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Late Quaternary Lake Dynamics in the Verkhoyansk Mountains of Eastern Siberia: Implications for Climate and Glaciation History

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Abstract: Lake Billyakh in the Verkhoyansk Mountains provides a lacustrine sediment record of the last 50 ka, which was studied by a palaeolimnological multi-proxy approach on the basis of sedimentological, geochemical, and micropalaeontological data series (diatoms, chironomids, palynomorphs). Lake history and its catchment point to two lake stages with high lake level during the Karginian (50 to 32 ka BP) and the Holocene (since 11.5 ka BP), interrupted by cold and dry conditions at low lake level during the Sartanian stage. Palaeoenvironmental changes were in accord with general trends of climate change across the higher latitudes of the northern hemisphere. The lake record moreover confirms mountain deglaciation prior to the last (global) glacial maximum, attributed to atmospheric moisture routing effects, which so far are poorly understood.

Zusammenfassung: Das lakustrine Sedimentarchiv des Billjach-Sees im ostsibirischen Werchojansker Gebirge liefert Hinweise auf die regionale Umweltgeschichte der letzten 50.000 Jahre. Auf Grundlage von sedimentologischen, geochemischen und mikropläontologischen (Diatomeen, Chironomiden, Palynomorpha) Datensätzen wurden Sedimentkerne mit einem paläolimnologischen Multi-Proxy-Ansatz ausgewertet. Die Entwicklungsgeschichte des Sees und seines Einzugsgebiets deutet auf zwei Hochstandsphasen während der Kargin-Warmzeit (50 bis 32 ka v.h.) und des Holozäns (seit 11,5 ka v.h.) hin. Die zwischenzeitliche Sartan-Kaltzeit war durch einen Seespiegelrückgang und Trockenheit gekennzeichnet. Die rekonstruierte Umweltgeschichte entspricht den paläoklimatischen Trends in den höheren Breiten der Nordhemisphäre. Die Befunde bestätigen zudem eine regionale Enteisung des Werchojansker Gebirges noch vor dem letzten (globalen) glazialen Maximum. Maßgeblich für dieses zeitlich inkonsistente Vereisungsmuster waren Einflüsse der atmosphärischen Zirkulation auf den Feuchtigkeitstransport.

INTRODUCTION

The study of sedimentary records from Lake Billyakh has been stimulated by former and ongoing research in the Verkhoyansk Mountains that mainly deals with northeastern Siberian landscape development during the late Quaternary (Rusanov et al. 1967, Grigoriev et al. 1989, Diekmann et al. 2007). Special emphasis was put on the chronology of mountain glaciations (Stauch & Gualtieri 2008), permafrost dynamics (Grigoriev et al. 1989, Popp et al. 2006), peat formation (Werner et al. 2009, Tarasov et al. 2007), and the origin of fluvial and loess-like sediments (Chebotarev et al. 1964, Alekseev 1997, Popp et al. 2007, Zech et al. 2010, 2013). Latest studies have confirmed the presence of repeated glacial advances, as outlined in older Russian literature (Kind 1975, Galabala 1997, Zamoruyev 2004), and resulted in a refined chronstratigraphic interpretation of regional glacial fluctuations in the past (Stauch & Lehmkuhl 2010, Zech et al. 2011). It became evident that regional mountain glaciers reached the Verkhoyansk foreland only before 100 ka BP and that younger glaciations were restricted to the mountain ranges. The Lake Billyakh area, although situated in the mountains, was ice-free since at least 80 ka BP (Fig. 1). The lake provides a continuous and promising lacustrine sediment record of the last 50 ka (Müller et al. 2010). Former studies of the Lake Billyakh pollen and biomarker record revealed marked changes in local vegetation, related to regional and northernhemispheric climate dynamics (Müller et al. 2009, 2010, Tarasov et al. 2013). They confirmed marked climate variability dring the last glacial cycle, also known from Beringia and northern Siberia (Lozhkin & Anderson 2011, Wetterich et al. 2014).

Here, we provide additional paleolimnological proxy information on the basis of sedimentological and micropalaeontological records. The objective is the reconstruction of lake development and its meaning in respect to palaeoenvironmental changes in eastern Siberia. In this context, we especially address two important aspects: (1) The question of the validity of former geomorphological reconstructions of glacial dynamics by another independent palaeolimnological approach, and (2) the nature and intensity of pre-Holocene interstadials during the last 50 ka.

REGIONAL SETTING

Lake Billyakh is situated in the central Verkhoyansk Mountains at 340 m a.s.l. (65.2° N, 120.7 °E) south of the Dyanushka River valley (Fig. 1 & 2). The surrounding mountains rise up to between 700 and 950 m a.s.l. The lake basin probably is of tectonic origin and occupies a NE-SW trending valley that perpendicularly cuts through the Muosuthanskiy and Tekir-Khaya Ridges (Fig. 2). The mountain ranges are built up of Permian Triassic sandstones and shales that form the most

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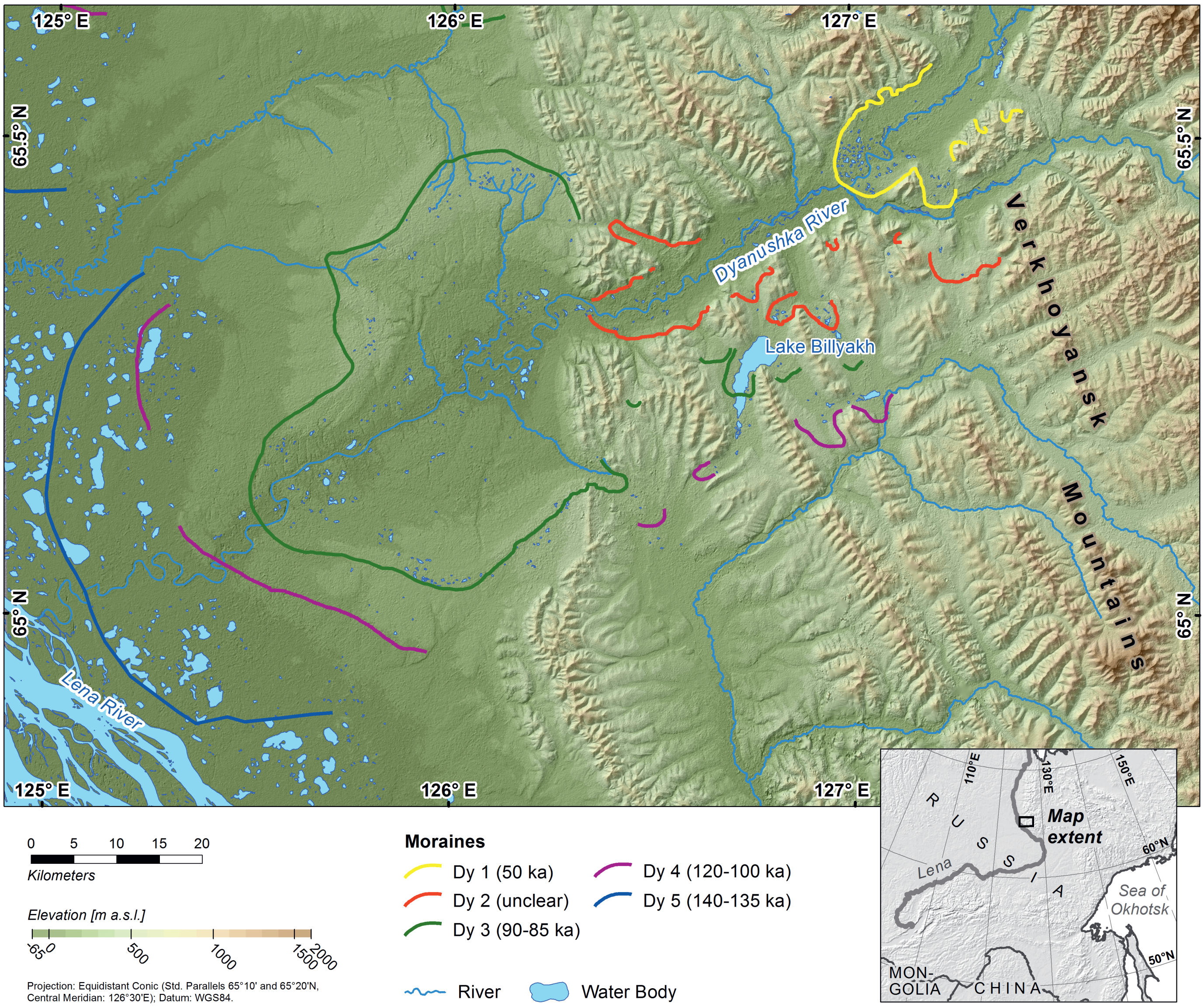

Fig. 1: Location of Lake Billyakh at the western margin of the Verkhoyansk Mountains on an ASTER Global Digital Elevation Model (ASTER GDEM is a product of NASA and METI, see references). The map also shows the distribution of morainic arcs related to the former glacial advances (Dy 1 to Dy 5) of the Dyanushka glacier lobes towards the Lena River (Stauch 2006, Stauch & Lehmkuhl 2010).

