Sedimentary environment, lithostratigraphy and dating of sediment sequences from Arctic lakes Revvatnet and Svartvatnet in Hornsund, Svalbard

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Abstract: The sedimentary environment, sediment characteristics and age-depth models of sediment sequences from Arctic lakes Revvatnet and Svartvatnet, located near the Polish Polar Station in Hornsund, southern Svalbard (77°N), were studied with a view to establishing a basis for paleolimnological climate and environmental reconstructions. The results indicate that catchment-to-lake hydroclimatic processes probably affect the transportation, distribution and accumulation of sediments in different parts of lakes Revvatnet and Svartvatnet. Locations with continuous and essentially stable sedimentary environments were found in both lakes between water depths of 9 and 26 m. We used several different dating techniques, including ^{137}Cs, ^{210}Pb, AMS ^{14}C, and paleomagnetic dating, to provide accurate and secured sediment chronologies. A recovered sequence from the northern basin of Revvatnet spans more than one thousand years long with laminated stratigraphy in the upper part of the sediment. Based on AMS ^{14}C dates, it is possible to suppose that Revvatnet

basin was not occupied by a valley glacier during the Little Ice Age. The dates were supported by ^{137}Cs chronologies, but not confirmed with other independent dating methods that extent beyond the last 50 years. A sedimentary sequence from the northern basin of Svartvatnet provides a potential archive for the study of climate and environmental change for the last *ca.* 5000 years. Based on the stratigraphy and a Bayesian age-depth model of AMS ^{14}C and paleosecular variation (PSV) dates, the recovered sediment sections represent a continuous and stable sedimentation for the latter half of the Holocene.

Key words: Arctic, Svalbard, Hornsun, Revvatnet, Svartvatnetd, sediment, stratigraphy, Holocene.

Introduction

Lake sediments are sensitive archives for the study of climate and environmental change. In lacustrine sedimentation, the quality and quantity of particles settling onto a lake bottom are driven by many interacting factors and dynamic processes within lakes and in their catchment areas (*e.g.* Håkansson and Jansson 1983). For example, sediment deposition is influenced by climate parameters affecting both the seasonal runoff via the delivery of catchment-derived allochthonous material and the limnology of the basin (*e.g.* Håkansson and Jansson 1983). Sediment records hold potential for paleoenvironmental studies in regions where other climate proxy records are scarce or unavailable, and can contribute to a richer understanding of the past environment when combined with other proxy records (Lamoureux 2012). High-latitude lakes have been of particular interest during recent decades, because Arctic regions are most severely impacted by the ongoing climate change (*e.g.* Serreze and Barry 2011), Arctic lakes maintain sensitive ecosystems, and because they lie in a pristine environment compared to lakes that are located in inhabited areas (*e.g.* Kaufman *et al.* 2009; Carey and Zimmerman 2014). Therefore, studies on Arctic lakes also allow us to understand the potential impacts of climate change and provide valuable insights into the consequences of climate change in the lacustrine environment (Vincent 2009).

A comprehensive understanding of the lacustrine sedimentary environment, changing landscapes, limnology, and catchment-to-lake hydroclimatic characteristics are important prerequisites for the use of paleolimnological proxies to infer the past climate and environmental changes. This type of information is often lacking or very scarce in Arctic lakes, and even bathymetric maps are often unavailable. In recent years, however, a number of process studies have been conducted on Arctic settings to enhance understanding of lacustrine sedimentary systems and to facilitate the crucially important selection of suitable coring locations and interpretation of paleolimnological data (*e.g.* Cockburn and Lamoureux 2008). Another important aspect of the paleolimnological approach is the accuracy of dating of the studied sedimentary records. As stated by Birks (2008), the chronology is the single most critical problem in establishing the temporal and spatial patterns of

Holocene climate changes, which particularly applies when aiming at multi-proxy regional- to global-scale climate reconstructions (*e.g.* Kaufman *et al.* 2009; Shi *et al.* 2013). Recent studies have demonstrated that with the use of multiple dating methods, thorough evaluation of the potential strengths and deficiencies of dates and reporting of the age uncertainties and dating error estimates, it is possible to achieve well-established sediment chronologies and accurate age-depth models for individual sequences (*e.g.* Ojala *et al.* 2012; Brauer *et al.* 2014).

This paper reports the sedimentary environment, sediment characteristics and age-depth models of selected sediment sequences from two Arctic lakes, Revvatnet and Svartvatnet, located near the Polish Polar Station in Hornsund, southern Svalbard. The present work is part of a larger project where the quantitative reconstruction of climate changes and the evolution and interactions of ocean-atmosphere circulation patterns will be constructed in the high Arctic Svalbard during the Holocene. The present work focuses on geology, sedimentology and dating of sediment sequences from Revvatnet and Svartvatnet to provide a basis for future paleoclimatic reconstructions based on fossil chironomid (Diptera: Chironomidae) assemblages (Luoto *et al.* 2014), the oxygen isotope composition ($\delta^{18}O_{chir}$) of their head capsules, and sediment palmitic acid δD values (*e.g.* Huang *et al.* 2002; Wooller 2008; Verbruggen *et al.* 2010). We assess the modern setting of the lacustrine sites and their catchment areas, evaluate their current hydroclimatic nature with sediment trapping and CTD measurements, describe their sediment lithostratigraphy, and discuss of results from multiple datings that are based on ^{137}Cs, ^{210}Pb, AMS ^{14}C, and paleosecular variation (PSV).

