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Climate of the Past

Vegetation history of central Chukotka deduced from permafrost paleoenvironmental records of the El'gygytgyn Impact Crater

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Abstract. Frozen sediments from three cores bored in the permafrost surrounding the El'gygytgyn Impact Crater Lake have been studied for pollen, non-pollen palynomorphs, plant macrofossils and rhizopods. The palynological study of these cores contributes to a higher resolution of time intervals presented in a poor temporal resolution in the lacustrine sediments; namely the Allerød and succeeding periods. Moreover, the permafrost records better reflect local environmental changes, allowing a more reliable reconstruction of the local paleoenvironments. The new data confirm that shrub tundra with dwarf birch, shrub alder and willow dominated the lake surroundings during the Allerød warming. Younger Dryas pollen assemblages reflect abrupt changes to grass-sedge-herb dominated environments reflecting significantly drier and cooler climate. Low shrub tundra with dwarf birch and willow dominate the lake vicinity at the onset of the Holocene. The find of larch seeds indicate its local presence around 11 000 cal yr BP and, thus a northward shift of treeline by about 100 km during the early Holocene thermal optimum. Forest tundra with larch and shrub alder stands grew in the area during the early Holocene. After ca. 3500 cal yr BP similar-to-modern plant communities became common in the lake vicinity.

1 Introduction

El'gygytgyn Impact Crater is located in central Chukotka, approximately 100 km north of the Arctic Circle (Fig. 1). The crater was formed 3.6 Myr ago (Gurov and Gurova, 1979; Layer, 2000). As inferred from geomorphologic research, the study area was never glaciated after the time of the impact ca. 3.6 Myr ago (e.g. Brigham-Grette et al., 2007 and references therein), and thus, the lake is probably the longest archive for Arctic terrestrial environmental and climate history. El'gygytgyn Late Quaternary lacustrine palynological records were first reported by Shilo et al. (2001), followed by more continuous and detailed records published by Lozhkin et al. (2007) and Matrosova (2009). The studied sediments comprise the oldest continuous Quaternary pollen record in the Arctic, which provides history of vegetation and climate changes since ca. 350 kyr.

Generally, sediments from large and deep lakes are valuable paleoenvironmental archives which contain pollen data reflecting vegetation and climate history of surrounding areas. However, such pollen records reflect predominately regional environmental changes because of the large input of long distance wind-transported pollen into the spectra. The Lake El'gygytgyn sediments, where the pollen from a several thousand square-kilometer source area is trapped, also provide a reliable record of extra-regional vegetation and climate changes (Lozhkin et al., 2007; Matrosova, 2009). The

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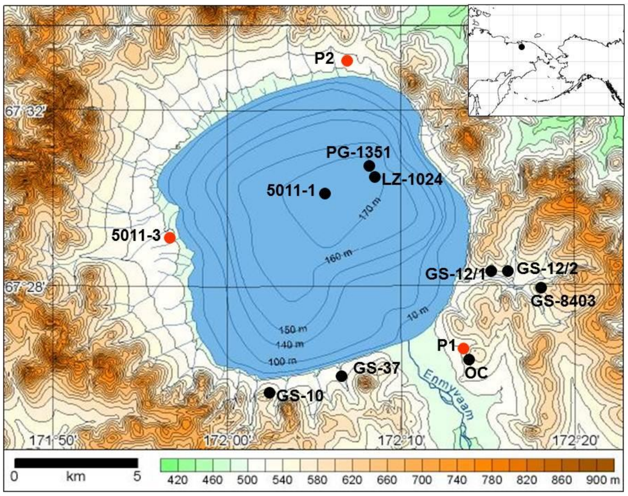

Fig. 1. Location map of the study sites and mentioned cores and sections. OC – Olga Creek terrace section from Enmyvaam River valley (Glushkova and Smirnov, 2007; Shilo et al., 2008; Glushkova et al., 2009).

importance of such continuous long-term regional records is obvious. Nevertheless, short-term palynological records reflecting local paleoenvironmental dynamics are also highly desired. These records document predominate changes in local vegetation and may be compared with extra-regional variations in order to better understand the role of local and regional vegetation in the paleobotanical records, resulting in more reliable environmental reconstructions. Moreover, these records often have better temporal resolution for some abrupt changes such as Younger Dryas, providing unique possibilities for high-resolution environmental studies.

Palynological studies of surface samples from the study area complement reliable reconstructions. A total of 56 surface sediment samples from Lake El'gygytgyn and 26 surface soil samples from the crater slopes have been recently studied (Matrosova et al., 2004; Matrosova, 2006, 2009; Glushkova et al., 2009). These studies demonstrate that pollen of trees and shrubs may reach up to 82 % of the recent lacustrine spectra although the only willow and dwarf birch stands grow in the crater in protected locations. Although soil pollen spectra reliably reflect the local vegetation, pollen of long-distance-transported taxa dominate even there (Matrosova, 2006; Glushkova et al., 2009). It is characteristic that pollen contents of *Pinus pumila* and *Alnus fruticosa*, species not growing in the crater vicinity, may reach up to 15 and 37 % of the spectra consequently. Thus, by interpretations of fossil pollen assemblages it has to be taken into consideration that a significant part of the pollen may have originated from some dozens and even hundreds of kilometers away.

This paper presents palaeoenvironmental and palaeoclimatic changes during the Lateglacial and Holocene inferred from permafrost pollen, plant macrofossil, and rhizopod records from the permafrost surrounding of the El'gygytgyn Crater Lake. The Lateglacial/Holocene transition is considered as a unique period of intensive glaciation and deglaciation events accompanied by remarkable changes in global temperature, atmospheric circulation, air humidity, precipitation and vegetation (Johnsen et al., 1995; Stuiver et al., 1995; Blunier and Brook, 2001). Our studies of three permafrost cores add to a better understanding of paleoenvironmental changes during these time intervals which are not well represented in a high temporal resolution in the lacustrine archive. A comparison of the palynological data from the new permafrost cores and previously studied exposures and lake cores were used to make a local chronostratigraphy scheme because of the partly insufficient geochronological datasets. Such comparison resulted in a more reliable reconstruction of vegetation and climate changes, especially during the transitional intervals from cold to warm periods.

2 Geographical setting

The El'gygytgyn Impact Crater is 18 km in diameter and holds a ca. 170 m deep lake that has a bowl-shaped morphology ca. 12 km in diameter (Fig. 1). The crater is superimposed on the Anadyr lowland and was formed in an Upper Cretaceous volcanic plateau (Belyi, 1998). The crater rim comprises peaks between 600 and 930 m a.s.l. (above sea level), and the lake level is situated at 492 m a.s.l. Unconsolidated Quaternary permafrost deposits cover the crater bottom surrounding the lake. They show a distinctly asymmetrical distribution with a broad fringe of loose sediment that is 500 to 600 m wide to the north and west, and only 10 to 20 m elsewhere around the lake (Fig. 1).

The study area belongs to the continuous permafrost zone with a mean annual ground temperature of −10 °C at 12.5 m depth (Schwamborn et al., 2008a). In 2003, the active layer was about 40 cm deep in peaty silts and reached 50 to 80 cm in sand, pebbles, and gravels. The region is characterized by extremely harsh climate with average annual air temperature ca. −10 °C, mean July temperatures of 4 to 8 °C and mean January temperatures of −32 to −36 °C. The precipitation consists of 70 mm summer rainfall (June–September) and ca. 110 mm water equivalent of snowfall (Nolan and Brigham-Grette, 2007). Climate variables are strongly dependent on oceanic influence expressed in decreasing summer temperatures (Kozhevnikov, 1993). According to Kozhevnikov (1993), long-distance atmospheric convection, bringing air masses from the south and north, dominates at the lake area. These air masses bring tree and shrub pollen grains playing an important role in the recent pollen assemblages from long distances. This situation may also have occurred in the past.

