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Palaeoenvironmental and climatic changes during the Late Glacial and Holocene in the Mongolia and Baikal region: A review

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ABSTRACT

Multilayer sections in lake bottom sediments and continental sections of loose sediments in Mongolia and the Baikal region provide rich palaeontological material and radiocarbon dating for palaeoenvironmental reconstructions of the Late Pleistocene (Late Glacial) to Holocene. Multidisciplinary data from lacustrine bottom sediments provide evidence of past lake level and vegetation dynamics in the watersheds. Palaeontological data from terrestrial deposits indicate a mosaic landscape structure and a temperate warm and humid climate during the Late Glacial and Holocene, with some regional variability.

Global and regional climatic changes at the end of the Pleistocene resulted in the mass extinction of components of the Mammoth faunistic complex, such as the woolly mammoth, cave lion, cave hyena, and big-horned deer; the number of tundra species decreased and migrated to the north, and arid animal species migrated to the south. During the Holocene, four vegetation types (steppe, forest, taiga, and desert) did not show radical changes, but their ratio and spatial distribution changed. Steppe landscapes were replaced by desert steppes during the arid phases of the Holocene. In contrast, the area of taiga forests expanded during humid Holocene phases, but the steppe landscapes remained dominant in the studied territory.

1. Introduction

The current territories of Mongolia and the Baikal region are characterised by a mosaic landscape formed under the influence of continental climate (i.e. cold winters and warm summers). Lacustrine (mainly) and terrestrial sequences composed of slope or fluvial genesis can be used to reconstruct the evolution of these landscapes, as well as the palaeo-floral and faunal biodiversity.

Studies of lacustrine bottom sediments in Mongolia and the Baikal areas have shown that the processes occurring in the lake catchment areas influence the lake characteristics, such as depth, water surface area, water chemistry, bottom sediment distribution and composition, and aquatic species composition. Tectonic movements, the ponding or migration of riverbeds, and human economic activity within the basin also imbalance the lake water characteristics within the Mongolian territories. These changes are especially pronounced in the arid and semi-arid regions of Mongolia and the eastern part of the Baikal area, with high amplitude heat and moisture fluctuations reflected in lake sedimentation. The study of continuous sections in bottom lake sediments provides accurate information on the local and regional environmental changes (Dorofeyuk, Tarasov, 1998, 2000, 2000; Dorofeyuk, 2008).

Several large international projects on the study of lacustrine bottom sediments have been conducted during the past decades and are still ongoing. Examples include the Joint Russian-Mongolian Complex Biological Expedition of Russian and Mongolian Academies of Sciences

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(JRMCBE) Project (1970–1980), Baikal Drilling Project (1989–1999), Hovsgol Drilling Project (2004–2009), and Kotokel Drilling Project (2009–2020); other projects have also assessed lacustrine sediments in Inner Asia. A significant amount of palynological data and radiocarbon dating has been obtained from the study of lacustrine sediments in Mongolia and the Baikal region, as well as peat sites from the Baikal region (Figs. 1–3).

The terrestrial record is generally more fragmented than the lacustrine data; however, the development of complex litho-, chrono-, and biostratigraphical criteria in terrestrial records provides essential correlations with more continuous lacustrine records. Terrestrial sites often contain mollusc shells and the bone remains of amphibians, reptiles, birds, and mammals, as well as palynological information.

The combined data help to reconstruct climate dynamics, landscapes, and biodiversity in the specified areas, and numerous publications demonstrate that these areas are a global priority in this research field (e.g. Bradley, 1990; Tarasov et al., 1994, 1996; Williams et al., 2001; Jennings et al., 2002; Weninger et al., 2002; Jiang et al., 2003; Stewart and Dalen, 2008; Yang et al., 2009; Villa et al., 2010; Miracle et al., 2010; Huang et al., 2013, 2015; Mackay et al., 2013; Xiao et al., 2015; Antoine et al., 2016; Baca et al., 2017; Chen and Huang, 2017; Hessl et al., 2018; Markova et al., 2018; Park et al., 2019; and Saha et al., 2020).

This study summarises approximately 50 years of data from palynological, palaeozoological, palaeoenvironmental, and climatological studies in the Baikal (Cis-Baikal and Trans-Baikal subregions) and Mongolian areas of Inner Asia (approximate coordinates: 60–50°N and 100–115°E) (Figs. 1–3). The data covers the end of the Late Pleistocene (MIS 2) and the Holocene (MIS 1) and combines both lacustrine and terrestrial data.

2. Regional setting

Inner Asia is a vast interior region of the Eurasian landmass, which historically includes Central Asia, Mongolia, China, the mountain belt of Southern Siberia, the Baikal region, and the neighbouring areas (Devyatkin, 1981; What is Inner Asia). These areas are located far from the ocean and are characterised by common geological development and general rhythmic changes in climatic conditions throughout the Quaternary (Devyatkin, 1981). The Mongolia and Baikal regions are briefly characterised below:

The territory of Mongolia is located within the interior of eastern Asia and has minimal oceanic influence. The country has a continental climate, with long and cold winters and short and cool-warm summers (Harris et al., 2021). The difference between the mean temperatures of January and July can reach 44 °C, and temperature variations of ~30 °C can occur within a day. Mean temperatures in the north are cooler than temperatures in the south: the mean January and July temperatures in the north (Ulaanbaatar area) are −22 °C and 17 °C, respectively, while the corresponding temperatures for the Gobi area are −15 °C and 21 °C. The mean annual air temperature ranges between −0.8 °C (Ulaanbaatar), −0.4 °C (Yaarmag), and 1 °C (Kharkhorin) (Mongolia. Climate-data org., 2021). Precipitation increases with elevation and latitude, with annual amounts ranging from <100 mm in the desert depressions of the south and west to ~350 mm in the northern mountains (Harris et al., 2021).

The area represents a vast mountainous plateau (average elevation of 1589 m a.s.l.) sloping from west to east. Moreover, the central, eastern, and southern parts are occupied by plains and depressions. The Mongolian Altai Mountains (the highest mountain is the Huiten Peak at 4374 m), Khentiin Nuruu Mountains, and Khangai Mountains are located in the country's northern region; the Khangai Mountains also

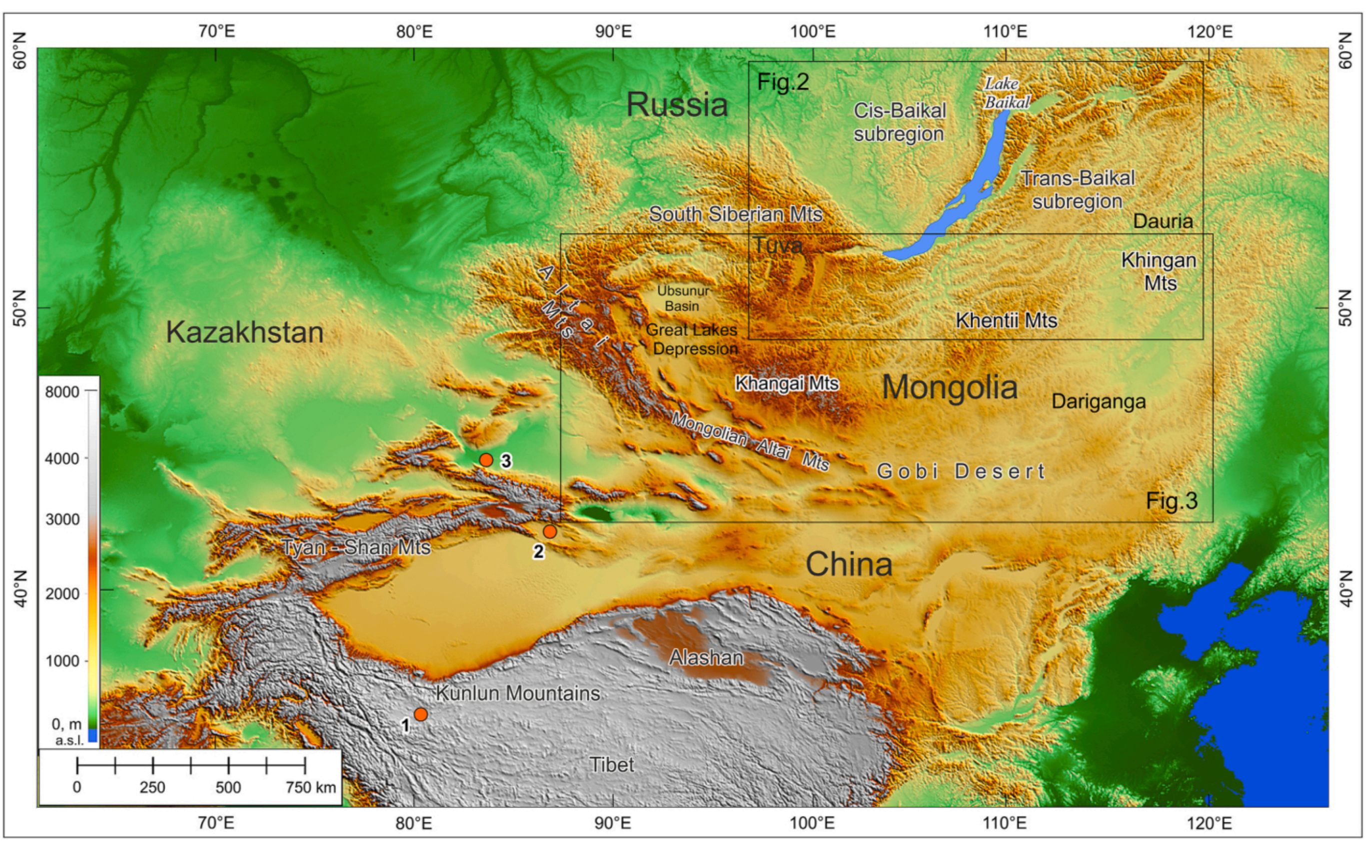

Fig. 1. Topographic map showing the Inner Asia territory and locations of objects discussed in the text. Elevation is based on 90-m resolution Shuttle Radar Topography Mission (SRTM).
Site localities: 1-Lake Sumxi, 2-Lake Bosten, 3-Lake Aibi.

