











Late Pleistocene to Holocene vegetation and climate changes in northwestern Chukotka (Far East Russia) deduced from lakes Ilirney and Rauchuagytgyn pollen records

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This paper presents two new pollen records and quantitative climate reconstructions from northern Chukotka documenting environmental changes over the last 27.9 ka. Open tundra- and steppe-like habitats dominated between 27.9 and 18.7 cal. ka BP. *Betula* and *Alnus* shrubs might have grown in sheltered microhabitats but disappeared after 18.7 cal. ka BP. Although the climate was rather harsh, local herb-dominated communities supported herbivores as is evident by the presence of coprophilous spores in the sediments. The increase in *Salix* and Cyperaceae ~16.1 cal. ka BP suggests climate amelioration. Shrub *Betula* appeared ~15.9 cal. ka BP, and became dominant after ~15.52 cal. ka BP, whilst typical steppe communities drastically reduced. Very high presence of *Botryococcus* in the Lateglacial sediments reflects widespread shallow habitats, probably due to lake level increase. Shrub *Alnus* became common after ~13 cal. ka BP reflecting further climate amelioration. Simultaneously, herb communities gradually decreased in the vegetation reaching a minimum ~11.8 cal. ka BP. A gradual decrease of algae remains suggests a reduction of shallow-water habitats. Shrubby and graminoid tundra was dominant ~11.8–11.1 cal. ka BP, later *Salix* stands significantly decreased. The forest-tundra ecotone established in the Early Holocene, shortly after 11.1 cal. ka BP. Low contents of green algae in the Early Holocene sediments likely reflect deeper aquatic conditions. The most favourable climate conditions were between ~10.6 and 7 cal. ka BP. Vegetation became similar to the modern after ~7 cal. ka BP but *Pinus pumila* came to the Ilirney area at about 1.2 cal. ka BP. It is important to emphasize that the study area provided refugia for *Betula* and *Alnus* during MIS 2. It is also notable that our records do not reflect evidence of Younger Dryas cooling, which is inconsistent with some regional environmental records but in good accordance with some others.

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Continuous and well-dated palaeoenvironmental records for the Late Pleistocene are rare in arctic Chukotka. Lacustrine sediments are valuable archives as they contain various palynomorphs, which can be used for reconstruction of regional past climate and vegetation changes. Unfortunately, the accumulation rates in large and deep arctic lakes are often very low and these records often do not permit high-resolution reconstructions of vegetation and climate changes (e.g. Melles *et al.* 2012; Biskaborn *et al.* 2016). However, such records are required to address the major open palaeoenvironmental questions in arctic Chukotka, especially for the time intervals older than the Holocene. One of these open questions is the Younger Dryas (YD) cooling in Siberia. This cooling is well reflected in the Lateglacial (c. 15–11.8 cal. ka BP) records from western parts of East Siberia, but in many areas in northeastern Siberia (West Beringia) this cooling seems to be much

weaker or even negligible (e.g. Anderson *et al.* 2002; Anderson & Lozhkin 2002; Kokorowski *et al.* 2008a, b; Lozhkin *et al.* 2018 and references therein). Kokorowski *et al.* (2008a, b) reported spatially heterogeneous climate conditions during the YD in Beringia: cooling in southern Alaska, East Siberia, and some parts of northeastern Siberia; and no cooling in different locations from a number of sites from northern Siberia and Far East Russia. Moreover, the Late Pleistocene and Holocene vegetation and climate history of the region is of particular interest as detailed reconstructions of the environmental changes, such as tree line dynamics and the identification of the Lateglacial refugia, is important for the reliable reconstruction of past climate and validating climate and vegetation models. Forest invasion may lag several centuries or even millennia to the warming, related to the number of local and regional factors, e.g. distance and size of

refugia, local permafrost and fire regime (Herzschuh *et al.* 2016; Herzschuh 2020).

The poorly investigated northwestern Chukotka (Fig. 1) limits our understanding of the complex Late Quaternary climatic and environmental history in West Beringia. Here, we present new pollen records from the region. The study aimed to document the local environmental changes during the Late Quaternary and Holocene. The lakes are located in the forest-tundra ecotone, which is especially sensitive to climate fluctuations, making the new pollen records valuable paleoenvironmental archives for the Lateglacial and the Holocene.

Geographical setting

The southern study site, Lake Ilirney (latitude 67°40'N, longitude 168°35'E, altitude 421 m a.s.l.), is about 12 km long and 3.6 km wide at its widest point with a maximum depth of ~44 m. Lake bathymetry shows prominent northeastern and southwestern sub-basins with a shallower (<10 m) region proximal to the lake

outflow (Fig. 2; Vyse *et al.* 2020). The modern lake area is about 29.7 km² with a catchment area of about 1214 km² (Biskaborn *et al.* 2019a). The lake is bounded by the Anadyr Mountains to the north, with the highest elevations in the study area reaching above 1000 m a.s.l. The mountains in the area consist chiefly of silicic igneous rocks of the Cretaceous age Okhotsk-Chukotka volcanic belt composed within the Ilirney catchment of feldspar-rich granodiorites, rhyolite, trachyte and some minor sedimentary lithologies including rare occurrences of carbonate sandstones (Ispolatov *et al.* 2004). Mica-rich phyllites and Quaternary glacial deposits occur on slopes surrounding Lake Ilirney (Zhuravlev *et al.* 1999). Terminal moraines were identified in the northeastern part of the lake catchment and moraine-like deposits were found on the southern and southwestern margins of the lake that evidence glacial activity through the action of valley glaciers during MIS 4 and MIS 2 (Fig. 2; Vyse *et al.* 2020).

The lake is situated within the forest-tundra ecotone and its vicinity is characterized by rather diverse

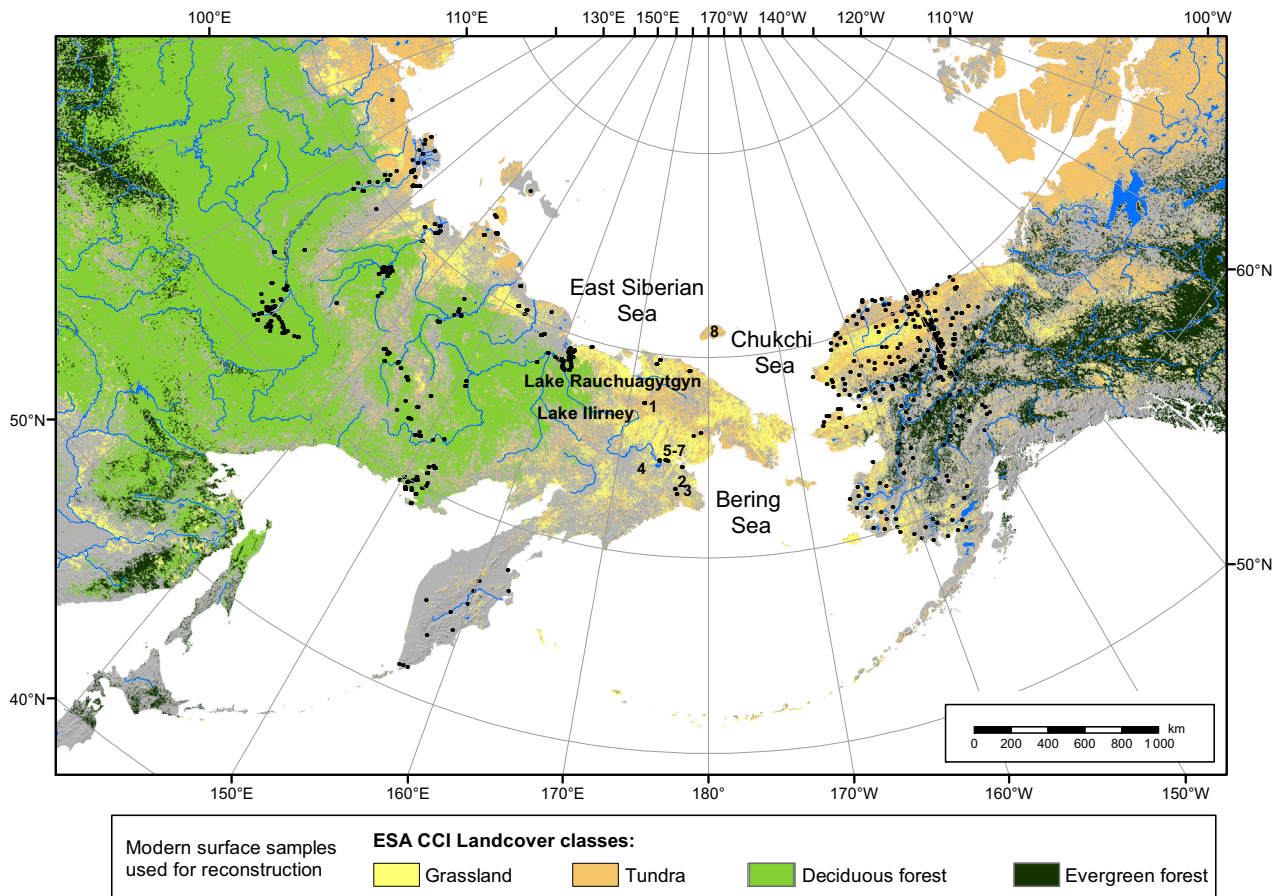


Fig. 1. Location of studied lakes and positions of mentioned sites: site 1 – Lake El'gygytyn (Lozhkin *et al.* 2007; Andreev *et al.* 2012; Melles *et al.* 2012); sites 2–3 – Patricia and Gytgykai lakes (Anderson & Lozhkin 2015); site 4 – Ledovy Obryv (Lozhkin *et al.* 2000; Kuzmina *et al.* 2011); sites 5–7 – Sunset, Malyi Kretchet and Melkoe lakes (Lozhkin & Anderson 2013); site 8 – Mamontovaya River exposure (Lozhkin *et al.* 2001). Black dots on the map are the surface pollen samples used for the climate reconstructions.

