J Paleolimnol (2007) 37:37–47
DOI 10.1007/s10933-006-9021-x

ORIGINAL PAPER

Pliocene to Holocene geomorphic evolution and paleogeography of the El'gygytgyn Lake region, NE Russia

O. Yu. Glushkova · V. N. Smirnov

Received: 26 June 2004 / Accepted: 1 May 2006 / Published online: 9 December 2006

Abstract Geomorphic, lithologhic, and stratigraphic field studies as well as pollen data and mineralogical study have been used to propose Pliocene and Pleistocene paleogeographic reconstructions of the El'gygytgyn meteorite crater area. The moment of impact is recorded above the early Pliocene hill denudation plain as a "chaotic horizon" consisting of fragments of impactite rocks. This chaotic horizon lies between layers of late Pliocene alluvial sediments. During the second half of the late Pliocene, the region was tectonically active, when the Anadyr lowland was uplifted causing alluvial sediments to accumulate in the basins to the south of the crater. Regional climatic cooling, which supported the spread of tundra and the formation of permafrost is characteristically to late Pliocene. The 35–40 m high terrace that roughly follows the 530 m contour interval along the Enmyvaam River formed during the middle Pleistocene. This terrace represents the maximum lake level. Erosion and incision of the upper Enmyvaam River increased due to another wave of uplift. Additionally, El'gygytgyn Lake discharge increased causing lake level to begin to drop in the Middle Pleistocene. Cooling continued, which led to the development of herb-dominated arctic tundra. middle and late Pleistocene glaciations did not reach the El'gygytgyn lake region. The 9–11 m high lacustrine terrace was formed around the lake during the late Pleistocene and the 2–3 m high lacustrine terrace formed later during the Holocene. During the last 5000 years, the lake level has continued to drop as the modern coastline developed.

Keywords El'gygytgyn Lake · Impact crater · Paleogeography · Paleoclimate · Pliocene · Pleistocene · Holocene · Terraces · Pollen · Chronology · NE Russia

This is the *third* in a series of eleven papers published in this special issue dedicated to initial studies of El'gygytgyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

O. Yu. Glushkova (✉) · V. N. Smirnov
North-East Interdisciplinary Scientific Research Institute FEB RAS, 16 Portovaya Street, 685000 Magadan, Russia
e-mail: glushkova@neisri.magadan.ru

Introduction

El'gygytgyn Lake, located in the meteorite crater of the same name in Chukotka, is a unique place to study the Late Cenozoic paleoclimate and paleo-environments of the eastern Arctic. The El'gygytgyn crater is recognized as the largest young meteorite crater on Earth. The crater was formed about 3.58 My ago (Layer 2000) and its geography, geology, and biology have been studied by a number of specialists (Obruchev 1934; Nekrasov and Raudonis 1963; Dietz and Mc Hone 1976; Kozhevnikov 1993). Data about its origin, age, structure, and petrological features related to the impact history of the crater were first published by Gurov and Gurova (1981, 1982), Gurov et al. (1980), Feldman et al. (1980) and later by Belyi et al. (1994), Glushkova (1993). In 1998, an international program encouraged collaborative study of the lacustrine sediment fill. The lake is now recognized for its unique qualities as an unglaciated basin containing late Cenozoic paleoclimatic record. Paleogeographic reconstructions, especially the geomorphic evolution of the basin, highlight the transformation of both the crater basin and the natural environment of the region during the Quaternary glacial and interglacial periods. The regional geomorphology of the basin and the drainage system is an essential ingredient for our understanding of the basin's history.

Paleogeographic reconstructions of the El'gygytgyn crater region are based on a stratigraphic sections of different ages found in exposures of both lacustrine and fluvial sediments. Our study is grounded on the geomorphology of the basin itself and the well-defined fluvial terraces found along the Enmyvaam River that drains El'gygytgyn Lake. We also include data on the lithology and pollen stratigraphy of the lacustrine and river sediments. These were obtained as a result of several expeditions to the El'gygytgyn Lake region between 1993 and 2000 and are presented in the context of published work on related regions of Chukotka.

Early Pliocene

Preserved remnants of ancient topography combined with the study of unconsolidated sediments found in central Chukotka river valleys provide a means of understanding the paleogeographic environments of the early Pliocene in the northwestern part of the Anadyr lowland. Within the low mountainous region surrounding El'gygytgyn Lake, it is still possible to recognize the ancient denudation surfaces that predate the modern river systems. Their altitudes range from 600 m to 900 m defining the maximum height of regional mountains and hills. These surfaces, as a rule, are isometric in plan view and are typically up to the several square kilometers in area. The surfaces are overlain by a 0.3–0.6 m thick mantle of alluvium composed of sand and sandy clay. This material exists due to the extensive weathering of late Cretaceous volcanic rocks of diverse composition: ignimbrites, rhyolites, basalts, and tuffs. Electronic-microscope analysis of the clay fraction in these alluvium deposits (determination of Anisimova, personal comm.) indicates the presence of kaolinite, iron oxides and iron bacteria together with hydromica and montmorillonite. Similar mineral associations were found in buried paleosols to the south of Elgygytgyn Lake in the fluvial outcrops of the Enmyvaam, Mechekrynnetveem and Chanuvenvaam rivers (Fig. 1). This regolith developed on the regional volcanic and sedimentary rocks and is typically composed of oxidized, 1–6 m thick sandy clay. Depending upon the composition of the parent material, the regolith varies in color from vividly-orange to black. Pollen spectra from sediments underlying and overlying the paleosols suggest that its formation began in Late Cenomanian time and finished in Pliocene (Belyi et al. 1994).

