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Quantitative dynamics of the early Pliocene climate and vegetation in the Lena River Delta (northern Yakutia, Eastern Siberia)

Olesia V. Bondarenko[1] & Torsten Utescher[2,3]

Olesia V. Bondarenko [1]*
e-mail: laricioxylon@gmail.com

Torsten Utescher [2,3]
e-mail: t.utescher@uni-bonn.de

[1] Federal Scientific Center of the East Asia Terrestrial Biodiversity FEB RAS, Vladivostok, Russia

[2] Senckenberg Research Institute and Natural History Museum, Frankfurt M., Germany

[3] Steinmann Institute, University of Bonn, Bonn, Germany

* corresponding author

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ABSTRACT

Early Pliocene climate and vegetation evolution in the Lena River Delta (northern Yakutia, Eastern Siberia) are quantitatively studied for the first time in detail, based on a palaeobotanical record. Palaeobotanical data for this time-interval were obtained on 28 palynofloras from the Sardakhskaya Formation in the coastal cliffs of the Sardakh-Sisse Island (Lena River Delta). In this first integrative study we apply the Coexistence Approach (CA) for quantification of palaeoclimate, the Plant Functional Types (PFT) approach and Integrated Plant Record (IPR) vegetation analysis for quantification of palaeovegetation. Our investigation documents the persistence of temperate climate with two warmer and colder phases. Moreover, our reconstructions show significantly higher mean values of all temperature parameters in comparison to previous estimations. Overall humid climate conditions (up to 1500 mm) prevailed throughout the early Pliocene correspond to an oceanic climate. Our reconstruction indicates relatively strong temperature and precipitation seasonality. Our data for vegetation show more open vegetation in comparison to previous studies reconstructing mixed conifer-deciduous forests for the early Pliocene of Northeast of Russia. Based on PFT, the early Pliocene vegetation of northern Yakutia in Lena River Delta mainly was presented by more or less open mixed deciduous woodlands of warmer or colder temperate type. The results obtained from the PFT approach generally are in accordance with our data obtained from IPR approach. However, based on IPR, periodically forests and grasslands were obtained in addition to open woodlands.

Keywords: temperature evolution, precipitation pattern, climate seasonality, structure of plant assemblages, vegetation type

РЕЗЮМЕ

Бондаренко О.В., Утешер Т. Количественная динамика раннеплиоценового климата и растительности в дельте реки Лена (северная Якутия, Восточная Сибирь). Климат и эволюция растительности раннего плиоцена в дельте реки Лены (северная Якутия, Восточная Сибирь) впервые количественно детально изучены на основе палеоботанической летописи. Палеоботанические данные для этого временного интервала получены по 28 палинофлорам сардахской свиты в прибрежных скалах острова Сардах-Сисе (дельта р. Лены). В этом первом интегративном исследовании мы применяем подход сосуществования (CA) для количественной оценки палеоклимата, подход функциональных типов растений (PFT) и анализ растительности с интегрированным реестром растений (IPR) для количественной оценки палеорастительности. Наше исследование документирует постоянство умеренного климата с двумя более теплыми и более холодными фазами. Более того, наши реконструкции показывают значительно более высокие средние значения всех температурных параметров по сравнению с предыдущими оценками. Общие влажные климатические условия (до 1500 мм), преобладавшие на протяжении всего раннего плиоцена, соответствуют океаническому климату. Наша реконструкция указывает на относительно сильную сезонность температуры и осадков. Наши данные по растительности показывают более открытую растительность по сравнению с предыдущими исследованиями, реконструирующими смешанные хвойно-широколиственные леса для раннего плиоцена северо-востока России. По данным PFT раннеплиоценовая растительность северной Якутии в дельте Лены была представлена в основном более или менее открытыми смешанными лиственными редколесьями более теплого или более холодного умеренного типа. Результаты, полученные с помощью подхода PFT, в целом согласуются с нашими данными, полученными с помощью подхода IPR. Однако, на основании IPR, периодически в дополнение к редким редколесьям существовали леса и луга.

Ключевые слова: динамика температуры, характер осадков, сезонность климата, структура растительных сообществ, тип растительности

The Pliocene is a key period in Earth's climate evolution, as it records the transition from the relatively warmer and more stable early Pliocene conditions to the prevailing cooler and more variable glaciated climate of the Pleistocene (Dowsett & Poore 1991, Mudelsee & Raymo 2005, Raymo et al. 2006, Lisieski & Raymo 2005, 2007). The Pliocene is recognized as the most recent example of prolonged global warmth in a higher-than-today CO_2 context in the geological past (Fedorov et al. 2013) and therefore a very good analog for future climate change (Robinson et al. 2008). Carbon dioxide reconstructions show around by 100 ppm higher-than-present values (Bartoli et al. 2011). The size of polar ice sheets were significantly reduced during the Pliocene causing sea levels higher by up to 25 m compared to today (Miller et al. 2005, Dowsett et al. 2010). The reduction in high-latitude terrestrial ice sheets and associated ice-albedo feedbacks are an additional contributing mechanism to the global Pliocene warmth (Haywood & Valdes 2004). Even though the Pliocene is thought to be a warmer period than today, a recent review by De Schepper et al. (2014) shows evidences of significant glaciations in both northern and southern Hemispheres during this epoch. Moreover, the Pliocene was also wetter than today on most continents, leading to an expansion of tropical savannas and forests in Australia and Africa at the expense of deserts (e.g., Leroy & Dupont 1994, Dodson & Macphail 2004). The early Pliocene (Zanclean stage; between 5.3 and 3.6 Ma) is a particularly interesting period because it encompasses the so-called early Pliocene climatic optimum ranging from 4.4 to 4.0 Ma, probably the warmest interval in this epoch with global average temperature ~ 4°C higher than today (Brierley & Fedorov 2010, Fedorov et al. 2013, Jimenez-Moreno et al. 2019). There are various attempts to connect this warm phase to raised CO2, but there still are some uncertainties and things under debate (see Guillermic et al. 2022).

The Arctic is one of the hard-to-reach and therefore least explored regions of the planet. Permafrost, harsh climatic conditions do not contribute to the rich diversity of modern flora. The main landscape-climatic zone here is the tundra. However, it is known that this was not always the case. Moreover, the state of the Earth, in which the poles are free of ice, is more characteristic of our planet. According to the Intergovernmental Panel on Climate Change (IPCC 2014), the Arctic today is warming dramatically, faster than almost all other parts of our planet, attributing to "polar amplification" (Lee 2014), and impacting global climate feedbacks and Arctic biota. The consequences of modern climate warming, which are most pronounced in the Arctic, are usually viewed as negative and catastrophic. Nevertheless, our knowledge of the warm climates of the Arctic and their role in the formation of the Earth's climate is currently insufficient for confident forecasting of climatic events in the future. One of the main reasons for this is the currently prevailing qualitative characteristic of palaeoclimates, which is not suitable for constructing modern mathematical modeling. The solution to this problem is the application of new methods of analysis of fossil climate indicators, which provide quantitative data.

Actually, extensive studies on climate proxies and models in the High Arctic have been conducted for the Cretaceous that revealed palaeoenvironmental conditions and vegetation responses in a "greenhouse" climate (e.g., Spicer & Parrish 1986, Spicer & Corfield 1992, Herman & Spicer 1996, 1997, Spicer & Herman 2010, Herman et al. 2016, Spicer et al. 2014, 2019). Quantitative climate data were obtained based on early to middle Eocene palynofloras of coastal plain sediments on the New Siberian Islands (Suan et al. 2017). Recently, quantitative palaeoclimate and vegetation studies have been conducted for the early Eocene section located at high latitudes, in the area of the present Lena River Delta (northern Yakutia, Eastern Siberia), provided new insights into short-term climate and vegetation dynamics succeeding the Paleocene – Eocene Thermal Maximum (PETM) (Bondarenko et al. 2022). A most recent study on an early Eocene section located in the area of the Tastakh Lake (the left bank of Indigirka River), provided a first higher-resolving time series for the climate and vegetation evolution before, during and after the Early Eocene Climatic Optimum (EECO) (Bondarenko & Utescher 2022).

Stratigraphic analyses of Pliocene/Neogene deposits in Northeast Russia in general and Yakutia in particular, as well as the reconstruction of the palaeoclimate and palaeovegetation, were previously tackled by Grinenko et al. (1989, 1997), Volobueva et al. (1990), Zharikova & Komzina (1991), Krutous et al. (1992), Fradkina (1995, 1996), and others. These studies were mainly devoted to regional stratigraphy, description of plant fossil remains, new fossil taxa, taxonomic diversity of plants, or palaeofloristic aspects and generally were based on qualitative interpretations of macro- and microfloral successions while quantitative studies are largely missing so far.

In the present study, we present a detailed and continuous pollen record (28 floras) from a continental sedimentary succession on the Sardakh-Sisse Island in Lena River Delta (northern Yakutia, Eastern Siberia). We aim at quantifying short-term palaeoenvironmental and palaeoclimatic trends throughout the early Pliocene in the study area, probably including the early Pliocene climatic optimum. This record shows that besides short-term trends, climate was also characterized by variability that forced terrestrial environmental changes (e.g., vegetation changes of forested vs. open vegetation).

MATERIAL AND METHODS

Sedimentary succession in the study area

The Sardakh-Sisse Island is located in the northeastern part of the Lena River Delta near the mouth, from the northern and northeastern sides it is washed by the waters of the Sardakh Channel (72°33'N 127°18'E; Fig. 1). It rises above the other islands of the Delta and has a peculiar domed shape, the maximum absolute height is 42 m above sea level. Along the northwestern coast of the island, Neogene-Quaternary deposits are exposed in the coastal ledge for almost 1.5 km (Khazin et al. 2019). This section has long been of interest to geologists working in the Arctic regions of Siberia, since Neogene deposits are extremely rarely exposed in the Lena River Delta. The Sardakh section has been described by Gusev (1958), Bol'shiyanov et al. (2013), Grakhanov et al. (2013), Khazin et al. (2019).

