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Environmental changes on the northern Taymyr Peninsula (Russian Arctic) during the last 62 ka inferred from the lacustrine pollen record

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Environmental changes on the northern Taymyr Peninsula were reconstructed based on a new pollen record from a 46-m-long sediment core recovered from Lake Levinson-Lessing (latitude 74°27′54″N, longitude 98°39′58″E). The record is continuous and has a relatively good age control and high temporal resolution. Reaching a basal age of 62 cal. ka BP, it provides a unique environmental archive for the central Russian Arctic. The results reveal that open landscapes dominated 62.0–50.8 cal. ka BP, but presence of shrubs reflects a relatively warm summer climate. Numerous *Pediastrum* colonies in the sediments point to a rather low lake stand. A decrease in algae remains in the pollen spectra reflects a higher lake level after *c.* 50.8 cal. ka BP. From *c.* 47.8 to 25.5 cal. ka BP, lower contents of *Betula* and higher percentages of herb pollen point to colder and drier conditions. Besides, larger amounts of Pre-Quaternary palynomorphs and *Pediastrum* colonies point to increased erosion processes and a lower lake stand. After *c.* 25.5 cal. ka BP, herb communities further increased. Poaceae and *Artemisia* show the highest contents between *c.* 20.3 and 19.2 cal. ka BP, suggesting the coldest and driest climatic conditions during the studied time interval coincident with the Last Glacial Maximum (LGM). Pollen spectra dated *c.* 19.20–16.05 cal. ka BP reflect a slightly warmer and wetter climate in comparison to the LGM. Increased amounts of coprophilous fungi spores indirectly indicate that grazing animals were abundant around the lake. After *c.* 16.05 cal. ka BP, increases in shrubs and sedges reflect somewhat warmer and/or wetter conditions. The pollen data also well document the Allerød warming and Younger Dryas cooling events, reflecting an Atlantic influence on the regional climate development during these times. The transition from the Lateglacial to the Holocene at *c.* 11.63 cal. ka BP is characterized by drastic increases in pollen of shrubs, which document a significant warming. The Early Holocene (*c.* 11.63–8.30 cal. ka BP) pollen spectra reflect the Holocene Thermal Maximum in the study region. After *c.* 8.3 cal. ka BP, gradual cooling prevailed and led to climate conditions similar to modern ones at *c.* 2 cal. ka BP.

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The Arctic is known to play an essential role, though not yet completely understood, within the global climate system. During recent decades, the High Arctic regions have experienced warming more dramatic than other parts of the globe (e.g. Sundqvist *et al.* 2010; Kumar *et al.* 2020 and references therein), as shown by numerous observations with a temperature rise of about 2 °C since 1961 (IPCC 2022). Predictions of future environmental changes in the Arctic under such quickly changing climate conditions and the associated feedback mechanisms involving the atmosphere, biosphere and cryosphere become increasingly important. However, reliable scenarios of possible future changes are still hampered by the complexity of the underlying natural processes and feedbacks, and remain a major scientific challenge. An important prerequisite for the validation and improvement of simulation scenarios is a better understanding of the long-term environmental history of the Arctic. Multidisciplinary investigations of lake sediment records (e.g. Müller *et al.* 2010; Melles *et al.* 2012, 2022; Brigham-Grette *et al.* 2013; Diekmann *et al.* 2017; Andreev *et al.* 2022; Lenz *et al.* 2022 and references therein), which may document environmental and climatic changes over long time periods, have contributed substantially to the understanding of these differences and related processes.

In the high latitudes, studies of long-term environmental changes have intensified significantly over recent decades. However, only a few records provide information on the palaeoenvironmental history older than the LGM, due to preceding ice cover and/or glacial erosion as well as technical limits of coring equipment and poor logistical accessibility of lakes (e.g. Melles *et al.* 2012, 2022; Brigham-Grette *et al.* 2013). In consequence, the regional and circum-Arctic differences in the environmental history and mechanisms in the past are still not sufficiently understood and new long-term environmental records from poorly studied Arctic regions are therefore highly desired.

New continuous palaeoenvironmental records going back to Marine Isotope Stage (MIS) 4 especially in the Siberian Arctic help to answer the open scientific

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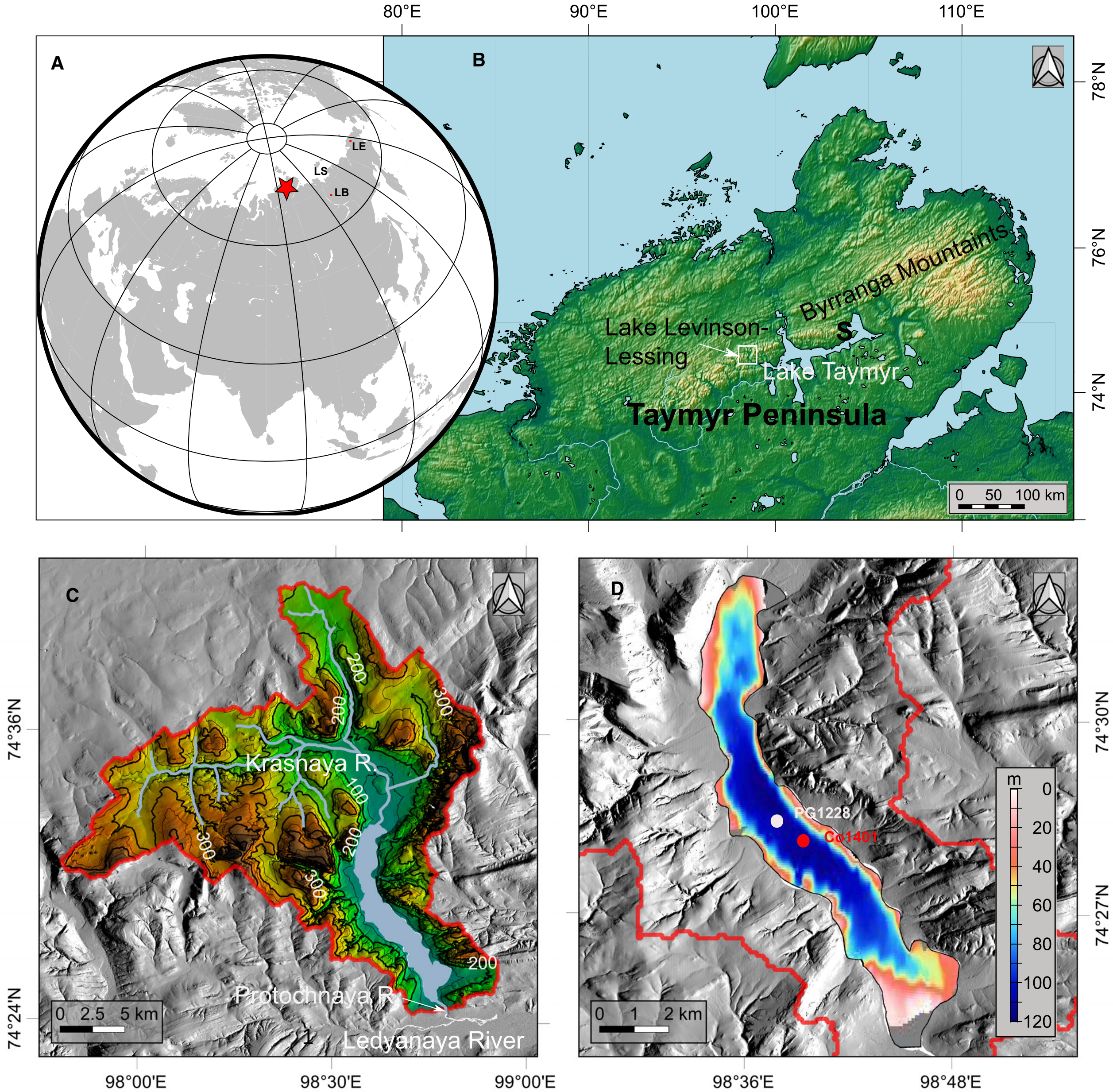

Fig. 1. A. The globe with the Lake Levinson-Lessing location marked by a red star: LB = Lake Billyakh (Müller *et al.* 2010); LE = Lake El'gygytgyn (Brigham-Grette *et al.* 2013; Andreev *et al.* 2016; Zhao *et al.* 2019); LS = Laptev Sea region records (Andreev *et al.* 2004, 2009, 2011; Sher *et al.* 2005; Schirrmeister *et al.* 2008). B. Topographical map of the Taymyr Peninsula showing Lake Levinson-Lessing (white frame); S = Cape Sabler sections (Kienast *et al.* 2001; Andreev *et al.* 2003; Jørgensen *et al.* 2012). C. Topographical map of the Lake Levinson-Lessing catchment (red line) with its main inflow, the Krasnaya River, entering the lake in the north, and the Ledyanaya River, draining the lake to the south. D. Bathymetry of Lake Levinson-Lessing with the two coring sites PG1228 (white dot) and Co1401 (red dot), where coring was conducted in 1996 and 2017, respectively.

questions in regional (Siberian) and continental (Eurasian) scales. For example: did the Eurasian Ice Sheet complex disappear completely during the early MIS 3 as suggested by Mangerud *et al.* (2023 and references therein)? Was the climate in Arctic Siberia during MIS 3 variable with some relatively warm stages or was it rather homogeneously cold and dry as suggested by Sher *et al.* (2005), Lozhkin & Anderson (2011) and Wetterich *et al.* (2014)?