Abb. 1: Lage des Billjach-Sees an der westlichen Abdachung des Werchojansker Gebirges. Kartengrundlage ist das ASTER Global Digital Elevation Model (ASTER GDEM ist ein Produkt der NASA und METI, siehe Schriftenverzeichnis). Die Karte zeigt zudem die Verbreitung von Moränenständen (Dy 1 bis Dy 5) früherer Vorstöße von Gletscherloben Richtung Lena-Vorland (Stauch 2006, Stauch & Lehmkuhl 2010).

widespread exposures in the Verkhoyansk fold-and-thrust belt (Parfenov 1991, Oxmann 2003, Prokopiev et al. 1994). In addition to tectonic faulting, the lake basin was subsequently sculptured by glacier advances, as shown glacial landforms (cirques, moraines, U-valleys) around the lake. The lake is situated on several hundred meters thick frozen ground in a zone of continuous permafrost (Gavrilova 1993). The continental climate is characterized by a strong seasonal temperature gradient with mean January and July temperatures of around -40 °C and +15 to +19 °C, respectively, and a low mean annual precipitation between 300 and 400 mm per year (Alpat'ev et al. 1976, Climatic Atlas of Asia 1981). Climate and active layer thaw during summer favours the growth of cold deciduous larch forests, which dominate the vegetation in the plains, mountain slopes and river valleys and is replaced by mountain tundra above 400 to 500 m a.s.l. (Gerasimov 1964).

Today, the lake is 3 × 11 km in maximum width and length with a surface of 23 km^2 (Fig. 2). Average depth is around 8 m, a deeper small basin of 25 m water depth appears in the central part of the lake (Diekmann et al. 2007). The catchment area is confined to 133.3 m^2 by the nearby mountain ridges and passes. The lake is fed by small creeks from the surrounding mountain slopes. Two small perennial streams enter the lake at its northern and north eastern end, respecttively. The drainage of the lake appears through a small stream at the southern part of the lake and reaches the Lena River 90 km to the southwest. Informations on the hydrological characteristics of the lake are only available from snap-shot measurements during the field campaign in April 2005 (Diekmann et al. 2007). During that time, an inverse temperature gradient from 0.5 °C below the 1.5 m thick lake ice cover to 3.0 °C in the deeper water was observed. Conductivity varied around 40 to 45 µS/cm and

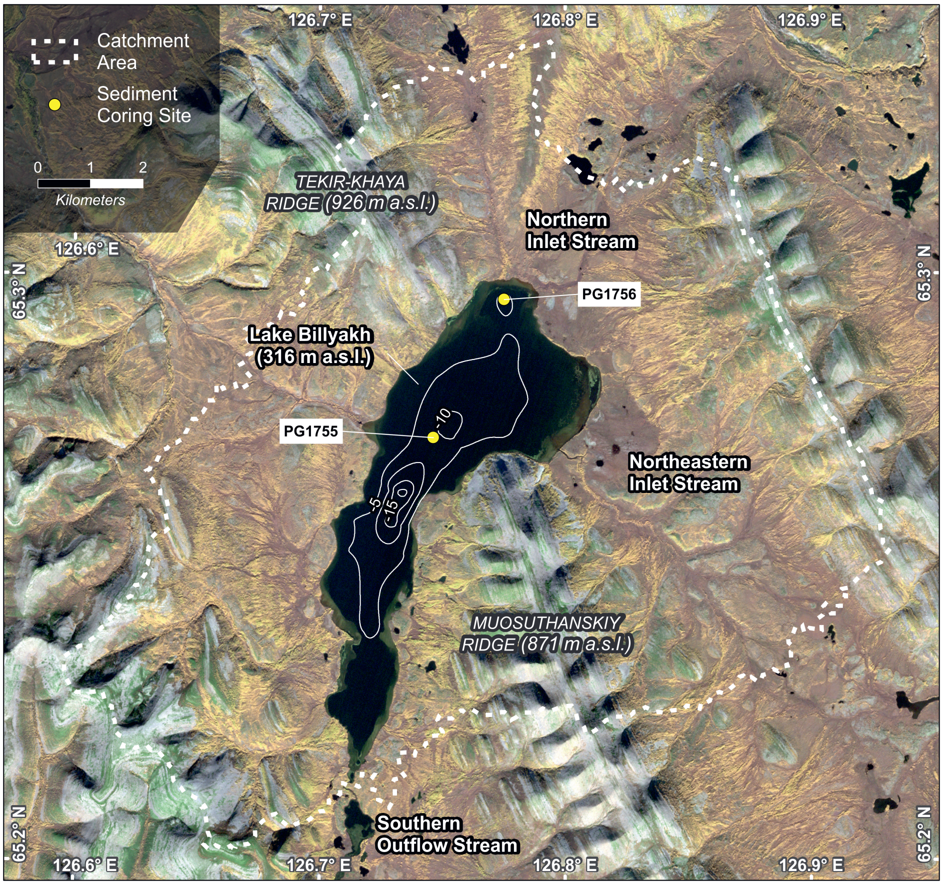

Fig. 2: Local setting, catchment, and bathymetry of Lake Billyakh with indication of sediment coring sites PG1755 and PG1756. Satellite image is a Copernicus Sentinel 2 Scene.

Abb. 2: Lage, Einzugsgebiet und Bathymetrie des Billjach Sees mit den Untersuchungs-Standorten PG1755 und PG1756. Grundlage des Satellitenbildes ist eine Copernicus-Sentinel-2-Szene.

indicated extreme fresh-water conditions. The pH values of 6.3-6.8 were in the neutral to slightly acidic range. Oxygen saturation decreased from 58 % at the surface to 29 % at the lake bottom, consistent with full ventilation. The trophic status could only be determined from some indirect indications for oligotrophic conditions, such as the presence of oxygen during the late stage of inverse winter stratification, the low macroscopic organic content in lake sediments, the deep transparency of the water column observed through the ice holes and the high abundance of freshwater perches and trouts.

MATERIAL AND METHODS

In this study, we analysed sediment cores from Site PG1755 at 7.8 m water depth in the central part of Lake Billyakh and from Site 1756 at 7.9 m water depth close to the northern shore (Fig. 2). Sediment cores were taken in April 2005 with an UWITEC piston corer system, operated from a tripod on the lake ice cover (Diekmann et al. 2007). Overlapping core segments provided a spliced sediment record of 9.35 m length at Site PG1755, and of 4.57 m length at Site PG1756. We adopt the age-depth models for both records, as inferred from radiocarbon dating for PG1755 (Müller et al. 2010) and PG1756 (Müller et al. 2009). Calibrated ages are expressed as ka BP (thousand years before Present) (Fig. 3). The comparison of both records is supposed to provide insights into temporal-spatial variations in paleoecology and the depositional environment in a distal and proximal setting, respecttively. We follow a multi-proxy approach. Used data and methods are specified below. All shown and supplementary data are available at http://dx.doi.org/10.1594/PANGAEA.875015. For further methodic details, the reader is referred to the cited studies.

High-resolution measurements of the elemental composition at 0.5-cm steps for PG1755 and 1.0-cm steps for PG1756 were obtained from core logging with an Avaatech XRF scanner at AWI Bremerhaven (e.g. Biskaborn et al. 2012). In this article, we especially use the Sr/Rb count ratios and Zn counts. The variability of the trace element Zn was verified quantitatively on selected samples by inductively coupled plasma emission spectroscopy measurements (ICP-OES) with a Perkin Elmer Optima 3000 XL device at AWI Potsdam (e.g. Diekmann et al. 2000).

Discrete sediment samples for sedimentological and micropalaeontological analyses were conducted at 10- to 20-cm steps for PG1755 and PG1756. Water contents was calculated from the difference between the weights of wet and dried samples and is expressed as weight percentage in the original wet sediment sample. Total organic carbon (TOC) was measured with a Vario MAX C element analyser, total nitrogen (TN) with a Vario EL III element analyser, either on freeze-dried an milled samples (e.g. Biskaborn et al. 2012). TOC/TN is expressed as atomic ratio. Grain-size analysis and separation followed after disaggregation and removal of organic matter from subsamples. Wet sieving at 63 mm was performed to separate silt and clay from sand, while the silt and clay fractions were obtained by settling and separation in 'Atterberg' tubes (eg. Popp et al. 2007). Sand, silt, and clay proportions are shown in weight percentages. The clay mineralogy of the clay fraction was analysed with the X-ray diffraction device Philips PW 1830 on glycolated and preferentially oriented sample mounts (e.g. Popp et al. 2007). Mineral proportions were calculated with the MacDiff software from weighted peak areas of the main clay-mineral groups in the diffractograms (e.g. Petschick et al. 1996).