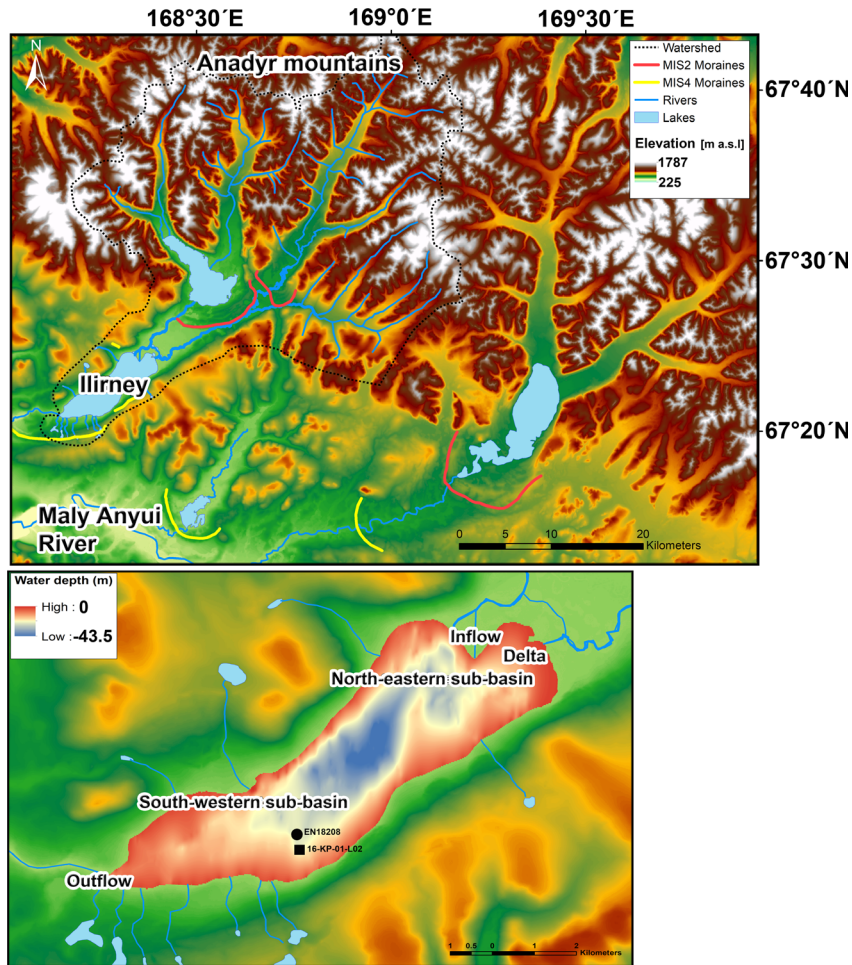


Fig. 2. Overview map of the Ilirney area. Moraines are defined from remote sensing data, field mapping by Zhuravlev *et al.* (1999), and inferences by Melles *et al.* (2005). The bathymetric model (lower panel) was created in Arcmap using inverse-distance based interpolation.

vegetation. The described vegetation patterns are different tundra and forest habitats (Shevtsova *et al.* 2020). Mountain tundra grows in harsh environments on stony and rubbly screes with a discontinuous vegetation cover (mostly *Dryas* sp., *Vaccinium uliginosum*, *V. vitis-idaea* and *Empetrum nigrum*), while tussock (*Eriophorum*) communities prevail in wetter areas. Steeper slopes around the lake are covered by *Pinus pumila*. Near the lake and westwards in the direction of the Kolyma River, *Larix cajanderi* (larch) stands comprise up to 30% vegetation cover. *Salix* (willow) and *Pinus pumila* (dwarf stone pine) are also common, whilst *Alnus fruticosa* (shrub alder) is seldom present. The moss and moss-lichen floor in these open *Larix* forests is also covered by dwarf shrubs and subshrubs (*Betula exilis*, *Vaccinium uliginosum*, *V. vitis-idaea*, *Ledum palustre*).

The northern study site, Lake Rauchuagytgyn (67°49'N, 168°44'E, 619 m a.s.l.), is about 4.35 km long with a maximum water depth of ~36 m. Bathymetry varies with a deep main basin giving way to shallower water (<6 m) close to the lake outflow. The lake area is

about 6.24 km² with a catchment area of about 215 km² (Biskaborn *et al.* 2019a). The lake is located in the northernmost part of the forest-tundra ecotone, in the Anadyr Mountains. The surrounding mountainous terrain has elevations up to 1500 m a.s.l. with a catchment geology dominated almost exclusively by silicic-intermediate extrusive volcanic lithologies including tuffs and lavas. Rare outcrops of carbonate sandstone occur within the lake vicinity.

The lake vicinity is dominated by prostrate dwarf shrubs, herb- and graminoid (mostly *Dryas octopetala* accompanied by different taxa from Poaceae, Fabaceae and Asteraceae) tundra that transits to barren land at higher elevations whilst forest tundra dominates at lower elevations along the river valleys and favourable habitats.

The region is characterized by extremely harsh climate with mean annual air temperature about -11.8 °C, mean July temperatures of +13 °C and mean January temperatures of -30 °C, short growing season (100 days per year) and low annual

precipitation of ~200 mm (Menne *et al.* 2012). The study area belongs to the continuous permafrost zone and evidence for permafrost processes is indicated by the presence of thermokarst lakes and ice-wedge polygons in the inflow regions at both lake sites.

Material and methods

Coring

Coring was carried out during a joint Russian-German expedition to the Chukotka region in summer 2016. Prior to coring, the water depth was measured from a boat using a handheld echo-sounder. The coring positions were selected at the deepest parts of the lake basins: for Lake Ilirney it was placed at 67°33.7953'N, 168°29.5433'E and for Lake Rauchuagytgyn at 67°78.876'N, 168°73.837'E. Sediment cores were retrieved by a modified hammer UWITEC gravity corer deployed from a catamaran. Precise positioning of the coring device was supported by a cable winch fixed to the catamaran. The sediment cores were collected within 3 m PVC plastic liners, cut into pieces of maximum 1 m and stored in dark and cool thermoboxes until further analyses at AWI laboratories in Potsdam, Germany. Under clean-laboratory conditions sediment cores were opened, halved and subsampled for pollen analysis every 2 cm.

Radiocarbon chronology

No dateable macrofossil remains were found in either of the analysed cores during subsampling. The Ilirney core (16-KP-01-L02) was ¹⁴C dated using 17 bulk sediment samples (Table 1). Ten samples from 16-KP-01-L02 were initially sent to the Poznań radiocarbon laboratory (Poland). These samples revealed very low carbon contents (nine samples <1 mg C), accompanied by unrealistically old radiocarbon ages, which may originate from an unsuitable carbon extraction targeting only the oldest carbon fraction. Therefore, these samples were discarded but are listed in Table 1. Eight larger samples from the 16-KP-01-L02 core were subsequently sent to the Mini Carbon Dating System (MICADAS) laboratory at AWI Bremerhaven (Germany) including an additional surface sample (EN18214 0–0.5 cm) retrieved during a follow-up expedition in 2018. To test the integrity of the age model for Lake Ilirney we used the high-resolution age model of core EN18208 from the same lake published by Vyse *et al.* (2020). As the acoustic profiles show very homogenous sediment patterns, we transferred modelled calibrated ages from EN18208 to the nearby (~250 m) 16-KP-01-L02 core using XRF-derived and additive log ratio transformed elemental K/Ti and Si/Al data (Vyse *et al.* 2020). We correlated between the

two cores using robust tie-points between distinct peaks (Fig. 3C) and reported the median ages and 2 sigma ranges from EN18208 onto 16-KP-01-L02 for comparison (Fig. 3A).

Poznań AMS radiocarbon ages were based on the alkali residuals from bulk total organic carbon (TOC) samples. MICADAS ages were also based on bulk TOC following acidification and graphitization. ¹⁴C ages were calibrated using the IntCal13 calibration curve and modelled in the package 'Rbacon' version 2.4.1 in Rstudio, version 1.2.5019 (Fig. 3; Blaauw 2010; Reimer *et al.* 2013). The Rauchuagytgyn core (16-KP-04-L19) was ¹⁴C dated using eight bulk sediment samples sent to Poznań including one surface sample of correction for the 'old carbon' effect (Table 1, Fig. 3).

Pollen

A standard HF technique was used for pollen preparation (Berglund & Ralska-Jasiewiczowa 1986). A tablet of *Lycopodium* marker spores was added to each sample to calculate total pollen and spore concentrations, following Stockmarr (1971). Water-free glycerol was used for sample storage and preparation of the microscopic slides. Pollen and spores were identified at magnifications of 400× with the aid of published pollen keys and atlases (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 fungal spores, remains of algae and invertebrates) were also identified when possible according to van Geel (2001).

At least 250–300 pollen grains were counted in each sample. Only 100 pollen grains were counted in a few samples with extremely low pollen concentration from the Lateglacial part of the Ilirney core. 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 fungal 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 diagrams (Figs 4, 5). The diagrams were zoned by a qualitative inspection of significant changes in pollen associations, pollen concentrations and occurrence of particularly indicative taxa.

Principal component analysis

A principal component analysis (PCA) was applied to the square-root transformed relative proportions for both pollen records using the RDA function from the 'vegan' package version 2.5.6 (Oksanen *et al.* 2019) in order to portray the major structure in the multivariate data set. The samples are pooled using the same zones as

Table 1. Radiocarbon and Intcal13 calibrated ages derived from bulk TOC samples from cores 16-KP-01-L02_L3 (Lake Ilirney) and 16-KP-04-L19_L2 (Lake Rauchaugytgyn). Samples with the prefix ‘Poz’ were dated at the Poznań radiocarbon laboratory, Poland, while samples with prefix ‘AWI’ were dated at the MICADAS laboratory, Germany. Ages marked with * were used for age modelling. Poznań dates from Lake Ilirney were discarded because of too low carbon contents.