The Neogene deposits unconformably lie on marbleized Upper Devonian limestones and dolomites (Grakhanov et al. 2013). At our locality, weathered limestones of the Upper Devonian are overlain by the Miocene Urasalakhskaya

Formation represented by alluvial ferruginous conglomerates with abundant mineralized wood and siderite nodules (Bol'shiyanov et al. 2014). Imprints of leaf flora found are confined to a layer of ferruginous sandstones at the base of the Sardakh-Sisse section (Khazin et al. 2019). The leaf imprints are well preserved, which indicates in situ burial. According to Khazin et al. (2019), the following taxa were identified: *Platanus* sp., *Alnus* sp., *Fagus* sp., *Salix* sp. In addition, a fossilized fruit was found belonging to *Magnolia* sp. All finds were made at the same stratigraphic level. According to earlier studies, it was found that the remains of lignitized wood belong to *Pinus sibirica* L., *Picea obovata* L., *Larix sibirica* Ledeb. and others (Gusev 1958). Apparently redeposited fruits of *Juglans cinerea* L., cones of *Picea obovata*, *Picea wollosowiczii* Sukacz were recovered from the sands overlying the conglomerates at the base of the section (Gusev 1958). Higher in the section, the Sardakhskaya Formation conformably overlies the Miocene Urasalakhskaya Formation, comprising an alternation of clays and sands with single pebbly levels deposited by a fluvial system. The total thickness of the Sardakhskaya Formation amounts to about 40 m and belongs to the early Pliocene (cf. 2.2; Fig. 2).

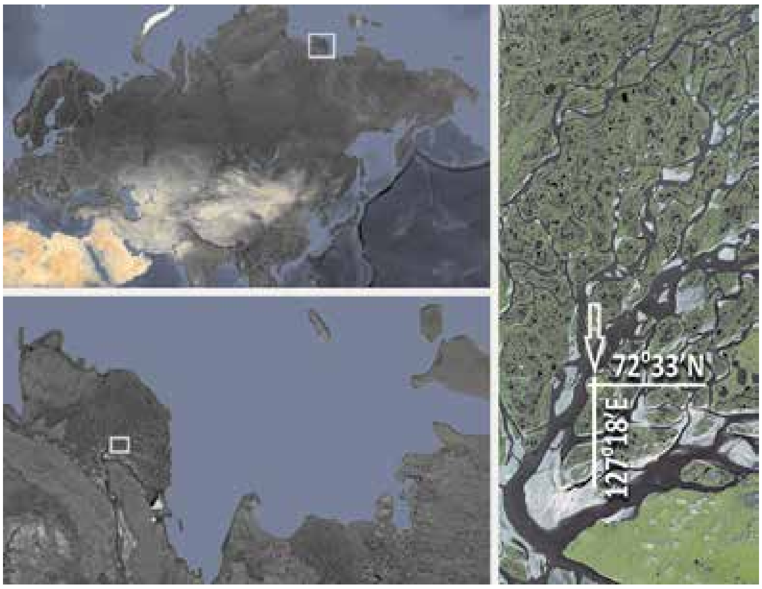

Figure 1 Map showing the location of the section studied

Table 1. PFT classification used for the present study (Popova et al. 2013)

Growth form	PFT Code	PFT
Herb	1	C3 herbs (humid)
	2	C3 herbs (dry)
	3	C4 herbs
Shrub	4	Broadleaved summergreen arctic shrubs
	5	Broadleaved summergreen boreal or temperate cold shrubs
	6	Broadleaved summergreen temperate warm shrubs
	7	Broadleaved evergreen boreal or temperate cold shrubs
	8	Broadleaved evergreen temperate warm shrubs
	9	Broadleaved evergreen xeric shrubs
	10	Subdesertic shrubs
	11	Tropical shrubs
Tree	12	Needleleaved evergreen boreal or temperate cold trees
	13	Needleleaved evergreen temperate cool trees
	14	Needleleaved evergreen trees, drought-tolerant
	15	Needleleaved evergreen trees, drought-tolerant, thermophilous
	16	Needleleaved evergreen subtropical trees, drought-intolerant
	17	Needleleaved summergreen boreal or temperate cold trees
	18	Needleleaved summergreen subtropical swamp trees
	19	Broadleaved evergreen trees, drought-tolerant
	20	Broadleaved evergreen trees, drought-intolerant, thermophilous
	21	Broadleaved evergreen subtropical trees, drought-intolerant
	22	Broadleaved summergreen boreal or temperate cold trees
	23	Broadleaved summergreen temperate cool trees
	24	Broadleaved summergreen temperate warm trees
	25	Broadleaved raingreen tropical trees
	26	Broadleaved evergreen tropical trees
Aquatic	27	Aquatic components

Stratigraphy and dating

Based on palaeontological data, the Sardakhskaya Formation corresponds to the early Pliocene. Following the stratigraphic concept of Grinenko et al. (1997), the Sardakhskaya Formation can be considered to be time-equivalent with the Begunovskaya Formation. According to palaeomagnetic studies carried out in the Nizhnekolymsky Trough, the stratotype of the Begunovskaya Formation, the Begunovskaya Formation can be assigned to the interval of 3.4–5.1 Ma within the Gilbert Chron (3.580–5.971 Ma) (Grinenko et al. 1989). Time-equivalent deposits of the Begunovskaya Formation have been identified in various different regions of the northeast Russia and have been combined to the so-called Begunovskii Regional Horizon (Grinenko et al. 1997).

Floral record

In the present study, microfloras (PFs) from 28 levels are considered, sampled in the study section from the Sardakhskaya Formation exposed in the coastal cliffs of the Sardakh-Sisse Island (Fig. 1). All palynological data are taken from Fradkina (1995). The microfloras yield evidence for a total of 42 different taxa (31 angiosperms, 4 gymnosperms, and 7 pteridophytes; Fig. 2) identified by A.F. Fradkina (Fradkina 1995). As reported in the original study, 300 or more pollen grains were counted per sample. The material is stored in Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences (DPMGI SB RAS, Yakutsk).

Quantitative palaeoclimate reconstruction – Coexistence Approach (CA)

To reconstruct climate from the palynomorph record we use the Coexistence Approach (CA) (Mosbrugger & Utescher 1997, Utescher et al. 2014). This approach is organ-independent, so that both macro- and microfossil plants are eligible as long as their modern botanical affinities are determinable (Mosbrugger & Utescher 1997, Utescher et al. 2007, Bruch et al. 2011). For a detailed description of the method the reader is referred to the original papers describing the procedure (Mosbrugger & Utescher 1997, Utescher et al. 2014). We use data sets from the Palaeoflora Database (Utescher & Mosbrugger 2018). Floral lists with corresponding nearest living relatives (NLRs) employed in

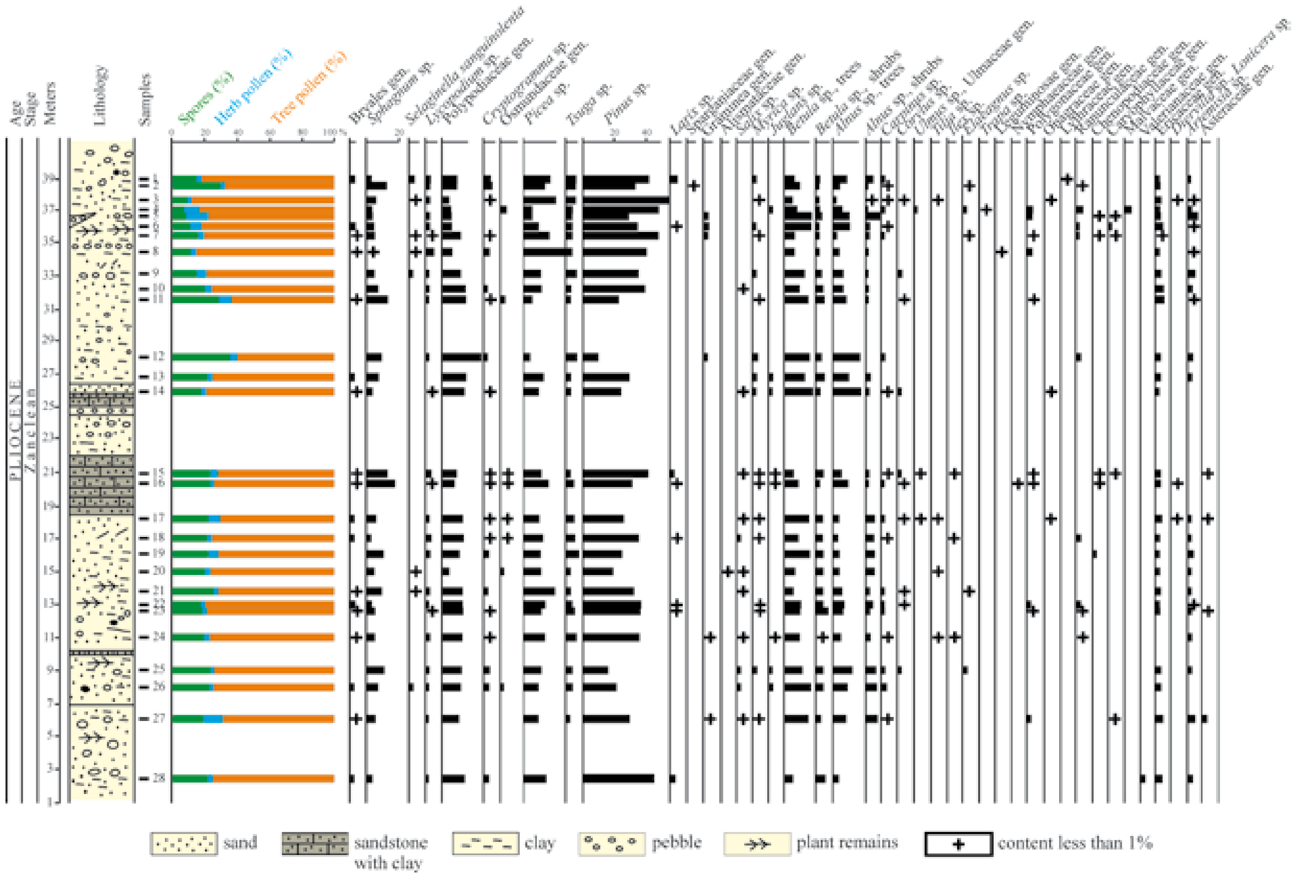

Figure 2 Palynological diagram (according to Fradkina 1995)

this study and their climatic requirements are made available in Supplementary electronic information 1.