The study area belongs to the subzone of southern shrub and typical tundra (Galanin et al., 1997). The modern treeline for larch (*Larix cajanderi*) and stone pine (*Pinus pumila*) is positioned roughly 100 km to the south and west of the lake (Galanin et al., 1997 and references therein). Although the northern boundary of shrub alder is reportedly much to the north of the lake, the only shrub alder stands grow approximately 10 km from the lake, in the Enmyvaam River valley (P. Minyuk, personal communication, 2010). The local vegetation has been well studied during the last decades (e.g. Belikovich, 1988, 1989, 1994; Kozhevnikov, 1993; Belikovich and Galanin, 1994 and references therein).

According to Belikovich (1994), ca. 40 % of the area (low parts of *smooth crater slope*s and low lake terraces) are covered by *hummock tundra* with *Eriophorum vaginatum*, *E. callitrix*, *E. polystachion*, *Pedicularis pennellii*, *P. albolabiata*, *Carex rotundata*, *C. lugens*, *Salix fuscescens*, *S. reticulata*, *Senecio atropurpureus*, *Ledum decumbens*, *Andromeda polifolia*, and *Vaccinium uliginosum*. Ca. 20 % (low-middle parts of *crater slope*s) are covered by moss-lichens tundra with *Cassiope tetragona*, *Rhododendron parvifolium*, *Senecio resedifolus*, *Ermania parryoides*, *Silene stenophylla*, *Dryas octopetala*, *Crepis nana*, *Potentilla elegans*, and *Androsace ochotensis*. Ca. 15 % (upper mountain plains) are covered by tundra with rare beds with *Salix phlebophylla*, *Pedicularis lanata*, *Artemisia furcata*, *Potentilla elegans*, *Eritrichium aretioides*, *Minuartia arctica*, *Potentilla uniflora*, *Arenaria capillaris*, *Poa pseudoabbreviata*, *Cardamine bellidifolia*, *Saxifraga serpyllifolia*, *Kobresia myosuroides*, and *Crepis nana*. Ca. 10 % are by nival vegetation with *Salix polaris*, *Cassiope tetragona*, *Carex tripartita*, *Phippsia algida*, *Koenigia islandica*, *Saxifraga hyperborea*, *Eritrichium villosum*, *Primula tschuktschorum*, *Hierochloe pauciflora*. Another ca. 10 % are covered by meadow and shrubby tundra with *Artemisia arctica*, *Aconitum delphinipholium*, *Arctagrostis arundinacea*, *Carex podocarpa*, *Festuca altaica*, *Luzula multiflora*, *Senecio tundricola*, *Thalictrum alpinum*, *Veratrum oxysepalum*. Rare steppe-like communities with *Potentilla stipularis*, *Artemisia kruhseana*, *Myosotis asiatica*, *Saxifraga eschscholtzii*, *Papaver lapponicum*, *Senecio jacuticus*, *Woodsia ilvensis*, *Dianthus repens* can be found in rocky habitats. Along the Enmyvaam River and alongside large creeks, grow low willow stands with *Salix tschuktschorum*, *S. saxatilis*, *Androsace ochotensis*, *Empetrum subholarcticum*, *Pleuropogon sabinii*, *Polemonium boreale*, *Beckwithia chamissonis*, *Saussurea tilesii*, *Lagotis minor*, *Pedicularis hirsuta* and meadow-shrub willow communities with *Salix alaxensis*, *S. krylovii*, *Deschampsia borealis*, *Chamerion latifolium*, *Equisetum variegatum*, *Stellaria fischerana*, *Potentilla hyparctica*, *Eutrema edwardsii*, *Cardamine blaisdellii*, *Trollius membranostylus*, *Polemonium acutiflorum*, *Parnassia kotzebuei* and *Poa paucispicula*.

3 Methods

A standard HF technique was used for pollen preparation (Berglund and Ralska-Jasiewiczowa, 1986). A tablet of *Lycopodium* marker spores was added to each sample for calculating total pollen and spore concentrations, following Stockmarr (1971). Water-free glycerol was used for sample storage and preparation of the microscopic slides. Pollen and spores were identified at magnifications of 400 × with the aid of published pollen keys and atlases (Kupriyanova et al., 1972; Kupriyanova and Alyoshina, 1978; Bobrov et al., 1983; Reille, 1992, 1995, 1998). In addition to pollen and spores, a number of non-pollen-palynomorphs, such as fungi spores remains of algae and invertebrate, were also identified when possible and counted. These non-pollen palynomorphs are also valuable indicators of past environments (e.g. van Geel, 2001 and references therein).

At least 250 pollen grains were counted in each sample. The relative frequencies of pollen taxa were calculated from the sum of the terrestrial pollen taxa. Spore percentages are based on the sum of pollen and spores. The relative abundances of reworked taxa (mineralized pollen and spores of Tertiary and early Quaternary age) are based on the sum of pollen and redeposited taxa, the percentages of non-pollen palynomorphs are based on the sum of the pollen and non-pollen palynomorphs, and the percentages of algae are based on the sum of pollen and algae. TGView software (Grimm, 2004) was used for the calculation of percentages and for drawing the diagrams (Figs. 3–5). The diagrams were zoned by a qualitative inspection of significant changes in pollen associations, pollen concentrations and occurrence of particularly indicative taxa. CorelDraw software was used for preparation of the final pollen diagrams.

At a depth of 146.5–151 cm in core P2, we detected a number of well-preserved plant remains, picked using a stereomicroscope and identified by comparison with a modern reference material from the Herbarium Senckenbergianum (IQW). Additionally, a *Carex* identification key (Egorova, 1999) was used.

The core sediments were also studied for testate amoebae tests. The samples were sieved through a 0.5 mm mesh and testate amoebae tests were concentrated with a centrifuge. A drop of suspension was placed on the slide, and then glycerol was added. Normally, 5 slides were examined at x200–400 magnification with a light microscope.

A total of 33 AMS ^{14}C ages were obtained from the studied deposits (Table 1). Plant macrofossils (i.e. grass remains) were picked from the cores P1 and P2 and the uppermost segment of 5011-3 for AMS radiocarbon dating. Because of the lack of plant remains in the lower part of core 5011-3, only bulk organic was dated. AMS datings were done at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research (Christian Albrechts University, Kiel, Germany) and the Poznan Radiocarbon Laboratory (Adam Mickiewicz

