Non-glacial paleoenvironments and the extent of Weichselian ice sheets on Severnaya Zemlya, Russian High Arctic

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Abstract

The extent of the Barents-Kara Sea ice sheet (northern Europe and Russia) during the Last Glacial Maximum (LGM), in Marine Isotope Stage (MIS) 2 is controversial, especially along the southern and northeastern (Russian High Arctic) margins. We conducted a multi-disciplinary study of various organic and mineral fractions, obtaining chronologies with \textsuperscript{14}C and luminescence dating methods on a 10.5 m long core from Changeable Lake (4 km from the Vavilov Ice Cap) on Severnaya Zemlya. The numeric ages indicate that the last glaciation at this site occurred during or prior to MIS 5d-4 (Early Middle Weichselian). Deglaciation was followed by a marine transgression which affected the Changeable Lake basin. After the regression the basin dried up. In late Middle Weichselian time (ca 25–40 ka), reworked marine sediments were deposited in a saline water body. During the Late Weichselian (MIS 2), the basin was not affected by glaciation, and lacustrine sediments were formed which reflect cold and arid climate conditions. During the termination of the Pleistocene and into the Holocene, warmer and wetter climate conditions than before led to a higher sediment input. Thus, our chronology demonstrates that the northeastern margin of the LGM Barents-Kara Sea ice sheet did not reach the Changeable Lake basin. This result supports a modest model of the LGM ice sheet in northern Europe determined from numeric ice sheet modelling and geological investigations.

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1. Introduction

Knowledge of the geographic extent and thickness of continental ice sheets during the Last Glacial Maximum (LGM) is important for modelling of past climates and sea level (e.g., Peltier, 1994). However, the Russian High Arctic remains the last continental area, where the LGM is uncertain (Clark and Mix, 2002). For the Russian High Arctic, both maximalist (Denton and Hughes, 1981; Grosswald, 1998; Grosswald and Hughes, 2002) and minimalist (e.g., Velichko et al., 1997; Svendsen et al., 1999; Gaultier et al., 2000; Mangerud et al., 2002) ice-extent estimates have been argued, with some intermediate estimates selected through numerical ice sheet and solid earth modelling (e.g., Peltier, 1994; Siegert and Marsiat, 2001; Siegert et al., 2001; Charbit et al., 2002).

In northern Europe and northwestern Russia, the extent of the Barents-Kara Sea ice sheet during the LGM has remained uncertain. This is largely because of disagreement over the age of recognized ice-margin deposits. Mangerud et al. (2002) have reviewed the glacial geology in northwestern Russia and their interpretation strongly support a minimalist estimate for the LGM extent of the Barents-Kara Sea ice sheet. Much of the critical evidence comes from luminescence ages for sand-sized quartz in discontinuous, subaerial deposits of non-glacial sediments from the Pechora Lowland (e.g., former beaches, exposed fluvial terraces). These age estimates range stratigraphically from ca 100 to 20 ka. Finite and lower-limit (“infinite”) radiocarbon
\(^{14}\text{C}\) ages from related material support these quartz luminescence age estimates. However, good records of continuous sedimentation related to this controversy have not been reported before.

The Taymyr Peninsula (Fig. 1) lies at the northeastern boundary of the minimalist estimates of the Barents-Kara Sea ice sheet (e.g., Svendsen et al., 1999; Alexanderson et al., 2002; Mangerud et al., 2002). In this paper we present geological, paleoenvironmental and geochronological evidence from a 10.5 m long sediment core from Changeable Lake (Severnaya Zemlya Archipelago, north of the Taymyr Peninsula) that provides the first well-dated support from a continuous sediment record for ice free conditions at the LGM. We employed a multi-disciplinary approach to obtain information not only on the glacial history, but also on past climate and sea-level changes that may have affected ice expansion and decay.

2. Regional context

In order to use a uniform stratigraphical nomenclature, we follow that proposed by Mangerud (1989): Early Weichselian (MIS 5d-5a; 117–74 ka); Middle Weichselian (MIS 4-3, 74–25 ka); Late Weichselian (MIS 2, 25–10 ka), as suggested by the QUEEN scientific community (Svendsen et al., 1999).

As summarized by Mangerud et al. (2002) and others (Thiede et al., 2001), the results of recent field studies preclude the existence of a large Panarctic Ice Sheet during the Late Weichselian. Instead, Asian Arctic glaciation during the Late Weichselian (MIS 2) is considered to have been restricted to Europe and Western Siberia, with alpine-valley glaciation in northeastern Siberia (Gaultieri et al., 2000).