The Taymyr Peninsula (Fig. 1A, B), the northernmost part of the Central Siberian mainland, is a vast and poorly studied territory with only a few well-dated palaeoenvironmental proxy records (e.g. Andreev *et al.* 2002a, b, 2003, 2004 and references therein). The longest continuous palaeoenvironmental records from the region are represented by the lacustrine sediments at the bottom of Lake Levinson-Lessing (Fig. 1C, D; Hahne & Melles 1999; Andreev *et al.* 2003; Lenz

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et al. 2022). They document the environmental history of the northern Taymyr Peninsula at least since MIS 5b (Niessen *et al.* 1999; Svendsen *et al.* 2004; Astakhov 2013; Möller *et al.* 2015; Lebas *et al.* 2019; Lenz *et al.* 2022).

Lake Levinson-Lessing and its vicinity were investigated for geology, permafrost, vegetation, soils, climatic, and hydrological conditions during fieldwork in 1993–1996, conducted under the framework of the Russian–German project 'Taymyr' (Overduin *et al.* 1996; Anisimov & Pospelov 1999). A 22.4-m-long sediment core (PG1228) was retrieved from the central part of the lake in 1995 (Fig. 1D; Overduin *et al.* 1996). The cored sediments document the regional environmental history for the last *c.* 32 ka (Hahne & Melles 1999; Andreev *et al.* 2003 and references therein).

In order to extend and complement the existing record, Lake Levinson-Lessing was studied within the scope of the Russian–German research project 'PLOT'. New seismic surveys were conducted in summer 2016, providing the basis for the determination of coring sites that were targeted in April 2017 (for details see Lebas *et al.* 2019; Lenz *et al.* 2022). The seismic studies revealed a sediment thickness of up to 135 m. The sediments are proposed to comprise glacial and postglacial sediments, supporting earlier suggestions that the lake catchment was glaciated during the Early Weichselian (Niessen *et al.* 1999; Lebas *et al.* 2019). Moreover, the seismic-stratigraphical record supports the view that the catchment area has not been glaciated since that time, as also suggested by Möller *et al.* (2015, 2019).

At site Co1401 (Fig. 1D) a 46-m-long sediment succession was recovered and studied for geochronology, lithology, granulometry, geochemistry, mineral magnetics and pollen, thus providing a reliable basis for the reconstruction of the lake and catchment development since late MIS 4 (Scheidt *et al.* 2021, 2022; Lenz *et al.* 2022 and references therein).

Here, we present the results of the palynological investigations of the undisturbed upper 38 m of sediment core Co1401, which allow detailed vegetation and climate reconstructions for the last 62 ka. For quantitative interpretations of pollen data, we applied the biomization method (Prentice *et al.* 1996). For the first time, four regionally tested biome–taxa matrices were applied to the same fossil data set. Comparison of the quantitative and qualitative reconstructions allows the most reliable interpretations of the pollen data.

Study site

Lake Levinson-Lessing (74°28′N, 98°38′E; Fig. 1) is situated in the southern part of the Byrranga Mountains at 47 m a.s.l. The lake basin is a tectonic fault reshaped by glacial abrasion presumably during the Early Weichselian, when the area was last glaciated (Niessen *et al.* 1999; Lebas *et al.* 2019; Lenz *et al.* 2022 and references therein). The modern lake is ~15 km long and up to 2 km wide, covering an area of ~25 km^2 with a maximum water depth of ~120 m. The lake is surrounded by low mountain ranges with a height of up to 570 m a.s.l. and has a catchment of ~515 km^2. The bedrock in the study area is composed of terrigenous Permian aleurolites with intrusions of dolerites (Bolshiyanov & Anisimov 1995). The Krasnaya River, the main inflow, enters the lake at its northern shore (Zimichev *et al.* 1999). Seasonally, the lake is fed also by numerous small streams draining the eastern and western lake catchment with relatively steep slopes (Bolshiyanov & Anisimov 1995). The lake outflow is the Protochnaya River, a tributary of the Ledyanaya River, which flows into Lake Taymyr, located ~50 km to the southeast.

The present climate in the study area is characterized by an annual precipitation of ~250 mm and long winters with mean temperatures below zero for 8 months and the lowest of ~−34 °C in January as well as short summers with the highest mean temperatures of ~6 °C in July (Siegert & Bolshiyanov 1995). Lake Levinson-Lessing is a monomictic lake with mixing occurring during summer, when the lake is ice-free (Hagedorn *et al.* 1996). The lake basin today is located in the zone of continuous permafrost, at the border between the sub-arctic and arctic tundra, with mostly grass, sedge and herb (such as *Dryas*, *Papaver*, *Draba*, *Artemisia*) communities (Zhurbenko 1995; Anisimov & Pospelov 1999).

Material and methods

Fieldwork

Coring site Co1401 is located in the central part of the lake (74°27′54″N, 98°39′58″E; Fig. 1C, D) at a water depth of ~112 m and ~1.3 km south of the previously studied core PG1228 (Andreev *et al.* 2003). At the coring position detailed seismic and echo-sounder data suggest continuous sedimentation and no sediment disturbances (for details see Lebas *et al.* 2019; Lenz *et al.* 2022).

Coring was conducted from the ice using a gravity corer to recover undisturbed near-surface sediments and a percussion piston-corer system with a 2-m-long core barrel (UWITEC, Austria) to retrieve deeper sediments (for details see Lenz *et al.* 2022). After recovery, the core segments were cut into up to 1-m-long sections and transported to the University of Cologne.

Core processing and dating

In the laboratories of the University of Cologne, the core sections were split lengthwise, lithologically described, and investigated for chemical and granulometric composition as well as magnetic susceptibility (Lenz *et al.* 2022). The overlapping gravity and uppermost piston-core sections were correlated using the Corelyzer 2.0.4 software, whereas the deeper, not overlapping core

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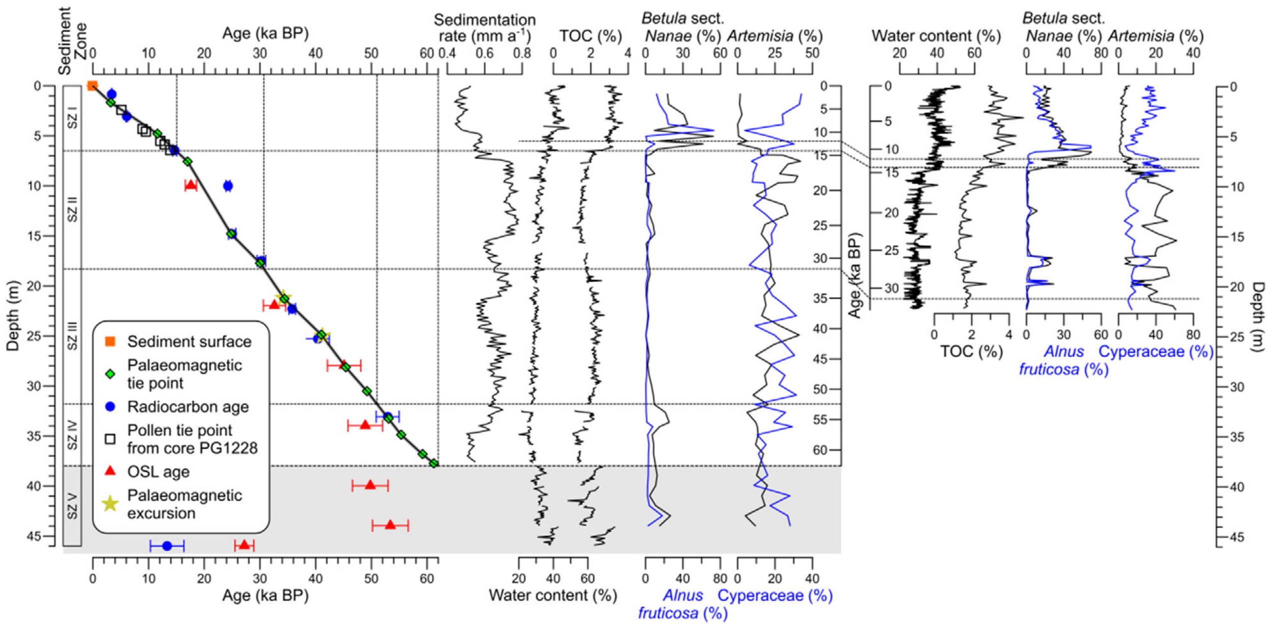