Floodplain alluvial sediments ranging from 1.5 m to 3 m thickness occur at the base of these

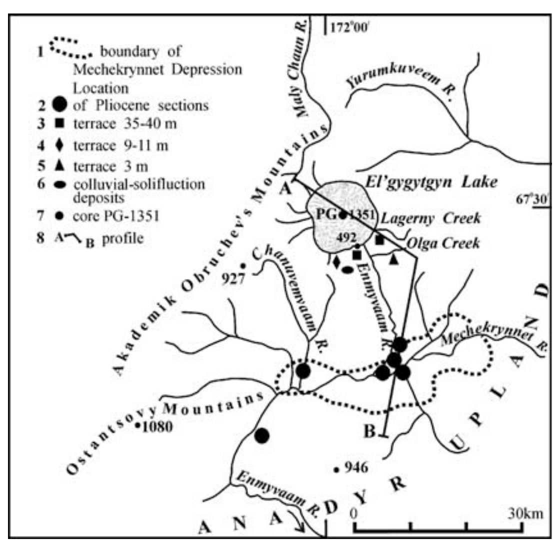

Fig. 1 Location of observation points and sections of Pliocene and Quaternary sediments

paleosols in the fluvial outcrops of the Enmyvaam and Chanuvenvaam rivers 20–24 km to the south of the El'gygytgyn Lake. The sediments are stratified consisting of well-rounded small pebbles, gravel, and fine-grained sand with lenses and interbeds of lignitized plant detritus and humus. The pollen spectra of these deposits suggest the existence of pine, larch, hemlock, birch and alder. Large areas were also occupied by sphagnum bogs, *Betula exilis, B. nana, Alnus* communities, heather and herb-dominated meadows and water tracks (Belyi et al. 1994).

Palynological data obtained from several sections along the Enmyvaam and Chanuvenvaam River valleys, are similar to those studied in the Lower-Kolyma region, on the northwest margin of the Chaunskaya lowland, on the Aion Island and in other regions of the Kolyma and Chukotka (Belyi et al. 1994). According to the regional stratigraphic framework for Paleogene and Neogene sediments in northeastern Russia, this complex most likely corresponds to the *Begunovsky* Formation (Table 1). Mean January temperatures during the time of deposition are estimated to be in the range of –13 to –17°C, with mean July temperatures of 14–17°C. Based upon paleomagnetic data, the *Begunovsky* formation is thought to date from sometime during the Gilbert Chron, 3.4–5.1 Ma ago (Grinenko et al. 1998). The lithological composition of the thick weathered regolith, paleosols, and flood plain alluvium facies as well as the presence of remnant erosional surfaces allow us to speculate that the region had planed relief in the early Pliocene. River drainage systems were dendritic across this relatively flat landscape. Flood plains at the time were covered by *Picea-Abies* taiga, *Larix-Pinus* taiga and *Betula-Alnus* shrubs communities.

End of the Early Pliocene: formation of the El'gygytgyn crater

The age of the El'gygytgyn crater is now well established. The first potassium-argon age determinations of the impactites suggested an age of about 3.5 ± 0.5 Ma (Gurov et al. 1980). More recently an age of 3.58 ± 0.04 Ma was determined by the $^{39}Ar/^{40}Ar$ method (Layer 2000).

Reconstructions of the original crater depth have been attempted by Gurov and Gurova (1981) and Feldman et al. (1980). Given that the diameter of the crater basin from rim to rim is 17–18 km, they estimated the crater ring height to be 0.6–0.9 km, and the crater depth initially in the range of 1.3–1.5 km. Since the time of impact, they suggest that the crater rim has been eroded some 400–500 m. Gurov and Gurova (1981)

Table 1 Location of studied sediments of the El'gygytgyn Lake region in stratigraphics scales (by Grinenko et al. 1998; Supplements to the Stratigraphic Code of Russia 2000; Anderson and Lozhkin (Editors) 2002; Kotlyakov and Komarova 2004

General						Regional stage		Elgygytgyn Lake area
International			Russia			NW Europa	Siberia	
System	Series	Stage	Series	Subseries	Stage			Location
Quaternary	Holocene		Holocene					Terrace 3 m
	Pleistocene	Upper	Pleistocene	Neopleistocene	Upper	Late Weichselian	Sartan	Terrace 9–11 m
						Middle Weichselian	Kargin	
						Early Weichselian	Zyryan	
						Eemian	Kazantsev	
		Middle			Middle			Terrace 35–40 m
					Lower		Oler	Enmyvaam Riv. Terrace 70 m (upper part)
		Lower		Eopleistocene	Upper			
					Lower			
Neogene	Pliocene	Gelasian	Pliocene		Upper		Kutuyakh	Mechekrynnet depression (lower part of sections)
		Piacenzian			Middle			
		Zanclean			Lower		Begunov	

estimated the approximate thickness of ejection out of the crater and suggested that at 17 km away, the ejection blanket was about 30 m thick; at a distance of 25.5 km, the thickness could have been as much as 8 m. They also calculated the thickness of the autigenic impact rocks to be 370–400 m, and the thickness of the lacustrine sediment fill to be in the range of 200–220 m. Seismic work in 2000 and 2003 by Niessen et al. 2007 determined that the total sediment fill in the Crater Lake was more in the range of 320–350 m.