Study sites

The study lakes Revvatnet (77.022°N, 15.368°E) and Svartvatnet (76.895°N, 15.676°E) are respectively located 5 km northwest and 12 km south of the Hornsund Polish Polar Station (Fig. 1). The study area is situated at the northernmost reach of the warmer North Atlantic current before it enters the Arctic Ocean and continues as the warm Atlantic layer below the cold surface waters (Rasmussen *et al.* 2007). The Polar Front develops between these water masses (Majewski *et al.* 2009). The climate in the area is typical for the Atlantic Arctic region, with the extensive influence of the seasonal sea surface temperatures and sea ice extensions. The annual mean of temperature (according to AD 1979–2009 statistics, Hornsund) is -4.3°C, the coldest months being December to March (-9.5 to -10.9°C), and the warmest July or August (+4.1 to 4.4°C). An increasing trend of 2–3°C in annual and seasonal temperatures has occurred at Hornsund Station since AD 1979 (Marsz 2013). The annual precipitation varies between 230 and 635 mm, the mean being 434 mm, of which *ca.* 44% occurs as rain or drizzle, 30% as snow and 26% as their mixed form. August, September, and October are the months with the highest atmospheric precipitation
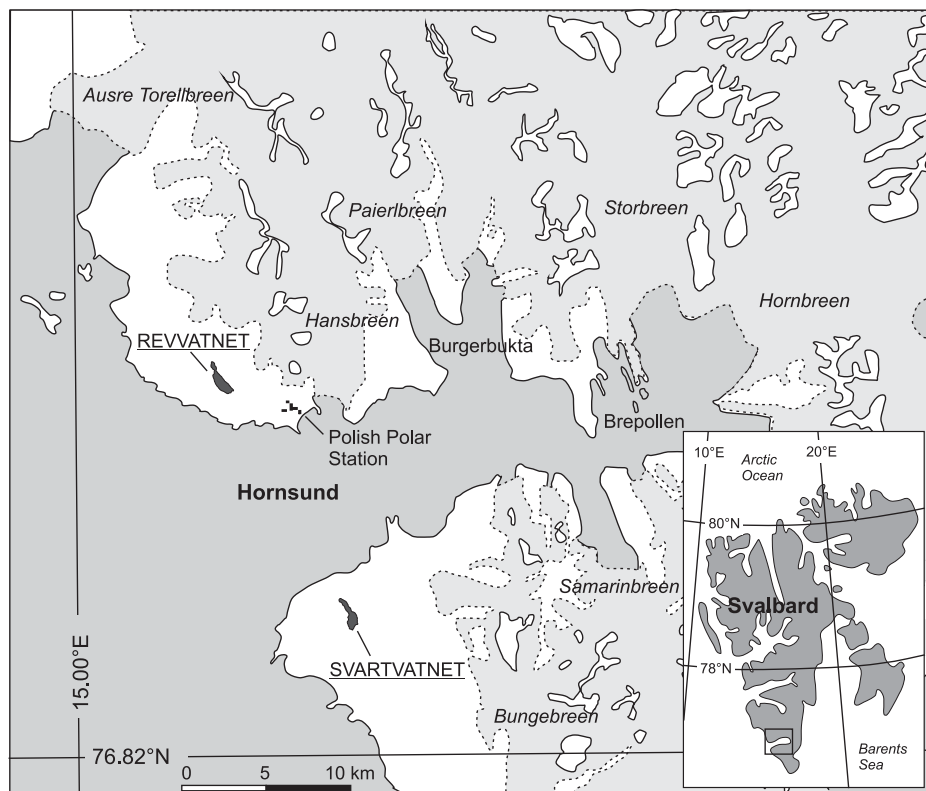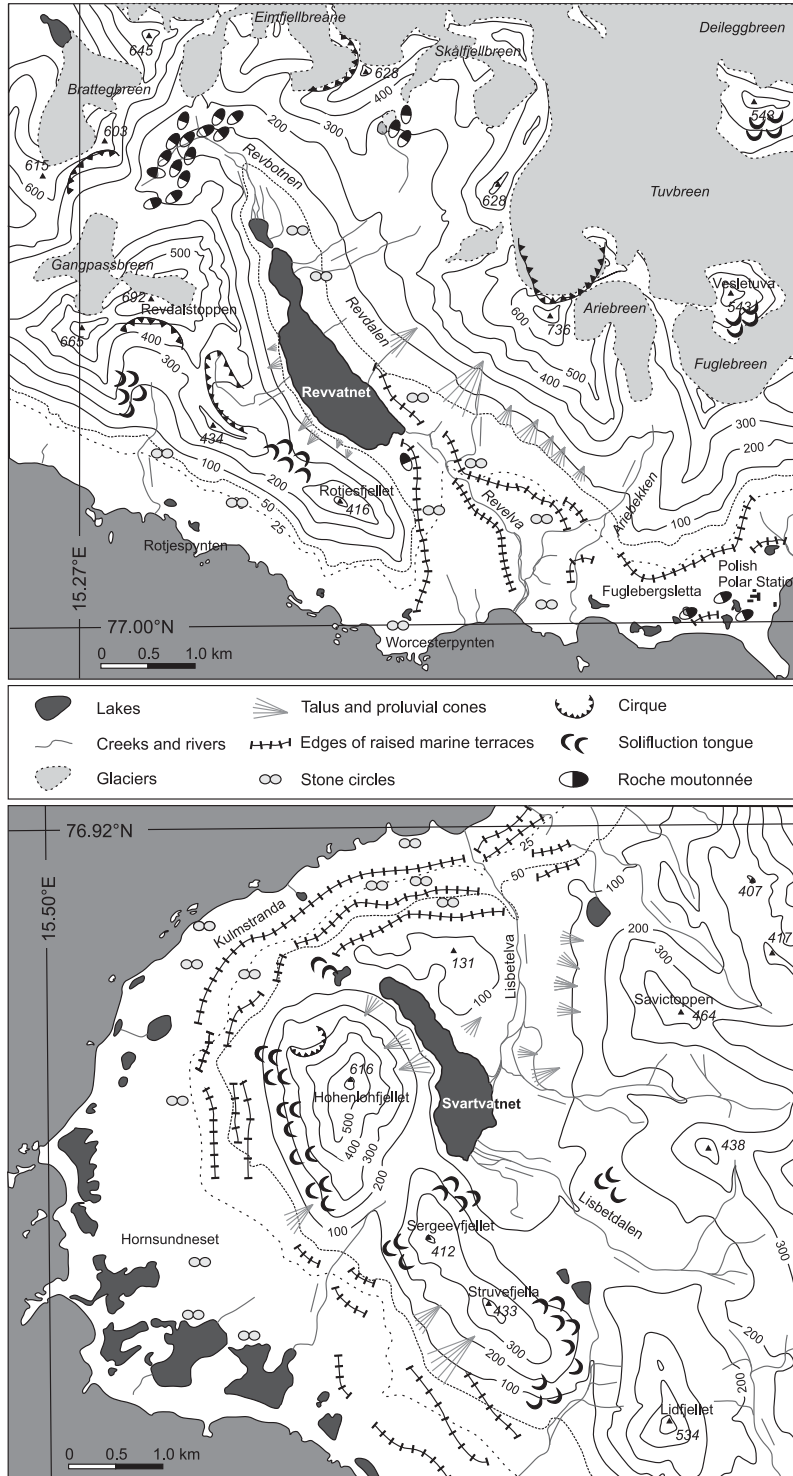
Fig. 1. Map of the Hornsund area in southern Svalbard. The study lakes Revvatnet and Svartvatnet are located some 15 km apart on the southern and northern sides of Hornsund.

(50–70 mm per month). Precipitation is heavily dependent on the atmospheric circulation, and the highest diurnal precipitation typically occurs during the advection of warm and moist air from the southwestern sector (Łupikasza 2013). The total annual precipitation has shifted less than temperature during the last 30 years, although the proportion of snow precipitation has evidently decreased, and the duration of the winter snow cover has become shorter (Marsz and Styszyńska 2013).

The studied lakes Revvatnet and Svartvatnet are ice-covered for a period of 9 to 10 months each year, and usually open from mid-July to the end of September. The catchment of the lakes is not human-influenced and much of the natural vegetation is intact. The landscape is covered by snow and ice for most of the year and its biozone is characteristic for Arctic tundra and the polar desert (*e.g.* Callaghan *et al.* 2005). The hydrology of the studied lakes is driven by a network of streams that originate from highly seasonal melting of ice and snow in the mountain areas.

Fig. 2. The main geomorphological characteristics of Revvatnet (upper) and Svartvatnet (lower) →
catchment areas. The Polish Polar Station on Fugbergsletta is indicated in the south-eastern corner of the upper map.

	Lakes		Talus and proluvial cones		Cirque
	Creeks and rivers		Edges of raised marine terraces		Solifluction tongue
	Glaciers		Stone circles		Roche moutonnée

Revvatnet is a dam lake composed of two pools of which the southern one forms the main basin (Fig. 2). There is also a third pool in north that is separated from these two for most of the time. Lake Revvatnet lies at an elevation of 30 m a.s.l. and has an area of about 0.9 km². A network of streams supply the lake from Revbotnen in the north, and smaller creeks also enter the lake from the east and west. According to Karczemski *et al.* (1981), the lake is an overflow type. There is one southeastern outlet stream, Revelva, that runs through the plain of Fuglebergs-letta and enters the sea in Hornsund, about 2 km downstream. The oligotrophic lake has a pH of 7.6, a water color of 0 CPU, a conductivity of 30 μS cm^{-1} and total dissolved solids (TDS) of 10 mg l^{-1} in the surface water of the main basin sampled at the end of June 2013.

Svartvatnet lies at an elevation of 63 m a.s.l. (Gullestad and Klementsen 1997) and has an area of about 0.8 km² (Fig. 2). The lake is supplied by snow melt water from higher altitudes that runs into the southern basin from Lisbetdalen via a set of shallow creeks. There is one eastern outlet stream, Lisbetelva, which has a gentle slope and shallow pools close to the basin. Further away towards the north, the Lisbetelva drops more steeply before entering the Hornsund about 3 km from the lake. Svartvatnet is an oligotrophic lake with a (June 2013) surface water pH of 7.2, color 0 CPU, conductivity 50 μS cm^{-1} and TDS 20 mg l^{-1}.

The geomorphology of the valleys where the study lakes are located is charac-terized by many typical features of the periglacial landscape, such as glacial cirque, stone circles and solifluction tongues (Karczewski *et al.* 1981; Karczewski 1984). Talus formations and proluvial cones are typical for the steep mountain slopes that surround these lakes. Distinct outwash routes and the related coarse--grained deposits characterize the area south of Revvatnet (Karczewski *et al.* 1981). Some of these routes cut through the edges of lower-lying (4.5–6 m a.s.l) marine terraces that are primarily southwest oriented. In general, the edges of raised marine terraces are typical features of both study sites, and they typically ap-pear between 10 and 70 m a.s.l. The area north of Svartvatnet is basically com-posed entirely of plains and edges of ancient marine terraces (Fig. 2). The shore-line formations at about 25 m a.s.l. represent the early-Holocene sea level *ca.* 10,000 yrs BP (Birkenmajer and Olsson 1970; Forman *et al.* 2004). The edges and raised marine terraces at 8–12 m a.s.l. near Svartvatnet are related to Sørkapp Land deglaciation, whereas relict sediments found in marine beaches at 40–70 m a.s.l. have been TL dated to 50–70 ka BP by Pękala (1989).

From a geological perspective, the study lakes can be regarded as glacial lakes formed in valleys by the scouring action and erosion of glaciers. The glacier-inter-glacial history of the Arctic Ocean has been reviewed in *e.g.* Svendsen *et al.* (2004) and Jakobsson *et al.* (2014). The relief of their drainage area and the location of lac-ustrine basins in valleys have a fundamental influence on the evolution of lakes with regards to valley glacier occupation and re-advances, seasonal hydrology, and many physical processes of sedimentation, such as the transportation and settling of parti-

cles in the lacustrine environment. There are several side hanging valleys with glaciers near Revvatnet, such as Eimfjellbreane, Gangsbreen, and Skålfjellbreen, whereas with Svartvatnet, the closest active valley glacier (Gåsbreen) occupies a valley about 5 km east of the lake and on the other side of Saviètoppen. Based on geomorphological evidence, Karczewski *et al.* (1981) proposed that a glacier advance occurred in Revdalen *ca*. 2400 yrs BP covering the entire Revvatnet basin. Then, about 2000 years later, during the Little Ice Age (LIA), the area was glaciated again, but this time covering only the northern part of the Revvatnet basin. No geomorphological evidence exists or has been presented from Lisbetdalen that would suggest covering of the Svartvatnet by a valley glacier during the late Holocene. Glacial sediments in Lisbetdalen were formed by a valley glacier during the middle and late Sørkapp Land glaciation and have been thermoluminescence (TL) dated to 22 to 47 ka BP by Butrym *et al.* (1987) and Lindner and Marks (1993).