In this study, three temperature and four precipitation variables are reconstructed: mean annual temperature (MAT), cold and warm month mean temperature (CMMT, WMMT), mean annual precipitation (MAP), and mean monthly precipitation of the wettest, driest and warmest month (MPwet, MPdry, and MPwarm). In the CA, at least 10 NLR taxa contributing with climate data are required to obtain reliable results (Mosbrugger & Utescher 1997). The climatic resolution of the CA results also depends on the taxonomical level of NLR identification (Mosbrugger & Utescher 1997).

Climate seasonality

In order to determine temperature seasonality of the early Pliocene climate of the Lena River Delta, the mean annual range of temperature (MART) was calculated as the difference of WMMT and CMMT for each level. To study precipitation seasonality, the mean annual range of precipitation (MARP – calculated as difference of MPwet and MPdry) was calculated.

Vegetation reconstruction methods

In order to reconstruct palaeovegetation based on fossil flora, several methods have been developed aiming at standardized, reproducible and thus comparable results, facilitating the analysis of spatio-temporal trends in the evolution of the vegetation cover. These methods differ mainly by scale of reconstruction from local plant communities (PFT) to biome level (IPR).

Quantitative palaeovegetation reconstruction – Plant Functional Type Approach (PFT)

The Plant Functional Type (PFT) concept goes back to works of Prentice (e.g., Prentice & Webb 1998, Prentice et al. 1992) and has been widely used to describe vegetation cover in vegetation modeling. A PFT is defined using traits and climatic thresholds of key taxa, and combines species related by morphological and phenological traits (François et al. 2011). The application of the PFT technique on the Neogene palaeobotanical record was first introduced by Utescher et al. (2007). The present study employs an extended PFT classification scheme described in details in Popova et al. (2013), comprising 26 herbaceous to arboreal PFTs based on physiognomic characters and bioclimatic tolerances of plants, complemented by an aquatic PFT (Table 1). The allocation of fossil taxa to the single PFTs is based on interpretation of their NLRs (Supplementary electronic information 2), and follows the procedure described in Utescher & Mosbrugger (2007) and Utescher et al. (2007).

To exclude unlikely PFTs we use the likelihood procedure according to François et al. (2011) and Henrot et al. (2017). This methodology is similar to the CA used in palaeoclimate reconstructions from palaeobotanical records. In cases when several classes of arboreal PFTs are possible for a taxon, only those that can coexist with the other classes identified at the site are retained. It narrows the range of plant types present at the site by suppressing extreme end members, such as cold boreal/temperate and tropical PFTs. The coexistence table is then used to evaluate the likelihood for the presence of each PFT at each site, according to the four following affinity levels of coexistence: H – high, M – moderate, L – low, and I – improbable. Finally, all PFTs of low and improbable levels of coexistence were excluded from the analysis (Supplementary electronic information 2). The PFT approach requires only information on presence and absence of taxa and thus is comparatively robust towards taphonomic bias. The approach can be applied on all types of fossil floras providing an adequate size of the sample.

Plant biome reconstruction – Integrated Plant Record vegetation analysis (IPR)

The Integrated Plant Record vegetation analysis (IPR) is a semi-quantitative method first introduced by Kovar-Eder & Kvaček (2003) to assess zonal vegetation based on the fossil plant record (leaf, fruit, and pollen assemblages). In order to employ the IPR, thirteen basic taxonomic-physiognomic groups, termed components, defined to reflect key ecological characteristics of an assemblage (Kovar-Eder & Kvaček 2003, 2007, Kovar-Eder et al. 2008, Teodoridis et al. 2011) are used: conifer component (CONIF), broadleaved deciduous component (BLD), broadleaved evergreen component (BLE), sclerophyllous component (SCL), legume-like component (LEG), zonal palm component (ZONPALM), arborescent fern component (ARBFERN), dry herbaceous component (D-HERB), mesophytic herbaceous component (M-HERB). Azonal components, i.e. azonal woody component (AZW), azonal non-woody component (AZNW) and aquatic component (AQUA). The component PROBLEMATIC TAXA includes elements with uncertain taxonomic-physiognomic affinity. For further analysis, all taxa (but not their abundances) of every single assemblage have to be assigned to those components and their relative proportions have to be calculated. The complete flora lists, assigned NLRs and their allocation to the components are given in Supplementary electronic information 3.

To characterize zonal vegetation, the following proportions of components are regarded as relevant: (a) the proportion of the BLD, BLE, and SCL+LEG components of zonal woody angiosperms, where "zonal woody angiosperms" means sum of BLD+BLE+SCL+LEG+ZONPALM+ARBFERN components; (b) the proportion of the ZONAL HERB (D-HERB+M-HERB) component of all zonal taxa, where "zonal taxa" means sum of the CONIF+BLD+BLE+SCL+LEG+ZONPALM+ARBFERN+D-HERB+M-HERB components. The reliability of the results increases with increasing number of zonal taxa preserved. Ten zonal taxa are regarded as a minimum to perform this method (Kovar-Eder et al. 2008). Recently, Kovar-Eder & Teodoridis (2018) raised the former threshold to 15 zonal taxa for the application of the IPR-vegetation analysis. The proportions of the components for definition of zonal vegetation types are given in Table 2.

Based on relative proportions of the components the following six zonal vegetation types are distinguished (Kovar-Eder & Kvaček 2007, Kovar-Eder et al. 2008): zonal temperate to warm temperate broadleaved deciduous forests (broadleaved deciduous forests, BLDF), zonal warm temperate to subtropical mixed mesophytic forests (mixed mesophytic forests, MMF), zonal subtropical broadleaved evergreen forests (broadleaved evergreen forests, BLEF), zonal subtropical, subhumid sclerophyllous or microphyllous forests (subhumid sclerophyllous forests, ShSF), zonal xeric open woodlands (open woodland), and zonal xeric grasslands or steppe (xeric grassland). Teodoridis et al. (2011) additionally defined ecotones between the BLDF and MMF and the BLEF and MMF and recently, Kovar-Eder & Teodoridis (2018) defined ecotone between the MMF/ShSF (Table 2).

RESULTS

Paleoclimate reconstruction

The analysis of 28 microfloras is based on 8 to 19 (mean 12.04) climate datasets of extant reference taxa. In 28 cases, all NLRs can coexist, attributing high significance. When reconstructing CA intervals of the MAT obtained from the microfloras CA ranges are comparatively wide owing to the commonly high taxonomic level of NLR assignment. For MAT the width of CA intervals is ca. 20°C at the mean (varies from 13.4°C to 26.6°C). Mean values of climatic parameters for each depth level are given in Table 3.

The mean values of MAT show a general smooth warming trend (Fig. 3). Within this general trend, two warmer and two colder phases can be identified (Table 3, Fig. 3). The phase in the interval of 6.5–11.0 m is the warmest with MAT 10.9–11.5°C, CMMT 0–1.1°C and WMMT 23.4°C. The second warmer phase in the interval 26.0–35.5 m is somewhat cooler, and characterized by MAT 8.4–10.9°C and CMMT 0°C. The first cooler phase in the intervals of 12.5–21.0 m is characterized by MAT 6.7–11.5°C, CMMT

Table 2. Zonal vegetation types as defined by the IPR vegetation analysis (Teodoridis et al. 2011)

<table>
<tr><th rowspan="2">Vegetation type</th><th colspan="3">Zonal woody components</th><th>Zonal herbaceous components</th></tr>
<tr><th>BLD</th><th>BLE</th><th>SCL + LEG</th><th>MESO + DRY HERB</th></tr>
<tr><td>Broadleaved deciduous forests, BLDF</td><td>> 80 %</td><td></td><td></td><td>≤ 30 %</td></tr>
<tr><td>Ecotone BLDF / MMF</td><td>75-80 %</td><td rowspan="2">< 30 %</td><td rowspan="3">< 20 %</td><td rowspan="3">< 30 %</td></tr>
<tr><td>Mixed mesophytic forests, MMF</td><td rowspan="2">< 75 %</td></tr>
<tr><td>Ecotone MMF / BLEF</td><td>30-40 %</td></tr>
<tr><td>Broadleaved evergreen forests, BLEF</td><td></td><td>> 40 %</td><td>(SCL+LEG) < BLE</td><td>< 25 %</td></tr>
<tr><td>Subhumid sclerophyllous forests, ShSF</td><td></td><td></td><td>≥ 20 %</td><td>< 30 %</td></tr>
<tr><td>Xeric open woodlands</td><td></td><td>< 30 %</td><td>≥ 20 %</td><td>30-40 %:
MESO HERB > DRY HERB up to 10 % of all zonal herbs</td></tr>
<tr><td>Xeric grasslands or steppe</td><td></td><td>< 30 %</td><td></td><td>≥ 40 %</td></tr>
</table>

