Late Weichselian to early Holocene vegetation and bird activity on Andøya, Nordland County –

As evidenced primarily by macrofossils

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List of papers

1. Elverland, E. & Alm, T. **High resolution macrofossil analysis of Late Weichselian Arctic lacustrine sediments on Andøya, northern Norway.** *Manuscript*.

2. Elverland, E., Bjerke, J.W. & Alm, T. **Is one core enough? A study of the intrasite macrofossil variability of a Late Weichselian lacustrine record on Andøya, North Norway.** *Manuscript.*

3. Alm, T. & Elverland, E. **A Late Weichselian *Alle alle* colony on Andøya, northern Norway – a contribution to the history of an important Arctic environment**. *Manuscript.*

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Abstract

This thesis shows that Late Weichselian vegetation on Andøya may have been more diverse than previous studies have revealed.

The thorough investigation of macrofossils in four parallel cores provides more reliable evidence for interpreting changes in vegetation cover than reconstructions based on a single core. The botanical macrofossils retrieved in this study largely support previous studies at the northern tip of Andøya. Arctic plant communities, probably dominated by *Papaver* and several species of *Poaceae* and *Brassicaceae* characterized the area. Climatic ameliorations occurred at c. 22 000 – 20 100, 20 100 – 19 500, 19 500 – 19 200, 18 800 – 18 100, 17 500 – 16 800 and 15 100 – 14 500 cal. yr BP, and during these ameliorations, the vegetation may have been more diverse than recorded both in the pollen- and macrofossil material.

Macrofossils (bones) of little auk (*Alle alle*), coupled with other evidence, suggest a long-lasting presence of sea birds in the area. Manuring by birds made a considerable impact on the local terrestrial environment, and during the ameliorations in particular, these favorable local habitats may have supported species not found in the present-day Arctic, e.g. *Urtica dioica.*

Sedimentary ancient DNA (sedaDNA) provides evidence that during the ameliorations, Andøya may have hosted small enclaves of boreal conifer trees. Their presence on Andøya has yet to be detected by macrofossil- or pollen analyses, but the DNA evidence provides an important contribution to the debate concerning glacial survival of boreal trees within Scandinavia.

Introduction

The key to the future lies in the past. This statement is much used in connection to the ongoing and occasionally much heated climate debate. In fact, a Google search on “key to future lies in past” + “climate” results in c. 3 260 000 hits, so it seems safe to conclude that people are mostly agreeing on the statement. However, having agreed on that, a whole new set of issues arises. Why is it important to find the key? How are we going to find it? And what are we going to do with it, once found?

The importance lies in the climatic situation today. The ongoing global rapid climatic changes have led to much debate and been a controversial issue over the last couple of decades. Scientists, politicians, media and the public have discussed, and still argue about the extent of human impact on recent climate changes. It is believed that the current global warming is largely due to increased emissions of greenhouse gases, such as carbon dioxide (CO_2), into the atmosphere (IPCC 2007). During the last 100 years (1906-2005) global mean temperatures increased by 0.74 ±0.18 °C, and over the last 50 years the rate of warming almost doubled that of the last 100 years (Trenberth et al. 2007). High northern latitudes are warming more than middle latitudes (ACIA 2004, SWIPA 2011) – as such the Arctic serves as a beacon for the status of the rest of the world, and much focus is directed towards high northern latitudes, as future climatic changes will have strong impacts on their ecosystems (IPCC 2007).

However, a global climate change is nothing new – changes have occurred multiple times before in Earth’s history, but the current changes are unique. For the first time, human activity is a major agent, and the changes are also proceeding at a faster pace than previous climatic shifts. In fact, regional near-surface air temperatures in the Arctic have been rising at 2-4 times the global average rate (IPCC 2007, Bekryaev et al. 2010, Miller et al. 2010a). Temperatures exceeding those of the warmest periods of the Holocene, and also the last interglacial climate optimum c. 120 000 years ago, are expected (Frenzel et al. 1992, Miller et al. 2010b). It is therefore of academic and societal interest to understand past climatic changes and their impact on past ecosystems, and thus to be able to forecast how future climatic shifts will probably proceed and affect ecosystems at high northern, Arctic and boreal latitudes.

To find the key, a wealth of approaches is taken, and often geological and biological archives are applied in the search. By analyzing records from ice cores, marine sediment cores, speleothems, coral reefs, tree rings, pack rat middens, and terrestrial and lacustrine sediment cores among others, information is revealed using different proxies as tell-signs of past climatic changes. The present rapid climatic change may find its equivalent in climatic events occurring at the end of the last glaciation, when the Fennoscandian Ice Sheet (FIS), covering northern Europe and the western part of Russia, melted (Svendsen et al. 2004). At that time, the climate was unstable, with reduced annual temperatures (Bartlein et al. 2010). A subsequent gradual intrusion of Atlantic water (Ślublowska-Woldengen et al. 2008), and large pulses of fresh melt water, slowed the thermohaline circulation, leading to cooling events such as the Younger Dryas period (Greenland Stadial 1, GS-1) (Broecker et al. 1989, Björck et al. 1998, Alley & Clark 1999), which gave rapid climatic shifts. By investigating and comparing climate proxies from various archives, these past climatic shifts can be studied and render better comprehension of natural climate changes during the last deglaciation and the present interglacial period.

Which doors are opened by the key? For inferring future climate changes, climate models are used. These are computer simulations based on mathematical descriptions of accepted principles in nature. Thus, improved understanding of past natural climate changes are important for validating and strengthening climate models and for detecting and distinguishing present natural climatic changes from human-induced changes. Scientific doors are often opened slowly, inch by inch and solutions to limited research questions acts as placing small pieces in a giant puzzle, which when assembled leads to more realistic projections of future climate. Multiproxy approaches for inferring past climates are important, because various sources of information, although sometimes differing, lead to increased research effort and increased potential for improvement of climate models.

As a proxy for past climates, plant remains (pollen and macrofossils) in terrestrial and lacustrine sediment cores are commonly used, a field of biology called palynology or palaeobotany. The distribution patterns of any species are determined by several environmental factors. Knowing these conditions and coupling them with fossil remains give palaeobotanists a useful tool for interpreting past climates. However, both pollen and macrofossil analyses have pros and cons. Pollen, rendering more information on the regional flora, may be transported over greater distances, making the distinction between local and long-distance transported pollen difficult (Birks 2001). In addition, many pollen types can only be identified to genus rank. In Arctic environments, pollen production is low, and studies of surface samples have shown that many species present in the surrounding vegetation are rarely found as pollen (Pardoe 2001). The heavier macrofossils, on the other hand, are usually of a more local origin and can often be identified to species level, thereby providing information on the flora close to the deposition site. Macrofossils of species with low pollen production can also frequently be found (Birks 1973, 2001). However, macrofossil deposition into a lake may be arbitrary, occurring mainly by chance (H.H. Birks 2007, Dieffenbacher-Krall 2007) and only a small proportion of the potential plant remains are eventually preserved as macrofossils (Warner 1988).

In pollen analysis, solid methods for determining pollen-plant relationships and pollen distributions in sediments have been developed (e.g. Seppä 2007, and references therein), and robust numerical methods are being applied, although there are still problems to overcome (e.g. H.J.B. Birks 2007, and references therein). In macrofossil analysis, variable production and dispersal makes macrofossil-representation difficult to quantify beyond general terms, and fragments may result in misleading numbers (Birks & Birks 2000). By comparing the characteristics of pollen and seeds in sediments, Watts and Winter (1966) found that although some basic concepts of pollen analysis (e.g. regional parallelism, over-represented species, and pollen sum) could be applied also to seed analysis, seeds were not as suitable as pollen for statistical studies because they are less efficiently mixed in the seed rain, and macrofossils are often regarded as inferior to pollen analysis (Jackson & Booth 2007).

In temperate regions, macrofossils mostly represent the flora near the lake in which they are formed, whereas in the open, treeless Arctic and alpine communities, they may be blown in from a wider area, become trapped in snowbeds and deposited on the ground or into lakes during snowmelt (e.g. Warren Wilson 1958, Glaser 1981, Birks 1991, Dieffenbacher-Krall 2007). Therefore macrofossils can be transported from a larger area into Arctic and alpine lakes and sediments, but their contribution to the local macrofossil material in sediments is probably small (Birks 1991, 2007). Studies of the distribution patterns of seeds and larger plant fragments in Arctic and alpine areas, and their distribution in rivers and ponds (Ryvarden 1971, Glaser 1981, Holyoak 1984) show that macrofossils are generally not transported very far (not more than five meters in Ryvarden's study), and that water currents are involved in macrofossil sorting.

The island of Andøya in Nordland County, northern Norway, has a unique position only 5 km east of the shelf break. It was therefore deglaciated very early (Vorren et al. 1988), as the shelf broke off the large Fennoscandian Ice Sheet (FIS), obstruction the formation of a large ice dome. Sediment records from the lakes situated at the northern tip of the island are therefore important for studying Late Weichselian palaeoenvironments.

Main objectives/ aim and approach

This study aims to shed further light on the vegetation and climate development on Andøya (and hence in the northern part of Norway) from the Last Glacial Maximum (LGM) towards the shift to the Holocene, to achieve a high-resolution record of palaeobotanical changes in macrofossils replicated over several closely-spaced cores. Sub-goals of this study have been:

- To investigate the intrasite variation of macrofossils in parallel and replicated cores to reveal the degree of chance in macrofossil deposition into an Arctic glacial lake.
- To outline the ecological implications a colony of seabirds might have had on the ecosystem.
- To investigate the sediment using the technique of ancient DNA (sedaDNA), to retrieve further information about the local vegetation, which may not be

detected by the more traditional palaeobotanical techniques of pollen and macrofossil analyses.

Study area

The Island of Andøya (490 km^2) is the northernmost island of the Vesterålen archipelago in northern Norway at 69°55'N (Fig. 1). The Norwegian Atlantic current, bringing heat from the south, passes by and ensures a mild maritime climate. At Andenes, mean temperatures in July and August are 11 °C, whereas annual mean temperature is 3.6 °C and annual precipitation is 1060 mm (E-klima 2012; station 87110, 10 m a.s.l., Andøya).

The topography consists of three main geomorphological elements: the strandflat, the mountain slopes and the paleic surface (Møller & Sollid 1972, Vorren 1978). The bedrock consists of Precambrian non-calcareous gneisses, and at Ramså on the eastern part of the Island a small area with Jurassic and Cretaceaous coal and sandstone exists. The island's highest mountains, Røyken (464 m a.s.l.) and Endleten (393 m a.s.l.) are situated near the island's northern tip.

The present vegetation is species-poor, characterized by nutrient-poor, acidic heaths dominated by *Empetrum nigrum* and *Vaccinium myrtillus* and short-stature *Betula pubescens* forest. The flat lowlands are dominated by ombrothropic bogs (Buys 1992, Bjerke 2005) whilst heath and mesic meadows prevail in the mountains (Alm 1984, 1986, Alm & Sortland 1988). The mires are characterized by *Salix glauca*, *Caltha palustris*, *Comarum palustre*, *Filipendula vulgaris* and *Crepis paludosa*. Sand dune vegetation on the western coast is characterized by calciphilous *Dryas* heaths with *Kobresia myosuriodes* and *Pimpinella saxifraga* meadows. Some species occur only at the northern part of the island; e.g. *Gentiana nivalis*, *Saxifraga nivalis*, *Viscaria alpina* and *Woodsia alpina* (Vorren 1978).

At the northern tip of Andøya several lakes have been cored. Lake Endletvatn consists of two sub-basins, the westernmost now overgrown, and as such is ideal for sediment coring. The overgrown sub-basin was a subject of the earliest biostratigraphic study performed in the area (Vorren 1978), and the present lake was investigated by Vorren and Alm (1999). The neighboring lakes Øvre and Nedre Æråsvatn have also been investigated (Vorren et al. 1988, Alm & Birks 1991, Alm 1993, Vorren et al. 2009).

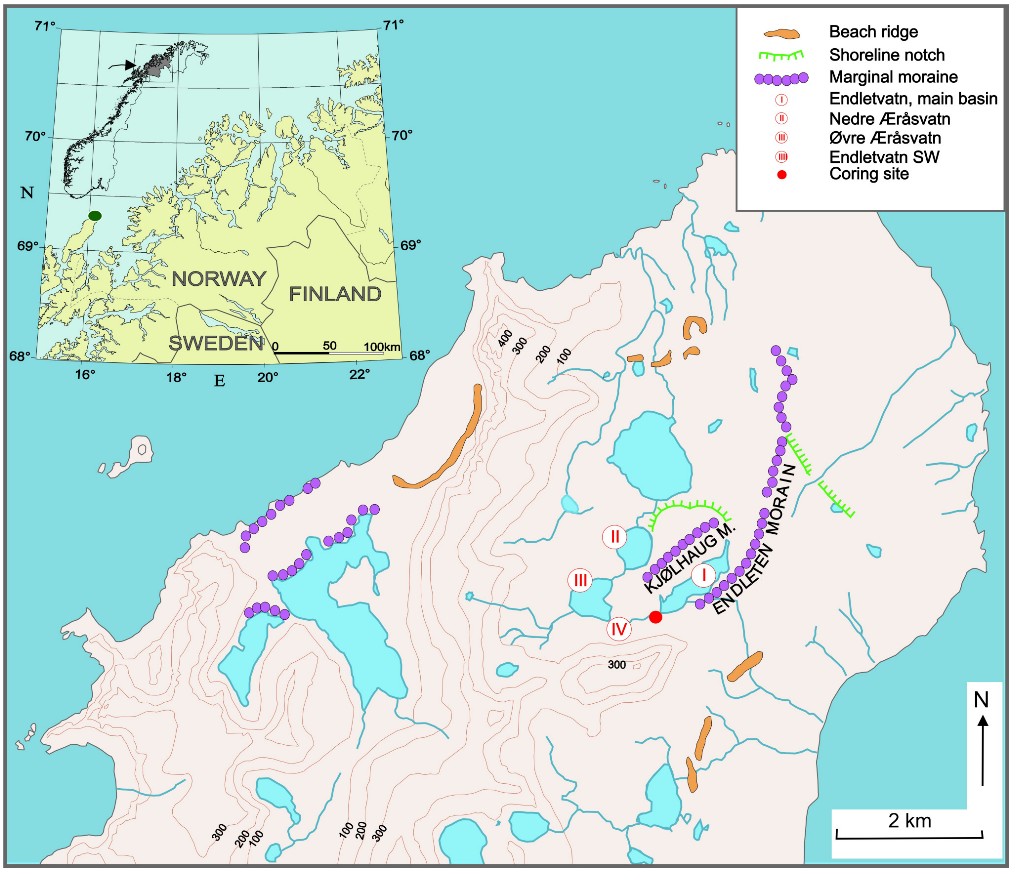

Figure 1: Map of the northern tip of Andøya. Red dot denotes the present coring site map. Redrawn from Vorren et al. 1988. I: present Endletvatn lake, investigated by Vorren and Alm 1999; II: Nedre Æråsvatn, investigated by Vorren et al. 1988 and Alm and Birks 1991; III: Øvre Æråsvatn, investigated by Alm (1993); IV: Endletvatn SW investigated by Vorren (1978).

History

During the last 40 years, many investigations have been conducted in the Andøya area, to a large degree concerning onshore biostratigraphy (Fjellberg 1978, Foged 1978, Vorren 1978, Vorren et al. 1988, Alm 1990, 1993, Alm & Birks 1991, Alm & Willassen 1993, Solem & Alm 1994, Birks et al. 1994, Vorren & Alm 1999, Vorren et al. 2009, Aarnes et al. 2012a) and several studies on onshore glaciology and sea level have also been conducted (Andersen 1968, Møller & Sollid 1972, Møller et al. 1992, Nesje et al. 2007). Considerable work has also been directed at elucidating offshore glaciology and past sea surface temperatures (Vorren et al. 1983, Hald & Vorren 1987, Vorren & Plassen 2002, Ebbesen & Hald 2004, Hald et al. 2007).

Radiocarbon dates from the bottom sediments in three lakes, Endletvatn (36 m a.s.l.), Øvre Æråsvatn (44 m a.s.l.) and Nedre Æråsvatn (35 m a.s.l.) ranged from 26 000 to 22 000 cal. yr BP. Offshore, in the Andfjord-Vågsfjord basin, Vorren and Plassen (2002) recorded seven main glacial events, the oldest being Egga I >22 000 ^{14}C BP (c. >26 400 cal. yr BP), Bjerka 18 700 – 16 800 ^{14}C BP (c. 22 300 – 20 000 cal. yr BP), Egga II >14 600 ^{14}C BP (c. >17 800 cal. yr BP), Flesen 14 500 ^{14}C BP (c. 17 700 cal. yr BP) and the D-event 13 800 – 13 200 ^{14}C BP (c. 16 900 – 16 200 cal. yr BP). They also found evidence for a final glacial advance at c. 14 600 ^{14}C BP (c. 17 800 cal. yr BP) and that Atlantic water intruded into the area 13 200 ^{14}C BP (c. 16 200 cal. yr BP), while an atmospheric warming started at 12 900 – 12 800 ^{14}C BP (c. 15 500 – 15 200 cal. yr BP) (Vorren & Plassen 2002).

Concerning onshore biostratigraphy, the pioneering study by Vorren (1978) in Endletvatn suggested several warm periods (thermomers) during the Late Weichselian, during which mean July temperatures rose to c. 10 °C in the most favorable periods. The thermomers were interrupted by cold periods (kryomers). Vorren et al. (1988) conducted a pollen analysis of sediment cores from Nedre Æråsvatn, adjusting the climate scale of Vorren (1978). Both studies applied vascular plants (pollen) and bryophytes as bioindicators.

Alm (1993) conducted a pollen investigation in Øvre Æråsvatn, but took a different approach in the climate reconstruction, as he mainly based the temperature estimation on pollen influx rates from all three lakes, comparing them to present-day pollen influx rates in Arctic and sub-Arctic areas. Hättestrand et al. (2008) support this approach by stating that in low pollen producing environments and for situations with no modern analogues, pollen influx rates are valuable for interpretation of the pollen data, as the sediments at the northern tip of Andøya have proven to be. In Alm's (1993) study, pollen influx values reached sub-Arctic levels during the periods of amelioration detected in two earlier studies (Vorren 1978, Vorren et al. 1988). Alm (1993), however, also included some bioindicators from all three studies, which did not deviate much from the pollen influx-based climate graph.