Methods

Fieldwork at lakes Revvatnet and Svartvatnet was performed during the summer of 2013. The survey began with echo sounding of the lakes for bathymetry in order to select suitable locations for surface cores and long core sediment samples. Depths were measured with a Garmin 276c GPS equipped with a 50/200 kHz GSD 21 sonar, and altogether *ca.* 450 and 200 points were recorded for lakes Revvatnet and Svartvatnet, respectively. The Kriging method, which uses a weighted average of neighboring points, was applied for interpolation of bathymetric curves from point data.

Water-column temperature and turbidity were measured at anchored stations with a CTD Sensordata SD 204 equipped with a Seapoint turbidity meter emitting light at 880 nm at scattering angles of 15–150°. The CTD measurements were made at 1-s intervals equivalent to 3–4 measurements per meter. The data on water turbidity are presented in formazin turbidity units (FTU).

Double cylindrical sediment traps with an opening of 6 cm and lengths of 0.6 m installed on the gimbaled frame were anchored 2 m above the lake bottom. The sedimentation rate from suspension (SR) in Revvatnet was measured for nine days from July 17–26 2013. The collected sediment was vacuum-filtered onto pre--weighed filters (MN GF5 with 0.4-μm openings). The filters were dried at 60°C for 24 h, weighed to determine the dry mass of sediment, combusted at 450°C for 24 h, and then re-weighed to obtain the organic matter mass from weight loss.

Coring of the sediment sequences was carried out with a light piston corer operated with a series of 2-m-long rigid aluminum rods (long cores) (Putkinen and Saarelainen 1998) and with a Kajak corer (surface sediment) (Renberg 1991). Altogether, 18 sediment cores were collected from Revvatnet and 7 from Svartvatnet (Table 1, Fig. 3). The recovery of longer cores was targeted to areas that were con-

Table 1

The analyses undertaken from different cores from lakes Revvatnet and Svartvatnet in the present study.

Core ID	Water depth (m)	Corer type	Core depth (cm)	Analysis*
SV1	12.3	kajak	0–21	Cs
SV2	24	kajak	0–42	Cs
SV3	12.3	kajak	0–23	Cs
SV4A	12.3	light pistoncorer	0–120	*unopened*
SV4B	12.3	light pistoncorer	0–149	L, S, MM, P, PA, Cs
SV4C	12.3	light pistoncorer	0–163	S, CH, O, Cs, Pb, C
SV5	22.7	light pistoncorer	0–59	–
RE1	26.6	kajak	0–6.5	L, S, Cs
RE2	25.3	kajak	0–30	L, S, Cs
RE3	25.3	kajak	0–34	L, S, Cs
RE4	9.7	light pistoncorer	0–10	L, S, Cs
RE5	17.4	light pistoncorer	0–53	*unopened*
RE6	13.4	light pistoncorer	0–103	*unopened*
RE7	13.5	light pistoncorer	0–85	*unopened*
RE8	9.5	light pistoncorer	0–131	S, CH, Cs, O
RE9	9.5	light pistoncorer	0–110	L, S, Cs, C
RE10	7.5	kajak	0–5	L, S
RE11	10.3	kajak	0–5	L, S
RE12	17.8	kajak	0–5	L, S
RE13	9.8	kajak	0–5	L, S
RE14	4.6	kajak	0–5	L, S
RE15	13.5	kajak	0–5	L, S
RE16	6.3	kajak	0–5	L, S
RE17	9.5	kajak	0–5	L, S
RE18	4.9	kajak	0–5	L, S

L = LOI, S = susceptibility (sensor), MM = mineral magnetism, CH = chironomids, O = $\delta^{18}O_{chir}$; P = palmitic acid δD, PA = paleomagnetism, Cs = ^{137}Cs, Pb = ^{210}Pb, C = AMS ^{14}C.

sidered to maintain stable and continuous sedimentation and that had a water depth of between 10–15 m. Two to three parallel sets of piston cores were taken from these primary coring locations to duplicate the sediment stratigraphy and to collect a sufficient amount of material for multiproxy paleolimnological studies and dating of the sequences. Of these, only sediment stratigraphy, its physical parameters and results from datings are presented here. Surface sediment samples taken with the Kajak corer were split into 1 cm thick sections in the field, while longer piston cores were carefully sealed and transported to a sediment laboratory for further processing and analysis.

The sediment cores were opened in the laboratory, their surfaces were cleaned and they were described in detail for sediment stratigraphy and components (Troell-
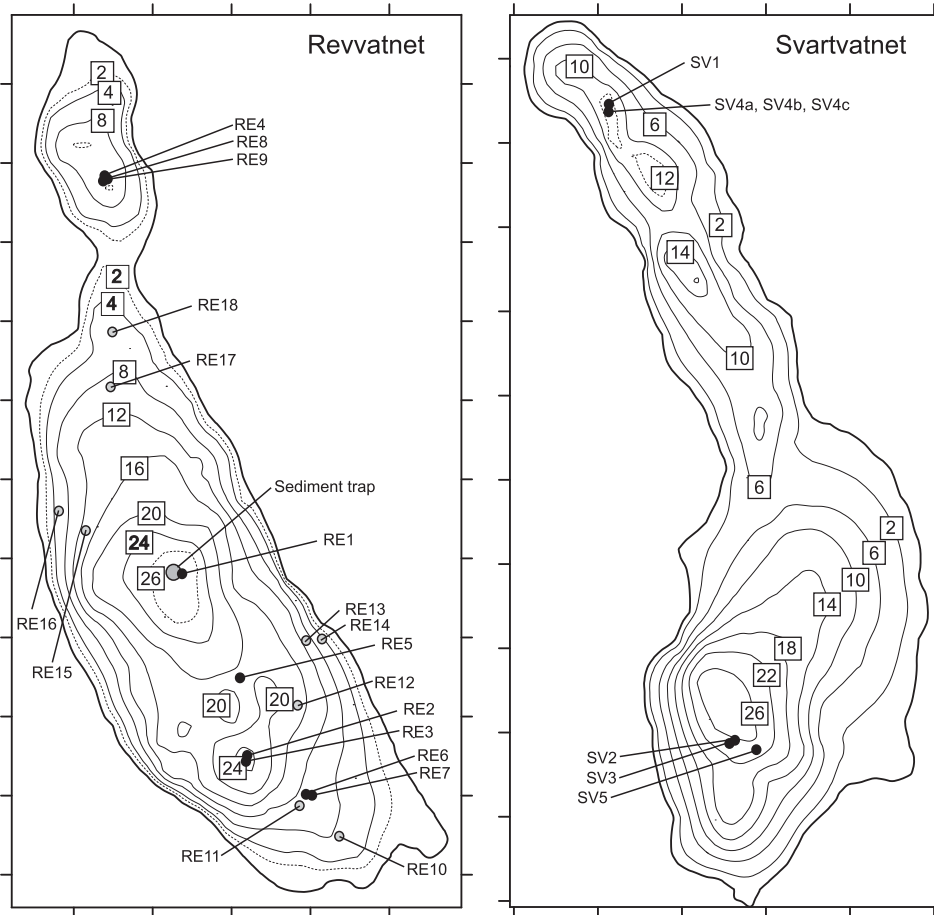
Fig. 3. Bathymetric map (in meters) of Revvatnet (left) and Svartvatnet (right) with the locations of the investigated cores and position of the sediment trap. Tick marks outside the map are placed at 100 m intervals.

-Smith 1955). The cores were logged for magnetic susceptibility with a Bartington MS2E1 surface-scanning sensor at 1 cm resolution, and selected cores were sub-sampled for loss on ignition (LOI) at 1 cm resolution (+550°C for 2 hours) (see Table 1; Håkansson and Jansson 1983).

Core SV4B from Svartvatnet was continuously sampled for paleo- and mineral magnetic measurements at 2.5-cm resolution using standard 7 cm³ polystyrene cubes. Sample cubes were first measured for magnetic susceptibility using a KLY-2 (Geofizika Brno) susceptibility bridge. Following this, natural remanent magnetization (NRM) was measured at the Geological Survey of Finland with a 2G Enterprises SRM-755-4K tri-axial SQUID magnetometer. All samples were then demagnetized along three axes with a 20 mT peak alternating field (AF) to re-move possible viscous magnetization, except samples 5, 15, 25, 35, and 44 (repre-

Radiocarbon dates and their calibrated ages from Revvatnet and Svartvatnet sediment sequences. Calibrated with Oxcal 4.2 (Reimer *et al.* 2013).