Diatom analyses were conducted according to the procedures of sample treatment, microscopy, and taxa identification and terminology described in Pestryakova et al. (2012). Diatom data are shown in percentages of individual diatom valves. The results of chironomid analyses are shown in percentages of individual remains of head capsules. They are based on the procedures of sample treatment, microscopy, and taxa identification and terminology described in Nazarova et al. (2011). This study also uses original data on pollen, spores and other non-pollen palynomorphs, generated by Müller et al. (2009, 2010).

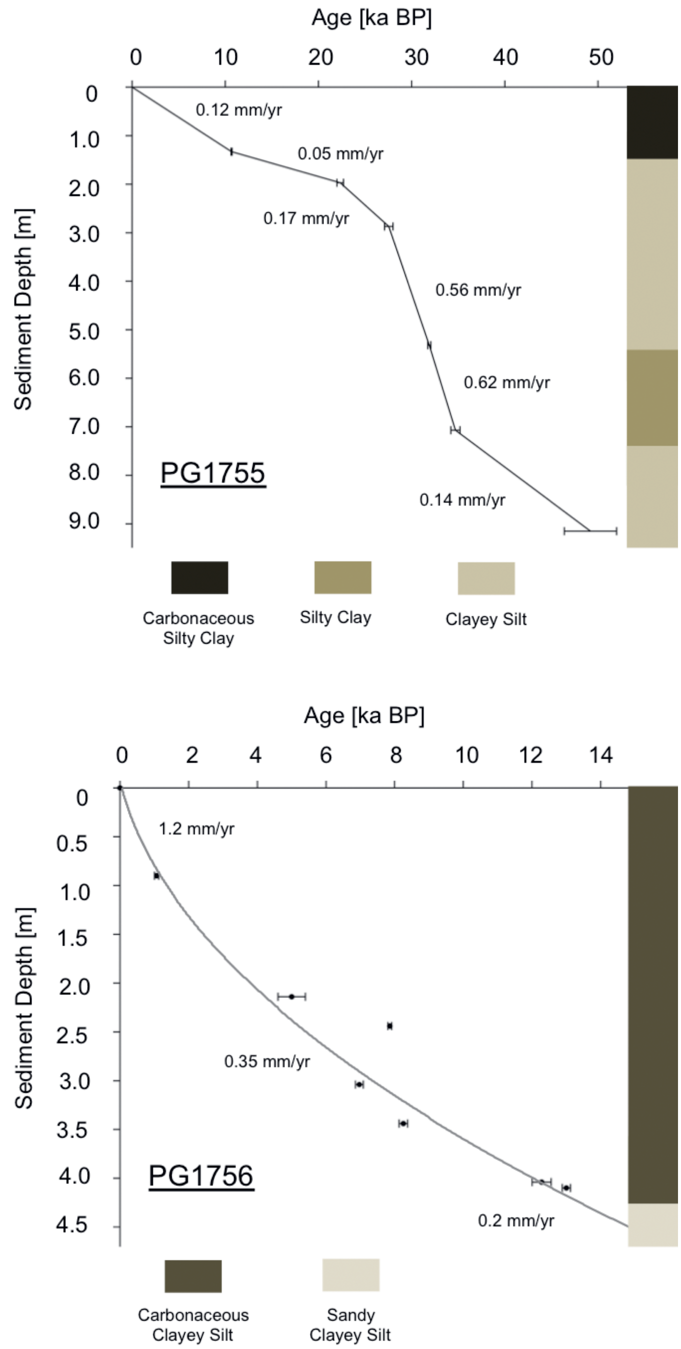

Fig. 3: Age-depth models and lithology of the studied sediment cores from Lake Billyakh, adopted from Müller et al. (2009) for PG1756 and Müller et al. (2010) for PG1755. Age marker are reported as calibrated ^{14}C ages in calendar years before present (ka BP).

Abb. 3: Alters-Tiefen-Modelle und Lithologie der untersuchten Sedimentkerne vom Billjach See, übernommen von Müller et al. (2009) für PG1756 und Müller et al. (2010) für PG1755. Alterspunkte stellen kalibrierte ^{14}C-Alter in Kalenderjahren vor heute dar (ka BP).

RESULTS AND DISCUSSION

Sedimentology

The lithological variations of the sediment cores (Fig. 3) are also displayed by downcore changes in sedimentological and geochemical data (Fig. 4). We use Sr/Rb ratios as another grain-size proxy (Kalugin et al. 2007, Biskaborn et al. 2013), which in carbonate-free sediments inversely runs along with variations in clay concentrations (Kalugin et al. 2007, Biskaborn et al. 2013).

At the distal site PG1755, the lowermost lithological unit (LU 55-4) is composed of compacted clayey silts with less than 30 % pore water. TOC concentrations reach maxima of around 2 % with TOC/TN ratios around values of 14. Such values point to a dominance of organic carbon derived from vascular plants, such as aquatic macrophytes and/or land plants (Meyers & Teranes 2001, Schleusner et al. 2015). The claymineral composition shows the typical signature of sediments derived from the Verkhoyansk Mountains with high amounts of illite and chlorite and low amounts of kaolinite and smectite (Popp et al. 2007, Zech et al. 2011). Another feature is the marked presence of mixed-layered illite-smectite (≥15 %), also prevailing in the overlying unit at same values. Otherwise the sediments of LU 55-3 (40-32 ka BP) show an increase in pore water (≥40 %) and clay concentrations (along with decreasing Sr/Rb ratios) and a decline in TOC/TN ratios to values around 12.0, the latter indicating a higher contribution of planktonic algae to organic carbon in the sediments. The increase in clay can be seen as a higher supply of aquatic suspensions to the lake. A decrease in clay occurs in LU 55-2 (32-12 ka BP) and is associated with a change in the clay-mineral assemblage, shown by higher illite concentrations and a decrease in mixed-layered illite-smectite. This assemblage persists through the remaining part of the sediment core. The switch in clay mineralogy indicates a change in sediment provenance.

The uppermost unit LU 55-1 comprises the Holocene and is characterized by the highest TOC concentrations (4-6 %) in the PG1755 record with the low values during the last 2000 years. An increase in TOC/TN ratios to values around 11.5 ka BP points to a higher contribution of vascular plant remains to organic matter, compared to the foregoing glacial stage. Clay concentrations increase by more than 20 % and indicate a high contribution of aquatic suspensions. At the proximal site PG1556, the record starts with basal silty sands, covered by carbonaceous silty clays with TOC concentrations around 4.0. The TOC/TN ratios reach values of around 14, because of a close position to the littoral zone, also indicated by lesser clay concentrations than at distal Site PG1755.