Following Alm (1993) and Vorren et al. (1988) the palaeoclimate at Andøya from 19 500 to 11 000 BP (c. 23 400 – 12 800 cal. yr BP) is summarized in brief here:

- Circa 19 500 to 19 000 BP (c. 23 400 to 22 500 cal. yr BP): low- to middle-Arctic, partly maritime, climate type.
- Circa 19 000 to 18 500 BP (22 500 to 22 100 cal. yr BP): Short-lasting glacial advance, ice-free areas still existed on Andøya.
- Circa 18 500 to 18 000 BP (c .22 100 to 21 400 cal. yr BP): A middle- or low-Arctic climate.
- Circa 18 000 to 16 000 BP (c. 21 400 to 19 100 cal. yr BP): A dry (continental) high-Arctic (polar desert) climate.

- Circa 16 000 to 13 700 BP (c. 19 100 to 16 800 cal. yr BP): Commenced with a climatic amelioration of a maritime type, indicating an open ocean. Later, a gradual cooling occurred, but it was still relatively mild until c. 13 700 BP (c. 16 800 cal. yr BP).
- Circa 13 700 to 12 800 BP (c. 16 800 to 14 800 cal. yr BP): Continental high-Arctic climate. Glacial re-advance recognized in the offshore stratigraphy.
- Circa 12 800 to 12 500 BP (c. 15 100 to 14 700 cal. yr BP): Sudden climatic amelioration.
- Circa 12 500 to 12 000 BP (c. 14 700 to 13 800 cal. yr BP): Climatic deterioration.
- Circa 12 000 to 11 000 BP (c. 13 800 to 12 800 cal. yr BP): A generally favorable climate corresponding to the Allerød Chronozone.

Vorren et al. (1988) regarded the climatic ameliorations at c. 16 000, 12 800 and 12 000 BP (19 100, 15 100, and 13 800 cal. yr BP) as the most important during the Late Weichselian on Andøya. However, two minor ameliorations were recognized, at c. 19 500 and 18 500 BP (23 400 and 22 100 cal. yr BP). Two periods with high-Arctic climate occurred at 18 000 to 16 000 and 13 700 to 12 800 BP (21 400 to 19 100 and 16 800 to 15 100 cal. yr BP).

Vorren et al. (2009) stated that between 12 300 and 11 950 cal. yr BP a polar desert vegetation existed. It was replaced by a moisture-demanding low-Arctic *Oxyria* vegetation at 11 950 – 11 050 cal. yr BP. Further, they proposed an amelioration during the period 11 050–10 650 cal. yr BP, with a sub-Arctic climate and heaths dominated by *Empetrum*, and concluded that although the climate was suitable for *Betula* woodland at about 10 800 cal. yr BP, it did not establish until 10 420 – 10 250 cal. yr BP. Warm and dry summers characterized the period between 10 150 and 9 400 cal. yr BP. Thereafter a change towards a moister, but still comparatively warm, climate prevailed.

At Lusvatnet, on the south-western part of Andøya, Aarnes et al. (2012a) found that an Arctic vegetation dominated by *Salix polaris* and herbs (e.g. *Saxifraga cespitosa*, *Saxifraga rivularis* and *Oxyria digyna*) characterized the area during the Allerød and the Younger Dryas, and the climate was cold and dry. They also found that during the Younger Dryas, the abundance of *Papaver* sect. *Scapiflora* and other high-Arctic herbs increased, suggesting the development of a polar desert as a response to increased aridity. A more oceanic and warmer climate developed after 11 520 cal. yr BP, and *Betula* established at the site at around 10 520 cal yr BP.

Among other important Late Weichselian macrofossils reported from Andøya, it is worth noting a birch root dated to 16 900±170 ^{14}C BP (c. 20 000 cal. yr BP) by Kullman (2006). In the Endletvatn cores, studied by Vorren (1978), Fjellberg (1978) found a vertebra of a carnivorous animal stoat (*Mustela erminea*) dated to c. 15 000 ^{14}C BP, its presence also indicating the presence of other animals. Vorren et al. (1988) found several bones of a duck, probably an eider duck (*Somateria* sp.) and also a terrestrial snail, *Arianta arbustorum*, as also reported in Waldén (1986). Vorren et al. (1988) and Alm (1993) investigated palynomorphs other than pollen (such as *Turbellaria*, *Trichoptera* larvae, *Chironomidae* larvae, *Pediastrum*, *Botryococcus*, etc.) which were used to determine the depositional environment, and from Nedre Æråsvatn, Stabell (1982) investigated diatoms. Several macroalgae were also found in this core. A diatom study is also available from Endletvatn (Foged 1978). Vorren (1978) investigated moss fossils in the Endletvatn core, using *Sphagnum* species and *Scorpidium scorpioides* as proxies for a temperature graph. A schematic overview of the climate graph of Alm (1993), pollen zones and important bioindicators in Vorren (1978) and Vorren et al. (1988), macrofossil records in Alm and Birks (1991) and other important identifications are presented in Figure 2.

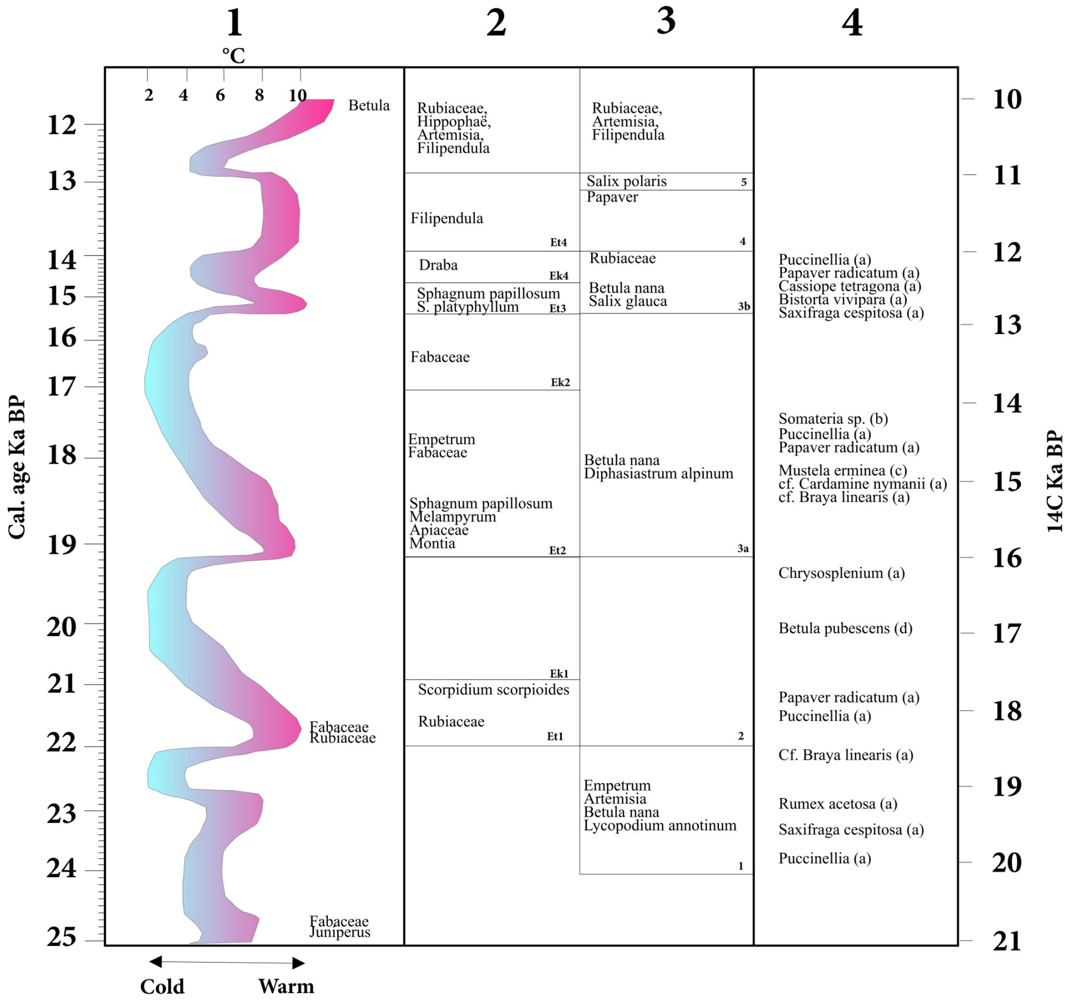

Figure 2: 1. Schematic overview of the climate graph of Alm (1993) which was based on pollen influx rates and supplemented with some bioindicators; 2. Pollen zones and important bioindicators identified by Vorren (1978); 3. Pollen zones and important bioindicators identified by Vorren et al. (1988); 4. (a) Macrofossils from Alm and Birks (1991); (b) bones of eider duck *Somateria* sp. (Vorren et al. 1988); (c) bone of *Mustela erminea* (Fjellberg 1978); (d) megafossil of *Betula pubescens* (Kullman 2006).

Material and methodological considerations

The material studied here consists of four parallel cores (C1-C4) which were retrieved from the deepest part of Endletvatn's south-west sub-basin. The internal distance was c. 5 m. A detailed description of the sediments, field- and laboratory procedures, core correlations, and chronostratigraphy of the basal parts of the four cores is provided by Vorren et al. (2012). The macrofossils of the four cores are the primary study objects of the investigation presented in this thesis. The basal parts of the four cores were divided into eleven stratigraphic units, A-K, (Vorren et al. 2012). These, and an upper sediment sequence named Unit L, were analyzed for macrofossils. The chronostratigraphy for unit L, and the macrofossil- and statistical methods applied to the entire sequence, are described in **paper 1**.

Chronostratigraphy, unit L

Unit L covers the late-glacial, the Younger Dryas and the transition to the Holocene, which is known to have been an unstable period. Several hiatuses are recorded in sediments from this part of Andøya (Vorren & Alm 1999, Vorren et al. 2009). In the course of this macrofossil study, it became clear that the sediment record in unit L was incomplete due to several hiatuses, which to a varying degree affected the sediment record in three of the cores (C1-C3). The multiple core approach gave valuable information as to the nature of these hiatuses, but their presence complicated the construction of a coherent chronology. The radiocarbon datings were of little help. They were carried out on a mix of bulk and macrofossil samples, with the bulk dates sometimes occurring in reversed order, which complicated the picture even further (Table 1). A chronological model allowing for the insertion of gaps at the hiatus level was chosen – the P-sequence deposition model in Oxcal 4.1 (Ramsey 2008, 2009) with IntCal09 (Reimer et al. 2009). With this model various combinations of the ^{14}C-results of unit L in C1 were applied to build three different deposition models, allowing the model to calculate different deposition rates for each sequence. The first model incorporated all dates; in the second model, bulk dates were adjusted by 300 years, as indicated by comparing adjacent bulk and macrofossil samples, and the third model applied dates done on macrofossils only.

Although all three model approaches suggested a steady sedimentation rate, the third run was applied to exclude problems connected to dates done on bulk vs. macrofossil samples. The bottom of unit L was fixed at 12 400 ^{14}C-years (c. 14 350 cal. yr BP) as inferred from the top of the chronology of Vorren et al. (2012).

Table 1: ^{14}C dates from unit L in core C1, C2 and C3

No.	Core	Depth in core (cm)	Bulk/macro	Lab. nr	14C age	Unmodelled cal. yr BP	Notes
1	C1	720-723	M	Tua-4923	7510±85	8396 - 8207	
2	C1	783.5-784.5	B	TRa-814A	8565±45	9550 - 9500	Excluded from age model
3	C1	785-787	M	TUa-4924	8215±75	9284 - 9033	
4	C1	788-789	B	TRa-813A	10725±55	12672 - 12581	Excluded from age model
5	C1	818-819	M	TUa-4887	10570±80	12595 - 12421	
6	C1	822-823	B	TRa-812A	11605±55	13562 - 13343	Excluded from age model
7	C1	848.5-849.5	M	TRa-811	11650±55	13589 - 13405	
8	C1	856-857	B	TRa-810A	12310±65	14509 - 14041	Excluded from age model
9	C1	857-858	M	TRa-809	12035±115	14016- 13770	
10	C1	875-876	M	TUa-4888	12290±95	14520 - 14008	
11	C2	858-859	M	TUa-4931	8205±85	9273 - 9031	Excluded from age model
12	C2	902-903	M	TUa-4932	12200±130	14468 - 13836	Excluded from age model
13	C3	931-932	M	TUa-5792	8430±55	9521 - 9427	Excluded from age model

Macrofossil analysis

Macrofossil analysis does not require much in terms of expensive equipment, apart from a microscope. However, it can be very time-consuming and good reference literature and extensive seed and fruit collections are essential.

Although both pollen and macrofossils should ideally be analyzed from the same core to strengthen the baseline for interpretations of past climate, the present investigation focused mainly on macrofossils. Thorough and extremely time-consuming pollen analytical investigations have been performed on cores from the area, and provided extensive knowledge of the local palaeovegetation (Vorren 1978, Vorren et al. 1988, Alm 1993, Vorren & Alm 1999, Vorren et al. 2009, Aarnes et al. 2012a). However, a common trait of these investigations is a very low pollen influx during most of the Late Weichselian, including most of the period from 22 000 to 12 800 BP (c. 26 400 – 15 200 cal. yr BP), and several pollen-barren zones were detected (e.g. Alm 1993). For this reason, priority was given to a thorough botanical macrofossil investigation of the four cores, aiming to recover as many macrofossils as possible to enhance the vegetation interpretation.

For every vertical centimeter of the four cores, macrofossils were extracted by washing through sieves with mesh sizes of 0.2 and 1.0 mm, with a gentle water jet and a brush. The material was stored at 4 °C in polyethylene boxes with distilled water until identification. Macrofossils were carefully studied, identified and stored at 4 °C in glass vials with distilled water. Identification was done under a stereomicroscope at 7-90 x magnification. Countable remains were standardized as number per 100 mL. For non-botanical remains, only presence was recorded.

Strong core correlations between the four cores (Vorren et al. 2012) enabled us to standardize the macrofossils onto one core, and core C3 was chosen to be the master core. In **paper 1** seeds of *Poaceae*, *Brassicaceae* and *Papaver* – the most abundant seed types – were not standardized onto C3, and were further used for the statistical investigation in **paper 2**.

Statistics

Ordination is a multivariate technique used for exploratory data analysis, which places similar samples close to each other, and dissimilar samples far from each other. In **papers 1** and **2,** ordination was used to investigate the similarities in macrofossil content between cores, rather than within a single core. Due to short gradient lengths (ter Braak & Prentice 1988), a principal correspondence analysis (PCA) (Lepš & Šmilauer 2003) was performed in **paper 2**, whereas in **paper 1** a detrended correspondence analysis (DCA) was applied using the program Canoco for Windows 4.5 (Microcomputer Power, Ithaca, New York, U.S.A.).

In **paper 2**, the statistical package SPSS statistics 19 (SPSS Inc., Chicago, IL, USA) was used to investigate the Pearson product-moment correlation coefficients (r) and the statistical significance of various variables within and between cores. The correlation coefficient range of the test varies from −1 to 1, where a value of 1 describes a perfect relationship between the two measured parameters – both parameters increase at the same rate. A value of −1 implies that one parameter increases, whereas the other decreases. A value of 0 implies that there is no linear correlation between the two variables, and that they vary independently of each other. It is, however, important to note that this investigation was done on a centimetre scale whereas the ordination was done on pooled 4-6 cm samples, to reduce the very large numbers of data points.

Results and main conclusions

The vegetation of the last glacial on Andøya is reconstructed based on a high-resolution, multi-core study of botanical macrofossils. Although the macrofossil material was sparse, it supports results from previous Late Weichselian studies on Andøya (e.g. Alm 1993) in suggesting a generally cold climate, but with several events of rapid climatic ameliorations, in brief periods reaching 10 °C July temperatures.

In **paper 1** we conduct a high-resolution multi-core investigation to enhance previous results from pollen analyses. We found that the macrofossil material of the earliest period 21 200 - 14 300 cal. yr BP was extremely poor, both in terms of species and number of fossils. Seeds of *Poaceae*-type, *Brassicaceae*-type and *Papaver* dominated the record. Climatic ameliorations are indicated by increases in loss on ignition (LOI) values and in the amounts of seed deposited, and the appearance of species with high bioindicator values. From c. 14 300 cal. yr BP onwards a richer material was available, but the period was unstable and several hiatuses were recorded.

In **Paper 2** we examined the intrasite variability of the major macrofossil content of the four cores, and the macrofossils relation to LOI and loss of water (LOW). Results show that the three major seed contributors *Poaceae*, *Papaver* and *Brassicaceae* were correlated with each other, and at the longest time scales, *Poaceae* and *Brassicaceae* were strongly correlated to LOI and LOW. However, *Papaver* was not, suggesting that its abundance is regulated by factors other than climate. The C3 core appeared to be the most representative. Intrasite variability was high, which suggests that future palaeolimnological studies in macrofossil-poor environments should be based on multiple cores.

We found several bones of the Arctic bird little auk (*Alle alle*) and other indeterminable bird bones and feathers. Together with a steady presence of *Cochlearia*, they support the presence of a bird colony in the area. In **paper 3**, we discuss this colony of little auks during the Late Weichselian and the ecological impact the birds had on a marginal Arctic environment, e.g. by providing a comparatively more favourable habitat, not least in terms of nutrient supply, for plants and other animals. A predominance of *Oxyria* pollen during the Allerød amelioration (ca. 12 000 to 11 000 BP, c. 13 800 – 12 800 cal. yr BP) (Vorren 1978, Vorren et al. 1988, Alm 1993) may partly reflect extensive stands of this nutrient-tolerant plant in moist, bird-manured vegetation close to the lakes.

It is commonly believed that trees were absent in Scandinavia during the last glaciation and first recolonized the Scandinavian Peninsula with the retreat of the Fenoscandian Ice Sheet some 9000 years ago. **Paper 4** was a collaborative project between several research institutions. Here we show the presence of a rare mitochondrial DNA haplotype of Norway spruce (*Picea glauca*) which is unique to Scandinavia, displaying its highest frequency in western Scandinavia. We also found DNA from this haplotype in lake sediments and pollen from Trøndelag in Central Norway dating back to c. 10 300 years, and chloroplast DNA of pine and spruce in lake sediments from Andøya c. 22 000 and 17 700 years ago, respectively. These findings imply that conifer trees survived in the ice-free refugia of Scandinavia, challenging current views on survival and spread of trees as a response to climate changes. Glacial survival of boreal trees somewhere in Scandinavia can no longer be disregarded. The presence of boreal trees during the Late Weichselian has been supported by a number of studies during recent years, including several ^{14}C dates of tree megafossils (Kullman 1998a, 1998b, 2002, 2004, 2008) and conifer stomata (Paus et al. 2011). In addition, new theories of the palaeogeography and environmental developments in central Sweden and Norway during the Weichselian deglaciation (Kolstrup & Olsen 2012 and references therein), give support to glacial survival or early immigration into the Scandinavian mountains.