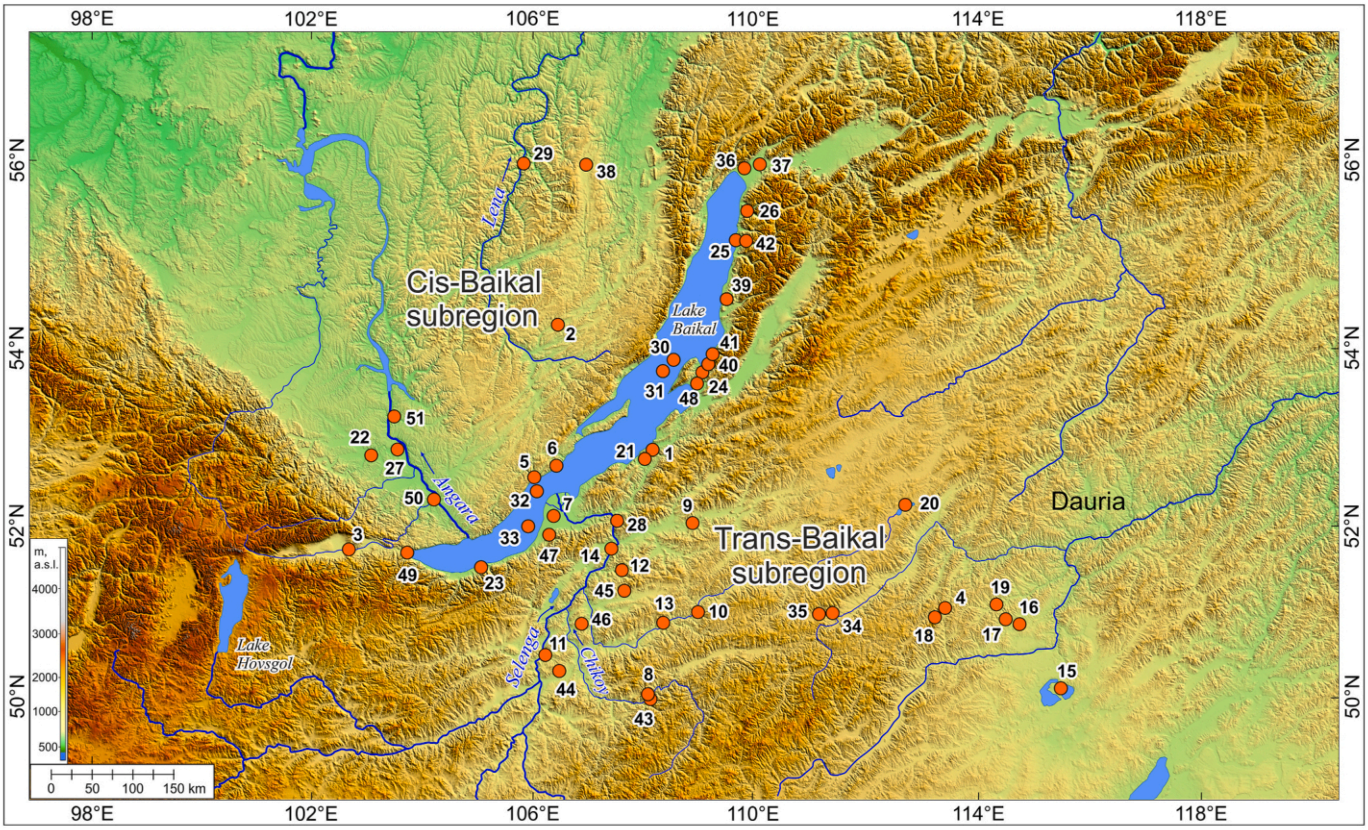

Fig. 2. Layout of the landscape areas of Baikal region and locations of objects discussed in the text. Topographic map is based on 90-m resolution Shuttle Radar Topography Mission (SRTM).
Site localities: 1-Lake Kotokel, 2-Lake Ochaul, 3-Bely Yar II, 4-Lake Balzino, 5-Buguldeika II, 6-Sagan-Zaba, 7-Fofanovo, 8-Studenoe-2, 9-Sannyi Mys, 10-Cheremuski, 11-Ust'-Kyakhta, 12-Kunalei, 13-Ust'-Obor, 14-Ivolga Xiongnu Fortress, 15-Torey Lakes, 16-Lake Nozhiy, 17-Zun-Soktui, 18-Ilya River floodplain, 19-Aga River floodplain, 20-Lake Arakhley, 21-Cheremushuka bog, 22-Ust'-Khaita, 23-Duliha bog, 24-Chivyrkui Bay, 25-Tompuda bog, 26-Froliha River, 27-Gorelyi Les, 28-Burdukovo, 29-Basovo, 30-Baikal Drilling Project (BDP)-98 borehole, 31-Baikal Drilling Project (BDP)-96 borehole, 32-Baikal Drilling Project (BDP)-93 borehole, 33-Baikal Drilling Project (BDP)-99 borehole, 34-Lake Tanga, 35-Lake Arey, 36-Verkhnyaya Zaimka, 37-Ukhta peat bog, 38-Khanda bog, 39-Duguldzeri River bog, 40-Krohalinaya Bay bog, 41-Bolshoi Chivyrkui River bog, 42-Tompuda end moraine, 43-Mel'nichnoe-2, 44-Arshan-Khundui dune, 45-Kharjaska-2, 46-Chernoyarovo, 47-Bolshaya Rechka bog, 48-Arangatui bog, 49-Shamanka-2, 50-Lokomotiv-Raisovet cemeteries, 51-Ust'-Ida cemetery.

occupy the central region of Mongolia (Harris et al., 2021). The largest intermountain depressions harbour numerous lakes, including the Great Lakes Basin between the mountains of the Mongolian Altai and the Khangai Highlands, and the Valley of Lakes between the southern spurs of the Khangai Range and the Gobi Altai (Fig. 3).

The Baikal region is an area located north of Mongolia and around Lake Baikal. It features a complicated system of landscapes, including four main natural complexes: high mountains (>1600–2000 m a.s.l.), middle mountains (1200–1800 m), low mountains (<1200 m a.s.l.), and plains (Atlas …, 2005).

Based on the regional morphotectonics, the Baikal region is conventionally divided into the Cis-Baikal and Trans-Baikal natural subregions (Atlas …, 2005) (Figs. 1 and 2). The Baikalian Rift Zone occupies the central position of the Baikalian area and consists of a chain of Cenozoic intracontinental rift valleys surrounded by high mountain ridges (>3000 m a.s.l., with the highest point at 4362 m in the Munkhkhairkhan Mountains). The mountain relief consists of landforms typical of mountain (alpine) glaciation, with glaciers present in the uppermost belt. Tectonically, the mountains of the Baikalian Rift Zone form a system of horsts oriented from SW to NE. The ridges form an important orographic barrier on the path of the main moisture-bearing air masses within Central Asia. Morphotectonically, the Cis-Baikal region is a southern protrusion of the Siberian Platform encircled by folded mountains of the Baikalian Rift Zone. The interchanging low and medium-sized mountain ridges and long depression stretching in north-easterly and east-north-easterly directions characterise the Trans-Baikal area. The most dissected area is the West Trans-Baikal (the Selenga middle mountains), where relative elevations reach >300 m and absolute elevations reach 800–1460 m. The location of this territory in the midlatitude belt (between 48°N and 64°N) as well as the aforementioned mountain and basin terrain features impact the climate formation in the Trans-Baikal region. The radiation regime in this region is more intense and contrasting than in surrounding areas of the same latitudes. The coldest month of the year is January, with average temperatures ranging from −20 to −30°C and absolute minimum temperatures reaching −55°C. The warmest month is July, with an average temperature of 15–20 °C and an absolute maximum temperature of 38 °C (Gerasimov, 1965). Annual precipitation rarely exceeds 200 mm, and winter precipitation only provides a small amount of the moisture to ecosystems, as frequent winds in this depression remove approximately 80% of the feeble snow cover.

The Cis-Baikal subregion lies west of Lake Baikal and is characterised by periglacial environments (Atlas …, 2005). The Trans-Baikal subregion lies east and southeast of Lake Baikal and was an unglaciated arid region during the Pleistocene (Gerasimov, 1965). The Cis-Baikal and Trans-Baikal areas belong to two different palaeozoogeographical subareas: the European-Siberian and Central-Asian subareas, respectively (Gerasimov, 1965).

3. Material and methods

Three main methods have been used to reconstruct the

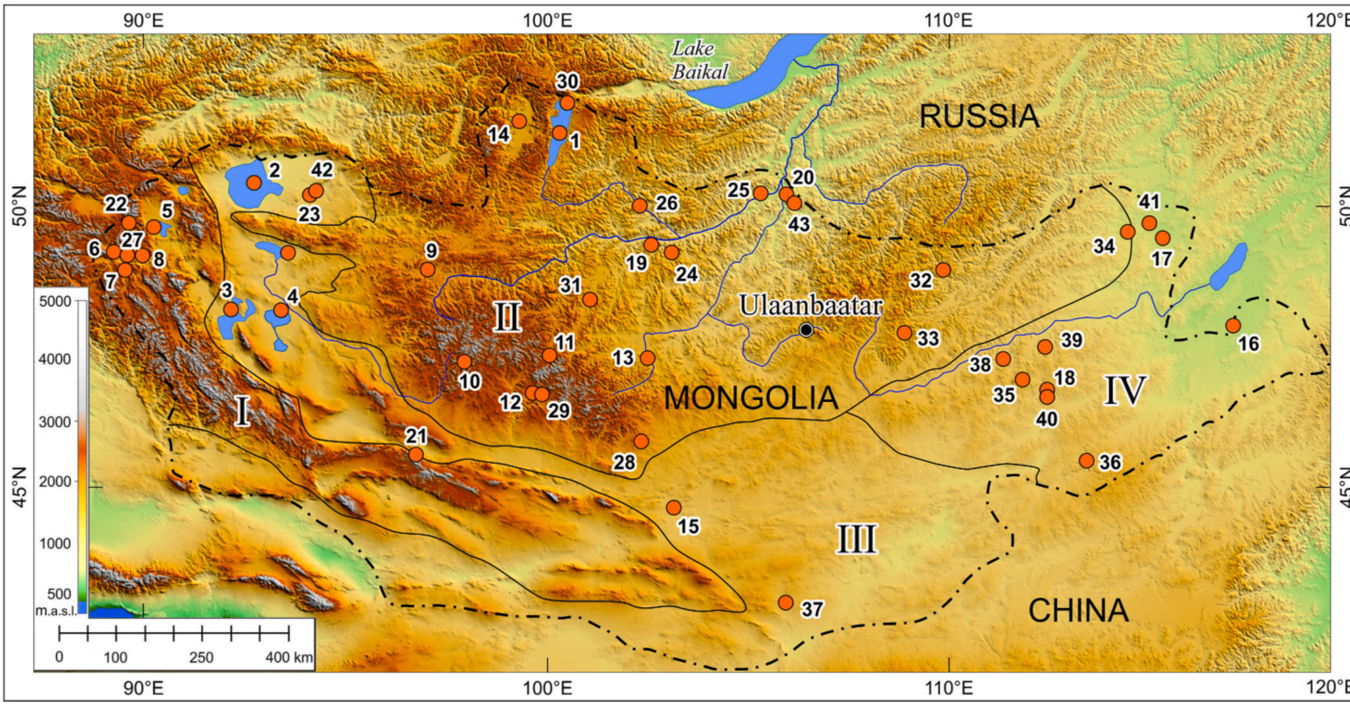

Fig. 3. Layout of the landscape areas of Mongolia (after: Sh. Tsegmid, 1962), as well as the location of key sections and archaeological sites. Topographic map is based on 90-m resolution Shuttle Radar Topography Mission (SRTM). Landscape areas: I-Altai mountainous, II-Khangai-Khentei mountainous, III-Gobi, IV-East Mongolian steppe. Site localities: 1-Lake Hovsgol, 2-Lake Ubsunur 3-Lake Khar-Us, 4-Lake Khar, 5- Lake Achit, 6-Lakes Hoton and Horgon, 7-Lake Dayan, 8-Lake Tolbo, 9-Lake Telmen, 10-Lake Huh, 11-Lake Daba, 12-Lake Terhiin-Tsagan, 13-Lake Ugii, 14-Lake Dood-Tsagan, 15-Lake Ulaan, 16-Lake Buir, 17- Lake Huh Nur, 18-Togootyn river terrace, 19-Tolbor, 20-Lake Gun, 21-Bayan-Sayr, 22-Lake Dund, 23-Lake Bajan 24-Lake Urmijn-Tsahan, 25-Lake Tsagan, 26-Lake Yamant, 27-Lake Danyagiin-Khar, 28-Lake Shiret, 29-Lake Khudo, 30-burial grounds Khankh, 31-burial grounds Khashat, 32-burial grounds Dulaan uul, 33-burial grounds Zenchermandal, 34-burial grounds Tsagaan Chulut, 35-burial grounds Ulaan Suukh, 36-burial grounds Sharkhad, 37-burial grounds Southern Gobi, 38-ancient city of Mongolia Avarga balgas, 39-Neolithic site Barga els, 40-Togootyn gol, 41-Uldza, 42-Khoit-Gol site, 43-Nur Sphagnum bog.

palaeoenvironment and palaeoclimatology of the Baikal and Mongolian areas—stratigraphical, palynological and palaeozoological—which were correlated with the available chronological data. During data evaluation, the results from palaeogeographical and geological-geomorphological studies were also considered.

3.1. Stratigraphical and chronological data

Data were correlated with the formal subdivisions of the Pleistocene (Cohen and Gibbard, 2019), as well as with the Holocene Epoch, which now has three distinct subsections ratified by the International Union of Geological Sciences: the Greenlandian (early Holocene; 11,700–8200 cal BP), Northgrippian (middle Holocene; 8200–4200 cal BP), and Meghalayan (late Holocene; 4200 cal BP) (Walker et al., 2009, 2018).