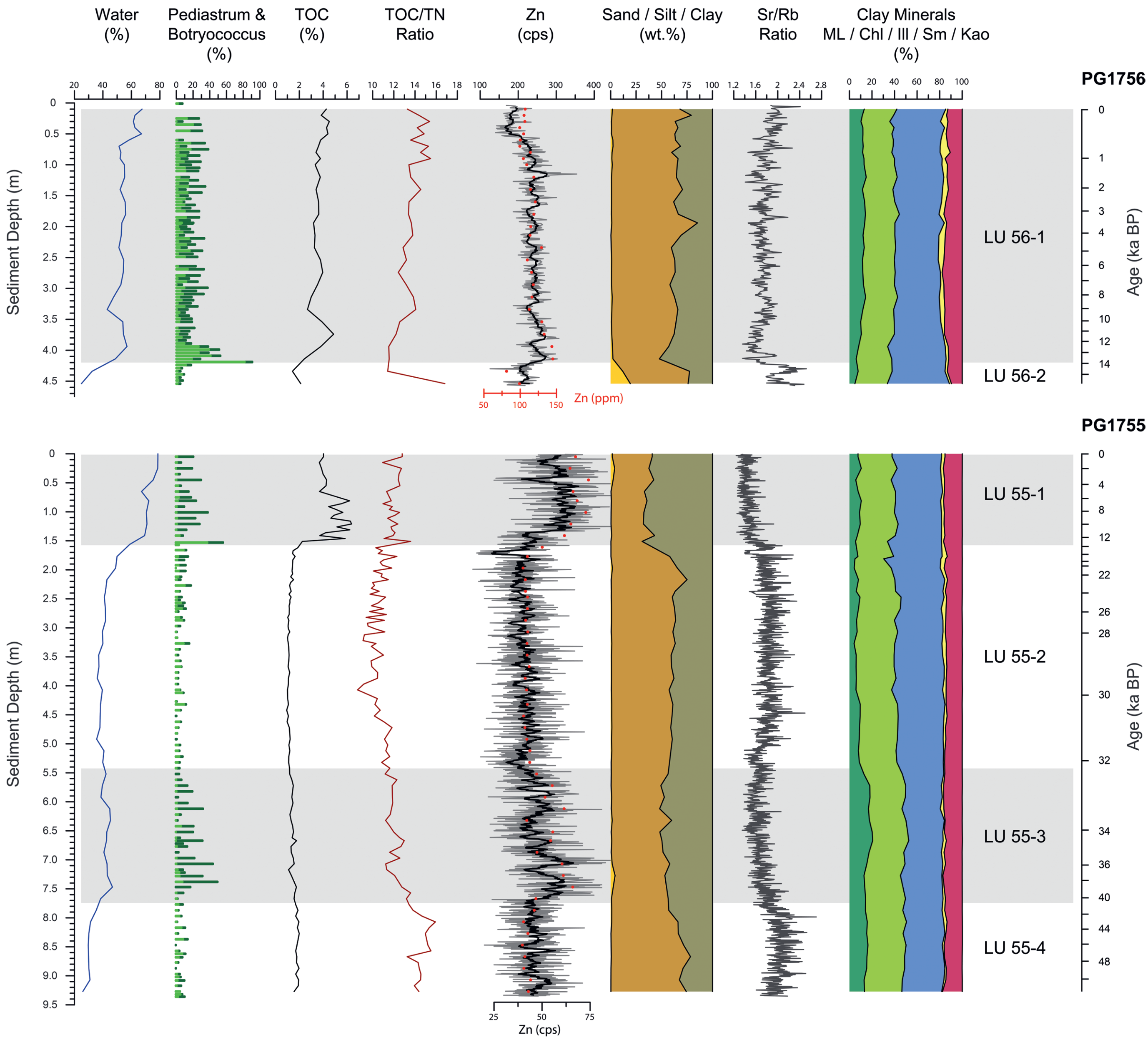

Fig. 4: Lithological Units (LU), compositional data and non-pollen palynomorphs (algal remains of *Pediastrum* and *Botryococcus*) in the sediment records from Lake Billyakh. Palynological data from MÜLLER et al. (2009, 2010). TOC: total organic carbon, TN: total nitrogen, Zn: zinc, Sr: strontium, Rb: rubidium, ML: mixed-layer illite/smectite, Chl: chlorite, Ill: illite, SM: smectite, Kao: kaolinite, wt. %: weight percentage.

Abb. 4: Lithologische Einheiten (LU), kompositionelle Daten und Nicht-Pollen-Palynomorphe (Algenreste von *Pediastrum* und *Botryococcus*) in den Sedimentkernen vom Billjach See. Palynologische Daten nach MÜLLER et al. (2009, 2010). TOC = Gesamter organischer Kohlenstoff, TN = Gesamt-Stickstoff, Zn = Zink, Sr = Strontium, Rb = Rubidium, ML = Wechsellagerungs-Illit/Smektit, Chl = Chlorit, Ill = Illit, Sm = Smektit, Kao = Kaolinit, wt. % = Gewichtsprozent.

Non-pollen palynomorphs

Cysts of the green algae *Pediastrum* and *Botryococcus* prevail throughout both sediment records (Fig. 4), indicating persistent aquatic conditions during the last 50 ka. At the proximal Site PG1756, *Pediastrum* is enriched in the oldest lake sediments (14-12 ky BP) consistent with enrichment during the pioneer stage of the lake. In contrast, maxima of Botryococcus appear at the distal site PG1755 in the units LU 55-3 and LU 55-1, which are characterized by high aquatic runoff and the higher presence of planktonic organic matter. Both algae are cosmopolitan in distribution and have been encountered even in arctic and subarctic lakes (ANDREEV et al. 2004, JANKOVSKA & KOMAREK 2000). Though the assessment of ecological demands is hard to raise on a non-species level, there seems to be some common ecological boundary conditions for both taxa. Thus, *Pediastrum* usually occurs in meso to eutrophic lakes (VAN GEEL 2001, JANKOVSKA & KOMAREK 2000). In arctic and subarctic cold regions it is often encountered in thermokarst lakes associated with the presence of peaty swamps and under littoral influences (ANDREEV et al. 2004, WECKSTRÖM et al. 2010, NIEMEYER et al. 2015, BISKABORN et al. 2016). Otherwise, *Botryococcus* tends to thrive under oligotrophic conditions (JANKOVSKA & KOMAREK 2000) and dominates over *Pediastrum* at lower trophic level, as observed in Swedish lakes (CRONBERG 1986).

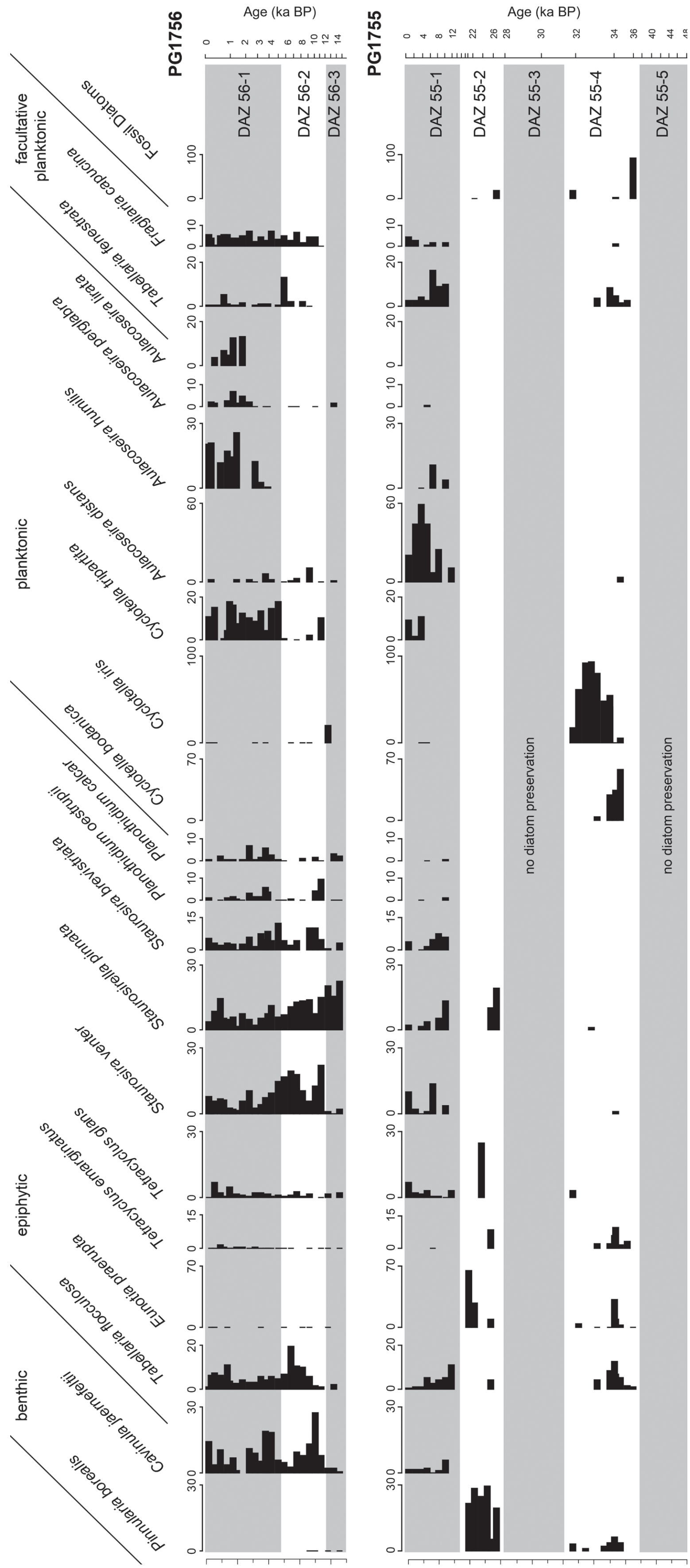

Fig. 5: Downcore distribution of selected diatom taxa and diatom-assemblage zones (DAZ) in the sediment records of Lake Billyakh.

Abb. 5: Verteilung ausgewählter Diatomeen-Taxa und Diatomeen-Vergesellschaftungs-Zonen (DAZ) in den Sedimentkernen des Billjach Sees.