The main conclusion of this study is that the botanical macrofossil investigation we undertook largely supports previous studies from the northern tip of Andøya. Arctic plant communities probably dominated by *Papaver* and several species of *Poaceae* and *Brassicaceae* predominated during most of the Late Weichselian, but climatic ameliorations occurred at c. 22 000 – 20 100, 20 100 – 19 500, 19 500 – 19 200, 18 800 – 18 100, 17 500 – 16 800 and 15 100 – 14 500 cal. yr BP. During these periods, the vegetation may have been more diverse than that recorded in the pollen- and macrofossil material, not least due to the long-lasting presence of a bird cliff in the area, as evidenced e.g. by recovered bird bones. Bird manure had a considerable impact on the local terrestrial environments, and favorable local habitats probably hosted species not found in an Arctic environment today, e.g. *Urtica dioica,* and perhaps small enclaves of boreal conifers and deciduous trees, as evidenced by sedimentary ancient DNA (sedaDNA) of *Pinus* and *Picea*. Although their actual presence on Andøya has not yet been detected either by macrofossil- or pollen analyses, the DNA evidence makes a strong contribution to the debate concerning glacial survival of boreal trees within Scandinavia. A thorough investigation of macrofossils in four parallel cores provides more reliable evidence for interpreting changes in vegetation cover than reconstructions based on a single core.

Future perspectives

In species-poor, late-glacial Arctic environments the traditional palaeobotanical disciplines – i.e. pollen analysis and macrofossil analysis – meet severe challenges. Pollen productivity is low, and many species are long-lived, have clonal reproduction, low flowering frequency, and produce seeds irregularly (Jónsdóttir 2011, Müller et al. 2011).

To improve the data output from fossil-poor sediments, methods for concentrating pollen may be applied, e.g. sieving larger sediment samples or retrieving larger samples for macrofossils. To shed further light on the vegetation types and their development, the relatively new technique of ancient DNA is a promising tool. Combined studies with pollen-, macrofossil- and sedaDNA analysis, as performed by Jørgensen et al. (2011), may prove to be a good approach, as these combined techniques may fill the knowledge gaps and uncertainties that arise when a single technique is applied. DNA may also be used to identify seeds and plant remains with no distinguishing characters, e.g. the Endletvatn stem fragment identified by Parducci et al. (2012) as *Urtica dioica*. There are still uncertainties to overcome related to the taphonomic processes which deliver both macrofossil remains and DNA into lacustrine sediments. Thorough investigations of present Arctic lakes and habitats regarding modern taphonomic processes can provide increased knowledge of these processes.

Inferring climate from macrofossil assemblages alone has progressed with the development of the probability density function approach (PDF) (Kuhl et al. 2002). In comparison with late-glacial climate reconstructions based on pollen and chironomids, the PDF-method has proved to be promising, although there are still problems to overcome (Aarnes et al. 2012b). The macrofossil material studied here probably included few species, probably as the cores were retrieved from what was the middle of the lake during the deglaciation interval. As near-shore sediments generally contain more macrofossils than those of the lake centre (Watts & Winter 1966, Birks 1980, Ritchie 1995, Dieffenbacher-Krall 2007), a core transect towards the shore must be considered for future Andøya studies and other studies in high-Arctic environments. Increasing the number of macrofossils recovered may make it possible to use the PDF-method, for species -poor Late Weichselian sediments as well.

Further, palaeobotanical analyses of cores from near the proposed bird cliff of Æråsen would help shed further light on the Late Weichselian bird colony in the area, and its impact on the vegetation and fauna. Based on its current endemic Fennoscandian distribution and molecular data, the Norwegian lemming (*Lemmus lemmus*) is supposed to have survived the glacial period in Scandinavia (Fedorov & Stenseth 2001). Moreover, Brunhoff et al. (2006) propose glacial survival on Andøya for the root vole *Microtus oeconomus*. Regarding other species groups, Coyer et al. (2011) suggest Andøya as a southern refugium for the cold-adapted marine macroalgae *Fucus distichus* during LGM. Hopefully further investigations on Andøya, applying both traditional and new techniques within the field of palaeobiology and palaeoclimatology, will give thorough answers to these questions – and as such the full key to the past might still lie in the future.

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En frosk begikk et bankrøveri
med kniv og kotelett
Han tok feil dør og flyktet ut
på bankens toalett

Politiet kom og banket på
-Du skal i fengsel, frekke tass
-Dere får meg aldri, svarte den
og skylte seg ned i dass

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Paper 1

Paper 2

Paper 3

Paper 4

Appendix

Palaeoenvironment in northern Norway between 22.2 and 14.5 cal. ka

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The stratigraphy of the lake Endletvatn on northern Andøya, northern Norway, has been revisited to improve the understanding of the palaeoenvironment in the region during the Last Glacial maximum (LGM). Four high-quality cores were analysed with respect to various lithological parameters, macrofossil content and 47 AMS radiocarbon dates. The sediments indicate a low energy environment with a mean sedimentation rate of 0.5 mm/year. We infer perennially frozen ground in the surroundings during the LGM. Climate proxies indicate a high-Arctic climate, i.e. July mean temperatures between 0 and 3 °C, throughout most of the LGM. The warmest periods are marked by rise in seed, moss and animal fossils, and often also by higher organic production in the lake. These periods took place from 21.4 to 20.1, from 18.8 to 18.1, around 17 and from 16.4 cal. ka onwards. The shifts between the different climatic regimes occurred rapidly – probably during one or two decades. The present data do not support recently published conclusions stating that *Picea, Pinus* and *Betula pubescens* grew on Andøya during parts of the LGM. The highest relative sea-level after the final deglaciation (Marine Limit) on northern Andøya is bracketed between 36 and 38 m a.s.l. It occurred between 21.0 and 20.3 cal. ka, peaking around 20.7 cal. ka. We infer the LGM glaciation history in the Andfjorden – Andøya region as follows: ~26-~23.5 cal. ka: an early glaciation of unknown extent on Andøya, but the glaciers did not override the mountains. 23.5±0.5 cal. ka: northern Andøya was deglaciated. 23-22 cal. ka: northern Andøya was glaciated and maximum extent of the LGM glacier might have occurred during this period. 22-18.7 cal. ka: early in this period the western margin of the Andfjorden ice stream receded to the Kjølhaugen moraine and shortly thereafter to the Endleten moraine. Possibly, the Andfjorden ice stream experienced two recessions later during this period. 18.7-17.6 cal. ka: the final drawdown and breakup of the Andfjorden ice stream started around 17.8 cal. ka, after a prolonged period of down melting. Two readvances/halts, the Flesen event (around 17.6 cal. ka) and the D-event 16.9 to 16.2 cal. ka occurred during the end of LGM.

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Introduction

The oldest onshore postglacial sediments in Norway are found on the northern tip of the island Andøya (Fig. 1). Radiocarbon dates from basal sediments from three lakes (Fig.1C) have yielded ages between 18.5 and 22 kyr ^{14}C BP (Vorren 1978; Vorren *et al.* 1988; Alm 1993). Thus, this region holds the prospect of unravelling the palaeoenvironment during most of the Last Glacial Maximum (LGM). A review of the earliest work related to the deglaciation history and palaeoclimate in this region was given by Vorren & Elvsborg (1979). During later years several onshore and offshore investigations have been conducted in the Andøya-Andfjorden area aiming at elucidating the palaeoenvironment of the region, in particular the glaciation history (e.g. Vorren *et al.* 1983; Møller *et al.* 1992; Hald & Aspeli 1997; Vorren & Plassen 2002; Plassen & Vorren 2002, Lambeck 2002; 2010; Nesje *et al.* 2007), and flora and fauna history (Fjellberg 1978; Foged 1978; Vorren 1978; Vorren *et al.* 1988; Alm & Birks 1991; Alm 1993; Alm & Willassen 1993; Solem & Alm 1994; Vorren & Alm 1999; Kullman 2006; 2008; Elverland *et al.* 2007; Vorren *et al.* 2009; Aarnes *et al.* 2012; Parducci *et al.* 2012).

Parducci *et al.* (2012) have recently concluded that *Picea* and *Pinus* grew on Andøya ~22 000, 19 200 and 17 700 years ago, based on analysis of sediment DNA, while Kullman (2006; 2008; 2012), based on radiocarbon dating of a *Betula* tree root, concluded that *Betula* trees grew in the area 20 cal. ka ago.

Nesje *at al.* (2007) used cosmogenic surface exposure dating of perched boulders/bedrock together with mapping of block fields and their associated clay mineralogy in order to constrain the surface geometry of the LGM ice sheet along a profile from Andøya towards the mainland. Surface exposure dating of erratics and bedrock on northern Andøya based on ^{10}Be provided age estimates between 20 and 56 ^{10}Be kyr (Nesje *et al.* 2007), indicating that the LGM ice sheet did not reach the mountain plateau of northern Andøya. However, they could not exclude past cover by non-erosive cold-based local glaciers. Exposure dates from the lowest altitude locality in the study area, Store Æråsen (105 m a.s.l., Fig. 1C), gave ages of 36-45 ^{10}Be kyr.

Lambeck *et al.* (2002) modelled the glacial rebound of the Scandinavian Ice Sheet. If the observed evidence of Vorren *et al.* (1988) from Andøya shall match the predicted values, they indicated that the ice sheet had to stand at the shelf edge, and be 1000-1500 m thick in the Andøya region. Lambeck *et al.* (2010) indicate that the overall maximum thickness occurred somewhat earlier than c. 23 cal. ka.

Detailed stratigraphies and chronologies spanning the LGM have emerged from the adjoining continental slope (Dahlgren & Vorren 2003; Laberg & Vorren 2004; Rørvik *et al.* 2010). Studies of the seabed morphology have shown that large ice streams occupied Andfjorden (Vorren & Plassen 2002; Ottesen *et al.* 2005) and Vestfjorden-Trænadjupet (Ottesen *et al.* 2005; Knies et al. 2007; Laberg *et al.* 2007) during the last glaciation (Fig.2). An important result of these marine-geological and geophysical studies is that the margin of the ice sheet in this region has fluctuated more often and more rapid than hitherto realised.

Some of the published results and interpretations are contradictory. Thus the aim of this paper is to 1) reappraise the chronology and the palaeoenvironmental LGM-history on Andøya, and 2) relate this to other palaeoenvironmental records from the region.

Physiographic setting

Andøya is characterised by mountains sharply rising to 300 to 600 m a.s.l., flanked by extensive areas of mire-covered strandflat. The up to 505 m deep fjord Andfjorden, which is situated to the east and north of Andøya, was an important drainage outlet for the Fennoscandian Ice Sheet during the LGM and the ice stream draining through Andfjorden led to the formation of a dense pattern of glacial lineations (Vorren and Plassen 2002; Ottesen *et al.* 2005).

The continental margin off the Lofoten-Vesterålen islands comprises a narrow and thin crustal segment overlain by a clastic sedimentary wedge of Permian through Palaeogene age. The bedrock on Andøya is largely composed of Precambrian gneissic rocks. A restricted near-coastal expanse of Mesozoic coal bearing sedimentary rocks occurs approximately 10 km south of the study area, as well as beneath the Quaternary cover in Andfjorden (Bergh *et al.* 2008).

Material and methods

Endletvatn is presently a NW-SE oriented 1.2 km long lake near the northern tip of Andøya Island (Fig. 1). A south-western extention is now filled with sediments and overgrown as a mire. In 2002 and 2003, four cores (from site 6, Fig. 1C) were sampled from this part of the original lake. Here, a small basin was mapped using ground penetrating radar (GPR) from the Geological Survey of Norway (Fig. 1C). The GPR was a digital pulse EKKO 100 (Sensor & Software INC., Canada). The recordings comprised 6 N-S profiles and 5 E-W crossing profiles, with a total length of 2223 m. A source of 1000 V and an antenna with a centre frequency of 100 MHz was used for all profiles. A marked reflection was recorded in all profiles. This reflection can be followed to a depth of 9-11 m. The limited range of depth recording is probably due to strong reduction of the signal in the fine-grained basin sediments. Evidently, the marked reflection represents the boundary between coarse-grained sediments below (diamictons and sandy gravel), and fine-grained basin infill sediments above. The four C-cores at site 6 all reached this boundary between 12 and 13 m, i.e. below the range of the GPR-recording, but in line with interpolation of the GPR-recordings. The C-cores are situated at or close to the deepest part of the basin.

The four cores C1-C4 were retrieved with a 100 mm Geonor clay sampler, mainly in PVC tubes. During coring the tube lengths were about 2 and 1 m long. The 2m cores were cut to lengths between 1- 1.5 meters after retrieval. The basal core sections in C1 and C2 were collected in aluminium tubes (C1, core section 12-12.6 m and C2, core section 11-12 m). The material in aluminium tubes was extracted using a hydraulic piston.

Physical properties, including p-wave velocity, wet-bulk density and magnetic susceptibility (MS) were measured using a Multi-Sensor-Core-Logger (MSCL). The measurements were carried out on unsplit cores, except of the magnetic susceptibility measurements of the cores in aluminium tubes. Here, measurements were done after removal from the tube.

On the split cores, colour determinations were done using a Munsell Soil Color Chart. They were photographed in 0.5 m overlapping intervals. For each vertical centimetre, 3 cm^3 samples were retrieved and analysed for loss on ignition (LOI) and water content (LOW).

Seven grain-size analyses were carried out. Prior to the measurements, carbonates and organic matter were removed with acetic acid and hydrogen peroxide, respectively. After allowing the chemicals to react overnight, the samples were washed with de-ionised water (twice after each treatment). Subsequently, sodium polyphosphate was added to each sample for dispersion and they were left on a shaking table overnight. The grain-size measurements were carried out with a Cilas 1180L laser-diffraction particle size analyser (range 0.04-2500 µm). Data processing and statistical analyses were performed on self-programmed routines and the software GRADISTAT (Blott & Pye, 2001). The results are presented in volume per cent.

Qualitative element-geochemical measurements of core C3 were performed using an Avaatech XRF Core Scanner that is equipped with a rhodium X-ray source. The measurements were carried out with a 2 mm down-core slit size and a 12 mm cross-core slit size using the following settings: 10 kV, 1000 µA, 10 sec. measuring time, no filter. During the measurements, the sediment surface was covered with a 4 µm ultralene foil. Selected results are presented as element ratios to minimise the influence of water and matrix effects (Tjallingii et al., 2007; Weltje & Tjallingii, 2008). Prior to the measurements, a colour image of the core was acquired using a Jai L-107CC 3 CCD RGB Line Scan Camera installed on the XRF core scanner.

Botanical macrofossils were washed out using sieves with mesh sizes of 1, 0.2 and 0.063 mm. All fragments >0.063 mm were collected. The sieves were cleansed by means of compressed air between each sample to be washed out. The macrofossils were identified and counted under a stereomicroscope. Identifications of vascular plant remains were done according to Beijerinck (1947) and Berggren (1981), and the seed/fruit collection at the Department of Arctic and Marine Biology, University of Tromsø.

Bryophyte macrofossils were studied in the core C3. The bryophyte abundance was determined by simple counting, where all free parts of a species were given equal weight; leaf fragments, entire leaves and shoots of different size were given the weight 1. The abundance has been adjusted to a fixed volume of 35 ml per sample. The samples were retrieved from the core in (vertically) 2 cm thick slices. In addition to the mosses, seeds were noted. Nomenclature of mosses follows Hill *et al.* (2006).

Two samples for cosmogenic surface exposure dating were obtained from the Kjølhaug and Endleten moraines respectively (Fig. 1). They were retrieved with a hammer and chisel from the uppermost 2 cm of horizontal crests of boulders. The samples were processed for ^{10}Be from quartz following procedures based on methods modified from Kohl & Nishiizumi (1992) and Child *et al.* (2000). AMS measurements were carried out at PRIME Lab, Purdue University, U.S.A., and measured ^{10}Be/^{9}Be was corrected by full chemistry procedural blanks. The ^{10}Be concentrations were converted to exposure ages using a ^{10}Be half-life of 1.5 Ma. To calculate apparent exposure ages, CRONUS-Earth ^{10}Be/^{26}Al exposure age calculator Version 2 (Balco et al. 2008) was used. The calculator uses a sea-level high latitude (>60°) nuclide production rate of 4.96 ± 0.43 atoms g^{-1} year^{-1} (^{10}Be) scaled to altitude and latitude using algorithms derived by a number of different authors. Variations in calculated ages are <4% between the different scaling models and here we quote the ages obtained by applying the Lm model (Balco et al. 2008). A correction was applied for sample thickness using an attenuation coefficient of 160 g cm^{-2} and a rock density of 2.65 g cm^{-3}. We conservatively corrected for snow shielding assuming 0.3 m of snow during 4 months per year. Shielding factors were calculated with a snow density of 0.3 g cm^{-3}.

Forty-seven samples from units A-K were radiocarbon-dated by AMS (Table 1). Most at the Laboratory for Radiological Dating in Trondheim, Norway (samples named Tra in Table 1). Some samples were age determined by the Svedberg Laboratory in Uppsala, Sweden (samples named TUa in Table 1). Three samples were analysed at the ^{14}Chrono Centre for Climate, The Environment, and Chronology at Queen's University in Belfast, Ireland (samples named UBA in Table 1). Bulk as well as macrofossil samples were analysed. In some cases, a bulk sample and a macrofossil sample from the same level were dated. All TUa/Tra-sample types were dried at 105 °C for 24 hours, before weighing. The bulk samples comprised 0.5 and 1.0 vertical centimetres, whereas the macrofossil samples could comprise as much as 11 vertical centimetres. Dates were calibrated according to IntCal09 (Reimer et al. 2009).

Radiocarbon dates

The results of the radiocarbon dates are listed in Table 1. The four cores were analysed with respect to lithological related parameters and divided into 11 lithostratigraphic units and nine correlating horizons (Fig. 3). Using the correlating horizons and lithostratigraphic units the age determinations (except two) were transferred to the C3 core (Fig 4). The two mentioned dated were sampled near core breaks (C1/931-932cm and 1105-1109 cm, Table 1), and are obviously contaminated by younger plant remains.