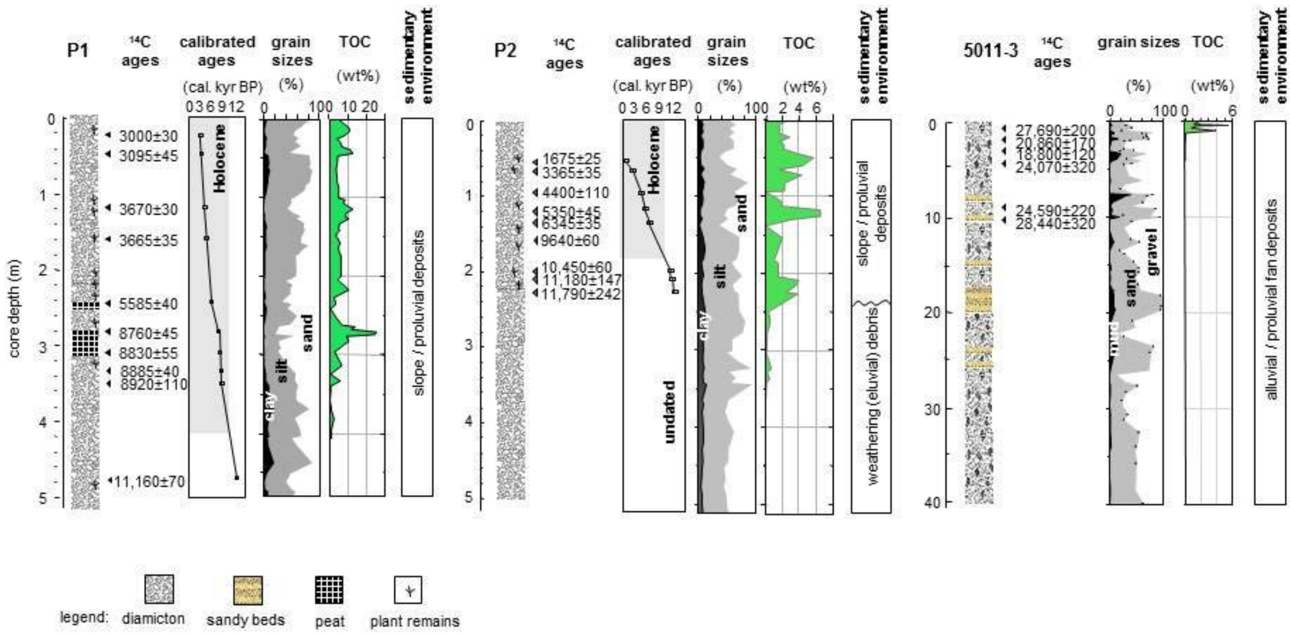

Fig. 2. Lithological, geochronological, grain size and TOC data from P1, P2, and 5011-3 cores.

University, Poznan, Poland). Calibrated ages (cal yr BP) were calculated using "CALIB 6.1.0" (Reimer et al., 2009).

4 Results

4.1 P1 core

The first permafrost core (P1) was extracted from a piedmont terrace about 1.7 km southeast of the lake (67°22′26″ N, 172°13′10″ E, Fig. 1) during field work in summer 2003 (for details see Schwamborn et al., 2006). The study site is located on a slope exposed to the southwest with the angle of 5°. The vegetation cover at core site was relatively dense (ca. 80 %).

The 5 m slope debris core consists mostly of a silty-to-sandy diamicton interpreted as a result from proluvial, colluvial and solifluctional deposition (Schwamborn et al., 2006). Prominent peaty layers interrupt the section between 330 and 220 cm core depth, which is also reflected in maximum values of total organic carbon (TOC on Fig. 2). Non-identified plant remains from several layers have been dated and show a correct depth-to-age relationship (Table 1, Fig. 2). The oldest date from 463 cm depth shows that the oldest core sediments are around 13 000 cal yr BP old or slightly older.

Generally the P1 sequence is very rich in pollen and palynomorphs (Fig. 3). The studied pollen spectra can be subdivided into 5 pollen zones (PZ). PZ-I (ca. 495–430 cm) is dominated by Cyperaceae, Poaceae, and *Betula* sect. *Nanae* and *Salix* pollen. PZ-II (ca. 430–380 cm) shows the significant increase of Cyperaceae pollen content, while *Betula* sect. *Nanae* content is decreased. PZ-III (ca. 380–330 cm) is notable for an increase in *Betula* sect. *Nanae* and appearance of small amounts of *Alnus fruticosa*. Pollen concentration is also increased in the upper part of the zone. The amounts of tree and shrub pollen (predominantly *Alnus fruticosa*) have a maximum in PZ-IV (ca. 330–265 cm). The pollen concentration is the highest in PZ-V (ca. 265–50 cm), which is notable for high amounts of *Betula* sect. *Nanae*, *Alnus fruticosa* and Cyperaceae pollen. Single pollen grains of *Pinus*, *Larix*, and *Picea* are also characteristic for this zone. PZ-V can be subdivided into 2 subzones, the upper one (50–0 cm) showing the higher contents of *Salix* pollen.

P1 has also been studied for rhizopods (Table 2). The only sphagnobiotic/hygrophilic *Heleopera petricola v. amethystea*, pointing to a very wet environment, has been found at 463–473 cm depth. Mostly soil-eurybiotic (e.g. *Centropyxis aerophila*, *C. constricta*, *C. sylvatica*) and hydrophilic (*Difflugia* and *Lagenodifflugia*) species dominated the sediments between 334 and 223 cm. However, sphagnobiotic taxa (*Arcella*, *Heleopera*, *Nebela*, *Centropyxis aculeata*) are also common. The role of soil-eurybiotic species gradually increases in the upper part.

4.2 P2 core

The core was retrieved 12.5 km away from P1 across the lake to the north (67°32′50″ N, 172°07′31″ E), Fig. 1). The site is placed on a gently inclined (< 3°) surface about 100 m from the north lake shoreline (for details see Schwamborn et al., 2008b). The surface is characterized by a boggy environment composed of a loamy substrate covered by grass tundra. Similar to core P1 deposits, core P2 is composed of

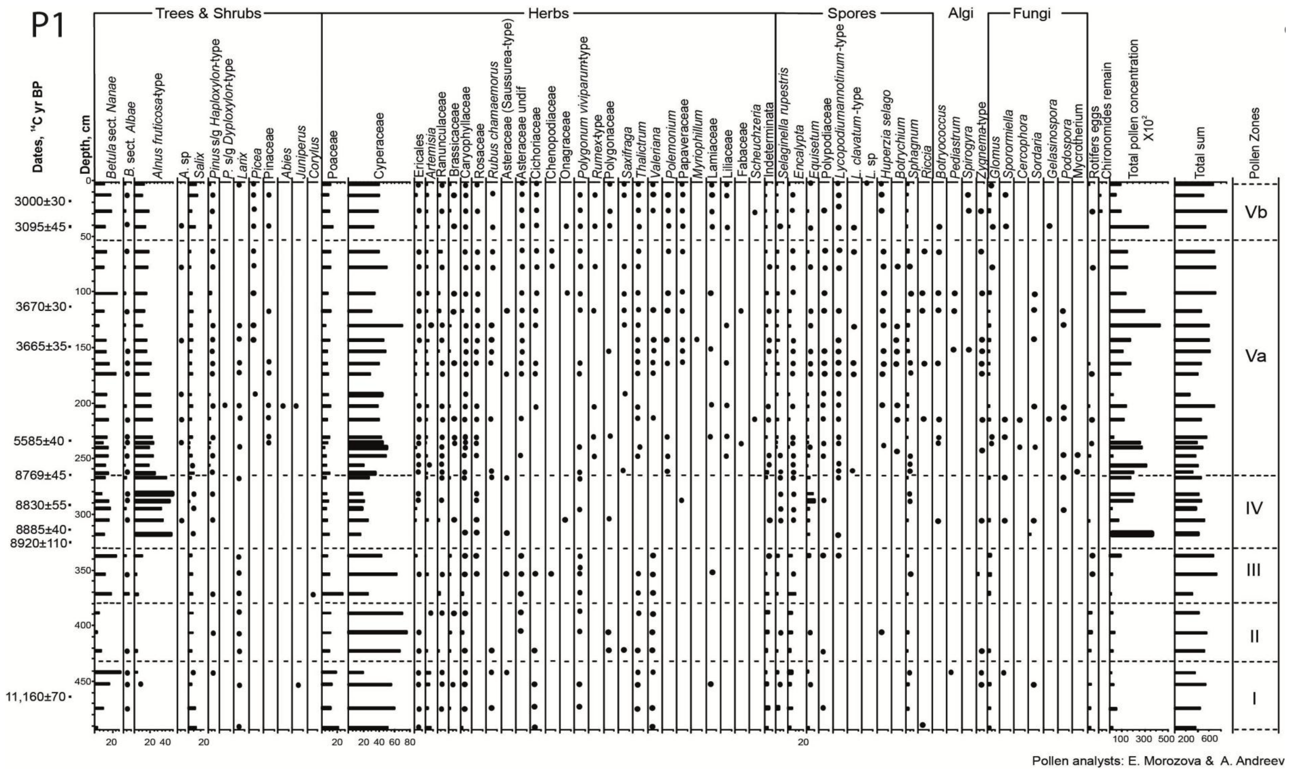

Fig. 3. Percentage pollen diagram of core P1. Dots are < 2 % pollen contents.