This study summarises the biostratigraphical and geochronological data of the Late Glacial (Late Pleistocene, MIS 2; 15,000–11,700 cal BP) and the early, middle, and late Holocene (Holocene, MIS 1) studied in more than 90 sites (including drilling cores and excavation logs) (Vipper et al., 1978, 1981, 1989; Sevast'yanov et al., 1989; Henzyhenova et al., 1991, 2005; Tarasov et al., 1994, 1996, 2000, 2004; Dorofeyuk and Tarasov, 1998, 2000; Gunin et al., 1999; Dorofeyuk, 2008; White et al., 2008, 2013; Rudaya et al., 2009; Mackay et al., 2013; Bazarova, 2014; Bazarova et al., 2008, 2011, 2014, 2015, 2019; Danukalova et al., 2015; Shchetnikov et al., 2015, 2019; Khenzykhenova et al., 2016a,b, 2020; Kobe et al., 2020) and summarised in various publications (Vipper, 1962; Vipper and Golubeva, 1976; Golubeva, 1976; Dinesman and Knyazev, 1984; Davydova, 1985; Volkova and Levina, 1985; Dinesman et al., 1989; Volkova, 1992; Sevast'yanov et al., 1993; Konstantinov, 1994; Bezrukova et al., 1996, 2005, 2006, 2009, 2010, 2011a, b, 2013; Mlikovsky et al., 1997; Tarasov et al., 1997, 2007, 2009, 2019; Continuous Paleoclimate, 1997; Horiuchi et al., 2000; D'Arrigo et al., 2000; Grunert et al., 2000; Kuz'min et al., 2000, 2014; Savel'ev et al., 2001; Peck et al., 2002; Fowell et al., 2003; Chen C.-T.A. et al., 2003; Krivonogov et al., 2004; Fedotov et al., 2004, 2012; Demske et al., 2005; Feng et al., 2005; Rioual and Mackay, 2005; Oberhänsli, 2005; Prokopenko et al., 2007; Blyakharchuk et al., 2007; Shichi et al., 2007, 2009, 2013; Lbova et al., 2008; Schwanghart et al., 2008, 2009; Reshetova et al., 2008, 2013; Ishiwatari et al., 2009; Solotchina et al., 2009, 2018; Khursevich and Prokopenko, 2009; Hovsgol ..., 2009; Nakamura, 2009; Wen et al., 2009; Ptitsyn et al., 2010; Chen H.-F. et al., 2010; Goldberg et al., 2010; Wang et al., 2011; Felauer et al., 2012; Derevianko et al., 2013; Sun A. et al., 2013; Lee et al., 2013; Kostrova et al., 2013, 2014, 2016; Müller et al., 2014; Losej et al., 2014; Erbajeva et al., 2015; Nomokonova et al., 2015; Losey and Nomokonova, 2017; Tian et al., 2017; Burkanova et al., 2017; Mischke et al., 2020).

Lacustrine bottom sediments from drilled boreholes in Mongolian lakes by the palaeobotanical team of the JRMCBE were dated by ^{14}C dating of total organic content (Gunin et al., 1999). A subsequent study conducted accelerator mass spectrometry (AMS) dating of organic content from 10 core samples from Lake Hoton (Rudaya et al., 2009). Six of these samples showed insufficient volumes of organic material for dating, and two samples showed ages exceeding the ^{14}C limit of the method. Only one date from this set was considered reliable and was used to reconstruct the palaeoenvironment of the Mongolian Altai. All reliable sediment radiocarbon dates in Lake Hoton were calibrated and compared with the data from other lakes (Rudaya et al., 2009) (Table 1).

The dates of organic material from terrestrial sites were obtained following the standard methodology for radiocarbon dating (^{14}C) as well as the AMS ^{14}C method. The geochronological data were obtained at different radiocarbon laboratories (Tables 1 and 2), and some of the ^{14}C ages were calibrated using the OxCal 4.3.2 (Bronk Ramsey, 2017) software. In this study, we used both calibrated dates (cal) and uncalibrated

Table 1
Radiocarbon dating results on the lacustrine and peat bog sediments (Mongolia). Calibrations were done in OxCal using the IntCal calibration dataset (https://c14.arch.ox.ac.uk/oxcal.html) (Bronk Ramsey, 2017).

Site name/references	Site number on Fig. 3	Date ^{14}C, BP	Age, cal BC	Mean cal. Date BP	Lab ID[a]	Depth, cm	Age, cal BP,68%
Mongolian Altai							
Lake Hoton (Gunin et al., 1999; Tarasov et al., 2000)	6	2950 ± 80	1172 ± 119	3122 ± 119	TA-1471	70–95	3002–3241
		3900 ± 140	2381 ± 199	4331 ± 199	TA-1440	147–170	4132–4530
		5360 ± 80	4191 ± 106	6141 ± 106	TA-1472	195–220	6035–6247
		5975 ± 150	4891 ± 188	6841 ± 188	TA-1439	245–270	6652–7029
		7910 ± 120	6830 ± 166	8780 ± 166	TA-1473	295–320	8613–8946
		9070 ± 150	8245 ± 229	10,195 ± 229	TA-1419	350–375	9966–10424
		14,250 ± 200	15,513 ± 290	17,463 ± 290	ANSTO OZB556U1OA1A	390–400	17,173–17753
		15,550 ± 630	16,807 ± 694	18,757 ± 694	ANSTO OZB556U1OA1A	410–420	18,063–19451
		20,900 ± 1160	23,190 ± 1488	25,140 ± 1488	ANSTO OZB556U1OA1A	480–490	23,652–26628
Lake Hoton (Rudaya et al., 2009)	6	9130 ± 42	8356 ± 58	10,306 ± 58	KIA32076	175–175.5	10,248–10364
Lake Dayan (Gunin et al., 1999)	7	3340 ± 70	1632 ± 86	3582 ± 86	TA-963	380–385	3496–3668
		3970 ± 80	2478 ± 120	4428 ± 120	TA-961	435–440	4307–4548
Lake Danyagiin-Khar (Gunin et al., 1999)	27	2450 ± 100	588 ± 139	2538 ± 139	TA-1032	115–135	2399–2677
Lake Dund (Gunin et al., 1999)	22	4830 ± 70	3609 ± 75	5559 ± 75	TA-1190	177–190	5464–5634
		5220 ± 60	4072 ± 86	6022 ± 86	TA-1189	195–200	5936–6108
Lake Achit (Gunin et al., 1999)	5	1000 ± 120	1025 ± 126	925 ± 126	TA-1030	52–65	799–1051
		3270 ± 90	1566 ± 99	3516 ± 99	TA-1029	215–227	3417–3615
		9470 ± 100	8865 ± 200	10,815 ± 200	TA-960	302–320	10,614–11015
Lake Achit (Gunin et al., 1999; Dorofeyuk, Tarasov, 2000)	5	6540 ± 100	5493 ± 93	7443 ± 93	TA-1832	152–165	7349–7536
		9397 ± 80	8684 ± 103	10,634 ± 103	TA-1192	175–190	10,531–10737
		10,150 ± 100	9817 ± 247	11,767 ± 247	TA-1191	205–220	11,520–12014
		11,500 ± 100	11,449 ± 140	13,399 ± 140	TA-1183	235–245	13,258–13539
Lake Achit (Sun et al., 2013)	5	2099 ± 35			AA94349	0–2	0
		2673 ± 38			AA94350	30–31	524–652
		2981 ± 39			AA94351	51–52	725–926
		4421 ± 38			AA94352	73–74	2180–2460
		5497 ± 40			AA94353	85–86	3488–3823
		6717 ± 61			AA94354	105–106	5258–5478
		9971 ± 52			AA94355	127–128	8547–8795
		11,300 ± 62			AA94356	148–149	10,235–10519
		11,796 ± 92			AA94357	165–167	10,755–11247
		18,600 ± 110			AA94358	190–191	19,463–19875
Great Lakes Basin							
Lake Khar-Us (Gunin et al., 1999)	3	1550 ± 100	1461 ± 96		TA-1080	90–115	1365–1557
		1960 ± 200	1929 ± 241		TA-1067	115–125	1687–2170
Lake Khar (Gunin et al., 1999)	4	2600 ± 60	717 ± 100	2667 ± 100	TA-1068	270–280	2567–2767
		3480 ± 80	1807 ± 99	3757 ± 99	TA-1061	290–310	3657–3856
Lake Telmen (Fowell et al., 2003)	9	640 ± 35	1336 ± 40 AD	614 ± 40	OS-27253	38.5	573–654
		1250 ± 40	762 ± 61 AD	1188 ± 61	OS-27254	78.5	1127–1249
		2380 ± 30	458 ± 47 BCE	2408 ± 47	OS-27255	138.5	2361–2455
		2930 ± 90	1148 ± 128 BCE	3098 ± 128	OS-25426	182	2969–3226
		4100 ± 35	2715 ± 111 BCE	4665 ± 111	OS-27256	239	4554–4776
		6090 ± 70	5038 ± 116 BCE	6988 ± 116	OS-26000	336	6871–7104
Lake Bayan (Grunert et al., 2000)	23	3250 ± 70	1539 ± 76	3489 ± 76	Beta 113,748	50	3413–3565
		6740 ± 80	5648 ± 65	7598 ± 65	Beta 99,133	321	7533–7663
		7310 ± 90	6194 ± 103	8144 ± 103	Beta 91,954	256	8041–8247
		11,230 ± 60	11,177 ± 105	13,127 ± 105	Beta 99,141	–	13,021–13232
		12,210 ± 80	12,319 ± 259	14,269 ± 259	Beta 101,484	565	14,010–14528

(continued on next page)

Table 1 (*continued*)

Site name/references	Site number on Fig. 3	Date ^{14}C, BP	Age, cal BC	Mean cal. Date BP	Lab ID[a]	Depth, cm	Age, cal BP,68%
		13,210 ± 90	14,191 ± 409	16,141 ± 409	Beta 101,483	1070	15,732–16550
Khangai							
Lake Tsagan (Gunin et al., 1999; Tarasov et al., 2004)	25	1050 ± 100	980 ± 119	970 ± 119	TA-1064	75–90	850–1089
		2660 ± 80	834 ± 73	2784 ± 73	TA-1063	315–340	2710–2857
		2850 ± 90	1054 ± 125	3004 ± 125	TA-1033	340–370	2879–3129
		7750 ± 80	6586 ± 77	8536 ± 77	TA-1027	228–233	8458–8613
Lake Daba (Dorofeyuk, Tarasov, 1998; Gunin et al., 1999; Tarasov et al., 2004)	11	3100 ± 120	1334 ± 152	3284 ± 152	TA-1355	75–100	3132–3436
		5600 ± 80	4451 ± 75	6401 ± 75	TA-1356	250–275	6326–6476
		7680 ± 100	6542 ± 83	8492 ± 83	TA-1357	325–350	8409–8575
		9400 ± 100	8724 ± 166	10,674 ± 166	TA-1358	375–400	10,508–10840
		10,580 ± 100	10,529 ± 194	12,479 ± 194	TA-1188	460–475	12,285–12673
		11,180 ± 120	11,121 ± 153	13,071 ± 153	TA-1028	490–505	12,917–13224
Lake Khudo (Gunin et al., 1999; Tarasov et al., 2004)	29	5450 ± 80	4274 ± 93	6224 ± 93	TA-1346	380–400	6131–6317
		7740 ± 80	6576 ± 74	8526 ± 74	TA-1345	610–630	8452–8600
		9230 ± 110	8476 ± 129	10,426 ± 129	TA-1344	760–780	10,297–10555
		9800 ± 100	9270 ± 130	11,290 ± 130	TA-1247	850–875	11,090–11350
Lake Terkhiin Tsagan (Sevast'yanov et al., 1989; Gunin et al., 1999; Tarasov et al., 2004)	12	2740 ± 60	906 ± 62	2856 ± 62	TA-1538	175–200	2793–2918
		3840 ± 50	2319 ± 92	4269 ± 92	TA-1339	275–300	4177–4361
		4150 ± 80	2730 ± 114	4680 ± 114	TA-1351	300–325	4566–4794
		4230 ± 50	2805 ± 86	4755 ± 86	TA-1340	325–350	4669–4841
		5050 ± 80	3843 ± 92	5793 ± 92	TA-1352	400–425	5701–5885
		5950 ± 120	4851 ± 146	6801 ± 146	TA-1353	450–475	6655–6947
		6690 ± 60	5610 ± 48	7560 ± 48	TA-1246	525–550	7512–7608
		6890 ± 100	5796 ± 95	7746 ± 95	TA-1248	550–575	7650–7841
Lake Shiret (Gunin et al., 1999; Tarasov et al., 2004)	28	1320 ± 100	733 ± 99 AD	1217 ± 99	TA-1474	50–75	1117–1316
		3150 ± 120	1409 ± 149	3359 ± 149	TA-1775	125–150	3210–3508
		8360 ± 100	7383 ± 125	9333 ± 125	TA-1420	200–220	9207–9458
Lake Yamant (Gunin et al., 1999)	26	14,300 ± 200	15,543 ± 291	17,493 ± 291	TA-1483 A	425–450	17,202–17784
Lake Urmijn-Tsahan (Gunin et al., 1999; Tarasov et al., 2004)	24	5200 ± 80	4045 ± 112	5995 ± 112	TA-1484	240–250	5883–6107
		7050 ± 150	5926 ± 140	7876 ± 140	TA-1485 A	260–280	7736–8016
Lake Ugii (Schwanghart et al., 2008)	13	3535 ± 30	3809 ± 57		POZ-16767	210	
		7770 ± 50	8538 ± 55		POZ-16847	510	
		9210 ± 50	10,382 ± 84		POZ-16768	580	
		4010 ± 35	4482 ± 37		POZ-15083	50	
		8500 ± 50	9506 ± 24		POZ-15084	148	
		9670 ± 50	11,031 ± 136		POZ-15085	198	
Lake Ugii (Wang et al., 2011)	13	756 ± 36			AA8 1667	3–5	
		1929 ± 39			AA8 1668	45–46	
		2014 ± 38			AA8 1669	86–87	
		2228 ± 36			AA6 4246	224–225	
		2117 ± 38			AA6 4247	280–261	
		2549 ± 36			AA6 4248	290–291	
		3283 ± 43			AA6 4249	330–331	
		3260 ± 44			AA6 4250	360–361	
		5442 ± 39			AA6 4255	504–505	
		6091 ± 49			AA6 4256	533–534	
		6727 ± 45			AA6 4260	630–631	
		7325 ± 70			AA6 4262	700–701	
		7077 ± 53			AA6 4263	730–731	
		7341 ± 54			AA6 4264	730–761	
Northern Mongolia							
Lake Dood (Kharmai) (Dorofeyuk, Tarasov, 1998; Gunin et al., 1999)	14	8150 ± 100	7170 ± 139	9120 ± 139	Vib-112	120–125	8981–9259
		11,470 ± 100	11,426 ± 143	13,376 ± 143	Vib-113	235–240	13,233–13519
Lake Hovsgol (Dorofeyuk, Tarasov, 1998; Gunin et al., 1999)	1	3910 ± 60	2389 ± 81	4339 ± 81	TA-670	100–112	4257–4420
		5800 ± 100	4660 ± 114	6610 ± 114	TA-671	190–202	6495–6724
		210 ± 32	181 ± 39		NUTA-2 6043	0,0–1,5	
		1291 ± 30	1232 ± 56		NUTA-2 7194	6,0–7,5	