For the rest, given that there is: 1) no hiatus below unit K in core C3; 2) that the sedimentation rate was rather constant within each individual lithostratigraphic unit; 3) the boundary between units J and K is 12.8 kyr ^{14}C BP/15.1 cal. ka (see below), a best fit curve representing all is drawn for the calibrated ages (Fig. 4).
Re 1): The fact that all four cores have the same stratigraphy, do not show any obvious signs of erosion, and that the individual units have almost the same thicknesses, indicate that hiatuses in units B to J are absent, except possibly in the lowermost part, i.e. unit A.
Re 2): The lithology within each unit is relatively uniform indicating relatively constant sedimentation rates.
Re 3): The boundary between units J and K has previously been dated by Vorren (1978) to 12,920±110, 12,710±200 and 11,800±2000 ^{14}C yrs BP, as well as by Vorren and Alm (1999) to 12,900±930 ^{14}C yrs BP. Furthermore, the corresponding boundary in the adjacent lakes Nedre and Øvre Æråsvatn, respectively, has been dated by Vorren *et al.* (1988) to 12,750±230, 12,760±150, and by Alm (1993) to 12,750±125 ^{14}C yrs BP. Thus it seems safe to suggest an age close to 12.8 ^{14}C ka/15.1 cal ka..

Several of the dates fall far outside the best fit curve (Fig4). Hence, it is obvious that some dating results are conflicting. The main reasons explaining these discrepancies probably is the "contamination" by reworked sediments. Most of the bulk samples from units K, J, I and the upper part of unit H are obviously too old (area 1 on Fig. 4). We believe that this is due to a mix of contemporary and older reworked organic material. It should be noted that the two samples from the same horizon in two different cores (C2 and C4) give the same age. This probably indicates that the amount of reworked material is of the same magnitude in this horizon. Too old ages are also given by three bulk samples in units, G, E and F (area 2 on Fig. 4).

Macrofossil samples from units E and G seem to provide too young ages (area 3 on Fig. 4). We have no simple explanation for this deviation. Contrary to this, three of the lowermost macrofossil samples (from unit C and B in core C3) are probably too old (area 4 on Fig. 4). The two next lowermost samples were extracted from the same layer. The algae (Table 1) gave a slightly younger age than the macrofossils (21,987 versus 22,224 yrs). We rely on the age determination of the algae since the algae were produced concurrently with the sediments settling in the basin. For the other samples giving older ages in this group we suggest that some of the macrofossil leaves were reworked from older deposits.

The $\delta^{13}C$ values range from -11.8 to -33.4 ‰ (Tab. 1). According to Mackie *et al.* (2005) and references therein, it is expected that marine organic matter should have $\delta^{13}C$ values of -10 to -22 ‰, whereas marine bulk organic matter has $\delta^{13}C$ values ranging from -19 to -22 ‰. In contrast, terrestrial plants in the northern hemisphere record (with C3 photosynthesis) have mean $\delta^{13}C$ values around -27 ‰, whereas the full range is -32 to -20 ‰. In the present material $\delta^{13}C$ values from the macro algae layer in unit C yielded values of -22.1, -24.9, -23.8 and -26.1 ‰, respectively (TUa-5341A, TUa-4925, TUa-4940 and TUa-5794). All these values lie outside the expected $\delta^{13}C$ range for marine organic matter and marine bulk organic matter. Vorren *et al.* (1988) also investigated $\delta^{13}C$ values in the nearby lake Nedre Æråsvatn where they found the same results. They explained the anomaly with the results of Deuser *et al.* (1968), who found that marine plankton from cold waters with abundant supply of CO_2 yielded $\delta^{13}C$ values as light as -28 ‰. Vorren *et al.* (1988) regarded that marine algae could behave similarly with regard to carbon sources and photosynthetic pathways. This could be the explanation for the light $\delta^{13}C$ values in the ^{14}C samples from the macro algae layer, thus no corrections for marine samples were performed.

Lithostratigraphy- results and interpretations

The split cores were placed side by side, and nine correlating horizons were defined (Figs. 3 and 5). Based on changes in colour, grain size (Figs. 3, 5 and 6), fluctuations in LOI, LOW and MS (Fig. 5), as well as chemical composition (Fig. 7), 11 lithostratigraphic units (A – lowermost to K – uppermost) were identified. Although not identical values, LOI, LOW and MS show the same general trends through all four cores (Fig. 5).

Unit A is found in core C1 and C3, and probably rests on bedrock. In C1, it comprises massive sand and gravelly sand with irregular lenses of laminated mud and sand. Unit A in core C1 is highly deformed and compacted (low water content). We suggest this is due to glacial tectonics occurring during the last glacial re-advance across the area. Unit A in core C3 is a sandy layer containing pebbles (Fig. 8A). These coarse sediments were probably glaciofluvially deposited during or just after the deglaciation of the area.

Unit B is found in cores C1 and C3, and units C in cores C1, 2 and 3. They comprise laminated clayey silt with sand lamina (Fig. 5). Faults occur in core C1, and in C3 there is an angular unconformity near the top of unit B (Fig. 8A). Unit B and the lower part of unit C contain some fine-sand laminas (Figs. 8A and 6). They may derive from small turbidites.Well sorted sand laminae occur in unit B and at the base of unit C. The contents of Ca and S are relatively high (Fig. 7). A dark layer occurs in the middle of unit C (Fig. 8A) where the brown seaweed (*Desmarestia aculeata*) and green microalgae (cf. Vorren *et al.* 1988) occur in abundance in this 8 cm thick laminated interval in unit C (about 20.5 cal. ka). This indicates that Lake Endletvatnet was transgressed by the sea for a short period during the LGM. The brown seaweed was also found in abundance in the marine LGM sediments in Lake Nedre Æråsvatn (Vorren *et al.* 1988). The species has a circumpolar distribution, extending south to Portugal in Europe. It is also found in sub-Antarctica and Antarctica (Algae base 2012). It is one of the most common halophytes in

Svalbard today where it is typically found in the intertidal zone and down to at least 20 m (Jaasund 1965).

The upper boundary between unit C and D is sharp, represented with a change to lighter colour. Unit D, E, F and G contains laminated silt and clay (Figs. 4 and 8B). Unit D is characterized by low LOI, increasing LOW (Fig. 5), as well as relatively low Ca and S contents (Fig. 7), while unit E is distinguished by a small peak in LOI, a sudden drop in LOW and relative increases in Ca and S (Figs. 5 and 7). The upper boundary towards unit F is gradual, mostly detected by a change in colour. Unit F is in many respects similar to unit D, i.e. low LOI values, and relatively low Ca and S contents, respectively. However, the LOW values are higher than in unit D. Unit G is characterized by high organic content reflected by several LOI-peaks (Fig. 5) and relatively high Ca and S contents (Fig. 7). This unit resembles unit E in most respects. The boundary between unit G and H is gradual, marked by a slight colour change and a decrease in LOI.

Unit H, I and J also contain packages of, finely laminated clayey silt (Fig. 8B). Unit H is somewhat disturbed by minor faults (Fig. 8B). The faulting is probably the result of small-scale internal gliding, possibly due to compaction, along the margin of the basin. The most characteristic feature of unit I is the pronounced peak in MS and a temporary decrease in LOW (Fig. 5). The visual boundary between unit I and J is marked by a gradual change in colour.

From the lower part of unit C and upwards to the base of unit K, the grains-size distribution and primary structures are rather uniform. Finely laminated clayey silt dominates. The sedimentation rate is low and almost constant, about 0.5 mm/year. This indicates a stable and low-energetic physical environment during the 7000 years, i.e. no severe erosional events transporting coarse-grained sediments from the nearby mountain sides to the basin. An arid climate with permafrost and a sparse vegetation cover could provide conditions leading to could give this type of sedimentary environment.

The variations in the chemical composition (Fig. 7) could be explained by changes in the provenance of the sediments transported to the basin, or changes in the intra-basinal sediment production. There is no indication of changes in the drainage area of the basin since the area was deglaciated. Thus, the provenance of the sediment transported to the basin by small brooks has probably not changed. However, changes in sediment source related to eolian transport may have occurred. The trimodal/bimodal grain-size distribution of samples from units D, E, and G can best be explained by eolian input (Fig.6). The shoreline regression that occurred after unit G time (see below) exposed new land areas and consequently new source areas for eolian erosion. The peak in magnetic susceptibility in unit I may possibly derive from eolian sediments from newly exposed areas. The changes in the LOI curve mostly follow the changes in the chemical composition. There is a relative increase in sulphur in units C, E, G and K. Calcium follows the same trend, but Ca also increases in units I and J. The internal production of organisms in the lake (mainly algae) is probably the main reason for the variations in chemical composition.

Unit K is found in C1, C2 and C3. In core C3 this unit is directly underlying a gyttja sequence (Fig. 8B). Radiocarbon dates indicate that this boundary marks a hiatus of varying length. The hiatus in core C3 is c. 3500 years. In core C1, the sediment comprises deformed laminated clayey silt with some organic content. This unit is characterized by a sudden increase both in LOI and LOW (Fig. 5).

Biostratigraphy - results and interpretations.

Vascular plant remains

Three types of seeds were found regularly in all four cores; namely Poaceae, *Papaver* and Brassicaceae. The majority of the Poaceae material probably belongs to genus *Puccinellia* and, as stated by Alm & Birks (1991), numerous Arctic *Puccinellia* species should be considered. All *Papaver* seeds belong to the group *Papaver* sect. *Scapiflora*, i.e. the arcto-alpine *Papaver*-group (cf. Berggren 1981). Seeds of the species belonging to this group are indistinguishable from each other, but all are distributed in alpine or arctic habitats. In the present analysis only the *Draba*-type is recorded. However another Brassicaceae seed type also occurs in the C3 sequence.in a parallel sample from the 985-987 cm level.

No seeds were found in units A and B. In unit C Poaceae and *Papaver* occur regularly below and above the layer of marine algae. Unit D is practically without seed occurrences, whereas E and F have sporadic occurrences. Unit G has a regular occurrence of Poaceae and *Papaver* seeds. In the middle part of unit H there are sporadic occurrences of the two seed types, whereas they are absent in the lower and upper part of H. In units I and J the seeds occur quite regularly – and in K especially the Poaceae number increases. The two occurrences of the *Draba*-type seeds are in the lower part of units I and K.

The seed maxima in this study are correlated to the LOI-increase in units C (lower and upper part), G, and K, indicating higher terrestrial biological productivity in these units. But there are also seed occurrencesin units, H (central part) and J that do not show increases in LOI. Fluctuations in seed types and frequencies are interpreted as signals of actual vegetation changes. This study, as well as earlier biostratigraphical, palynologically based works (Vorren, 1978; Vorren *et al.* 1988; Alm & Birks 1991; Alm 1993), all show that the vegetation during the LGM was dominated by Poaceae, *Papaver* and Brassicaceae.

Bryophytes

The sediments from units B to K in the core C3 have been investigated for their bryophyte contents. Only mosses, no liverworts were recorded (Fig. 9). The three dominating taxa were *Syntrichia ruralis*, *Aulacomnium turgidum* and *Bryum* spp.

Units H (middle part) and K represent the highest diversity. Almost clean layers of *Syntrichia ruralis* occur in units B and C sediment, whereas *Bryum* spp. form an almost clean layer in the middle of H.

The ecology and distribution of the different mosses (especially *Syntrichia ruralis* and the *Tortula* species) found in units B to K indicate a cold and dry, continental climate and basic soil allowing discontinuous vegetation cover with much disturbance. However, indications of moisture-demanding vegetation also occur such as *Bryum calophyllum* (occurring at brooks and on banks at lakes). There are also species typical of wet soil surrounding small brooks, which is to be expected, considering the local topography. The present geographical distribution of the mosses is primarily Holarctic, though with a northern and mountainous tendency. The moss assemblage could be characterized as an impoverished version of the zonal vegetation type on patterned ground in the northernmost sub-zone A of Canada, i.e. the Polar Desert or *Papaver radicatum* sub-zone (Walker *et al.*(2011) – as is the vascular seed assemblage. Parducci *et al.* (2012) arrived at a similar conclusion based on i.a. cpDNA analysis of core C1.

Fauna.

Several bones of the arctic bird Little auk (*Alle alle*) were found in the cores (Elverland *et al.* 2007), in particular in units C and G (about 20.5 and 18.5 cal. ka) and the basal part of unit K (15.0 cal. ka). The little auk is an Arctic species that at present breeds on eastern Baffin Island, Greenland, Jan Mayen, Svalbard, Iceland, Franz Josef Land, Novaya Zemlya and Severnaya Zemlya. Two sub-species of the little-auk are recognized; the nominate race *A. a. alle* and the significantly larger *A. a. polaris*. The latter inhabits Franz Josef Land, whereas the nominate race inhabits the rest of the breeding range, including Svalbard (http://www.npolar.no/en/species/litle-auk.html). The fossil bones found are relatively large, indicating that they may derive from *A. a. polaris*.

An earlier finding of a well preserved vertebrae of stout *(Mustela erminea)* at a stratigraphic level corresponding to unit C was reported by Fjellberg (1978). Presently, *M. erminea* has a wide distribution including arctic and alpine environments. As indicated by Fjellberg (1978) the presence of this carnivorous animal indicates the presence of other animals as well. The prey of stout mainly consists of small rodents.

Discussion

Shoreline displacement

Several studies have been carried out to reconstruct the shoreline displacement on Andøya (Bergstrøm 1973; Undås 1967; Andersen 1968; Møller & Sollid 1972, Møller 1985; Fjalstad & Møller 1994; Fjalstad 1997). Lake Nedre Æråsvatn (35 m a.s.l., Fig 1C) contains marine sediments from 22.2 to 18.7 cal. ka, i.e. corresponding to units (B?), C, D, E and F in Lake Endletvatn. Our present results show that the middle part of unit C in Endletvatn (36 m a.s.l.) is deposited in a marine environment. Thus, we can now bracket the age of the highest relative sea level after the final deglaciation (the marine limit, ML) on Lake Endletvatn to between or 21.0 and 20.3 cal. ka, peaking around 20.7 cal. ka (Fig. 10). Clark *et al.* (2009) has found a rapid 10-m rise in sea level from the LGM lowstand sometime between 19 and 20 cal. ka. Possibly the ML on Northern Andøya reflect this sea level rise.

Endletvatn provides a minimum altitude of 36 m for the relative sea level. The entire sequence of Lake Øvre Æråsvatn is lacustrine, showing that the maximum sea level since the deglaciation has been less than 43 m a.s.l. (Alm 1993). The present outlet of Endletvatn is to the east but was probably dammed by the glacier during the LGM. Thus, it is reasonable to assume that lake Endletvatn drained to the north or west across passes 38 m a.s.l. Fjalstad & Møller (1997) describe a section just north of Lake Endletvatn with i.a. laminated low-angle sandy crossbeds which they interpret as shore sediments. The relative sea-level altitude for these sediments is given to approximately 38 m. These sediments were dated to 18.0 +/- 2 kyr by photoluminescence and thermoluminescence dating techniques. Thus the sediments were deposited within the age range of unit C. We conclude that the marine limit on northern Andøya is between 36 and 38 m, and that this took place was around 20.7 cal. ka ago.

The younger part of the sea-level curve has been adjusted to a date from lake Storvatnet (26 m a.s.l., Fig.1B) where gyttja just above the marine isolation contact gave and age of 14,020±280 ^{14}C yrs BP. Furthermore, peat at 10 m depth offshore Andenes (Fig. 1B) gave an age of 9,580±55 ^{14}C yrs BP (Fjalstad & Møller 1994).

LGM palaeoclimate

The sedimentary environment seems to have been quite stable throughout the nearly 7000 years, from 22.2 cal.ka to 15.1 cal. ka, represented by the LGM sequence in Endletvatn (units B to J). The sedimentation rate is rather modest (0.5 mm/year), and the sediments do not show any signs of flooding events. We infer this to mirror a dry climate with perennial frozen ground. This is also the general picture provided by the fossil record.

The fossil bird bones indicate an Arctic environment. If it is correct that the fossil bird bones derive from *A. alle polaris*, mean July temperatures of as low as +2 °C may have prevailed (based on mean July temperatures in the present habitat of *A. alle polaris* on the archipelago Franz Josef Land).

We compare our results of the fossil moss assemblages with Walker *et al.* (2011) studies of the modern zonal vegetation in the Arctic Canadian archipelago. In their Polar Desert zone (Arctic sub-zone A reflecting a mean July temperature between 0 and 3 $^{\circ}$C, *Syntrichia ruralis* occurs in 90 % of the relevees and *Aulacomnium turgidum* in 48 %. However, these mosses may also occur in other sub-zones. *Aulacomnium turgidum* occurs in its greatest quantities in the southernmost sub-zone E, and *Syntrichia ruralis* also occur in sub-zone B and C in smaller quantities. The combination of *Syntrichia ruralis and Aulacomnium turgidum* which are the two dominating taxa here, is unique for the Polar Desert zone.

The sub-zone B of Walker *et al.* (2011), also called the *Dryas* zone, reflects a July mean temperature between 3 and 5 $^{\circ}$C. Common to the northernmost sub-zones A and B are the mosses *Sanionia uncinata* and *Polytrichastrum alpinum*. The total absence of those mosses in the 22-15 ka sediments may indicate an even harsher climate during the Andøya Late Weichselian polar deserts than in the modern Canadian polar deserts. It should be mentioned here that the Allerød sediments of Andøya are rich in those two moss species. Referring to the general assemblage of mosses within the units B-J, they indicate that the average July temperatures oscillated between 0 and 3 °C during the LGM.

It seems likely that the mean July temperatures at Andøya in the period 22.2-14.5 ka cal. BP were closer to 0 °C than the 3 °C. Due to the variations in lithology and biostratigraphy we infer that the climate has been variable within this narrow limit. The seed production seems to mirror climatic oscillations, pointing at the C, G and I-K units as representing the more optimal phases. The mosses indicate the middle of unit H as a potentially favourable period, starting with a moist phase (*Bryum* spp. maxima) and optimally with a very dry phase as evidenced by *Syntrichia ruralis* and the *Tortula* species.

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Vorren (1978) inferred two “warm” periods, the Endletvatn thermomer 1 and 2 (ET1 and ET2 experiencing July mean temperatures between 8 and 10 °C. Evidently ET1 can be correlated with units B (22,2 to 21.4 cal. k) and (C?), and ET2, having an age between 19.3-18.1 cal. ka (Alm 1993), correlates with units E, F and G (19.5-18.1 cal. ka). The ET1 was inferred from pollen spectra in the lowermost part of Endletvatn containing *Betula nana*, Ericales, Rubiaceae, and *Scorpidium scorpiodies*, indicating a climate of Middle to Low Arctic type (Vorren 1978). In Øvre Æråsvatn, a climatic amelioration was indicated by an increase in pollen concentration between 18.3 and 17.9 ^{14}C ka (Alm 1993). Nedre Æråsvatn showed no indication (Vorren *et al.* 1988). The ET2 was inferred from pollen of Apiaceae and cf. *Melampyrum* and moss fossils of *Sphagnum papillosum* in Endletvatn (Vorren 1978). In the present material there are no similar indications of such high mean July temperatures. Since the present material has been taken from larger samples where risk of contamination should be negligible, we contemplate that the 1978-data probably suffered from reworked fossils and/or contaminated samples. Reworked fossils may derive from sediments from *i.a.* the previous ice free period around 23.5 cal. ka that experienced low-middle Arctic vegetation and fauna (Vorren *et al.* 1988).