During geomorphic studies of El'gygytgyn crater, it became apparent that the Lagerny Creek basin also has an interesting morphostructure. This creek flows into the lake from the southwestern shore and drains a catchment nearly circular in plan view that sharply intersects the circular rim of the lake basin. Fieldwork in 2000 confirmed that the morphological structure of the Lagerny Creek basin is concentric similar to the El'gygytgyn crater, but much smaller (radius 3.2 km). We distinguished two concentric rims around the basin (Fig. 3) including an inner uplift core of bedrock separated from the outer uplift defined by the arced fractures in the bedrock. Also, a morphologically defined, rounded central basin with the radius of 1 km is clear. Based on these observations and other structural geology, we have proposed that the Lagerny Creek basin may represent a crater-satellite formed at the same time as El'gygytgyn crater (Glushkova et al. 2001).

The moment of impact 3.6 Ma ago is also expressed by the formation of a peculiar ejecta complex composed of impact rock fragments embedded and stratified within existing soils at various distances from the crater (Fig. 2). On the right and left banks of the Enmyvaam River and in the Chanuvenvaam River valley at some sites, a chaotic horizon (''schlieren'' after V. F. Belyi) 1.5–3 m thick occurs overlying the lacustrine-alluvial sediments of Early Pliocene age (Glushkova 1993; Belyi et al. 1994). It consists of deformed sections of weathered paleosols analogous to the undeformed bedding in the soils of the Mechekrynnetveenskaya Basin about 20–24 km to the south of El'gygytgyn Lake (Fig. 3). Bedding is absent in this deformed horizon representing the single moment of impact. Oxidized sandy clays in this horizon are deformed in places as chaotic blocks or as fractured and twisted layers and lenses of irregular form and size. They contain confused inclusions of pebbles of different sizes, boulders, and angular fragments including numerous impactites. Sediments in the chaotic horizon sharply differ from the underlying and overlying alluvial sediments. By composition and texture, this horizon is similar to the chaotic nature of debris flow or landslide deposits (Zaruba and Mencl 1979; Belyi 1982). It is known that landslides commonly occur during earthquakes. It's possible that an earthquake and simultaneous outburst of large quantities of impactites and target rock fragments caused the chaotic horizon to form after the meteorite impact. As a result of this earth motion, mass movement of paleosols with impactite rocks to the valley has occurred. They have covered alluvial sediments. Sandy clays with lenses of small sandy pebbles are tracks of preserved fluvial deposits that overlie the chaotic horizon. Pollen spectra in these deposits suggest an age of the later part of the Early Pliocene (Belyi et al. 1994).

Middle to late Pliocene

The tectonic evolution of northeastern Russia is known to have continued well into the second half of the Pliocene (Smirnov 2000). The Anadyr lowland, in particular, experienced differential uplift, basin development throughout the late Pliocene and early Pleistocene Local uplift caused increased erosion, which fractured the impact crater's outer structure and caused the crater to partially fill with sediments (Glushkova et al. 2001).

Neotectonic movements and the resulting structure around the El'gygytgyn crater region were reconstructed on the basis of elevation and by mapping cross-cutting relationships among faults, fractures and landforms. We speculate that two poorly differentiated uplift episodes occurred within the Akademik Obruchev and Ostantsovy Mountains to the west of the crater. The first uplift is represented by a large block striking to the northeast. Elgygytgyn Lake situated on the southeastern slope of the uplift. Based on the inherited radial to concentric relief expressed in