(continued on next page)

Table 1 (*continued*)

Site name/references	Site number on Fig. 3	Date^{14}C, BP	Age, cal BC	Mean cal. Date BP	Lab ID[a]	Depth, cm	Age, cal BP,68%
Lake Hovsgol (Fedotov et al., 2004; Nara et al., 2005; Prokopenko et al., 2007; Murakami et al., 2010)	1	4365 ± 36	4917 ± 65		NUTA-2 6044	21,0–22,5	
		8162 ± 37	9079 ± 68		NUTA-2 7195	36,0–37,5	
		11,692 ± 43	13,547 ± 132		NUTA-2 6262	51,0–52,5	
		15,003 ± 49	18,319 ± 258		NUTA-2 7200	66,0–67,5	
		16,634 ± 61	19,738 ± 188		NUTA-2 6045	72,0–73,0	
		18,218 ± 50	21,645 ± 373		NUTA-2 7201	80,5–82,0	
		18,812 ± 66	22,352 ± 141		NUTA-26263	95,5–97,0	
		21,371 ± 213	25,658 ± 342		NUTA-2 7202	110,5–112,0	
		23,489 ± 87	26,307 ± 35		NUTA-2 6268	127,0–128,5	
Lake Gun (Dorofeyuk, Tarasov, 1998; Gunin et al., 1999)	20	1395 ± 80	640 ± 69 AD	1310 ± 69	TA-1441	50–75	1241–1379
		2870 ± 70	1068 ± 107	3018 ± 107	TA-1481 A	150–175	2911–3125
		3300 ± 80	1594 ± 89	3544 ± 89	TA-1482 A	200–225	3455–3633
		7970 ± 100	6876 ± 145	8826 ± 145	TA-1417 A	270–300	8681–8971
		8150 ± 100	7170 ± 139	9120 ± 139	TA-1350 A	325–350	8981–9259
		8760 ± 150	7904 ± 223	9854 ± 223	TA-1348 A	467–470	9630–10077
		9550 ± 150	8928 ± 216	10,878 ± 216	TA-1349 A	480–483	10,661–11094
Lake Gun (Wang et al., 2004)	20	1900 ± 40	1880–1820		Beta 171,822	64–65	
		2530 ± 40	2580–2510		Beta 171,823	151–152	
		3250 ± 40	3480–3440		Beta 171,824	240–242	
		4910 ± 40	5660–5600		Beta 171,825	342–344	
		5820 ± 50	6670–6560		Beta 171,826	391–392	
		9500 ± 50	10,760–10690		Beta 171,827	743–744	
Nur Sphagnum bog, Kh-1 (Fukumoto et al., 2014)	43	1135 ± 20	1024 ± 56		PLD-16824	47	
		3765 ± 20	4133 ± 50		PLD-14353	150	
		5575 ± 25	6356 ± 49		PLD-23948	233	
		7100 ± 25	7949 ± 29		PLD-14354	290	
		8205 ± 30	9175 ± 101		PLD-14353	350	
Nur Sphagnum bog, Kh-2 (Fukumoto et al., 2014)	43	3050 ± 20	3241 ± 35		PLD-23002	196	
		3980 ± 20	4493 ± 27		PLD-19385	255	
		5900 ± 25	6725 ± 59		PLD-23003	367	
		7155 ± 25	7977 ± 37		PLD-23949	446	
		8830 ± 30	9844 ± 112		PLD-19386	541	
Nur Sphagnum bog, Kh-3 (Fukumoto et al., 2014)	43	605 ± 20	616 ± 36		PLD-16825	72	
		2820 ± 25	2928 ± 67		PLD-16826	198	
		4820 ± 25	5507 ± 25		PLD-23950	349	
		5815 ± 25	6614 ± 82		PLD-16827	444	
		8445 ± 30	8445 ± 30		PLD-16828	582	
Southern Mongolia							
Lake Ulaan (Lee et al., 2013)	15	5982 ± 45			NZA 30880	50	6944–6697
		6036 ± 35			NZA 30881	100	6982–6788
		8390 ± 50			NZA 30876	150	9521–9293
		9894 ± 50			NZA 30879	200	11.601–11.207
		10,541 ± 60			NZA 30877	250	12.637–12.222
		12,295 ± 60			NZA 30882	300	14.880–13.954
Lake Bayan Tohomiin (43°34′N,103°11′E) (Felauer et al., 2012)		5495 ± 35	6299 ± 24		Poz-37868	247	
		5880 ± 46	6709 ± 45		Erl-13181	253	
		8697 ± 56	9674 ± 85		Erl-12109	353	
		9270 ± 50	10,441 ± 88		Poz-37949	367	
		9320 ± 60	10,523 ± 90		Poz-37869	367	
		6037 ± 47	6884 ± 64		Erl-13182	526	
		6920 ± 40	7222 ± 36		Poz-37870	536	
		10,661 ± 56	12,661 ± 65		Erl-12110	674	
		11,170 ± 70	13,073 ± 125		Poz-37871	665	
Eastern Mongolia							
Lake Buir (Gunin et al., 1999)	16	1320 ± 80	726 ± 77 AD	1224 ± 77	TA-1831	80–100	1147–1301
		1650 ± 70	396 ± 99 AD	1554 ± 99	TA-1830	100–115	1454–1653
		3290 ± 80	1584 ± 89	3534 ± 89	TA-1193	235–260	3444–3623
Site of Togootyn gol-V (Bazarova et al., 2019)	40	636 ± 27			AAR-22183		573–652
		5087 ± 30			AAR-22181		5775–5893

[a] Laboratory codes for dates: AA – NSF, USA; AAR – University of Aarhus, Denmark; ANSTO OZB – ANSTO-ANTARES, Australia; Beta – Beta Analytic, USA; Erl – Erlangen AMS Facility, Germany; KIA – Kiel AMS, Germany; NZA – Rafter Radiocarbon Lab (AMS), New Zeqland; PLD – Paleo Laboratory Co., Ltd., Japan; POZ – Poznan Radiocarbon Laboratory, Poland; TA – Tartu, Estonia; Vib – Vilnius laboratory, Lithuania.

Table 2
Radiocarbon dating results on the lacustrine and terrestrial deposits (the Baikal region).

Sampling places (locality, layer)	Age in yr BP	Calibrated yr BP 68% c.i. (1σ)	Reference of specimen[a]	Material	References
Late Glacial (15,000–11,700 cal BP)					
Cis-Baikal subregion					
Lake Ochaul	12,180 ± 50/ 11,580 ± 50	13,465–13355	Poz-114,421	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	11,070 ± 50/ 10,470 ± 50	12,545–12242	Poz-114,420	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	10,410 ± 50/9810 ± 50	11,250–11197	Poz-114,119	bulk total organic carbon	Kobe et al. (2020)
Bely Yar	12,405 ± 125		SOAN-7291	*Coelodonta antiquitatis* bone	Shchetnikov et al. (2015)
Ust'-Kyakhta-17	12,230 ± 100		GIN-84-930	bone	Khenzykhenova et al. (2016)
Ust'-Kyakhta-17	11,375 ± 110		SOAN-3093	bone	Mlikovsky et al., 1997
Ust'-Khaita (layer X)		12,610–12224	OxA-27347	*Cervus* bone	Losey and Nomokonova (2017)
Ust'-Khaita (layer IX)		12,398–11991	OxA-32346	*Cervus* bone	Losey and Nomokonova (2017)
Trans-Baikal subregion					
Lake Arakhley		13009.5	Poz_	bulk total organic carbon	Reshetova et al. (2013)
Cheremushuka bog	12,100 ± 60		Beta-115,297	peat	Krivinogov et al. (2004)
Tompuda bog	14,090 ± 50		Beta-136,814	gyttja	Krivinogov et al. (2004)
Early Holocene (11,700–8200 cal BP)					
Cis-Baikal subregion					
Basovo	9880 ± 80	11,195–11260	TO-9435	charcoal	White et al., 2008
Basovo	9490 ± 80	10,665–10485	TO-9432	charcoal	White et al., 2008
Basovo	8770 ± 100	9595–9915	TO-9434	charcoal	White et al., 2008
Basovo	8260 ± 130	9025–9430	TO-10553	charcoal	White et al., 2008
Lake Ochaul	8630 ± 50/8030 ± 50	9012–8780	Poz-114,518	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	9550 ± 50/8950 ± 50	10,202–9941	Poz-114,571	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	8790 ± 50/8190 ± 50	9244–9032	Poz-114,417	bulk total organic carbon	Kobe et al. (2020)
Sagan-Zaba II, layer VII	8745 ± 45	9900–9560	OxA-22411	*Phoca sibirica*	Nomokonova et al. (2013)
Sagan-Zaba II, layer VII	8010 ± 40	9010–8730	OxA-22363	*Capreolus pygargus*	Nomokonova et al. (2013)
Sagan-Zaba II		9410–9130	OxA-23955	Cervidae bone	Losey and Nomokonova (2017)
Ust'-Khaita (layer VII)		9410–9134	OxA-27352	*Capreolus* bone	Losey and Nomokonova (2017)
Gorelyi Les, layer VII		10,758–9142	KRiL-0234	unknown	Losey and Nomokonova (2017)
Gorelyi Les, layer VII		9883–9090	Ri-0051	charcoal	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		8991–8549	TO-6484	bone	Losey and Nomokonova (2017)
Trans-Baikal subregion					
Burdukovo (depth 340–350 cm)	5560 ± 650	5667–7157	TO-11666	Plant remains	White et al. (2013)
Burdukovo (depth 258 cm)	8230 ± 120	9031–9397	TO-10550	charcoal	White et al. (2013)
Burdukovo (depth 245 cm)	6890 ± 80	7660–7826	TO-10552	charcoal	White et al. (2013)
Burdukovo (depth 220–230 cm)	7370 ± 70	8056–8315	TO-11668	bulk soil	White et al. (2013)
Lake Kotokel (depth 685–689 cm)	12,680 ± 60	15,190 ± 110	Poz-27585	gyttja	Bezrukova et al. (2010)
Lake Kotokel	10,680 ± 40		Beta-209638	gyttia layer	Bezrukova et al. (2008), 2011b
Lake Kotokel (depth 507–511 cm)	10,190 ± 50	11,890 ± 110	Poz-27593	gyttja	Bezrukova et al. (2010)
Lake Kotokel (depth 501–505 cm)	9990 ± 50	11,470 ± 130	Poz-27584	gyttja	Bezrukova et al. (2010)
Duliha (depth 399 cm)	9185 ± 55		AA-37974	peat	Krivinogov et al. (2004); Bezrukova et al. (2005)
Chivyrkui (depth 300 cm)	10,820 ± 120		NUTA-3326	bulk total organic carbon	Bezrukova et al. (2005)
Arangatui bog	9400 ± 60		Beta-113,968	wood	Krivinogov et al. (2004)
Bolshaya Rechka (depth 508–510 cm)	8380 ± 40		Beta-098,421	peat	Krivinogov et al. (2004)
Middle Holocene (8200–4200 cal BP)					
Cis-Baikal subregion					
Basovo	6350 ± 120	7200–7420	TO-10973	charcoal	White et al., 2008
Lake Ochaul	6655 ± 35/6055 ± 35	6954–6808	Poz-114,416	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	5930 ± 35/5330 ± 35	6186–6016	Poz-114,415	bulk total organic carbon	Kobe et al. (2020)
Lake Ochaul	4430 ± 30/3830 ± 30	4286–4155	Poz-114,413	bulk total organic carbon	Kobe et al. (2020)
Buguldeika II, layer IY-I	4940 ± 30	5730–5600	OxA-23948	*Bos primigenius*	Losej et al., 2014
Buguldeika II, layer IY-I	4894 ± 29	5660–5590	OxA-23950	*Capreolus pygargus*	Losej et al., 2014
Sagan-Zaba II, layer VA	6784 ± 37	7680–7580	OxA-22418	*Phoca sibirica*	Nomokonova et al. (2013)
Gorelyi Les, layer VI		7976–7842	OxA-20576	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7947–7791	OxA-20575	bone	Losey and Nomokonova (2017)