In Europe and Western Siberia, glaciation was somewhat larger during Early/Middle Weichselian times (MIS 5d-4), than during the LGM when it expanded onto most of the Taymyr Peninsula (Möller et al., 1999; Svendsen et al., 1999; Mangerud et al., 2001; Andreev et al., 2002; Alexanderson et al., 2002) (Fig. 2). Geomorphological investigations and absolute age determination (\(^{14}\text{C}\), quartz luminescence) of the North Taymyr ice-marginal zone (NTZ) by Alexanderson et al. (2001, 2002) indicate that at most a relatively thin Late Weichselian Kara Ice Sheet had advanced onto only the northwestern part of the Taymyr Peninsula between 20 and 12 ka. This makes a restricted glaciation on the Severnaya Zemlya Archipelago, as proposed by Makeyev and Bolshiyanov (1986) and Bolshiyanov and Makeyev (1995), questionable. According to numerical ice sheet modelling by Siegert, M.J. et al. (1999a, 2001), and Siegert and Marsiat (2001) a restricted glaciation of the Severnaya Zemlya Archipelago could have occurred only if the precipitation across the Kara Sea was suppressed by a polar desert environment.

3. Study site

The Severnaya Zemlya Archipelago is a key area for the understanding of the Late Quaternary palaeoenvironmental history in the Russian High Arctic. This region is extremely sensitive to environmental changes, due to its geographical position both in the high latitudes and in the transition zone from West Siberian marine to East Siberian continental climate (Ebel et al., 1999; Hahne and Melles, 1999; Harwart et al., 1999).

The archipelago is located in northern Siberia (78–81°N, 96–106°E), between the Kara Sea to the west and the Laptev Sea to the east (Fig. 1). The archipelago consists of more than 30 islands, with the largest being October Revolution Island, and is the easternmost area affected by modern glaciation. For instance, the Vavilov Ice Cap near to Changeable Lake covers 1820 km\(^2\) and rises up to 728 m a.s.l.

The climatic conditions on the Severnaya Zemlya Archipelago are extremely severe due to the combination of low air temperature (annual mean: −13 to −14°C) and strong winds. The ablation season has especially changeable weather conditions. Summer temperatures can rise up to 10–15°C, and snow storms can also occur in this season, being similar in magnitude to those in winter (Vaikmäe et al., 1988). The annual precipitation on October Revolution Island varies between 240 and 400 mm, with about 70% falling as snow. The amount of precipitation depends on the distance from both the sea and the Vavilov Ice Dome, which functions as an orographical barrier for air masses from southwest, causing precipitation to be highest on the ice cap (Andreev et al., 1997).

The vegetation on the archipelago is typical of polar desert/high arctic tundra: mosses and lichen dominate, whereas flowering plants are rare. A larger diversity in plant species occurs on river terraces in the central parts of the islands and on climatically favoured sites with peat growth (Alexandrova, 1988; Andreev et al., 1997).

The Severnaya Zemlya Archipelago belongs to the Taymyr-Severnaya Zemlya fold area. October Revolution Island consists of Paleozoic highly fractured sedimentary carbonaceous rocks with Ordovician and lower Silurian rocks overlain by Quaternary marine sediments (Bolshiyanov, 1985). The geomorphology of October Revolution Island is characterized by U-shaped valleys, cold based glaciers and outwash plains (Makeyev and Bolshiyanov, 1986). Periglacial processes have produced patterned ground, arctic soils and limited chemical weathering (Pfeiffer et al., 1996).

Changeable Lake (79°07′N, 95°07′E) is located on southwestern October Revolution Island, 4 km to the
southwest of the Vavilov glacier edge (Fig. 1). The lake lies in an oblong, SSW to NNE trending depression (Fig. 3a), which penetrates below the Vavilov Ice Dome and is believed to be an old karst form, developed in calcareous and gypsiferous bed rock (Bolshiyanov, 1985). Changeable Lake consists of several basins, divided by sills (Fig. 3b). The lake is 10 km² large and at its maximum 18 m deep. The modern lake level is situated about 6 m a.s.l. This hydrologically open, hardwater lake is predominantly fed by glacial meltwater (July–September) from the north across an outwash plain. The outlet is at the south via an <40 m deep canyon, which leads to the Kara Sea (Bolshiyanov, 1985). The lake has an ice cover most of the year.

4. Methods

4.1. Coring

Sediment coring in Changeable Lake was conducted in two different basins (Fig. 3b). The cores where
recovered through holes in the ice cover using a percussion piston corer that consists of steel tubes and inner PVC liners of 6 cm diameter (Melles et al., 1994). The sediment record was obtained by coring of succeeding and partly overlapping up to 3 m long sections. At sites PG1238 and PG1239 (Fig. 3b), coring yielded complete sediment successions of 10.5 and 12.7 m lengths, respectively (Fig. 4). Their final depths were determined by correlation of the overlapping core sections.

4.2. Laboratory methods

Prior to the opening of the cores, measurements of the magnetic susceptibility, p-wave velocity (Vp) and gamma-ray density (GRD) were conducted at intervals of 1 cm (Multi-Sensor Core Logger MSCL 14, Geotek corp.) as described by Weber et al. (1997).