Revvatnet					
Sample	Depth (cm)	Lab ID	^{14}C age PB	Cal AD/BC (2s)	Remark
RE9-42	39–40	Poz-61160	270 ± 30	AD 1632 ± 167	0.5 mg C
RE9-54	50–51	Poz-61162	240 ± 30	AD 1662 ± 141	0.9 mg C
RE9-64	58–59	Poz-61171	380 ± 30	AD 1501 ± 131	
RE9-70	63–64	Poz-61172	640 ± 80	AD 1340 ± 109	0.1 mg C
RE9-73	66–67	Poz-61173	940 ± 90	AD 1100 ± 164	0.07 mg C
RE9-86	78–80	Poz-61174	685 ± 30	AD 1294 ± 94	0.6 mg C
RE9-97	87–89	Poz-61175	920 ± 30	AD 1099 ± 85	
Svartvatnet					
Sample	Depth (cm)	Lab ID	Age ^{14}C	Cal AD/BC (2s)	remark
SV4c	32–33	ETH-59395	1295 ± 55	AD 723 ± 151	0.07 mg C
SV4c	81–82	ETH-59396	2920 ± 75	1119 ± 204 BC	0.04 mg C
SV4c	106–107	ETH-59397	3650 ± 60*	2026 ± 142 BC	0.017/0.07 mg C
SV4C-106	106–107	Poz-61177	3695 ± 30	2086 ± 72 BC	
SV4c	153–154	ETH-59398	4490 ± 100	3185 ± 277 BC	0.02 mg C

* mean of replicated dates: 3596 ± 82 and 3702 ± 78.

senting depths between 19.9 and 121.3 cm), which were selected for stepwise AF demagnetization (0 to 120 mT peak AF) in order to test the stability of the NRM. Following NRM measurements, the sample cubes were subjected to anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM) and the S-ratio in order to determine the carrier of the remanence and to study stratigraphical variations in magnetic mineral concentration and grain sizes (*e.g.* Thompson and Olfield 1986; Snowball and Sandgren, 2001). ARM was induced with a biasing direct field of 0.05 mT superimposed on a peak AF of 100 mT. SIRM was produced with 1000 mT, which was considered to saturate the samples, and the S-ratio was determined as $IRM_{-100\ mT}/SIRM_{1000\ mT}$. Mineral magnetic measurements were carried out with a SQUID magnetometer.

We used several dating techniques to determine the age-depth curves for Revvatnet and Svartvatnet sediment sequences. These included ^{137}Cs, ^{210}Pb, AMS ^{14}C, and paleomagnetic dating based on paleosecular variations (PSV). The ^{137}Cs analysis was performed for cores longer than 5 cm at the Geological Survey of Finland using an EGandG Ortec ACE TM-2 K gamma spectrometer equipped with a four-inch NaI/TI detector. In addition, dried sediment samples of the uppermost 10 cm from Svartvatnet core SV4C were analyzed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. The procedure of NRM measurements for

PSV dating is explained above. The obtained NRM curves were compared with the FENNOSTACK PSV reference curves (Snowball *et al.* 2007), and labeling of the major characteristics of declination and inclination followed Creer *et al.* (1976).

Plant macrofossils were picked from the long sediment cores RE9 and SV4C for AMS ^{14}C dating (Table 2). Enough material for "standard" AMS ^{14}C determination, performed at the Poznan Radiocarbon Laboratory, was obtained from seven (RE9) and one (SV4C) depth intervals, respectively. Additionally, plant macrofossil remains from four depth intervals in SV4C were picked for a gaseous ^{14}C measurement technique performed at the Laboratory for Ion Beam Physics at Eidgenössische Technische Hochschule (ETH), Zürich. The technique avoids graphitization and employs direct measurements of carbon dioxide, allowing ^{14}C-based age determination on small samples containing less than 50 mg carbon (Ruff *et al.* 2010). Briefly, 0.2–0.5 mg of sample material was cleaned with an acid-base-acid treatment and wrapped in aluminum capsules for combustion. The capsules were combusted in an elemental analyser (EA), the formed CO_2 trapped and then directly introduced into the gas ion source of a compact accelerator mass spectrometer (AMS) at ETHZ for radiocarbon analysis in a fully automated setup (Wacker *et al.* 2014). Data reduction was performed with standards and blanks of corresponding size, measured with the samples on the EA-AMS system.

Results and discussions

Lake bathymetry and hydroclimatic settings

Revvatnet. — Bathymetric characteristics of Revvatnet are presented in Fig. 3. The main basin in Revvatnet has a central location with a maximum water depth of 27 m, whereas northern and southern depressions are smaller in area and *ca.* 10 and 25 m deep, respectively. The northern basin is separated from the main basin by a narrow and only 2-m-deep passage that clearly affects the hydroclimatic settings and sedimentological characteristics of the lake. During the melting season, the water column is clearly warmer and more turbidic in the northern pool, as presented in Fig. 4. This is probably due to the discharge of warmer surface runoff waters via creeks into the basin from the north, which also increases the yield of allochthonous mineral matter. As a consequence, water in the northern pool is about 2°C warmer (5.5–6.5°C) than in the main pool (4.0–4.5°C) and twice as turbidic when determined with Formazin turbidity units (FTU). Some portion of the increased turbidity in the northern pool may be caused by increased growth of phytoplankton due to the higher water temperature.

In general, our bathymetric observations support the suggestion of Kuziemski (1959) that the profundal zone (> 7 m water depth) is extensive in Revvatnet, and its area covers approximately two-thirds of the lake's surface area. Even though Revvatnet is an overflow type of lake, as suggested by Karczewski *et al.* (1981),
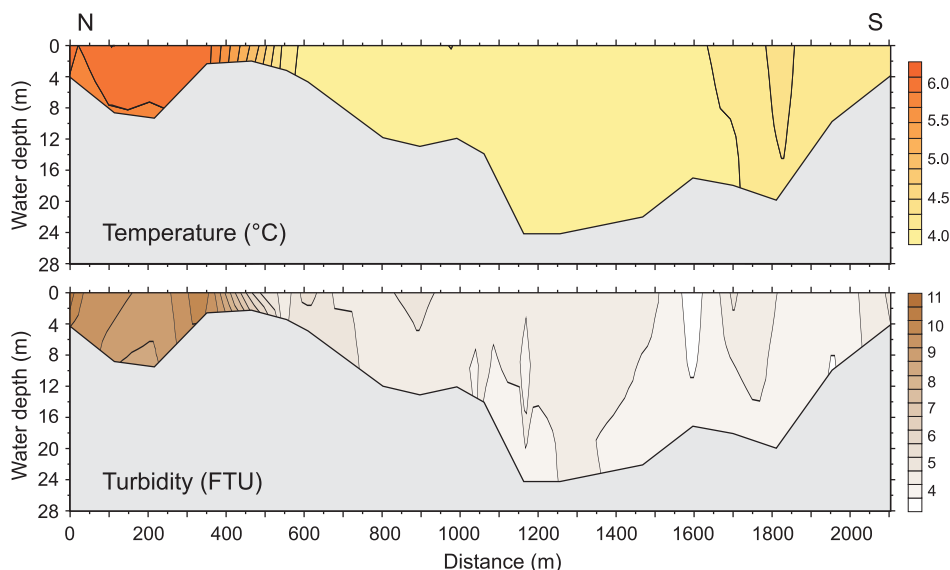
Fig. 4. The CTD profile data presented here for Revvatnet were collected along an approximately N-S-oriented survey line (20 points) in the middle of the lake. The upper panel indicates the 2D distribution of temperature and the lower panel the turbidity of the water column. The data were collected on June 17, 2013.

the shallow passage between pools clearly affects the sediment quality and rate of sedimentation between basins. Based on ^{137}Cs dating profiles, the northern basin maintains a higher rate of sedimentation than the main basin. Surface sediments are also more minerogenic (lower LOI and higher magnetic susceptibility) in the northern part of the lake than they are in the southern basin (Fig. 5). It appears that the northern basin effectively traps much of the sediment yield from the main allochthonous source (*e.g.* via creeks) in the north, and thus also maintains a fairly high rate of sedimentation. This observation is supported by sediment lithostratigraphy with abundant sand and clayed laminae in the RE8 sequence (Fig. 5). The turbidity of the Revvatnet water column and difference between separated pools was also clearly observed during fieldwork in summer 2013.

Despite the hydrological and bathymetrical characteristics of Revvatnet, monitoring by sediment trapping in the deepest point of the lake revealed that significant deposition also occurs in the southern main basin. The rate of sediment deposition during the summer open water season in late July was 1.68 g m^2 d^{-1}. We observed that much of the settled material was composed of fine-grained mineral material, and the organic fraction did not exceed 14% of the total sediment deposition from suspension.