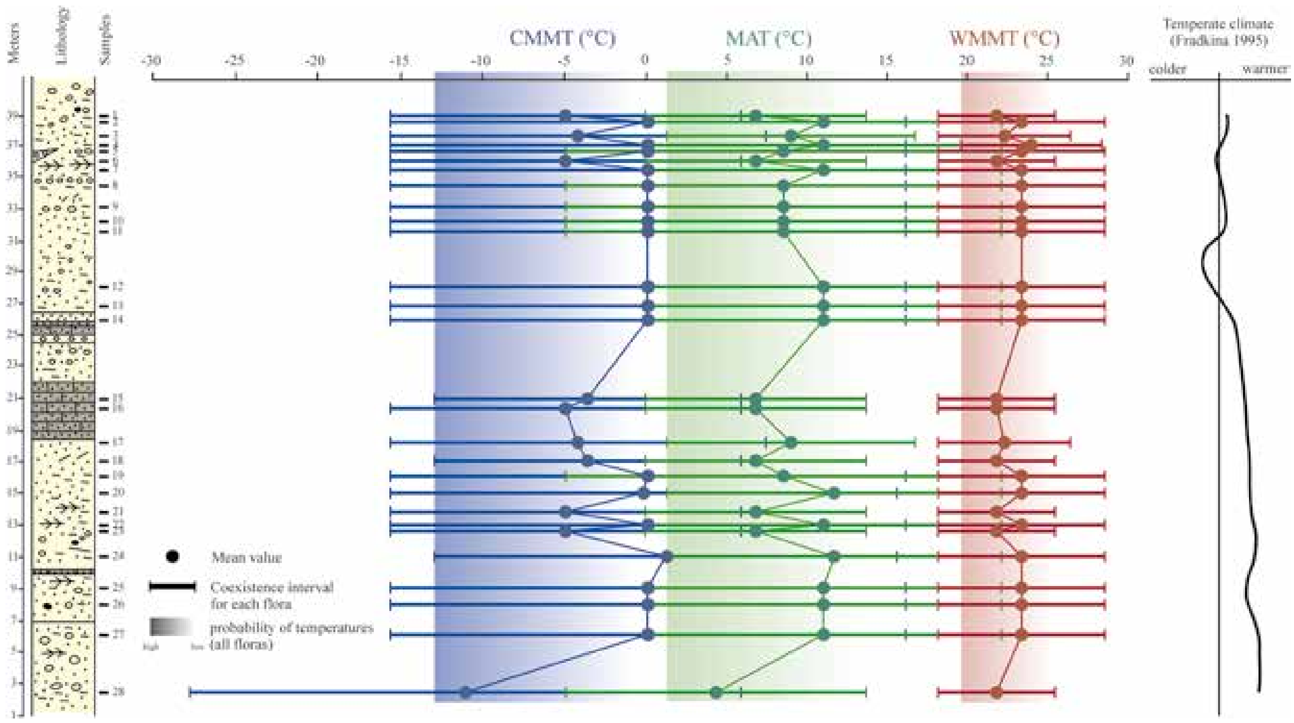

Figure 3 Temperature variables by CA method in present study (A): MAT – mean annual temperature, CMMT – cold month mean temperature, WMMT – warm month mean temperature; qualitative curve of climate by Fradkina (1995)

Table 3. Temperature and precipitation seasonality parameters and related values.

Flora	Height (m)	Number of taxa		Temperature parameters				Precipitation parameters					
		total	with climatic data	MAT mean (°C)	CMMT mean (°C)	WMMT mean (°C)	MART (°C)	MAP mean (mm)	MPwet mean (mm)	MPdry mean (mm)	MARP (mm)	RMPwet (%)	RMPdry (%)
Current conditions													
–	–	–	–	–12.8	–37.3	7.7	45.0	277	39	21	18	14.1	7.6
Early Pliocene													
PF 1	39.0	17	11	6.7	–5.0	21.8	26.8	1475	199	37	162	13.5	2.5
PF 2	38.5	14	11	10.9	0	23.4	23.4	1452	199	48	151	13.7	3.3
PF 3	37.5	19	14	8.9	–4.3	22.3	26.6	1001	124	50	74	12.4	5.0
PF 4	37.0	19	15	10.9	0	24.0	24.0	1534	199	48	151	13.0	3.1
PF 5	36.5	14	9	8.4	0	23.4	23.4	1204	199	43	157	16.5	3.5
PF 6	36.0	17	11	6.7	–5.0	21.8	26.8	1475	199	37	162	13.5	2.5
PF 7	35.5	21	13	10.9	0	23.4	23.4	1204	199	43	157	16.5	3.5
PF 8	34.5	15	9	8.4	0	23.4	23.4	1549	199	48	151	12.8	3.1
PF 9	33.0	13	10	8.4	0	23.4	23.4	1204	196	43	153	16.2	3.5
PF 10	32.0	12	9	8.4	0	23.4	23.4	1425	199	48	151	14.0	3.4
PF 11	31.5	16	11	8.4	0	23.4	23.4	1204	196	43	153	16.2	3.5
PF 12	28.0	15	10	10.9	0	23.4	23.4	1549	199	48	151	12.8	3.1
PF 13	27.0	12	10	10.9	0	23.4	23.4	1534	199	48	151	13.0	3.1
PF 14	26.0	16	13	10.9	0	23.4	23.4	1204	196	43	153	16.2	3.5
PF 15	21.0	25	19	6.7	–3.7	21.8	25.5	1300	221	37	184	17.0	2.8
PF 16	20.5	22	18	6.7	–5.0	21.8	26.8	1001	124	45	80	12.4	4.4
PF 17	18.5	24	18	8.9	–4.3	22.3	26.6	1001	124	50	74	12.4	5.0
PF 18	17.0	19	14	6.7	–3.7	21.8	25.5	1520	224	37	187	14.7	2.4
PF 19	16.0	12	9	8.4	0	23.4	23.4	1204	199	43	157	16.5	3.5
PF 20	15.0	15	11	11.5	–0.3	23.4	23.6	1393	209	49	161	15.0	3.5
PF 21	14.0	17	13	6.7	–5.0	21.8	26.8	1204	196	37	159	16.2	3.1
PF 22	13.0	16	11	10.9	0	23.4	23.4	1204	196	43	153	16.2	3.5
PF 23	12.5	18	11	6.7	–5.0	21.8	26.8	1475	199	37	162	13.5	2.5
PF 24	11.0	18	12	11.5	1.1	23.4	22.3	1489	224	49	176	15.0	3.3
PF 25	9.0	17	14	10.9	0	23.4	23.4	1204	196	43	153	16.2	3.5
PF 26	8.0	16	12	10.9	0	23.4	23.4	1425	199	48	151	14.0	3.4
PF 27	6.5	17	11	10.9	0	23.4	23.4	1425	199	48	151	14.0	3.4
PF 28	1.5	13	8	4.3	–11.1	21.8	32.9	1362	198	37	161	14.5	2.7

Means by each flora (calculated using coexistence interval means). MAT – mean annual temperature; CMMT – cold month mean temperature; WMMT – warm month mean temperature; MRAT – mean annual range of temperature (MART = WMMT – CMMT); MAP – mean annual precipitation; MPwet – mean monthly precipitation of the wettest month; MPdry – mean monthly precipitation of the driest month; MARP – mean annual range of precipitation (MARP = MPwet – MPdry); RMPwet – ratio of MPwet on MAP (RMPwet = MPwet/MAP*100); RMPdry – ratio of MPdry on MAP (RMPdry = MPdry/MAP*100).

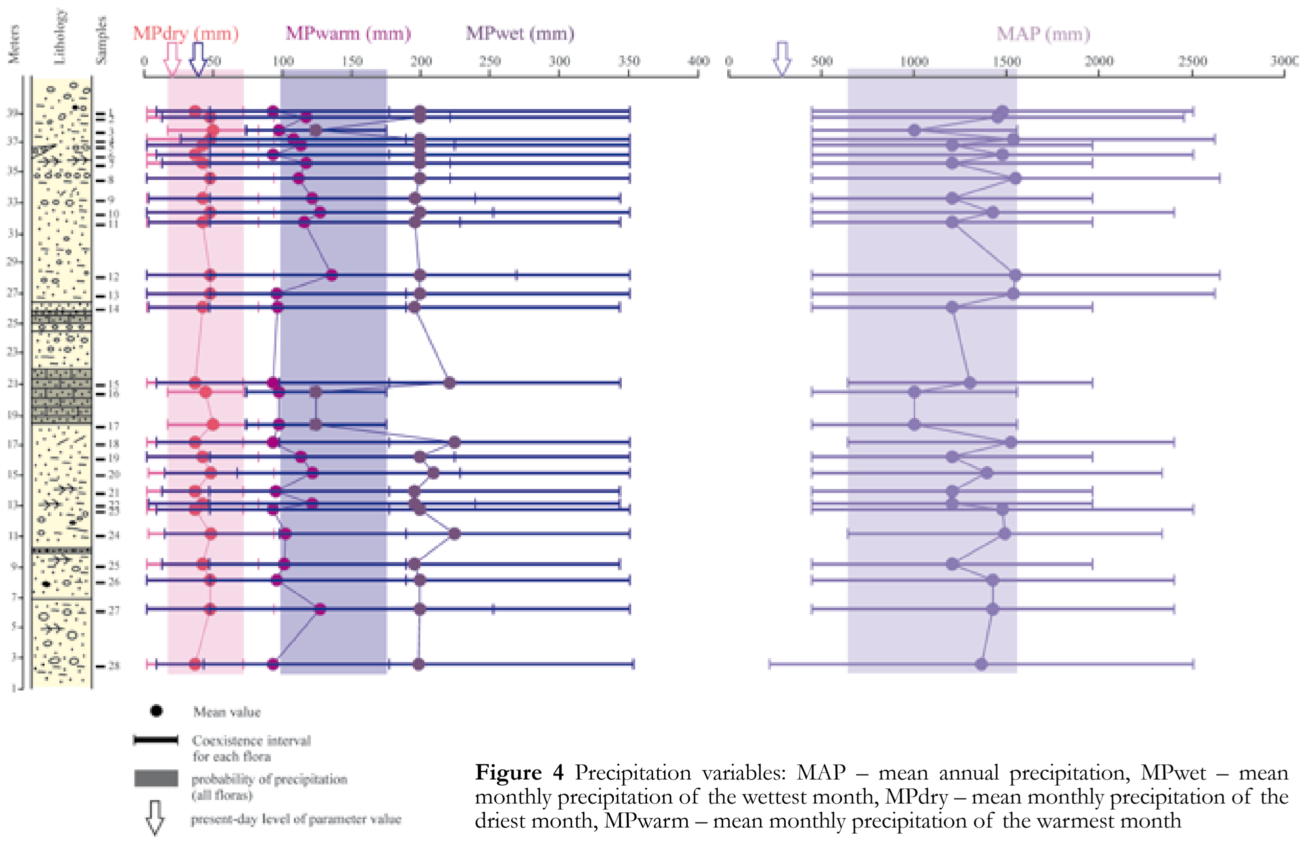

Figure 4 Precipitation variables: MAP – mean annual precipitation, MPwet – mean monthly precipitation of the wettest month, MPdry – mean monthly precipitation of the driest month, MPwarm – mean monthly precipitation of the warmest month