The cores were split along their axis into two halves. Following a photodocumentation and sediment description, smear slides were taken for a first microscopical investigation of sample characteristics and diatom content. Subsequently, one core half was subsampled continuously in 2 cm segments. The subsamples were freeze-dried and the water content per wet bulk sediment was calculated from the difference of the wet and the dry sample. Further sedimentological, mineralogical, geochemical, biogeochemical, geochronological and microfossil analyses were conducted only on core PG1238 which, according to the analyses described above, shows a comparable sediment succession to that of core PG1239 (Fig. 4).

Grain-size analyses were carried out on a laser particle analyser (Galai-CIS) after sample dispersion with ammonia. The total carbon (TC wt%), total nitrogen (TN wt%) and total sulphur (TS wt%) contents were determined with an automatic CNS 932 Mikro analyser (Leco corp.). The total organic-origin carbon (TOC wt%) content was measured on corresponding samples after HCl (10%) acid digestion to remove the carbonate on a CS-Analyser Metalyt (Eltra corp.). The total inorganic-origin carbon (TIC wt%) was calculated from the difference of TC (wt%) and TOC (wt%).

The bulk mineralogy was analysed by X-ray diffraction (Philips PW3020) on powder samples with corundum as standard (5:1) for semi-quantitative analysis.
as described by Vogt (1997). The evaluation of the X-ray spectra was made with the MacDiff 3.3.1 PPC-software (by R. Petschik). The results are presented in peak intensity ratios: $I_{\text{mineral}} / I_{\text{corundum (030)}}$.

The bulk geochemistry was determined by X-ray fluorescence analysis (SRS3000, Siemens) on fused glass beads of lithium tetraborate (6:1). The major element and trace element concentrations were normalized to titanium (element/titanium ratio).

Water-soluble cations and anions were extracted by a method modified from Gerasimov and Glazovskaya (1965). One gram of sample was mixed with 25 ml distilled, deionized water, shaken for 3 min, and finally filtered through a 45 μm mesh sieve. Prior to the measurement of element concentrations, electrical conductivity (EC) and pH of the water extracts were determined. Cations were analysed with an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Perkins Elmer) and anions with an Ion Chromatograph (IC2001, Eppendorf, Biotronik). For all chemical analyses international standards (NBS, SRM) were used to check the analytical precision. Analytical errors are below 5% for major ions and anions, and below 10% for trace elements.

$^{14}$C dating was conducted by accelerator mass spectrometry (AMS) on different organic fractions. Humic acids were extracted by the standard AAA-method (acid-alkali-acid). One pollen sample was extracted by a modified method according to Brown et al. (1989, 1992). This sample was pretreated with the AAA-method. The silica portion was removed by heavy liquid (ZnCl$_2$, 2.0 g/cm$^3$) separation and treatment with HF acid, and $^{14}$C dating was carried out on the pretreated and sieved 20–100 μm pollen fraction. Undetermined insect fragments, undetermined organic matter and mixed benthic foraminifera were extracted by wet-sieving (> 63 μm), followed by hand-picking from the dry sample under a stereo microscope. The $^{14}$C dating was carried out at the University of Erlangen-Nürnberg (Erl) and at the Leibniz Laboratory in Kiel (Kia). All $^{14}$C ages are uncalibrated, and therefore reported here as “BP”. Calibration would not affect our conclusions.

Infrared-stimulated luminescence (IRSL), multi-aliquot dating (e.g., Aitken, 1998; Berger and Doran, 2001) was conducted on the polymineral fine-silt fraction, and blue-photon-stimulated-luminescence (B-PSL) dating of sand-size (90–180 μm) quartz was carried out by the single-aliquot-regenerative-dose (SAR) method (e.g., Murray and Wintle, 2000). Details of these methods and results (dose-rate and luminescence data) as well as full age-interpretation of the results will be published elsewhere. In order to obtain the required sample size of 2 g quartz for the SAR method, we isolated the sand from 9.5 and 10.5 cm thick segments by wet sieving. Further treatment and dating was carried out at the Nordic Laboratory for Luminescence Dating, Risø National Laboratory, in Roskilde (Denmark). Eight IRSL ages were obtained from feldspar grains in the fine-silt fraction (4–11 μm) from 2.5 cm thick segments.

Fig. 3. (A) Sketch map of the Changeable Lake surrounding showing the Changeable Lake depression that penetrates below the Vavilov Ice Cap, the location of marine sediments in the northeastern catchment and the bed dip inclination of basement rocks (crossed arrows) (Bolshiyano and Makeyev, 1995). (B) Bathymetrical map of Changeable Lake showing several basins divided by sills (Bolshiyano and Makeyev, 1995) and the coring sites PG1238 and PG1239 in two different basins.
The samples were prepared and dated at the Desert Research Institute, Reno (USA) by Berger.

4.3. Statistical analysis

An analysis of variance (ANOVA) was carried out on the data of selected water-soluble elements, electrical conductivity, pH and on selected major and trace elements. The F-test clearly showed that the differences in the element composition between individual facies (see below) are significant. The multiple comparison of the averages using the LSD-test statistics showed significant differences also between the facies at a confidence level $\alpha = 0.05$ (Tables 1 and 2).