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Table 2 (*continued*)

Sampling places (locality, layer)	Age in yr BP	Calibrated yr BP 68% c.i. (1σ)	Reference of specimen[a]	Material	References
Gorelyi Les, layer VI		7850–7681	OxA-31920	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7843–7681	OxA-31850	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7913–7310	Ri-0050a	unknown	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7581–7249	TO-6485	bone	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7567–7306	TO-6483	bone	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7563–7278	TO-4830	charcoal	Losey and Nomokonova (2017)
Gorelyi Les, layer VI		7558–7338	OxA-20573	bone	Losey and Nomokonova (2017)
Gorelyi Les, layers V and Va		7167–6974	OxA-31848	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layers V and Va		7158–6912	OxA-31849	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer Va		7161–6974	OxA-31848	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer Va		7158–6912	OxA-31849	*Capreolus*	Losey and Nomokonova (2017)
Gorelyi Les, layer V		6169–5058	GIN-4366	bone	Losey and Nomokonova (2017)
Gorelyi Les, layer Va		6442–5936	Ri-0052	unknown	Losey and Nomokonova (2017)
Gorelyi Les, layer V		6539–6353	OxA-20574	bone	Losey and Nomokonova (2017)
Trans-Baikal subregion					
Burdukovo (depth 219 cm)	5720 ± 430	6019–7149	TO-10551	Plant remains	White et al. (2013)
Burdukovo (depth 170–180 cm)	5970 ± 60	6737–6887	TO-11669	bulk soil	White et al. (2013)
Lake Kotokel	6070 ± 60		Beta-207356	gyttia layer	Bezrukova et al. (2008), 2011b
Lake Kotokel (depth 309–313 cm)	5890 ± 40	6720 ± 40	Poz-27583	gyttja	Bezrukova et al. (2010)
Lake Kotokel (depth 289–293 cm)	5690 ± 35	6480 ± 40	Poz-27582	gyttja	Bezrukova et al. (2010)
Lake Kotokel (depth 208–212 cm)	4575 ± 35	5230 ± 110	Poz-27581	gyttja	Bezrukova et al. (2010)
Lake Kotokel (depth 137–141 cm)	3855 ± 35	4290 ± 80	Poz-27580	gyttja	Bezrukova et al. (2010)
Chivyrkui (depth 195 cm)	7480 ± 100		NUTA-3325	bulk total organic carbon	Bezrukova et al. (2005)
Fofanovo 4	6350 ± 50	5220	GIN 4128		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 5	6640 ± 140	5490	GIN 4470		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 6	6670 ± 100	5520	GIN 4472		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 2	6720 ± 70	5570	GIN 4127		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7/1	6450 ± 50	5300	GIN 4131		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7/2	6780 ± 110	5630	GIN 4478		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7	6780 ± 120	5630	GIN 4471		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7	6830 ± 60	5680	GIN 4476		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7	7000 ± 60	5850	GIN 4130		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7	7040 ± 100	5890	GIN 4129		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 7	7610 ± 210	6460	GIN 4477		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 11	6670 ± 120		SOAN-6508	human bone	Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 12	6650 ± 130	5673–5479	SOAN-6827		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 13	6980 ± 140		SOAN-6509		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 14	6760 ± 140	5784–5536	SOAN-6828		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Fofanovo 17	6800 ± 180	5879–5558	SOAN-7183		Lbova et al. (2008); Lbova and Zhambaltarova (2009)
Late Holocene (4200 cal BP to the present)					
Cis-Baikal subregion					
Basovo, AMS^{14}C dates	3380 ± 80	3550–3695	TO-9433	charcoal	White et al., 2008
Basovo	2790 ± 60	2840–2950	TO-10554	charcoal	White et al., 2008
Basovo	2910 ± 60	2950–3080	TO-10555	charcoal	White et al., 2008
Basovo	2620 ± 90	2710–2780	TO-9436	charcoal	White et al., 2008
Basovo	2780 ± 360	2430–3360	TO-9431	charcoal	White et al., 2008
Basovo	1410 ± 60	1290–1350	TO-10556	charcoal	White et al., 2008
Basovo	1630 ± 90	1415–1615	TO-10557	charcoal	White et al., 2008
Buguldeika II, layer II-3	2751 ± 26	2920–2780	OxA-23939	*Equus* cf. *ferus caballus*	Losej et al. (2014)
Buguldeika II, layer II-3	2823 ± 26	3000–2860	OxA 23938	*Cervus elaphus*	Losej et al. (2014)
Sagan-Zaba II, layer IIIB	2129 ± 27	2300–2000	OxA-22388	*Cervus elaphus*	Nomokonova et al. (2013)
Sagan-Zaba II, layer I	1123 ± 26	1120–960	OxA-20645	Terrestrial mammal	Nomokonova et al. (2013)
Trans-Baikal subregion					

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Table 2 (*continued*)

Sampling places (locality, layer)	Age in yr BP	Calibrated yr BP 68% c.i. (1σ)	Reference of specimen[a]	Material	References
Burdukovo (depth 150–155 cm)	5970 ± 60	3690–3866	TO-10972	bulk soil	White et al. (2013)
Lake Arakhley		2353.5	Poz	bulk total organic carbon	Reshetova et al. (2013)
Ivolga Xiongnu Fortress		2037 ± 30	Ua-47734	bone of a dog	Losey et al., 2018
Ivolga Xiongnu Fortress		2029 ± 37	OxA-38662	charcoal	Khenzykhenova et al. (2020)
Chivyrkui (depth 30 cm)	550 ± 60		NUTA-324	bulk total organic carbon	Bezrukova et al. (2005)

[a] Laboratory codes for dates: AA – NSF, USA; Beta – Beta Analytic, USA; GIN – Geological Institute, Russian Academy of Sciences (RAS); LU – St. Petersburg University, Russia; NUTA - Tandetron AMS Lab, Japan; OxA – Oxford Accelerated, University of Oxford, UK; POZ – Poznan Radiocarbon Laboratory, Poland; Ri - Radiochemistry, Inc., USA; SOAN – Institute of Geology and Geophysics, Siberian Branch, Russia; TO – IsoTrace Laboratory, Canada; Ua – Uppsala Accelerator, Sweden.

^{14}C dates.

3.2. Palynological analysis

Samples taken from drilled borehole cores from the bottom of freshwater lakes were used for the palaeovegetation studies. Well-dated, high-resolution, continuous records of lacustrine sediments provide the most complete and reliable picture of vegetation change over time. Samples collected from excavations and trenches of unconsolidated sediments of slope and fluvial origin were also summarised.

The palynological analysis was conducted using the standard methods (Berglund and Ralska-Jasiewiczowa, 1986). The relative pollen and spore abundances were calculated from the total sum of pollen and spores in the sample. Spore-pollen diagrams were produced using the Tilia/Tilia-Graph/TGView software (Grimm, 2004) and divided into local pollen zones (LPZ) using the visual control and CONISS, which is a stratigraphically limited cluster analysis for zoning (Grimm, 1987). The variety of received pollen taxa was converted into functional vegetation types and assigned to biomes (Gunin et al., 1999; Tarasov et al., 2007). The dynamics of the forest, tundra, steppe, and desert vegetation were then used to provide supplementary definitions of environmental and climatic changes. The redeposition coefficient (RC) was then calculated as the ratio of redeposited pollen to the in situ deposited pollen (Burkanova et al., 2017). The RC provides additional information on the intensity of erosion processes, and higher values reflect a higher inflow of allochthonous components to the sediments.

3.3. Palaeozoological analysis

Standard methods were used to collect and process mollusc shells and vertebrate bone remains (fishes, amphibians, reptiles, birds, and mammals) (Danukalova et al., 2015; Shchetnikov et al., 2019; Khenzykhenova et al., 2020). Vertebrate remains and mollusc shells were recovered from sediments using traditional techniques of washing deposits through 1.0–0.5 mm mesh sieves. In the laboratory, the faunal remains were carefully cleaned of soil particles, and bones were impregnated with adhesive solution. Mollusc systematics were assessed according to Falkner et al. (2002), Sysoev and Shileyko (2009), and the WoRMS (2020) data.

Notably, stenobiont species (living in certain landscapes and climate, as opposed to eurybionts) of wild animals are excellent biomarkers of certain climates and landscapes and are widely used in palaeogeographic reconstructions globally (e.g. Flynn and Jacobs, 1982; Kolfschoten, 1995; Agadjanian, 2009; Erbajeva et al., 2015; Baca et al., 2017).

4. Review of regional data on palaeovegetation and palaeozoology

4.1. Late Pleistocene (Late Glacial, 15,000–11,700 cal BP): palynological and palaeozoological data of the Baikal region and Mongolia

4.1.1. Baikal region

Vegetation data. Late Glacial palynological data have been derived from the bottom sediments of Kotokel, Baikal, Ochaul, and Arakhlei Lakes (Demske et al., 2005; Tarasov et al., 2007; Bezrukova et al., 2005, 2009, 2010, 2011b; Reshetova et al., 2013; Kobe et al., 2020), as well as from lacustrine and underlying deposits from drilled borehole cores from Cheremushuka, Duguldzeri River, and Tompuda bogs (Krivonogov et al., 2004) (Figs. 1 and 2; Table 3). However, there are still no continuous records for this period, and the younger events have higher resolution/more continuous records than the older ones (Krivonogov et al., 2004).

During the Late Glacial, vegetation in the Baikal region was generally patchy, with the occurrence of shrubby tundra and isolated open forests consisting primarily of *Pinus sylvestris* with an admixture of *Betula* and *Pinus sibirica*; *Picea* also occurred locally in wetter valleys. The coasts of the lakes were well wetted and occupied by xero-mesophytic and mesophytic meadow vegetation (Tarasov et al., 2007; Bezrukova et al., 2011b). Moreover, open steppe and forest-tundra landscapes were typical in the Trans-Baikal area (Reshetova et al., 2013).