Fig. 2. Bayesian age-depth model of the sediment core Co1401 after Lenz *et al.* (2022) based on palaeomagnetic excursions (Scheidt *et al.* 2022) and supported by ^{14}C and OSL datings from the core Co1401 (Lenz *et al.* 2022), and pollen tie points from core PG1228 (Andreev *et al.* 2003). To the right of the age-depth model are the sedimentation rate, TOC content, selected pollen taxa from the core Co1401 and a correlation to core PG 1228 (Ebel *et al.* 1999; Hahne & Melles 1999; Andreev *et al.* 2003) based on water and TOC contents and selected pollen taxa.

segments were inserted into the composite profile based on their field depths (for details see Lenz *et al.* 2022). The core composite has a total length of 45.95 m.

A Bayesian age-depth model was constructed for the core based on the modern sediment surface (AD 2017) and 13 palaeomagnetic tie points (Fig. 2, for detail see Scheidt *et al.* 2022). Palaeomagnetic tie points were supplemented by 10 radiocarbon (^{14}C) dates of plant remains from the core at the Cologne AMS facility (for details see Lenz *et al.* 2022). The ^{14}C and palaeomagnetic data provide good coverage for the upper 38 m of the core presented in the current study. Complementary information for constructing the age-depth model was also derived from seven OSL ages, which were determined at the Cologne Luminescence Laboratory (for details see Lenz *et al.* 2022). These dates supported earlier proxy evidence for a disturbed character of the Co1401 sediments below 38 m, which probably is due to an unintended release of the piston leading to sediment entry into the core barrel before reaching the intended coring depth (for details see Scheidt *et al.* 2021; Lenz *et al.* 2022).

Pollen analyses

The samples for palynological analyses were taken at 8-cm resolution and freeze-dried. A total of 125 samples (~1 g of dry sediment) were prepared using a standard hydrofluoric acid (HF) technique (Berglund & Ralska-Jasiewiczowa 1986). One tablet of *Lycopodium* marker spores (batch 100320201) was added to each sample for calculating total pollen and spore concentrations following Stockmarr (1971). Water-free glycerol was used for sample storage and preparation of microscopic slides. Pollen and spores were identified at magnifications of 400× with the aid of published pollen keys and atlases (e.g. Kupriyanova & Alyoshina 1972, 1978; Bobrov *et al.* 1983; Reille 1992, 1995, 1998). In addition to pollen and spores, a number of non-pollen palynomorphs (namely fungi spores, remains of algae and invertebrates) were identified when possible and counted (van Geel 2001 and references therein).

At least 250 terrestrial pollen grains were counted in each sample. The relative frequencies of pollen taxa were calculated from the sum of the terrestrial pollen taxa. Spore percentages are based on the sum of pollen and spores. The percentages of fungal spores are based on the sum of the pollen and fungi spores and the percentages of algae are based on the sum of pollen and algae. TGView software version 1.7.16 (Grimm 2004) was used for the calculation of percentages and for drawing the pollen diagram. The diagram was zoned according to significant changes in palynomorph contents, total pollen concentration and occurrence of particularly indicative palynomorphs. The cluster analysis (CONISS) in TGView supports the zone boundaries.

Quantitative biome reconstructions

The biomization approach was introduced by Prentice *et al.* (1996) for objective quantitative interpretations of

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pollen data in terms of the major vegetation types (biomes). First tested with a set of modern pollen spectra from Europe (Prentice *et al.* 1996), the method was adapted and successfully applied to the Middle Holocene and LGM pollen data from various regions of the world, including middle and high latitudes of northern Eurasia (e.g. Tarasov *et al.* 1998, 2000), Beringia (e.g. Edwards *et al.* 2000) as well as western (Thompson & Anderson 2000) and eastern North America (Williams *et al.* 1998, 2000) under the BIOME6000 global vegetation mapping project (e.g. Prentice & Webb 1998; Prentice *et al.* 2000). Although researchers working in different geographical regions used the standard approach and universal equations based on fuzzy logic published by Prentice *et al.* (1996) for calculating biome affinity scores, they also experimented with the assignment of plant taxa to biomes, the number and order of biomes, and the pollen taxa percentage thresholds, in order to find the best match between actual natural vegetation and pollen-derived biomes. In particular, Bigelow *et al.* (2003) proposed a scheme to distinguish five tundra types (cushion forb tundra, graminoid and forb tundra, prostrate dwarf-shrub tundra, erect dwarf-shrub tundra, and low- and high-shrub tundra) based on their tests with modern pollen surface samples.

The later work also revealed the necessity of a re-examination of the pollen data sets from arctic regions using consistent assignment of plant/pollen taxa to biomes. A systematic comparison of the results obtained with the regional biomization schemes applied to the same fossil data set has not been performed yet. For the purpose of our study, we selected four biome–taxon matrices to be applied. Two of these were used in vegetation reconstructions in northern Eurasia (Tarasov *et al.* 1998, 2000) and in the circumpolar Arctic region (Bigelow *et al.* 2003) at 0, 6 and 18 ^{14}C ka BP and in the data–model comparison experiments (e.g. Braconnot 2000; Kageyama *et al.* 2001; Kaplan *et al.* 2003). The other two matrices were tested with modern pollen data sets from northern Yakutia and Chukotka and applied to the long fossil pollen records from Lake Billyakh (65°17′N, 126°47′E; Müller *et al.* 2010) and Lake El'gygytgyn (67°30′N, 172°05′E; Brigham-Grette *et al.* 2013; Andreev *et al.* 2016; Zhao *et al.* 2019). Although these two lakes are also located in Arctic Siberia, their long distances from Lake Levinson-Lessing (~1500 and ~2500 km, respectively) hamper the application of the respective matrices to the Levinson-Lessing pollen record without prior verification, such as that performed in the current study. In addition to the affinity scores of the major regional vegetation types (tundra, cold deciduous forest, taiga and cold grassland/steppe) calculated using the four published biomization schemes, landscape openness was assessed as the difference between the maximum forest biome score and the maximum open biome score at each analysed level (for details see Tarasov *et al.* 2013). The landscape openness estimate provides a qualitative assessment of changes in vegetation cover around the studied lake.

Results

Pollen assemblages

The pollen analyses were restricted to the upper 38 m of core Co1401, which corresponds to Sediment Zones (SZ) 1–4 in Lenz *et al.* (2022). The pollen assemblages (Fig. 3A, B) from the sediment depths between 38 and 0 m were subdivided into 12 main pollen zones (PZ).

PZ I (38.00–31.55 m, *c.* 62.0–50.8 cal. ka BP) approximately coincides with SZ 4 (38.0–31.8 m). It is characterized by a dominance of pollen of herbs (Poaceae, *Artemisia*, Cyperaceae), however, and by relatively high pollen contents of *Betula nana*, *Alnus fruticosa* and *Salix*. Large amounts of mineralized Pre-Quaternary pollen (mostly Pinaceae) and spores as well as remains of green algae colonies (mostly *Pediastrum*) and spores of coprophilous fungi (mostly *Sordaria*) are also notable.

PZ II (31.55–29.55 m, *c.* 50.8–47.8 cal. ka BP) coincides with the lower part of SZ 3 (31.8–18.3 m). Generally, pollen spectra of this zone are similar to those of PZ I, but they differ by a drastic reduction of Pre-Quaternary palynomorphs and green algae colonies. Another characteristic is also a significant increase in *Sporormiella* spore contents.