In conclusion, throughout the period between 22.2 and 14.5 cal. ka the mean July temperature fluctuated between 0 and 3°C. The warmest periods occurred during the units C, G middle H and I-K; i.e. from 21.4 to 20.1, from 18.8 to 18.1, around 17 and from 16.4 onwards. The coldest periods are represented by units D, F parts of H and I (Fig.11). The shifts between the different climatic regimes were rapid – probably within less than two decades.

Did trees live on Andøya during LGM?

Parducci *et al.* (2012) state: "Results from macrofossil and cpDNA analysis indicate the presence of a polar desert or open pioneer vegetation community from ~22,000 cal. yr B.P. […] Tundra herb diversity increased with a climatic warming around 15,000 cal. yr. B.P.“ This is in general accordance with our results. However, they also claim that *Picea* and *Pinus* grew on Andøya ~22 000, 19 200 and 17 700 years ago. But they do not explain how this polar desert can host *Pinus* and *Picea*. . We suggest that their finding of traces of pine and spruce is due to reworked sediments. As mentioned above the radiocarbon dates of bulk material also indicates older carbon in the sediments which probably derive from older interglacial/interstadial plant remains.

Another intriguing finding has emerged in the last decade. Kullman (2006; 2008; http://www.kullmantreline.com/empty_31.html) claim that *Betula pubescens* s.lat. grew on Andøya 20,130 cal. yr. BP. In Stavedalen, 60 m a.s.l, (Fig.1B) he found that "wood remnants protruded 5-10 cm above the surface of a *Sphagnum* hummock. One piece of wood, a root from *Betula pubescens*, 40 cm in length and 8 cm in diameter was retrieved." (Kullman 2006). We do not find any indication in our material of *B. pubescens* during this time. Furthermore the nature of the finding site leads us to seriously doubt that the age determination of the tree remains is correct. Thus we did field studies at Kullman's finding site, properly indicated on the photo in Kullman (2006). One remnant of a *B. pubescens* tree root was found on the spot he indicates. The root contained minerogenic matter between the growth rings. A well cleaned sample gave a radicocarbon age of 101±35 ^{14}C yrs BP (UBA-20621). The two most likely explanations to this age discrepancy are: 1) we have not dated the same root, or 2) the dated root of Kullman contained old carbonaceous material.

The LGM glaciation history

Vorren *et al.* (1988) and Vorren & Plassen (2002) reconstructed the LGM glacial events on the northern part of Andøya as well as in the adjoining Andfjord.

We have refined this reconstruction of the glacial history based on the results of the present study, other results from northern Andøya that have emerged in the last three decades from northern Andøya, and result from the continental slope off Vesterålen–Lofoten. If our assumption that the base of unit B represents the start of the deglaciation is correct, the result from Lake Endletvatn seems to corroborate the lake Nedre Æråsvatn record. Two ^{10}Be exposure ages from boulders on the Kjølhaug moraine and the Endleten moraine (Fig. 1C), respectively, also seem to corroborate the lake Nedre Æråsvatn record. The Kjølhaug moraine has an apparent age of 22.1±2.2 cal. ka, and the exposure age of the boulder on the Endleten moraine was 20.0±2.1 cal. ka.

Dahlgren & Vorren (2003) and Rørvik *et al.* (2010) studied the glaciation history using data retrieved from the continental slope just south and west of the Lofoten islands (Fig. 2). Both works indicate that the start of the LGM occurred around 26.0±0.5 cal. ka, and that several oscillations of the glacier front occurred during LGM. The 24 m long core studied by Rørvik *et al.* (2010) was retrieved from a contourite at a depth of 1120 m. The LGM was represented by 9 m, giving a very high temporal resolution. The ice rafted detritus (IRD) flux (Fig. 11) most probably reflects the fluctuations in the large ice-stream draining through the Vestfjorden-Trænadjupet trough (Ottesen *et al.* 2005).

The relation between IRD flux and ice-stream behaviour is probably as follows: During advance (positive mass balance) and stillstand (equilibrium mass balance) the IRD flux is moderate to high. During a climatic amelioration (negative mass balance) the calving and IRD flux must be low during an early phase. After a period of thinning due to a negative mass balance the ice stream will lift off and calve rapidly, and produce large numbers of icebergs. In consequence, the IRD flux will be high to very high. However, it must be taken into account that ice streams are subject to surges that may occur independently of mass balance and climate change.

Based on the IRD flux from the Lofoten contourite and the currently known data from the Andøya-Andfjorden region, we suggest the following glacial development in the mentioned region:

1. Early LGM (c. 26.0-~23.5 cal. ka). During this period the Fennoscandian ice sheet had advanced to the shelf break in Trænadjupet. This might be the period when the LGM-ice sheet was thickest on Andøya according to Lambeck *et al.* (2010). However, exposure dates indicate that the ice sheet did not cover the mountain areas on Andøya (Nesje *et al.* 2007). The glacier may have had an extent as indicated in Fig. 12 (see below). For comparison, it is interesting to note that on the western shelf off Svalbard the glacier front reached its maximum, the shelf edge, between 24 and 23.5 cal. ka (Jessen *et al.* 2010).

2. 23.5±0.5 cal. ka. The low IRD flux at this time (Fig. 11) occurred synchronously with the deposition of Unit II in Lake Nedre Æråsvatn (Vorren *et al.* 1988) reflecting a period when this lake and surroundings were deglaciated and the lake was inundated by the sea. Based on the fossils found in Unit II, middle to low Arctic climate was inferred to prevail during this period (Vorren *et al.* 1988). Olsen *et al.* (2001) reconstructed nine glaciaton curves across Norway from the inland area to the coast and shelf. They define a Trofors interstadial (25-20.2 cal. ka). The Trofors interstadial probably comprises more than one deglaciation period (interstadial). The occurrence of animal bones and calcareous concretions from a cave at Kjøpsvik indicate that the ice front receded to the inner fjord areas during this period (Lauritzen *et al.* 1996).

3. 23-22 cal. ka. During this period the IRD flux on the continental slope was high (Fig. 11), indicating that the Trænadjupet-Vestfjorden ice stream was situated at the shelf break. Lake Nedre Æråsvatn was overrun by glacier at the same time. Vorren *et al.* (1988) discussed the extent of the glaciers on northern Andøya during this period, i.e. the period just before the final deglaciation of this area. The extent of the glaciers is reconstructed on Fig. 12. This reconstruction is in conflict with the basal dates of silty gyttja from Lake Øvre Æråsvatn (26.1-25.8 cal. ka; Alm 1993) and the exposure dates from Lake Store Æråsen (45-36 ka; Nesje *et al.* 2007). However, the upper sediment in Unit II in Lake Nedre Æråsvatn is highly deformed and consolidated indicating that the ice deforming the sediments must have had some thickness. Furthermore a lateral till terrace about 100 m a.s.l. along the mountain side of Røyken (Fig. 1B) probably marks the margin of the ice sheet during this period. If this is correct it implies that Lake Øvre Æråsvatn and Stor Æråsen experienced a glacial cover during this period. Alternatively, if the basal dates in Øvre Æråsvatn are correct this lake may have been covered by glaciers during the early LGM and deglaciated as early as ~26.0 cal. ka. Then, the reconstruction (Fig. 12) could illustrate this period, implying that the glaciation after unit II was deposited had a more restricted extent. We favour the first alternative.

4. 22-18.7 cal. ka. This more than three thousand year long period witnesses several marked fluctuations of the Trænadjupet-Vestfjorden ice stream (Figs. 2 and 11). Early during this period, the western margin of the Andfjorden ice stream receded to the Kjølhaugen moraine and shortly thereafter to the Endleten moraine or further beyond (Fig. 1C). Vorren & Plassen (2002) tentatively correlated the the Kjølhaug moraine with the Bjerka moraine in outer Andfjorden, and the Endleten moraine with the Egga-II event when the ice stream reached the shelfbreak. Møller *et al.* (1992) have recovered shell fragments of *Mya truncata* at Bleik (Fig. 1B) giving an age of c. 21.5 cal. ka, indicating that also the Bleik area was deglaciated at this time. Furthermore, Dahl *et al.* (2010) suggest, based on OSL dating of beach ridges 20 m a.s.l. on Bleik, a limited ice extent and seasonally open water around 19 ka and suitable condition for rock glacier formation close to the present sea level between 19 and 15 ka.

Few data are available that can reveal the behaviour of the Andfjorden ice stream later during this period. The rather stable position of the shoreline during three thousand years (c. 22 to 18.5 cal. ka; Fig. 11) could indicate that the Andfjorden ice-stream was relatively stable during this period. On the other hand, the IRD-lows occurring at the end of unit C and unit E time (Fig.11) point to periods with down melting and subsequent drawdown and calving of the ice stream in Trænadjupet –Vestfjorden. This may have occurred in Andfjorden as well.

Paasche et al. (2007) have indicated that local glaciation occurred on southern Andøya between 21,050 and 19,100 cal. yr BP. We are reluctant to accept their conclusion as it is based on assumptions of the modern equilibrium line altitude (ELA) that are in conflict with existing glaciers, and consequently incorrect estimates concerning the magnitude of the depression of the ELA. Rather this local glaciation occurred during Younger and Older Dryas as found in adjoining areas (e.g. Andersen 1968; Rasmussen 1984).

5. 18.7-17.6 cal. ka. This period seems definitely to have an analogue history in Andfjorden and Trænadjupet-Vestfjorden. The low IRD flux on the continental slope (Fig. 11) during unit G-time indicates a negative mass balance, probably due to a climatic amelioration. This resulted in the final drawdown and breakup of the Andfjorden ice stream in the outer and middle reaches around 17.8 cal. ka (Vorren & Plassen 2002) as well as the Trænadjupet-Vestfjorden ice stream, as witnessed by the last marked IRD-peak (Fig. 11).

6. 17.6-15.1 cal.ka. Shortly after the break up, the Andfjorden ice stream readvanced/halted at the Flesen Moraine in inner Andfjorden, and later at the innermost part of Andfjorden between 16.9 and 16.2 cal. ka (Vorren & Plassen 2002).

Conclusion

This study of the lake Endletvatn on northern Andøya has provided more detailed and precise dates for a better understanding of the sedimentary environment, floral, faunal, climate and glacial development in the Andøya-Andfjorden region during LGM.

1. The structures and texture of the sediments indicate a low energy environment with a mean sedimentation rate of 0.5 mm/year and perennially frozen ground in the surroundings through the LGM. The sediment influx was from small brooks, eolian activity as well as intrabasinal organic production which varied in the course of time.

2. Brown seaweed occurs in abundance between between 21.0 and 20.3 cal. ka, peaking around 20.7 cal. ka indicating that Lake Endletvatnet (36 m a.s.l.) was transgressed by the sea for a short period during the LGM. Maximum relative sea level was 38m a.s.l..

3. The climate proxies indicate a dry, high Arctic climate, i.e. July mean temperatures between 0 and 3 °C between 22.2 and 14.5 cal. ka. The highest July mean temperatures were from 21.4 to 20.1, from 18.8 to 18.1, around 17 and from 16.4 cal. ka onwards The shifts between the different climatic regimes were rapid – probably they occurred in the course of one or two decades.

4. Given a dry, high Arctic climate from 22.2 to 14.5 cal. ka., we find it implausible that *Pinus*, *Picea*, or *Betula* should have existed during parts of LGM on Andøya as suggested by Parducci *et al.* (2012) and Kullman (2006; 2008), respectively.

5. We infer the LGM glaciation history in the Andfjorden – Andøya region as follows:
~26-~23.5 cal. ka: Possibly maximum extent, but the glaciers did not override the mountains. **23.5±0.5 cal. ka:** Northern Andøya was deglaciated. **23-22 cal. ka:** Northern Andøya was glaciated. Maximum extent of the LGM glacier might have occurred during this period.**22-18.7 cal. ka:** During an early stage of this period the western lateral margin of the Andfjorden ice stream receded to the Kjølhaugen moraine and shortly thereafter to the Endleten moraine. The Andfjorden ice stream possibly experienced two recessions later during this period. **18.7-17.6 cal. ka:** The final drawdown and breakup of the Andfjorden ice stream commenced around 17.8 cal. ka, after a period of down-melting. **17.6-14.5 cal. ka:** Readvances/halts of the Andfjorden ice stream occurred at the Flesen Moraine around 17.6 cal. Ka, and in innermost Andfjorden during the D event between 16.9 and 16.2 ka. cal.

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Illustrations

Fig. 1. A: Overview map of Scandinavia, arrow points on Andøya. B: Map of northern Andøya showing location of investigated lakes and important observations of moraines, ancient shoreline features and glacial striae. ØÆ, NÆ, E and S denote Øvre Æråsvatn, Nedre Æråsvatn, Endletvatn and Storvatnet respectively. C: Map of the framed area in B, showing coring sites,1 and 2: Vorren 1978; 3: Vorren *et al.* 1988; 4: Alm 1993; 5: Vorren & Alm 1999 and 6: present study. Sites (*) and ages of surface exposure dates are also indicated. The dates on Store Æråsen are from Nesje et al. (2007).

Fig .2. Map showing the location of the Trænadjupet-Vestfjorden – and Andfjorden ice streams. The sites of cores JM 98-625/1 (Dahlberg & Vorren, 2003) and MD99-2294 (Rørvik *et al.* 2010) referred to in the text are marked. Note that the latter one is retrieved from a contourite drift, indicating that downslope transport has been negligible here during LGM.

Fig. 3. Photos and lithological logs of cores C1, C2, C3 and C4 displaying texture and structures of the sediments. Lithostratigraphic units A-K and correlation horizons 1-9 are indicated. The vertical scale shows cm below surface.

Fig.4. Age-depth diagrams comprising radiocarbon dates from all four cores (C1, 2, 3 and 4). Vertical axes show the lithostratigraphic units and correlation horizons within core C3. The horizontal axes indicate ages Calibrated ages are according to Intcal09 (Reimer et al., 2009). The radiocarbon dates marked by the areas 1, 2, 3, and 4 are discussed in the text.

Fig. 5. Logs of cores C1, C2, C3 and C4 showing sampling depth in cm below surface, correlating horizons between the cores, radiocarbon dates in ^{14}C ka BP where B, M and A denote radiocarbon dates of macrofossils, bulk and algae respectively, magnetic susceptibility (MS (SI)), water content (LOW), loss on ignition (LOI), lithostratigraphic units (L.u.) and. Horizontal scales show content of LOW and LOI given in per cent and MS in 10^{-5} standard units. Note the marked peak in MS in unit J and the marked increase in LOW and LOI from unit J to K. Noticeable are also the increase in LOI in units E and G an partly in units B and C.

Fig . 6. Grain-size distribution of samples from unit B, C, D, E and G presented as volume percentages in a ternary diagram (A) and as volume frequency curves (B). Note the tri/bi modal distribution of the samples from units D, E and G. The origin of the well sorted sand sample from the lower part of unit C (cf. Fig. 8) is probably deposited from a small turbidite.

Fig. 7. Colour photo, lithological log, lithostratigraphic units, loss on ignition (LOI) and selected element ratios of core C3. Note the rapid shift in chemistry between the units.

Fig. 8. Photos of selected intervals of core C3.Fig. 8A: Unit A (lower right) shows a pebble in a sandy matrix. Unit B shows an inconformity near the top. Unit C (lower part) show well sorted sandy beds near the base. The fold at the boundary to unit B is due to disturbances during coring. Unit C (middle part) shows the bed (dark colour) containing lamina with brown seaweed. Fig .8 B: The two lower photos show the light coloured finely laminated unit D and the transition to the darker coloured unit E that contains more organic matter. The photos of unit H demonstrate small faults and some darker coloured lamina. The upper photo to the left shows the upper boundary of unit K and the superposing sediments. This boundary marks a break in sedimentation. The photos to the left shows the upper part of unit J and the boundary to unit K (The dark segment is a sampling site for a radiocarbon date).

Fig. 9. To the left: Moss fossils in the core C3: The total number of moss (Bryophyte) shoots, singular leaves and singular parts of leaves for the different moss taxa recorded in 35 ml large. The combination of the thwo dominant Bryophyte taxa *Syntrichia ruralis* and *Aulacomnium turgidum* characterises the environment as a polar desert throughout units B-K. To the right: Total number of seeds pr. 35 ml sediment for the three most abundant seed types within the core C3. The seed assemblage correlates with earlier palynological data, and indicates a polar desert vegetation.

Fig. 10. Shoreline displacement curve for northern Andøya based on data from Vorren *et al.* (1988), Fjalstad & Møller (1994) and this study.