a silty-to-sandy diamicton deposition (Schwamborn et al., 2008b). The lower part of the core (510–250 cm) is interpreted as weathering debris of the local volcanic basement. The upper 250 cm consists of proluvial slope washout deposits. The lithological transition between the units is also very distinguishable by an increase of TOC contents (Fig. 2).

Non-identified plant remains found in the P2 deposits have also been dated and show a rather reliable depth–age relationship (Table 1, Fig. 2). Three radiocarbon dates from the sediments between 205 and 226 cm depth demonstrates that these sediments might have accumulated about 14 000–12 400 cal yr BP. Taking into consideration the comparison with other dated pollen records from the area (Lozhkin et al., 2007; Matrosova, 2009; Glushkova et al., 2009), the youngest date seems to be the most reliable.

P2 core sediments are rich in pollen and palynomorphs except for the lowermost 170 cm. The studied pollen spectra can be subdivided into 6 PZ (Fig. 4). Sediments from PZ-I (ca. 510–350 cm) contain only single pollen grains of Pinaceae, *Betula* sect. *Nanae*, *Alnus fruticosa*, and Cyperaceae. Pollen concentration is slightly higher in the lowermost sample which contains few pollen of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Pinus* s/g *Haploxylon* and Cyperaceae. Pollen concentration is higher (up to 2650 grains/g) in PZ-II (ca. 350–330 cm), which is also notable for high content of *Lycopodium* and *Botrychium* spores. The lowermost PZ-I and PZ-II were not used for paleoenvironmental reconstructions because of very low pollen concentration in many samples, which may lead to over-representing some taxa due to possible contamination or selective preservation of palynomorphs (e.g. abnormal presence of spores may indirectly point to it). Pollen concentration is much higher (up to 5800 grains/g) in PZ-III (ca. 330–265 cm), which is characterized by high pollen contents of *Betula* sect. *Nanae*, *Alnus fruticosa*, Cyperaceae, and Poaceae. Rather high amounts of *Pinus* s/g *Haploxylon* and Pinaceae are also notable in this zone. The pollen concentration increases significantly (up to 35 700 grains/g) in PZ-IV (ca. 265–180 cm). *Betula* sect. *Nanae* and *Alnus fruticosa* pollen contents decreased dramatically at the beginning of the zone and gradually increased in the upper part. The zone can be subdivided in two subzones based on the shrub pollen contents. Pollen concentration is highest (up to 83 600 grains/g) in PZ-V (ca. 180–40 cm), which is dominated by pollen of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Cyperaceae, and Poaceae. Additionally, on the 146.5–151 cm depth seeds and short spurs of *Larix dahurica* as well as numerous utricle and nutlets of *Carex rostrata* were found. The uppermost PZ-VI (ca. 40–0 cm) is characterized by decreasing *Betula* sect. *Nanae* and *Alnus fruticosa* pollen contents, while Cyperaceae, *Pinus* s/g *Haploxylon* and *Salix* pollen contents increased.

The P2 core has been also studied for rhizopods, but no tests were found there.

Table 1. Radiocarbon and calibrated ages enclose the two-sigma range of highest probability. The ages have been calibrated using CALIB Rev 6.1.0. (Reimer et al., 2009). The obviously inversed ages were *rejected dates* and marked with *.

Depth (cm), core	Dated material	^{14}C ages (yr BP)	Calibrated age intervals (cal yr BP)	Lab. number	Reference
20, P1	plant remains	3000 ± 30	3078–3268	KIA25979	Schwamborn et al. (2006)
43, P1	plant remains	3095 ± 45	3209–3403	KIA25980	Schwamborn et al. (2006)
114, P1	plant remains	3670 ± 30	3906–4087	KIA23976	Schwamborn et al. (2006)
150, P1	plant remains	3665 ± 35	3890–4090	KIA25981	Schwamborn et al. (2006)
207, P1	plant remains	*8145 ± 45**		KIA28241	Schwamborn et al. (2006)
233, P1	plant remains	5585 ± 40	4493–6447	KIA23977	Schwamborn et al. (2006)
265, P1	plant remains	8760 ± 45	9558–9914	KIA23978	Schwamborn et al. (2006)
292, P1	plant remains	8830 ± 55	9695–10 159	KIA23979	Schwamborn et al. (2006)
314, P1	plant remains	8885 ± 40	9887–10 182	KIA24865	Schwamborn et al. (2006)
325, P1	plant remains	8920 ± 110	9660–10 249	KIA28242	Schwamborn et al. (2006)
463, P1	plant remains	11 160 ± 70	12 801–13 243	KIA23980	Schwamborn et al. (2006)
46, P2	grass remains	1675 ± 25	1526–1626	KIA24866	Schwamborn et al. (2008b)
52, P2	grass remains	3365 ± 35	3553–3692	KIA27258	Schwamborn et al. (2008b)
95, P2	grass remains	4400 ± 110	4812–5320	KIA27259	Schwamborn et al. (2008b)
119, P2	grass remains	5350 ± 45	5998–6218	KIA27260	Schwamborn et al. (2008b)
132 P2	grass remains	6345 ± 35	7171–7330	KIA24867	Schwamborn et al. (2008b)
146–151, P2	*Larix* seeds	9640 ± 60	10 775–11 193	Poz-42874	this study
170–184, P2	bulk organic	*1890 ± 100**		Poz-42875	this study
205, P2	grass remains	10 450 ± 60	12 116–12 560	KIA24868	Schwamborn et al. (2008b)
210, P2	grass remains	11 180 ± 147	12 706–13 320	KIA28243	Schwamborn et al. (2008b)
226, P2	grass remains	11 790 ± 242	13 113–14 220	KIA28244	Schwamborn et al. (2008b)
0–40, 5011-3	plant remains	modern		Poz-33404	this study
40–50, 5011-3	plant remains	modern		Poz-33406	this study
50–60, 5011-3	plant remains	modern		Poz-33407	this study
60–70, 5011-3	plant remains	modern		Poz-33408	this study
70–100, 5011-3	plant remains	modern		Poz-33409	this study
100–110, 5011-3	plant remains	modern		Poz-33410	this study
173–183, 5011-3	bulk organic	*27 690 ± 200**		Poz-35975	this study
208–230, 5011-3	bulk organic	*20 860 ± 170**		Poz-35977	this study
315–325, 5011-3	bulk organic	*18 800 ± 120**		Poz-35978	this study
395–400, 5011-3	bulk organic	*24 070 ± 320**		Poz-35979	this study
845–852, 5011-3	bulk organic	*24 590 ± 220**		Poz-35980	this study
899–910, 5011-3	bulk organic	*28 440 ± 320**		Poz-35981	this study