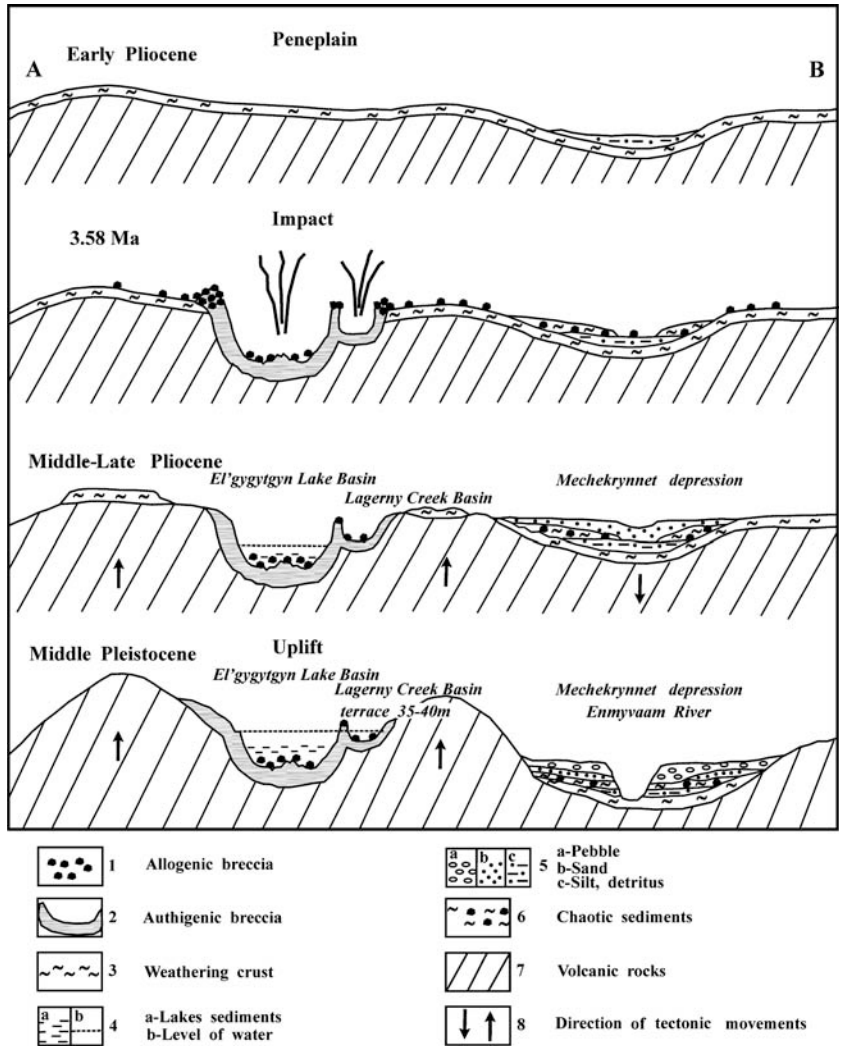

Fig. 2 Major stages of surface transformation in the Elgygytgyn Lake region during the late Cenozoic (A–B—profile, see Fig. 1.)

the hydrology and local mountain massifs, this structural adjustment took place after the crater formed (Glushkova 1993; Glushkova et al. 2001).

Changes in regional uplift are expressed in adjacent basins by the fluvio-lacustrine accumulation of coarse stratified sand and gravel alluvium that contains large woody fragments. These deposits are in the range of 12–22 m thick and are found overlying the chaotic impact horizon. Exposures of these unconsolidated sediments in the Enmyvaam River valley yield pollen spectra that suggest the presence of open grasslands and coniferous forests with the rare admixture of broad-leaved trees. Birch shrubs occupied large areas and alder grew interspersed with wetlands near the rivers (Belyi et al. 1994). The spectra are similar to spectra that characterize the *Kutuyakhsky* horizon (middle–late Pliocene, Table 1) which records the gradual change of the landscape toward tundra and the expansion of larch-birch forests over new areas of permafrost (Grinenko et al. 1998). Similar pollen spectra were found in sediments of deep cores in the Anui and Chaun Basins, in the Zolotoi Range, and in the low-gradient streams of the Kolyma River basin (Belyi et al. 1994).

Early to middle Pleistocene

Erosional activity and the gradual downcutting of the outlet at El'gygytgyn Lake resulted in the

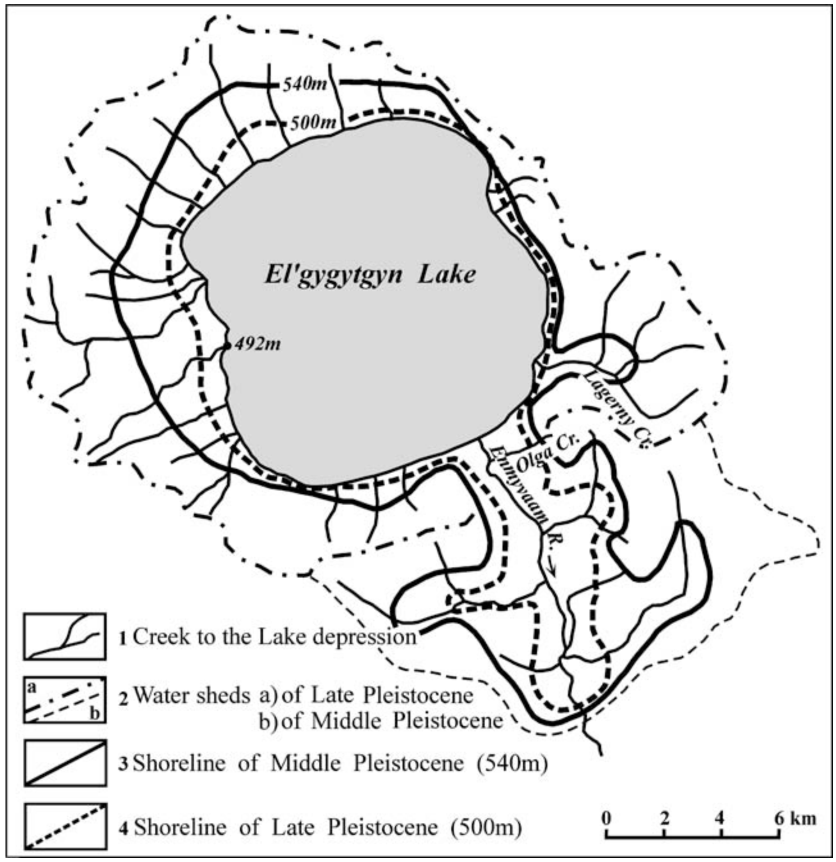

Fig. 3 Reconstructions of the El'gygytgyn Lake coast line during the Middle and Late Pleistocene