5. Facies classification and interpretation

Six facies can be distinguished in the Changeable Lake sediment cores: (1) a glacigenic facies, (2) an in situ marine facies, (3) a drying-up facies, (4) a reworked marine facies, (5) a saline facies and (6) a freshwater facies (Fig. 4). Since both cores show the same facies succession, local sedimentation effects in the lake are negligible. Thus, the results from core PG1238, presented and discussed in this paper, are considered representative of the evolution of the entire Changeable Lake and its surroundings.

5.1. Glacigenic facies

The glacigenic facies at the base of the sediment core (10.43–10.13 m) is characterized by a greyish, consolidated and massive diamicton that has a larger grain-size median and a higher gamma-ray density (GRD) than the overlying sediments (Figs. 4 and 5). The diamicton is interpreted as till. It has a sharp upper boundary and consists of debris from red-coloured Devonian sandstone. The occurrence of low amounts of TOC and TN indicate that older organic material is incorporated. Single Quaternary foraminifera and high TIC contents hint at the incorporation of carbonaceous rocks and Quaternary marine sediments.

5.2. In situ marine facies

The in situ marine facies (10.13–9.90 m) is built up by an olive-green coloured, fine grained (clay/silt) and massive sediment (Fig. 5). Benthic foraminifera from several taxa (e.g., Amonia, Astronionion, Cassidulina, Cibicides, Elphidiella, Fursenkoina, Islandiella, Lagena, Lobulatulus, Melonis, Nonionella, Triloculina; A. Mackensn, pers. comm., 1998) are abundant, and single ostracodes and fragments of mussel shells are present. The interpretation of this facies as being of in situ marine origin is based mainly on the good preservation of the microfossils, which argues against their redeposition, and on the foraminifera assemblage that represents a typical arctic shelf fauna indicating full marine conditions. Therefore, the lack of stratification of the sediment is probably caused by bioturbation due to a rich marine endobenthic fauna. Further support for a marine origin of the sediment is provided by the maximum in pyrite concentrations (Fig. 6), occurring as framboids and inside foraminifera shells. Marine conditions are indicated also by the composition of the water-soluble elements (Table 1), particularly the contents in Cl$^-$ and SO$_4^{2-}$ which reflect the ion concentration of the interstitial water and easy soluble salt precipitates. Diatoms are absent in the entire core.

5.3. Drying-up facies

The drying-up facies (9.90–9.88 m) is represented by a 2 cm thick layer of calciferous, sulphur-containing sediment. It is characterized by distinct maxima in Ba/Ti, Sr/Ti, Co/Ti, Mo/Ti and Fe/Ti element ratios (Table 1), indicating the presence of gypsum. The geochemical composition of the facies hints at a period when the lake basin was isolated from the sea and dried up. Missing relict sediments and sediment sorting suggest that the gypsum is unlikely to have been reworked into the lake from the catchment area.

5.4. Reworked marine facies

The reworked marine facies (9.88–8.50 m) is in contrast to the in situ marine facies well laminated. The laminae (thickness 0.1–1 cm) are defined by sediment colour (olive-green) and grain-size (silt/clay) variations. They suggest variable sediment supply from the catchment area and the absence of bioturbating marine fauna. Pyrite is abundant (Fig. 6). The water-soluble element composition shows high concentrations in Na$^+$, Cl$^-$ and SO$_4^{2-}$ (Table 1), and the electrical conductivity of the water extracts, being twice as high as in the in situ marine facies suggests formation during the establishment of a saline water body in the formerly dried-up lake basin.

5.5. Saline facies

The saline facies (8.50–7.85 m) is a black clay/silt fraction which shows a distinct and variable lamination (1–5 mm thicknesses) (Fig. 5). These suggest sediment formation in anoxic bottom water, possibly due to a density stratification of the water column in consequence of a high salt concentration and/or a perennial lake-ice cover, both of which preclude water mixing. A high salt concentration is indicated by a high electrical conductivity reflecting extraordinary high concentrations of the cations Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$, Sr$^{2+}$, Ba$^{2-}$...
Table 1
Analysis of variance (ANOVA) on the data of water-soluble elements, electrical conductivity and pH as well as on the data of bulk geochemistry of sediment core PG1238

**Water-soluble elements, electrical conductivity and pH**

<table>
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<tr>
<th>Facies</th>
<th>EC (µS/cm)</th>
<th>pH</th>
<th>Ca²⁺ (ppm)</th>
<th>Mg²⁺ (ppm)</th>
<th>K⁺ (ppm)</th>
<th>Na⁺ (ppm)</th>
<th>Al³⁺ (ppm)</th>
<th>Fe(aq) (ppm)</th>
<th>Mn⁴⁺ (ppm)</th>
<th>Si(aq) (ppm)</th>
<th>Sr²⁺ (ppb)</th>
<th>Ba²⁺ (ppb)</th>
<th>P(aq) (ppm)</th>
<th>Cl⁻ (ppm)</th>
<th>SO₄²⁻ (ppm)</th>
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<td>2.27</td>
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<td>15.80</td>
<td>2.12</td>
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**Bulk geochemistry**