PZ III (29.55–10.88 m, *c.* 47.8–20.3 cal. ka BP) coincides with the upper part of SZ 3 and the lower/middle part of SZ 2 (18.3–6.5 m). The zone is characterized by lower contents of *Betula nana*, higher percentages of herb taxa and larger amounts of Pre-Quaternary pollen and spores as well as green algae colonies in comparison to the lower PZ II. The zone can be subdivided into two subzones. PZ IIIb (14.93–10.88 m, *c.* 25.5–20.3 cal. ka BP), belonging to the middle part of SZ 2, differs from PZ IIIa (29.55–14.93 m, *c.* 47.8–25.5 cal. ka BP) by a further increase in herb pollen and Pre-Quaternary pollen and spores, while pollen percentages of shrubs decrease.

PZ IV (10.88–10.00 m, *c.* 20.3–19.2 cal. ka BP) belongs to the upper SZ 2. The zone is notable for the highest contents of Poaceae and *Artemisia*. The amounts of coprophilous fungal spores, Pre-Quaternary pollen and spores, and remains of green algae colonies are lower than in PZ III.

PZ V (10.00–7.40 m, *c.* 19.20–16.05 cal. ka BP) also belongs to the upper part of SZ 2. In comparison to PZ IV, this zone is characterized by higher contents of *Betula nana* and *Salix* pollen as well as remains of *Botryococcus* and coprophilous fungal spores.

PZ VI (7.40–6.20 m, *c.* 16.15–13.77 cal. ka BP) also belongs to the uppermost SZ 2. This zone is

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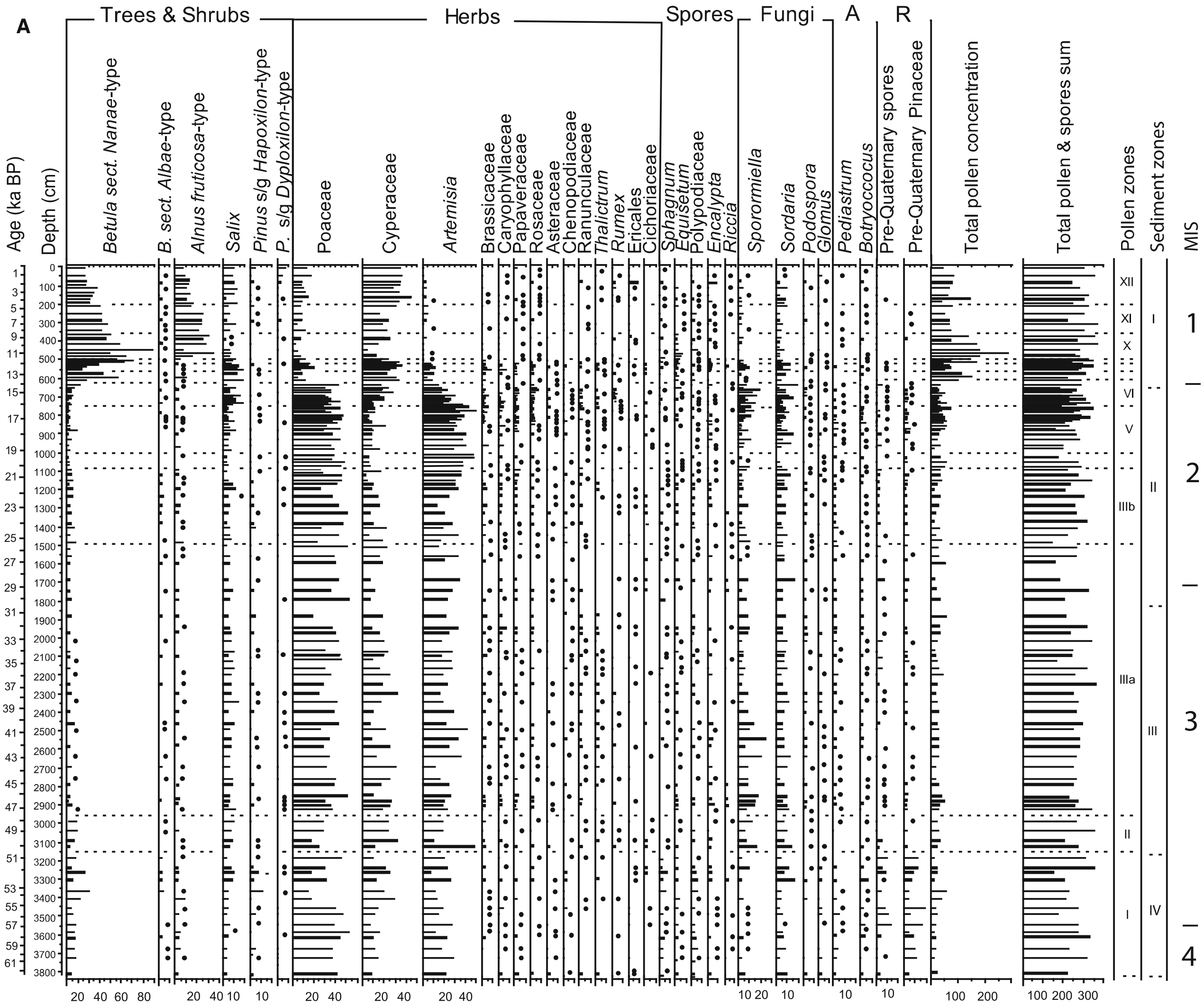

Fig. 3. A. Percentage pollen, spore, and non-pollen-palynomorph diagram of the sediment core Co1401 with the most common palynomorphs. The dots signify that percentages of taxa are <1%. A = algae taxa; R = reworked palynomorphs. The stratigraphical units and chronology are after Lenz *et al.* (2022). B. Percentage pollen, spore, and non-pollen palynomorphs diagram with minor palynomorph types. The dots signify that percentages of taxa are <1%. A = algae taxa; Z = remains of invertebrates.

characterized by further increases in *Betula nana*, *Salix* and Cyperaceae pollen percentages, while *Artemisia* gradually decrease. The contents of coprophilous spores are also higher than in PZ V.

PZ VII (6.20–5.63 m, *c.* 13.77–12.75 cal. ka BP) belongs to the lowermost SZ 1 (0–6.5 m). This zone is notable for a drastic increase in *Betula nana* and Poaceae pollen percentages. Besides, the contents of coprophilous fungi spores are lower than in PZ VI.

PZ VIII (5.63–5.19 m, *c.* 12.75–11.98 cal. ka BP) is characterized by a drastic decrease in *Betula nana* pollen percentages, while percentages of herb taxa (mostly Poaceae) and spores of coprophilous fungi increase.

PZ IX (5.19–5.00 m, *c.* 11.98–11.63 cal. ka BP) is notable for a drastic increase in *Betula nana* and a small increase in *Alnus fruticosa* pollen percentages. Besides, percentages of herb pollen decrease and *Artemisia* pollen almost disappear from the spectra.

PZ X (5.00–3.56 m, *c.* 11.63–8.30 cal. ka BP) is characterized by the highest percentages of *Alnus fruticosa* (up to 35%) and *Betula nana* (up to 72%) pollen, and the highest pollen concentration throughout the core.

PZ XI (3.56–2.00 m, *c.* 8.3–4.4 cal. ka BP) pollen assemblages show a gradual decrease in arboreal pollen percentages, while percentages of non-arboreal pollen increase.

The pollen spectra of the uppermost PZ XII (2.00–0 m, *c.* 4.4–0 cal. ka BP), corresponding with the upper part of SZ 1, demonstrate a further decrease in *Betula* and *Alnus* pollen percentages, while percentages of Cyperaceae and *Salix* increase. Spores of coprophilous fungi almost disappeared after *c.* 2 cal. ka BP.

