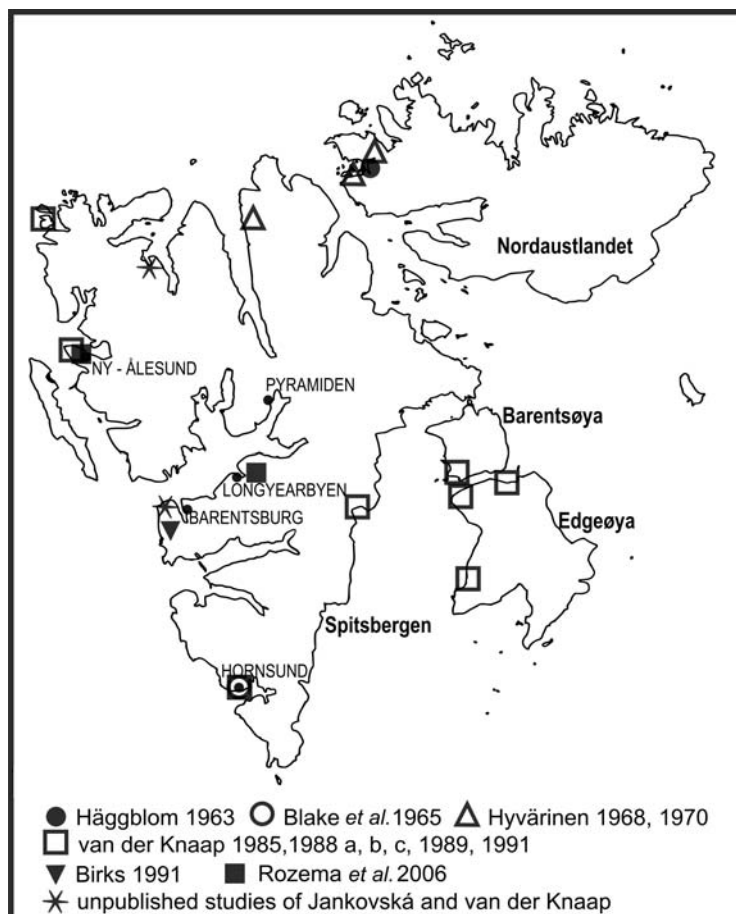


Fig. 1. Schematic map with localities of studies on past vegetation. For more details, refer to the references.

Cerealia, that were carried to the study area by the whalers. After the abandonment of the area, local succession of *Phippsia* was observed in the fossil record.

All of the studies mentioned above mostly concern the outer part of the island, whereas studies from the inner fjord are limited in number, although a sediment core from the vicinity of Pyramididen was studied by Jankovská in 1988 (V. Jankovská, personal communication). There are a few old studies concerning Svalbard in Russian (Serebryanny *et al.* 1984, 1993; Surova *et al.* 1988; Zelikson 1971).

Study site

Billefjorden, which is located in the central part of Spitsbergen, the main island of the Svalbard archipelago (Fig. 2), was ice free by about 11 200–11 300 cal