formation of fluvial terraces which today are recognized at elevations 60–70 m and up to 140 m above the modern river level (Glushkova 1993; Glushkova et al. 2001). Alluvial sediments have been studied from the upper part of a 70 m high terrace located on the east bank of the Enmyvaam River 18 km down stream from the mouth of the Chanuvenvaam River. There the deposits consist of coarse stratified pebbles of different sizes with interbeds and lenses of fine to coarse-grained sand rich in plant detritus. Some of the horizons are characteristically highly cemented with ferrous oxides, which adds to their compactness. Palynological studies of the upper part of these section by Belaya (personal comm.) grass and grassy, boggy tundra vegetation. Some river valleys were covered by larch forest with minor amounts of birch, rare Siberian spruce, and alder. The underbrush was *Corylus* and *Myrica*. *Selaginella sp*. dominates on the rocky and frost-shattered slopes. This type of vegetation is characteristic of a rather cold climate. This distinctive palynological complex is similar to the *Olersky* horizon of Belyi et al. (1994), considered in the modern Russian stratigraphic framework from the Eopleistocene to lower part of early Neo-pleistocene (equivalent to the Lower Pleistocene and lower parts of the middle Pleistocene in accordance with the international scale) (Table 1).

Middle Pleistocene

Based on fieldwork in 2000, we distinguish a prominent terrace about 35–40 m above lake level along the southeast coast of the El'gygytgyn Lake toward Lagerny Creek (Fig. 3). This section of the terrace is well preserved as a wavecut platform in bedrock. Accumulations of well-rounded pebbles of lacustrine origin occur on the less inclined surface, which is mantled in places by solifluction. The age of the terrace is not known, but we believe it to be of Quaternary age based on its elevation and a morphometric comparison of this paleo shoreline with lacustrine terraces dated Upper Quaternary 9–11 m above the Enmyvaam River. Lacustrine terraces at higher levels have not yet been found downstream. For this reason we consider that the terrace of 35–40 m in the basin marks the highest lake level. The terrace lies approximately along the 530 m topographic contour (Fig. 3). If it is of a middle Pleistocene age, then the diameter of the lake was increased in the western and northern parts of the crater depression by more than 2 km beyond the modern shoreline. In the eastern and southern parts of the crater, the coast line difference would have been small, extending beyond the modern shore for only tens to hundreds of meters. Lagerny Creek basin at this time must have been a small bay of the Elgygytgyn Lake some 3 km in diameter. Based on widespread terraces downstream from the lake, it appears that the lake surface extended for a distance of 10 km down to the Enmyvaam River valley. At this point there is a sharp narrowing of the valley from 3.3 km to 1.3 km. We believe this constriction, at 530 m a.s.l., represents the outlet of the lake during the middle Pleistocene.

Regional assessments of the paleoecology of Chukotka suggest that interglacials became increasingly cooler during the middle Pleistocene while the vegetation continued to evolve. Based upon the palynological work of Verkhovskaya (1986), who has analyzed most of 80 stratigraphic sections of continental and marine sediments in Chukotka, it seems clear that early Pleistocene larch forests with some spruce, pine, fir, *Tsuga* and small and broad-leaved trees and shrubs changed, during the first half of the Middle Pleistocene, to larch-birch forests with some spruce. This vegetation changed to typical tundra during the second half of the Middle Pleistocene (Verkhovskaya 1986). This cooling in the first half of the Middle Pleistocene resulted in the growth of glaciers that filled both the mountain valleys and large areas of lowlands. Even though the physical evidence of glaciation is fragmentary and poorly preserved, our impression is that glaciations during the middle Pleistocene were extensive, perhaps the largest of the Pleistocene. This is consistent with glacial mapping in Alaska (c.f., review by Hamilton 1994). Continued cooling also ran parallel to an increase in regional aridity and continentality. Glacial periods at the very end of the Middle Pleistocene may have been very severe (Verkhovskaya 1986).

Thirteen pollen zones were established by palynological studies of the lacustrine core PG1351 from Lake El'gygytgyn (Shilo et al. 2001; Stetsenko and Lozhkin 2001). Zone E1, representing the basement of the acquired section is dominated by grasses and spores. This result suggests that a herb-dominated arctic tundra was well developed by the late middle Pleistocene. The next pollen zones from E2 to E5 contain more trees and shrub taxa and reflect numerous shifts between grass-birch tundra and grass or grass-alder-birch tundra. Tectonic movements continued during this time, particularly to the south of El'gygytgyn Lake, in the middle of the Enmyvaam River basin where warping up of the Mechekrynnetveemskaya Basin continued. Further lowering of this region likely caused local erosion which resulted in the gradual downcutting of the Enmyvaam River and an increased discharge from El'gygytgyn Lake. Due to the downcutting, the lacustrine terrace at 35–40 m was abandoned.