Svartvatnet. — The bathymetric characteristics of Svartvatnet are presented in Fig. 3. With regards to the catchment geomorphology and bathymetry, Svartvatnet is almost like a horizontal mirror image of Revvatnet. The maximum water
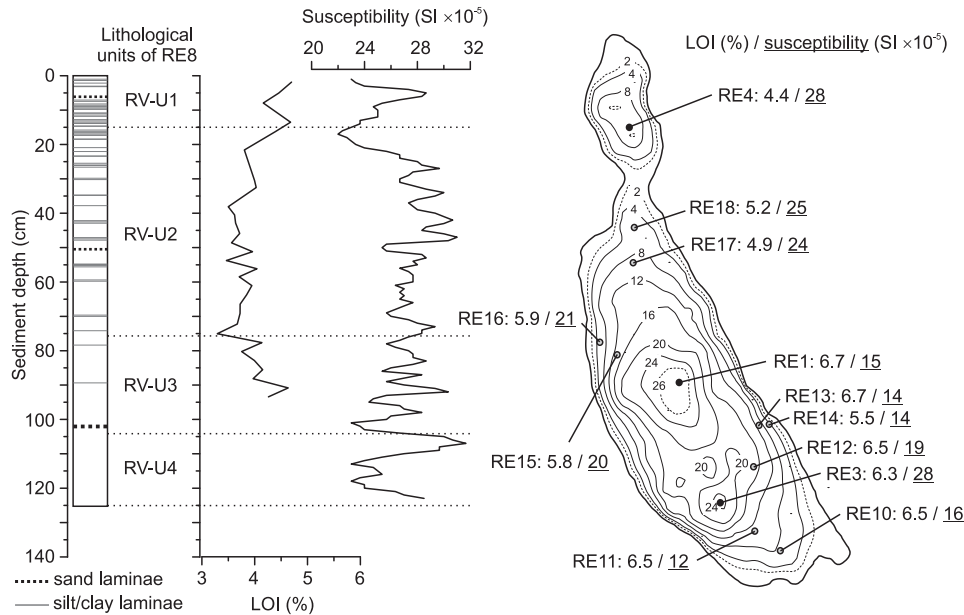
Fig. 5. Left: A lithostratigraphical log of the Revvatnet RE8 sediment sequence and its lithological units, LOI, and magnetic susceptibility. Right: LOI and magnetic susceptibility of surface sediment (0–1 cm) samples from Revvatnet.

depth of Svartvatnet is 26.5 m in the southwestern part of the lake. This depression is clearly steeper from south and west sides that from eastern and northern sides. The more narrow northern part of the lake contains several individual depressions that are mainly between 6 and 14 m deep.

Similarly to Revvatnet, the surface runoff and input of allochthonous material via creeks from the east and southeast determine the sediment accumulation in Svartvatnet. Temperature and turbidity measurements from two locations with a CTD sensor indicate that the lake is thermally stratified during the melting season, with the uppermost 5 m having a temperature of 4–5°C, and below this level *ca.* 4°C in the northernmost and the southern parts of the lake (Fig. 6). Spatial temperature deviation was not as evident as in Revvatnet, which may be due to the larger discharge of surface runoff entering the main basin of Svartvatnet, thus mixing more efficiently with the larger water body. However, compared with the northern basin, the water column in the southern basin of Svartvatnet was more evenly turbidic from the surface to the deepest water, suggesting ongoing deposition of sediment particles. CTD profiles also indicate that much of the allochthonous material is effectively trapped in the deepest southern part of the lake during the current melting season. A higher rate of sedimentation in the southern sector of Svartvatnet is supported by ^{137}Cs dating of cores SV2 and SV3 in comparison to cores SV1 and SV4C (Fig. 3). An interesting way of interpreting these results is that the sedimentation in the northern 12- to 14-m-deep basins is more dominated by deposition from an autochtho-
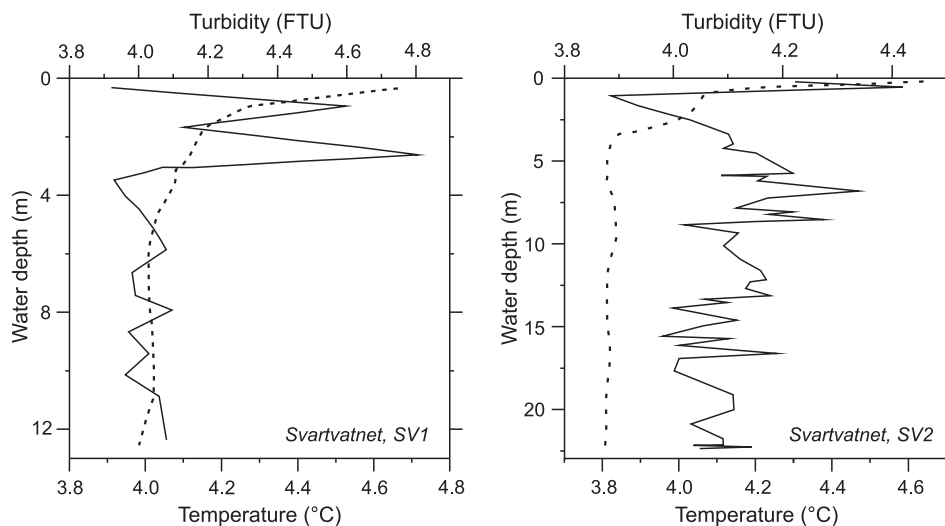
Fig. 6. Two points of CTD profiles from northern (SV1) and southern (SV2) parts of Svartvatnet (see Fig. 3 for their locations). The solid lines indicate water turbidity and the dotted lines water temperature changes with depth. The data were collected on June 14, 2013.

nous source, which is important from the viewpoint of studying biological parameters (*e.g.* chironomids) and their isotopic proxies (*e.g.* $\delta^{18}O_{chir}$), which are quantitatively indicative of summer air and water temperatures. Sediment sequences from the northern basins are also probably less affected by sediment redeposition and disturbance by the episodic input of massive allochthonous mineral material.

Sediment stratigraphy

Based on the environmental settings and observations of lake bathymetry, turbidity, and temperature, we selected several primary locations for the coring of long sediment sequences in both lakes. In this section, we report their sediment stratigraphy, physical characteristics based on LOI and mineral magnetics, and components of cores RE8 and RE9 from Revvatnet, and cores SV4B and SV4C from Svartvatnet (Fig. 3).

Revvatnet. — Visual characteristics of the sediment stratigraphy and results from LOI and magnetic susceptibility indicated that parallel cores RE8 and RE9 contained the same sedimentary strata, providing a solid basis for their correlation. The lithological units and physical proxies in Fig. 5 are presented against the RE8 depth scale, and the analyses undertaken from each core are summarized in Table 1.

The 125-cm-long sequence RE8 was divided into four separate lithological units (RV-U1 to RV-U4) based on lithostratigraphy, sediment structures, and physical parameters. The unit RV-U1 (0–15 cm) is composed of olive yellow (Munsell 2.5Y 6/6) gyttja clay with frequent laminae of clay and silt and occasional layers of fine sand. The observed laminae typically consist of a darker fine

sand (or silt) lower part and a light-colored finer-grained upper part of clay (Fig. 7). The thickness of these mineral laminae couplets varies between 0.5 and 4 mm, typically being about 2 mm. Individual laminae are so thin that they cannot be identified with LOI or suscepti-bility, except for the thickest sandy layer at the depth of 5–7 cm causing a peak in susceptibil-ity. These laminae couplets clearly represent episodic runoff events loaded with suspended sediment that have occurred during the snow-melt season, but they are not necessary true varves that reflect a regular and constant pat-tern of annual deposition (*e.g.* Cockburn and Lamoureux 2008; Ojala *et al.* 2012). However, the appearance of these laminae couplets indi-cates that this is a high-resolution sediment re-cord without any temporal mixing of the sedi-ment sequence, for example, by burrowing an-imals (bioturbation) or wind-driven wave activity.

Fig. 7. A photograph of the typical clastic laminated sediment structure of the Rev-vatnet surface sediment (RE8). A thick sandy lamina (5–7 cm) is partly seen in the upper part of the figure.

The unit RV-U2 (15–76 cm) is composed of grayish brown (2.5Y 5/2) silty laminated gyttja clay. Laminae couplets still reflect grain-size variability in min-eral matter, but their regularity and appearance decreases downwards in the unit. This may suggest that the increased episodic runoff intensity is only a phenome-non of the more recent past, during which the upper part of unit RV-U2 and the en-tire RV-U1 were deposited. LOI also decreases downwards in this unit, RV-U2, and susceptibility fluctuates according to more silty (or sandy) layers. The unit contains occasional granules and clasts, suggesting rafting from ice during the melt season. Layers of particulate organic material (plant macrofossils) appear at depths of 39, 50, 58, 63, and 66 cm.

Unit RV-U3 (76–103 cm) is composed of faintly laminated gray (2.5Y 5/1) gyttja clay. Occasional mineral layers are detectable and there are two 1–2-cm-thick layers of plant macrofossil remains at depths of 78 and 88 cm. A gradual contact to the upper unit RV-U2 is characterized by the lowest LOI recorded in the entire sec-tion. Unit RV-U3 clearly represents more massive sedimentation than the units above, thus lacking of any episodic runoff events. The basal contact contains a 1-cm-thick layer of sand and granules, possibly indicating an erosional boundary with the unit below. The lowermost unit RV-U4 (103–125 cm) is composed of mas-sive gray (2.5Y 6/1) gyttja clay/clay.