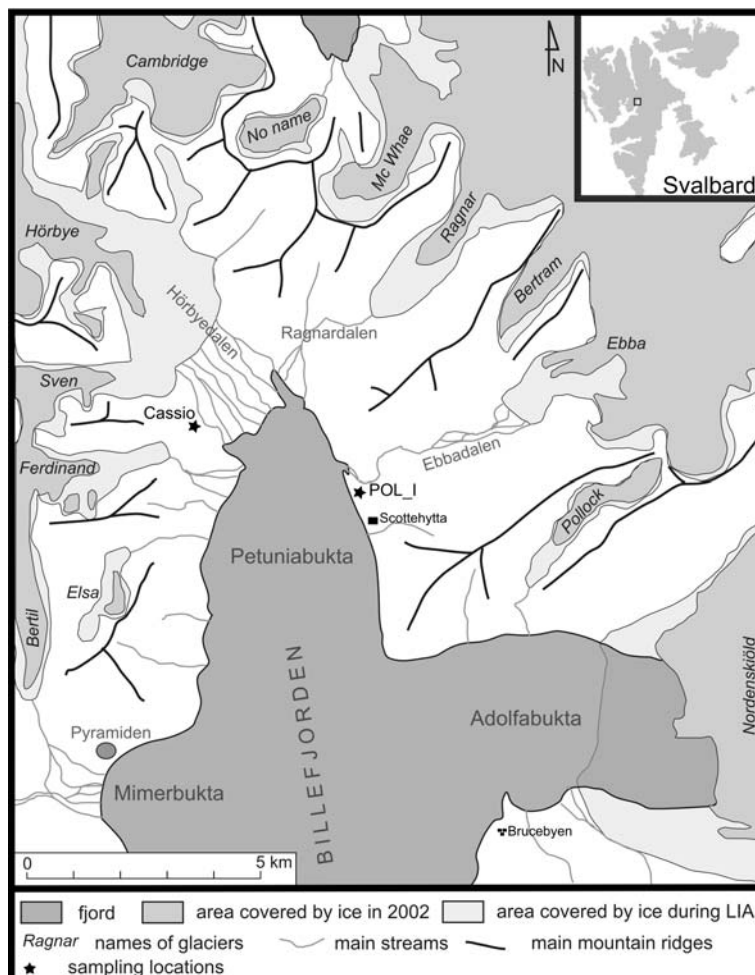


Fig. 2. Map of the studied area with sampling locations, after Rachlewicz *et al.* (2007).

yr BP (Beaten *et al.* 2010). Two Late Pleistocene (87 ky, 40–56 ky Petuniabukta stage) and three Holocene (8 000–9 000 yr Ebbadalen stage; 2 000–3 000 yr; 500–100 yr LIA) glacial periods are distinguished in the Billefjorden region (Kłysz *et al.* 1988). Raised marine beaches at 40–45 m, 30–35 m, and 20–25 m were developed between Petuniabukta and the Ebbadalen stage when successive warming took place. Subsequent beaches at 12–15 and 5–8 m a.s.l. were developed during the Middle Holocene warming (8 000–4 000cal yr BP), while the lowest beach is connected to glacial advance during the LIA.

Annual precipitation in Billefjorden is about 200 mm. Average annual temperature is about -6.5°C, with mean July temperatures of 5–6°C, although recently above 7°C (Rachlewicz *et al.* 2007). Five vegetation types were classified for the area of Petuniabukta by Prach *et al.* (2010). These types are listed in Table 1.

Table 1
 Vegetation types in the area of Petuniabukta after Prach *et al.* (2010)

1	Open stands dominated by <i>Dryas octopetala</i> . Vegetation cover is low, usually less than 20%, occurring on dry, exposed or changeable sites. Moss cover is relatively low, usually under 5%.
2	Stands dominated by <i>Dryas octopetala</i> accompanied by <i>Carex misandra</i> . This vegetation type occurs on wetter sites than (1) and (3). <i>Salix polaris</i> is frequent. Moss cover is usually well developed (ca 50%).
3	Closed tundra stands dominated by <i>Dryas octopetala</i> and accompanied by <i>Carex rupestris</i> . Vegetation cover is usually about 50%, occurring on less exposed, stabilised substrates. <i>Cassiope tetragona</i> occurs locally, on more snow-protected sites. This may represent the potential (“climax”) vegetation in this area (Walton 1922; Elvebakk 2005). The moss layer is similar to the previous unit.
4	Stands dominated by mosses, especially <i>Scorpidium cossonii</i> , <i>S. revolvens</i> , <i>S. scorpioides</i> , <i>Pseudocalliergon brevifolium</i> , <i>P. turgescens</i> , and <i>P. trifarium</i> , on peaty soils of various thickness. In addition, <i>Carex subspathacea</i> is very typical of depressions between hummocks, <i>i.e.</i> cryogenic forms developed in this compact vegetation.
5	Stream marginal vegetation. A highly variable and changeable vegetation mosaic is found along the streams (Acock 1940). <i>Carex parallela</i> , <i>C. misandra</i> , <i>Dupontia psilosantha</i> , <i>Eriophorum angustifolium</i> subsp. <i>triste</i> and <i>Juncus biglumis</i> are the most frequent species. The moss layer is well developed, but typically reaches lower cover than the previous unit.