Late Pleistocene

In northeast Russia, the late Pleistocene is traditionally separated into four chronostratigraphic units: two interbedded glacial and two interglacial horizons (Saks 1953). We distinguish the Kazantsev Interglacial (Eemian) and Kargin Interstadial period (approximately equivalent with the Middle Weichselian) subdivided by the Zyryan (Early Weichselian) and Sartan (late Weichselian) Glaciations (Table 1). Our data and geological surveys in the lake region have shown that the El'gygytgyn Basin has never been glaciated; moraines and other glacial landforms are totally absent in this area. Kundyshev and Verkhovskaya (1984) suggest that ''... in the studied region Late Pleistocene glaciers did not break out of the cirques, as found only on the south-eastern slope of the Ostantsevy Mountains outside the basin''. Lacustrine sediments from the bottom of

El'gygytgyn Lake were deposited continuously, without direct influence from glaciers, back to ca. 250,000 years and probably back to the time of impact (Brigham-Grette et al. 2007; Nowaczyk et al. 2007). The nearest evidence of glacier activity is 40 km to the west in the Ilirnei Range where glaciers extended 25 km to the south toward the Malyi Anui River valley along the Tytylveem and Ilirneiveem River valleys (Glushkova et al. 2001).

In core PG-1351 from El'gygytgyn Lake, the beginning of the Late Pleistocene (Kazantsev Interglacial) is defined at a depth interval of 610–448 cm (Shilo et al. 2001; Nowaczyk et al. 2002). Palynological analysis suggests that during the peak of the last interglacial the lake region was dominated by large-shrub tundra containing *Pinus pumila*, a shrub that requires deep snow in winter. Transitional phytocoenosis between tundra and larch taiga were also present. Climatic conditions varied during the full interglacial and included two episodes of warming separated by one episode of cooling or at least a change in moisture. Sediments of this age have not been found in exposures of the lacustrine alluvial terraces.

During the subsequent Zyryan Glaciation (approximately equivalent to MIS 4), valley and cirque glaciers occupied only the highest mountains of the Anadyr lowland and surrounding ranges. Sediments of an age similar to the Zyryan Glaciation are represented in the zone EG9 of core PG-1351 (Shilo et al. 2001; Lozhkin et al. 2007). The spectra of this zone are dominated by herb tundra grass communities which reflect the deep cooling of climate at this time.

The Kargin Interstadial is a well presented zone EG-10 according to Shilo et al. (2001), Lozhkin et al. (2007). The palynological spectra for this period are dominated by *Artemisia* and herb taxa tundra-stepp with some small shrubs, reflecting conditions only slightly more severe than today. Similar spectra is also found in sediments from the lower part of the 9–11 m high lacustrine terrace on the south bank of the lake (Fig. 1). Terrace fragments at this level are widespread on the south bank of the lake. During this higher lake level, continuous deposition in shallow water occured. Along the southern and southwestern bank these deposits are exposed in steep bluffs that reach the modern beach line. The terrace ranges in width between 20 to 60 m and is composed of a matrix-supported, dark-gray, coarse-layered gravel infilled with sandy loam and lenses and interbeds of poorly rounded pebbles and coarse sand. The pollen in these deposits suggests that the lake was surrounded by shrub birch tundra with some shrub alder and *Pinus pumilla*.

The Sartan Glaciation is reflected in pollen zone EG11 from core PG-1351. The pollen of Herb tundra communities, reflecting deep cooling and aridity, dominate this zone. The Sartan stage is also found in sediments of the lacustrine terraces especially in deposits from the middle and upper parts of the 9–11 m terrace on the south bank of the El'gygytgyn Lake (Glushkova 1993). The sediments are brown–gray loam and loamy-cemented, poorly rounded pebbles.

Continuous deposition on the 9–11 m terrace requires that the lake level was higher to follow the contours of the coast line during the late Pleistocene (Fig. 3). In comparison with the middle Pleistocene, the lake area was much smaller at this time. Using the 500 m line as the modern shoreline, this higher lake level was only some hundreds of meters from the modern shore and only in the western basin was the shoreline nearly a kilometer landward of the modern shore. At this time, a lake no longer filled the Lagerny Creek Basin and the Enmyvaam River tributary valleys. However, the steep southeastern contour of the shoreline did not change in position (Fig. 3). Thus, during the Late Pleistocene, the Enmyvaam River valley attained its modern contours.

Holocene

The beginning of the Holocene is recorded at about 75 cm depth of the core PG1351 (pollen zone EG12) by a sharp change in the pollen spectra. This transition from the late Pleistocene to the Holocene is characteristic of all records from western Beringia and dated to about 12.3 Ka (Shilo et al. 2001). Sediments dated by ^{14}C to the early, middle and late Holocene are also found in exposures of lower lacustrine terraces and in alluvial terraces of Lagerny Creek and the Enmyvaam River. Stratified flood plain

Table 2 Radiocarbon dates in the El'gygytgyn Lake area

Regions	Radiocarbon date and lab. no.	Material dated	Depth, m	References
Olga Creek (Enmyvaam River) alluvial terrace 2.5–3.0 m	6620 ± 30 (MAG-1476)	Peat	1.15	Glushkova et al. (1995)
	7700 ± 50 (MAG-1480)	Peat	1.25	
	8120 + 25 (MAG- 1475)	Wood fragments	1.50	
	9125 ± 30 (MAG-991)	Wood fragments	1.70	
	9250 ± 90 (MAG-1477)	Roots and wood fragments	1.75	
Colluvial-solifluction deposits in the south flange of the El'gygytgyn crater	4650 ± 400 (MAG-1436)	Peat	0.4	
	5080 ± 35 (MAG-1435)	Peat	0.8	
Enmuvaam River terrace 7–9 m	7450 ± 55 (MAG-1433)	Root and wood fragments	3.5	