| Sample ID | Depth (cm) | Lab. ID | ¹⁴ C age and error (a BP) | Reservoir corrected, calibrated age (cal. a BP) with minimum and maximum age range | Dating remark |
|--------------------------------|------------|--------------|--------------------------------------|--|---------------|
| Lake Ilirney core | | | | | |
| EN18214 surface | 0–0.5 | AWI-3754.1.1 | 1721±28* | | – |
| 16-KP-01_L02_L3 | 0–1 | Poz-101663 | 8300±80 | | 0.1 mg C |
| 16-KP-01_L02_L3 | 6–8 | AWI-4278.1.1 | 5950±25 | 4748 (4530–4965) | – |
| 16-KP-01_L02_L3 | 6–8 | Poz-101738 | 9910±50 | | 0.8 mg C |
| 16-KP-01_L02_L3 | 19–20 | AWI-4279.1.1 | 6605±29* | 5630 (5365–5796) | – |
| 16-KP-01_L02_L3 | 20–21 | Poz-92932 | 11 530±60 | | 0.8 mg C |
| 16-KP-01_L02_L3 | 58–60 | AWI-4280.1.1 | 9562±34* | 8733 (8519–9045) | – |
| 16-KP-01_L02_L3 | 60–61 | Poz-92933 | 14 410±90 | | 0.6 mg C |
| 16-KP-01_L02_L3 | 88–89 | Poz-105336 | 14 190±90 | | 0.2 mg C |
| 16-KP-01_L02_L3 | 98–100 | AWI-4281.1.1 | 11 414±37* | 11 188 (10 817–11 399) | – |
| 16-KP-01_L02_L3 | 100–101 | Poz-92934 | 15 350±80 | | – |
| 16-KP-01_L02_L3 | 118–120 | Poz-105337 | 10 020±210 | | 0.4 mg C |
| 16-KP-01_L02_L3 | 137–138 | Poz-92936 | 19 220±100 | | 0.7 mg C |
| 16-KP-01_L02_L3 | 138–140 | AWI-4282.1.1 | 15 259±47* | 16 268 (15 550–16 764) | – |
| 16-KP-01_L02_L3 | 185–186 | Poz-92937 | 23 540±350 | | 0.2 mg C |
| 16-KP-01_L02_L3 | 186–188 | AWI-4283.1.1 | 23 102±72* | 25 453 (23 940–26 125) | – |
| 16-KP-01_L02_L3 | 228–230 | AWI-4284.1.1 | 24 546±62* | 27 619 (27 119–27 998) | – |
| 16-KP-01_L02_L3 | 235–236 | Poz-92938 | 28 680±350 | | 0.4 mg C |
| Lake Rauchaugytgyn core | | | | | |
| 16-KP-04-L19-L2 | 0–0.5 | Poz-105349 | 1030±30* | | 0.5 mg C |
| 16-KP-04-L19-L2 | 20–21 | Poz-92947 | 2125±30* | 1005 (864–1169) | – |
| 16-KP-04-L19-L2 | 60–61 | Poz-101739 | 3680±30* | 2780 (2531–2931) | – |
| 16-KP-04-L19-L2 | 110–111 | Poz-92992 | 5560±35* | 5121 (4874–5329) | – |
| 16-KP-04-L19-L2 | 160–161 | Poz-101850 | 6390±35* | 6192 (6001–6348) | – |
| 16-KP-04-L19-L2 | 202–203 | Poz-92993 | 7140±40* | 7094 (6893–7283) | – |
| 16-KP-04-L19-L2 | 249–250 | Poz-101852 | 9120±50* | 8736 (8390–8979) | – |
| 16-KP-04-L19-L2 | 290–291 | Poz-92995 | 9290±50* | 9389 (9166–9571) | 0.6 mg C |

those used for the pollen diagrams for both sites. Principal component (PC) 1 and 2 axis scores were extracted and visualized in biplots. For better visibility, only the names of the taxa that explained most variance in the PCAs are presented (Figs 6, 7).

Climate reconstructions methods

Climate reconstructions were based on a modern pollen training data set that was selected from sites within a 2000-km radius around Lake Ilirney (1037 modern sites) from various sources (Whitmore *et al.* 2005; Davis *et al.* 2020; Fig. 1). The area from which modern pollen analogues were taken is restricted because same pollen taxa can represent different plant taxa in different regions; however, the area should also be not too small so as to cover a reasonably large gradient (for details see Cao *et al.* 2017; Herzsuh *et al.* 2019). Thus, the selected 2000-km radius area covering East Siberia (West Beringia) as well as Alaska (East Beringia), which were connected during the glacial period, is a reasonable compromise. The created data set was taxonomically harmonized with the fossil taxa (Table S1). For all modern pollen sites the corresponding mean July

temperature (T_{July}) and annual precipitation (P_{ann}) were extracted from WorldClim 2 data (Fick & Hijmans 2017; <https://www.worldclim.org/>) covering a T_{July} range from 0.9 to 18.7 °C and P_{ann} range from 109 to 1058 mm. The climate reconstructions were performed using the modern analogue technique (MAT) transfer function (Overpeck *et al.* 1985), taking seven analogues in the modern pollen training data set into account by using the MAT-function in the *rioja* package (version 0.9-21, Juggins 2019) for R (R Development Core Team 2010). In addition, a statistical significance test according to Telford & Birks (2011) was performed for the reconstruction using the randomTF-function in the *palaeoSig* package (version 2.0-3; Telford 2019). T_{July} and P_{ann} were tested as single variables. Furthermore, the significance of T_{July} reconstruction was tested with taking P_{ann} as conditional variable (and vice versa) in the inherent constrained ordination.

Estimation of the root mean square error of prediction (RMSEP) is derived from cross-validation of the calibration set. It yielded a RMSEP of 2.04 °C for T_{July} and of 94.32 mm for P_{ann} . These prediction errors point to the potential range of the absolute biases; however, the relative changes in climate have likely much lower biases.

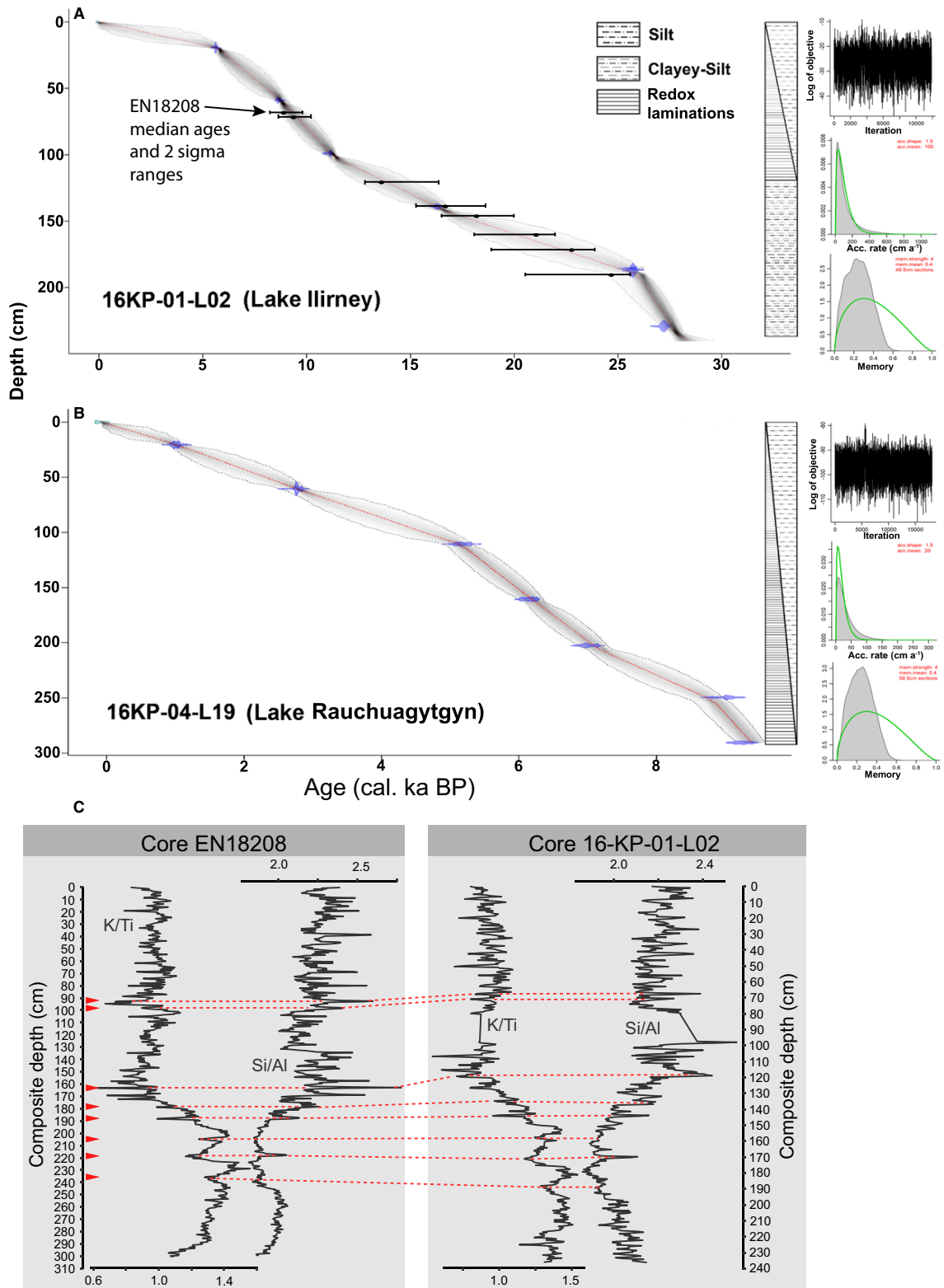


Fig. 3. Age-depth models for sediment cores 16-KP-01-L02 (A – Lake Ilirney) and 16-KP-04-L19 (B – Lake Rauchaugytgn) modelled using package ‘rbacon’ (Blaauw 2010). Calibrated and modelled ages are based on the Intcal13 calibration curve (Reimer *et al.* 2013). Samples dated in Poznań as well as one sample (from 6–8 cm depth) dated in MICADAS were not included in the age model for Lake Ilirney. Correlation between core EN18208 and 16-KP-01-L02 (C) based on XRF-derived and ALR transformed elemental data (Vyse *et al.* 2020) to compare median ages and sigma ranges between the cores shown in (A) and validate established chronologies.