Methods

Sampling. — Two sites were sampled in August 2009. A trench was made to extract the sediments for palaeoecological analysis till the gravel terrace was reached and no further sampling was possible. Because of limited opportunity of transport, the profile was sampled directly from the side wall of the trench with 3 cm intervals placed into separate plastic bags. The volume of each sample was approximately 200 cm³. A list of current vegetation was made for the area around each sampling site. From each sample, 10 cm³ were removed for further analysis (pollen analysis, LOI), 10 cm³ were kept for reference and the rest was used for analysis of macro-fossils.

Sediment description and chronology. — Samples for radiocarbon dating were processed at the “CAIS lab” in Georgia, USA. Radiocarbon data were calibrated using “ClamR” software by Blaauw (2010). Marine reservoir effect of 440 years was used (Mangerud and Gulliksen 1975) for calibrating sea shell data.

Core POL_1

A sample core was obtained from a small periodic lake located close to the hut “Scottehytta” (N 78°42.179', E 16°36.901') (Fig. 2). The lake is close to the sea, at the end of Ebba River, on a Holocene raised beach ca 4 m a.s.l. (above sea level). The lake has a surface area of ca 1 000 m² and a maximum water depth of 0.6 m and turns to wetland marsh at the end of season (Fig. 3). Samples were collected in mid-August when there was almost no water. Zwoliński *et al.* (2008) classified it



Fig. 3. Sampling site POL_I. The position of trench is marked with black circle. Photo taken in August 2009.

according to Warner and Rubeck (1997) as a tundra lake located on a marine terrace. According to the study of Zwoliński *et al.* (2007), the lake is supplied by meltwater, by hillslope runoff and saturated overland flow from wetlands and creeks, and/or seasonal thawing of permafrost. The local vegetation of the lake/marsh is dominated by mosses, especially *Scorpidium cossonii*, *S. revolvens*, *S. scorpioides*, *Pseudocalliergon brevifolium*, *P. turgescens*, and *P. trifarium*, and higher plants such as *Eriophorum scheuchzeri* and *Carex subspathacea*. In the close vicinity the vegetation consist of sparse cover of *Dryas octopetala*, *Salix polaris* and *Polygonum viviparum* together with *Saxifraga oppositifolia*, *S. aizoides*, *S. cernua*, and *Draba* sp. The lithology of the core is described in Table 2.

Table 2

Lithology of core POL_ I

Depth (cm)	Lithology
0–3	active (fresh) moss layer
3–9	humidified peat with silt
9–15	sandy-clay sediment with irregular lamination
15–17	dark clay layer
17–18	sandy-clay sediment with irregular lamination
18–21	humidified peat layer
21–27	sandy-clay sediment with gravels and shell fragments
27 (core base)	gravel and shell fragments, predominantly <i>Astarte sulcata</i>

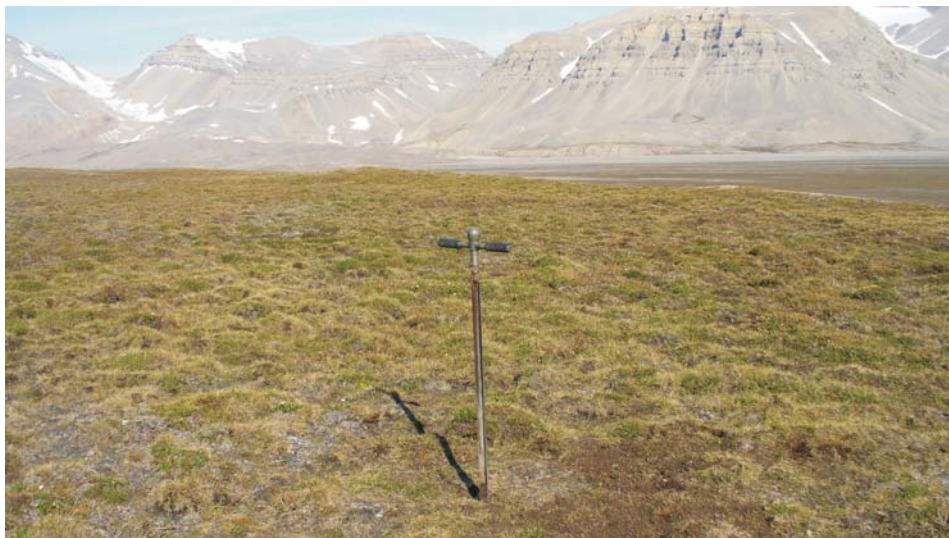


Fig. 4. Sampling site Cassio. The position of the trench is in the place of the soil corer. Photo taken in August 2009.