Diatoms

In the two sediment records of PG1755 and PG1756, remains of 249 different diatom taxa are preserved. The diatomassemblage zones (DAZ) with the 20 most abundant taxa are shown in Figure 5. In contrast to green algae remains, reported in the last section, diatoms are not preserved throughout the entire sediment record. Though the green algae indicate prevalance of lacustrine conditions during the last 50 ka, changes in water chemistry apparently led to diatom dissolution during distinct intervals.

The two periphytic to planktonic and halophobic species *Tabellaria flocculosa* and *Tabellaria fenestrata* appear throughout the diatom-bearing sections of the sediment record in variable amounts and give evidence of generally low supply of dissolved nutrients to the lake (Pestryakova et al. 2012). Otherwise, the diatom assemblage reveals distinct spatiotemporal trends.

No diatoms are included in DAZ 55-5, the lowermost unit in the record at the distal site PG1755. The overlying DAZ 55-4 (38-31 ka BP) first starts with reworked fossil diatoms and then is dominated by modern planktonic taxa (up to 95 %), starting with *Cyclotella bodanica* replaced upwards by *Cyclotalla iris*. Cyclotella species in such dominance of are typical planktonic species in deeper and oligotrophic arctic and subarctic lakes, such as Lake El'gygytgyn (Cremer & Wagner 2003) and Lama Lake (Kumke et al. 2004). Species *Cyclotella iris* also occurs in sediments of the last glacial cycle in Lake Baikal (Swann et al. 2005). DAZ 55-3 again does not include any diatom remains. DAZ 55-2 (27-14 ka BP) shows a dominance of the benthic taxon *Pinnularia borealis*, which represents a cosmopolitan species living under oligoto mesotrophic conditions (van Dam et al. 1994). It is also encountered in deep and shallow arctic lakes (Cremer et al. 2001) and even in soils, mosses, and ponds of Antarctica (Pinseel et al. 2017). It thus can thrive under harsh polar environmental conditions. Epiphytic diatoms in DAZ 55-1 are mainly represented by *Eunotia praerupta*, indicative of low pH values (Biskaborn et al. 2012, Pestryakova et al. 2012).

The uppermost sediments of the late glacial stage to Holocene in DAZ 55-1 reveal diversification of the diatom assemblage with reappearance of planktonic taxa. In addition to low amounts of *Cyclotella* taxa and *Fragilaria capucina*, the dominance of *Aulacoseira distans* points to wind-induced turbulence in the upper water body (Rühland et al. 2003, Rudaya et al. 2009). In modern lakes of Yakutia, this species is found in more acidic lakes (Pestryakova et al. 2012). At the proximal site PG1756, the time-equivalent diatom assemblages (DAZ 56-3 to DAZ 56-1) also include high amounts of *Aulacoseira* species, but – because of a closer position to the littoral zone – reveal higher proportions of benthic and epiphytic diatoms, such as *Cavinula jaernefeltii* as well as taxa of *Staurosira* and *Planothidium*. These are characteristic diatoms for Yakutian thermokarst lakes of the Holocene (Pestryakova et al. 2012, Biskaborn et al. 2012, 2016). Stepwise increases in the planktonic diatoms mark the boundaries between DAZ 56-3, DAZ-56-2, and DAZ 56-1 around 12.5 and 4.5 ka BP, respectively.

Chironomids

In contrast to the diatoms, chironomids are present throughout the studied sediment cores. About 89 different taxa were identified in the proximal record of site PG1756 and 64 taxa in the distal record of site PG1755. Downcore variations of the most significant taxa and chironomid assemblage zones (CAZ) are shown in Figure 6.

The basal part of the distal record PG1755 (CAZ 55-5: 51-43 ka BP) includes high amounts of taxa of *Tanytarsini* as well as *Chironomus anthracinus*-type and *Chironomus plumosus*-type. This assemblage is consistent with eutrophic conditions, shallow water depth (<3-4 m) and July air temperatures between 10 and 12 °C (Brooks et al. 2007, Nazarova et al. 2015). The two Chironomus taxa often represent pioneer species in developing lake systems (Brooks 1997). CAZ 55-4 (43-33 ka BP) is strongly dominated by profundal taxa, such as the cold stenotherm *Micropsectra insignilobus*-type (Brundin 1956, Brooks et al. 2007). It is associated with other oligothrophic, profundal and acidphilic taxa *Mesocricotopus, Heterotrissocladius maeaeri*-type *1+2, Zalatuschia zalutschicola, Protanypus, Heterotrissocladius grimshawi*-type, *Heterotrissocladius subpilosus*-type. Compared to the underlying assemblage, these taxa indicate similar summer temperatures conditions, but lake deepening and a shift towards more oligotrophic conditions (Brooks et al. 2007, Nazarova et al. 2011). This assemblage develops towards a dominance of *Heterotrissocladius taxa* in CAZ 55-3, pointing to lake deepening to possibly ≥6 m water depth between 33 and 28 ka BP. Decline of *Heterotrissocladius* taxa and an increase in *Parakiefferiella nigra*-type and *Abiskomyia* in CAZ 55-2 (28-12 ka BP), taxa, that are attributed to shallow water littoral and sublittoral conditions in arctic lake ecosystems (Walker et al. 1992, Walker & MacDonald 1995) indicates lake shallowing.

The Holocene part of PG1755 (CAZ 55-1) switches to increased percentages of *Sergentia coracina*-type and *Zalatuschia zalutschicola*, indicating lake deepening and enhanced acidity under mesotrophic conditions (Il'Yashuk & Il'Yashuk 2000, Olander 1999). The chironomid assemblage in the proximal record of site PG1756 also covers the Holocene, but is quite different from the assemblage of site PG1755. CAZ 56-3 and -2 shows prevailing *Sergentia coracina*-type, consistent with mesotrophic and acidophilic conditions in a sublittoral setting (Brodin 1986). The younger part, represented by CAZ 56-1 (<2.0 ka BP), exhibits a shift towards the dominance of *Cladotanytarsus mancus*-type. Together with other associated macrophytes taxa *Polypedillum nubeculosum*-type, *Psectrocladius sordidellus*-type, *Corynoneura arctica*-type, pointing to enhanced nutrient supply, lake shallowing and spreading of macrophytes in the littoral zone of the lake (Brodersen 2001, Nazarova et al. 2013).

LAKE DEVELOPMENT

The interpretation of the palaeoenvironmental record of Lake Billyakh has to invoke two important aspects: (1) the regional late Quaternary glacial history of the area (Stauch & Lehmkuhl 2010, Zech et al. 2011), and (2) the palaeoclimatic and palaeobotanical boundary conditions revealed by former