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<th>Fe/Ti</th>
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<th>Mg/Ti</th>
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<th>Na/Ti</th>
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<td>1.81</td>
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<tr>
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<td>31.97</td>
<td>11.21</td>
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<td>8.21</td>
<td>0.20</td>
<td>1.07</td>
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<td>0.02</td>
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<td></td>
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<td>Average</td>
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<td>10.27</td>
<td>0.30</td>
<td>1.13</td>
<td>5.12</td>
<td>0.25</td>
<td>0.25</td>
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<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
</tr>
<tr>
<td><strong>In situ marine f.</strong></td>
<td>(n = 1)</td>
<td></td>
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<td>Average</td>
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<td>0.15</td>
<td>12.10</td>
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<td>0.26</td>
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<td>0.00</td>
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</table>
and anions \( \text{SO}_4^{2-} \) and \( \text{Cl}^- \) in the water-soluble element assemblage (Table 1). These elements probably derive from the input of reworked marine sediments. Due to higher evaporation than the sum of precipitation and glacial meltwater supply, a concentrated brine developed in the water body that led to an enrichment in some elements and to the precipitation of easily soluble mixed salts. Observations on lakes in Antarctica have shown that evaporites can be formed even in lakes with an ice cover of up to 4.5 m, still allowing the exchange of gases, liquids and solids (Andersen et al., 1993).

5.6. Freshwater facies

The freshwater facies (7.85–0 m) is a reddish-brown silt/clay derived from the red-coloured Devonian sandstones in the catchment or from the cover loams derived from these sandstones (Bolshiyanov et al., 1990). The water-soluble element assemblage differs distinctly from that in the underlaying saline facies (Tables 1 and 2) with low \( \text{Na}^+ \), \( \text{Cl}^- \) and \( \text{SO}_4^{2-} \) values, and an absence of marine organisms, and indicating deposition in freshwater. Today, Changeable Lake has a non-stratified, freshwater body (U. Wand, pers. comm., 2002).

In the lower part of the facies (7.85–2.56 m) black layers and irregular but well expressed laminae, defined by colour and grain-size variations, occur. These layers indicate that periods with anoxic bottom water conditions, characteristic for the underlaying saline facies, still occurred from time to time. The upper part (<2.56 m) of the facies, in contrast, has a reddish-brown colour and is poorly stratified to massive. This may reflect less stable climatic conditions, also shown by marked fluctuations of TOC, TN and TIC (Fig. 5).

Generally, low organic content indicate that biogenic production was low in the lake and its catchment area, or that the concentration of organic compounds in the sediments was restricted by their dissolution in the oxic water column or dilution by a high clastic-sediment supply. The TOC/TN-ratio of <10 evidences that the organic material derives mostly from non-vascular plants (e.g. algal production). An exception to this is a sandy layer at 25 cm depth, whose TOC/TN-ratio of >10 points to a single inflow event, when more coarse-grained sediments and more terrestrial organic material was supplied to the lake.

### Table 2

Similarity of the different facies according to the data of water-soluble elements, electrical conductivity (EC) and pH of PG1238 (+ denotes a statistically significant difference at \( \alpha = 0.05 \))

<table>
<thead>
<tr>
<th></th>
<th>Freshwater facies vs. saline facies</th>
<th>Freshwater facies vs. reworked marine facies</th>
<th>Freshwater facies vs. in situ marine facies</th>
<th>Reworked marine facies vs. in situ marine facies</th>
<th>Saline facies vs. reworked marine facies</th>
<th>Saline facies vs. in situ marine facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>pH</td>
<td>+</td>
<td>+</td>
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</tr>
<tr>
<td>( \text{Ca}^{2+} )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>( \text{Mg}^{2+} )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>( \text{K}^+ )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<td>+</td>
</tr>
<tr>
<td>( \text{Na}^+ )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>( \text{Al}^{3+} )</td>
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<tr>
<td>( \text{Fe(aq)} )</td>
<td>+</td>
<td>+</td>
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<td>+</td>
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<tr>
<td>( \text{Mn}^{2+} )</td>
<td>+</td>
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<td>+</td>
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</tr>
<tr>
<td>( \text{Si(aq)} )</td>
<td>+</td>
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<tr>
<td>( \text{Sr}^{2+} )</td>
<td>+</td>
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<td>+</td>
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<tr>
<td>( \text{Ba}^{2+} )</td>
<td>+</td>
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<td>( \text{P(aq)} )</td>
<td>+</td>
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<tr>
<td>( \text{Cl}^- )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<td>+</td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} )</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
assemblage, and good preservation that strongly suggests that they are autochthonous, rather than redepited. If this SAR age estimate was accurate, one would expect the $^{14}$C ages to lie in the finite range of 30–35 ka BP. Possibly this sample of quartz was accidentally exposed to light during sampling or sample preparation,
Fig. 5. Grain-size median, contents of total inorganic carbon (TIC), total organic carbon (TOC), total nitrogen (TN), total sulphur (TS) and TOC/TN-ratio in sediment core PG1238 (for legend see Fig. 4).