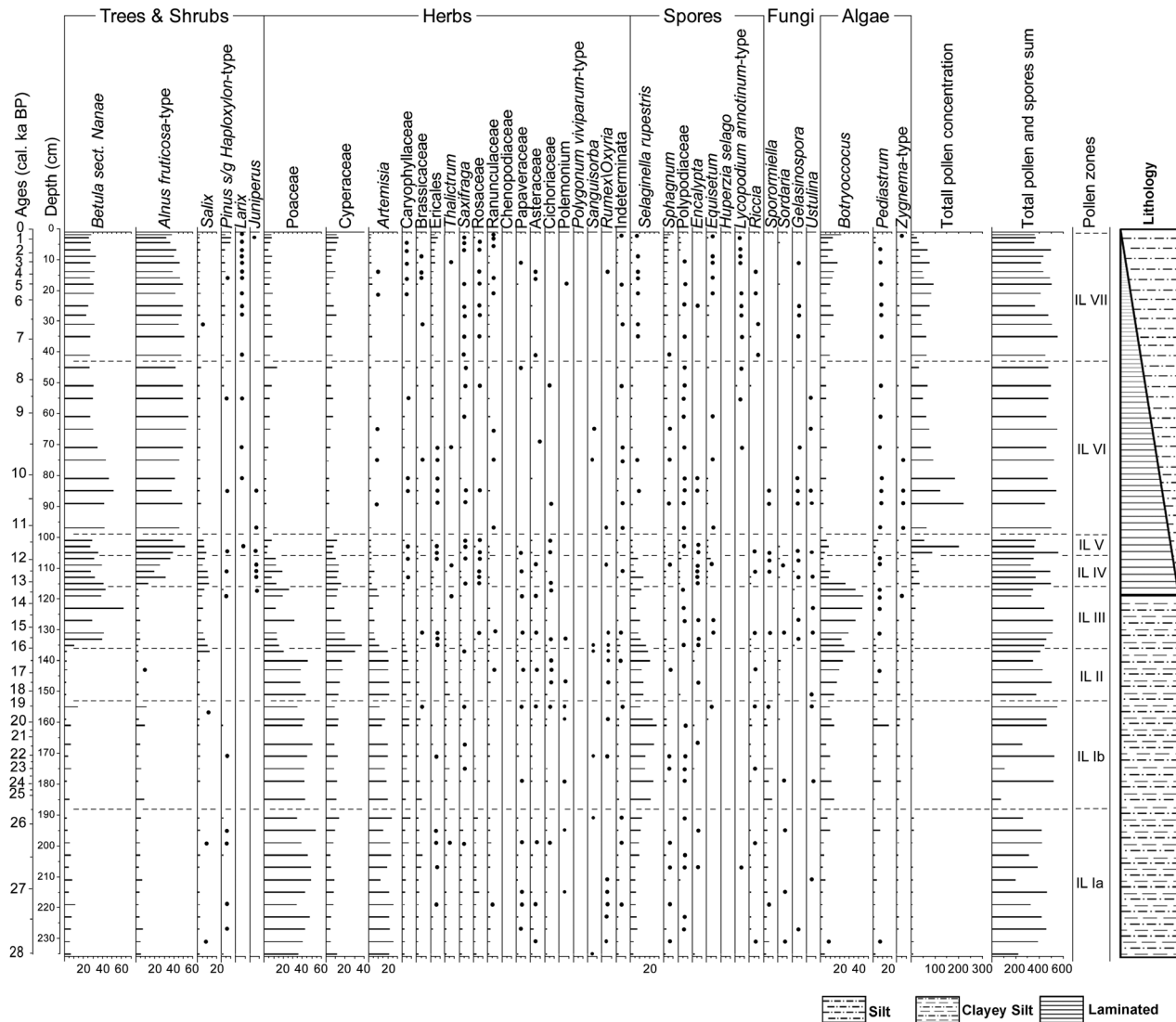


Fig. 4. Percentage pollen, spore, and non-pollen-palynomorph diagram of the sediment core 16-KP-01-L02. The dots signify that percentages of taxa are <1%.

This means that maybe the climate time series needs to be shifted to the left or right by about the RMSEP. Trends between sections rather than fluctuations between single samples should be interpreted because the MAT technique is sensitive to the availability of analogues. The inclusion or exclusion of single modern samples during the MAT routine may artificially cause some fluctuations, which may increase the already low signal-to-noise ratio of pollen data e.g. originating from the abundance changes of high pollen producers and the fact that pollen data are a ‘closed’ data set (i.e. percentage data where changes of one taxon affects all other taxa). See Birks & Seppä (2004) for further discussion of the concept and potential biases of pollen-based climate reconstructions.

For plotting of the reconstructions we applied a Gaussian smoother with 2000 years smoothing length

on irregularly sampled time series using the *CorIrregTimer*-function from the *corit* R software package, version 0.0.0.9000 (Reschke *et al.* 2019). The smoothed time series were plotted on top of the reconstructed time series in red colour for T_{July} and in blue colour for P_{ann} .

Results

Iirney core (16-KP-01-L02)

Core lithology. – The core is 235 cm in length and is dominated mainly by silty sediments containing irregularly distributed, millimetre to centimetre size vivianite aggregations. This mineral was identified visually by its distinctive change from white to blue coloration, and may have formed diagenetically below the water–sediment interface due to reducing conditions at low sedimentation

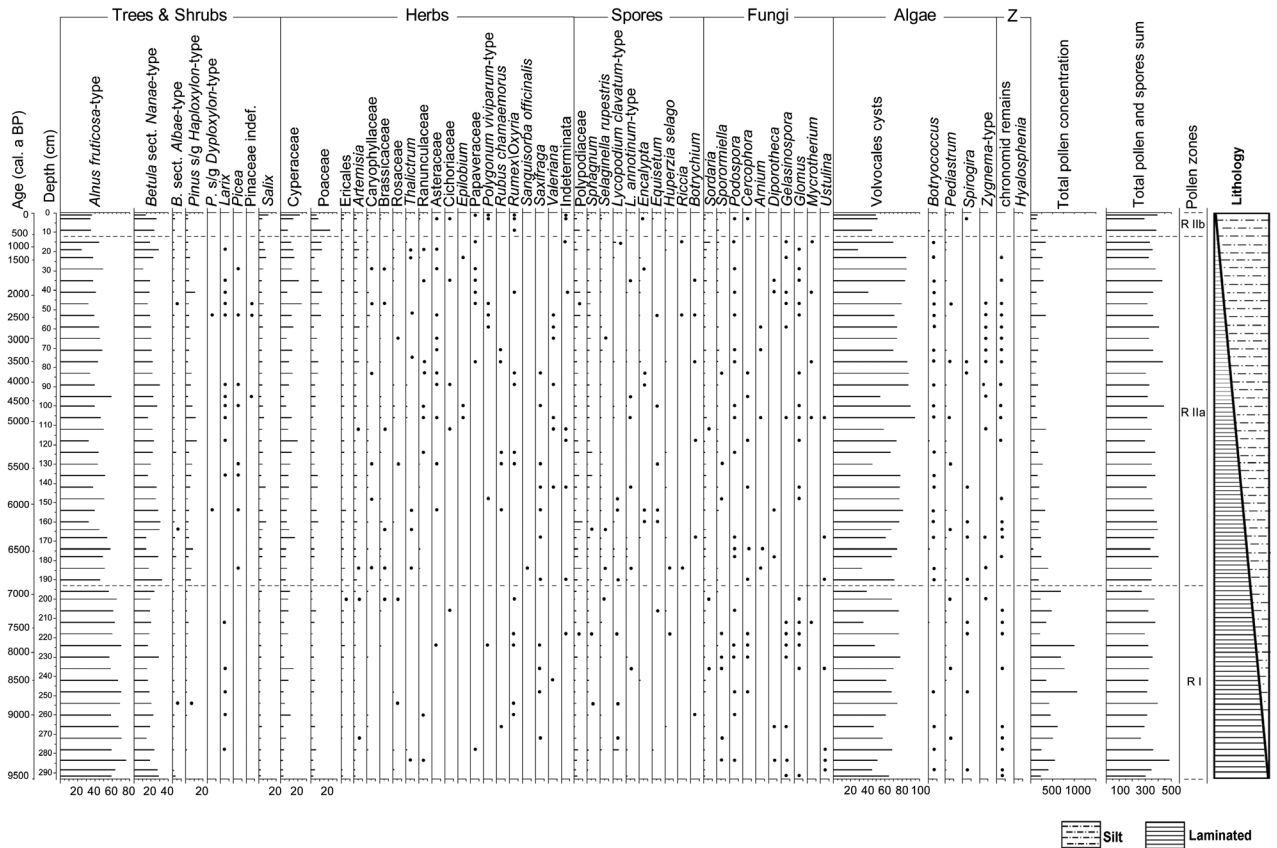


Fig. 5. Percentage pollen, spore, and non-pollen-palynomorph diagram of the sediment core 16-KP-04-L19. The dots signify that percentages of taxa are <1%.

rates (Biskaborn *et al.* 2013b). Clayey silt forms the dominant lithology between 235 and 120 cm. The upper 120 cm consists of grey-brownish silty sediments of coarser grain size and is characterized by irregularly spaced laminations and higher total organic content.

Age/depth model. – To establish an age-depth model for core 16-KP-01-L02 0–1 cm from Lake Ilirney we used the radiocarbon dating results of eight samples from MICADAS (Table 1). Dating of surface sediment samples from Lake Ilirney yielded a ^{14}C age of 1.721 ka (EN182140–0.5 cm). We used this value to represent the old carbon effect at Lake Ilirney. This date was subtracted from all 16-KP-01-L02 radiocarbon dates prior to calibration (Table 1) under the mandatory assumption of a temporally constant reservoir effect (Biskaborn *et al.* 2012; Philippsen 2013). Though the reservoir effect may not be uniform with age, without the application of alternative comparative dating techniques, this cannot be effectively constrained. We found that the distributions of reservoir corrected ages represent realistic age-depth relationships without reversals. However, we treated the sample at 6–8 cm depth (5950±25 ^{14}C a BP) as an outlier because of too low radiocarbon concentra-

tions. XRF derived elemental data allowed a robust correlation between the published age model from the nearby (~250 m) core EN18208 (Vyse *et al.* 2020) and core 16-KP-01-L02 used here (Fig. 3C). The approach of correlation is valid considering the generally homogeneous pattern of sedimentation revealed by acoustic studies at Lake Ilirney (Vyse *et al.* 2020). Eight robust tie-points allowed transfer of median ages and respective 2 sigma ranges from EN18208 onto the age model established for 16-KP-01-L02. All EN18208 median ages fit into the 2 sigma ranges modelled for 16-KP-01-L02 and thus validate the developed chronology. The minor change in sedimentation rate as observed at around 20 cm is probably related to the overall error of the dating strategy and the necessary assumption of a constant old carbon effect over time. It is possible that around 20 cm depth true ages can be several hundred years younger, which should be taken into account when interpreting the data. The old carbon corrected and calibrated samples show a maximum age at the 235 cm depth of 27.9 cal. ka BP. Mean accumulation rate calculated from the age/depth model was 0.015 cm a^{-1} with predominantly low values ($0.006\text{--}0.011 \text{ cm a}^{-1}$) between ~190 and 101 cm (26.03–11.36 cal. ka BP).