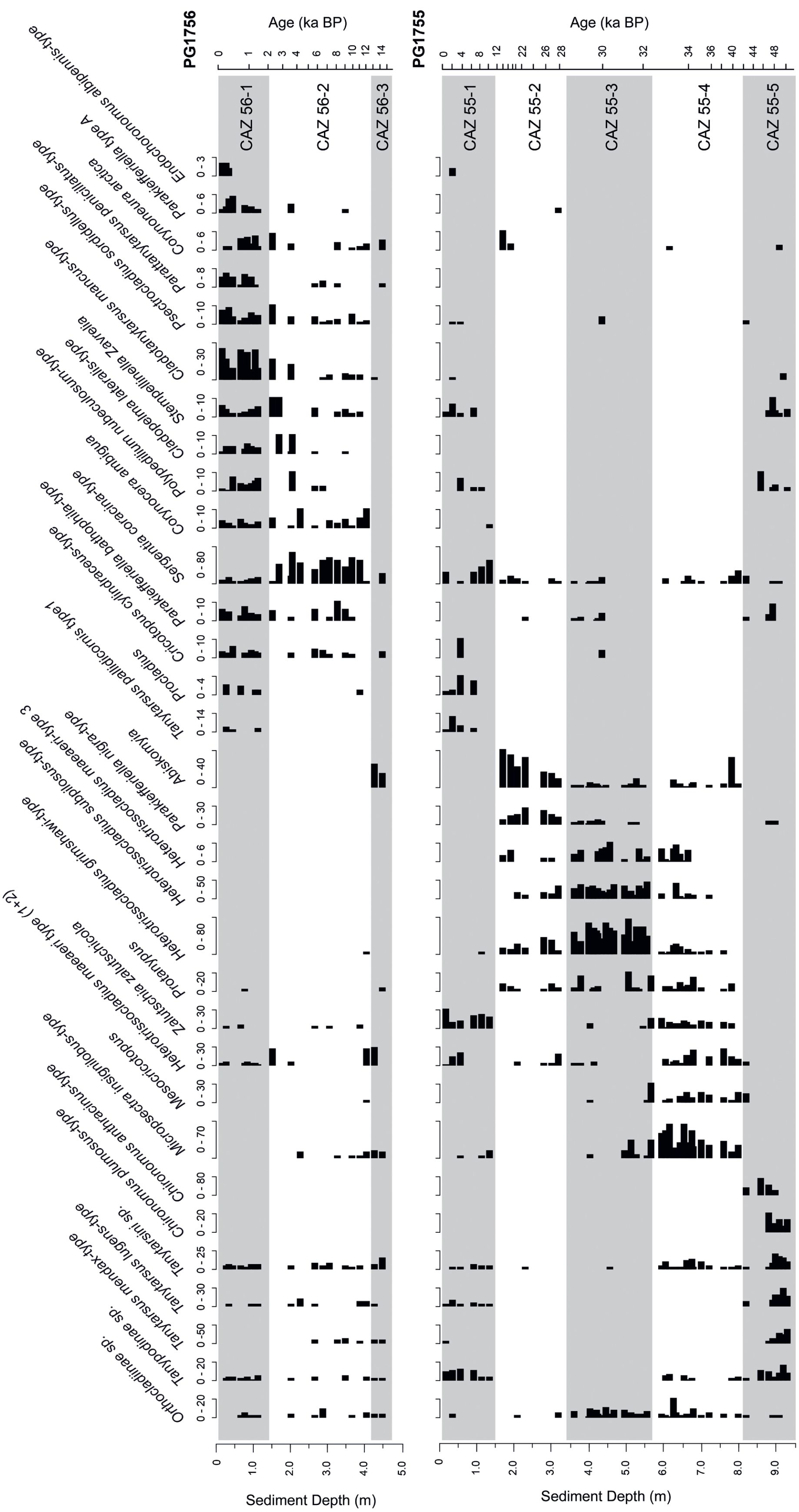

Fig. 6: Downcore distribution of selected chironomid taxa and chironomid-assemblage zones (CAZ) in the sediment records of Lake Billyakh.

Abb. 6: Verteilung ausgewählter Chironomiden-Taxa und Chironomiden-Vergesellschaftungs-Zonen (CAZ) in den Sedimentkernen des Billjach Sees.

palaeobotanical studies (Müller et al. 2009, 2010, Tarasov et al. 2013) (Fig. 7 & 8). The findings suggest distinct turning points in the development of Lake Billyakh:

Lake Stage ≥50 ka BP

This time is not represented by the Billyakh sediment record. During field work, however, basal sands were recovered in the core catcher that prevented deeper penetration (Diekmann et al. 2007). It can be assumed that the two core sites were not covered by water and that lacustrine conditions were confined to the deep basin of Lake Billyakh, if they existed at all. The basal sands might be of aeolian, fluvial, or glacial origin. A former glacial advance is documented by glacial moraines at the southern modern outflow of Lake Billyakh. Remote sensing data indicate that these moraines are connected to a morainic arc in the neighbouring Dyanushka Valley, which was formed not younger than 80-90 ka BP and is referred to as Dyanushka Moraine III (Stauch & Lehmkuhl 2010) (Fig. 7). This age has been inferred from loess-like cover sediments that were dated by IRSL (infrared optically stimulated luminescence) (Stauch & Lehmkuhl 2010).

Lake Stage 50-40 ka BP

From 50 ka BP on, the Billyakh basin permanently was under lacustrine conditions, as suggested by the chironomid record (Fig. 6) and the persistent presence of aquatic palynomorphs in

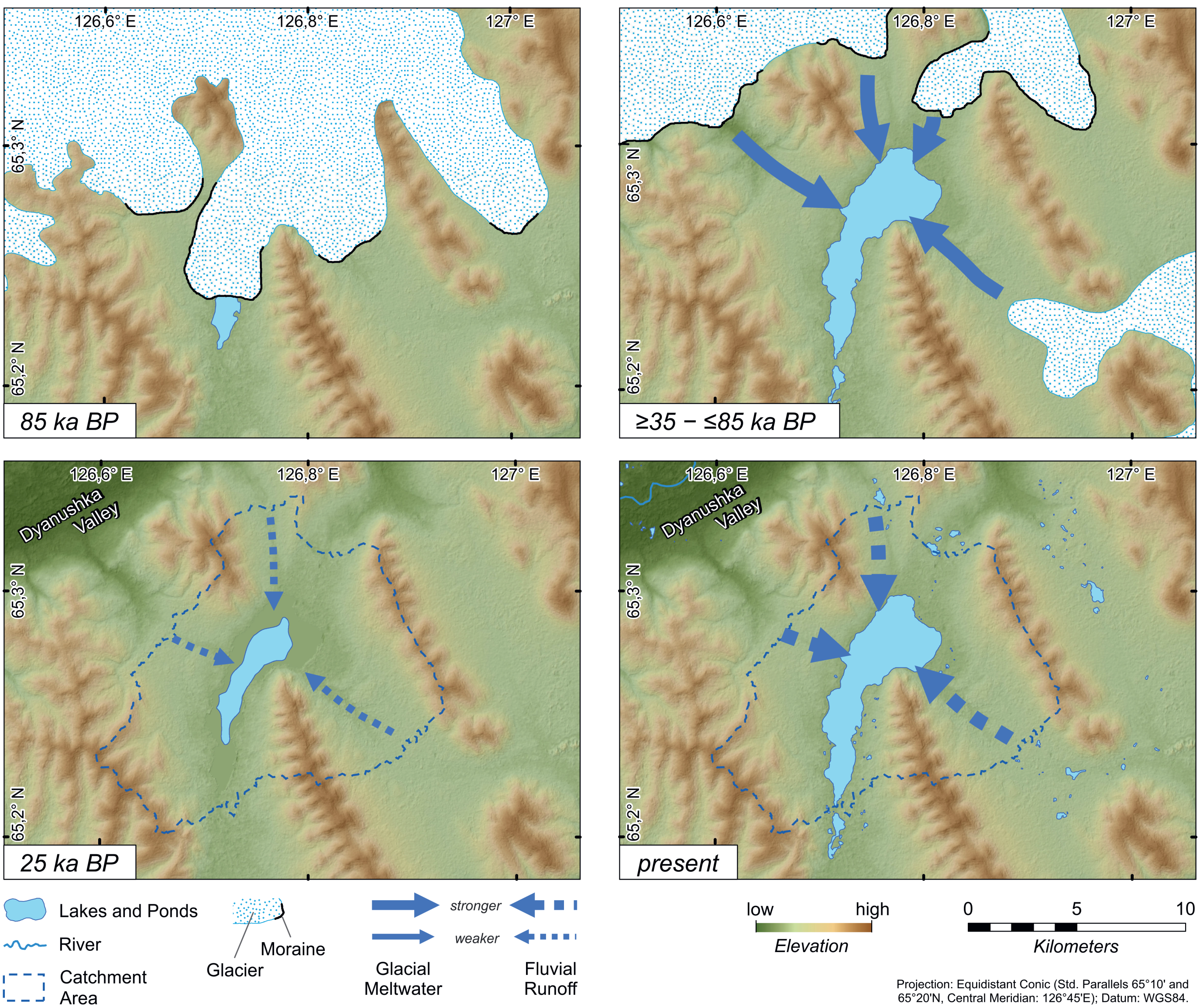

Fig. 7: Palaeogeographic scenarios in the Lake Billyakh area during distinct time slices of the late Quaternary. 85 ka BP: Glacial advance during the late Zyryanian Dy 3 moraine stage; 85-35 ka BP: Strong melt-water influx sometime during the Karginian interstadial climate optimum; 25 ka BP: Lake-level low stand during the cold and dry Sartanian stadial; present: modern conditions. Scenes are on an ASTER Global Digital Elevation Map (ASTER GDEM is a product of NASA and METI, see references).

Abb. 7: Paläogeographische Szenarien im Billjach-Gebiet während ausgewählter Zeitscheiben im Spätquartär. 85 ka BP = Glazialvorstoß während der späten Zyryan-Dy-3-Moränen-Phase; 85-35 ka BP = starker Schmelzwassereintrag irgendwann während des Kargin-Klimaoptimums; 25 ka BP = Seespiegel-Niedrigstand während des kalt-trockenen Sartan-Stadials; present = heutige Bedingungen. Kartengrundlage ist die ASTER Global Digital Elevation Map (ASTER GDEM ist ein Produkt der NASA und METI, siehe Schriftenverzeichnis).

all younger sediments (Fig. 4). The incomplete diatom record thus can be explained by non-preservational rather than palaeolimnological effects. The lake surrounding was occupied by tundra vegetation, indicated by the pollen record of Lake Billyakh (Müller et al. 2010, Tarasov et al. 2013) (Fig. 8). According to the chironomids, this lake stage can be seen as the pioneer phase in lake ontogeny, characterized by shallow and acidic conditions, which might indicate peat wetlands in the catchment. High silt concentrations in the lake sediments may point to aeolian loess supply to the lake, which is well documented in the ice-free valleys and foreland of the Verkhoyansk Mountains during that time.