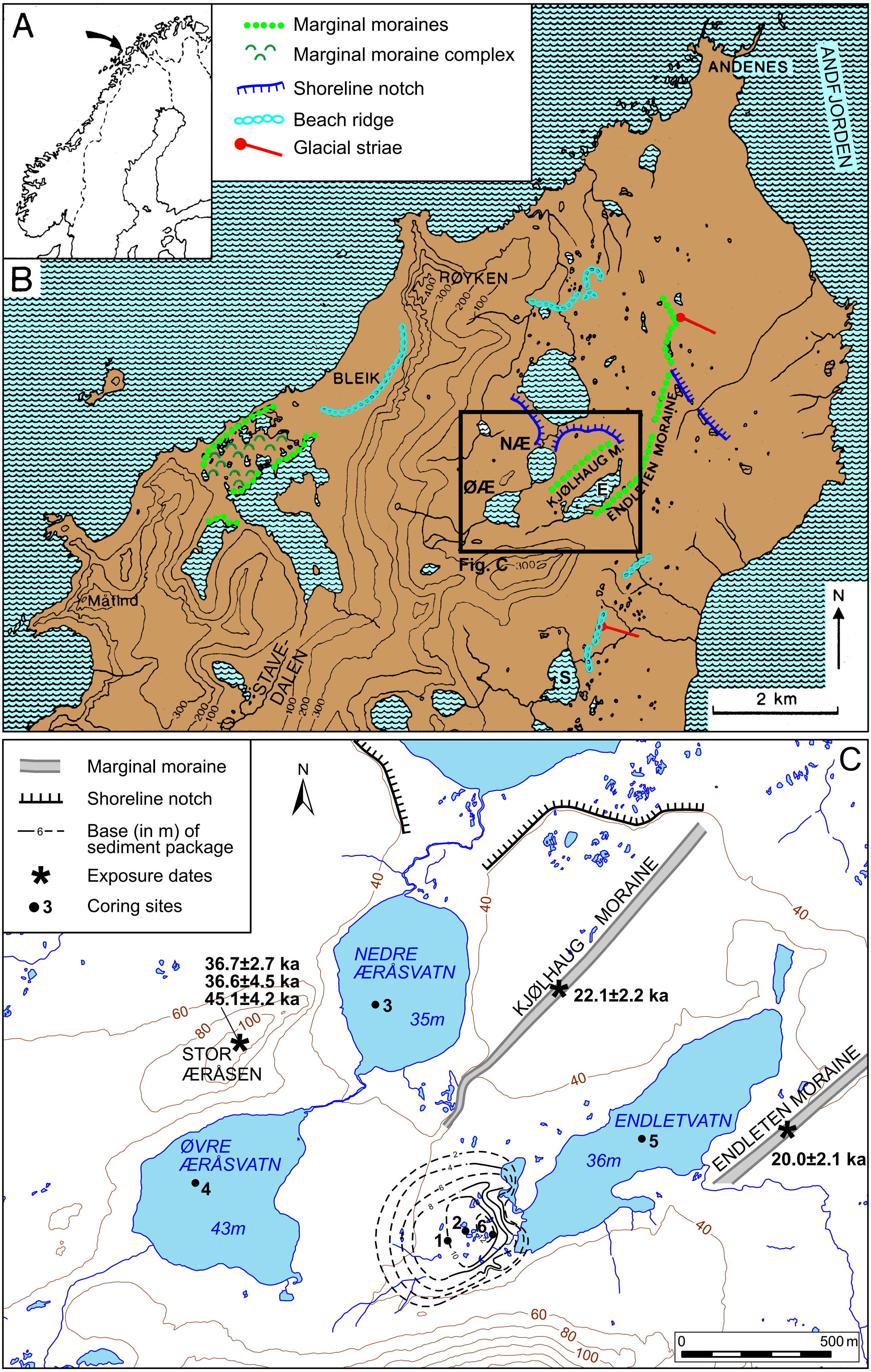
Fig. 11. Figure illustrating: calibrated ages, chronology of the stratigraphic units in Endletvatn, IRD curve from the Lofoten Contourite Drift displaying a five times running average based on the original data in Rørvik *et al.* (2010), important glaciation/deglaciation events in the Andøya-Andfjord region, shoreline displacement on northern Andøya, and July mean temperature on Andøya as deduced from the present data.

Fig. 12. Palaeogeographic reconstruction of the northern tip of Andøya. The reconstruction shows the extent of the glaciers around 23 or 24-25 ka (preferably around 23 ka). The configuration of the glacier west of Andøya is based on work in progress by the first author.

Table 1.
Radiocarbon dates. The samples consist of macrofossil samples (M), bulk samples (B) and algae (A). Macrofossil samples comprise mainly bryophytes and seeds. Dates were calibrated according to IntCal09 (Reimer *et al.* 2009), using 1 sigma. In cases where the relative area under probability distribution was divided, the mean of the larger area was chosen to represent the samples point in the age-depth curve.

Core	**Cm below surface**	**M/B**	**Lab-nr**	**14C**	**Cal. BP (1 sigma)**	**Mean**	**δ13C ‰**
C1	904-910	M	TUa-4941	12040±80	13800-13981	13890	-25,0
C1	911-912	B	TRa-808A	12800±80	15012-15279	15145	-14,8
C1	923-924	B	TRa-807A	12770±65	14963-15255	15109	-11,8
C1	930-935	M	TUa-4889	11115±150	12808-13149	12978	-22,2
C1	932-932,5	B	TUa-5339A	12730±95	14874-15258	15066	-12,0
C1	963,5-964,5	B	TRa-790A	13910±75	16860-17075	16967	-16,5
C1	973,5-974,5	B	TRa-793A	15535±140	18621-18833	18727	-22,8
C1	1035-1044	M	TUa-4894	14240±130	17116-17543	17329	-23,5
C1	1068-1068,5	B	TRa-797A	15315±105	18505-18702	18603	-19,7
C1	1077,5-1078,5	B	TRa-800A	15375±95	18549-18706	18627	-16,1
C1	1086-1086,5	B	TUa-5340A	15130±110	18083-18306	18194	-12,9
C1	1084-1089	M	TUa-4892	12915±145	15109-15885	15497	-25,8
C1	1104-1109	M	TUa-4893	6810±90	7576-7728	7652	-27,7
C1	1108,5-1109,5	B	TRa-804A	15990±135	18975-19318	19146	-19,8
C1	1150-1150,5	B	TUa-5341A	16910±145	19890-20294	20092	-22,1
C1	1150-1151	M	Tua-4925	17725±190	20929-21446	21187	-24,9
C1	1203-1206	M	TUa-4895	1825±55	1698-1825	1761	-27,7
C2	922-927	M	TUa-4934	12155±115	13840-14153	13996	-27,7
C2	945-956	M	TUa-4933	12445±105	14207-14770	14488	-27,7
C2	981,5-982,5	B	TRa-791A	13775±75	16789-16970	16879	-16,7
C2	1014,5-1015,5	B	TRa-795A	16105±145	19231-19427	19329	-25,4
C2	1098,5-1099,5	B	TRa-798A	15135±75	18100-18292	18196	-18,0
C2	1100-1110	M	TUa-4937	14185±100	17070-17459	17264	-26,0
C2	1143-1155	M	TUa-4938	14900±120	18260-18490	18376	-25,3
C2	1146-1146,5	B	TUa-5342A	17125±165	20068-20537	20302	-22,0
C2	1193,5-1194,5	B	TRa-806A	17215±185	20186-20568	20377	-21,5
C2	1202-1204	M	TUa-4940	17245±135	20248-20557	20402	-23,8
C3	931-932	M	TUa-5792	8430±55	9427-9520	9473,5	-33,4
C3	965,5-966,5	B	TRa-789A	13050±70	15436-16083	15759	-18,3
C3	1014,5-1015,5	B	TRa-794A	16975±245	19843-20430	20136	-25,3
C3	1067-1069	M	TUa-5793	14285±90	17183-17557	17370	-26,0
C3	1100,5-1105,5	B	TRa-799A	14470±90	17456-17849	17652	-17,9
C3	1114-1115	B	TRa-801A	15495±105	18615-18793	18704	-16,6
C3	1132,5-1133,5	B	TRa-802A	15770±130	18735-18988	18861	-15,6