4.3 5011-3 core

The core was drilled on the western margin of the crater (67°29′04″ N, 171°56′40″ E) approximately 300 m west from the lake shore (Fig. 1). This 141.5 m long core was recovered during a drilling campaign in winter 2008 within the framework of the international ICDP funded project "El'gygytgyn Drilling Project" (Melles et al., 2011). The main objective of the coring was to extend the permafrost record back in time in order to better understand the interaction between catchment processes and lake sedimentation. The sediment core drilled in an alluvial fan consists of sediment layers of sandy gravel to gravelly sand, which is interpreted to represent alternating subaerial and subaquatic parts of the fan. Occasionally intercalations of sandy beds occur, e.g. at 7, 9, 14.5, 18–19.5, 24, and 26 m. The modern setting of the coring site is placed in an alluvial-proluvial sediment fan, and from aerial imagery it is obvious that the fan has a subaquatic prolongation into the lake. In total, 12 samples from the core were AMS ^{14}C dated (Table 1). Although the non-identifiable plant remains (possibly grass roots) were picked throughout the upper meter of the core and expected to provide reliable age control for studied sediments, the ages appeared to be modern, reflecting the presence of modern plant roots in the active layer. The bulk AMS ^{14}C dates from some selected horizons (Table 1) did not provide reliable ages either. These ages are not in a chronological order, reflecting the reworked character of TOC in the samples. The ages are obviously too old, taking into consideration the comparison with other dated pollen records from the area (e.g. Matrosova, 2009; Glushkova et al., 2009; P1 and P2 records). Therefore, age estimations for the 5011-3 core are

Table 2. List of testate amoebae species found in the P1 core sediments. Ecological preferences are according Chardez (1965): Sh – *Sphagnum*, m – green moss, s – soils, w – water.

species	depth, cm/ ecology	114–120	187–200	207–212	212–217	217–223	223–227	227–233	233–236	236–242	242–252	252–262	265–268	268–271	271–274	274–277	277–283	283–288	288–292	292–296	296–314	314–325	325–334	463–473
Arcella arenaria	m												1											
A. arenaria v. compressa	m													2		3								
A. discoides	w						2																	
Bullinularia indica	ms												1											
Centropyxis aculeata	w									2				3	2	3			10		2			
C. aerophila	m	18	4	3		13	19		3	10			14	7	4		5	15	34	19	62	4	2	
C. aerophila v. grandis	w												1					2	2					
C. aerophila v. sphagnicola	Shm			2															6					
C. cassis	shSwm						1						7											
C. cassis v. spinifera	wm													2										
C. constricta	ws	8	4	3	2	1	8	6	3	3		2	11	25	9	6	13	26	87	11	4	5	1	
C. constricta v. minima	w			5		11						2									1			
C. discoides	w												4											
C. ecornis	w			2		3				10		3	16	2	1	10		3	38	2				
C. ecornis (sensu Ogden, Hedley, 1980)	w																	1						
C. elongata	ms					2						1												
C. gibba	wm									2						1					1			
C. orbicularis	wShm												2									1		
C. plagiostoma	s					7								3				3	9	4				
C. plagiostoma f. A (longa)	s								2				1	1	1									
C. platystoma	swm		3	3		2	4	2					3	7		3	6	2	44	30		2		
C. sylvatica	wShm	54	2			9	10	2	3				16	11			20	13	29	5	31	48	3	
C. sylvatica v. microstoma	s	1																						
Cyclopyxis arcelloides	Shwm	5																						
C. eurystoma	wSh	71											1	10										
C. eurystoma v. parvula	s	10		3		2				1						2		7		9	3			
C. kahli	wm		1			3				2		2		2								1		
Plagiopyxis bathystoma	s	5		2									2											
P. callida	wShms			4		3						5										4		
P. declivis	Shs		1																1			5		
Heleopera petricola	ws			3			3						2											
H. petricola v. amethystea	wSh													3										2
H. sylvatica	ms													1										
Nebela penardiana	s						1									1								
N. tubulosa	Sh													5										
Difflugia acuminata	w																							
D. globulosa	wSh	7											3			2	3		5					
D. globulus	wSh	8		7		2	12	8	3			1	5	3	1	32	9	23	19		2	11		
D. lucida	wShm					1								1	1			1						
D. microstoma	w	1																						
D. minuta	w		2				6											1		3		1		
D. penardi	w													2					1				1	
D. pristis	w												1				1	2	1	3				
D. mammilaris	w													3				1						
D. angulostoma	w																	5						
D. mica	w																	6						
D. oblonga v. angusticollis	w																		1					
D. oblonga v. venusta	w																	1						
D. gassowskii	w						2																	
Lagenodifflugia vas	w													1	1									

based on a comparison with the dated pollen sequences from the area.

Generally, the upper 9 m of 5011-3 sediments are rich in pollen and palynomorphs, but only single pollen grains were found below this depth, except in sediments between 19.8 and 19.3 m (Fig. 5). The studied pollen spectra can be subdivided into 7 PZ. PZ-I (ca. 1980–1930 cm) is dominated by *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Cyperaceae, Poaceae, and Ericales pollen. The presence of *Larix* pollen and high contents of *Sphagnum* and *Lycopodium* spores is also characteristic for the zone, where pollen concentration is rather low (up to 3500 grains/g). No pollen has been found between ca. 1930 and 1400 cm and only few pollen grains of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Cyperaceae, Poaceae and single spores of *Sphagnum* and *Lycopodium* have been found in PZ-II (ca. 1400–900 cm). PZ-III (ca. 900–330 cm) is notable for much higher pollen concentration (up to 101 330 grains/gr). The spectra are dominated by *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Cyperaceae, Poaceae, Ericales and spores of *Sphagnum*. Contents of *Sphagnum* as well as pollen concentration reduced significantly in the upper PZ-IV (ca. 330–250 cm). PZ-V (ca. 250–180 cm) is notable for the significant increase of Poaceae pollen content, while contents of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Ericales and *Sphagnum* are dramatically decreased. The pollen concentration is the highest in the zone (up to 829 400 grains/g). The contents of *Betula* and *Alnus* pollen increased again in PZ-VI (ca. 180–100 cm), which is also notable for high content of *Artemisia*. The pollen concentration significantly (up to 15 000 grains/g) reduced in this zone. The uppermost PZ-VII (100–0 cm) is dominated by *Betula* sect. *Nanae*, *Alnus fruticosa*, Cyperaceae, Poaceae, and Ericales, where pollen concentration is very high (up to 770 000 grains/g). Single pollen of long-distance transported *Pinus* and *Picea* are also characteristic for this zone.

The 5011-3 core was also studied for rhizopods, but no tests were found.

5 Discussion: paleoenvironmental reconstructions

5.1 MIS 7(?) environment

The oldest pollen spectra are presented in the lower part (1980 to 1930 cm) of the studied section of the core 5011-3 (PZ-I, Fig. 5). The pollen assemblages are dominated by *Alnus fruticosa*, *Betula* sect. *Nanae* and Poaceae. However, pollen of *Larix*, *Salix*, Cyperaceae, Ericales, Caryophyllaceae and spores of *Sphagnum*, *Lycopodium* and *Huperzia* are also important components of the revealed spectra. They are not dated but the comparison with lacustrine pollen records shows that spectra of our PZ-I are similar to those from the zone E14 of the TL-dated lacustrine core LZ1024 (Matrosova, 2009) and to those from the zone EG2 of the core PG1357 (Lozhkin et al., 2007). Based on the comparison of our record with the lacustrine records, we may suggest a MIS 7 (marine isotope stage 7) age for our PZ-I zone. However, an older age for the revealed interglacial interval cannot be completely excluded.