Core Cassio

The coring site of Cassio is situated at the 24 m a.s.l. marine terrace on the west side of Petuniabukta (N 78°43.062', E 16°26.337') (Fig. 2). The present-day vegetation is mature tundra with *Cassiope tetragona* (Fig. 4). Other recorded species are *Silene acaulis*, *Polygonum viviparum*, *Dryas octopetala*, *Salix polaris*, *Carex rupestris*, *C. misandra*, *Equisetum variegatum*, *Luzula arctica*, *Saxifraga aizoides*, *S. oppositifolia*, *Minuartia biflora*, *Pedicularis* sp., *Draba* sp., *Cerastium alpinum*, *Braya purpurascens*, and *Tofieldia pusilla*.

The lithology of core is described in Table 3. A shell fragment from 15 cm depth was radiocarbon dated to 9470 ± 30 BP (Table 4).

Table 3

Lithology of the core Cassio

Depth (cm)	Lithology
0–3	active (fresh) moss layer
3–25	sandy-clay sediment with sharp gravels
25–39	sandy-clay sediment with gravels
39 (core base)	gravel and shell fragments

Macrofossil and pollen analysis. — The sediment for pollen analysis was treated following standard methods (Berglund and Ralska-Jasiewiczova 1986) and examined under a light microscope with maximal magnification of 1000×. Samples for macrofossil analysis were soaked in water and washed through a 0.25 mm

Table 4
The results of radiocarbon dating of sediment layers. Calendar years (BP) with calibrated ranges at 2 sd are presented

Sample ID	Core name	Radiocarbon age (years BP)	Calendar years BP (at 2 sd)
UGAMS#8427, depth 11 cm, humified peat	POL_I	580 ± 25	587–645 (prob. 63.7%) 536–565 (prob. 31.1%)
UGAMS#5899, depth 25 cm, shell fragment (<i>Astarte sulcata</i>)	POL_I	5080 ± 30	5747–5832 (prob. 59.1%) 5841–5908 (prob. 35.8 %)
UGAMS#8426, depth 15 cm, shell fragment	Cassio	9470 ± 30	10647–10786 (prob. 82.8%)

mesh sieve. The residue was examined under a binocular microscope with maximal magnification of 400× and macrofossils were picked out. For determination of macro-fossils, the plant and seed collection of the Laboratory of Archaeobotany in České Budějovice, Czech Republic, and macrofossil keys (Anderberg 1994; Berggren 1964, 1981; Katz *et al.* 1965) were used. The concentrations of macrofossils were calculated to a volume of 100 cm³. The Braun-Blanquet (1928) ratio scale was used to express the abundance of mosses in the sample, which was transformed to percents for graphical visualization.

Results

Core POL_I

Very low pollen concentrations were found in the samples from POL_I (maximum of 30 pollen grains per 1 cm³), so the results were not incorporated into this study and no further pollen analysis was undertaken. On the other hand, Tardigrade exuviae and eggs were found on the pollen slides. These microfossils are not commonly used in palaeoecological studies, mainly because they have been reported only rarely (Jankovská 1991; Miller and Heatwole 2003).

The base of the core is dated to the mid-Holocene. This corresponds to the approximate age of the raised marine terraces analysed by Kłysz (1988). Wetland mosses dominate the entire core (Fig. 5). Moss fragments ascribed to *Scorpidium revolvens/cossoni* and *Pseudocalliergon brevifolium* were present from the core base (27 to 21 cm). The latter started to be abundant and then dominant between 21–18 cm, where it forms a visible moss layer. Its representation suddenly declines in the top stratigraphic unit, when is replaced by *Scorpidium revolvens/cossoni*. Other moss species, such as *Scorpidium scorpioides*, *Calliergon richardsonii*, *Bryum calophyllum*, and *Cinclidium arcticum*, were found only in minor quantities. The uppermost unit is dominated by *Scorpidium revolvens/cossoni*.

In the deepest part of the core (27–24 cm), leaf and bud fragments of *Salix polaris* and *Dryas octopetala* leaves were present in only a single occurrence. Their

abundance increased in upper layers. Other vascular-plant species were only rarely found. *Polygonum viviparum* bulbils were quite common in the top two layers. *Saxifraga oppositifolia*, considered as a pioneer species of deglaciated or newly emerged areas (Prach and Rachlewicz 2012 this issue), was found only in one case, at 12 cm depth. *Silene acaulis* was found only once, at 15 cm depth. Root and stem fragments of *Equisetum variegatum/scirpoides* were found in the two topmost layers.