Svartvatnet. — Similarly to the Revvatnet sequences, parallel cores SV4C and SV4B from the northernmost basin of Svartvatnet were correlated using lithostratigraphy and sediment physical proxies. Compared with RE8, the litho-
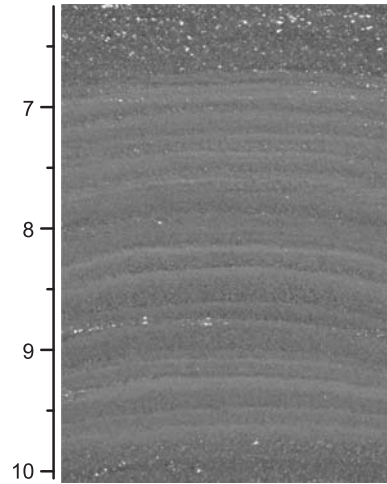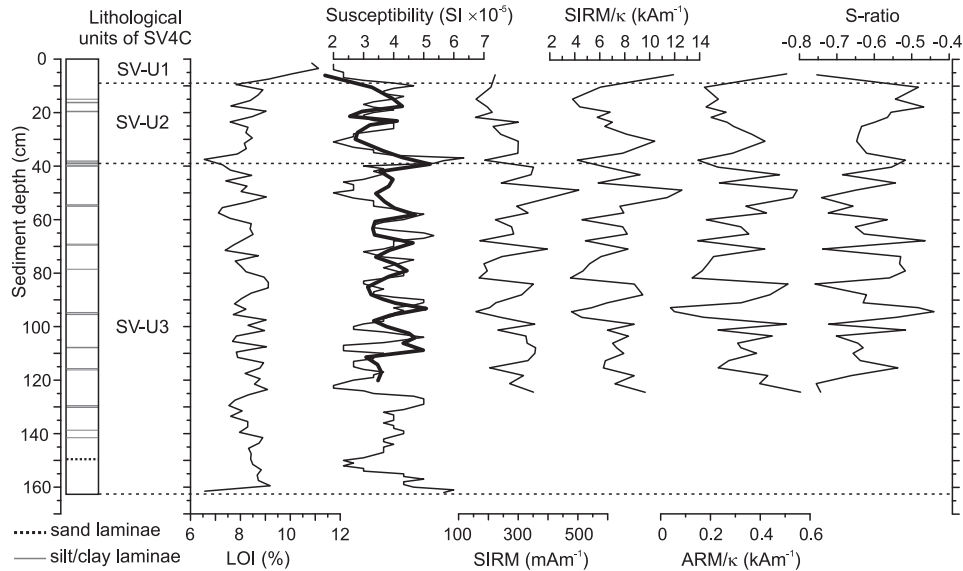
Fig. 8. A lithostratigraphical log of the Svartvatnet SV4C sediment sequence and its lithological
units, LOI, magnetic susceptibility, and mineral magnetic parameters.

stratigraphy of SV4C is generally more massive with less distinct sediment struc-
tures, a higher organic content (LOI) and lower susceptibility. This implies that the
process of sedimentation at the SV4 coring location has been less impacted by
fluctuations in river discharge and allochthonous sediment yield than was de-
scribed for the northern basin of Revvatnet, and probably also occurs in the south-
ern basin of Svartvatnet.

We identified three lithological units from the Svartvatnet section that are plot-
ted against the SV4C depth scale in Fig. 8. All boundaries between these three
units are gradational and in general all lithological units are characterized by same
type of sediment, with only minor differences in sediment composition, structure,
and visual appearance. The uppermost unit SV-U1 (0–10 cm) is composed of olive
brown (2.5Y 4/3) poorly compacted clay gyttja lacking any sedimentary struc-
tures. It represents the most recent sediment deposits with a higher organic content
(LOI) than anywhere else in the section. The magnetic parameters SIRM/κ and
ARM/κ indicate an increase in finer-grained magnetite possibly related to a higher
LOI due to lower catchment-derived mineral matter (erosion) in this unit.

Unit SV-U2 (10–40 cm) is composed of light olive brown (2.5Y 5/3) clay gyttja
with a more compacted appearance than the unit above. Under this lies unit SV-U3
(40–163 cm), which is composed of dark gray (2.5Y 4/1) clay gyttja. Units SV-U2
and SV-U3 contain thin black layers of organic remains at approximately 10-cm in-
tervals and also sections that are lighter in color, probably due to a minor increase in
mineral matter deposition. The rhythmic pattern of allochthonous mineral matter de-

position can be detected with LOI values and mineral magnetic parameters. In places with a lighter sediment color, LOI is characterized by a dip, while there is a peak in values for susceptibility. At the same time, there appear low points in SIRM/κ and ARM/κ curves indicating a relative increase in coarser-grained magnetite in the sediment sequence. Sediment depths of 40 cm and 95 cm are typical examples of such sections. The reason for this oscillation is unclear, but it may be related to the past hydroclimatic regime in the lake-catchment system, where the more minerogenic sections could represent times of increased water turbidity due to extensive mineral suspension charge and overflow of allochthonous clastic material.

Dating of sediment sequences

Revvatnet. — Dating of the Revvatnet sediment stratigraphy presented in Fig. 5 is based on seven radiocarbon dates (Table 2) and ^{137}Cs profiles from long cores RE8, RE9, and surface sediment sample RE4 taken with a Kajak corer. The results are presented in Fig. 9. Below a sediment depth of 27 cm, the cesium activity is essentially zero. The first clear indication of activity appears at the depth 25 cm, which may represent the onset of cesium fallout in the early 1950s. Upwards in the sequence, there is a peak of ^{137}Cs at the depth of about 15 cm, which probably corre-
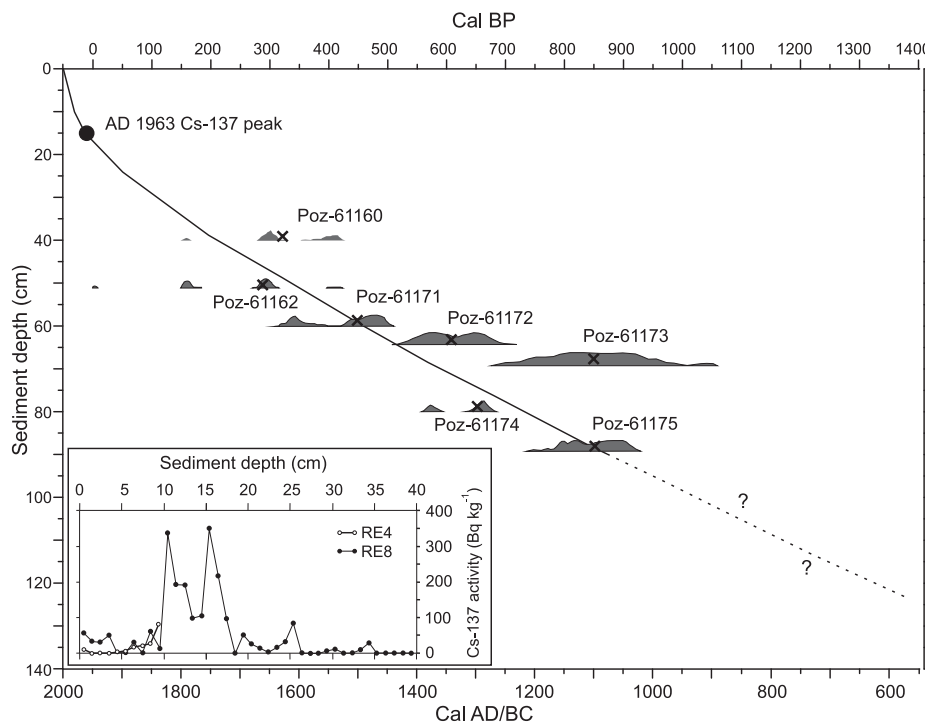

Fig. 9. An age-depth profile of the Revvatnet RE8 sequence. The black circle indicates the tight point AD 1963 from ^{137}Cs dating, grey areas are calibrated AMS ^{14}C dates with 95.4% confidence levels (2s) (Oxcal 4.2, Reimer *et al.* 2013) and squares represent their median probability (see Table 2).

sponds to the AD 1963 nuclear weapons testing maximum. It is followed by another peak at 10 cm depth, which possibly represents redeposition of AD 1963–1964 fall-out, either from the catchment to the lake or within the lake itself. In any case, the lower peak provides a date and a rough estimate for the rate of recent sedimentation in the northern basin of Revvatnet. Excluding the massive sand layer (5–7 cm) from calculations, the mean rate of annual sedimentation is of the magnitude 2.6 mm for the last 50 years, which actually corresponds relatively well with the estimated thickness of laminae couplets in the Revvatnet stratigraphy.