C3	1155,5-1156,5	B	TRa-805A	17040±125	20067-20407	20237	-18,7
C3	1208-1209	M	TUa-5794	16775±120	19832-20146	19989	-26,1
C3	1226-1228	M	UBA-19461	18650±145	22096-22438	22267	-24.9
C3	1228-1231	M	TUa-5795	18570±190	21866-22410	22138	-26,0
C3	1246-1248	M	UBA-19462	18584±111	22071-22377	22224	-26.5
C3	1246-1248	A	UBA-19463	18416±109	21754-22220	21987	-17.7
C3	1252-1253	M	TUa-5796	19480±160	22956-23575	23265	-24,1
C4	1014,5-1015,5	B	TRa-792A	13635±95	16679-16896	16787	-27,7
C4	1057,5-1058,5	B	TRa-796A	16210±215	19222-19549	19385	-25,3
C4	1082-1084	M	TUa-5797	14120±95	16984-17257	17120	-23,5
C4	1144-1154	M	TUa-4942	14920±105	18260-18490	18375	-25,1
C4	1148-1148,5	B	TUa-5343A	14910±95	18265-18489	18377	-15,5
C4	1174-1184	M	TUa-4943	15510±205	18557-18885	18721	-27,7
C4	1178,5-1179,5	B	TRa-803A	17985±350	21072-22085	21578	-21,8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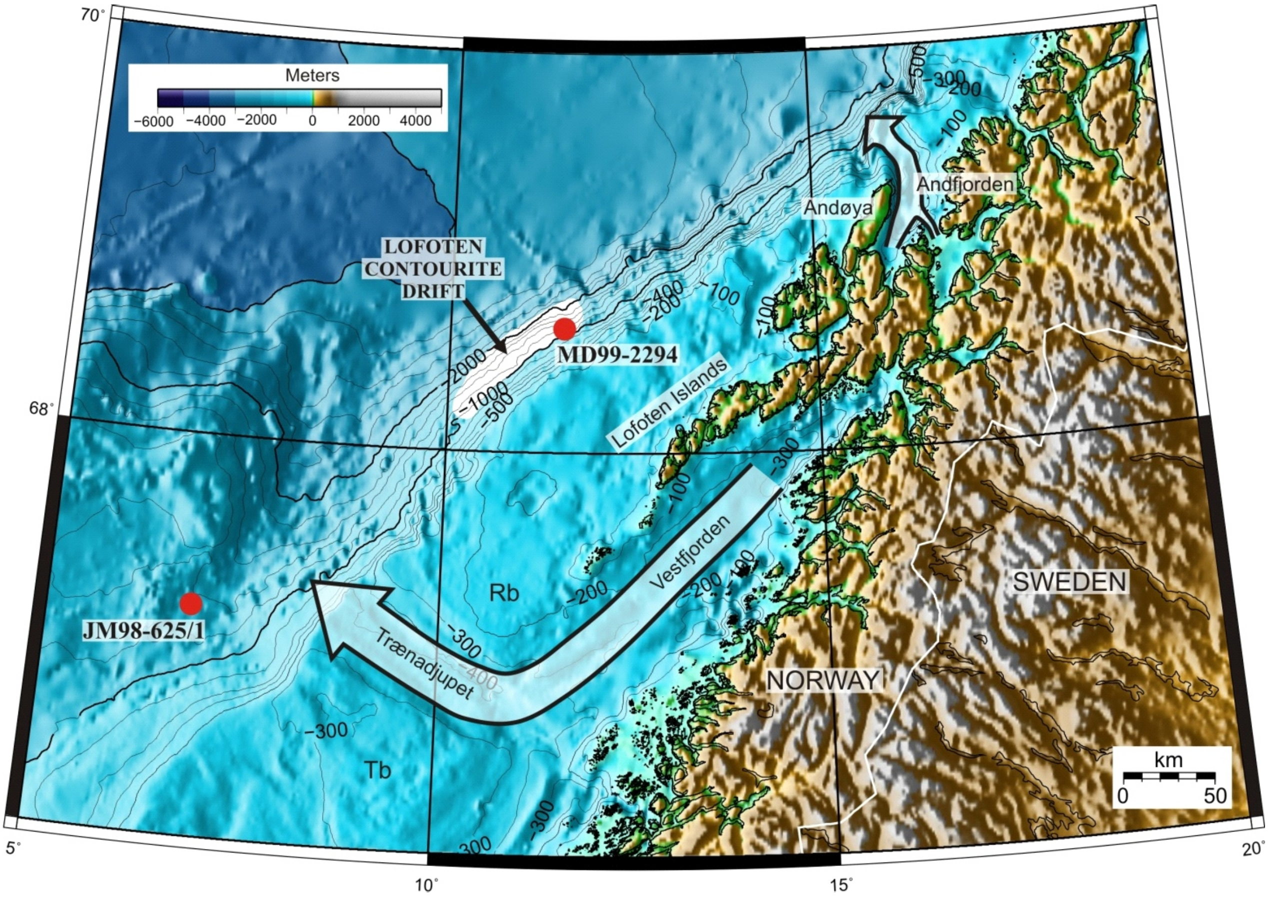
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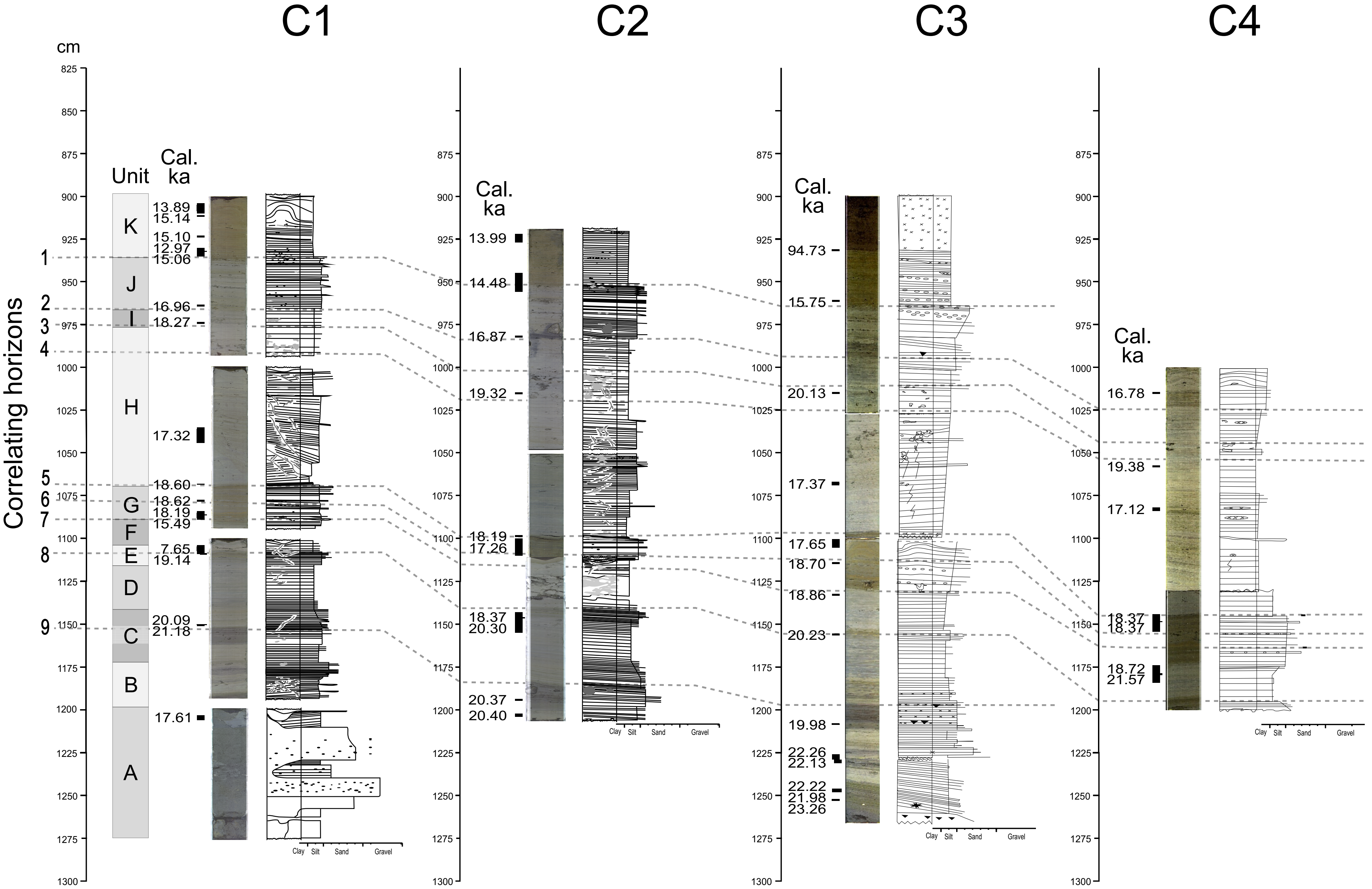
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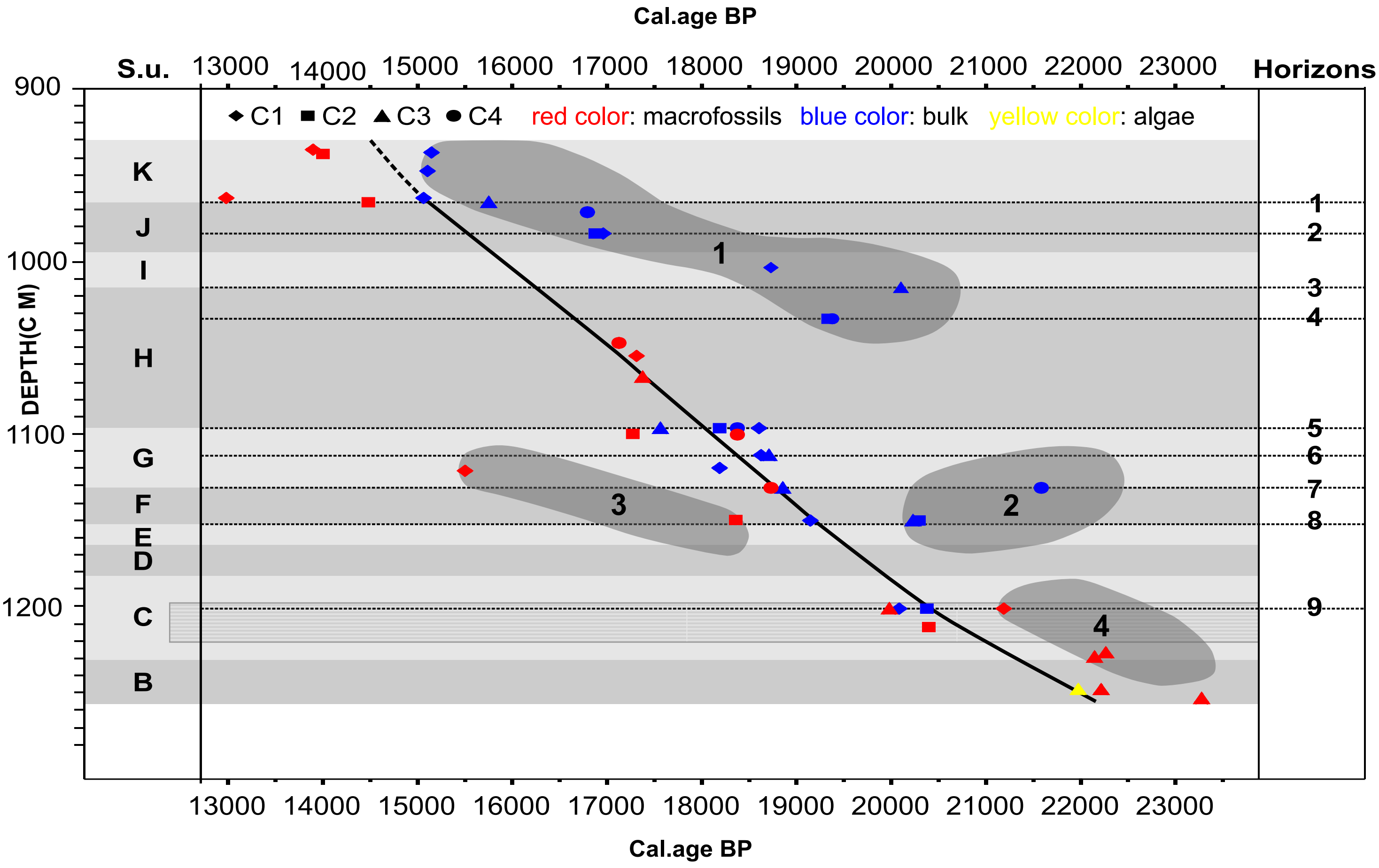
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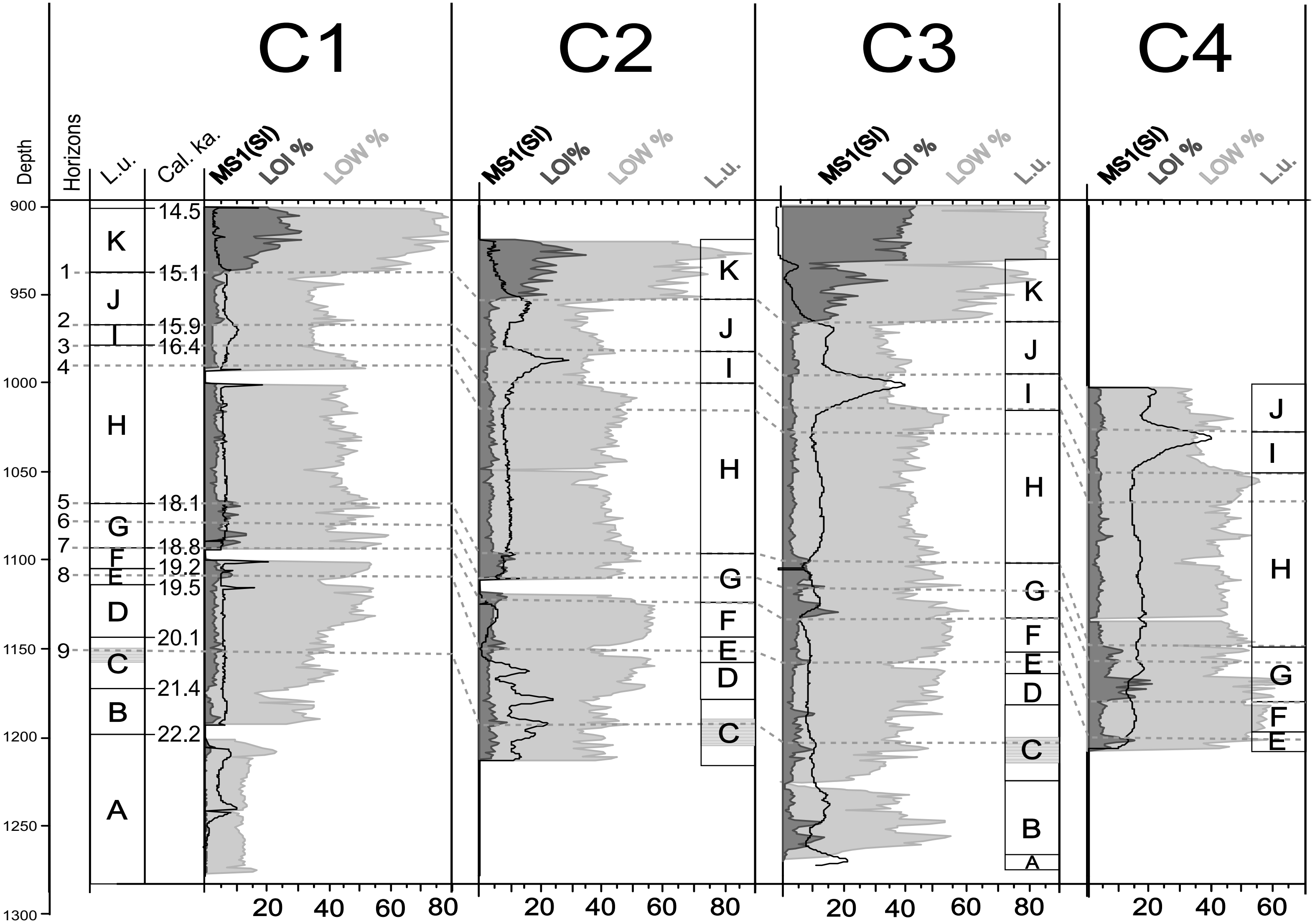
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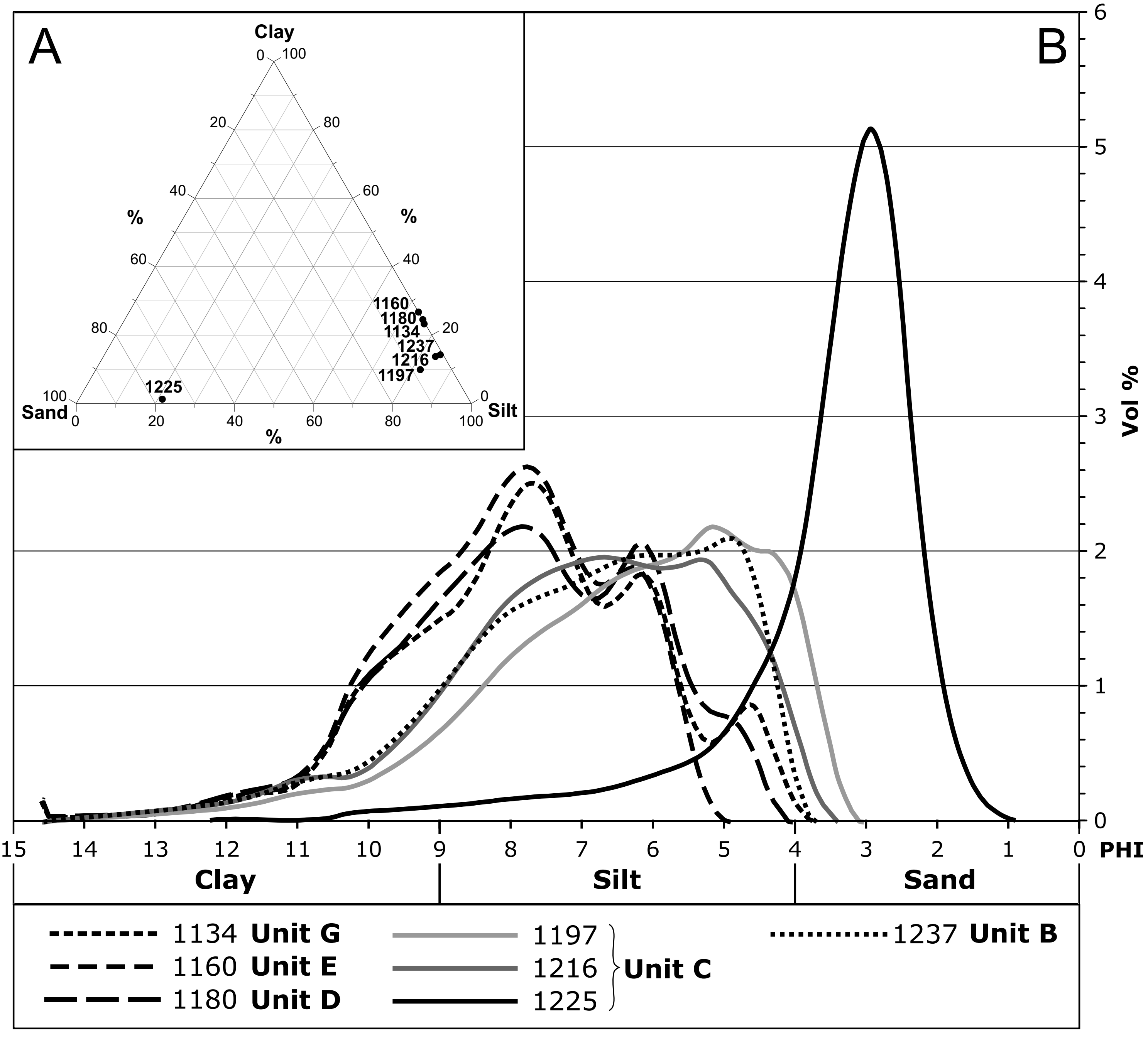
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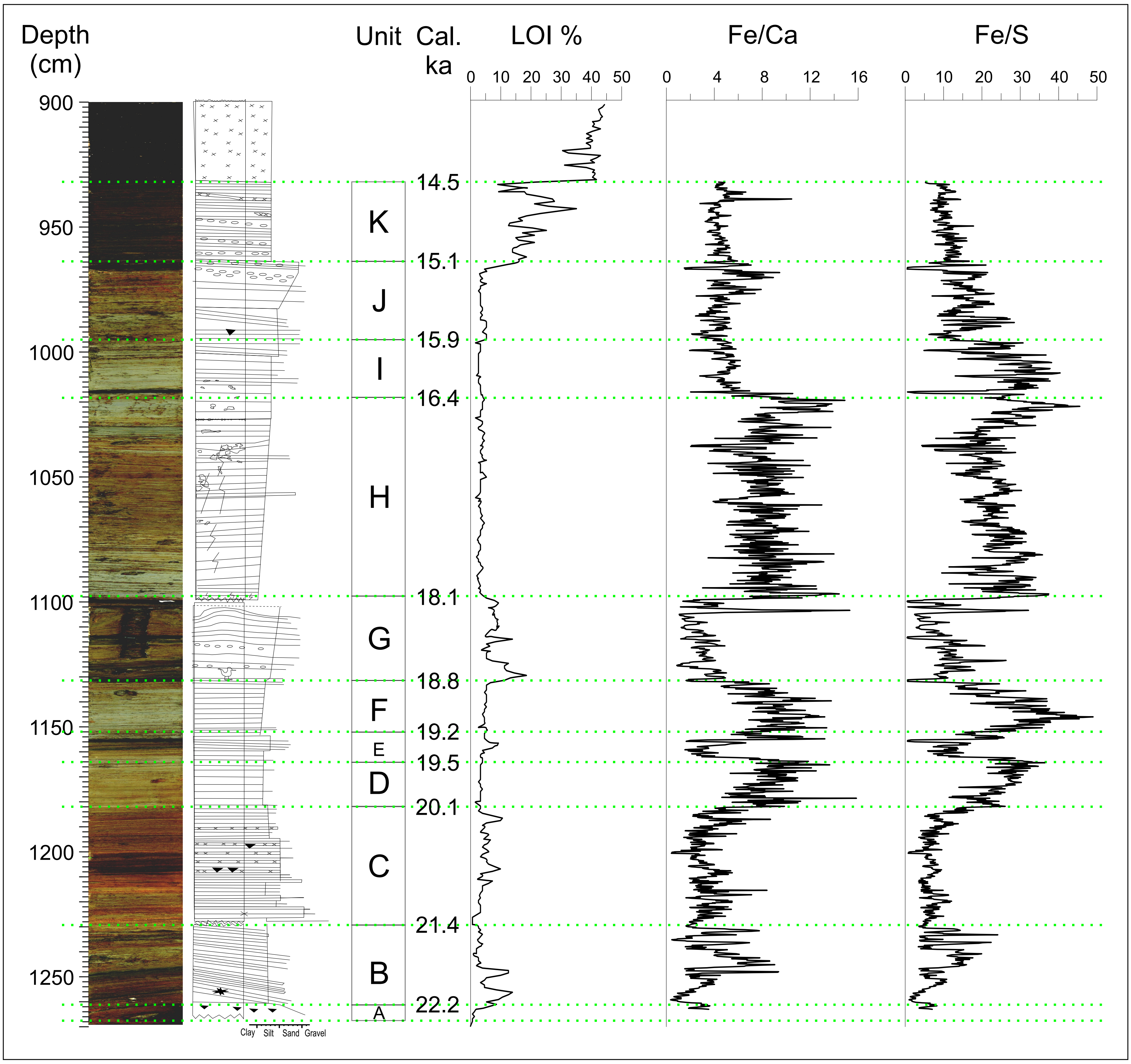
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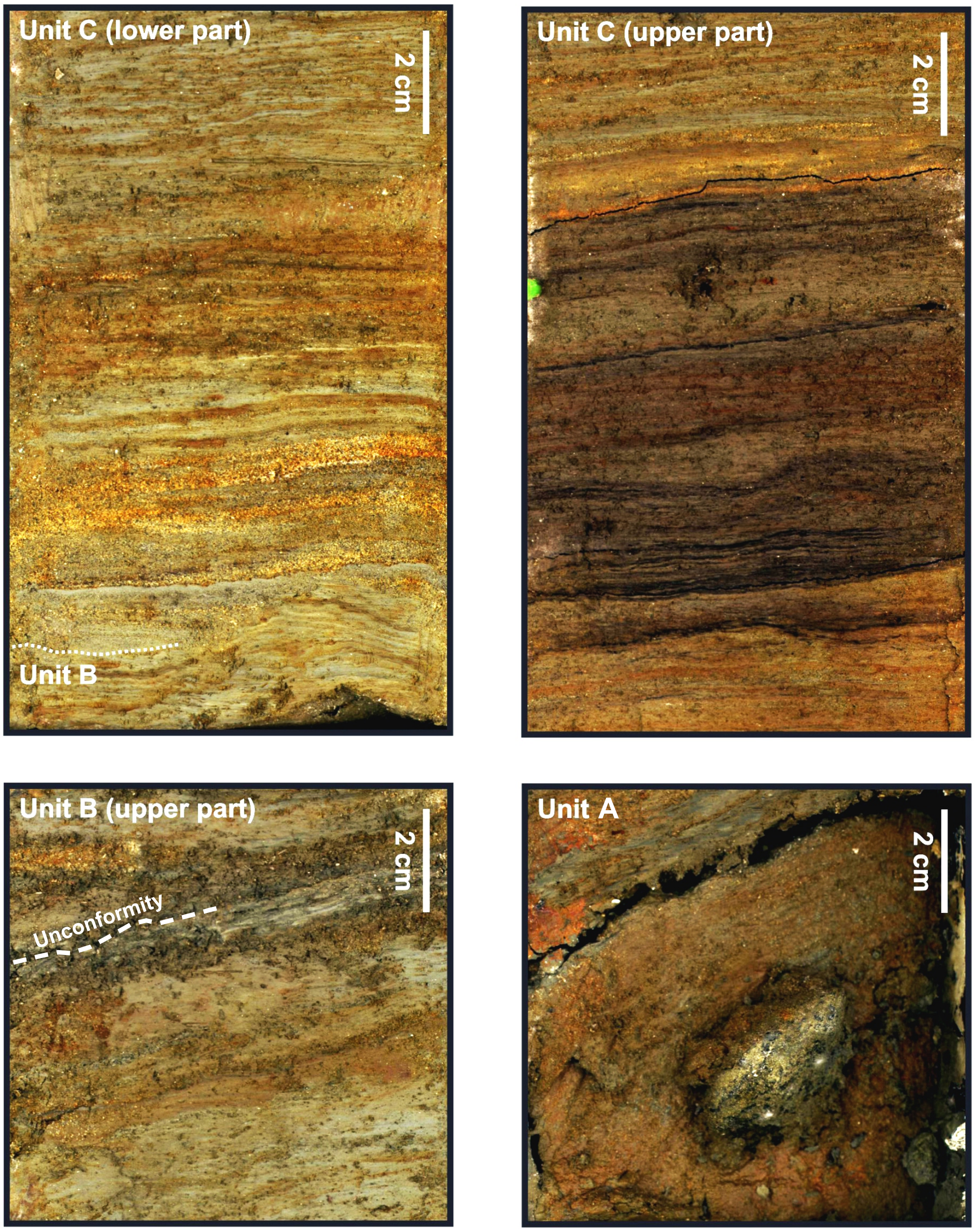
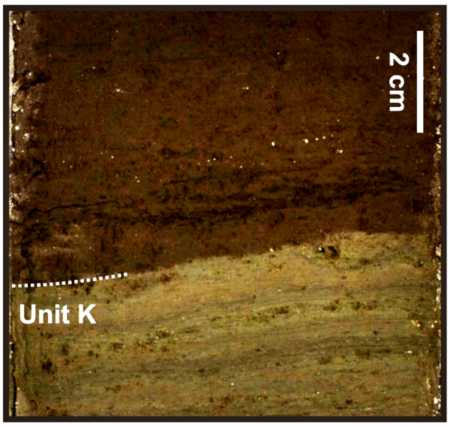
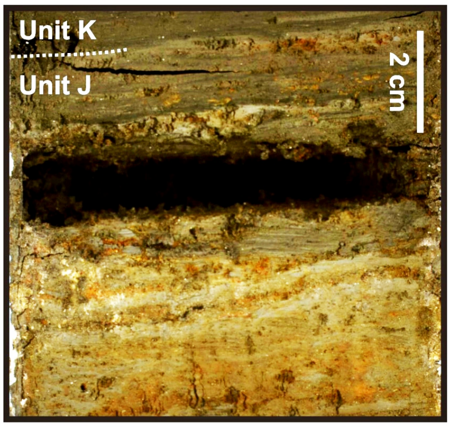
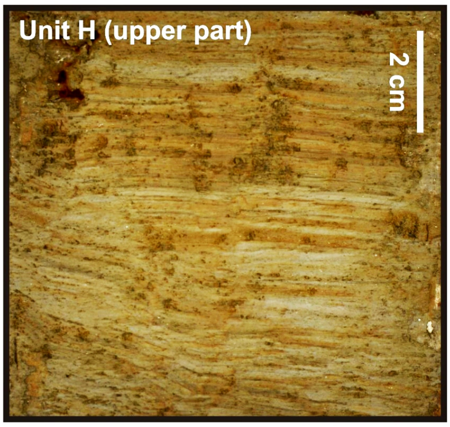
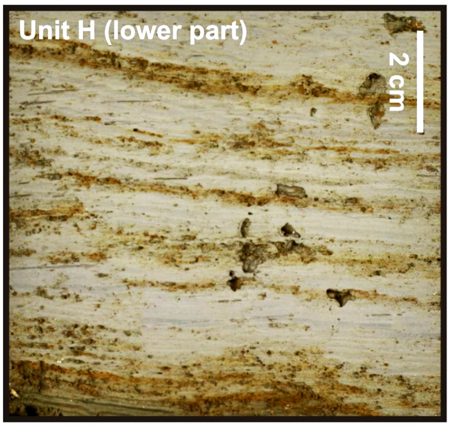
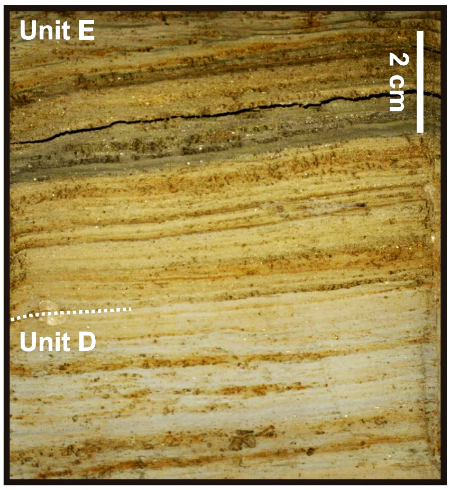

