WARM CLIMATIC INTERVALS IN THE EASTERN ARCTIC DURING THE QUATERNARY: PALYNOLOGICAL DATA FROM LAKE EL'GYGYTGYN, NORTHERN CHUKOTKA

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The continuous sediment record from Lake El'gygytgyn indicates that conifer forest characterized the warmest intervals during the Quaternary in northern Chukotka, where today herb and shrub tundra dominates. Most of these intervals occurred in the Early Pleistocene (e. g., marine isotope stage MIS93, MIS91, MIS81, MIS71) and are associated with pollen assemblages that indicate the widespread presence of light coniferous forest with *Larix* and tree *Betula* and *Alnus*. The most extreme warmth over the past ~2.6 Ma also occurred during the Pleistocene "ice ages". During MIS31 and MIS11, dark coniferous forest with *Picea*, *Pinus*, and *Larix* formed the regional vegetation, representing a northern range extension of ~2000 km for some species. Relatively cool climates characterize the two most recent thermal maximum during MIS5 and the Early Holocene. Although Northern Hemisphere climates generally cooled throughout the Pleistocene, the El'gygytgyn data show the nonlinear nature of climate change and suggest a loss of arctic communities under future global warming.

Keywords: Pleistocene, Holocene, thermal maximum, coniferous forest, pollen analysis.

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INTRODUCTION

The remarkable period within Earth's history, when glaciers became more extensive and persistent in the Northern Hemisphere and modern biocenoses developed, was recognized as early as 1759, but the term "Quaternary" was not used until 1833 when it was first introduced by H. Raboul (Gibbard and Head, 2009). Initially the base of the Quaternary, or the Pliocene-Pleistocene boundary (the division between the Quaternary and Neogene periods; Fig. 1), was placed at 1.8 million years (Ma). While the age of this boundary has long been debated, it became a particular focus in 1948, in part because new geological data indicated that the initial global cooling, a key characteristic of the Pleistocene, began in what was then classified as the Late Tertiary (~2.8–2.4 Ma; Gibbard et al., 2010, Head and Gibbard, 2015). Consequently, many Quaternary scientists argued for an earlier basal age for the Quaternary, whereas Neogene specialists maintained that the original classification should stand. Extensive discussions by Cenozoic stratigraphers ultimately led to the definition of the Pliocene – Pleistocene boundary by the Executive Committee of the International Union of Geological Sciences (IUGS) as 2.588 Ma based on the Gelasian (previously included as the latest age

in the Pliocene) stratotype from the Vrica site in Calabria, southern Italy, supplemented with new data from Monte San Nicola, Sicily (Gibbard and Head, 2009; Gibbard et al., 2010; Head and Gibbard, 2015). The initiation of the Holocene, the most recent epoch within the Quaternary, was ratified by the IUGS as 11.7 cal ka (thousand calendar years before AD 2000) based on the NorthGRIP ice core from Greenland (Walker et al., 2009).

The Pleistocene epoch dominates the Quaternary both in terms of its relative length as compared to the Holocene, but also because of the extraordinary changes to the Earth's climate system that occurred between ~2.6 Ma and 11.7 cal ka. Although conditions during the Early Pleistocene were generally colder than during the Late Pliocene, the major shifts in global climate occurred during the Early-to-Middle Pleistocene transition (EMPT, ~1400–400 ka; McClymont et al., 2013; Head and Gibbard, 2015). This interval is characterized by the: i) increase in amplitude of climatic oscillations; ii) intensified cooling beginning ~1200; iii) increase in global ice volume ~1250–700 ka; iv) progressively longer and stronger glaciations; and v) shorter interglaciations. The most extensive Quaternary glaciations occurred in the last 900 ka during the Middle and Late Pleistocene (Head and Gibbard, 2015). Although much of the fascination with the Pleistocene relates to the