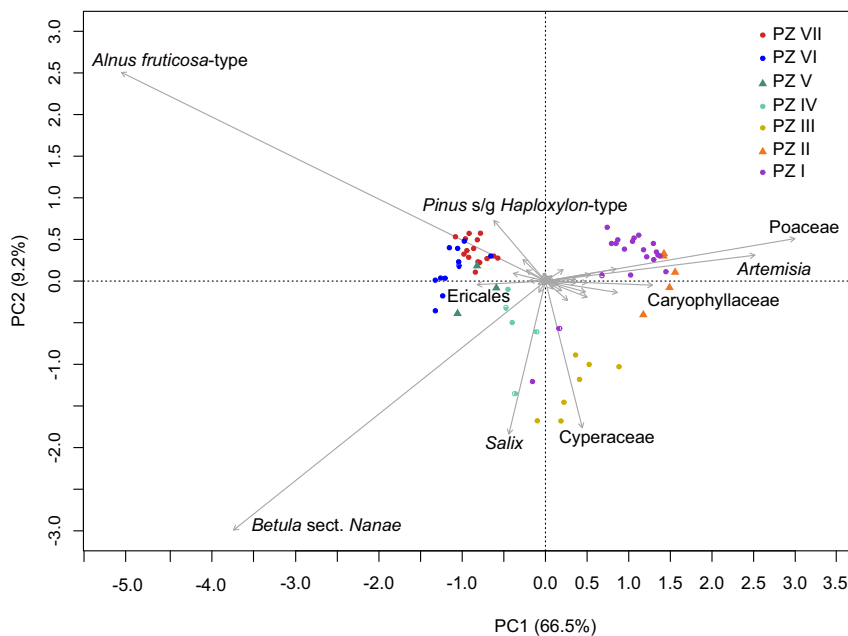


Fig. 6. PCA biplot of pollen taxa detected in the sediment samples from Lake Ilirney. Only the nine taxa explaining the most variance are shown. Samples are coloured according to the corresponding zone. The explained variances of the two principal components (PC1 and PC2) are shown in parentheses.

Pollen stratigraphy. – A total of 66 samples were analysed for pollen and NPPs. The pollen spectra (Fig. 4) were visually subdivided into seven main pollen zones (IL). IL I (235–153 cm, *c.* 27.90–18.65 cal. ka BP) is dominated by pollen of *Poaceae*, *Cyperaceae* and *Artemisia*. Relatively high percentages of *Betula sect. Nanae* (up to 12%) and *Alnus fruticosa* (up to 8%) pollen are also characteristic for IL I. Spores of *Selaginella rupestris* and remains of green algae colonies (*Pediastrum* and *Botryococcus*) are also very common in the spectra. Pollen concentration is rather low (up to 4350 grain g⁻¹). IL I can be subdivided into two subzones: IL Ib (187–153 cm, *c.* 25.45–18.65 cal. ka BP) differs from IL Ia by higher percentages of *Selaginella rupestris* (up to 27%) spores and remains of *Botryococcus* (up to 18%).

IL II (153–136 cm, *c.* 18.65–15.90 cal. ka BP) is notable by significantly lower percentages of *Betula sect. Nanae* (up to 3%) and *Alnus fruticosa* (up to 2%) pollen as well as spores of *Selaginella rupestris* (up to 17%). The uppermost pollen spectra demonstrate a decrease in *Poaceae* pollen percentage (up to 26%), while percentages of *Salix* (up to 13%) and *Cyperaceae* (up to 38%) pollen and *Selaginella* spores (up to 20%) as well as remains of *Botryococcus* (up to 36%) increased.

IL III (136–116 cm, *c.* 15.9–13.2 cal. ka BP) is dominated by *Betula sect. Nanae* (up to 63%) pollen, while percentages of herb pollen (especially *Poaceae* – up to 18%, *Cyperaceae* – up to 15% and *Artemisia* – up to 8%) are reduced. Numerous remains of *Botryococcus* colonies (up to 47%) are also very characteristic for the zone. Pollen concentration is higher (up to

12 910 grain g⁻¹) in IL III in comparison to the lower zones.

IL IV (116–106 cm, *c.* 13.20–11.84 cal. ka BP) is notable by an increase in *Alnus fruticosa* percentages (up to 42%) and high percentages of *Betula sect. Nanae* (up to 43%) and *Salix* (up to 13%), while percentages of herb pollen and remains of *Botryococcus* colonies decreased. Pollen concentration is higher than in IL III (up to 34 170 grain g⁻¹).

IL V (106–99 cm, *c.* 11.84–11.19 cal. ka BP) is notable by a further increase in *Alnus fruticosa* percentages and high percentages of *Betula sect. Nanae* and *Salix*, while percentages of herb pollen and *Selaginella* spores decreased. Pollen concentration is significantly higher than in IL IV (up to 198 630 grain g⁻¹).

The pollen concentration is the highest (up to 219 560 grain g⁻¹) in IL VI (99–43 cm, *c.* 11.19–7.53 cal. ka BP), which is also notable for high amounts of *Alnus fruticosa* and *Betula sect. Nanae* pollen. Single pollen grains of *Larix* and *Pinus* are also characteristic for this zone.

The uppermost zone, IL VII (43–0 cm, *c.* 7.53–0 cal. ka BP), demonstrates the higher percentages of *Pinus* and herb taxa pollen as well as remains of *Botryococcus* colonies; however, *Alnus* and *Betula* pollen dominate the pollen assemblages. The pollen concentration is lower than in IL VI (up to 93 240 grain g⁻¹).

PCA results. – The PCA biplot of the first two axes (Fig. 6) explains 75.73% of the variance in the pollen data set, supporting the zonation of the pollen assemblages. Samples from IL I are situated mostly in the top

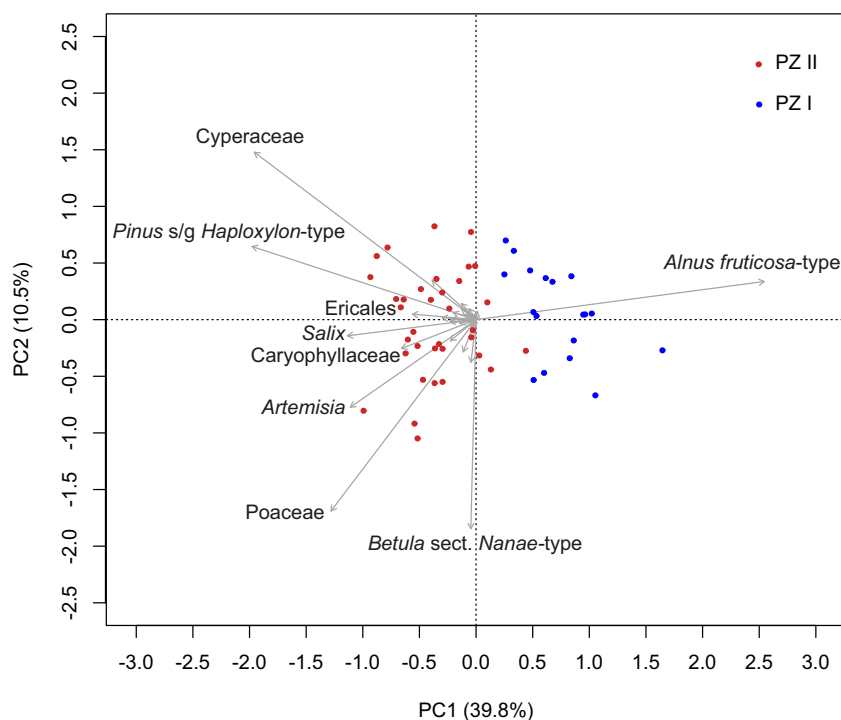


Fig. 7. PCA biplot of pollen taxa detected in the sediment samples from Lake Rauchaugytgyn. Only the nine taxa explaining the most variance are shown. Samples are coloured according to the corresponding zone. The explained variances of the two principal components (PC1 and PC2) are shown in parentheses.

right quadrant and the main pollen taxa are Poaceae, *Artemisia* and Caryophyllaceae. The samples from IL II are also located within the right quadrants, spread across PC2, and mixed with samples from IL I. Samples from IL III are mostly located in the bottom right quadrant and characterized by the percentages of Cyperaceae and *Salix*. Samples from IL IV are located in the bottom left quadrant and represented by the percentages of *Salix*, Cyperaceae as well as *Betula* sect. *Nanae*. Samples from IL V are located in the left quadrants, spread across PC2 and mixed with samples from IL IV, IL VI and IL VII. IL V samples are represented by pollen of Ericales, *Betula* sect. *Nanae* and *Alnus fruticosa*. Samples from IL VI and IL VII are located in the top left quadrant and characterized by the percentages of *Alnus fruticosa*, *Pinus s/lg Haploxyylon*, and Ericales pollen types.

Climate reconstructions. – Climate reconstructions were performed for the Ilirney core. Comparison of fossil pollen data with the modern training data revealed poor analogues before the Holocene but very good analogues for the Holocene period (Fig. 8). The reconstructed T_{July} fluctuated between 7.7 and 9.4 °C from 27.90 to 15.72 cal. ka BP (Fig. 9A). A strong temperature increase (~1.6 °C) occurred around 15.72–15.47 cal. ka BP. The general temperature increase continued to the end of the Holocene Thermal Maximum (HTM, ~10.6–

7.0 cal. ka BP), with T_{July} rising from 11.4 to 13.3 °C. There are three cooler episodes: at ~14.70 (10.1 °C), ~13.38 (10.2 °C) and ~12.31 (11.0 °C) cal. ka BP. After ~7 cal. ka BP T_{July} decreased slightly again except for one period around 1.33 cal. ka BP, when temperatures reached a peak of 13.5 °C.

P_{ann} ranged from 200 to 250 mm between *c.* 27.9 and 14.2 cal. ka BP (Fig. 9B). A stronger rise in P_{ann} (up to 282 mm) occurred around 14.7 cal. ka BP. Climate conditions gradually became more humid during the Lateglacial as indicated by increasing P_{ann} values. The highest precipitation was reconstructed for the HTM, when P_{ann} values reached 343.5 mm around 8.9 cal. ka BP. After the HTM the climate became drier again, but with strong fluctuations in P_{ann} , reflecting wetter and drier periods.

According to cross-validation results of the calibration set, the T_{July} reconstructions ($r^2 = 0.56$) are more reliable compared with the P_{ann} reconstructions ($r^2 = 0.31$). The T_{July} reconstruction was significant (according to Telford & Birks 2011) when included as the single variable in the significance test ($p < 0.001$) as well as when including the precipitation reconstruction as a conditional variable ($p < 0.001$). P_{ann} was only significant when included as the single variable ($p < 0.04$) but not when taking the T_{July} reconstruction as a conditional variable ($p < 0.1$).