Lake Stage 40-30 ka BP

Lake Billyakh entered into a deep-lake stage under oligotrophic conditions, shown by all discussed proxies. The concentration of trace elements, such as Zn, point to suboxic conditions in the sediments, which might be connected to temporal stratification of the water column. High clay amounts and high sedimentation rates point to strong aquatic runoff. Though the chironomids do not show summer air warming, climate boundary conditions were less harsh than before and repeatedly allowed for local tree and shrub coverage (Müller et al. 2010, Tarasov et al. 2013). In detail, variations in the pollen record show fluctuations at millennial time scales with affinities to stadials and interstadials recorded in Greenland (Fig. 8). Actually, the highly resolved Zn and Sr/Rb curves shown in this study confirm these short-term cycles and give evidence of fluctuating runoff. In regard to the known regional glacial history, the mid-Karginian deep-lake stage might be related to a time of strengthened deglaciation (Fig. 7). After the glacial advance around 80-90 ka BP, documented by the Dyanushka Moraine III, two younger advances took place and left the arcs of Dyanushka Moraines II and I. Moraine Dyanushka II can be recognized closely north of Lake Billyakh, while Moraine Dyanushka I persisted in the Dyanushka Valley roughly 20 km northeast of Lake Billyakh (Stauch 2006) (Fig. 1). The age of the Dyanushka II advance is unknown, the one for Dyanushka I is dated to 50 ka BP. The latter advance would be consistent with a later retreat after 40 ka BP, observed at Lake Billyakh, but would not have affected the Billyakh catchment according to the evaluation of satellite images and digital terrain models (Stauch 2006). Since the exact reconstruction of the moraines is not supported by field work and dating results outside the Dyanushka Valley, this reconstruction might be ambiguous. From our data, we conclude glacial meltwater runoff from glacier lobes across transfluences into the Billyakh catchment (Fig. 7). The timing with meltwater runoff is also consistent with a meltwater event in the Dyanushka River foreland around 37 ka BP (Zech et al. 2011). An alternative interpretation would be enhanced summer precipitation and/or winter snow melt, lifting up lake level. This interprettation, however, is not consistent with sediment provenance signals that first changed during the next lake stage.

Lake Stage 30-11.5 ka BP

This time interval was characterized by a lowered lake level and strong aeolian silt supply. General aridity is supported by the Billyakh pollen record, which provides evidence for the replacement of wet tundra by drylands with herbs and grasses (Müller et al. 2010, Tarasov et al. 2013) (Fig. 8). The onset of this lake stage is marked by a very apparent change in sediment provenance, which supports the interpretation of a wider glacial connection during the foregoing stages. The clay mineral assemblage in the older lake sediments is consistent with those in loess-like sediments and Moraine I of the Dyanushka Valley, revealed by the data set of Popp et al. (2007). The mineralogical change observed after 30 ka BP at Lake Billyakh gives evidence of the restriction of the catchment to present dimensions after the final retreat of regional glaciers (Fig. 7).

Lake Stage 11.5 ka BP to present

Holocene climate amelioration went along with the second deep-lake stage of Lake Billyakh during the late Quaternary. The lake extended across its former limits and also reached site PG1756 after 14 ka BP. Runoff of aquatic suspensions increased in the boundaries of the modern catchment area and fertilized the lake that led to mesotrophic conditions with enhanced biological productivity and carbon preservation. Vegetation around the lake first was replaced by tundra and shrubs and evolved to the modern boreal forest of today after 7.0 ka BP (Müller et al. 2009, 2010, Tarasov et al. 2013).

PALAEOENVIRONMENTAL IMPLICATIONS

The Billyakh proxy record of the last 50 ka covers the time period of the last three marine isotope stages (MIS), which were characterized by profound insolation-driven climatic and palaeoenvironmental changes on the northern hemisphere (Fig. 8). MIS 1 corresponds to the present Holocene interglacial stage, while MIS 2 is related to the last glacial maximum (LGM) with maximum ice-sheet extent in northern America, northern Europe, and western Siberia that led to a global sea level low (e.g. Cronin 2010). MIS 3 is regarded as a modest interglacial stage, but was punctuated by strong climate fluctuations at millennial time scales, as recorded in Greenland ice cores and in marine sediments of the North Atlantic realm (Bond et al. 1999, Svensson et al. 2008) (Fig. 8). This general and complex pattern of climate change to some extent can also be recognized in eastern Siberia, but also reveals discrepancies, especially in regard to the regional glacial history.

The onset of the lacustrine environment at Lake Billyakh falls into the time frame of MIS 3 and corresponds to the cimate optimum of the Karginian stage in northern Siberia and adjoining Beringia (Lozhkin & Anderson 2011, Wetterich et al. 2014). This warming apparently led to enhanced local runoff at Lake Billyakh, though the interpretation of related glacial retreat and enhanced meltwater runoff is not straightforward in relation to former findings (Stauch & Lehmkuhl 2010). Regardless of the interpretations, Karginian warming is evident by local changes in vegetation (Tarasov et al. 2013) and also supported for winter conditions, as documented by stable-isotope signals in regional ice wedges (Popp et al. 2006). In contrast to subarctic regions further to the east, Karginian warming was less pronounced at Lake Billyakh (Lozhkin & Anderson 2011). The Sartanian interval at Lake Billyakh was characterized by colder and dryer conditions