0–(-5.0)°C and WMMT 21.8–23.4°C. The second cooler phase with MAT 6.7–10.9°C, CMMT 0–(-5.0)°C and WMMT 21.8–24.0°C is distinguished in the intervals of 26.0–35.5 m. The coldest flora (PF 28) at depth level 1.5 m is characterized by the lowest mean values of MAT, CMMT and WMMT.

The mean values of MAP, MPdry, MPwet and MPwarm do not show any trend (Table 3, Fig. 4). MAP varies from 1000 to 1500 mm throughout the early Pliocene. MPdry means in the early Pliocene of Yakutia were at ca. 37–50 mm. The mean values of MPwet attain high values (124–224 mm).

Climate seasonality

Temperature (MART) and precipitation (MARP) seasonality parameters and the mean values of related climatic parameters for each flora are given in Table 3 in comparison to the present-day values. The MART ranges in 22.3–32.9°C during the early Pliocene. The MARP varies from 74 to 187 mm. The RMPwet fluctuates within 12.4–17.0 %, while the RMPdry varied from 2.4 to 5.0 % (Table 3).

Vegetation: PFT approach

Using the PFT approach, palaeovegetation data of northern Yakutia were obtained for 28 palynofloras. The number of PFTs encountered in each sample is lower than the number of fossil taxa contributing with PFT data (Table 4), which we consider meaningful. Proportions of the different groups of PFTs are given in Table 4. Aquatic plants (PFT 27) are present in 17 palynofloras, and the proportion of aquatic plants varies from 2.6 to 6.7 % (Fig. 5, Table 4). Herbaceous plants (PFTs 1–3) are present in all floras. The diversity of herbaceous PFTs varies from 11.8 to 40.0 % of total diversity of the flora (Figs. 5, 6, Table 4). Shrubs (PFTs 4–11) are presented in all floras studied – from 26.3 to 51.4 % (Fig. 5, Table 4). Arboreal plants (PFTs 12–26) are present in all floras studied 26.8–47.4 % of total diversity (Fig. 5, Table 4). Needleleaved (PFTs 12–18) are present in all floras. The proportion of conifers varies within the range of 11.4–33.3 % of total diversity of the flora (Fig. 5, Table 4). Broadleaved deciduous plants (PFTs 4–6, 22–25) are present in all floras. The diversity of deciduous PFTs varies from 23.3 to 55.9 % of total diversity of the flora (Table 4). Broadleaved evergreens (PFTs 7–9, 19–21, 26) are present in all floras. The proportion of broadleaved evergreens varies from 6.7 to 15.6 % of total diversity of the flor (Figs. 5, 6, Table 4).

The diversity spectra of the early Pliocene floras analyzed (Fig. 5) show that broadleaved summergreen shrubs (PFTs 4, 5, and 6) are the most important functional types (up to 20 %) and are present in all floras. They are followed by broadleaved summergreen trees (PFTs 22, 23 and 24 – up to 18 %) and needleleaved evergreens (PFTs 12, 13 and 16 – up to 12 %). Subdesertic shrubs (PFT 10), needleleaved summergreen subtropical swamp trees (PFT 18), broadleaved raingreen tropical trees (PFT 25) and broadleaved evergreen tropical trees (PFT 26) are absent in the spectra after having applied the likelihood procedure. Herbaceous plants in the early Pliocene floras of Yakutia are mainly represented by humid herbs (PFT 1 – up to 24 %).

IPR vegetation analysis

To apply IPR vegetation analysis, 28 microfloras were analyzed. The number of taxa assigned to the components for each flora is given in Table 5. The proportions of the

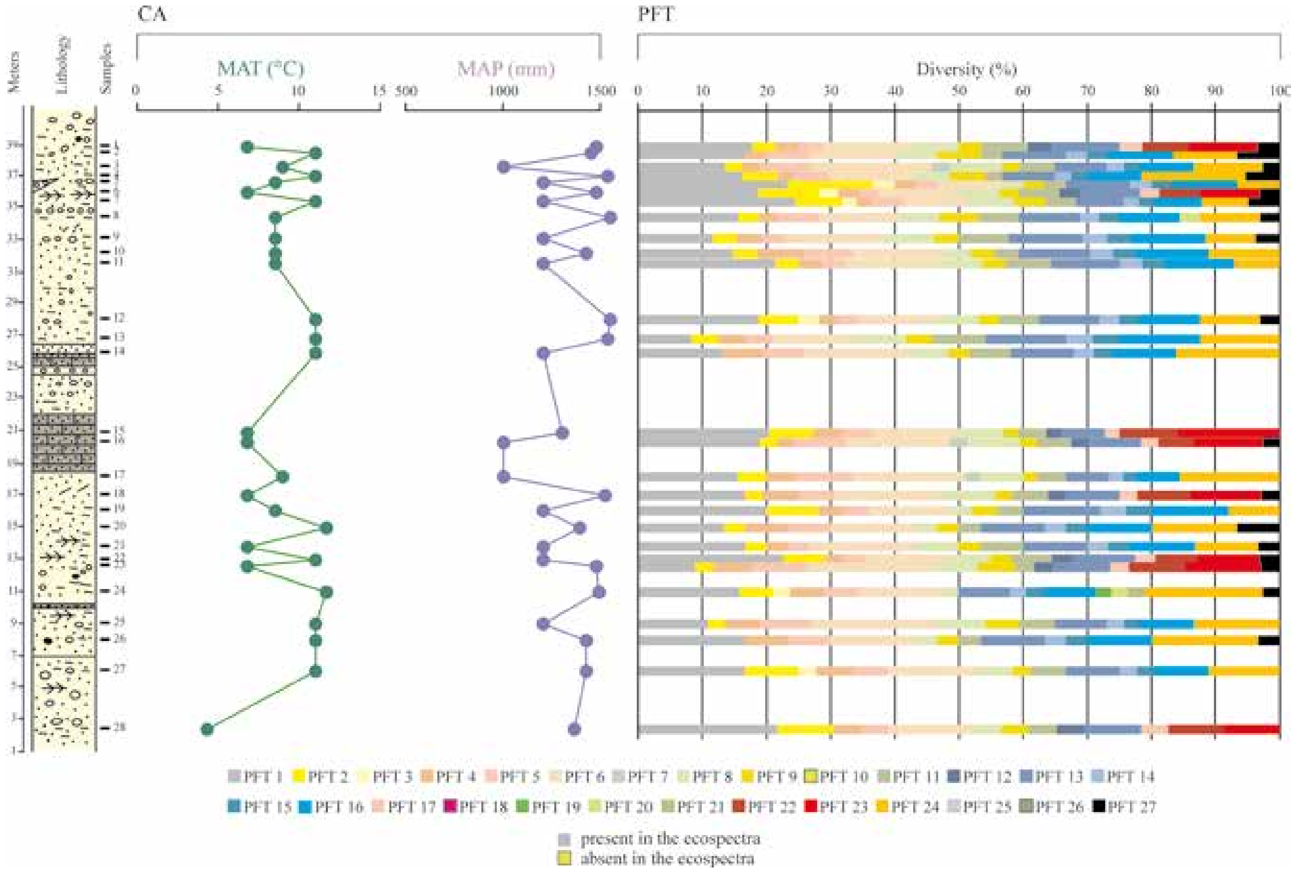

Figure 5 Ecospectra of PFT next to lithological profile of the studied core and curves of MAT and MAP: MAT – mean annual temperature, MAP – mean annual precipitation, PFTs are given in Table 1

Table 4. Proportions of the different groups of PFTs for each depth level.