Era	Period	Epoch & Subepoch	Age	Age (Ma)	GSSP
Cenozoic	Quaternary	Holocene			
		Pleistocene	'L'	'Tarantian'	0.012
			'M'	'Ionian'	0.126
			'Early'	'Calabrian'	0.781
				Gelasian	1.806
	Neogene	Pliocene		Piacenzian	2.588
				Zanclean	3.600
		Miocene		Messinian	5.332
				Tortonian	7.246
				Serravalian	11.608
				Langhian	13.65
				Burdigalian	15.97
				Aquitania	20.43

Fig. 1. Quaternary stratigraphic scheme. GSSP – Global Stratotype Section and Point (GSSP) (Gibbard et al., 2010)

Рис. 1. Четвертичная стратиграфическая схема. GSSP – глобальная стратотипическая секция и местонахождение (Gibbard et al., 2010)

build-up of continental ice sheets, this epoch is also punctuated by milder intervals, some of which are characterized by extreme warmth in northern high latitudes (Lozhkin et al., 2007, 2013; Melles et al., 2012; Wennrich et al., 2016). Understanding the effects of warmer than present conditions on landscapes, particularly in the Arctic, has become a great priority in the scientific community as changes related to global warming are becoming increasingly

evident (IPCC..., 2007). We highlight here several of these remarkable interglaciations (MIS93, MIS91, MIS81, MIS71, MIS31, MIS11, MIS5, and the most recent the postglacial thermal maximum (PGTM – Postglacial thermal maximum); Table 1) by examining Quaternary-age palynological data from Lake El'gygytyn, located in polar Chukotka (67°30'N, 172°05'E, 492 m a. s. l.). We focus on the thermal maxima within these warm intervals.

STUDY SITE

A 317-m composite sediment core from Lake El'gygytyn provides an extraordinary, continuous record of changing environments over the last ~ 3.6 Ma (Melles et al., 2012; Brigham-Grette et al., 2013; Wennrich et al., 2016). Formed by a meteorite impact, the ~ 12 km wide lake occupies the center of a ~ 18 km wide crater, which lies within the Anadyr Plateau. The age of crater is based on an $^{40}\text{Ar}/^{39}\text{Ar}$ date (3.58 ± 0.04 Ma; Layer, 2000), whereas the core chronology itself relies primarily on its magnetostratigraphy, as further refined by aligning sediment characteristics (e. g., Si/Ti ratios, biogenic silica) with the marine isotope (Lisiecki & Raymo, 2005) and the 65° N summer insolation (Laskar et al., 2004) curves (see Nowaczyk et al., 2013 for more detail). Today mean annual, July, and January temperatures in the El'gygytyn area are -10.4°C, +8°C and -32°C, respectively (<http://meteo.ru>). Dry conditions in the crater prevail year around (~ 73–200 mm rainfall, 108 mm water equivalent snowfall; Nolan, 2013). Hypoarctic tundra characterizes the local vegetation and is dominated by a discontinuous cover of lichens and Poaceae (Kozhevnikov, 1993; Lozhkin et al., 2007). Woody plants are limited to low-growth forms of *Salix krylovii* and *S. alaxensis* and *Betula exilis*. These shrubs are found in protected areas with organic accumulation (e. g., along streams and terraces).

Table 1. Pollen percentages of conifer taxa (Lake El'gygytyn) for select warm intervals of the Quaternary

Таблица 1. Процентные содержания пыльцы хвойных таксонов (оз. Эльгыгытгын) для определенных интервалов потепления климата в четвертичный период

MIS	Age, ka	Subepoch	<i>Pinus</i> , %	<i>Picea</i> , %	<i>Larix</i> , %
93	2373–2387	Early Pleistocene	50–60	5	20–30
91	2333–2350	Early Pleistocene	60–75	5–10	5
81	2125–2146	Early Pleistocene	50–65	0	< 2
71	1875–1898	Early Pleistocene	15–40	< 2	< 2
31	1062–1081	Early Pleistocene	10–20 (one sample at 55)	15	< 2
11	374–424	Middle Pleistocene	20	20–60	< 5
5	71–130	Middle to Late Pleistocene	10	0	0*
PGTM	13–10	Late Pleistocene to Early Holocene	0	0	0**