sediments consisting of lenses and interbeds of mud, sand, and red–brown, poorly decomposed peat, together with large shrub branches and roots can be found at the mouth of the first left tributary of the Enmyvaam River (informally Olga Creek). These sediments have been dated to 9125 ± 30 ^{14}C years BP (MAG-994) up to 7450 ± 55 ^{14}C years BP (MAG-1433) (Table 2). The pollen spectra from these deposits reflect the dominance of high shrub tundra with birch forests, which implies rather warm climatic conditions in the early Holocene. The upper part of the Olga Creek section accumulated during the Middle Holocene, 6620 ± 30 ^{14}C years BP (MAG-1476), when *Pinus pumila* played an important role in the vegetation (Glushkova et al. 1995). Colluvial-solifluction deposits were laid down over the crater valley and lower lacustrine terraces 2.5–3.0 m in elevation during the Late Holocene, starting as early as 5080 ± 35 ^{14}C years BP (MAG-1435), and 4850 ± 400 ^{14}C years BP (MAG-1434) (Fig. 1, Table 2). During the last 5000 years, the lake level has decreased to its present level. We speculate, however, that lake level drop was slower during the early Holocene. The modern contours of the coast line formed in the last 5000 years.

Conclusions

1. In the early Pliocene the El'gygytgyn Lake region was a hilly peneplain covered by a chemical weathering crust. This landscape included poorly incised river valleys filled with a small layer of alluvial sediments.
2. The Elgygytgyn crater and possibly the Lagerny crater-satellite were formed as a result of a meteoritic impact 3.58 Ma years ago.
3. At the middle and late Pliocene, uplift of the Anadyr lowland began. Small amplitude uplifts and creation of local basins also occurred. This resulted in increased erosion, which deformed the outer crater structure and hastened its infilling by sediment.
4. During the middle Pleistocene rates of regional orogenic movements increased, leading to the evolution of the modern drainage system, mountain systems and intermontane depressions. Deposition of the 35–40 m high lacustrine terrace representing the maximum lake position during the Pleistocene began.
5. During the middle and late Pleistocene the region was located in the periglacial zone. As erosion cut deeper, lake level became lower. The 9–11 m high terrace formed during the second half of the Kargin interval, in the Sartan epoch (25–12.5 Ka years ago) and the Enmyvaam River assumed current conditions.
6. The first half of Holocene is characterized by a warming climate. Large shrub vegetation occupied the valleys and the lower parts of slopes. Formation of bogs and pits took place in the lowlands. During the late Holocene, the climate cooled and the lake level lowered to its modern position.

Acknowledgements For comments on the manuscript we wish to thank Lutz Shirrmeister and an anonymous reviewer. We are much indebted to Julie Brigham-Grette for valuable discussions and editing the English version of this manuscript.

References

Anderson PM, Lozhkin (eds) (2002) Late Quaternary vegetation and climate of Siberia and the Russian Far East (Palinological and Radiocarbon Database). NESC FEB RAS, Magadan, 369 pp

Belyi VF (1982) El'gygytgyn Lake Hollow-meteorite impact or geologic stluktula novee estapa larazveteya. Central Chukotka, Tuhokeanckya Geologia, 5:85–91 (in Russian)

Belyi VF, Belaya BV, Raikevich MI (1994) Pliocene sediments of the upper stream of the Enmyvaam River and the age of impact genesis of the El'gygytgyn lake basin. Magadan: North-East Interdisciplinary Scientific Research Institute Far East Branch Russian Academy Sciences, 24 pp. (in Russian)

Brigham-Grette J, Melles M, Minyuk PS (2007) Overview and Significance of a 250 ka Paleoclimate Record from El'gygytgyn Crater Lake, NE Russia. J Paleolimnol DOI 10.1007/s10933-006-9017-6 (this issue)

Dietz RS, Mc Hone J (1976) El'gygytgyn: probably world's largest meteorite crater. Geology 4:391–392

Feldman VI, Granovsky LB, Naumova IG, Nikoshina NN (1980) Some peculiarities of the chemical composition of impactites from the El'gygytgyn meteoritic crater (Chukotka). Meteoritics 39:110–113 (in Russian)

Glushkova O Yu (1993) Geomorphology and the history of the relief development of the El'gygytgyn lake region: The nature of the El'gygytgyn lake basin (problems of study and preservation). North-East Interdisciplinary Scientific Research Institute Far East Branch Russian Academy Sciences, Magadan, pp 26–48 (in Russian)

Glushkova O Yu, Lozhkin AV, Solomatkina TB (1995) Stratigraphy and paleogeography of the El'gygytgyn Lake in the Holocene (Northeastern Chukotka). Pacific Geol 14:23–30

Glushkova O Yu, Smirnov VN, Minyuk PS, Sharpton B (2001) New data on morphostructure of the El'gygytgyn meteoritic crater. Problems of geology and metallogeny in northeast Asia at the boundary of the millennium: Quaternary geology, Geomorphology, Placers, vol 3. North-East Interdisciplinary Scientific Research Institute Far East Branch Russian Academy of Sciences, Magadan, pp 20–22 (in Russian)