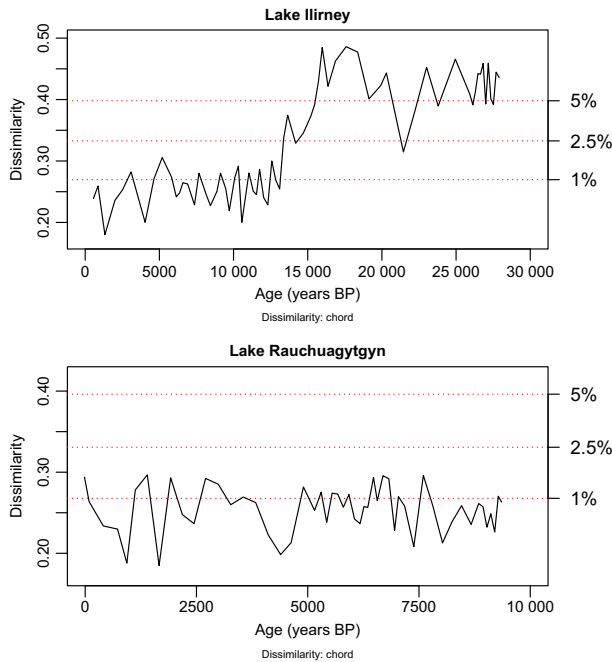


Fig. 8. Dissimilarity (chord distance) between modern pollen assemblages and fossil pollen assemblages from Lake Ilirney and Lake Rauchaugytyn. Dotted red lines indicate poor (<5%), good (<2.5%) and very good (<1%) analogues as derived from pair-wise comparisons of the modern calibration set.

Rauchaugytyn core (16-KP-04-L19)

Core lithology. – The core is characterized by homogeneous brown-coloured laminated silts similar to those observed in the Holocene part of the Ilirney core (16-KP-01-L02), which also contain irregularly distributed

vivianite aggregations. The core sediments show a slight darkening towards the sediment surface reflecting increasing total organic carbon content.

Age/depth model. – A surface sediment age of 1.03 cal. ka BP found for Lake Rauchaugytyn was subtracted from all radiocarbon dates, applying an identical procedure to 16-KP-01-L02. Due to the higher carbon content of dated radiocarbon samples (six samples >1 mg C), samples were not dated additionally at the MICADAS laboratory and the final age model was constructed from Poznań dated samples. The old carbon corrected and calibrated samples show an age at the 16-KP-04-L19 core base of 9.47 cal. ka BP (Fig. 3B). Mean accumulation rate for core 16-KP-04-L19 was 0.044 cm a^{-1} and thus approximately three times the accumulation rate observed for core 16-KP-01-L02.

Pollen stratigraphy. – A total of 53 samples were analysed for pollen and NPPs. The pollen spectra can be subdivided into two main pollen zones (Fig. 5). R I (290–193 cm, c. 9.47–6.89 cal. ka BP) is dominated by *Alnus fruticosa* and *Betula* sect. *Nanae* pollen with some Poaceae and Cyperaceae. Pollen concentration is very high (up to $107\,010 \text{ grain g}^{-1}$) in the zone.

R II (193–0 cm, c. 6.89–0 cal. ka BP) is also dominated by *Alnus* and *Betula* pollen, but increased amounts of *Pinus* and *Salix* pollen are characteristic for this zone. Percentages of Poaceae, Cyperaceae and *Artemisia* pollen as well as spores of Polypodiaceae and *Sphagnum* are higher than in R I. Pollen concentration is significantly lower (up to $32\,120 \text{ grain g}^{-1}$) than in R I. R II can also be subdivided into two subzones: R IIa (193–12 cm,

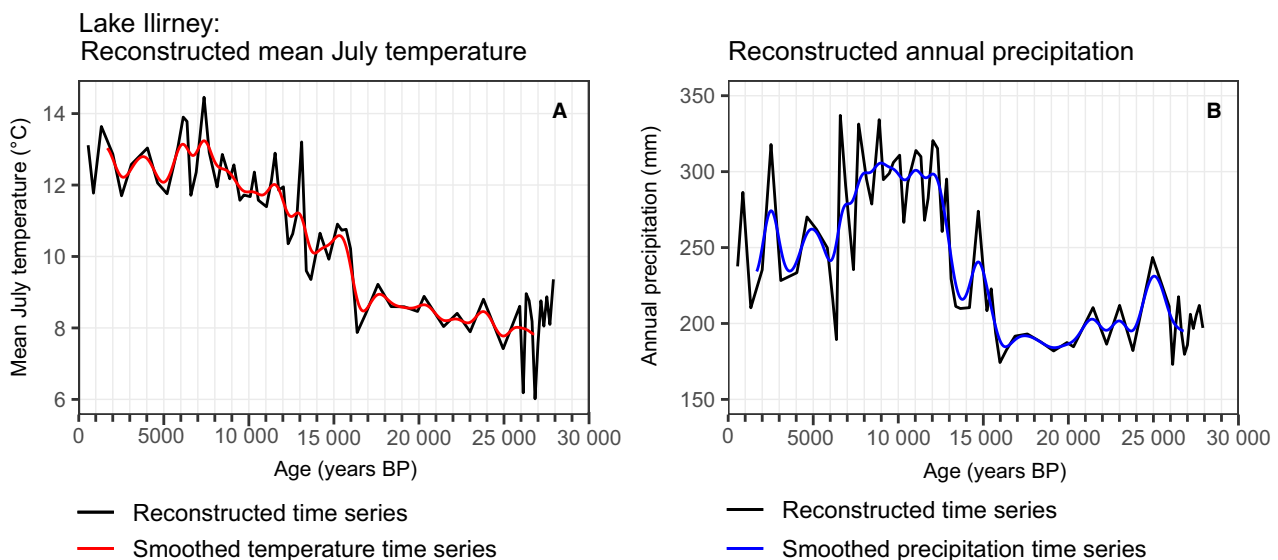


Fig. 9. Climate parameters reconstructed with the MAT transfer function (2000 km) from Lake Ilirney pollen record: July temperature (A) and annual precipitation (B).

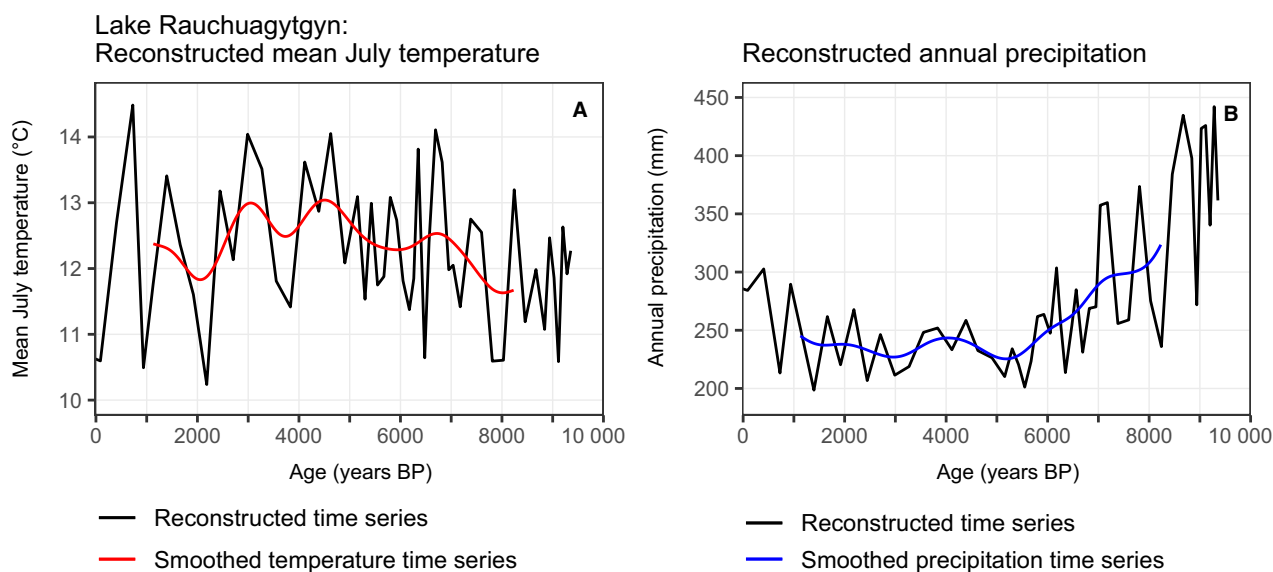


Fig. 10. Climate parameters reconstructed with the MAT transfer function (2000 km) from Lake Rauchuagytgyn pollen record: July temperature (A) and annual precipitation (B).

c. 6.89–0.32 cal. ka BP) differs from R IIb by slightly higher percentages of *Pinus* pollen and spores of coprophilous fungi.

PCA results. – The PCA biplot of the first two axes (Fig. 7) explains 50.29% of the variance in the data set. Samples from R I are spread across PC2 and are located mostly in the right quadrants. R I is characterized by the presence of *Alnus fruticosa*. The R II samples, located in the left quadrants, are spread across PC2 and represented by *Salix*, *Pinus* s/g *Haploxydon*, *Cyperaceae*, *Artemisia* and *Poaceae* pollen. The presence of pollen types from *Rosaceae* or *Betula* sect. *Nanae* does not discriminate between the two zones.

Climate reconstructions. – Comparison of fossil pollen data with the modern training data revealed very good analogues (Fig. 8). The reconstructed T_{July} values for the Rauchuagytgyn core range between 11.1 and 13.3 °C with a mean value of 12.3 °C for the whole time interval (Fig. 10A). T_{July} values were 11.4–12.6 °C between c. 9.36 and 8.03 cal. ka BP. A decrease (11.1 °C) in T_{July} occurred around 7.81 cal. ka BP, representing the lowest temperature value of for the entire time interval. T_{July} increased up to 13.3 °C at c. 6.82 cal. ka BP and gradually decreased again reaching 12.1 °C ~5.3 cal. ka BP. T_{July} increased towards a maximum of 13.3 °C at c. 4.63 cal. ka BP with a subsequent cooling with strong fluctuations during the Late Holocene, after c. 4.2 cal. ka BP.

Reconstructed P_{ann} values fluctuated strongly between c. 9.36 and 7.04 cal. ka BP, reaching the highest reconstructed value of 379.6 mm at 7.18 cal. ka BP and

the lowest value of 266.5 mm at 7.6 cal. ka BP (Fig. 10B). Thereafter until 1.66 cal. ka BP, P_{ann} became more stable showing lower fluctuations within the range of 239.1 to 281.3 mm around the mean value of 260.5 mm, with a significantly higher peak of 313.1 mm at 4.39 cal. ka BP. Subsequently, climate conditions became slightly wetter again, reaching its highest level of 297.9 mm at 0.4 cal. ka BP. For Lake Rauchuagytgyn only the reconstructed P_{ann} is significant at p -value level <0.09 when P_{ann} reconstruction was included as a single variable.