Changes in vegetation dynamics were interpreted for local areas. For example, in the Cis-Baikal subregion during the intervals of 13,500–12,620 and 12,790–11,720 cal BP, Kobe et al. (2020) used Lake Ochaul bottom sediments to infer a dominance of shrubby tundra followed by taiga/cold deciduous forests and then tundra. Vegetation on the eastern coast of Lake Baikal during 12,900–11,700 yrs BP was dominated by yernics *(Betula* sect. *nana* and *Duschekia)*. The presence of *Artemisia* and Amaranthaceae pollen indicated the development of steppe landscapes (Bezrukova et al., 2005, 2011a, 2011b). In the Cis-Baikal subregion, Bezrukova et al. (2009, 2011b) inferred the expansion of the *Salix* and mesophyte-herbaceous associations as well as the spreading of *Picea* and *Larix* forests at the beginning of 12,400–10,800 yrs BP.

Krivonogov et al. (2004) inferred the spreading of forest vegetation in the Lake Baikal area at the end of the Late Glacial, which replaced the periglacial tundra and forest-tundra associations. Demske et al. (2005) also inferred the expansion of forest vegetation throughout the Baikal Lake basin during the Late Glacial to early Holocene transition.

Paleozoology data. Late Glacial faunal remains have been identified in the Cis-Baikal subregion from the terrestrial deposits of the Bely Yar (Adamenko et al., 1975; Shchetnikov et al., 2015), Basovo site (White et al., 2008, 2013), and Ust'-Khaita archaeological site (layer X) (Savel'iev et al., 2001; Henzykhenova et al., 2005; Losey and Nomokonova, 2017); faunal remains in the Trans-Baikal subregion were obtained from the Ust'-Kyakhta-17, Studenoe-2, Sannyi Mys,

Table 3
The main stages of the vegetation development in the Mongolia and Baikal region according to palynological data in correlation with climate changes during Late Glacial – Holocene.

Chronological units (cal BP).	Time intervals, years ago (BP) (Bezrukova et al., 2011; Reshetova et al., 2013).	Climate (Tarasov et al., 2007; Dorofeyuk, 2008; Bezrukova et al., 2011).	Vegetation (Time intervals, years ago)		
			Baikal region		Mongolia (Golubeva, 1976; Vipper et al., 1976; Malaeva, Murzaeva, 1987; Dorofeyuk, 2008; Bazarova et al., 2019).
			Cis-Baikal subregion (Krivonogov et al., 2004; Tarasov et al., 2002, 2007; Bezrukova et al., 2005, 2006, 2009, 2011, 2006, 2011; Kobe et al., 2020).	Trans-Baikal subregion (Vipper, 1962; Tarasov et al., 2002; Reshetova et al., 2013; Bazarova et al., 2008, 2011, 2015).	
Late Glacial (15,000–11,700)	15,500–14,700	Very cold and dry.T_c – 10 °C below T modern	ca. 15,000–13,300.The western coasts of Baikal Lake were covered shrub-tundra and steppe plant communities. The eastern coasts of Lake were well wetted and occupied by xero-mesophyitic and mesophytic meadow vegetation.	15,000–13,500.Open steppe and forest-tundra landscapes dominated.	15,500–12,210Treeless vegetation with steppe grasses dominance at the lowlands and tundra vegetation on the 2000 m a.s.l.
	14,700–13,200	Slightly warm and humid	14,700–13,200.*Pinus* open forests. *Picea* and *Abies* locally spread in better-wetted valleys.	13,500–12,880.Decreasing of steppe landscapes. Spreading of shrub- and grass-tundra. Gradual appearance of open forests.	
	13,200–11,700	Cold and dry.T_w – 2–3 °C; T_c – 8–10 °C below T modern. P_{ann} decreased by 50–80 mm.	12,900–11,700.On the eastern coast of Lake Baikal yernic (*Betula* sect. *Nana* and *Duschekia*) landscape spread. Expansion of the willow and mesophytes-forb associations.	12,700–11,800.Shrub- and grass-tundra. *Larix* open forests.	
Holocene	Early Holocene 11,700–8200	11,500–10,580Cool and slightly humid than before.	12,400–10,800.On eastern part of Lake Baikal – spreading of birch- spruce forests and forest-tundra. 10,400–7800.On western part of Lake Baikal – *Abies* and *Pinus* spread.11,000–6000.Maximal *Abies* distribution in Siberia.	11,700–10,500.On the northern part of the subregion – *Betula* forests. Meso- xerophytic grass associations.On the central and southern parts – the first appearance of *Pinus* forests.	11,500–10,580Steppe vegetation dominance on low and middle mountains of the west Mongolia; cold steppe (tundra-steppe) dominated at 2000 m and above: from dry to semi-desert steppe dominated in the mountain' depressions. Coniferous forests – existed only in the north of the country.
		10,150–8150Cool and dry. Summer insolation increased. 9000–7000Warm and wet climate.T_w ~16 °C,T_c ~ −21 °C, P_{ann} ~480 mm, α ~0.9–1.	10,400–8200. Coniferous and hardwood forests with birch predominance.	10,400–8200.*Larix-Betula* forests with rare *Pinus* s/g *Haploxylon* (most probably *Pinus sibirica*) and *Picea*.	10,150–9230.Steppe and desert were located to the north compared with their modern distribution. Dry steppe and semi-desert steppe dominated.Taiga forests – Hovsgol Lake vicinity; cold steppe with small *Larix* forests – Khangai mountains.
			8500–8000.Fast distribution of *Betula* and *Picea* forests.Maximal spreading of *Picea* in Kotokel basin.		9070–8150Steppe dominated on the most part of the area. Flat interfluves were covered by desert vegetation. Taiga and boreal leaved forests saved only in the north.
	Middle Holocene 8200–4200	7900–6500. Cool and moderate humid. T_w ~16.5 °C, T_c ~ −23 °C, P_{ann} ~460 mm, α ~0.85.	8000–3000. Forests of *Betula, Pinus, Abies, Picea, Pinus sibirica* and *Larix*.	6615–6350 On southeastern part of the subregion in forest-steppe zone, *Pine-Betula* forest were spread. In high mountain zone – *Pinus sibirica-Larix* forests grew. On plains – *Artemisia* communities dominated.	7970–6510. Steppe wide developed on the mountain slopes and interfluves.
		Warmest and most humid	7400–6000. *Picea-Betula* and *Larix* forests.	ca. 6500. On central part of the subregion pine-Larix forests with insignificant present of *Abies*, *Quercus* and *Ulmus* distributed.	5500–4900. *Pinus–Larix* forests with admixture of *Picea* and *Abies* were widely distributed in the Khentii Mountains. The *Quercus mongolica* penetrated the valleys of Uldza and Kerulen Rivers. Afforestation of

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Table 3 (*continued*)

Chronological units (cal BP).	Time intervals, years ago (BP) (Bezrukova et al., 2011; Reshetova et al., 2013).	Climate (Tarasov et al., 2007; Dorofeyuk, 2008; Bezrukova et al., 2011).	Vegetation (Time intervals, years ago)		
			Baikal region		Mongolia (Golubeva, 1976; Vipper et al., 1976; Malaeva, Murzaeva, 1987; Dorofeyuk, 2008; Bazarova et al., 2019).
			Cis-Baikal subregion (Krivonogov et al., 2004; Tarasov et al., 2002, 2007; Bezrukova et al., 2005, 2006, 2009, 2011, 2006, 2011; Kobe et al., 2020).	Trans-Baikal subregion (Vipper, 1962; Tarasov et al., 2002; Reshetova et al., 2013; Bazarova et al., 2008, 2011, 2015).	
			7000–5000. The vegetation was presented by polydominant coniferous taiga. *Picea* and *Pinus sibirica* occupied the leading position. The thermophile species (*Tilia, Corylus* and *Ulmus*) presented in insignificant amounts.	6000–4500. Maximum distribution of broad-leaved species (*Quercus mongolica, Ulmus*). This species did not form independent forests; but were only a small accompanying element in the composition of *Betula-Pinus* and *Pinus sylvestris-Pinus sibirica* formations.	the Eastern Mongolian territory was the highest for the entire Holocene period. The borderline of the taiga-forest zone shifted 250–300 km to the south of the modern one.
			4800-4550. On northern coast of Lake Baikal, distribution of *Pinus sibirica* and *Picea* forests increased.	As a whole, the period of 7000–4900 cal BP is characterised by maximal afforestation of Cis-Baikal, Trans-Baikal and Mongolia territories.	
	Late Holocene 4200–recent	4200–4000 Cold and dry.			ca. 4000–3000. Area covered by taiga forests existed in the north of the country (Mongolian Altai) slowly decreased. On eastern part of the region, the borderline of forest zone moved to the foothills of the Khentii Mountains. Area of dry steppe increased.
		3500–2800 Moderate warm and humid.	ca. 2500. Role of *Larix* and *Pinus* increased in tree composition.	ca. 2600. On central part of subregion – a widespread development of *Picea* and *Abies* trees.	ca. 2000 Vegetation became close to the modern one and remained the same without significant changes until now.
		800–1200 AD (Medieval Warm Period). Warm and humid.	800–1200 AD (Medieval Warm Period). Intensification of *Abies* role in middle-mountain and taiga zones.		
			1200–1700 AD. On northern coast of Baikal Lake role of *Larix* forests became more essential.	Since ca. 1700 AD on southeastern part of subregion – steppe landscape.	Since ca. 1700 AD dry steppe dominated on eastern Mongolia.
		1755–1855 AD (The Little Ice Age). Cold and dry.	After 1700 AD pine and Siberian pine forests dominated.		
		1800 AD–recent. Moderate warm and slightly humid.	After ca. 1700–1800 AD modern-look vegetation began to form on all subregions.		

Legend: T – temperature, °C; T_w – summer temperature, °C; T_c – winter temperature, °C; P_{ann} – annual precipitation, mm; α – moister index.

Table 4
Late Glacial and Holocene vertebrates of the Mongolia and Lake Baikal region (Russia).

Taxa	Mongolia						Lake Baikal region																									
							Cis-Baikal subregion												Trans-Baikal subregion												
	LG	Holocene					Late Glacial		Holocene										Late Glacial										Holocene		
		EH	Middle			LH			Early				Middle					LH												EH	MH	LH
	T	–	TG	D	BS	ArS	BY	Ukh	SZ	UKh	Sh	LR	SZ	B	GL	Sh	Ul	Ukh	F	Uky	S2	SM	Ch	K	M	AK	Kh	C	UO	S2	–	XF
Amphibia																																
Strauchbufo sp.			+																													
Strauchbufo raddei (Strauch, 1876)																											+	+				+
Hyla sp.																																+
Rana cf. *amurensis* Boulenger, 1886																																+
Rana sp.						+																										
Anura gen. indet.																																+
Reptilia																																
Elaphe cf. *dione* (Pallas, 1773)																																+
Lypotyphla																																
Sorex sp.																														+		
Lagomorpha																																
Lepus timidus Linnaeus, 1758									+																	+						
Lepus tolai Pallas, 1778				+																												
Lepus sp.						+				+	+	+															+					
Ochotona daurica (Pallas,1776)				+		+														+						+	+	+				+
Ochotona sp.			+																													
Rodentia															+																	
Eutamias sibiricus (Laxmann, 1769)																														+		
Marmota sibirica (Radde, 1862)				+		+					+	+								+						+						
Marmota sp.									+																		+					
Spermophilus undulatus (Pallas, 1779)						+				+	+	+				+					+			+	+	+	+	+				
Spermophilus dauricus (Brandt, 1844)				+																												
Castor fiber Linnaeus, 1758									+	+	+	+				+	+	+														
Allactaga sibirica (Forster, 1778)				+																												
Allactaga sp.						+																				+	+					
Micromys minutus (Pallas, 1771)										+																						
Muridae gen. indet.									+																							
Phodopus sungorus (Pallas, 1773)				+																												
Cricetulus barabensis (Pallas, 1773)				+		+																				+						
Cricetulus sp.																											+	+				

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Table 4 (*continued*)