Grinenko OV, Sergeenko AI, Belolyubskyi IN (1998) Paleogene and Neogene of the North-East of Russia. Part 1. Explanatory note to the regional stratigraphic scheme of Paleogene and Neogene sediments in the North-East of Russia. Yakutsk Scientific Center Siberian Branch Russian Academy of Sciences, Yakutsk, 68 pp. (in Russian)

Gurov YeP, Gurova YeP (1981) Geological structure and impact metamorphism of volcanogenic rocks in the El'gygytgyn crater. IGS AS USSR, Kiev. Preprint 81-4: 61 pp. (in Russian)

Gurov YeP, Gurova YeP (1982) El'gygytgyn meteoritic crater on Chukotka as an example of young morphologically expressed crater. In: Ryabenko VA (ed) Geology and petrology of meteorite impact craters. Science Thought Dumka, Kiev, pp 125–135 (in Russian)

Gurov YeP, Gurova YeP, Ryabenko VA (1980) Impactites and glass bombs of the El'gygytgyn meteoritic crater on Chukotka. News of Akademy of Sciences, USSR Geological Series 1:54–61 (in Russian)

Hamilton T.D. 1994. Late Cenozoic glaciation of Alaska. In: Plafker G. and Berg H.C. (eds) The Geology of Alaska. Boulder, Colorado: Geological Society of America, The Geology of North America, v.G-1, 813–844

Kotlyakov VM, Komarova AI (2004) Geographic as the multidisciplinary science. News of Akademy of Sciences, Geographical Series 3:8–17 (in Russian)

Kozhevnikov YuP (1993) Vascular plants in the vicinities of the El'gygytgyn Lake. The nature of the El'gygytgyn lake basin (problems of study and preservation). Magadan: North-East Interdisciplinary Scientific Research Institute Far East Branch Russian Academy Sciences, pp 62–82 (in Russian)

Kundyshev AS, Verkhovskaya NB (1984) Development of the drainage network in the upper Anadyr Basin. Geomorphology 4:68–73 (in Russian)

Layer P (2000) Argon-40/argon-39 age of the El'gygytgyn impact event, Chukotka, Russia. Meteorit Planet Sci 35:591–599

Lozhkin AV, Anderson PM, Matrosova TV, Minyuk PS (2007) The pollen record from El'gygytgyn Lake: implications for vegetation and climate histories of northern Chukotka since the late middle Pleistocene. J Paleolimnol DOI 10.1007/s10933-006-9018-5 (this issue)

Nekrasov IA, Raudonis PA (1963) Meteoritic craters. Nature 8:102–104 (in Russian)

Niessen F, Gebhardt AC, Kopsch C, Wagner B (2007) Seismic investigation of the Elgygytgyn impact crater lake (Central Chukotka, NE Siberia): preliminary results. J Paleolimnol DOI 10.1007/s10933-006-9022-9 (this issue)

Nowaczyk NR, Minyuk PS, Melles M, Brigham-Grette J, Glushkova O Yu, Nolan M, Lozhkin AV, Stetsenko TV, Anderson PM, Forman SL (2002) Magnetostratigraphic results from impact crater Lake El'gygytgyn, northeastern Siberia: a 300 kyr long high-resolution terrestrial palaeoclimatic record from the Arctic. Geoph J Intern 150:109–126

Nowaczyk NR, Melles M, Minyuk PS (2007) A revised age model for core PG1351 from Lake El'gygytgyn, Chukotka, based on magnetic susceptibility variations tuned to northern hemisphere insolation variations. J Paleolimnol DOI 10.1007/s10933-006-9023-8 (this issue)

Obruchev SV (1934) On the Airline in Eastern Arctic. All-Union Arctic Institute of General Departament of Northern Marine Way, Leningrad, 184 pp

Saks VN (1953) Quaternary Period in the Soviet Arctic. Water Transport Editorial, Moscow- Leningrad, 627 pp (in Russian)

Supplements to the Stratigraphic Code of Russia (2000) All-Union Geological Institute, St. Petersburg, pp 22–27 (in Russian)

Shilo NA, Lozhkin AV, Anderson PM, Belaya BV, Stetsenko TV, Glushkova O Yu, Brigham-Grette J, Melles M, Minyuk PS, Nowaczyk N, Forman S (2001) The first continuous pollen record of climate and vegetation change during the last 300,000 years. Proc Acad Sci 376(2):231–234 (in Russian)

Smirnov VN (2000) North-East Eurasia. In: Grachev AF (ed) Heotectonics, geodinamics and seismicity of Northern Eurasia. United Institute of Phisics of the Earth Russian Academy of Sciences, Moscow, pp 120–135 (in Russian)

Stetsenko TV, Lozhkin AV (2001) Continuous pollen records of the vegetation cover change during isotopic stages 1–8 – pollen as an indicator for the environmental state and paleoecological reconstruction. International Palynological Meeting, St-Petersburg, pp 206–209 (in Russian)

Verkhovskaya NB (1986) Pleistocene in Chukotka, palynostratigraphy and the major paleogeographic events. Russian Academy of Sciences, Vladivostok, 112 pp (in Russian)

Zaruba K, Mencl V (1979) EngineeringGeology. Publishing House ''World'', 468 pp (in Russian, translation from English)