Flora	Height (m)	Number of fossil taxa allocated to PFTs	Number of scores before likelihood procedure	Number of scores after likelihood procedure	Aquatic (PFT 27)	Terrestrial (PFTs 1-26)	Herbaceous (PFTs 1-3)	Shrubby (PFTs 4-11)	Arboreal (PFTs 12-26)	Conifer (PFTs 12-18)	Deciduous (PFTs 4-6, 22-25)	Evergreen (PFTs 7-9, 19-21, 26)
PF 1	39.0	16	38	28	3.6	96.4	21.4	39.3	35.7	17.9	39.3	10.7
PF 2	38.5	14	36	30	6.7	93.3	16.7	40.0	36.7	26.7	33.3	13.3
PF 3	37.5	19	47	37	2.7	97.3	16.2	48.6	32.4	21.6	40.5	13.5
PF 4	37.0	19	49	37	5.4	94.6	21.6	35.1	37.8	21.6	37.8	10.8
PF 5	36.5	14	35	30	0	100	40.0	26.7	33.3	26.7	23.3	6.7
PF 6	36.0	16	42	32	3.1	96.9	31.3	34.4	31.3	15.6	34.4	9.4
PF 7	35.5	20	49	41	4.9	95.1	34.1	34.1	26.8	19.5	24.4	12.2
PF 8	34.5	14	40	32	3.1	96.9	18.8	40.6	37.5	25.0	31.8	15.6
PF 9	33.0	13	33	26	3.8	96.2	15.4	42.3	38.5	30.8	30.8	11.5
PF 10	32.0	12	34	27	0	100	18.5	40.7	40.7	29.6	40.7	7.4
PF 11	31.5	15	35	28	0	100	25.0	39.3	35.7	28.6	28.6	10.7
PF 12	28.0	15	40	32	3.1	96.9	28.1	34.4	34.4	25.0	28.1	9.4
PF 13	27.0	11	33	24	0	100	12.5	41.7	45.8	33.3	33.3	12.5
PF 14	26.0	15	43	31	0	100	12.9	45.2	41.9	25.8	45.2	9.7
PF 15	21.0	24	66	44	0	100	27.3	36.4	36.5	11.4	47.7	9.1
PF 16	20.5	21	49	37	2.7	97.3	21.6	45.9	29.7	13.5	43.2	13.5
PF 17	18.5	23	61	45	0	100	20.0	46.7	33.3	17.8	46.7	11.1
PF 18	17.0	18	53	36	2.8	97.2	19.4	44.4	33.3	13.9	47.2	11.1
PF 19	16.0	12	30	25	0	100	28.0	32.0	40.0	32.0	28.0	8.0
PF 20	15.0	15	39	30	6.7	93.3	16.7	36.7	40.0	26.7	40.0	6.7
PF 21	14.0	16	43	34	2.9	97.1	11.8	50.0	35.3	14.7	55.9	11.8
PF 22	13.0	15	38	30	3.3	96.7	20.0	40.0	36.7	26.7	33.3	10.0
PF 23	12.5	17	41	31	3.2	96.8	29.0	35.5	32.3	16.1	35.5	9.7
PF 24	11.0	17	52	38	2.6	97.4	23.7	26.3	47.4	21.1	42.1	10.5
PF 25	9.0	17	49	37	0	100	13.5	51.4	35.1	21.6	45.9	13.5
PF 26	8.0	15	40	30	3.3	96.7	16.7	36.7	43.3	26.7	43.3	6.7
PF 27	6.5	16	46	36	0	100	27.8	38.9	33.3	22.2	36.1	8.3
PF 28	1.5	12	29	23	0	100	30.4	34.8	34.8	17.4	39.1	8.7

References and complete flora lists including Nearest Living Relatives used for vegetation analysis are given in Supplementary electronic information 2.

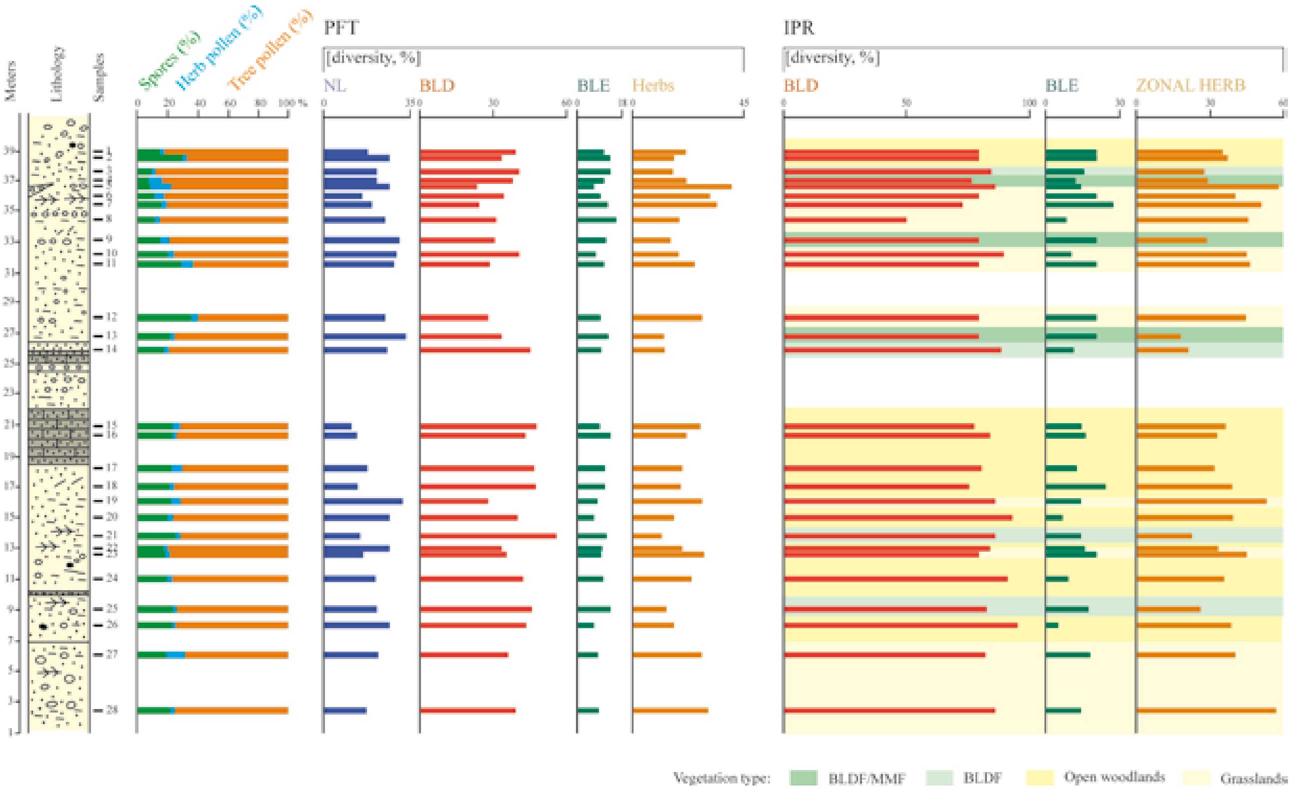

Figure 6 Quantitative characteristics of the main groups of plants according to palynology, PFT, and IPR methods next to lithological profile of the studied core: MAT – mean annual temperature, MAP – mean annual precipitation, NL – needleleaved plants, BLD – broadleaved deciduous plants, BLE – broadleaved evergreen plants, SCL+LEG – sclerophyllous and legume-like plants

components were calculated for each flora and are given in Table 5. Based on the relative proportions of the components, three zonal vegetation type and one ecotone were revealed for the early Pliocene of northern Yakutia (Table 5, Fig. 6). Grasslands were obtained for most floras (11 out of 28). High proportions of herbs (40.5–57.9%) characterize

Table 5. IPR scores, component proportions, and IPR vegetation types for each depth level.

Flora	Height (m)	ZONAL									Total	BLD prop (%)	BLE prop (%)	SCL+LEG prop (%)	ZONAL HERB prop (%)	Vegetation type
		CONIF	BLD	BLE	SCL	LEG	ZON PALM	ARB FERN	D-HERB	M-HERB						
PF 1	39.0	2.5	2.7	0.7	0	0	0	0	0.5	2.7	9.1	79.4	20.6	0	35.2	open woodlands
PF 2	38.5	2	2.7	0.7	0	0	0	0	0	3.2	8.6	79.4	20.6	0	37.2	open woodlands
PF 3	37.5	2	6.45	1.2	0	0	0	0	0.75	3	13.35	84.3	15.7	0	27.7	BLDF
PF 4	37.0	2	4.36	0.7	0.66	0	0	0	0.5	2.7	10.92	76.2	12.2	11.5	29.3	BLDF/MMF
PF 5	36.5	2	1.2	0.2	0	0	0	0	1.49	3.2	8.08	85.7	14.3	0	57.9	grasslands
PF 6	36.0	2.5	2.7	0.7	0	0	0	0	1.16	2.9	9.92	79.4	20.6	0	40.5	grasslands
PF 7	35.5	2	3.2	1.2	0	0	0	0	0.99	5.7	13.08	72.7	27.3	0	51.1	grasslands
PF 8	34.5	2	1.2	0.2	0	1	0	0	0.5	3.2	8.1	50.0	8.3	41.7	45.7	grasslands
PF 9	33.0	2	2.7	0.7	0	0	0	0	0.5	1.7	7.6	79.4	20.6	0	28.9	BLDF/MMF
PF 10	32.0	2	1.7	0.2	0	0	0	0	0.5	2.7	7.1	89.5	10.5	0	45.1	grasslands
PF 11	31.5	2	2.7	0.7	0	0	0	0	0.5	4.2	10.1	79.4	20.6	0	46.5	grasslands
PF 12	28.0	2	2.7	0.7	0	0	0	0	0.83	3.5	9.76	79.4	20.6	0	44.7	grasslands
PF 13	27.0	2	2.7	0.7	0	0	0	0	0.5	0.7	6.6	79.4	20.6	0	18.2	BLDF/MMF
PF 14	26.0	2	5.45	0.7	0	0	0	0	0.25	2	10.35	88.6	11.4	0	21.3	BLDF
PF 15	21.0	2.5	6.36	1.2	0.66	0	0	0	0.99	5.2	16.9	77.4	14.6	8.0	36.6	open woodlands
PF 16	20.5	2.5	6.2	1.2	0	0	0	0	0.33	4.5	14.76	83.8	16.2	0	32.9	open woodlands
PF 17	18.5	2	7.61	1.2	0.66	0	0	0	1.08	4.3	16.83	80.4	12.7	7.0	31.8	open woodlands
PF 18	17.0	2.5	3.7	1.2	0	0	0	0	0.5	4.2	12.1	75.5	24.5	0	38.8	open woodlands
PF 19	16.0	2	1.2	0.2	0	0	0	0	0.83	3	7.26	85.7	14.3	0	53.2	BLDF
PF 20	15.0	2	2.7	0.2	0	0	0	0	0.5	2.7	8.1	93.1	6.9	0	39.5	open woodlands
PF 21	14.0	2.5	4.2	0.7	0	0	0	0	0.5	1.7	9.6	85.7	14.3	0	22.9	BLDF
PF 22	13.0	2	3.7	0.7	0	0	0	0	0.5	2.7	9.6	84.1	15.9	0	33.3	open woodlands
PF 23	12.5	2.5	2.7	0.7	0	0	0	0	0.83	4	10.76	79.4	20.6	0	45.2	grasslands
PF 24	11.0	2	5	0.5	0	0	0	0	0.83	3.3	11.66	90.9	9.1	0	35.7	open woodlands
PF 25	9.0	2	5.7	1.2	0	0	0	0	0.5	2.7	12.1	82.6	17.4	0	26.4	BLDF
PF 26	8.0	2	3.7	0.2	0	0	0	0	0	3.7	9.6	94.9	5.1	0	38.5	open woodlands
PF 27	6.5	2	3.2	0.7	0	0	0	0	1.16	2.9	9.92	82.1	17.9	0	40.5	grasslands
PF 28	1.5	1.5	1.2	0.2	0	0	0	0	0.83	3	6.76	85.7	14.3	0	57.1	grasslands