According to the pollen spectra, shrub alder, dwarf birch, and willows grew in the lake catchment. Relatively high content of larch pollen in the spectra (up to 4.5 %) requires the movement of northern boundary of larch forest at least 100 km to the north. Our conclusion is also supported by the lacustrine pollen records (Lozhkin et al., 2007; Matrosova, 2009). However, the cores drilled in the center of the El'gygytgyn Lake do not contain larch pollen at all and show low presence of *Salix*, Ericales, Caryophyllaceae pollen and *Sphagnum*, *Lycopodium* and *Huperzia* spores. This difference most likely reflects the larger presence of the local components in the 5011-3 core, pointing to the importance of studying of the terrestrial (non-lacustrine) sediments in addition to the lacustrine ones. Taking into consideration all El'gygytgyn pollen records, we assume that open larch forest with shrub alder, dwarf birch and willows dominated the local vegetation during the revealed warm interval. However, grass-sedge dominated communities with other herbs and *Sphagnum* and *Lycopodium* growing in mesic habitats were also common in lake vicinity.

5.2 Lateglacial

Lateglacial sediments are revealed in both radiocarbon dated slope cores (P1 and P2) and in the long permafrost 5011-3 core. Unfortunately, we do not have a good age control for the lowermost part of the core P1. Taking into consideration the P1 bottom age of $11\,160 \pm 70\,^{14}$C yr BP (12 283–13 424 cal yr BP), the most reliable P2 age of $10\,450 \pm 60\,^{14}$C yr BP (12 124–12 654 cal yr BP), and pollen-based correlation with lacustrine pollen records (zone E4 of LZ1024 in Matrosova, 2009) we may assume that our PZ-I of P1 (Fig. 3), PZ-III of P2 (Fig. 4) and PZ-III and PZ-IV of 5011-3 (Fig. 5) accumulated during the Allerød, before 13 cal kyr.

Sediments attributed to the Allerød are dominated by pollen of *Betula* sect. *Nanae*, *Alnus fruticosa*, *Salix*, Cyperaceae, Poaceae, Ericales and spores of *Sphagnum*. The relatively high pollen concentration is also characteristic for the sediments. However, a number of samples show very low pollen concentrations or do not contain pollen at all. Most likely, this reflects a very high accumulation rate during the sedimentation. This conclusion is in a good agreement with thicknesses of Allerød-attributed deposits of about 2.5 m in the P2 core, and at least 6.5 m in the 5011-3 core. Warmer and wetter climate conditions in the Allerød may have intensified erosion and, therefore, produced higher influx of terrestrial material. The absence or very low thickness of the underlying Late Pleistocene sediments might also be connected with these erosion processes.

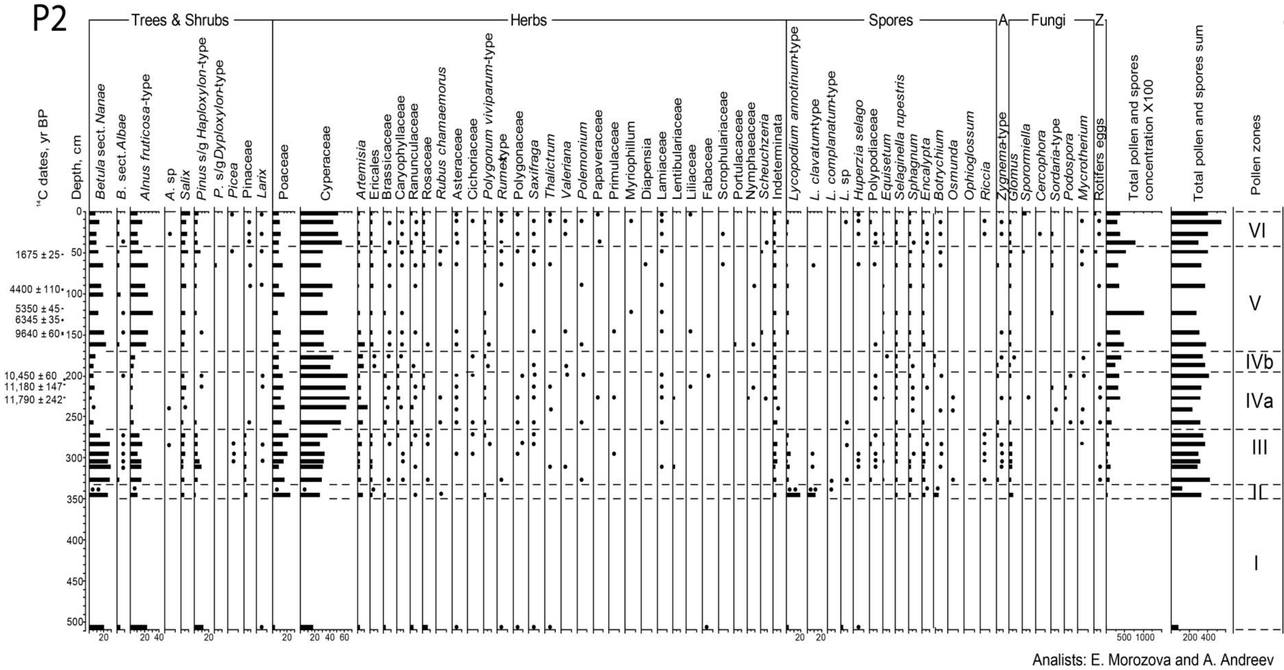

Fig. 4. Percentage pollen diagram of core P2. Dots are < 2 % pollen contents.

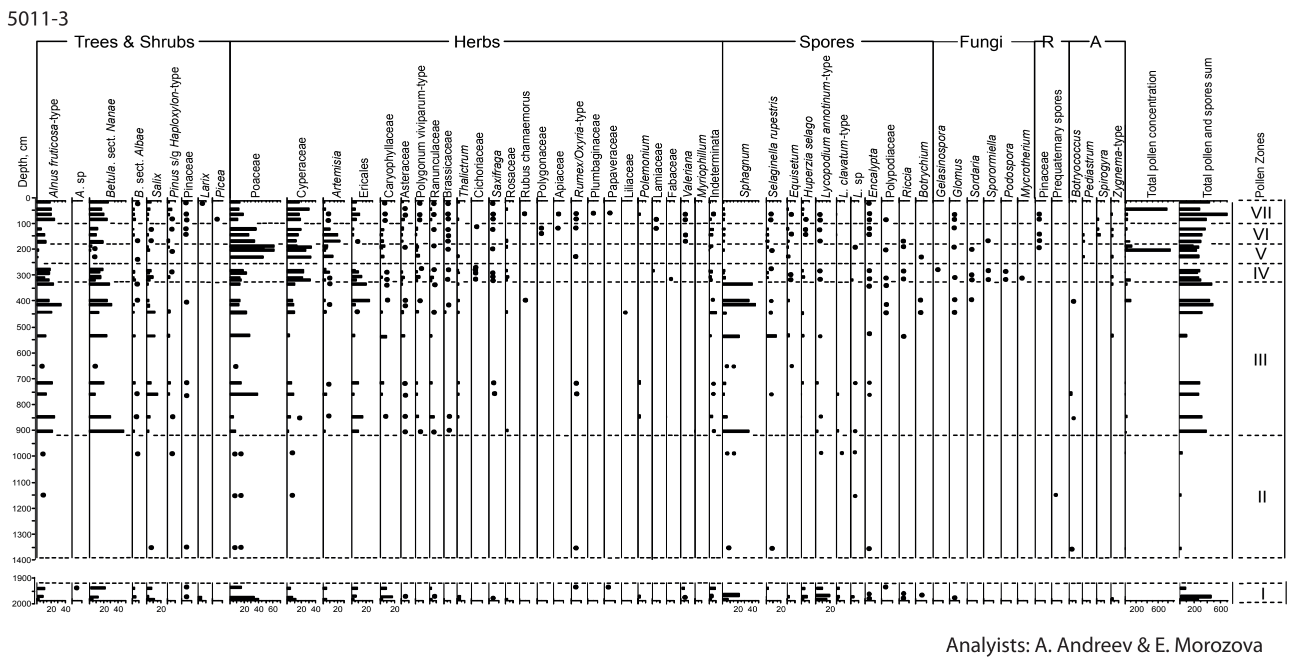

Fig. 5. Percentage pollen diagram of core 5011-3. Dots are < 2 % pollen contents.