Fig. 6. Semi-quantitative bulk mineralogy of the sediment core PG1238. Presented are the peak intensity ratios $I_{\text{mineral}}/I_{\text{corundum}(030)}$. 1.4 nm = 14 Å-minerals, 1.0 nm = 10 Å-minerals, Q = quartz (100), Or = orthoclase (002), Al = albite (002), Cc = calcite (104), Dol = dolomite (104), Pyrite = pyrite (311) (for legend see Fig. 4).
accounting for an age underestimation. In comparison, the stratigraphic consistency of the IRSL ages suggest that they are more reliable, including the result of 53 ka at ca 10 m. Furthermore, fine-silt feldspar luminescence dating of polar-region lake core sediments has been shown elsewhere (Berger and Anderson, 2000; Berger and Doran, 2001) to be capable of accuracy over the age range studied here. In any case, all reasonable age estimates here give a minimum age of Middle Weichselian time. In any case, all reasonable age estimates have a minimum age of Middle Weichselian (MIS 3–4) for the in situ marine facies as well as the glacigenic facies.

In the reworked marine facies $^{14}$C ages of 25.6, 27.4, 23.0 and 24.2 ka BP were measured on mixtures of insect remains and plant debris, which had to be combined to provide sufficient sample sizes, and on humic acids (Table 3, Fig. 7). A more detailed determination of the organic remains was excluded due to their poor preservation. Keeping in mind that AMS $^{14}$C age estimates can be influenced by a variety of natural contamination and reservoir effects, by sample size and sample processing (Björck et al., 1991; Snyder et al., 1994; Wolfarth et al., 1998; Turney et al., 2000; Kilian et al., 2002), resulting in $^{14}$C ages of up to several thousand years different from time of deposition, our measured $^{14}$C ages indicate a formation of the reworked marine facies during Middle/Late Weichselian time. This is supported by an IRSL age (silt feldspar) of 33±2 ka from the lower part of the facies.

In the saline facies no $^{14}$C dating could be carried out due to insufficient organic content. However, two IRSL ages of 21±1 ka from the lower part and of 19±1 ka from the upper part of the saline facies (Table 3, Fig. 7) delimit its formation during Late Weichselian time.

In the freshwater facies, $^{14}$C ages were obtained from insect remains (6.0 ka BP), a pollen extract (11.4 ka BP) and 4 humic acid samples (bottom to top: 8.2, 8.3, 8.4 and 10.9 ka BP) (Table 3, Fig. 7). Two age inversions in this data set (360–362 cm and 11–17 cm depths), along with large age differences between two samples from the same depth (770–776 cm), as well as an unrealistic age close to the sediment surface (11–17 cm), make the $^{14}$C age estimates highly questionable. At best, these $^{14}$C age estimates hint at a formation of the freshwater facies after the Late Weichselian. In contrast, the IRSL age estimates (top to bottom: 4.4, 4.0, 5.1, 12.1 ka) define a clearer age-depth trend, one that is highly consistent with the IRSL age-depth trend deeper in the core (Table 3, Fig. 7). This was expected because laminated lake sediments, such as these, are ideal for luminescence dating of the fine-silt feldspars (Berger, 1990; Berger and Easterbrook, 1993). Possibly the IRSL age estimate of 4.4±0.4 ka for the top-most sample exceeds the deposition age, but given the analytical uncertainties (all at a 67% confidence level) and the uncertainties of sediment–water interface core recovery with the type of coring device employed here, this IRSL age estimate is reasonable. Certainly it is more accurate than the comparable $^{14}$C result (10.9 ka BP), and does not affect our main conclusions about the paleoenvironmental history of this sediment record.
7. Climatic and environmental history