Taxa	Mongolia						Lake Baikal region																									
							Cis-Baikal subregion													Trans-Baikal subregion												
	LG	Holocene					Late Glacial		Holocene											Late Glacial										Holocene		
		EH	Middle			LH			Early				Middle					LH												EH	MH	LH
	T	–	TG	D	BS	ArS	BY	Ukh	SZ	UKh	Sh	LR	SZ	B	GL	Sh	UI	Ukh	F	Uky	S2	SM	Ch	K	M	AK	Kh	C	UO	S2	–	XF
Meriones unguiculatus (Milne-Edwards, 1867)				+																												
Meriones sp.																																			+	+				
Myodes rufocanus (Sandewall, 1846)										+																						
Ellobius tancrei Blasius, 1884																								+								
Myopus schisticolor (Liljeborg, 1844)										+																	+			+		
Alticola argentatus (Severtzov, 1879)				+																												
Alticola sp.																				+												
Lagurus lagurus (Pallas, 1773)																										+	+					
Arvicola terrestris (Linnaeus, 1758)								+		+								+														
Lasiopodomys brandti (Radde, 1861)			+	+		+														+	+	+	+	+	+	+	+	+	+			
Lasiopodomys gregalis (Pallas, 1779)										+										+							+	+				
Alexandromys fortis Buchner, 1889																														+		
Alexandromys maximowiczii (Schrenck, 1859)																											+	+				
Microtus oeconomus (Pallas, 1776)										+																						
Carnivora																																
Canis lupus Linnaeus, 1758										+																						
Canis sp.									+		+	+					+															
Vulpes vulpes (Linnaeus, 1758)										+	+		+	+																		
Vulpes sp.						+			+																							+
Ursus arctos Linnaeus, 1758											+	+			+	+	+	+														+
Martes zibellina Linnaeus, 1758										+	+	+				+																
Martes sp.									+																							
Gulo gulo Linnaeus 1758												+																				
Meles sp.																											+					
Lutra lutra Linnaus, 1758									+		+																					
Lynx lynx (Linnaeus, 1758)											+																					
Mustela sp.											+																					+
Artyodactyla																																

(*continued on next page*)

Table 4 (*continued*)

Taxa	Mongolia						Lake Baikal region																								
							Cis-Baikal subregion													Trans-Baikal subregion											
	LG	Holocene					Late Glacial		Holocene											Late Glacial										Holocene		
		EH	Middle			LH			Early				Middle					LH												EH	MH	LH
	T	–	TG	D	BS	ArS	BY	Ukh	SZ	UKh	Sh	LR	SZ	B	GL	Sh	UI	Ukh	F	Uky	S2	SM	Ch	K	M	AK	Kh	C	UO	S2	–	XF
Sus scrofa Linnaeus, 1758									+	+	+	+	+	+		+	+															+
Moschus moschiferus (Linnaeus, 1758)											+	+				+	+															
Capreolus pygargus (Pallas, 1771)								+	+	+	+	+	+	+	+		+															+
Cervus elaphus Linnaeus, 1758					+			+	+	+	+	+	+	+		+	+	+		+												
Cervus sp.																				+												
Rangifer tarandus (Linnaeus, 1758)													+	+						+												
Alces alces (Linnaeus, 1758)										+	+																					+
Spiroceros kiakthensis M. Pavlova, 1910																				+												
Procapra gutturosa (Pallas, 1777)																																+
Pinnipedia																																
Pusa sibirica (Gmelin, 1778)											+	+	+	+																		
Perissodactyla																																
Equus. caballus (Linnaeus, 1758)														+			+															
Equus sp.						+				+										+												
Coelodonta antiquitatis (Blumenbach, 1799)							+																									
Ovis sp.																											+					
Bison sp.																				+												
Bison sp./*Bos* sp.										+				+	+																	
Bos primigenius Bojanus, 1827													+	+			+															
Proboscidea																																
Mammuthus sp.											+	+																				
Aves																																
Struthio camelus Linnaeus, 1758	+																															
Cygnus sp.											+						+		+													
Anser cygnoides (Linnaeus, 1758)											+																					
Anas platyrhinchos Linnaeus, 1758																			+													
Anas sp.									+																							
Melanita sp.											+																					
Mergus cf. *merganser*											+																					
M. cf. *serrator*											+																					
Mergus sp.											+																					
																																+

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Table 4 (*continued*)

Taxa	Mongolia						Lake Baikal region																									
							Cis-Baikal subregion												Trans-Baikal subregion													
	LG	Holocene					Late Glacial		Holocene										Late Glacial											Holocene		
		EH	Middle			LH			Early				Middle					LH												EH	MH	LH
	T	–	TG	D	BS	ArS	BY	Ukh	SZ	UKh	Sh	LR	SZ	B	GL	Sh	UI	Ukh	F	Uky	S2	SM	Ch	K	M	AK	Kh	C	UO	S2	–	XF
Perdix daurica (Pallas, 1811)																																
Tetrao tetrix (Linnaeus, 1758)																																+
Grus grus (Linnaeus, 1758)											+																					
Gavia stellata (Pontoppidan, 1763)											+																					
Gavia sp.											+					+																
Botaurus stellaris (Linnaeus, 1758)											+																					
Phalacrocorax carbo (Linnaeus, 1758)									+																							
Phalacrocorax sp.											+																					
Larus cf. *ichtyaethus* Pallas, 1773																			+													
Accipiter cf. *gentilis* (Linnaeus, 1758)											+																					
Accipiter nisus (Linnaeus, 1758)											+																					
Accipiter sp.											+																					
Mulvus cf. *migrans* (Linnaeus, 1758)											+																					
Circus cf. *aeruginosus* (Linnaeus, 1758)																			+													
Buteo cf. *buteo* (Linnaeus, 1758)									+																							
Buteo lagopus (Pontoppidan, 1763)											+																					
Buteo hemilasius (Temminck & Schlegel, 1844)											+																					
Buteo sp.											+																					
Aquila sp.																			+													
Haliaeetus/Aquila											+																					
Haliaeetus sp.									+																							
Accipitriformes											+																					
Alauda arvensis (Linnaeus, 1758)																																+
Corvus cf. *corax* (Linnaeus, 1758)									+																							
Coccothraustes coccothrathraustes (Linnaeus, 1758)											+																					
Emberiza sp.																																+
Emberizidae gen. indet.																																+

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Table 4 (*continued*)

Taxa	Mongolia						Lake Baikal region																									
							Cis-Baikal subregion													Trans-Baikal subregion												
	LG	Holocene					Late Glacial		Holocene											Late Glacial										Holocene		
		EH	Middle			LH			Early				Middle					LH												EH	MH	LH
	T	–	TG	D	BS	ArS	BY	Ukh	SZ	UKh	Sh	LR	SZ	B	GL	Sh	UI	Ukh	F	Uky	S2	SM	Ch	K	M	AK	Kh	C	UO	S2	–	XF
Aves gen. indet																																+
Fishes																																
Coregonus migratorius (Georgi, 1775)																																+
Coregonus pidschian (Gmelin, 1788)																																+
Coregonus sp.									+																							
Hucho taimen (Pallas, 1773)																																+
Thymallus articus (Pallas, 1776)									+																							
Thymallus brevipinnis Svetovidov, 1935																																+
Leuciscus baicalensis (Dybowski, 1874)									+																							
Leuciscus idus (Linnaeus, 1758)																																+
Rutilus rutilus (Linnaeus, 1758)									+																							+
Acipenser baeri baikalensis Nikolskii, 1896									+																							+
Acipenser sp.											+		+	+																		
Esox lucius Linnaeus, 1758									+		+		+	+	+																	+
Lota lota (Linnaeus, 1758)									+																							+
Perca fluviatilis Linnaeus, 1758									+																							+
Carassius gibelio (Bloch, 1782)									+																							+

Late Glacial (LG). *Mongolia:* T-Tolbor-4, Tolbor-15, and Tolbor-16 sites (Derevianko et al., 2013). *Cis-Baikal:* BY-Bely Yar locality (Shchetnikov et al., 2015); UKh-Ust'-Khaita archaeological site (layer X) (Henzyhenova et al., 2005; Savel'ev et al., 2001). *Trans-Baikal:* UKy-Ust'-Kyakhta-17, S2-Studenoe-2, SM-Sannyi Mys, Ch-Cheremuski, K-Kunalei, M-Mel'nichnoe-2 (Khenzykhenova et al., 2016a); AK-dune Arshan-Khundui, Kh-Kharjaska-2, C-Chernoyarovo, UO-Ust'-Obor (Henzyhenova et al., 1991).
Early Holocene (EH). *Cis-Baikal:* SZ-Sagan-Zaba II (Nomokonova et al., 2015; Losey and Nomokonova, 2017); UKh-Ust'-Khaita (layers IX-VI) (Henzyhenova et al., 2005; Savel'ev et al., 2001; Losey and Nomokonova, 2017); Sh-Shamanka-2, LR-Locomotiv-Raisovet cemeteries (Losey and Nomokonova, 2017). *Trans-Baikal*: S2-Studenoe-2 (layer 2) (Khenzykhenova et al., 2016a).
Middle Holocene (MH). *Mongolia:* TG-Neolithic site Togootyn-gol (Bazarova et al., 2019); D-Dzotol'skoe (Dinesman et al., 1989); BS-Bayan-Sayr (Dinesman, Knyasev, 1984). *Cis-Baikal:* SZ-Sagan-Zaba II, B-Buguldeika II, GL-Gorelyi les, Sh-Shamanka-2, UI-Ust'-Ida (Losej et al., 2014; Losey and Nomokonova, 2017).
Late Holocene (LH). *Mongolia:* ArS-all archaeological sites together: Barga els, Khankh, Khashat, Dulaan uul, Zenchermandal, Tsagaan Chulut, Ulaan Suukh, Sharkhad, Southern Gobi, Avarga balgas (Khenzykhenova et al., 2016b). *Cis-Baikal:* UKh-Ust'-Khaita archaeological site (layer IV) (Henzyhenova et al., 2005; Savel'ev et al., 2001). *Trans-Baikal*: F-Fofanovo (Lbova et al., 2008); XF-Ivolga Xiongnu Fortress (Davydova, 1985; Khenzykhenova et al., 2020).

Table 5
Late Glacial and Holocene molluscs of Lake Baikal region (Russia).