References and complete flora lists including Nearest Living Relatives used for vegetation analysis are given in Supplementary electronic information 3.

the floras assigned to this zonal vegetation type. 10 out of 28 floras were assigned to open woodlands with proportions of herbs from 31.8 to 39.5%. Only seven floras were assigned to forestry vegetation type. The floras assigned to zonal vegetation type of temperate to warm temperate broadleaved deciduous forest (BLDF) are characterized by proportions of the BLD component from 82.6 to 88.6 %, BLE component – 11.4–17.4 %, and 21.3–27.7 % of herbs. The ecotone BLDF/MMF was revealed only for three floras, characterized by 76.2–79.4 % of BLD, 12.2–20.6 % of BLE, 0–11.5% of SCL + LEG, and 18.2–29.3 % of herbaceous components (Table 5, Fig. 6).

DISCUSSION

Climate evolution

For all known uncertainties and delimited climatic resolution primarily caused by high taxonomical rank of NLR identification, basic conclusions on the early Pliocene climate of the high-latitudinal Lena River Delta can be drawn. Given the scarcity of high-latitude continental quantitative palaeoclimate data for the early Pliocene in general, also estimates with lower resolution may provide valuable information. With MAT of ca. 11°C and CMMT at least ca. 0°C in the warmer parts of the record and ca. 7–9°C / -5°C in the cooler parts (Table 3), cool temperate climate prevailed throughout the deposition of the strata but may have approached warm temperate conditions in the warmest phases. However, we can assume that at such high latitude real values are close to the lower limits of the Coexistence Intervals (cf. Pross et al. 2000). Thus, mean values can be estimate for MAT of ca. 1°C, CMMT of -13°C, WMMT of 18°C (Fig. 3). The climate was overall humid, with very high MAP rates of ca. 1000–1500 mm (Table 3, Fig. 4). This level of precipitation corresponds to the oceanic type of climate.

Unfortunately, there are still no quantitative reconstructions of the Pliocene climate for both Yakutia in particular and the northeast of Russia in general. However, Fradkina (1995) provides a climate record based on the same palynological data from the Sardakhskaya Formation on the Sardakh-Sisse Island (shown in Fig. 3), but does not indicate which method was used. The comparison of Fradkina´s (1995) climate record and the data obtained in this study by the CA method shows that these data do not coincide and sometimes even diametrically opposed. According to Grinenko et al. (1989), the climate in the early Pliocene in northeastern Russia was colder than in the late Miocene, and the MAT was below 3°C. For the early Pliocene of northeastern Russia (Begunovskii Regional Horizon) in general, Fradkina (1995) and Grinenko et al. (1997) estimate a CMMT of -13 to -17°C, and a WMMT of ca. 14–17°C. While for CMMT these estimates are at the lower end of our reconstruction and still partially overlap, CA-derived WMMTs of at least 18°C are significantly higher.

Even though a progressive cooling occurred during the Cenozoic, the Pliocene world appears to have been, on average, warmer than present day (Jansen et al. 2007). Our results are in line with these data. The mean values of all temperature parameters for the coldest flora (at the level of 1.5 m) are significantly higher than the present-day mean values (Table 3). The ancient distribution of planktonic foraminifera along with terrestrial fossil fauna and flora indicates that winter and summer temperatures in the mid-latitudes were often several degrees higher than present (e.g., Thompson 1991, Dowsett et al. 1996, Thompson & Fleming 1996, Salzmann et al. 2009). The greatest warming apparently affected the polar regions where temperatures were often elevated enough to allow species of animals and plants to exist at higher latitudes than their nearest modern relatives (Adam 1994, Francis & Hill 1996, Ashworth & Kuschel 2003, Ashworth & Preece 2003, Ashworth & Thompson 2003, Ashworth & Cantrill 2004, Ballantyne et al. 2006, Francis et al. 2007, Salzmann et al. 2009). Realization that significant warming took place at high latitudes has potentially important ramifications for the behaviour and extent of Pliocene sea ice, ice sheets and sea level (Dwyer & Chandler 2009, Lunt et al. 2009, Naish & Wilson 2009).

Apart from information on the general Pliocene temperature level in the study area our data provide the first more detailed time series possibly spanning most of the early Pliocene. As mentioned above, according to palaeomagnetic studies (Grinenko et al. 1989), the Begunovskii Regional Horizon is assigned to the part (3.4–5.1 Ma) of the Gilbert Chron. However, it is highly unlikely that our section corresponds with the entire Zanclean – continental strata including riverine to coastal deposits have a high sedimentation rate and have many gaps, omissions and reworking phases. At the same time, the early Pliocene climatic optimum is placed from 4.4 to 4.0 Ma. For the Sardakh-Sisse record, two warmer phases are obtained in the intervals of 6.5–11.0 m and 26.0–35.5 m, respectively. These intervals are characterized by higher mean values of all temperature parameters, show stable climate conditions and can be correlated with the declining trend in $d^{18}O$ values in the global isotope stack for the early Pliocene (Zachos et al. 2008), corresponding to the early Pliocene climatic optimum. The interval of ca. 17–27 m in our records most likely corresponds to the early Pliocene climatic optimum (Fig. 7).

Seasonality of climate

The modern regime of this region is characterized by pronounced temperature seasonality but almost no humidity seasonality. Today, MART is at the very high level of 45.0°C, at a mean, while MARP is around 18 mm. The cold period (November – March) accounts for approximately 20–25 %, and the warm (April – October) 75–80 % of MAP. The minimum precipitation is observed in most of the territory in February – March. The modern RMPwet and RMPdry calculated based on the mean values using station data of Tiksi (Müller & Hennings 2000, New et al. 2002), are 14.1 % and 7.6 %, respectively (Table 3).

All our climatic data suggest a relatively strong seasonal control of the early Pliocene climate of northern Yakutia. The much higher-than-present early Pliocene WMMTs in combination with a higher difference in CMMTs indicate still a distinctly lower-than-present seasonality of temperature during the early Pliocene. Our MART values for the early Pliocene range from 23–27°C, only occasionally dropping

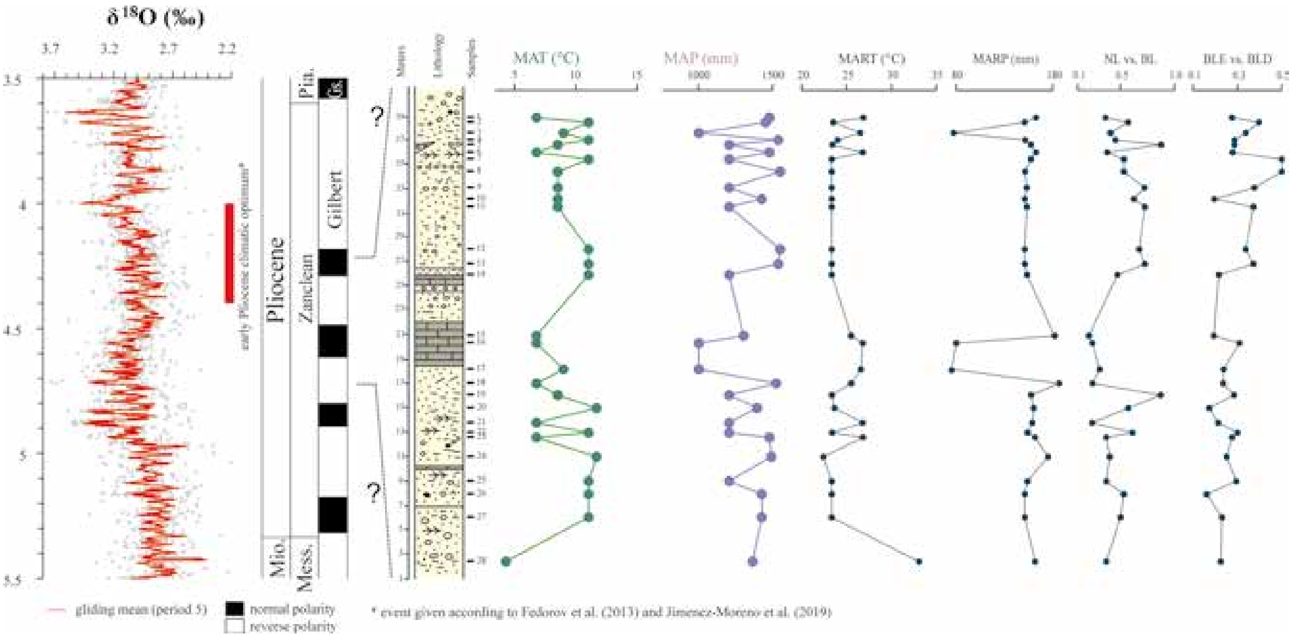

Figure 7 Lithological profile of the studied core and curves for various climate and vegetation characteristics next to the composite deep-sea benthic foraminiferal oxygen isotope record after Zachos et al. (2008)

below 32°C (Table 3). Moreover, seasonal temperature reconstructions show that the warming was primarily a winter phenomenon, with little variability in summer temperatures throughout the profile (Fig. 3).