The main pollen taxa in the spectra slightly differ from site to site. For example, 5011-3 sediments contain large amounts of *Salix* and Ericales pollen and *Sphagnum* spores; P1 and P2 sediments contain numerous pollen of Cyperaceae; lacustrine pollen records contain larger amounts of long-distance pollen (including *Betula* and *Alnus*). However, the PG1351 lacustrine record also contains large amounts of *Sphagnum* spores in the late glacial sediments confirming wet habitats in the lake vicinity (Lozhkin et al., 2007). The sphagnobiotic rhizopod, *Heleopera petricola*, found in the Allerød-dated P1 sediments is in good agreement with numerous *Sphagnum* spores in the pollen records. Such habitats were probably common along the creeks as today.

Our interpretation of the studied sediments is very similar to those from the PG1351 lacustrine record (Lozhkin et al., 2007; Matrosova, 2009) and from LZ1024 (Glushkova et al., 2009; Matrosova, 2009). Glushkova et al. (2009) also have reported pollen spectra with dominance of shrub pollen taxa from the undated terrace sediments (sections GS-10 and GS-12/1 in Fig. 1) attributed to a Late Glacial warm interval. Similar paleoenvironmental records are also known from adjacent regions (e.g. Brubaker et al., 2005; Lozhkin and Anderson, 2006; Shilo et al., 2006, 2007; Kokorowski et al., 2008; Andreev et al., 2009 and references therein). Lozhkin et al. (2007), based on their PG1351 lacustrine pollen record, have suggested that birch was regionally present at about 12 800 yr ^{14}C BP (15 300 cal yr BP), while alder established in the area around 10 700 yr ^{14}C BP (12 700 cal yr BP).

There are plant macrofossil data from the sediments of section GS-37 (Fig. 1) ^{14}C dated to $12\,215 \pm 40$ yr BP (14 027–14 491 cal yr BP). The studied sediments do not contain any shrub remains. Glushkova et al. (2009) interpreted this as the absolute absence of any shrub stands in the lake vicinity and very severe climate conditions. Thus, it seems that Allerød pollen and plant macrofossil data are contradictory. However, the conclusion about herb dominated tundra vegetation around 14 250 cal yr BP is based on the single studied sample, which reflects very wet, but not a typical tundra habitat. Moreover, they interpret the sediments containing numerous pebbles and eggs of *Daphnia* as the lake terrace periodically overflowed by the lake (Glushkova et al., 2009). It is obvious that shrubs cannot survive in such flooded habitats. Therefore, the found plant macrofossils reflect a very local, flooded habitat, which cannot be extrapolated to the whole lake vicinity.

Thus, according to the pollen spectra, shrub alder, dwarf birch and willows grew in the lake surrounding during the Allerød interstadial with relatively warm and wet climate (Melles et al., 2012). We can reconstruct shrub tundra vegetation with dwarf birch, shrub alder and willow around the lake.

Pollen spectra from PZ-II of P1 (Fig. 3), PZ-IVa of the core P2 (Fig. 4), and PZ-V of 5011-3 (Fig. 5) are dominated mostly by Cyperaceae and Poaceae pollen and reflect disappearance of shrubs from the area, pointing to drier and colder climate which can be attributed to the Younger Dryas. The most reliable ^{14}C dates from core P2 and P1 (Table 1) confirm this conclusion. Pollen spectra with a significant increase in herbs (mostly Poaceae) and *Selaginella rupestris* have also been revealed in the lacustrine sediments (E3 of LZ1024 in Matrosova, 2009), and are interpreted as reflecting the Younger Dryas event (Glushkova et al., 2009; Matrosova; 2009; Melles et al., 2012). Thus, grass-herb tundra dominated the area during the Young Dryas cooling. Younger Dryas-dated pollen records from the adjacent regions (e.g. Anderson et al., 2002; Kokorowski et al., 2008; Andreev et al., 2009, 2011 and references therein) reflect similar environmental changes.

5.3 Holocene

Pollen spectra of the PZ-IVb of P2 (Fig. 4) accumulated before 9640 ± 60 ^{14}C yr BP (11 200–10 780 cal yr BP) show a gradual increase of *Alnus fruticosa* and *Betula* sect. *Nanae* pollen contents reflecting early Holocene climate amelioration. The early Holocene pollen assemblages are also well represented in the undated PZ-III of P1 (Fig. 3), where they are dominated mostly by pollen of *Betula* sect. *Nanae*, Cyperaceae and Poaceae with few *Alnus fruticosa* and *Salix*. Four ^{14}C dates (Table 1) confirm that these sediments were accumulated before 9000 ^{14}C yr BP (10 200 cal yr BP). Similar pollen assemblages have been revealed in the lowermost pollen zone of the so-called Olga Creek section (OC on Fig. 1, Shilo et al., 2008; Glushkova et al., 2009), situated ca. 100 m from P1 coring site. These lowermost spectra are also not ^{14}C dated, however two ^{14}C dates: 9250 ± 90 and 9125 ± 30 yr BP from overlain sediments confirm that these sediments were accumulated before 9300 ^{14}C yr BP (10 550 cal yr BP). Similar undated early Holocene pollen assemblages are also reported by Glushkova et al. (2009) from the section GS-12/1 (Fig. 1). Thus, we may assume that the earliest shrub tundra, with dwarf birches and willows and probably a few shrub alder, dominated the lake vicinity at the onset of the Holocene. The early Holocene pollen records from adjacent regions (e.g. Anderson et al., 2002; Anderson and Lozhkin, 2002; Kokorowski et al., 2008; Andreev et al., 2009 and references therein) have revealed similar environmental changes.

The contents of *Alnus fruticosa* are significantly higher in the PZ-V of the core P2 (up to 30 %) ^{14}C dated to ca. 9600 yr BP (11 200–10 780 cal yr BP) and PZ-IV of the core P1 (up to 50 %) ^{14}C dated around 8900–8800 yr BP (9940–9700 cal yr BP). Most likely, this increase reflects the further distribution of shrub alder stands in the area during the early Holocene. Pollen spectra of the PZ-V of P2 (Fig. 4) radiocarbon dated to about 7200–7300 cal yr BP, PZ-VI of 5011-3 (Fig. 5) and bottom spectra from the terrace section GS-8403 (Glushkova et al., 2009) and the section OC in the Enmyvaam River valley (Glushkova and Smirnov, 2007; Shilo et al., 2008; Glushkova et al., 2009) also demonstrate high amounts of *Alnus fruticosa* pollen in the early Holocene sediments. Moreover, the lacustrine sediments (Matrosova, 2009; Melles et al., 2012) accumulated above sediments attributed to the Younger Dryas also contain very high amounts of *Alnus* (up to 60 %). Large shrub alder trunks and smaller twig fragments ^{14}C dated to 9250 ± 90 and 9125 ± 30 yr BP respectively, as well as numerous undated alder nuts from the same layers, well confirm that shrub alder grew in the lake vicinity at least 10 550 cal yr BP (Shilo et al., 2008). Thus, it is likely that shrub alder stands were well established in the El'gygytgyn Lake Crater at about 11 200 cal yr BP or even slightly earlier.