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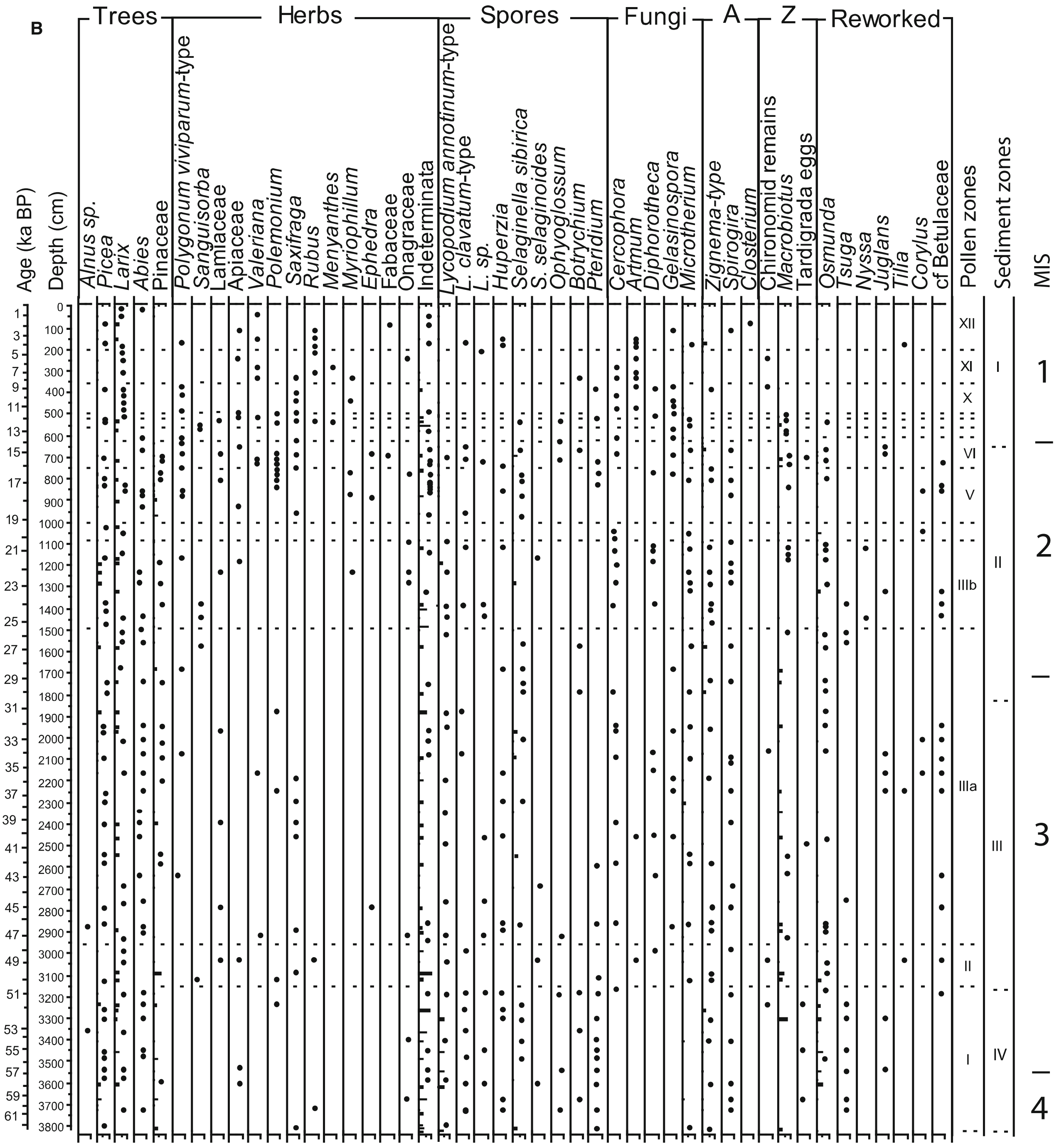

Fig. 3. Continued.

Quantitative biome reconstructions

Four relevant biome–taxon matrices previously applied to the Pliocene-Pleistocene and Holocene pollen record from the Eurasian Arctic (e.g. Tarasov *et al.* 1998, 2000; Bigelow *et al.* 2003; Müller *et al.* 2010; Brigham-Grette *et al.* 2013) were applied to the Co1401 pollen record. The results are summarized in Fig. 4. All four reconstructions show the most pronounced change in the regional biome affinity scores between *c.* 15.2 and 10.6 cal. ka BP (~7–4.5 m core depth). Another less pronounced change occurs in the lower part of the core around 48.47 cal. ka BP (~30 m core depth). However, the reconstructions differ in detail.

Figure 4A demonstrates the codominance of the cold grassland/steppe (STEP) and tundra (TUND) biomes before 15 cal. ka BP (below 6.9 m core depth), followed by a drastic, albeit oscillating, decrease in STEP values

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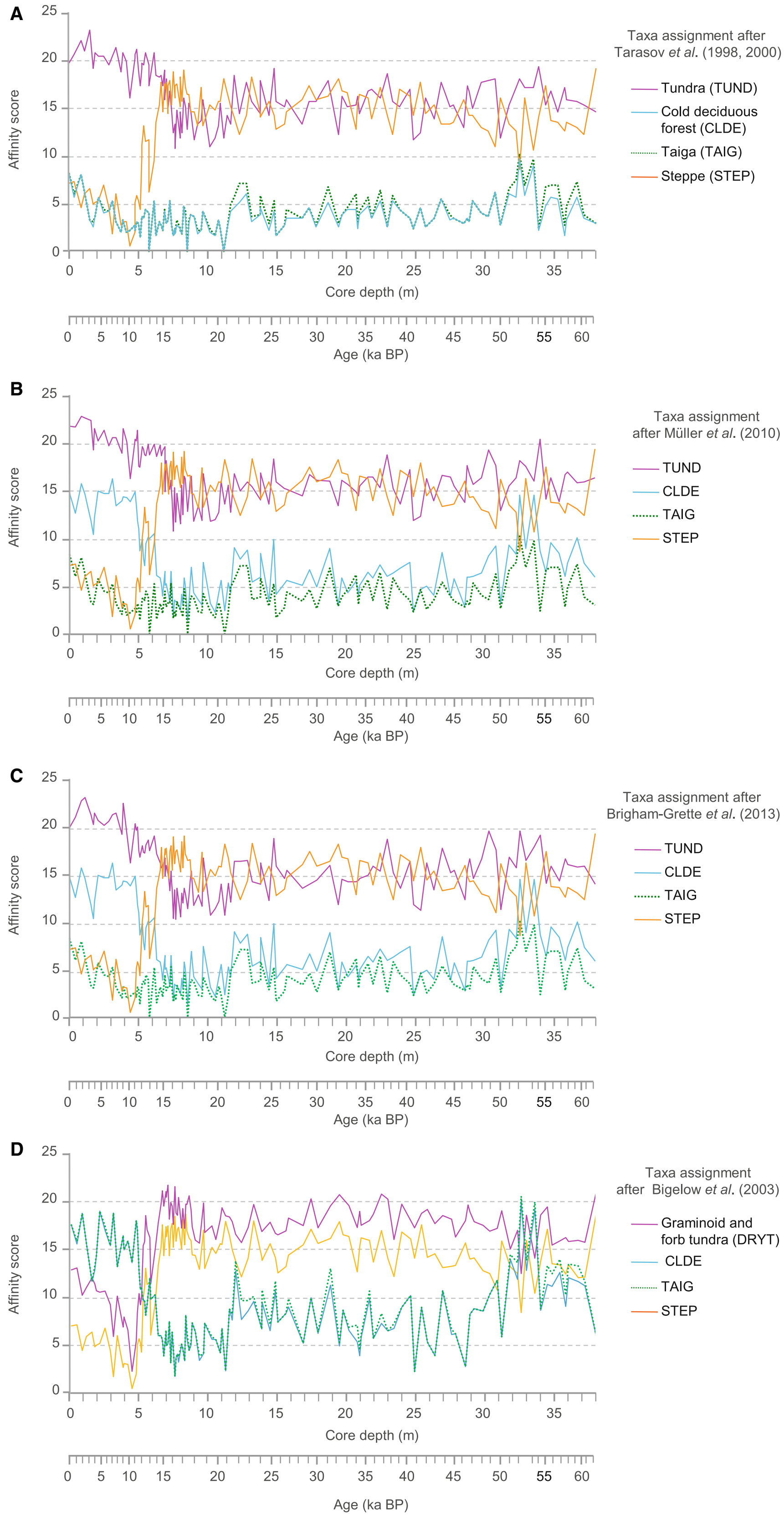

Fig. 4. Biomes reconstructed from the Co1401 pollen record, using taxa assignments of (A) Tarasov *et al.* (1998, 2000), (B) Müller *et al.* (2010), (C) Brigham-Grette *et al.* (2013) and (D) Bigelow *et al.* (2003).