7.1. Early and Middle Weichselian

The glacigenic facies at the base of the sediment record, consisting of a till, is interpreted as a relict from the last glaciation of the Changeable Lake area (Fig. 8a). The till pre-dates the in situ marine facies that from our data is evidently Middle Weichselian in age or older. The glacigenic facies thus could have been formed during the Early Weichselian or early Middle Weichselian. This is in agreement with the Early/Middle Weichselian glacial limits presented by Mangerud et al. (2001) and Svendsen et al. (1999) (Fig. 2), which indicate a complete ice coverage of Severnaya Zemlya, and with tills exposed on October Revolution Island which are classified as Early/Middle Weichselian (Alekseev, 1997). In addition, Knies et al. (2001) describe a well-defined moraine ridge, occurring in 385 m water depth west of Komsomolets Island, that yielded an “infinite” age of > 44 ka BP. Based on marine sediment records Knies et al. (2001) also propose a grounded ice sheet along the outer shelf of northern Severnaya Zemlya in at least 340 m water depth during the Middle Weichselian (MIS 4) glaciation. Relicts of an Early/Middle Weichselian glaciation on the Taymyr Peninsula, to the south of the archipelago, are buried glacier ice bodies, found at the “Ice Hill” site at the Jenissej River (Astakhov and Isayeva, 1988) and at the Labaz Lake in the Taymyr Lowland (Siegert et al., 1999a). Additionally, glacial erosion features identified in high-resolution seismic data from Levinson-Lessing lake are interpreted to be older than LGM (Niessen et al., 1999).

The in situ marine facies that overlays the glacigenic facies reflects the deglaciation and a marine transgression which led to full marine conditions in the Changeable Lake region, probably during Middle Weichselian time (Fig. 8b). This corresponds with ESR ages of 50–60 ka determined on foraminifera and mollusk shells from Quaternary marine sediments occurring near the...
Vavilov glacier margin and in the Changeable Lake catchment (Makeyev et al., 1992). A partial marine transgression is also reported for the North Siberian Lowland; however, this transgression was estimated to have taken place somewhat later, between 50 and 26 ka BP (Kind and Leonov, 1982).

The subsequent drying up of the marine basin, reflected by the drying-up facies, was the consequence of a regression, an arid climate and a limited meltwater supply (Fig. 8c). The dried basin probably lasted for less than 20 ka, as inferred from IRSL ages in the overlying (33 ± 2 ka) and underlaying (53 ± 3 ka) facies. Erosion,
as another possible explanation for the time gap, is regarded as unlikely, because neither a relict sediment nor compaction or deformation structures occur in the underlaying sediment. Interestingly, the interval 30–50 ka was a time of development of peat beds on the underlying sediment. Melles et al. (1996), Hahne and Melles (1999) and Siegert et al. (1999a) found evidence for predominantly cold and arid continental climate conditions, interrupted by warmer periods with still very cold winters but with summer temperatures sufficient for the development of increased vegetation.

7.2. Late Weichselian

Parts of the Late Weichselian are represented in the Changeable Lake record by the saline facies (Fig. 8e). Formation of this facies started earlier than 21 ka and lasted until after 19 ka. It reflects sedimentation under a permanent lake ice cover, with a limited meltwater and precipitation supply that led to a precipitation of readily soluble salts due to evaporation of the saline water, and in a stratified water column with anoxic bottom water. These processes suggest a particularly cold and dry climate. An extreme continental climate is assumed for the Late Weichselian of Northwestern Siberia by Kind and Leonov (1982) and Velichko et al. (1997). The same conclusion was drawn by Siegert et al. (1999a) from permafrost sequences at Labaz Lake, Eastern Taymyr Lowland, which show salt accumulation in a dried lake depression, connected with evaporation and freezing-out processes in the active layer.

The continuous limnic sedimentation and the lack of glacial and glacio-lacustrine sediments during the Late Weichselian in the Changeable Lake depression also indicate a small glaciation of October Revolution Island at the LGM. Although at present the glacier margin is only in about 4 km distant, the Vavilov Ice Cap did not reach Changeable Lake during the LGM. This supports earlier investigations on the Severnaya Zemlya Archipelago, where Alekseev (1997), Velichko et al. (1984) and Stiévenard et al. (1996) suppose small and relatively thin ice for the Late Weichselian maximum between 18 and 14 ka BP. According to Makeyev and Bolshiyanov (1986) the ice sheet covered the Changeable Lake depression, but was still restricted to local ice caps on October Revolution Island (Fig. 1). The latter interpretation is based on mammoth finds next to the modern margin of the Vavilov Ice Cap, dated to 24.9, 20.0, 19.3 and 11.5 ka BP (summarized by Vasilchuk et al., 1997). However, the lake cores reported in this paper demonstrate that a glacier expansion did not take place and that fine-grained lake sedimentation was continuous throughout this period. This suggests that during the LGM the Eurasian ice sheet did not extend eastward onto the Severnaya Zemlya Archipelago, and by implication, perhaps also did not extend onto the Taymyr Peninsula. Further numeric dating of relevant deposits on the Taymyr Peninsula is needed to test this implication.

A scenario of limited glaciation during the LGM of the Eurasian Arctic has been modelled by Siegert et al. (1999b) and by Siegert and Marsiat (2001). They propose for the LGM climate of the Eurasian Arctic that the eastern margin of the LGM ice sheet, and the central area of the Barents and Kara Seas experienced very low amounts of ice accumulation (< 200 mm yr⁻¹), and that the rate of ice accumulation over the Kara Sea was less than 100 mm yr⁻¹, making this area similar to the polar desert conditions in central East Antarctica.