The pronounced seasonality of precipitation (MPwet 124–224 mm; MPdry as 37–50 mm) in northern Yakutia weakly fluctuated during the early Pliocene and does not show any distinct increasing/decreasing trend. The early Pliocene MARP was significantly higher-than-present. However, the much higher past MPwet coupled with distinctly higher MPdry indicate that the climate of northern Yakutia was much more humid at that time. The calculated proportions of MPwet and MPdry to yearly precipitation (MPwet: 12.4–17.0 %; MPdry: 2.4–5.0 %) are similar compared to present-day (Table 3) and suggest similar precipitation seasonality of the early Pliocene climate of northern Yakutia in comparison to the present-day one.

Vegetation change

Using PFT diversity spectra as proxies for vegetation type (Table 4, Fig. 5), the early Pliocene vegetation of northern Yakutia in Lena River Delta mainly was presented by more or less open mixed deciduous woodland of warmer or colder temperate type. The results obtained from the PFT approach generally are in accordance with our data obtained from IPR approach. However, based on IPR, periodically forests and grasslands were obtained in addition to open woodlands (Table 5, Fig. 6).

According to the data of Fradkina (1995), the prevalence of arboreal pollen (50–60 %), mainly *Pinus* and *Betula*, as well the constant participation of *Larix*, *Abies*, *Tsuga*, *Picea*, and *Alnus*, is typical for the palynocomplexes of the Begunovskaya regional horizon. In addition, a noticeable participation of shrubby *Alnus* and *Betula* is characteristic. There is also a noticeable amount of spores (15–20 %), sometimes they dominate. The early Pliocene palynocomplexes are characterized by a high diversity of herbs (up to 10 % in total, occasionally higher) – Graminae, Chenopodiaceae, Caryophyllaceae, Alismataceae, Polemoniaceae, Ranunculaceae, *Thalictrum*, Valerianaceae, Leguminosae, Onagraceae, Polygonaceae, Umbeliferae, Liliaceae, Nymphaeaceae, Sparganiaceae, Cruciferae, Cyperaceae, Asteraceae, *Artemisia*, etc. Ericaceae attain 5–10 %, occasionally higher. Another typical feature of these assemblages is the absence of Taxodiaceae pollen and the rare occurrence of pollen of thermophilic angiosperms (usually 1–2%). Pollen of thermophilic angiosperms such as *Corylus*, *Carpinus*, and *Myrica* is most common, pollen of *Juglans*, *Tilia*, *Ulmus*, *Ilex* is very rare and single.

According to Fradkina (1983, 1995, 1996), Giterman (1985) and Grinenko et al. (1989, 1997), forest vegetation continued to exist in the early Pliocene almost everywhere in northeast Asia, even at places of modern tundra and forest tundra. These were forests of *Picea*, *Pinus*, *Larix*, *Betula*, *Alnus*, with a very small admixture of thermophilic angiosperms – mostly *Myrica*, *Carpinus*, *Corylus*, and occasionally *Tilia*, *Juglans*, etc. However, compared with the late Miocene, these areas in the early Pliocene were more occupied by shrubs – *Alnus* and *Betula*, as well as grasses quite diverse in composition. Based on carpological remains, Nikitin (1979) suggested that in the early Pliocene, in the northeast of Russia, taiga-type forests with a minor admixture of relics – *Myrica*, *Epipremnum*, *Weigela*, etc., prevailed. According to Grinenko et al. (1989), the climate in the early Pliocene in northeastern Russia was temperate, and quite humid due to the presence of *Picea*, *Abies*, *Alnus*, etc. Grinenko et al. (1989) assumed that modern coniferous forests with *Tsuga*, *Pinus*, *Picea*, *Abies*, etc. growing in the Great Lakes region of North America are similar to those existing in the early Pliocene of northeastern Russia.

Warm-temperate evergreen conifer forests covered the western and southernmost coastal zones of North America, indicating warmer or near modern temperatures throughout the Piacenzian (e.g., Thompson 1991, Hansen et al. 2001). Warm-temperate broadleaved forest became the dominant vegetation in most parts of Europe throughout the Pliocene. The forests consisted of a combination of subtropical and temperate floral elements which partially became extirpated throughout the later Pliocene and Pleistocene. Characteristic elements of the European Middle Pliocene assemblages include *Fagus*, *Quercus*, *Ulmus*, *Tilia*, *Pinus* and *Betula* as well as thermophilous taxa such as *Engelhardia*, *Liquidambar*, *Sequoia*, *Taxodium*, *Gingko*, *Nyssa*, *Glyptostrobus* and *Magnolia*. For the northern Mediterranean and western Europe the highly diverse forest vegetation implies MATs 3–6°C higher than today with an increase in MAP by 400 mm and 230 mm respectively (e.g. Fauquette et al. 1999, Utescher et al. 2000). With decreasing temperatures throughout the course of the Pliocene the dominant European vegetation changed gradually from highly diverse subtropical and warm-temperate forests to temperate deciduous forests with East Asian and North American affinities (Mai 1995).

It is known that vegetation changes are often induced by climate change. As is shown in Fig. 7, our early Pliocene data suggest a strong impact of climate change and variability on vegetational composition in Lena River Delta. The observed vegetation patterns and their changes through the early Pliocene in many cases can be correlated with warmer or cooler temperate climate patterns. The change in the proportion of some groups of PFTs (needleleaved vs. broadleaved, broadleaved deciduous vs. broadleaved evergreen) throughout the early Pliocene also reflects changes in some climatic parameters (Fig. 7). This is mainly evident from changes in the ratio of broadleaved evergreen versus deciduous PFTs that largely co-varies with MAT exemplifying the affinity of evergreens to warmer climates. The almost constant presence of aquatic plants (PFT 27) in most of studied floras throughout the early Pliocene suggests a high humidity in general, and agrees with the precipitation reconstruction demonstrating considerably much wetter conditions than at present. The constant presence of humid herbs (PFT 1) also coincides with the above mentioned high humidity throughout the early Pliocene.

Today, the climate in the Lena River Delta is very severe and maritime polar (Labutin et al. 1985). The entire study area is located beyond the Arctic Circle and therefore the non-setting sun characterizes it in summer, and the polar night – in winter. Weather conditions are mainly formed under the influence of two centers of high pressure (Arctic and Asian Highs) and the Icelandic Low in winter; the Siberian spur of the Asian High has a dominant influence, which until December is often disturbed by intrusions of the Icelandic Low. The Arctic maximum acts permanently, especially in the warm season. The MAT is -13.2(-14.3)°C, 3–4°C lower than in central Yakutia. In the Lena River Delta, precipitation is slightly higher compared to central Yakutia, but the annual distribution of rainfall is similar in each case: almost 3/4 of it falls in the warm season. The entire region lies within the distribution area of continuous permafrost, reaching a thickness of 400–600 m (Kudryavtsev et al. 1978).

At present, the study area is occupied by subarctic tundra (Labutin et al. 1985). According to our results, the early Pliocene vegetation cover in the study area fundamentally differed from modern. Moreover, permafrost did not yet exist (Grinenko et al. 1989). Based on the high proportion of herbaceous PFTs (up to 34.1 %), our data indicate that the Lena River Delta during the early Pliocene was entirely covered by open woodlands and only sometimes by forest vegetation (Table 4, Fig. 5). The results obtained from the PFT approach again are in accordance with data obtained from IPR approach. According to Kovar-Eder et al. (2008) and Teodoridis et al. (2011), with zonal herb proportions ranging from 18.2 to 57.1 %, open woodland and even grasslands were mainly reconstructed for the Lena River Delta throughout the early Pliocene based on the IPR-vegetation analysis (Table 5, Fig. 6). Thus, open woodlands and grasslands likely dominated in the Lena River Delta throughout the early Pliocene. However, the changes occurring along the section are all over fairly minor. Even for the levels where the IPR indicates grassland the diversity and abundance of arboreal pollen is still high pointing to the persistence of temperate conditions and absence of phases supporting Arctic tundra only.

CONCLUSION

The Sardakh-Sisse Island record provides the first quantitative climate and vegetation data for the early Pliocene in the high latitudes of the Northeast of Russia enlightening the environmental evolution around the early Pliocene climatic optimum. Our results show a temperate climate with two warmer and cooler phases. The reconstructed early Pliocene temperatures still indicate a high anomaly with respect to present-day climate, with a CMMT difference of up to 40°C. Seasonality of temperature was correspondingly high, but generally still twice lower than present-day. Precipitation was at the high level up to 1500 mm. All our climate data suggest relatively strong temperature seasonality and pronounced precipitation seasonality for the early Pliocene climate of northern Yakutia in Lena River Delta.

Quantitative data obtained from the application of the PFT and IPR approaches allow for tracing vegetation evolution in northern Yakutia throughout the early Pliocene. Both methods prove the prevalence of open woodlands and grasslands and sometimes existence of mixed deciduous forest of warm temperate character having a diverse shrub layer throughout the studied time-span (IPR types: BLDF and BLDF/MMF). Herbaceous components are constantly present, often attain high diversities only (<30 %). Hence, our vegetation data in general indicate open conditions within the studied territory during the early Pliocene, but more forested than at present. The persistent occurrence of PFTs indicative for humid conditions such as mesic herbs and aquatic plants (PFTs 1, 27) coincides with the assumption of humid climate conditions in the early Pliocene of northern Yakutia.

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