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between *c*. 15.0 and 11.64 cal. ka BP (6.9 and 5 m core depth) and the absolute predominance of TUND over other biomes during the last 11.6 cal. ka BP (the uppermost 5 m of the core). Figure 4B, C shows the similarly high TUND and STEP biome scores before 15 cal. ka BP (below 6.9 m core depth) and the dominance of TUND after 15 cal. ka BP (above that depth). Both reconstructions show also relatively high scores of the cold deciduous forest (CLDE) biome, which is particularly evident for the last 11.6 cal. ka BP (the uppermost 5 m part of the core) and between *c*. 60.35 and 51.47 cal. ka BP (37–32 m depth). Figure 4D shows the highest values of the CLDE and taiga (TAIG) biomes compared to other reconstructions. The CLDE biome dominates after 11.87 cal. ka BP (above 5.13 m core depth), while the dominance of TAIG is reconstructed at the four levels between *c*. 62.0 and 52.2 cal. ka BP (37.76–32.5 m core depth). Although STEP values remain high in the middle and lower parts of the core (Fig. 4D), graminoid and forb tundra (DRYT) remain the dominant biome below 5.2 m (until *c*. 12 cal. ka BP).

Discussion and interpretation

Late MIS 4 – middle MIS 3 environments

In Lake Levinson-Lessing, sediments older than 62 cal. ka BP have been recorded only in the hydro-acoustic data but have not been recovered. However, the lack of distinct changes in the hydro-acoustic data led Lebas *et al*. (2019) to extrapolate the sedimentation rates downward, suggesting that the catchment has not been glaciated since MIS 5d–5b.

The sedimentological and geochemical proxy data from the late MIS 4 – middle MIS 3 part of the studied core show frequent turbidites and high magnetic susceptibility and Sr/Rb values reflecting intense physical weathering, catchment erosion and sediment redeposition (Lenz *et al*. 2022). This suggests that the time interval *c*. 62 to 51 cal. ka BP in the area of Lake Levinson-Lessing was associated with cold, but relatively wet conditions. These relatively wet conditions might be connected with particularly high summer insolation during this time (Berger & Loutre 1991), which probably fostered the melting of snow fields in the lake catchment and led to relatively high riverine input, sediment erosion and redeposition (Lenz *et al*. 2022).

Generally, the pollen assemblages document that open steppe- and tundra-like plant communities (mostly Poaceae, *Artemisia*, Cyperaceae) were dominant *c*. 62.0–47.8 cal. ka BP (PZ I of Fig. 3), which is in good accordance with sedimentological and geochemical data reflecting harsh climate conditions in the study area. However, rather high percentages of *Betula nana*, *Alnus fruticosa* and *Salix* suggest that environmental conditions allowed these shrubs to survive in the study area. The pollen spectra reflect a relatively warm interval between *c*. 54.0 and 47.8 cal. ka BP (early MIS 3). Biome reconstruction supports this interpretation and shows a dominance of steppe and tundra, accompanied by a relative increase in forest biome scores most pronounced between *c*. 54.0 and 51.0 cal. ka BP. The rather large amounts of ancient Pre-Quaternary pollen and spores in the sediments below 31.55 m depth (before *c*. 50.8 cal. ka BP, PZ I of Fig. 3) suggest a high degree of erosion in the lake catchment. This interpretation is in accordance with the other proxy data, which show frequent turbidite layers and high magnetic susceptibility and Sr/Rb values, suggesting intense physical weathering, catchment erosion and sediment redeposition during this time (Lenz *et al*. 2022). More intense catchment erosion and increased redeposition might be connected with seasonally increased riverine input and increased precipitation, as is evident from the build-up of the Barents–Kara Sea Ice Sheet (Svendsen *et al*. 2004; Möller *et al*. 2015, 2019). The rather common occurrence of remains of green algae colonies (mostly *Pediastrum*) in the sediments accumulated before *c*. 50.8 cal. ka BP indicates a lower lake stand and more numerous shallow water habitats (Jankovská & Komárek 2001) or a shorter distance between these habitats and the coring location.

The notable increase in the amounts of coprophilous fungi spores (mostly *Sordaria* and *Sporormiella*) in the sediments deposited after *c*. 54 cal. ka BP (early MIS 3) can be explained by a high abundance of grazing animals around the lake, and thus would suggest more favourable environmental conditions providing sufficient food resources for these animals during this interval. Simultaneously, the presence of reworked Pre-Quaternary palynomorphs drastically decrease in the studied sediments, also indicating a denser vegetation cover and relatively stable soil conditions in the lake catchment that may have led to less erosion and redeposition of sediments into the lake.

Amounts of green algae colonies are lower in the sediments accumulated between *c*. 50.8 and 47.8 cal. ka BP (PZ II of Fig. 3A), in comparison to the previous interval. This suggests a higher lake-level stand during this period resulting in fewer and/or more distant shallow-water habitats. This is in good accordance with a relatively low turbidite abundance and a higher proportion of silt and clay in the sediments, indicating a relatively calm depositional environment, far away from fluvial supply and near-shore wave action in comparison with previous time intervals (Lenz *et al*. 2022). The suggestion of a relatively high lake level between *c*. 50.8 and 47.8 cal. ka BP is also supported by the hydro-acoustic data (Lebas *et al*. 2019).

Generally, our data reflect relatively warm and humid environmental conditions that are in good agreement with ice-free and warm conditions in other parts of Eurasia at the same time (Mangerud *et al*. 2023 and references therein). Likely, the Kara Ice Sheet was very far away if it existed at all by that time.

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Middle MIS 3 – LGM environments

Percentages of *Betula nana* are significantly lower in the sediments deposited between *c*. 47.8 and 20.3 cal. ka BP (PZ III of Fig. 3A), while herb pollen percentages increase. This points to harsher environmental conditions in the study area in comparison with the previous interval. It is in good agreement with the environmental reconstructions based on plant macrofossil and pollen and DNA records from permafrost sections around Lake Taymyr (~50 km to the east of Lake Levinson-Lessing), which suggest a mosaic tundra-steppe environment in the study area during this time interval (Jørgensen *et al*. 2012). However, the numerous coprophilous fungal spores in the sediments reflect that grazing animals were common in the study area, which indirectly indicates rather rich herb communities (mostly Poaceae, Cyperaceae, *Artemisia*, Caryophyllaceae, Rosaceae, Ranunculaceae) around the lake. Plant macrofossil and DNA data document that a higher proportion of wet/mesic taxa in the vegetation existed before *c*. 36 cal. ka BP, while pioneer and/or disturbed habitats taxa prevailed after *c*. 35 cal. ka BP around Lake Taymyr (Jørgensen *et al*. 2012). Similar, rather harsh cold and dry environmental conditions were also reconstructed for the late MIS 3 and the early MIS 2 based on the pollen record from core PG1228 from Lake Levinson-Lessing (Andreev *et al*. 2003; Fig. 1D), pollen and plant macrofossil data from Cape Sabler at Lake Taymyr (Kienast *et al*. 2001; Andreev *et al*. 2003) and other palaeoenvironmental records from the Laptev Sea region (e.g. Andreev *et al*. 2002a, b, 2004, 2009, 2011; Sher *et al*. 2005; Schirrmeister *et al*. 2008 and references therein).

Gradually decreasing amounts of Cyperaceae pollen in the sediments deposited 25.5–20.3 cal. ka BP (PZ IIIb of Fig. 3A) reflect that the climate became drier during this interval. Open steppe-like vegetation with Poaceae and *Artemisia* with some tundra-like communities (*Betula* sect. *Nanae*, *Salix*, Cyperaceae and other herb taxa) dominated in the lake catchment. The biome reconstruction also suggests an open landscape covered with dry steppe and/or graminoid and forb tundra vegetation. These reconstructions are in good agreement with pollen records from the lake (Andreev *et al*. 2003) and other regional sites (e.g. Andreev *et al*. 2002a, b, 2009, 2011 and references therein). The reduced vegetation cover in the period 25.5–20.3 cal. ka BP also explains the slightly increased amounts of Pre-Quaternary pollen and spores in the sediments (PZ IIIb of Fig. 3), which probably originate from an increase in erosion processes in the lake catchment. This is in good agreement with a higher clastic proportion of the sediment composition, the sporadic presence of small pebbles and higher abundances of up to 10-cm-thick turbidite layers in MIS 2 sediments (Lenz *et al*. 2022).