Calibrated AMS radiocarbon dates of plant macrofossil remains (mainly terrestrial and aquatic bryophytes; *e.g.* Aulacomnium, Tomentypnum nitens, Calliergon sp, Rhizomnium sp, Warnstorfia ex annulata) from seven levels in the Revvatnet sediment sequence are plotted in Fig. 9. The scattered distribution of the dates with 95.4% confidence levels (2s) shows the challenge in dating temporally short records with the radiocarbon dating technique. Another point with the present ^{14}C dates for the Revvatnet sequence is that many of them contain a rather small amount of carbon for dating, thus causing potential errors in age determinations (Table 2). Nevertheless, the calibrated ^{14}C dates show primarily older ages with sediment depth and without any outliers with dates offset by thousands of years. This indicates that the deposition of macrofossils follows a rather logical pattern of sedimentation according to the law of superposition.

The oldest age of about 1100 cal AD from the sediment depth of 87–89 cm indicates that the entire 125-cm-long sequence from the northern basin of Revvatnet probably covers some 1300–1500 years of sediment accumulation. Considering the generally accepted occurrence of the Little Ice Age (LIA) from about AD 1350 to about AD 1850, the lowermost radiocarbon dates of the Revvatnet sequence are clearly in contradiction with Karczewski *et al.* (1981), who suggested that the northern basin of Revvatnet was covered by a valley glacier during the LIA. According to several studies around Svalbard (*e.g.* Svendsen and Mangerud 1997), the readvances of glaciers to LIA maximum extensions occurred as late as in the 19th century. If this had been the case for the Hornsund area, and if the LIA readvance had covered the northern basin of Revvatnet, one would expect to have younger ^{14}C ages or more mixed ages with depth in the case of considerable macrofossil redeposition. Interestingly, Reusche *et al.* (2014) suggested that prior to the LIA there was another readvance of Linnébreen that occurred some time after 4.6 ka ago and with a retreat at about 1.6 ka ago. They proposed that this was due to increased summer temperatures rather than changes in precipitation and that the position of Linnébreen was roughly equivalent to its LIA maximum extent. The timing of this pre-LIA glacier retreat corresponds very well with the Revvatnet sediment chronology presented here. Therefore, it seems possible that the northern basin of Revvatnet was not occupied by a valley glacier during the LIA. It may also be possible that a glacier advance in Revdalen extended further during the pre-LIA than during the LIA, thus covering at least the northern basin of Revvatnet.

By selecting only those dated samples that contain an adequate amount of organic material for radiocarbon dating (58–59 cm and 87–89 cm) and the ^{137}Cs peak in the upper section, we can derive an age-depth relationship that indicates a high rate of sedimentation (2–3 mm yr^{-1}) for the last about 50 years and approximately 0.5–0.6 mm yr^{-1} for the preceding millennia. This type of age-depth curve has been fitted in Fig. 9 with errors within the confidence limits of the selected radiocarbon dates. Samples with the lowest carbon (63–64 and 66–67 cm) are the most offset from this curve. Note, however, that the curve is not based on any series of regression models fitted to radiocarbon dates, which we found rather misleading for the presently studied temporally short Revvatnet sequence.

Svartvatnet. — Dating of the Svartvatnet core SV4C sediment stratigraphy presented in Fig. 8 is based on five radiocarbon dates (Table 2), ^{210}Pb and ^{137}Cs profiles, and comparisons of PSV curves with regional reference curves by Snowball *et al.* (2007).

Total ^{210}Pb activity reaches an equilibrium with the supported ^{210}Pb at a depth about 8 cm in the SV4C sediment sequence (Fig. 10, Table 3). Unsupported ^{210}Pb activity is calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity. The declining trend in the gradients of unsupported ^{210}Pb activities from 8 cm towards the sediment surface suggests a gradual increase in the rate of sedimentation towards the present day. In addition, the ^{137}Cs activity of the same samples indicates a well-resolved peak at the depth of 3.5 cm. The peak was derived from the atmospheric testing of nuclear weapons, with maximum fallout in AD 1963, which is confirmed by the ^{241}Am peak at the same depth. Based on these observations, the constant initial concentration (CIC) model was precluded by the non-monotonic variations in unsupported ^{210}Pb activities, and the constant rate of supply (CRS) model was applied as a primary method for the ^{210}Pb chronology (Appleby and Oldfield 1978). Accord-
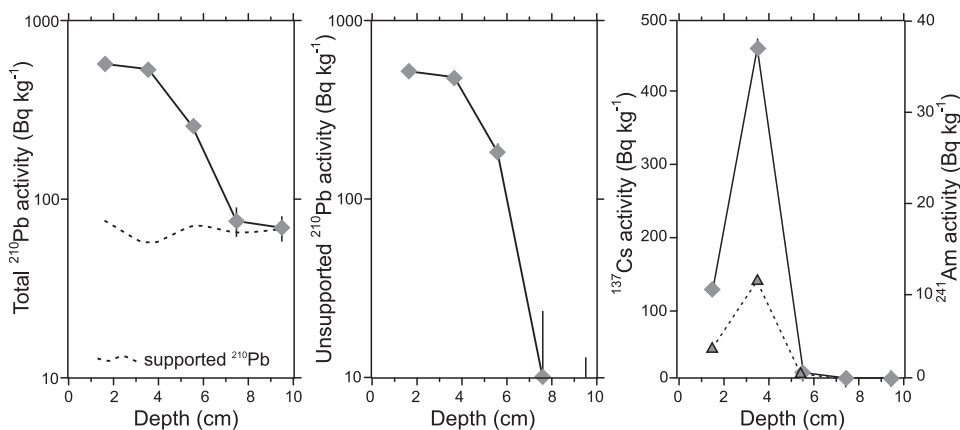

Fig. 10. Results of ^{210}Pb dating of the Svartvatnet core SV4C. Fallout radionuclide concentrations are shown as total and supported ^{210}Pb activity (left), unsupported ^{210}Pb activity (center), and ^{137}Cs (solid line) and ^{241}Am (dotted line) activities (right).

[210]Pb concentrations in Svartvatnet core SV4C.

| Pb-210 | | | | | | Cum Unsupported | |
| Total | | Supported | | Unsupp | | Pb-210 | |
Bq Kg[-1]	±	Bq Kg[-1]	±	Bq Kg[-1]	±	Bq m[-2]	±
571.82	33.6	73.31	6.11	498.51	34.15	4535.7	276.9
519.04	34.37	55.07	6.65	463.97	35.01	7854.4	393.1
249.65	17.47	67.7	3.9	181.95	17.9	9974.4	465.1
73.11	13.31	63.11	3.32	10	13.72	10458.3	485.3
67.21	11.15	65.64	2.61	1.57	11.45	10504.7	501.7
64.48	28.25	65.74	7.26	-1.26	29.17	10506.4	535.9

ingly, the depth of 3.5 cm in the core is ^{210}Pb-dated to AD 1967, which is in good agreement with a date AD 1963 from the ^{137}Cs and [241]Am profiles. The age-depth chronology and sedimentation rates for the surface sediment of SV4C is based on ^{210}Pb dating. The data show that the rate of sedimentation has gradually increased from 0.009 g cm^{-2} yr^{-1} in the early 20th century to 0.037 g cm^{-2} yr^{-1} at present.

On the basis of the stepwise AF demagnetizations of every tenth sample measured for NRM, a ferromagnetic mineral, most likely magnetite, carries the main portion of the magnetic remanence in the Svartvatnet sediments (Fig. 11; *e.g.* Thompson and Olfield 1986; Snowball and Sandgren 2001). All test samples were completely demagnetized in the AF field of 100 mT and they were characterized by a median destructive field (MDF) of about 40–45 mT. This is typical behavior for fine-grained single domain and/or pseudo single domain magnetite (*e.g.* Thompson 1986), which is known to potentially record a strong and stable signal of NRM in the lacustrine sedimentary environment. The NRM of Svartvatnet test samples was dominated by a stable primary component of magnetic direction. Downcore variations in Svartvatnet NRM declination and inclination curves are presented and compared with the FENNOSTACK reference curve in Fig. 12. They show characteristic features that are typically seen around northern Europe, including the FENNOSTACK reference curve that is based on Finnish and Swedish lacustrine varves (Snowball *et al.* 2007). In particular, the correspondence between relative declination features e, f, and g and inclination features g, d, and e´ can be applied for comparisons between records and importantly for assigning paleomagnetic ages for different depth levels of the Svartvatnet sediment sequence. The dated levels and assigned ages include 1290, 1840, 2210, 2590, 2670, and 4230 cal BP (see Ojala and Tiljander 2003; Snowball *et al.* 2007).