The well-preserved larch seeds (Fig. 6) found in peaty layer in the core P2 prove the local presence of trees

Fig. 6. Seeds of *Larix* found in core P2.

directly at the lake crater as early as 11 200–10 780 cal yr BP. Larch remains were also found in the sediments accumulated shortly before 9300 ^{14}C yr BP (10 550 cal yr BP) from the OC section (Fig. 1, Shilo et al., 2008; Glushkova et al., 2009), thus, also confirming local presence of the larch trees at the area during the early Holocene. Such forest (tundra-forest) environments are also good habitats for the shrub alder stands. The local presence of *Larix* indicates a treeline shift of about 100 km northward (CAVM-Team, 2003) as a result of the early Holocene climate amelioration. Larch requires a mean temperature of the warmest month of at least 10 °C, thus such climate conditions must have existed at the lake crater during the early Holocene.

The studied early Holocene pollen assemblages slightly differ from site to site. For example, the early Holocene 5011-3 spectra (PZ-VI) show high contents of *Artemisia* (up to 25 %), while GS-8403 spectra reported by Glushkova et al. (2009) contain up to 23 % of Ericales. The difference may reflect the mosaic character of the local vegetation cover and/or different age of the revealed pollen assemblages. The lacustrine record (Matrosova, 2009; Melles et al., 2012) accumulated above the sediments attributed to the Younger Dryas shows very high amounts of *Alnus* (up to 60 %), which might have been transported from a distance and, thus, reflect the regionally dominated vegetation.

Rhizopod tests of soil-eurybiotic *Centropyxis* and hydrophilic *Difflugia* taxa (Table 2) are numerous in the P1 early Holocene sediments; however, sphagnobiotic *Arcella*, *Heleopera*, and *Nebela* are also common. The high contents of hydrophilic and sphagnophilic taxa point to wet oligotrophic and mesotrophic soil environment at the core site. Later, after ca. 6300 cal yr BP, the role of soil-eurybiotic species increased, reflecting drier soil environment.

Thus, pollen and macrofossil data show that forest and/or forest-tundra communities with larches, shrub alder, dwarf birches, and willows were well distributed at the low elevations around the lake during the early Holocene, at least between 11 200 and 9100 cal yr BP. It is most likely that larch and shrub alder grew in the close vicinity to the lake only before ca. 8200 cal yr BP. Similar changes in the high Arctic vegetation cover are also characteristic for coastal areas of the Laptev and East Siberian Seas (e.g. Andreev et al., 2009, 2011 and references therein). Recovered larch remains document that larch grew approximately 100 km from its modern northern distribution limit. The mean July temperatures were at least 10–12 °C (Lozhkin and Anderson, 1995), ca. 4–5 °C higher them modern July temperatures (Shilo et al., 2008). This is in agreement with the early Holocene pollen-based paleoclimate reconstruction from the El’gygytgyn lacustrine record (Lozhkin et al., 2007; Melles et al., 2012) and other high arctic sites (e.g. Andreev et al., 2009, 2011 and references therein).

A number of ^{14}C dates (Table 1) from P1 (PZ-Va) and P2 (PZ-V) cores confirm that permafrost sediments containing relatively high amounts of *Alnus fruticosa* pollen were accumulated until ca. 3500 cal yr BP. Therefore, we may assume that shrub alder might grow around the lake in more protected habitats or very close to the lake vicinity before this time. This conclusion is in good agreement with pollen and plant macrofossil data from adjacent regions, documenting the presence of shrubs and trees to the north from modern distribution areas (e.g. MacDonald et al., 2000; Andreev et al., 2009, 2011; Binney et al., 2009 and references therein). However, the dated woody remains from the Enmyvaam River valley (Glushkova and Smirnov, 2007; Lozhkin et al., 2011) confirm the presence of high shrubs in the area only until ca. 7400 ^{14}C yr BP (8200 cal yr BP). The studied deposits also contain the rather high amounts (up to 35 %) of *Alnus fruticosa* pollen in the sediments accumulated after 7400 ^{14}C yr BP (Shilo et al., 2008; Lozhkin et al., 2011), pointing to a possible local presence of shrub alder; however, the age of the pollen assemblages is unknown.

Generally, late Holocene pollen spectra from the uppermost sediments (upper spectra of PZ-Vb of the core P1, Fig. 3; PZ-VI of the core P2, Fig. 4; LZ-1024 record in Matrosova, 2009 and Melles et al., 2012) show a decrease in contents of *Alnus fruticosa* (mean values are up 20 % and less) and some increases of contents of *Salix*, *Pinus*, *Betula*, Ericales, and Cyperaceae. These changes can be interpreted as disappearance of shrub alder from the lake vicinity. The main components of pollen assemblages slightly change from site to site, reflecting local vegetation cover at coring sites.

The late Holocene pollen assemblages are characterized by higher amounts of *Pinus* s/g *Haploxylon*. The modern boundary of the stone pine (*Pinus pumila*) is about 80 km from the study area (Vas’kovskiy, 1958); thus, it is most likely that all *Pinus* pollen grains are of long distance origin.

Its pollen presence is especially remarkable in the uppermost lake sediments (Lozhkin et al., 2007; Matrosova, 2009) and the modern spectra (Matrosova, 2006), reflecting the extra-regional vegetation pollen influx. Taking into consideration all pollen records from the study area, we may assume that stone pine did not grow around the lake during the Holocene.

Late Holocene sediments dated between ca. 900 and 450 cal yr BP (Glushkova et al., 2009) contain pollen spectra similar to those revealed in this study. They also show lower contents of *Alnus* pollen in many spectra and high fluctuations in *Betula*, Ericales, *Thalictrum*, and *Selaginella rupestris*, reflecting local environments. Thus, pollen data show that herb tundra communities started to dominate in the lake catchment after ca. 3000 cal yr BP.

6 Conclusions

New permafrost records document vegetation and climate changes in the El'gygytgyn Lake Crater during the Late Quaternary. The studied records reflect the local vegetation changes, resulting in a better understanding of the possible role of local and regional components in the fossil pollen spectra and in more reliable environmental reconstructions. It is evident that terrestrial records better reflect the local environments than the lacustrine ones where long-distance transported pollen overshadows the local components.

The oldest pollen spectra of the studied sections of the core 5011-3 are possibly of the MIS 7 age. They document that open larch forest with shrub alder, dwarf birch and willows dominate vegetation, suggesting the northern movement of larch forests. Treeless grass-sedge dominated communities with other herbs and *Sphagnum* and *Lycopodium* growing in mesic habitats were also common in the lake vicinity.

Lateglacial pollen records show that shrub tundra with dwarf birch, shrub alder and willow dominated in the lake surroundings during the relatively warm Allerød interstadial. Rather low pollen concentrations in many samples of Allerød age reflect very high accumulation rate during the sedimentation.

Younger Dryas pollen records reflect dramatic changes in the vegetation cover. Grass-sedge-herb tundra dominated the area, pointing to significantly drier and colder climate.

Forest-tundra with larches, dwarf birches and willows dominate the lake vicinity at the onset of the Holocene between ca. 11 200 and 9100 cal yr BP. Shrub alder stands might grow at the low elevations around the lake during the Holocene, between ca. 11 200 and 3500 cal yr BP. Later, similar-to-modern herb tundra communities dominated the El'gygytgyn Impact Crater.

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