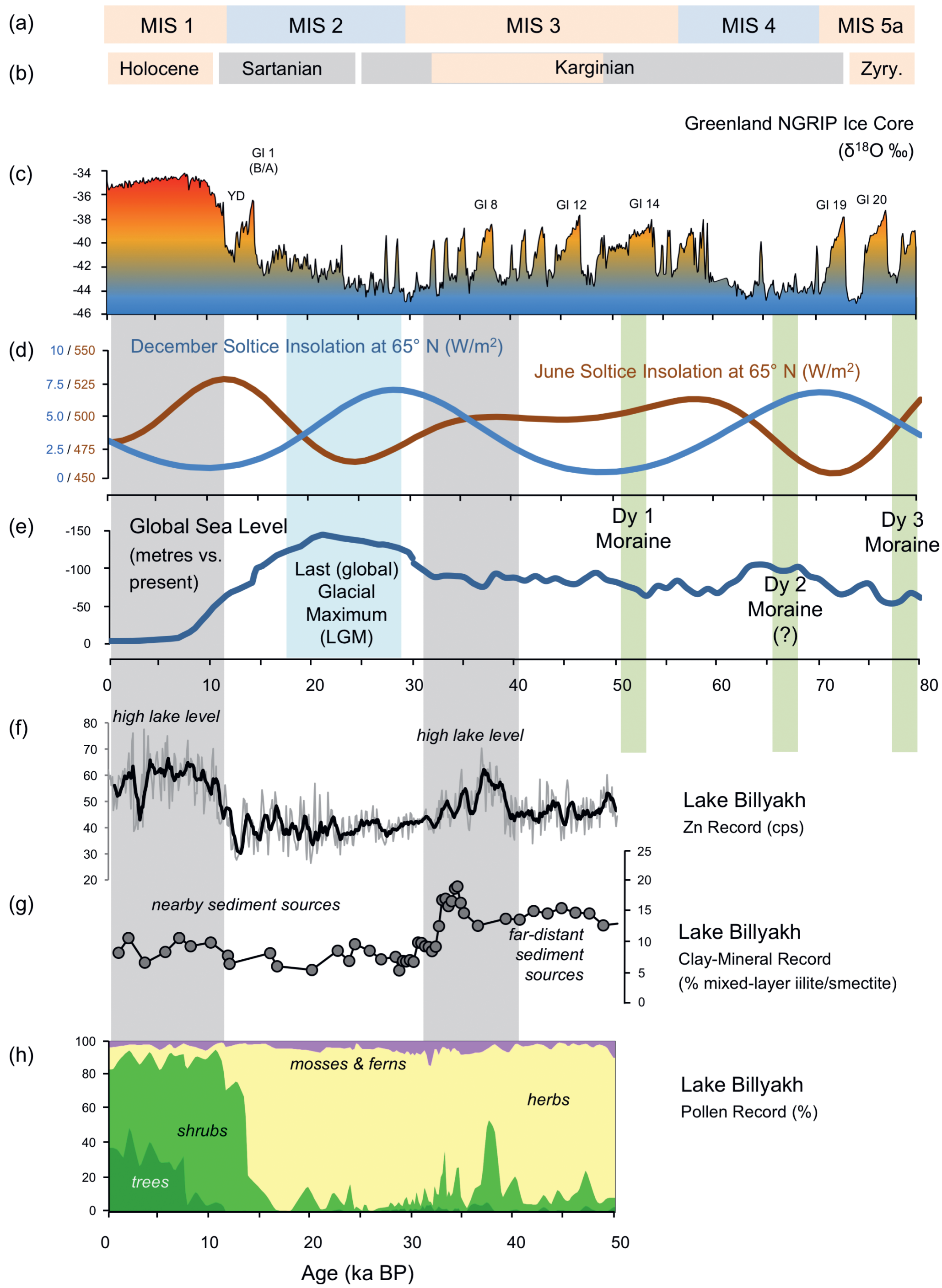

Fig. 8: Compilation of case-study-related palaeoenvironmental informations. (a): global stratigraphy according to marine isotope stages (MIS; Lisiecki & Stern 2016); (b): Russian stratigraphy of the late Quaternary (Lozhkin & Anderson 2011); (c): Greenland ice-core record (Svensson et al. 2008) with indications of Greenland Interstadials (GI), (the Bølling-Allerød interstadial (B/A), and Younger Dryas stadial (YD); (d): summer and winter insolation at the latitude of Lake Billyakh (Laskar et al. 2004); (e): ice-volume equivalent sea level curve (0-30 ka BP from Lambeck et al. 2014, 30-80 ka BP from Rohling et al. 2009) with indication of local Dyanushka moraines (Dy 1-Dy 3, after Stauch 2010); (f): zinc element proxy for lake-level changes at Lake Billyakh, (g): claymineral proxy for changes in detrital sediment provenance into Lake Billyakh; (h): vegetation changes around Lake Billyakh (Tarasov et al. 2013). The lake-level high during the Karginian climate optimum between 50 and 30 ka BP likely was caused either by strong local deglaciation or enhanced precipitation (see scenario ≥35 ka BP in Fig. 7). The Holocene lake-level rise is consistent with climate amelioration after 11.5 ka BP and reaches a maximum during the mid-Holocene, while forests spreaded over the catchment area after 7 ka BP.

Abb. 8: Zusammenstellung von Paläoumweltinformationen der Fallstudie. (a) = Global Stratigraphie nach marinen Isotopenstadien (MIS; Lisiecki & Stern 2016); (b) = russische Stratigraphie des Spätquartärs (Lozhkin & Anderson 2011); (c) = Grönländische Eiskern-Daten (Svensson et al. 2008) mit Angaben von grönländischen Interstadialen (GI), dem Bølling-Allerød-Interstadial (B/A), und des Jüngeren-Dyras-Stadials (YD); (d) = Sommer- und Winter-Insolation auf Breite des Billjachsees (Laskar et al. 2004); (e) = eisvolumenäquivalente Meerespiegelkurve (0-30 ka BP von Lambeck et al. 2014, 30-80 ka BP von Rohling et al. 2009) mit Angabe der lokalen Djanuschka-Moränenstände (Dy 1-Dy 3, nach Stauch 2010); (f) = Zink-Element-Proxy für Seestandsänderungen des Billjachsees, (g) = Tonmineral-Proxy für Änderungen der detritischen Sedimenherkunft in den Billjachsee; (h) = Vegetationsänderungen in der Umgebung des Billjachsees (Tarasov et al. 2013). Der Seespiegelhochstand während des Kargin-Klimaoptimums zwischen 50 und 30 Jahren vor heute wurde entweder durch Schmelzwassereinrag während einer starken Enteisungsphase oder durch gesteigerte Niederschläge verursacht (siehe Abb. 7). Der holozäne Hochstand entwickelte sich mit der postglazialen Klimaerwärmung im Holozän und erreichte einen Höhepunkt vor 7000 Jahren als sich gleichzeitig die heutige Taiga-Vegetation etablierte.

than before at low lake level. This is also indicated by the surrounding vegetation, which was dominated by grass and shrub lands (Tarasov et al. 2013). Also the winter conditions became slighly cooler (Popp et al. 2006). Climate detoriation is consistent with palaeoenvironmental signals at the present coast line of eastern Siberia, where silt-and ice-rich sediments of the Yedoma Formation indicate both summer and winter cooling and arid conditions (Meyer et al. 2002, Wetterich et al. 2014, Schirrmeister et al. 2017), also recorded in the El'gygytgyn lake record of Chukotka (Melles et al. 2007).

The onset of the second high lake level stage after 12 ka BP is consistent with the beginning of insolation-driven Holocene warming (Fig. 8). The response to external climate forcing over the high northern-hemispheric latitudes showed marked temporal differences in respect to the timing of the Holocene thermal maximum (Kaufmann et al. 2004, Brooks et al. 2015). In eastern Siberia, a temporal delay of the onset of the thermal maximum is evident from north to south, which can be attributed to the combined effects of insolation forcing, seasonality changes, and the routing of westerly air masses controlled by the decay of the western Siberian ice sheet remnants (Renssen et al. 2009, Biskaborn et al. 2016). Thus, the climate maximum started between 10 and 9 ka BP in the arctic tundra regions of northern Yakutia (Laing et al. 1999, Andreev et al. 2004, Klemm et al. 2013, Biskaborn et al. 2016) and reached the taiga areas south of the northern polar cycle after 7.0 ka BP (Velichko et al. 1997, Fradkina et al. 2005, Nazarova et al. 2013). This timing is in good agreement with reforestation and warming around Lake Billyakh after 7.0 ka BP (Müller et al. 2009, Tarasov et al. 2013) and maximum lake-level rise at Lake Billyakh (Fig. 8).

While the overall climate history of eastern Siberia more or less matches the trends across the northern hemisphere, the sequence of mountain glaciation in the Verkhoyansk Mountains is out of phase with the global ice-volume pattern, mainly dictated by the ice sheets around the North Atlantic (Fig. 8). Regardless of the exact timing of final deglaciation in the study area, it is evident that the last (global) glacial maximum apparently saw no extended mountain glaciation in the Verkhoyank Mountains of eastern Siberia. This observation is also valid for areas further to the east, including the Kamchatka peninsula (Stauch & Gualtieri 2008, Barr & Solomina 2014). In contrast, the penultimate (global) glacial maximum (MIS 6), represented by Moraine Dy 5 in the study area (Fig. 1), revealed strong glaciations across eastern Siberia (Stauch & Gualtieri 2008, Barr & Solomina 2014). These glaciations even reached the Arctic Ocean to the northeast of the study area (Niessen et al. 2013) and the Sea of Okhotsk (Nürnberg et al. 2011). An explanation of this MIS 6 to MIS 2 paradoxon so far is poorly understood, but has to invoke different configurations of orbital forcing and contrasting boundary conditions of moisture supply (Krinner et al. 2011, Barr & Solomina 2014). During both MIS 2 and MIS 6, the shielding effects of the western Siberian ice sheet prevented moisture supply to Eastern Siberia. In contrast to MIS 2, moisture supply to eastern Siberia likely was possible through Pacific air masses during MIS 6, when northern American ice sheets were reduced and altered atmospheric circulation in the North Pacific (Barr & Spagnolo 2013). The clarification of see-saw effects of northern-hemispheric ice-sheet dynamics thus remains one of the challenging issues in respect to ice age research.

CONCLUSIONS

The study of lacustrine sediments from Lake Billyakh of the eastern Siberian Verkhoyansk Mountains by a palaeolimnological multi-proxy approach reveals the following findings on the regional palaeoenvironmental history: The mountain lake existed during the last 50 ka and was formed by deglacial processes. Our lake record suggests final deglaciation around 35 ka BP in association with a high lake-level stage during the Karginian interstadial. Geomorphological findings, however, point to earlier deglaciation sometime after 85 ka BP. Karginian warming with muted signs of centennial climate variability is documented by short-term lake-level fluctuations and vegetation dynamics. The nature of these variations in relation to Greenland Interstadials in the North Atlantic realm is hard to determine and assess, because of inadequate dating of the sediment record. The Sartanian glacial stage was characterized by low lake level and colder and dryer conditions, followed by Holocene climate amelioration and lake-level rise. The overall climate history of eastern Siberia is consistent with trends across the northern hemisphere, while the sequence of mountain glaciation is out of phase with the global ice-volume pattern, because of complex atmospheric moisture routing effects, which so far are poorly understood.

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