The AMS ^{14}C dates (Table 2) from the direct CO_2 measurements at ETH Zürich yielded results in excellent agreement with other chronological data. The result for sample SV4C in the depth interval 106–107 cm (ETH-59397: 3650 ± 60), matches that from the "normal-sized" AMS ^{14}C determination at the Poznan Radiocarbon laboratory (Poz-61177: 3695 ± 30) within analytical uncertainty. Furthermore, the
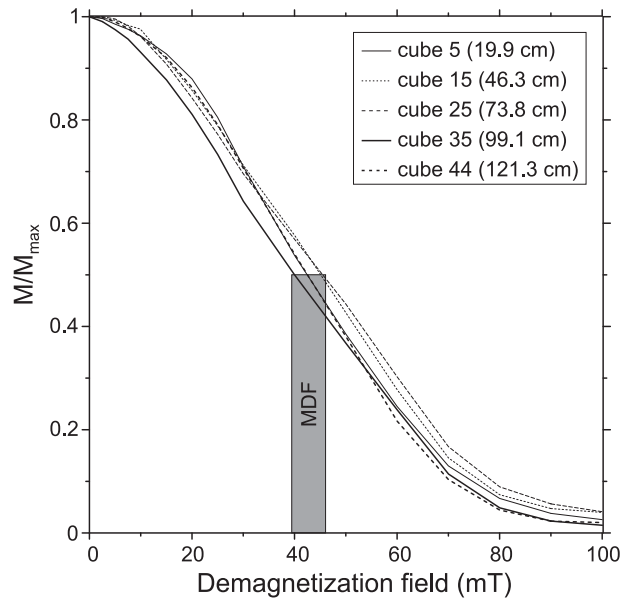
Fig. 11. AF demagnetization of samples 5, 15, 25, 35, and 44 indicate that the fine-grained magnetite is the probably carrier of NRM in the Svartvatnet SV4B sediment sequence.
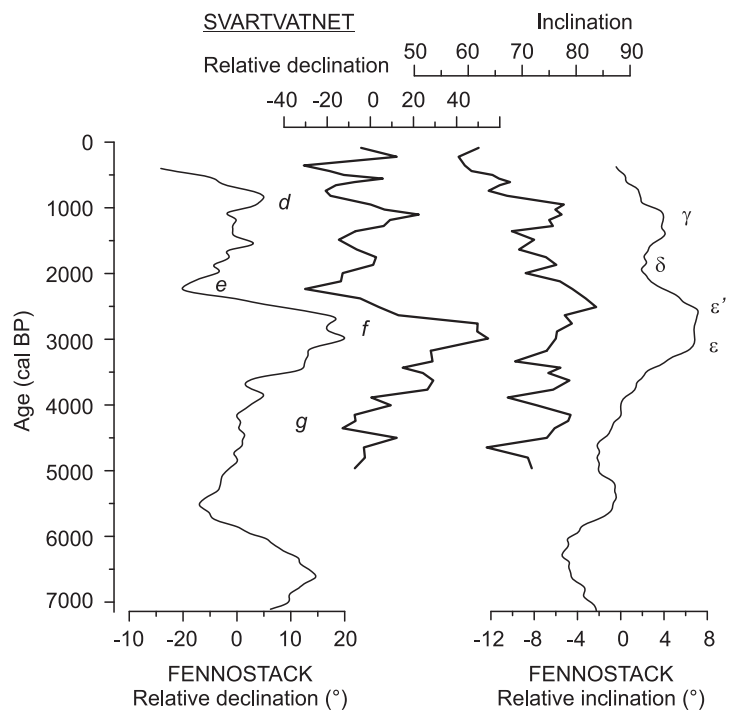

Fig. 12. Records of NRM inclination and declination from Svartvatnet core SV4B compared with FENNOSTACK reference curves (Snowball *et al.* 2007, see also Ojala and Tiljander 2003).
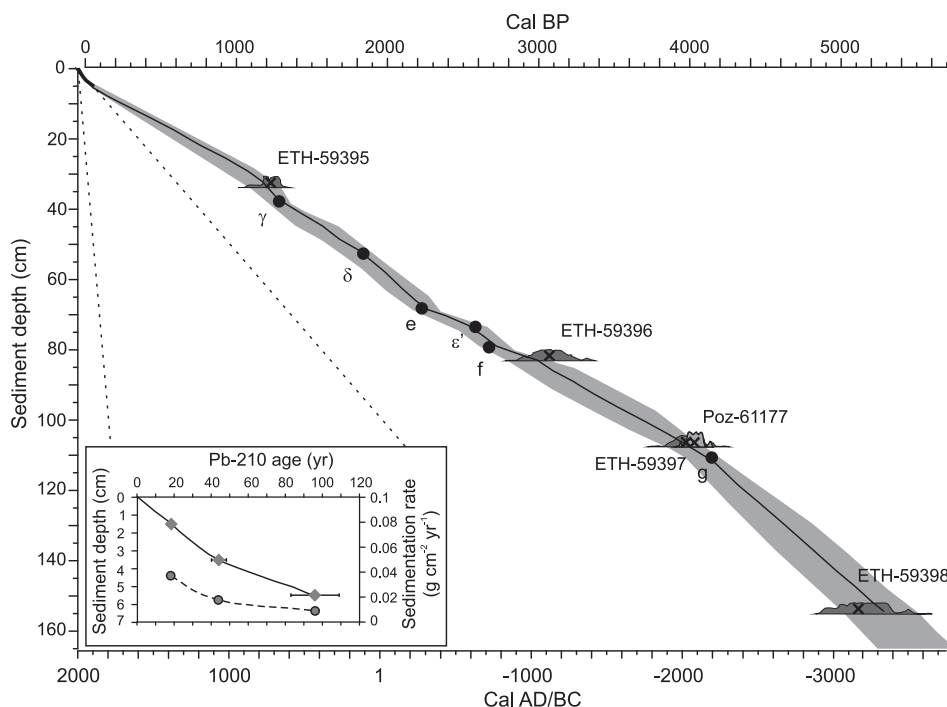
Fig. 13. An age-depth profile of the Svartvatnet SV4C sequence. Dating of the topmost *ca.* 5 cm is based on ^{210}Pb and ^{137}Cs (solid black line). Calibrated AMS ^{14}C dates with 95.4% confidence levels (2s) are given in darker gray, black crosses represent their 2s median probability (Oxcal 4.2, Reimer *et al.* 2013) and black dots represent PSV dates from Ojala and Tiljander (2003) and Snowball *et al.* (2007) (see Fig. 12). The age-depth relationship shaded with light gray is based on the Bayesian P-sequence deposition model by Bronk Ramsey (2008, 2009).

calibrated (IntCal13; Reimer *et al.* 2013) ^{14}C data are consistent with the paleomagnetic PSV ages, supporting the reliability of the obtained chronology.

An age-depth model for the Svatvatnet SV4C core was constructed based on ^{210}Pb, five AMS radiocarbon dates and six PSV age constrains using a Bayesian P-sequence deposition model in Oxcal 4.2 software (Bronk Ramsey 2008, 2009) (Fig. 13). PSV points were fitted to the model with ±2% uncertainties that are based on varve chronological age error estimates of the FENNOSTACK reference curves (Snowball *et al.* 2007). The dating results and the constructed age-depth model demonstrate that the SV4C sediment sequence covers a more than 5000-year-long sedimentary archive with an average deposition rate of about 0.3 mm yr^{-1} for the entire sequence. The rate of sedimentation probably increased during the 20th century, as indicated by the ^{210}Pb dating. The dating results also indicate that the SV4C sequence is characterized by a stable and continuous sedimentation throughout the section. No hiatuses or indications of erosion or slumping of sediment (turbidites) are observed in the sequence, which is supported by a smooth fit of the age-depth model. Such a fit and well-established sediment chronology provides a solid basis

for paleoclimatic reconstructions from fossil chironomid assemblages, the oxygen isotope composition ($d^{18}O_{chir}$) of their head capsules, and sediment palmitic acid dD values of the Svartvatnet sediment sequence.

Conclusions

In the environmental settings of the present study area, hydroclimatic processes evidently affect sediment transportation, distribution, and accumulation in lakes Revvatnet and Svartvatnet. Results from CTD measurements and sediment trapping, combined with sedimentological characteristics, indicate that there are several basins in Revvatnet and Svartvatnet that potentially maintain stable and continuous sedimentation.

The northern basin of Revvatnet has an interesting high-resolution stratigraphy with laminated sediment sequence, and an increased rate of sedimentation and catchment-derived sediment yield towards the present day. However, the sediment sequence is highly minerogenic, contains too coarse-grained material for dating with PSV method, and does not contain a sufficient quantity of fossil chironomid head capsules for paleoclimatic reconstructions. Nevertheless, the AMS ^{14}C dating results suggest that the 130-cm-long sequence could represent sedimentation of the last 1000–1500 years, which is somewhat contradictory with the previous assumptions that LIA glacier advance would have covered at least the northern part of the Revvatnet basin.

The northern basin of Svartvatnet provides a potential sedimentary sequence for studies of environmental and climate change in Arctic lake during the last approximately 5000 years. Based on stratigraphy, dating, and a Bayesian age-depth model, cores SV4B and SV4C probably represent continuous and stable sedimentation with an interesting oscillation feature and a sufficient amount of fossil chironomid head capsules for paleolimnological reconstructions. Such a secured chronology with multiple dating methods provides an intriguing starting point for multiproxy studies on climate change and the environmental response in this remote Arctic lake.

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