Unit C (lower part)
2 cm
Unit B
Unit C (upper part)
2 cm
Unit B (upper part)
2 cm
Unconformity
Unit A
2 cm

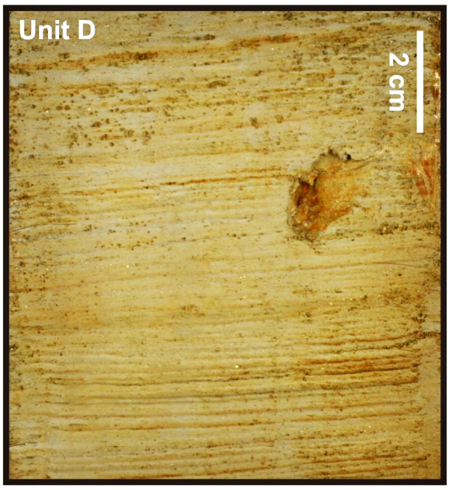

2 cm
Unit K

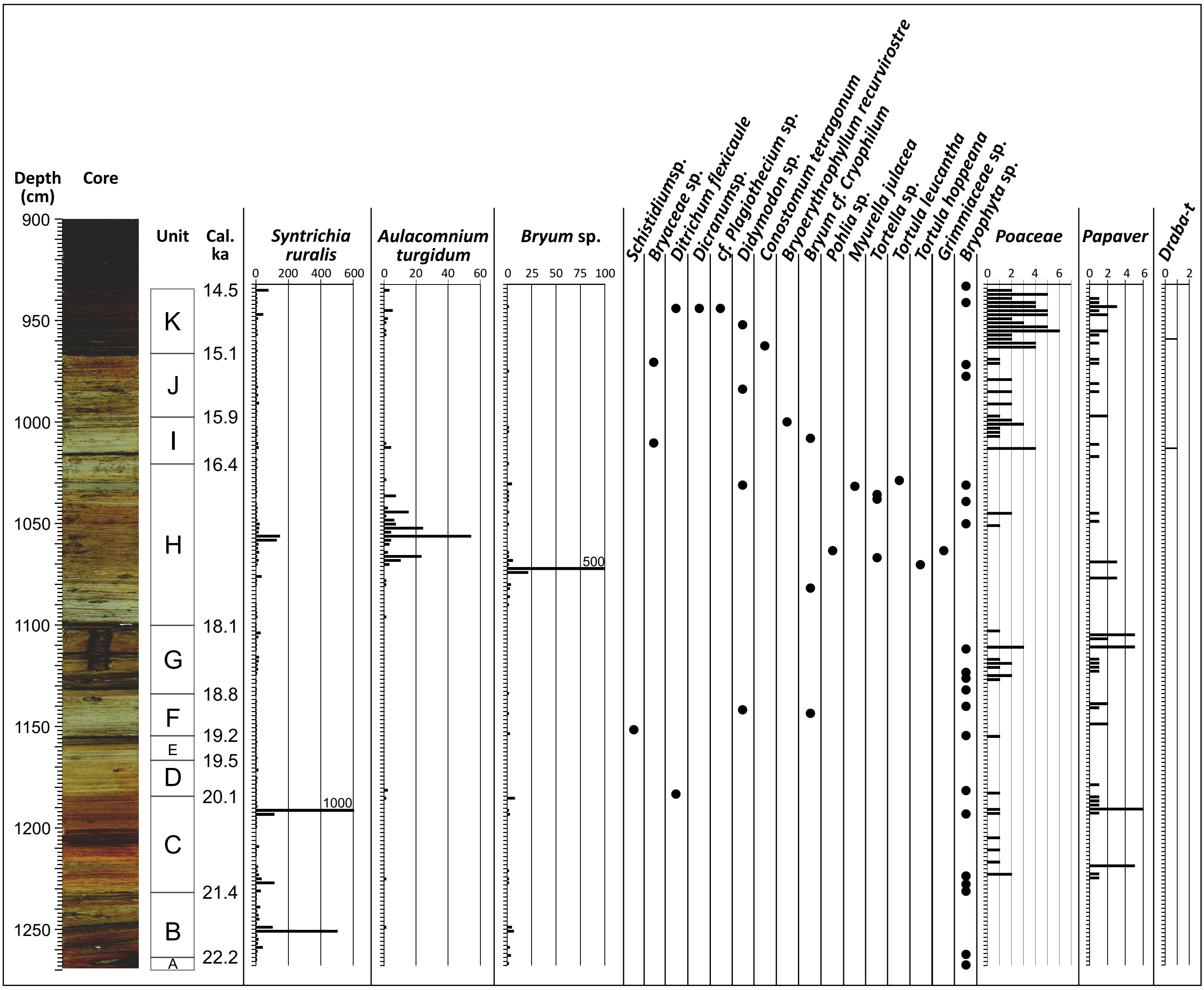

Unit K
Unit J
2 cm

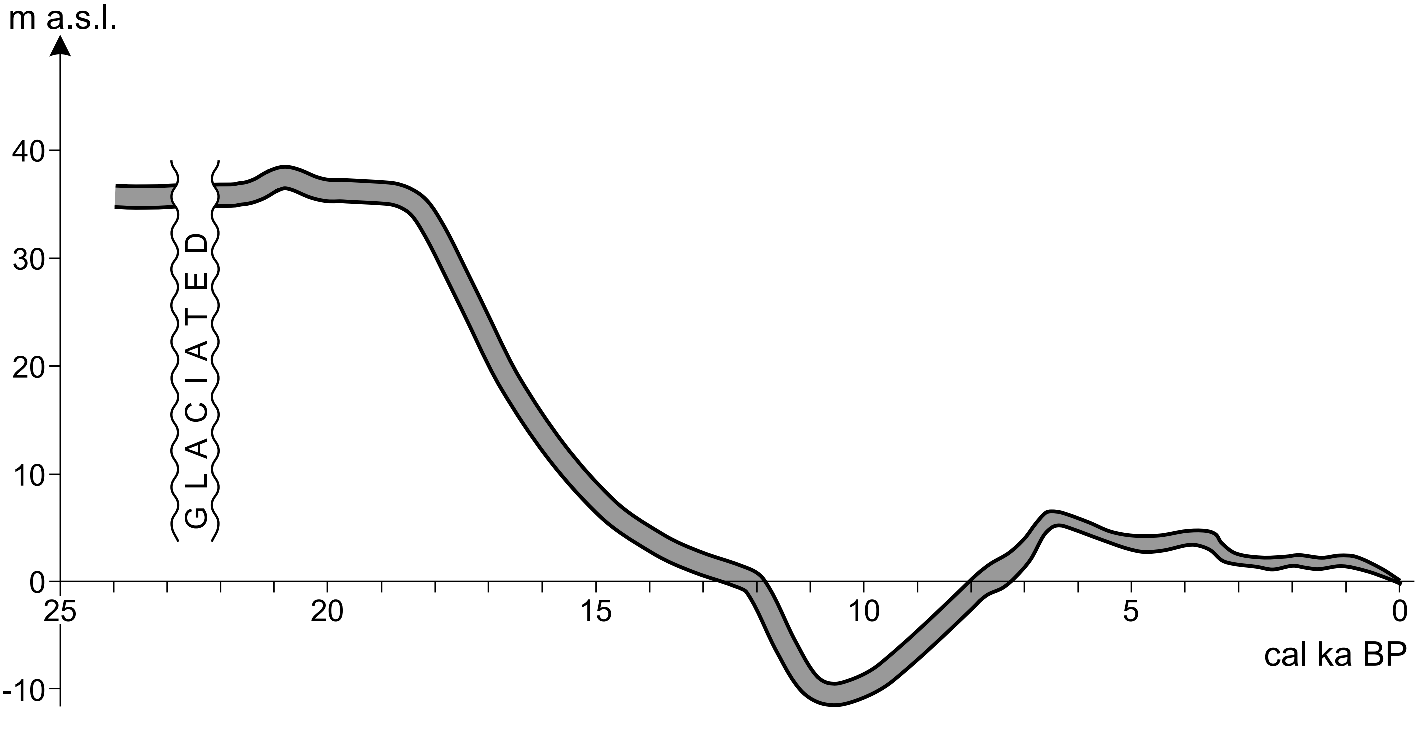

Unit H (upper part)
2 cm

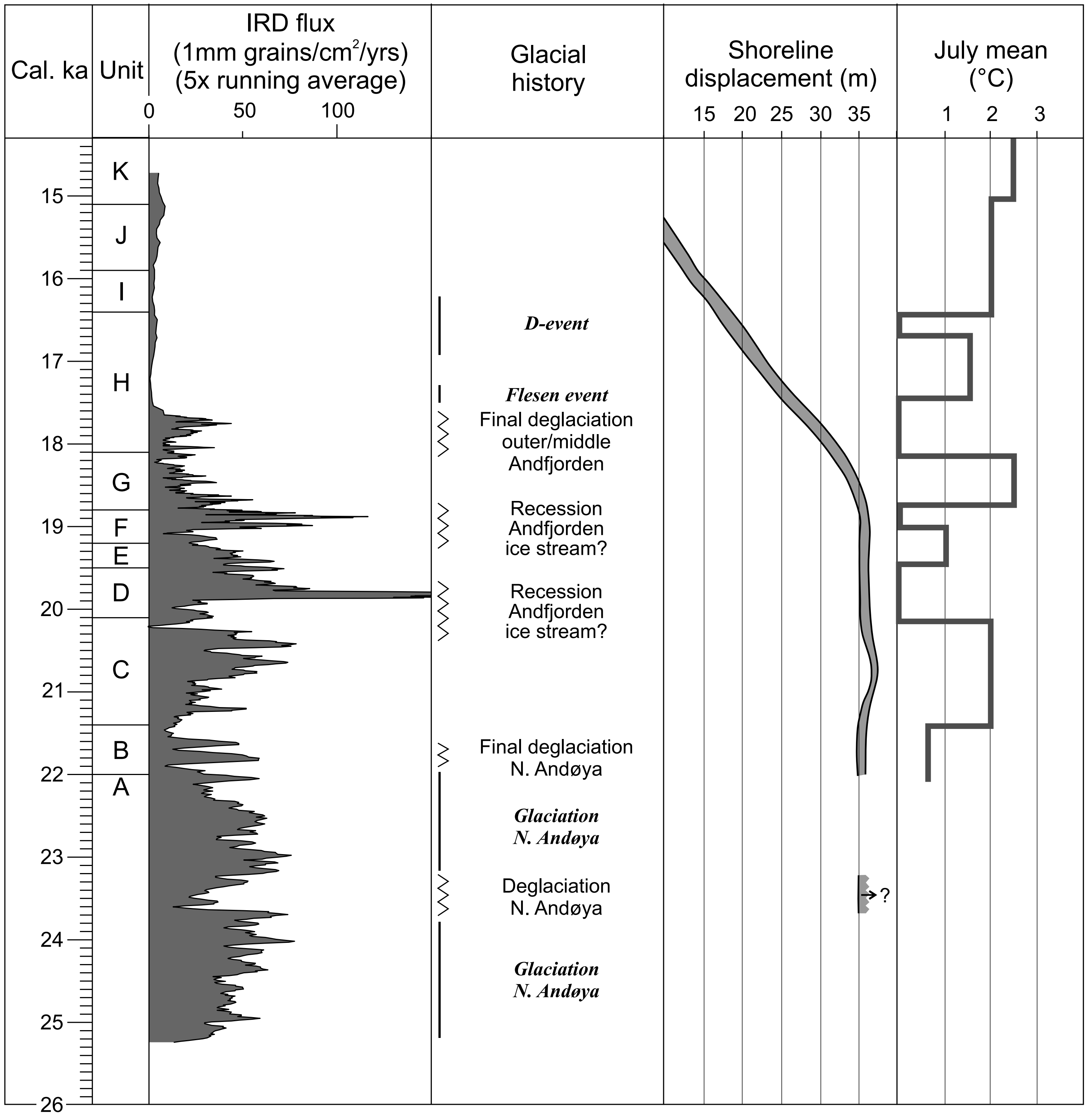

Unit H (lower part)
2 cm

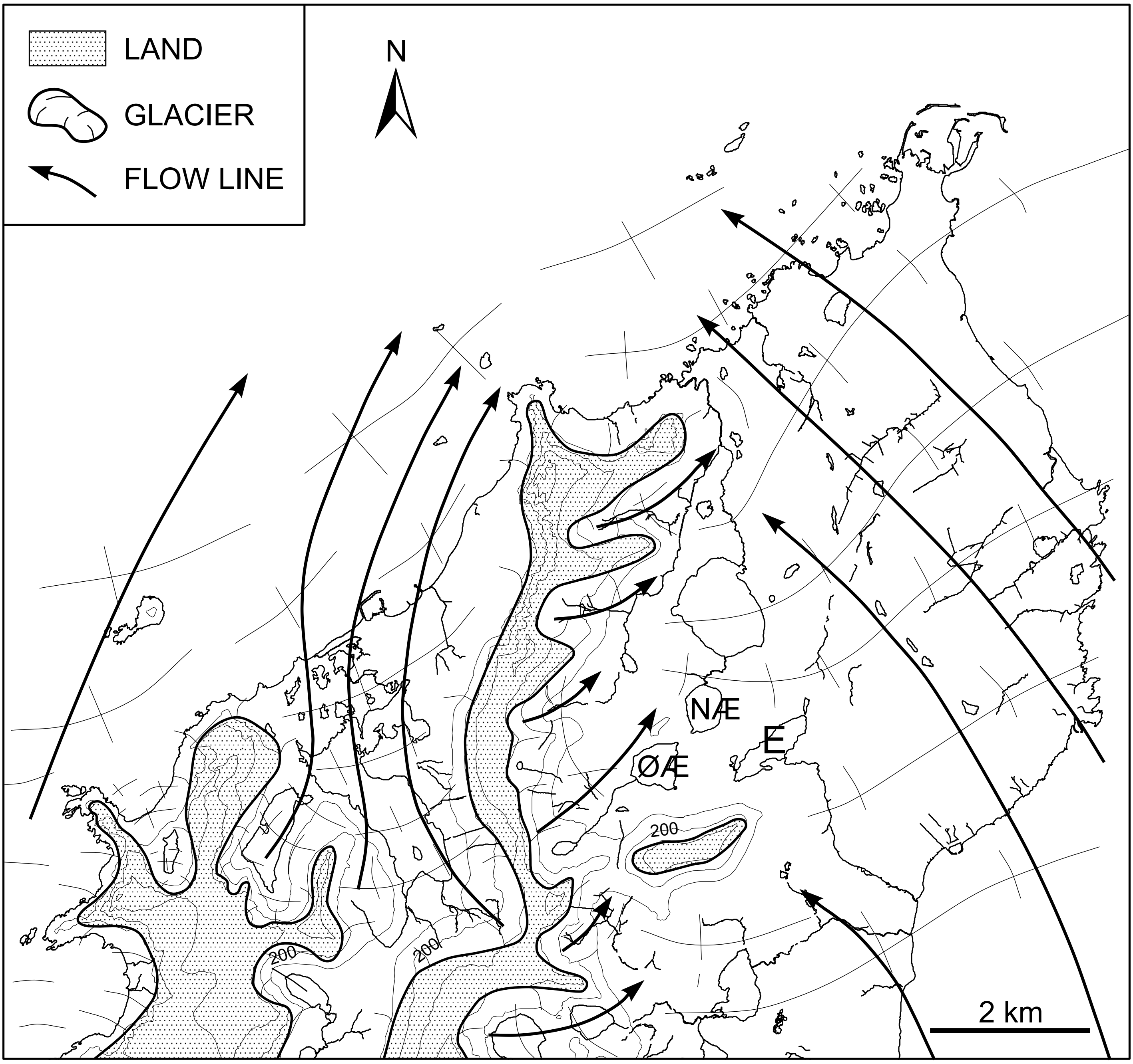

Unit E
2 cm
Unit D


Unit D
2 cm


Depth (cm)
Core
900
950
1000
1050
1100
1150
1200
1250
Unit
K
J
I
H
G
F
E
D
C
B
A
Cal. ka
14.5
15.1
15.9
16.4
18.1
18.8
19.2
19.5
20.1
21.4
22.2
Syntrichia ruralis
0
200
400
600
1000
Aulacomnium turgidum
0
20
40
60
Bryum sp.
0
25
50
75
100
500
Schistidiumsp.
Bryaceae sp.
Ditrichum flexicaule
Dicranumsp.
cf. Plagiothecium sp.
Didymodon sp.
Conostomum tetragonum
Bryoerythrophyllum recurvirostre
Bryum cf. Cryophilum
Pohlia sp.
Myurella julacea
Tortella sp.
Tortula leucantha
Tortula hoppeana
Grimmiaceae sp.
Bryophyta sp.
Poaceae
0
2
4
6
Papaver
0
2
4
6
Draba-t
0
2


m a.s.l.
40
30
20
10
0
-10
GLACIATED
25
20
15
10
5
0
cal ka BP


Cal. ka
Unit
IRD flux
(1mm grains/cm²/yrs)
(5x running average)
0
50
100
Glacial
history
Shoreline
displacement (m)
15
20
25
30
35
July mean
(°C)
1
2
3
15
16
17
18
19
20
21
22
23
24
25
26
K
J
I
H
G
F
E
D
C
B
A
D-event
Flesen event
Final deglaciation
outer/middle
Andfjorden
Recession
Andfjorden
ice stream?
Recession
Andfjorden
ice stream?
Final deglaciation
N. Andøya
Glaciation
N. Andøya
Deglaciation
N. Andøya
Glaciation
N. Andøya
?


LAND
GLACIER
FLOW LINE
N
NÆ
E
ØÆ
200
200
200
2 km

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