**Larix* found in permafrost core, El'gygytyn crater.

***Larix* found in outlet stream from El'gygytyn Lake.

In contrast, the vegetation of the Anadyr Plateau consists primarily of a continuous mosaic of low shrub and herb-dominated tundra with scattered *Pinus pumila* and *Duschekia fruticosa* (shrub *Alnus*). To the north, wet to mesic tundra communities occur in the coastal lowlands. To the south, shrubs have an increased presence on the landscape, in optimal areas forming *Pinus pumila*-*Duschekia fruticosa* high shrub tundra. *Larix cajanderi* forest-tundra has established ~ 150 km to the south and west of Lake El'gygytyn, although the main body of the forest is ~ 300–500 km away.

TRENDS IN SELECT WARM-INTERVAL PALEOVEGETATION, LAKE EL'GYGYTGYN

The warmest climates represented in the El'gygytyn record occurred between 3.5 and 3.35 Ma, (the Piacenzian age of the Late Pliocene) when the regional vegetation was *Picea-Larix-Pinus-Abies-Tsuga* forest (Andreev et al., 2014, 2016). These forests possibly resembled modern conifer forests of eastern Canada and are in stark contrast to the present-day hypoarctic tundra of the El'gygytyn crater and the low shrub tundra of the surrounding Anadyr Plateau. As mentioned above, global cooling began prior to the Pleistocene. By the latest Pliocene, climates had deteriorated sufficiently to eventually eliminate *Abies* from the forest and cause a significant decrease in *Picea*. Tundra and forest/tundra communities became more common in northern Chukotka beginning ~ 3.31 Ma. This change is reflected both in terms of the spatial extent of these vegetation types and in the number and length of periods when nonarborescent pollen dominated.

The warmest intervals recorded in the Quaternary sediments of Lake El'gygytyn all share a common paleovegetational feature with the Late Pliocene in that they are characterized by the regional establishment of conifer forest (Lozhkin et al., 2007, 2017, 2019a, b; Melles et al., 2012; Brigham-Grette et al., 2013; Lozhkin and Anderson, 2013; Andreev et al., 2014, 2016; Zhao et al., 2015, 2017; Wennrich et al., 2016). By the Early Pleistocene (~ 2.6 Ma), the role of conifers in the regional vegetation was greatly reduced as compared to the Pliocene and is indicative of the deteriorating climate. For example, the role of *Pinus* in the northern vegetation was greatly reduced by the Early Pleistocene, and *Larix* was the only conifer species to appear consistently in the El'gygytyn record, occurring in both warm and cool intervals until the latest Pleistocene. The trend towards increasingly cool/dry climates and treeless landscapes through the Quaternary, with the eventual dominance of graminoid-*Artemisia* and *Betula* or *Betula-Alnus* tundra, is punctuated by the widespread establishment of conifer forests in northern Chukotka (e. g., MIS93, MIS91, MIS71, MIS31, and MIS11). The thermal maxima in the most recent in-

terglaciations (MIS5, PGTM), in contrast, lack a significant conifer component.