Between *c*. 20.3 and 19.2 cal. ka BP (PZ IV of Fig. 3A), the amounts of Cyperaceae, *Salix* and *Betula* pollen and the scores of forest biomes are the lowest in the studied sediments, thus suggesting the coldest and driest climatic conditions since 62 cal. ka BP. The presence of coprophilous fungal spores is also strongly reduced in comparison with previous intervals. This reflects fewer grazing animals in the area and, thus, supports the suggestion that harsh environmental conditions prevailed in the region. Most likely this can be associated with the LGM. The occurrence of steppe-like vegetation with dominant steppe xerophytes and tundra cryophytes was also reconstructed for this interval based on ^{14}C-dated macrofossil remains from the Cape Sabler permafrost sections on the northern coast of Lake Taymyr (Kienast *et al*. 2001).

Increased amounts of sedge and shrub pollen and coprophilous fungi spores in the sediments deposited between *c*. 19.20 and 16.05 cal. ka BP (PZ V of Fig. 3) point to a slightly warmer and wetter climate in comparison to the LGM. The study area was dominated by open steppe- and tundra-like communities, as indicated in previous studies nearby (Kienast *et al*. 2001; Andreev *et al*. 2002a, b, 2011 and references therein).

Generally, we can conclude that environmental conditions during most of MIS 2 were not much different from MIS 3. It was a cold and continuously dry period with no pronounced climatic variability. Hampered moisture transport and stable cold conditions may be evidence of the continuous existence of the Kara Ice Sheet at that time. As suggested by Nazarov *et al*. (2022) the Kara Ice Sheet was present continuously during MIS 3 but did not reach modern land area.

Lateglacial environments

High pollen percentages of *Salix* and Cyperaceae and a gradual increase in *Betula nana* in the sediments deposited between *c*. 16.05 and 13.77 cal. ka BP (PZ VI of Fig. 3A) reflect that tundra communities with shrub willows were dominant in the area, while typical steppe communities gradually disappeared in the lake catchment, reflecting wetter and warmer climate conditions. Abundant coprophilous fungal spores in this period indicate that grazing animals were again abundant around the lake, which also points to more favourable environmental conditions. Similar changes in pollen assemblages were revealed in the PG1228 core sediments (Andreev *et al*. 2003).

The pollen assemblages that accumulated between *c*. 13.77 and 12.75 cal. ka BP (PZ VII of Fig. 3) document that shrubby tundra plant communities with dwarf birches, willow and sedges became dominant. This change, also captured by the biome reconstruction, reflects rather warm climate conditions representing the Allerød warming in the area. The palynological

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change at 13.77 cal. ka BP coincides well with a pronounced increase in total organic carbon (TOC) in core Co1401 (Fig. 2), which Lenz *et al.* (2022) related to a high sensitivity of the site to an increase in summer insolation. A strong increase in the contents of shrub pollen and a significant decrease in herb taxa pollen contents are also documented in the Lateglacial sediments from core PG1228, the Cape Sabler sections (Andreev *et al.* 2003) and pollen records from the adjacent Siberian regions (e.g. Velichko *et al.* 1997; Andreev *et al.* 2003, 2011; Tarasov & Andreev 2023 and references therein).

Between *c.* 13.77 and 12.75 cal. ka BP (PZ VII of Fig. 3), the accumulation of coprophilous fungal spores in Lake Levinson-Lessing was also lower than during the previous intervals. This decrease indicates fewer grazing animals in the lake catchment, which might be connected with a spread of wetter habitats during this period. Besides, remains of green algae colonies are almost absent in the sediments, pointing to a higher lake stand due to larger amounts of meltwater supply to the lake as a consequence of the warmer climate conditions. This coincides well with the massive deglaciation of the Putorana Plateau further south at *c.* 13.6 BP (Gromig *et al.* 2022 and references therein).

The period *c.* 12.75–11.63 cal. ka BP (PZ VIII of Fig. 3) was characterized by a decrease in birches in the local vegetation, while grass-dominated coenoses became more common again and increased amounts of coprophilous spores indicate the recurrence of numerous grazing animals in the lake vicinity. These changes and reconstructed peaks in the affinity scores of herbaceous biomes (i.e. STEP and DRYT) suggest cold and dry climatic conditions likely associated with the Younger Dryas cooling in the area. Similar fluctuations in pollen spectra are documented in the Lateglacial sediments of core PG1228, the Cape Sabler sections (Andreev *et al.* 2003) and pollen records from the adjacent Siberian regions (e.g. Velichko *et al.* 1997; Andreev *et al.* 2003, 2011; Tarasov & Andreev 2023 and references therein).

Holocene

The Lateglacial/Holocene transition in core Co1401 is reflected by a strong increase in *Betula nana* pollen percentages, disappearance of *Artemisia* and a remarkable reduction in Poaceae and other herbs in the pollen assemblages deposited between *c.* 11.98 and 11.63 cal. ka BP (PZ IX of Fig. 3). This suggests a change towards low shrub tundra with dwarf birches, willow and sedges as a consequence of warmer and wetter climate conditions. The quick response of the local vegetation to increased summer insolation coincides with a distinct increase in TOC in the sediments (Fig. 2; Lenz *et al.* 2022). This might have been connected with the large number of southward-orientated slopes in the lake catchment (Fig. 1C), where vegetation response to climate warming could have been especially prompt.

The onset of the interglacial is well reflected in the biome reconstruction results, which show a sharp increase in TUND and CLDE scores and a parallel decrease in STEP scores to an absolute minimum of about 10 cal. ka BP. The sediments that accumulated from *c.* 11.63 to 8.30 cal. ka BP (PZ X of Fig. 3) are characterized by the highest percentages of *Betula nana* (up to 72%) and *Alnus fruticosa* (up to 35%) pollen, and the highest pollen concentration of the whole core. Similar pollen assemblages are also recorded in core PG1228 from Lake Levinson-Lessing (Fig. 1D), but lack reliable age control. The presence of alder around the lake is supported by the finding of alder macrofossil remains in Early Holocene sediments north of its present distribution, close to Lake Levinson-Lessing (Andreev *et al.* 2003 and references therein). We assume that such high shrub percentages in core Co1401 reflect the maximal distribution of alder to the north. Hence, the interval *c.* 11.63–8.30 cal. ka BP represents the Holocene Thermal Maximum in the study area. The vegetation cover in the study area was similar to the southern (shrub) tundra. Alder stands were probably restricted to well-protected habitats, as is the case in the modern shrub tundra zone. Earlier studies had already evidenced that the tree line on the Taymyr Peninsula during the Early Holocene was 50–100 km further north than today (Velichko *et al.* 1997; MacDonald *et al.* 2000; Andreev *et al.* 2002a, b; Binney *et al.* 2009, 2017). At that time, the Arctic Ocean still had a weaker influence on the inner parts of Taymyr Peninsula than nowadays, because a lower sea level led to a larger distance to the coast (Velichko *et al.* 1997; Andreev *et al.* 2002a, b). Moreover, summer insolation, another important factor for the vegetation cover, was higher than at present (MacDonald *et al.* 2000).

The pollen assemblages from the sediments that accumulated between *c.* 8.3 and 4.4 cal. ka BP (PZ XI of Fig. 3) reflect that herb-tundra communities with Cyperaceae and Poaceae gradually replaced the shrubby tundra. However, scattered occurrence of shrub alder in some more protected habitats in southern parts of the study area until *c.* 4.4 cal. ka BP is possible, as percentages of *Alnus fruticosa* remained relatively high (up to 25%). Similar trends are reflected in the pollen assemblages of core PG1228 (Andreev *et al.* 2003). The gradual decrease in shrubby vegetation in the lake catchment after *c.* 8.3 cal. ka BP is most likely related to a rising sea level, resulting in a stronger influence of the Arctic Ocean and therefore, more maritime climate conditions. The onset of cooler climate conditions is also connected with declining summer insolation during this time (e.g. Wolf *et al.* 2000).