Interpretation and discussion

Chronological limitations

The ^{14}C -based age/depth models presented for lakes Rauchuagytgyn and Iirney are among the first to be developed for northern Chukotkan glacial lakes and as such can provide valuable information regarding the timing of major climatic changes. The lack of age-reversals within both age/depth models from both lakes suggests continuous lacustrine sedimentation over the studied time periods. The broadly consistent timing of major vegetation and climate changes at both lake sites as well as of palynological data from other Chukotkan sites provides support to the consistency of major regional vegetation changes (e.g. Lozhkin & Anderson 2015). In addition, the agreement between XRF tie-point ages and 2 sigma-range overlaps from the age/depth model of core EN18208 give (Fig. 3C) support to the presented age/depth model for core 16-KP-01-L02 (Vyse *et al.* 2020). Chronologies of arctic lakes should however be treated

with caution as radiocarbon dating of lacustrine sediments from high latitude sites situated within the continuous permafrost zone have been shown to be limited by numerous factors that increase uncertainty associated with age/depth modelling (e.g. Biskaborn *et al.* 2012, 2013a, 2019b; Bouchard *et al.* 2016). Long landscape residence times of organic matter within lake catchments situated within permafrost regions followed by erosion, entrainment and redeposition by glacial and/or fluvial pathways to lake basins can act to produce sediment ages that are unrealistically old (Nelson *et al.* 1988; Zimov *et al.* 1997; Oswald *et al.* 2005). This is especially problematic within lake systems where datable macrofossil remains are sparse or absent and hence dating is restricted to sediment bulk TOC as is the case at both lake sites discussed here (Kaufman *et al.* 2004). Recent studies have shown that the usage of bulk sediment ^{14}C ages may result in age offsets when compared with dated macrofossils in particular within sediments of low organic carbon content deposited under glacial conditions where sediments are particularly susceptible to contamination by old carbon (Oswald *et al.* 2005; Gaglioti *et al.* 2014; Strunk *et al.* 2020). A comparison however between ages derived from macrofossils and bulk sediment could not be applied to the lakes considered within this study, due to the absence of appreciable quantities of macrofossils for ^{14}C dating. The low amount of organic carbon availability for ^{14}C dating and small sample sizes of ^{14}C samples, particularly those dated at Poznań, leading to their exclusion from age/depth modelling here, can also contribute to age/depth model uncertainty (Baumer *et al.* 2021). Quasi-permanent ice cover during cold phases may also impact uncertainty by leading to variations in lake reservoir age as has been suggested to explain reservoir effects affecting ^{14}C chronologies at Lake El'gygytyn (Melles *et al.* 2007; Swann *et al.* 2010). The influence of detrital carbonate from catchment carbonates is likely of minimal influence at both lake sites due to the minor presence of carbonate lithologies (Zhuravlev *et al.* 1999). Limitations associated with ^{14}C dating of lacustrine and other terrestrial sites have been widely discussed for Chukotkan sites as well as records from Arctic regions of North America (Anderson & Lozhkin 2001, 2015; Kaufman *et al.* 2004; Lozhkin & Anderson 2011). Despite uncertainties pertaining to the age/depth models presented within this study, support is garnered from regional vegetation comparisons and a within-lake correlation that supports the presented chronologies.

Palaeoenvironmental reconstructions

c. 27.90–18.65 cal. ka BP. – The oldest pollen assemblages (*c.* 27.90–18.65 cal. ka BP, Marine Isotope Stage 2 (MIS 2)) indicate that open tundra- and steppe-like landscapes were dominant. Relatively high percentages of *Betula* sect. *Nanae* (up to 12%) and *Alnus fruticosa* (up

to 8%) pollen in these MIS 2 sediments are comparable with modern pollen assemblages from high arctic Chukotka sites (e.g. Lozhkin *et al.* 2001). We assume that *Betula* and *Alnus* shrubs might have survived in small refugia in the Lake Ilirney vicinity between *c.* 27.90 and 18.65 cal. ka BP. Sheltered microhabitats in deep valleys and protected lower slopes might provide conditions where summer temperatures, effective moisture and snow accumulation were enhanced as compared to the regional climate conditions (Lozhkin *et al.* 2018). The presence of their DNA in the lake sediments confirms this suggestion (Huang *et al.* 2020). The probability that these taxa might survive in the lake vicinity is in line with other records from West Beringia including from the Kankaren Range (southern Chukotka (sites 2–3 on Fig. 1; Anderson & Lozhkin 2015)) and the Ledovy Obryv sediments (southwestern Chukotka, site 4 on Fig. 1; Lozhkin *et al.* 2000, 2018).

Our reconstructions show that T_{July} in the lake area were $\sim 4\text{--}5\text{ }^{\circ}\text{C}$ below the modern values during this MIS 2 interval (Fig. 9A). Although P_{ann} reconstructions are less reliable than those for T_{July} they show that P_{ann} varied between 200 and 250 mm in this time (Fig. 9B). The high amounts of *Selaginella rupestris* spores (indicator of dry and cold climate conditions) found in all records from Chukotka reflect severe environmental conditions. Rather high percentages of coprophilous fungi spores (mostly *Sporormiella*) represent indirect evidence for the presence of rather numerous herbivores at the lake vicinity during this time. It is also indirect evidence that the bioproductivity of local plant communities was sufficient to support these herbivores.

c. 18.65–15.90 cal. ka BP. – The sediments accumulated between *c.* 18.65–15.90 cal. ka BP (153–136 cm, IL II of Fig. 4) indicate that open tundra- and steppe-like vegetation dominated around the lake.

Only single pollen grains of *Betula* and *Alnus* were found, which probably reflect the decrease or disappearance of shrubs in the study area during this time interval. However, some dwarf *Betula* probably survived in more protected habitats as is evident from DNA data (Huang *et al.* 2020) but they may not have produced much pollen due to extremely unfavourable environmental conditions (Lozhkin *et al.* 2018 and references therein).

The uppermost IL II pollen assemblage demonstrates that shortly before 16.1 cal. ka BP *Salix* shrubs and Cyperaceae significantly increased their presence around the lake. These changes suggest the beginning of Lateglacial climate amelioration in the area. T_{July} increased up to $1.6\text{ }^{\circ}\text{C}$ shortly after 16 cal. ka BP compared to the previous interval (Fig. 9A).

c. 15.90–13.34 cal. ka BP. – The increased percentages of *Betula* sect. *Nanae* pollen in the IL III (Fig. 4) spectra reflect the fact that dwarf *Betula* started to grow in the lake vicinity at about 15.9 cal. ka BP. After 15.52 cal. ka

BP, dwarf *Betula* and *Salix* communities became dominant in the Ilirney area. The rapid increase of *Betula* pollen percentages around this time is well known from Beringian pollen records (e.g. Brubaker *et al.* 2005; Edwards *et al.* 2005 and references therein) and is associated with the onset of Lateglacial climate amelioration. The revealed increase started earlier than in the majority of West Beringia records reflecting that shrub *Betula* tundra became dominant *c.* 14.7–13.8 cal. ka BP. However, the Ilirney record coincides well with the southern Chukotka records, where *Betula* percentages started to increase as early as ~18–19 cal. ka BP (Anderson & Lozhkin 2015).

Small increases in Ericales and Cyperaceae pollen percentages suggest the spread of wetter habitats. Spores of *Selaginella rupestris* decreased in the pollen assemblages, but remained relatively high until *c.* 13.34 cal. ka BP suggesting still rather harsh climate conditions in the study area. T_{July} reached 10.1–10.4 °C between *c.* 15.70 and 13.38 cal. ka BP (Fig. 9A). P_{ann} also gradually increased up to 280 mm (Fig. 9B).

Similar changes in pollen assemblages were documented in the southern Chukotka records for an equivocal time interval (Anderson & Lozhkin 2015). Thus, the Lateglacial pollen records suggest gradual climate amelioration in Chukotka between *c.* 15.52 and 13.34 cal. ka BP.

The slightly increased amounts of *Alnus* pollen may suggest the northward migration of shrub alder confirming climate amelioration during the IL III interval; however, *Alnus* probably did not grow yet in the study area. Although the Kankaren Range (sites 2–3 on Fig. 1; Anderson & Lozhkin 2015) and the Anadyr Lowland (sites 5–7 on Fig. 1; Lozhkin & Anderson 2013) records document that shrub alder was already widespread in southern and central Chukotka around 13.8 cal. ka BP, it is unlikely that shrub *Alnus* grew in the Ilirney area earlier than *c.* 13.34 cal. ka BP.

Very high presence of *Botryococcus* remains in the IL III sediments reflects widespread shallow habitats favourable for these green algae. One possible explanation of the observed *Botryococcus* peak could be short-term lake level increases resulting in flooding of flat shore areas within the lake outflow area. These lake level pulses may reflect melting of local glaciers due to higher air temperatures (Vyse *et al.* 2020) and may also be associated with increasing mean annual precipitation during the Lateglacial.

c. 13.34–11.84 cal. ka BP. – The gradual increase in *Alnus fruticosa* pollen percentages starting at the beginning of IL IV (Fig. 4) documents that alder stands became common in the study area after *c.* 13 cal. ka BP. Herbs and *Selaginella rupestris* gradually decreased further within the vegetation cover, reaching a minimum at the Pleistocene/Holocene boundary. Changes in pollen assemblages and a significant increase in pollen

concentration reflect gradual climate amelioration with T_{July} rising slightly above 12 °C (Fig. 9A) and increasing P_{ann} (Fig. 9B).

At the end of the interval, the pollen spectra do not reflect any significant fluctuations, which can unequivocally be interpreted as YD cooling. The only pollen assemblage showing some increase in *Artemisia* and Poaceae pollen percentages (IL IV) may indicate cooling around *c.* 12.5 cal. ka BP. This is inconsistent with the El'gygytgyn environmental records (Andreev *et al.* 2012; Melles *et al.* 2012), where the YD cooling is well pronounced, and with records from the Anadyr Lowland (Lozhkin & Anderson 2013) and from a number of sites across West Beringia (Anderson & Lozhkin 2002 and references therein), which also show a significant decrease of shrub pollen percentages at the Lateglacial/Holocene transition coinciding with the YD cooling. The well-dated Lateglacial sediments from Wrangel Island (northern Chukotka, site 8 on Fig. 1; Lozhkin *et al.* 2001) with drastic increases in percentages of *Selaginella rupestris* spores, a good indicator of dry and cold environmental conditions, and a simultaneous decrease in *Betula* pollen percentages also reflect climate deterioration at the Lateglacial/Holocene boundary coinciding with the YD, although Lozhkin *et al.* (2001) did not interpret this event as the YD. Palynological records located west of the Ilirney Lake (Lena and Indigirka drainages) also demonstrate the cooler climate reversal at the Lateglacial/Holocene boundary (Andreev *et al.* 2011; Lozhkin *et al.* 2018 and references therein).