The four earliest warm intervals of the Early Pleistocene are characterized by similar vegetation (Table 1; Andreev et al., 2014; Zhao et al., 2015; Lozhkin et al., 2019b; Lozhkin and Anderson, unpublished data). While there is general agreement that the regional vegetation was forest dominated by *Larix*, opinions differ concerning the composition of the forest communities. Unfortunately, the growth forms of the prevalent pollen taxa in these assemblages (i.e., *Betula*, *Alnus* and *Pinus* subg. Haploxylon) can not be reliably differentiated by their pollen morphology. Modern ecological associations suggest that the forest understory included shrubs of *Betula*, *Alnus* and *Pinus pumila*. Andreev et al. (2014) and Zhao et al. (2015) interpret the high *Pinus* percentages in MIS93, MIS91, and MIS81 as representing dense thickets of *Pinus pumila* in the forest understory and the presence of *Pinus* shrub tundra at sites beyond altitudinal treeline. Lozhkin and Anderson (unpublished data) suggested that while *Pinus pumila* was probably present, tree *Pinus* along with tree species of *Betula* and *Alnus* were important components of the MIS71 forest. Modest amounts of *Picea* pollen, particularly in MIS93 and MIS91, perhaps indicate the local establishment of the trees, but if so, their presence was limited.

Although these Early Pleistocene intervals indicate strong responses of the vegetation to interglacial conditions, these responses are less striking than that seen during the youngest of the Early Pleistocene (MIS31) and the older Middle Pleistocene (MIS11) warm events (Lozhkin and Anderson, 2013; Lozhkin et al., 2017, 2019a). During the thermal optima of these “super” interglaciations, dark coniferous forest again established in and around the El'gygytyn crater. Members of this forest included *Larix*, *Picea* sect. *Omorica* (likely *Picea ajanensis*), *Picea* sect. *Eupicea* (possibly *Picea obovata*), and *Pinus* subg. *Diploxylon* (*Pinus silvestris*). *Pinus* subg. Haploxylon pollen could represent *Pinus sibirica* or *Pinus koraiensis*. The conifer element of these assemblages is similar to that in modern plant communities of Primor'ye and the Amur basin in southern regions of the Russian Far East (Korotky et al., 2005). This similarity would suggest that *Betula* and *Alnus* in the pollen spectra includes tree species, which likely mixed with *Larix* occupied the most favorable settings along warmer southern and eastern slopes within the crater and the valleys of the Anadyr Plateau. *Picea* and *Pinus* trees were probably restricted to the cooler and wetter northern and western slopes, possibly with *Pinus pumila* thickets at highest elevations. The extremely low percentages of herb pollen (< 5% of total arboreal and nonarborescent pollen) suggests that the conifer forest was closed and extended to higher elevation sites both within the crater and on

the Plateau. These low percentages might also indicate paucity or absence of *Pinus pumila* in the forest understory, as the shrub requires an open canopy.

The climatic optimum of MIS5, unlike the above warm intervals, lacks conifer pollen (note: *Larix* pollen was found in a permafrost core taken adjacent to the lake; Andreev et al., 2012), but like these earlier interglaciations, *Betula* and *Alnus* pollen is abundant (Lozhkin et al., 2007; Lozhkin and Anderson, 2013). The data from the Lake El'gygytyn core suggests the presence of *Betula-Alnus* forest mixed with shrub tundra. Data from riverine sections, which tend to have few radiocarbon dates but whose regional stratigraphy indicates their deposition during the last interglaciation, suggest the establishment of open *Betula* forest in the Anadyr basin and *Larix-Betula-Alnus* forest with *Pinus pumila* in northern Chukotka.

The PGTm is not clearly defined in the El'gygytyn pollen record, although *Larix* macrofossils were found in an exposure along the lake's outlet stream (Shilo et al., 2008). However, analog analyses suggest increased summer and winter warmth and greater summer precipitation between ~9.6–12.7 ka cal (Lozhkin et al., 2007; Lozhkin and Anderson, 2013). Macrofossils from this time indicate the presence of tree *Salix* and *Alnus* beyond modern latitudinal treeline in northern Chukotka (Lozhkin, 1993). Biome analysis of late glacial assemblages from across Beringia indicates the dominance of deciduous forest and forest-tundra between ~13 and 10 cal ka (Edwards et al., 2005).