The pollen assemblages in the sediments deposited after *c.* 4.4 cal. ka BP (PZ XII of Fig. 3) reflect a further decrease in dwarf birch stands around the lake and

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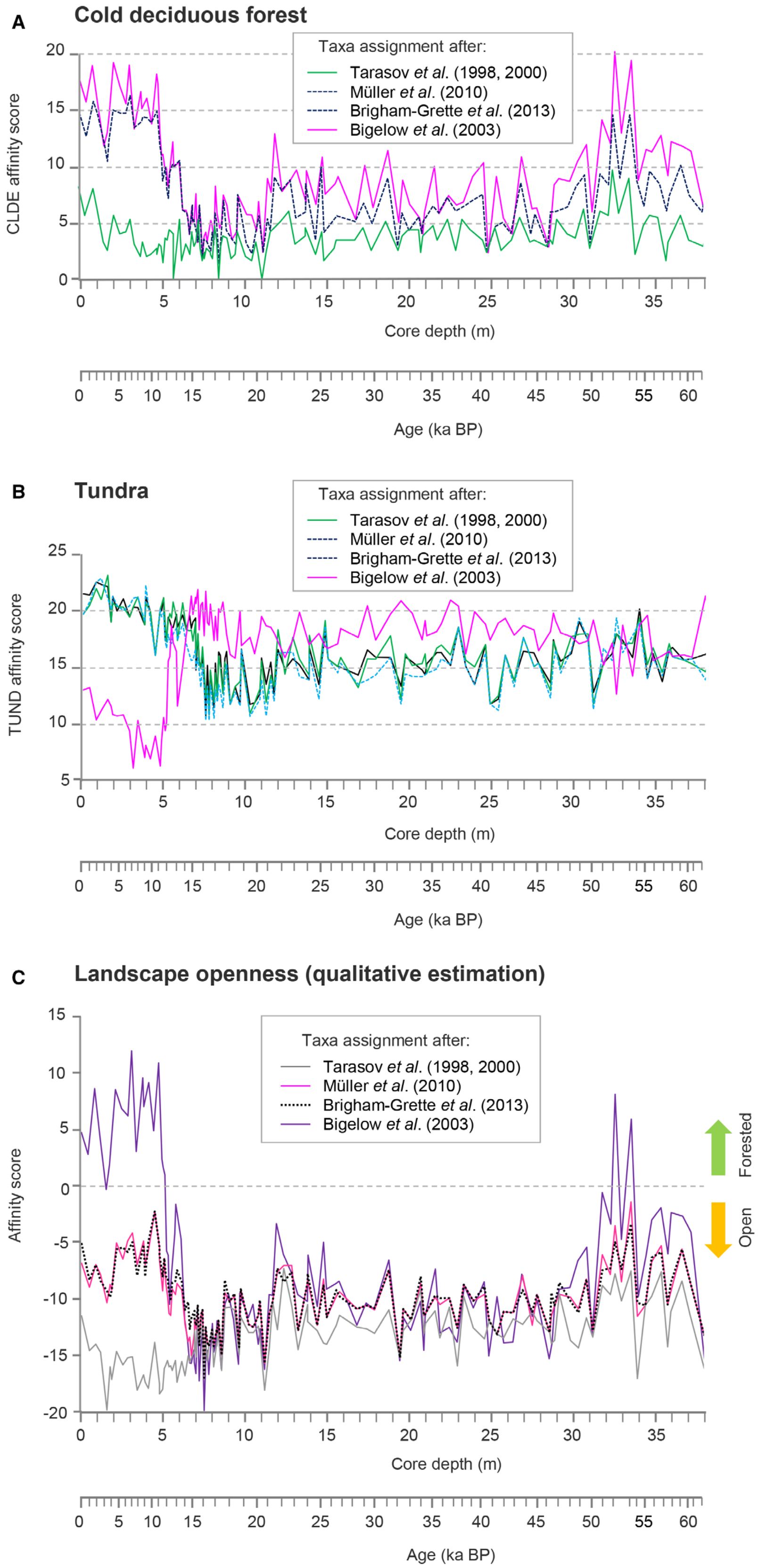

Fig. 5. Affinity scores of the cold deciduous forest (CLDE) and tundra (TUND, DRYT) biomes and landscape openness calculated using biomization schemes applied to the Co1401 pollen record. A. Cold deciduous forest biome. B. Tundra biome. C. Landscape openness.

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point to a colder climate in the study area. Increased percentages of *Salix* pollen document that willows became the only dwarf shrubs common in the lake catchment, which was predominantly occupied by herb-moss tundra communities, similar to modern ones. A noticeable drop in CLDE around 4 cal. ka BP coupled with rising TUND scores support the interpretation of a cooler but relatively humid environment. The southward retreat of the arctic tree line after 4 cal. ka BP is also documented in dated woody macrofossils from the Siberian Arctic (MacDonald *et al*. 2000; Binney *et al*. 2009, 2017). It was probably triggered by a further decrease in summer insolation associated with cooling of arctic waters and landscapes resulting in lower temperatures during the growing season.

It is notable that spores of coprophilous fungi almost disappeared in the sediments after 2 cal. ka BP indicating that grazing animals became rare in the lake vicinity. This coincides well with a further decrease in shrub pollen percentages and a shift to less dense vegetation cover, similar to the present day, shortly after 2 cal. ka BP. The modern warming of the Arctic resulting in vegetation changes in southern tundra and forest-tundra regions is not yet reflected in the uppermost pollen assemblages of the sediment core Co1401, probably due to the high-latitude location of the lake and low sedimentation rate.

Effect of the biomization matrices on the results of pollen-based biome reconstructions

Summing up the results of the quantitative biome reconstructions (Fig. 4), it becomes obvious that the main changes in regional vegetation occurred during the Pleistocene–Holocene transition, i.e. between *c*. 15 and 10.5 cal. ka BP. All reconstructions well reflect Lateglacial climatic fluctuations, including the Allerød warming and the Younger Dryas cooling, as well as the beginning of the Holocene. The most notable differences between the applied biomization schemes appear in the absolute values of the two major vegetation types, i.e. cold deciduous forest (Fig. 5A) and tundra (Fig. 5B), which in turn influence the reconstruction of landscape openness (Fig. 5C). The landscape openness allows the assessment of the different biomization schemes by comparison with the qualitative interpretation of the fossil pollen record and modern vegetation around Lake Levinson-Lessing, presented in this study. Reconstructing cold deciduous forests throughout the Holocene (Fig. 4D) seems unrealistic considering that the modern vegetation in the lake basin is the sub-Arctic and Arctic tundra mainly represented by grass, sedge and herb communities (Zhurbenko 1995; Anisimov & Pospelov 1999). On the other hand, very low (both absolute and relative) CLDE values derived from the Holocene pollen spectra (Fig. 4A) lead to the reconstructed openness of the regional landscape, the lowest in the entire Co1401 record, which is implausible. In contrast to these extreme scenarios (Fig. 4A, D), the other two biomization schemes appear to provide reliable results (Fig. 4B, C) that are in good agreement with the qualitative interpretations of the Co1401 pollen data. The differences between the two are minimal; they only concern the TUND scores (see Fig. 5B) and could be explained by the greater number of pollen taxa considered in the Brigham-Grette *et al*. (2013) study.

Conclusions

The new pollen record from the Lake Levinson-Lessing sediment core Co1401 provides a unique archive of palaeoenvironmental changes for the last 62 ka. The record is continuous, has relatively good age control and high temporal resolution, and the range of 62 cal. ka BP strongly extends the so far existing records in the region. Open tundra-steppe landscapes dominated 62.0–50.8 cal. ka BP; however, shrub birches grew in more protected habitats indicating relatively warm summers. A decrease in birch communities in the local vegetation after *c*. 47.8 cal. ka BP points to colder and drier conditions.

The new record well confirms the previous reconstructions of regional environments which were limited to the last *c*. 37 ka. Open tundra and steppe vegetation dominated the area until the Lateglacial time. The coldest and driest climatic conditions between *c*. 20.3–19.2 cal. ka BP coincide well with the LGM.

Our data documenting a relatively warm and humid climate during early MIS 3 do not demonstrate significant environmental variability during the late MIS 3 and MIS 2, which could reflect the existence of an ice sheet on the Kara Sea shelf during this time interval.

The results of qualitative and quantitative reconstructions show that the most pronounced changes (including Allerød warming, Younger Dryas cooling and the onset of the Holocene) occurred between *c*. 15.2 and 10.6 cal. ka BP with drastic increases in shrubs *c*. 11.63 cal. ka BP. The Early Holocene (*c*. 11.63–8.30 cal. ka BP) was the warmest time in the northern Taymyr Peninsula. After *c*. 8.3 cal. ka BP, the environmental conditions became gradually colder and similar to modern times after *c*. 2 cal. ka BP.

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acquisition: MM, BW, GF. All authors contributed to the article and approved the submitted version.

Data availability statement. – All data are accessible in the PANGAEA data repository (https://www.pangaea.de/) after publication.

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