Figure 5 presents the numbers of resting eggs or exuviae of Tardigrada found in the 1 cm³ of sediment prepared for pollen analysis. The laboratory preparation for pollen analysis (acetolysis) is not optimal for Tardigrada, as described by Cromer *et al.* (2008) but nevertheless provides a good preliminary overview for that proxy. *Macrobotus cf. harmsworthii* dominated the whole core. *Macrobotus cf. hastatus* and *M. cf. coronifer* were also abundant. Other species were found only rarely. Exuviae of *Echiniscus cf. blumii* were very abundant in the uppermost layer.

Core Cassio

According to Kłysz *et al.* (1988), the 20–25 m a.s.l. terrace, from which the Cassio sediment profile was obtained, is considered as one of the youngest Pleistocene terraces. However, the base of the core has not yet been dated. The only available radiocarbon date is for the 12–15 cm layer: 10 646–10 786 cal. BP with a marine reservoir effect of 440 years (Table 4). The results of the macrofossil analysis of the Cassio core are presented in Fig. 6. The first finds of macrofossils (Poaceae) are at 25 cm depth. *Dryas octopetala* leaves appear for the first time at 20 cm depth. Three species of *Salix* occur above 15 cm: *Salix reticulata*, *S. polaris* and *S. herbacea x polaris*. Mosses only occur in small amounts, just as fragments of leaves or stems, and could not be determined to species level. The lower part of the profile (39–25 cm) is poor in macrofossils, but with finds of *Equisetum* sp. roots that had very probably grown through from the upper layers. It seems that this sediment has still marine origin, although fragments of shells or sea urchins were found in upper parts as well, together with macro-fossils. It is surprising that although the trench was made in tundra with occurrence of *Cassiope tetragona*. This species was not found as macrofossils, not even in the topmost layer.

Discussion

Arctic or Antarctic lake environments are generally thought suitable for preservation of botanical and zoological macro- and microfossils. In our two lake sediment cores, pollen concentrations were very low and defied detailed analysis. In contrast, plant macrofossils were abundant, as were the remains of Tardigrada (in core POL_I). The latter are abundant likely due to the cold temperatures and the related lower pressure of predators (Cromer *et al.* 2008). The observed species could extend current knowledge about the biogeographic distribution of these species