CONCLUSIONS

Interglacial thermal maxima throughout the Pleistocene are marked by the expansion of conifer forests within the El'gygytyn crater and surrounding Anadyr Plateau. For most intervals (e. g., MIS93, MIS91, MIS81, MIS71, MIS5) the vegetation was a cold deciduous or light coniferous forest. *Larix* was the dominant component, but the forest probably also included tree species of *Betula* and *Alnus*. However, in the extreme or “super” interglaciations of (MIS31, MIS11) a cold evergreen or dark coniferous forest of *Larix*, *Picea* (possibly *Picea ajanensis* and *Picea obovata*), and *Pinus* (*Pinus silvestris* and *Pinus koraiensis* or *Pinus sibirica*) characterized the vegetation of northern Chukotka and represent the mildest regional climates of the Quaternary. The Holocene thermal maximum is poorly recorded in the El'gygytyn pollen record suggesting a more modest warming as compared to the Pleistocene. Other paleobotanical data from northern Chukotka, however, indicate a latitudinal extension of treeline and presence of a cold deciduous forest of *Larix*, *Betula*, and *Alnus* in areas that are now shrub tundra.

Despite the general characterization of the Pleistocene as a time of extensive and persistent glaci-

ation, the Lake El'gygytyn pollen data indicate that the warmest and wettest climates (i. e., MIS31, MIS11) of the last 2.6 Ma occurred during the “ice ages” and not the Holocene. The El'gygytyn record further suggests that the two most recent thermal maxima (i. e., MIS5.5, PGTm) are relatively cool compared to the warm intervals of the Early Pleistocene and certainly as compared to the “super” interglaciations. Melles et al. (2012) speculated that high levels of greenhouse gases and acidification of the oceans were significant factors influencing the extreme warmth of MIS31 and MIS11. The effects of increasing greenhouse gases and ocean acidification are being seen today in northern regions (e. g., reduced extent and duration of sea ice). Additionally, linked climate and vegetation models show the strong likelihood of significant changes in the composition and structure of arcto-boreal vegetation as greenhouse gas emissions rise (Nolan et al., 2018). If the Lake El'gygytyn data provide any insight to the extent of possible vegetation response to a warm earth scenario, arctic vegetation will disappear from northeasternmost Asia to be replaced by a *Picea-Larix-Pinus* forest.

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ИНТЕРВАЛЫ ПОТЕПЛЕНИЯ КЛИМАТА В ВОСТОЧНОЙ АРКТИКЕ В ЧЕТВЕРТИЧНЫЙ ПЕРИОД: ПАЛИНОЛОГИЧЕСКИЕ ДАННЫЕ ОЗЕРА ЭЛЬГЫГЫТГЫН, СЕВЕРНАЯ ЧУКОТКА

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Непрерывные палинологические данные осадков оз. Эльгыгытгын показывают, что хвойный лес был характерен для теплых интервалов четвертичного периода на севере Чукотки, где сегодня преобладают травянистые и кустарниковые тундры. Большинство таких интервалов относятся к раннему плейстоцену (например, морские изотопные стадии MIS93, MIS91, MIS81, MIS71) и ассоциируют с пылевыми спектрами, которые указывают на широкое распространение светлохвойных лесов с *Larix* и, возможно, с древовидными *Betula* и *Alnus*. Самые экстремальные потепления за последние ~ 2.6 млн лет происходили также и в плейстоценовые «ледниковые периоды». Во время MIS31 и MIS11 темнохвойный лес с *Picea*, *Pinus* и *Larix* формировал региональную растительность, представляющую расширение северного ареала примерно на 2000 км для некоторых видов. Относительно прохладный климат характеризует два самых последних максимума тепла во время МИС5 и раннего голоцена. Хотя климаты Северного полушария в целом холодные в течение плейстоцена, данные оз. Эльгыгытгын показывают нестабильность изменения климата и позволяют предположить, что арктические сообщества могут исчезнуть в результате глобального потепления в будущем.

Ключевые слова: плейстоцен, голоцен, термический максимум, хвойный лес, анализ пыльцы.

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