Although the Ilirney pollen assemblages of YD age, which do not show any significant cooling, differ from other northern records they show a good similarity with the contemporaneous pollen records from southern Chukotka (sites 2–3 on Fig. 1; Anderson & Lozhkin 2015), which also do not show evidence of any significant cooling. The relatively warm climate conditions during the YD time were also inferred from peat records from other locations in the northern regions of Far East Russia (Lozhkin *et al.* 2011 and references therein). Generally spatially heterogeneous climate conditions during the YD were reported by Kokorowski *et al.* (2008a, b). Based on 75 lake and peat records, they revealed coherent but spatially complex patterns: cooling in southern Alaska, eastern Siberia and some parts of northeastern Siberia; and uniform to warmer-than-present conditions in different locations from a number of sites from central and northern Alaska, northern Siberia and Far East Russia. As a possible explanation for the observed geographical differences it was suggested that large-scale climatic forcing was further modified by local non-climatic factors, such as topography, soil substrates, and disturbance of sediments (Kokorowski *et al.* 2008a, b). However, it is difficult to explain why rather closely situated Ilirney and El'gygytgyn sites demonstrate such different environments during the YD time. Pollen records from southern and southeastern Chukotka (the

relatively closely located Kankaren and Anadyr Lowland sites) also demonstrate a similar discrepancy (Lozhkin & Anderson 2013; Anderson & Lozhkin 2015). The local topography, soils, as well as the disturbance of sediments during deposition and age/depth model uncertainty may play important roles resulting in such discrepancies at both northern and southern locations. These closely situated, but spatially heterogeneous records have to be additionally studied with high-resolution sampling and supported by reliable age control, which may reveal possible hiatuses and/or extremely low sedimentation rates. Unfortunately, the lack of organic material in the Lateglacial, and especially within YD sediments often prevents such control making direct comparison of the sediment records problematic.

Holocene. – The Holocene sediments from both study sites (IL V–VII of Fig. 4 and R I–II of Fig. 5) are dominated by *Alnus* and *Betula* pollen with some *Salix*, Poaceae and Cyperaceae. These pollen assemblages reflect that shrub and graminoid tundra communities were dominant around Lake Ilirney between *c.* 11.84 and 11.10 cal. ka BP. *Salix* stands significantly decreased after *c.* 11.1 cal. ka BP. Single pollen grains of *Larix* occurring in the Early Holocene sediments probably reflect that first larch stands established in the region. This suggestion is in good agreement with the pollen and macrofossil data from the El'gygytyn Crater where larch seeds and needles found in the permafrost sediments were dated between 11.2 and 9.0 cal. ka BP (Shilo *et al.* 2008; Andreev *et al.* 2012). Thus, a forest-tundra ecotone seems to be established in the study area already in the Early Holocene, shortly after 11.1 cal. ka BP.

The Early Holocene sediments show the highest pollen concentration reflecting the most favourable climate conditions during the HTM (*c.* 10.6–7.0 cal. ka BP). T_{July} reached 13.3 °C at the end of the HTM in the Ilirney area and slightly decreased after *c.* 7 cal. ka BP (Fig. 9A). P_{ann} reached 343.5 mm *c.* 8.9 cal. ka BP, but climate conditions became drier after 7 cal. ka BP (Fig. 9B). However, there are several increases in P_{ann} , reflecting wetter intervals. T_{July} and P_{ann} reconstructed from the Rauchuagytyn pollen assemblages show similar trends (Fig. 10A, B). The small differences most likely are associated with local topography as both lakes are situated in mountainous terrain.

Our data are in good agreement with other existing environmental records from Chukotka and the adjacent arctic areas (e.g. Lozhkin & Anderson 2006, 2013; Andreev *et al.* 2011, 2012; Lozhkin *et al.* 2011, 2018; Anderson & Lozhkin, 2015 and references therein). The pollen-based biome and climate reconstructions from the Lake El'gygytyn record also show that the most favourable environmental conditions occurred during the Early Holocene, *c.* 11.7–8.0 cal. ka BP (Melles *et al.* 2012; Tarasov *et al.* 2013). However, T_{July} and P_{ann}

values reconstructed from the El'gygytyn record are lower than at our sites, which is most likely related to a more easterly location of the lake and/or local topography. The difference might be also connected with different modern pollen sample data sets. Direct support for warmer-than-present temperatures is obtained from ^{14}C -dated macrofossil remains of trees and shrubs found beyond their modern distribution limits (e.g. Binney *et al.* 2009, 2017; Lozhkin *et al.* 2011 and references therein). The Early Holocene (HTM) was the warmest time in high arctic Siberia in comparison to the continental regions as the coastline at the time was 200–500 km farther north, causing more continental conditions and lessened influences of the cool arctic seas (Kokorowski *et al.* 2008b; Biskaborn *et al.* 2016 and references therein).

The contents of green algae colony remains in the Early Holocene sediments are significantly lower than in the Lateglacial ones. This most likely reflects further melting of local glaciers and higher precipitation at the Holocene onset resulting in increased lake levels with deeper aquatic conditions, less favourable for *Botryococcus* and *Pediastrum* as they need shallow environments where water-masses can be warmed up quickly (Jankovská & Komárek 2000 and references therein).

Amounts of *Pinus* pollen started to increase after *c.* 7.5 cal. ka BP in the Ilirney sediments and after *c.* 6.8 cal. ka BP in the Rauchuagytyn sediments. These slight increases in *Pinus* pollen percentages do not confirm that dwarf stone pine grew close to the study areas at this time, but it may reflect the appearance of shrub stone pine in southerly locations. The southern Chukotka pollen records (Anderson & Lozhkin 2015) show that *Pinus pumila* was probably present there as early as 7.4 cal. ka BP, which coincides well with a slight increase of *Pinus* pollen percentages in our studied sediments starting *c.* 7.5 cal. ka BP. The uppermost pollen zones from both studied cores (IL VII and R II) demonstrate the highest percentages of *Pinus*. It is important to note that *Pinus* percentages are higher (up to 20%) in the Rauchuagytyn sediments than in the Ilirney sediments, although *Pinus pumila* is absent close to Lake Rauchuagytyn. The El'gygytyn records also demonstrate increases in *Pinus* pollen percentages, but later, after 5 cal. ka BP (e.g. Melles *et al.* 2012). However, dwarf stone pine was also found similarly to not grow close to Lake El'gygytyn. Thus, the most northern pollen records (Rauchuagytyn and El'gygytyn) demonstrate rather high *Pinus* percentages, although *Pinus pumila* is not currently growing around these lakes. Surprisingly, the Ilirney sediments do not show significant *Pinus* percentages even in the uppermost samples, whilst *Pinus pumila* stands are rather common in the lake vicinity. The DNA of *Pinus* was also not found in the Ilirney sediments.

The overrepresentation of *Alnus* pollen is also characteristic for both studied sediment cores. Very high

percentages (40–60%) of *Alnus* pollen is documented in the Rauchuagytyn sediments, whilst the nearest alder stands can be found only at about 5 km from the lake. Although shrub alder stands were found in the Lake Iirney vicinity, they are very rare in the study area; however, the *Alnus* pollen percentages reach up to 40–50% in many samples. Very low presence of *Alnus* was found in the sedimentary ancient DNA in the uppermost sediments of Lake Iirney (Huang *et al.* 2020). Pollen assemblages including modern assemblages from the El'gygytyn crater also demonstrate high percentages of *Alnus* (Matrosova 2006, 2009; Andreev *et al.* 2012 and references therein); however, no shrub alder currently grows in the lake vicinities. These examples demonstrate that considerable input of pollen grains from distant sources of several hundred kilometres must be considered when interpreting high arctic pollen records.

The uppermost pollen zones of both study sites demonstrate higher percentages of herb pollen taxa suggesting an increase of open herb-dominated habitats in both study areas. The slightly increased percentages of Ericales pollen and *Sphagnum* spores reflect that wetter habitats became more common suggesting increased humidity in both study areas around *c.* 7 cal. ka BP. Generally, other available records also show that vegetation cover in northern Chukotka became similar to modern *c.* 7 cal. ka BP. However, it remains unclear when stone pine (*Pinus pumila*) inhabited the Iirney area.

Conclusions

The continuous lacustrine pollen records from Lake Iirney and Lake Rauchuagytyn offer valuable insights into the Late Pleistocene and Holocene vegetation and climate history of northwestern Chukotka:

- Predominantly open steppe- and tundra-like vegetation dominated the area between 27.9 and 18.7 cal. ka BP producing sufficient biomass to support herbivores. Dwarf *Betula* and *Alnus* might have survived in some sheltered habitats. They probably completely disappeared after 18.7 cal. ka BP due to harsh climate conditions during the LGM.
- The beginning of climate amelioration in the area is evidenced by the increase of *Salix* and Cyperaceae ~16.1 cal. ka BP. First *Betula* stands re-established in the study area ~15.9 cal. ka BP, and became dominant together with *Salix* at around ~15.52 cal. ka BP suggesting a gradual climate amelioration during the Lateglacial.
- *Alnus* stands became common in the area after ~13 cal. ka BP reflecting further climate amelioration. However, typical steppe communities disappeared at the Lateglacial/Holocene boundary, ~11.8 cal. ka BP. Shrubby and graminoid tundra communities were dominant during the Early Holocene, ~11.8–11.1 cal.

ka BP. The first larch stands may have established in the study region at this time. Warmest climate conditions existed during the Middle Holocene, *c.* 8–6 cal. ka BP. The vegetation cover in northwestern Chukotka became similar to modern ~7 cal. ka BP. However, *Pinus pumila* first arrived in the southern part of the study area rather recently, after 1.2 cal. ka BP.

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Author contributions. – KSL, SK, LAP and UH participated in the field campaign to the lakes in 2016. BKB and SAV provided interpretation of sedimentological and ¹⁴C data and the corresponding figures. ER and AAA conducted pollen analyses. UH and TB provided climate reconstructions and interpretations and corresponding figures. AAA provided the pollen-based environmental interpretations and took the lead in writing the manuscript. All authors were involved in the data interpretation, took part in the scientific discussions and helped with writing and editing the manuscript.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at <http://www.boreas.dk>.

Table S1. Taxa used in the quantitative climate reconstruction. Herbs were harmonized to family level. Woody taxa (when possible) to genus level.