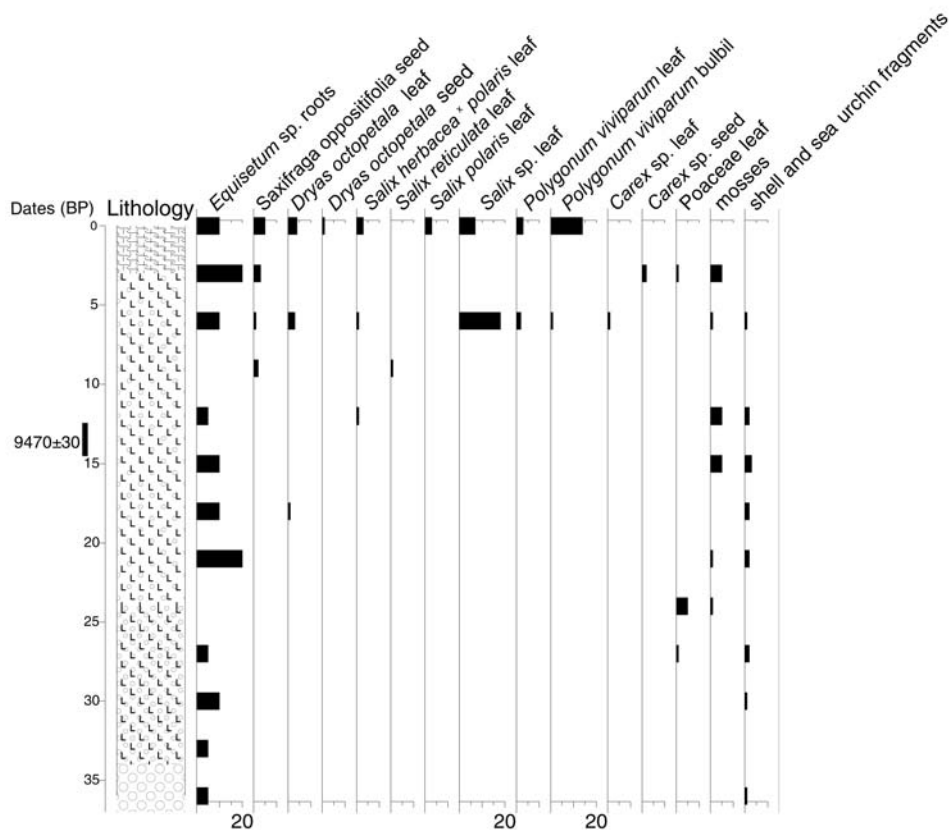


Fig. 6. The results of analysis of macro-fossils of the core Cassio. The macrofossil counts are given as the total count.

(Gibson *et al.* 2007; Cromer *et al.* 2008) and help to reconstruct past environmental conditions in the lake. However, the ecological conditions for Tardigrada are not well known yet. Similar findings were reported from Arctic regions (Svalbard) by Jankovská (1991), high altitudes in the Andes by Montoya *et al.* (2010) or from late glacial sediments from the Czech Republic (Jankovská 1990, 2006). The continuous presence of Tardigrada remnants, and also the occurrence of moss-dominated vegetation, indicate that water was accumulating there since the terrace uplift and then formed into a shallow lake.

Saxifraga oppositifolia is generally assumed to be one of the first colonizers of barren ground, only a few years after deglaciation or denudation of substrate. In the case of our work, both sample sites were drowned beneath the sea after the ice retreat and uplifted during the early and mid-Holocene respectively. It is surprising that this species appears only once in our two cores, when *Salix polaris* was the most abundant (in core POL_I) or after *Dryas* and *Salix* species appeared. According to Nakatsubo *et al.* (2010), *Salix polaris* can be recorded in deglaciated areas as

fast as within 70 years. The scarcity of *Saxifraga oppositifolia* in the samples could be caused by its sporadic occurrence on barren ground, and thus worsen its possibilities for preservation, or the fact that the lake formed sometime after deglaciation following emergence from the sea. However, the abundance of plant and animal remains (mosses, leaves of *Salix* and *Dryas*, Tardigrada remains) found at the core base suggests a very quick colonization of newly exposed land (Prach and Rachlewicz 2012 this issue).

The occurrence of the hybrid of *Salix polaris* and *S. herbacea* is of particular interest. *Salix herbacea* is now restricted to the southern part of the archipelago at Bjørnøya and Sørkappland (Rønning 1996), and hybrids are described from the same areas. Birks (1991) found fossil leaves of *Salix herbacea* in the sediment from Skardtjørna Lake, where its occurrence is correlated with the Holocene climatic optimum (9000 to 4000 BP). Hybrids produced viable seeds and were also reported from the west coast of Danskøya and Wijdefjorden and from Isfjorden (Elvebakk and Prestrud 1996). Hybrids were reported by the Cambridge polar expedition in 1927 from Whales and Mohn bay on the east coast of Spitsbergen (Michelmore 1927). A similar case could be the occurrence of *Salix herbacea* in Petuniabukta. It could be a relict since the Holocene optimum, when many species were more abundant and spread northwards (Birks 1991), or the viable seeds could have spread out through the island. The early Holocene radiocarbon date of the layer in Cassio core (10 646–10 786 cal. BP) agrees with the relative sea level data of Petuniabukta area. Since that the vegetation started to develop in mature tundra.

Conclusion

Sediments from the inner fjords of Svalbard have the potential to bring new insights into the development of vegetation since the last glaciation. To track the changes more precisely, a finer sub-division of the sample cores would be required. On the other hand, the method we used was adequate to demonstrate the initial colonization of the lakes studied and to prove the fossil occurrence of the warmth-demanding taxon, *Salix herbacea* x *polaris*, that spread to the inner fjord probably during the Holocene thermal optimum between 8000–4000 BP. This study has shown that tardigrade eggs and exuviae can be abundant in arctic lake sediments. With more detailed study they could provide insight into patterns of Tardigrada colonization of the area and related changes in ecological conditions.

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