The regions to the east of Severnaya Zemlya, and the greater part of the Taymyr Peninsula, were certainly not affected by glaciation during the LGM (Fig. 2). This is demonstrated by lacustrine sediments, massive ground ice, thick Yedoma (ice-loess) complexes and numerous mammoth finds in these areas (e.g., Isayeva, 1984; Sulerzhitsky, 1995; Vasilchuk et al., 1997; Hahne and Melles, 1999; Siegert et al., 1999a). An exception is the northwestern Taymyr Peninsula, where a thin glacier originating from the Kara Ice Sheet inundated the present land area forming the North Taymyr ice-marginal zone (NTZ) between 20 and 12 ka BP (Alexanderson et al., 2001, 2002).

7.3. Latest Weichselian and Holocene

The global warming at the termination of the Pleistocene led to an enhanced meltwater supply and to a freshwater body in Changeable Lake earlier than 12 ka (Fig. 8f). In the lower part of this freshwater facies, during the transition from the Late Weichselian to the Holocene, anoxic bottom water conditions developed possibly due to perennial ice cover of the lake.
Therefore, these represent temporary cold periods. During most of the remaining Holocene the climate seems to have been warmer and more stable, resulting in well-developed laminations caused by annual meltwater discharge and by low but constant biomass production. During the later part of the Holocene the lack of laminations and stronger fluctuations in the biogeochemical data suggest that conditions became more instable. Therefore, sedimentation conditions pass into modern climate conditions, being characterized by a direct dependence of the sedimentation processes on the air temperature (Bolshiyanov, 1985).

The global ice retreat at the Weichselian/Holocene transition led to a sea-level rise that resulted in the separation of the Severnaya Zemlya Archipelago from the continental mainland (Alekseev, 1997). The low relative land uplift, indicated by the low marine limit on western October Revolution Island is a further argument against a large Late Weichselian ice cover on the Severnaya Zemlya Archipelago, since glacial loading would have led to a larger isostatic rebound and, consequently, a higher marine limit. More detailed information about the Holocene climatic and glacial history on the Severnaya Zemlya Archipelago comes from ice-core data and investigations of peat sections. According to oxygen isotope analyses on ice cores from the Vavilov Ice Dome and the Academy of Science glacier, the Holocene thermal climate optimum on the Severnaya Zemlya Archipelago occurred between 10 and 8 ka BP (Bolshiyanov et al., 1990; Vaikmäe, 1991; Stiévenard et al., 1996; Andreev et al., 1997) and it is presumed that the glaciers that existed on the archipelago were smaller than at present. This is indicated by $^{14}$C ages of lake-swamp samples between about 11.5 and 8.8 ka BP and of soil horizons with wood remains between 10.2 and 9.0 ka BP, lying below the recent Vavilov glacier (Velichko et al., 1984).

A milder climate than today, during the Early to Middle Holocene, is also assumed for regions adjacent to Severnaya Zemlya. This is based, for example, on pollen analyses on $^{14}$C dated peat sections from different locations in the Russian Arctic (Makeyev et al., 1992; Kondratjeva et al., 1993; Alekseev, 1997; Serebryannyy and Malysova, 1998; Serebryannya et al., 1998; Siegert et al., 1999a). The same conclusions were drawn from palynological, biogeochemical and diatom investigations on lake sediment cores from the Taymyr Peninsula (Hahne and Melles, 1999; Harwart et al., 1999; Kienel, 1999).

8. Conclusions

Based on our multi-disciplinary investigation of the Changeable Lake sediment record, the following conclusions can be drawn concerning the climatic and environmental history of the Severnaya Zemlya Archipelago since Early Weichselian time.

- The last ice advance to the Changeable Lake is represented by a till. This glaciation took place prior to ca 45 ka but most probably just before 53 ka.
- Deglaciation of the area commenced sometime after 53 ka, and was followed by marine transgression into the Changeable Lake basin.
- The basin dried up between 53 and 33 ka, suggesting a time of an arid climate and a geomorphological stability.
- Enhanced humidity or temperature during the Middle to Late Weichselian transition (ca 33–21 ka) led to the development of a lake in the basin. The lake water was saline, in consequence of a fluvial supply of marine sediments and the corresponding ions from the catchment area.
- During the Late Weichselian (between 21 and 19 ka), a cold and arid climate led to a permanent ice cover on the lake, limited meltwater and precipitation supply, a density stratification of the water column and sedimentation in anoxic bottom water. This limnic sediment formation, and the lack of glacigenic sediments, are evidence for a restricted or only local glaciation of the Severnaya Zemlya Archipelago during the time of the LGM. Our dating of a continuous non-glacial sedimentary record provides a significant constraint on the northeastward limit of the Eurasian ice sheet during the LGM stage.
- During the termination of the Pleistocene and the entire Holocene (since about 12 ka) sediment formation took place under freshwater conditions. A warmer and more humid climate led to higher sedimentation rates than during the Weichselian. Holocene climate changes are only weakly reflected in the Changeable Lake record.

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