Taxa	Cis-Baikal subregion												Trans-Baikal subregion			
	LG	LG-H		Holocene									LG	Holocene		
				Early				Middle				Late		Early	Middle	
	Ba	BY/4-5	BY/3	Ba	UKh	Sh	LR	Ba	B	Sh	UI	Ba	Bu	Bu	Bu	XF
Carychium pessimum Pilsbry, 1901								+				+				
Succinea putris (Linnaeus, 1758)			+													
Succinella oblonga (Draparnaud, 1801)	+	+	+	+				+				+			+	
Oxyloma/Succinea	+		+					+	+	+		+	+	+	+	
Cochlicopa lubrica (O.F. Müller 1774)	+		+	+									+	+		
Gastrocopta theeli (Westerlund, 1877)				+				+				+	+			
Vertigo modesta modesta (Say, 1824)			+	+				+				+				
Vertigo modesta alpestris Alder, 1838	+							+								
Vertigo extima (Westerlund, 1877)	+			+				+				+	+	+		
Vertigo microsphaera Schileyko, 1984				+				+				+			+	
Vertigo parcedentata (A. Braun, 1847)				+				+								
Vertigo antivertigo (Draparnaud, 1801)								+				+		+		
Vertigo pygmaea (Draparnaud, 1801)								+				+				
Vertigo sp.			+													
Columella columella (G. von Martens, 1830)				+				+							+	
Pupilla muscorum (Linnaeus, 1758)	+	+	+					+				+	+	+	+	
Pupilla sterii (Voith in Furnrohr, 1840)			+													
Vallonia costata (O.F. Müller, 1774)				+				+				+		+		
Vallonia tenuilabris (Braun, 1843)	+		+	+				+				+	+		+	
Vallonia sinensis Suzuki, 1944	+			+				+				+	+	+		
Vallonia kamtschatica Likharev, 1963	+			+				+				+	+	+		
Vallonia pulchella (Studer, 1820)				+				+				+		+		+
Punctum pygmaeum (Draparnaud, 1801)	+			+								+	+	+	+	
Euconulus fulvus (O.F. Müller, 1774	+			+								+	+		+	
Zonitoides nitidus (O.F. Müller, 1774)								+				+				
Deroceras/Limax	+			+								+	+			
Nesovitrea hammonis (Ström, 1765)	+		+	+								+	+	+	+	
Fruticicola schrenckii (Middendorf, 1850)				+	+			+				+		+		
Discus pauper (Gould 1853)													+			
Discus ruderatus (Hartmann, 1821)				+	+			+				+			+	
Valvata aliena Westerlund, 1876	+															+
Valvata (Tropidina) macrostoma (Mörch, 1864)	+											+				
Valvata (Tropidina) sibirica Middendorf, 1851			+													
Galba truncatula (O.F. Müller, 1774)	+		+					+				+	+	+	+	
Stagnicola palustris (O.F. Müller, 1774)								+								+
Stagnicola sp.														+		
Radix auricularia (Linnaeus, 1758)			+													
Radix pereger (Linnaeus, 1758)		+	+													
Radix sp.	+							+				+				
Physa sibirica Westerlund, 1877			+													
Aplexa hypnorum (Linnaeus, 1758)								+				+				
Anisus (Anisus) leucostoma (Millet, 1813)								+				+		+		
Gyraulus (Torquis) laevis (Alder, 1838)																+
Gyraulus (Lamorbis) rossmaessleri (Auerswald, 1852)								+				+				
Gyraulus (Gyraulus) acronicus (A. Ferussac, 1807)	+		+					+				+				+
Gyraulus (Armiger) crista (Linnæus, 1758)	+											+				
Gyraulus sp.												+				
Anodonta sp.						+	+				+					
Segmentina nitida (O.F. Müller, 1774)																+
Sphaerium (Sphaerium) corneum (Linnaeus, 1758)																
Sphaerium sp.	+															
Musculium (Musculium) lacustre (O.F. Muller, 1774)	+											+				
Pisidium (Euglesa) casertanum (Poli, 1791)								+								
Pisidium (Henslowiana) henslowanum (Sheppard, 1823)	+															
Pisidium (Cingulipisidium) nitidum Jenyns, 1832	+															
Pisidium (Pseudeupera) subtruncatum Malm, 1855	+															
Pisidium sp.												+				

Late Glacial (LG). *Cis-Baikal*: Ba-Basovo (White et al., 2008); Trans-Baikal: Bu-Burdukovo (White et al., 2013).
Late Glacial-Holocene (LG-H). *Cis-Baikal*: BY-Bely Yar I and Bely Yar II localities (layers 5–3) (Adamenko et al., 1975).
Early Holocene (EH). *Cis-Baikal*: Ba-Basovo site (White et al., 2008); UKh-Ust'-Khaita (Savel'ev et al., 2001); Sh-Shamanka-2 cemetery (Losey and Nomokonova, 2017); LR-Locomotiv-Raisovet graves (Losey and Nomokonova, 2017). *Trans-Baikal*: Bu-Burdukovo site (White et al., 2013).
Middle Holocene (MH). *Cis-Baikal*: UI-Ust'-Ida (Losey and Nomokonova, 2017); Ba-Basovo (White et al., 2008).
Trans-Baikal: Bu-Burdukovo (White et al., 2013); B-Buguldeika II (Losej et al., 2014; Losey and Nomokonova, 2017); Sh-Shamanka-2 (Losey and Nomokonova, 2017).
Late Holocene (LH). *Cis-Baikal*: Ba-Basovo site (White et al., 2008); *Trans-Baikal*: XF-Ivolga Xiongnu Fortress (Davydova, 1985; Khenzykhenova et al., 2020).

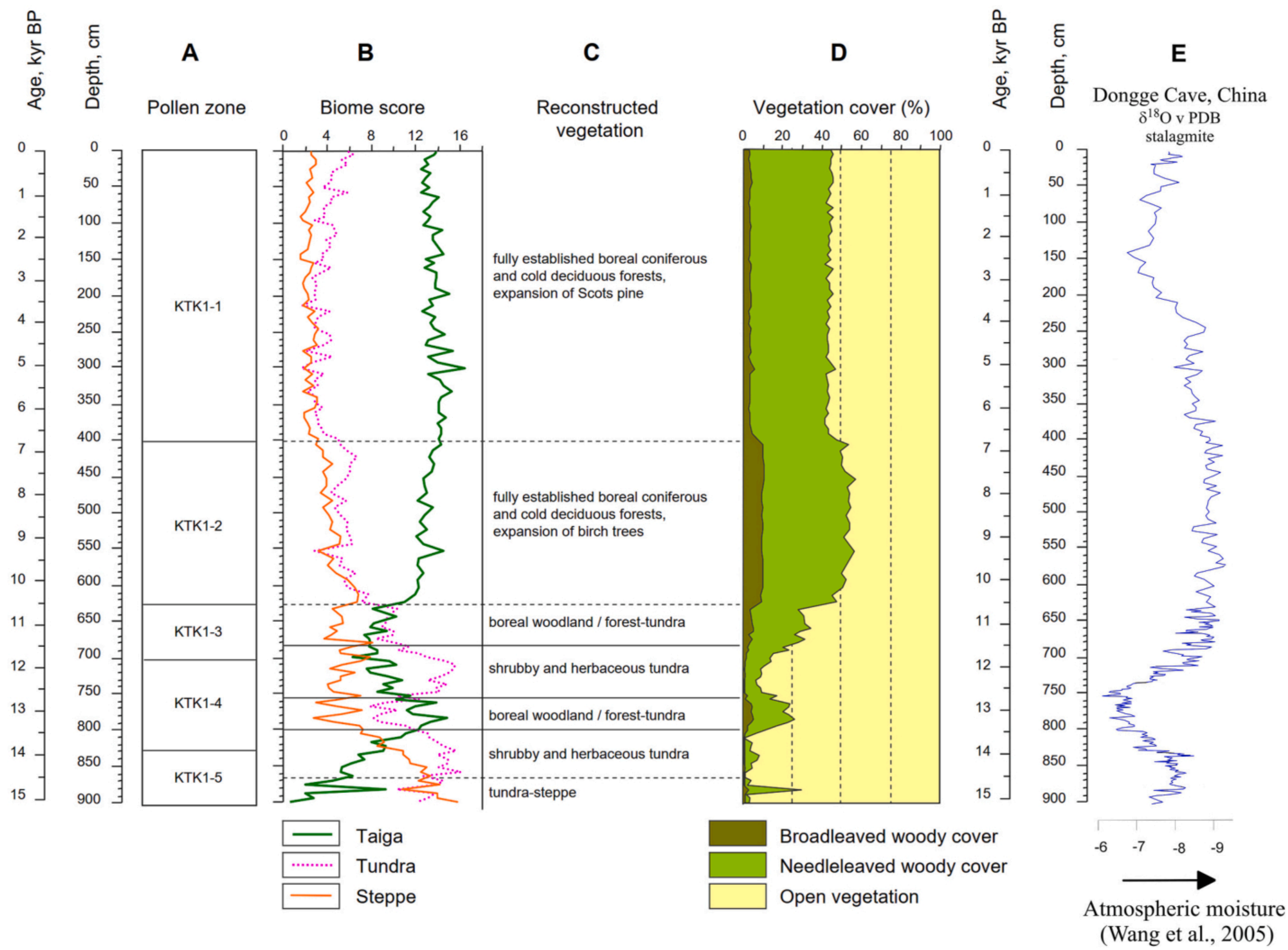

Fig. 4. Local pollen assemblages zones (A) and time series of individual vegetation types (biomes) dominating in the study area since 15 kyr BP (B), along with the qualitative characteristics of vegetation (C), and quantitative changes in woody cover percentages (D) derived from the Lake Kotokel (KTK1) pollen record, plotted along the time axis (after Tarasov et al., 2009), compared with the δ18O records from Chinese stalagmites (after Wang et al., 2005) as an indicator of the East Asian summer Monsoon (EASM) intensity (E).

Cheremuski, Kunalei, Mel'nichnoe-2, dune Arshan-Khundui, Kharjaska-2, Chernoyarovo, Burdukovo, and Ust'-Obor sites (Henzyhenova et al., 1991; Mlikovsky et al., 1997; Khenzykhenova et al., 2016a), and Burdukovo site (White et al., 2013) (Figs. 1 and 2, Tables 2, 4, and 5).

Large mammal bones of woolly rhinoceros were identified in the Bely Yar site and were dated to 12,405 ± 125 yrs BP (SOAN-7291) (Shchetnikov et al., 2015) (Tables 2 and 4). Molluscan assemblage is known from the Late Pleistocene – Holocene (not subdivided) deposits of Bely Yar site which contain terrestrial and freshwater molluscs (Adamenko et al., 1975) (Table 5).

The fauna corresponding to the Late Glacial period from the Ust'-Khaita multilayered site (cultural layer X) (Losey and Nomokonova, 2017) includes *Arvicola terresris* (Henzyhenova et al., 2005) and large mammals, such as *Equus* sp., *Capreolus pygargus,* and *Cervus elaphus* (Savel'ev et al., 2001) (Table 4).

The Basovo site located in the Cis-Baikal subregion contains data on terrestrial and freshwater mollusc assemblages (Bsv1), which are characteristic of cool and moist conditions with open-ground and marsh habitats (White et al., 2008) (Table 5). There are no direct radiocarbon dates for these mollusc assemblages, but the sediments overlying these deposits were dated to 11,195–11,260–9435 cal BP (White et al., 2008).

Faunal remains in the Trans-Baikal region corresponding to the Late Glacial include one bird *Delichon urbica* (Linnaeus, 1758) (Mlikovsky et al., 1997), one Amphibia *Strauchbufo raddei,* and several mammals: *Lepus* sp.*, Ochotona daurica* (Pallas, 1776), *Marmota* sp.*, Spermophilus undulatus* Pallas, 1778*, Cricetulus* sp., *Allactaga* sp., *Meriones* sp., *Myopus schisticolor* Lilljeborg, 1844*, Lagurus lagurus* (Pallas, 1773)*, Lasiopodomys brandti* (Radde, 1861), *L. gregalis* (Pallas, 1779)*, Alexandromys maximowiczii* Schrenk, 1859, *A. fortis* (Buchner, 1889), *Meles* sp., *Equus caballus* Linnaeus, 1758*, Coelodonta antiquitatis* Blumenbach, 1799*, Cervus elaphus* Linnaeus, 1758, *Rangifer tarandus* (Linnaeus, 1758)*, Spiroceros kiakthensis* M. Pavlova, 1910, *Ovis* sp., *Bison priscus* Bojanus, 1827*, Mammuthus primigenius* (Blumenbach, 1799) (Henzyhenova et al., 1991; Khenzykhenova et al., 2016a) (Table 4). Among the small mammals, Brandt's voles prevailed and typically inhabited dry steppes and semideserts. The occurrence of large mammals, such as steppe bison, horse, woolly rhinoceros, and woolly mammoth, also indicate an open landscape, while red deer prefer taiga and other types of forests. Reindeer inhabit both forests and tundra landscapes.

The ^{14}C dates of the Ust'-Kyakhta-17 archaeological site indicates an age of 12,230 ± 0.100–11,375 ± 110 yrs BP (GIN-84-930, SOAN-3093) (Mlikovsky et al., 1997; Khenzykhenova et al., 2016a) (Table 2).

The molluscan assemblage (zone Brd 1) from the lower part of the fluvial deposits from the Burdukovo site consists of mainly terrestrial and one freshwater species (*Oxyloma/Succinea* spp., *Cochlicopa* cf. *lubrica* (O.F. Müller 1774), *Vallonia* cf. *chinensis* Suzuki, 1944, *V. kamtschatica* Likharev, 1963, *Pupilla muscorum* (Linnaeus, 1758), *Punctum pygmaeum* (Draparnaud, 1801), *Vertigo extima* (Westerlund, 1877), *Gastrocopta theeli* (Westerlund, 1877), *Euconulus fulvus* (O. F. Müller, 1774), *Deroceras/Limax* spp., *Discus pauper* (Gould 1853), *Nesovitrea hammonis* (Strom, 1765), and *Galba truncatula* (O.F. Muller, 1774)). There are no available radiocarbon dates for this assemblage, but it is presumed to date to the Late Pleistocene (White et al., 2013) (Table 5). Another molluscan assemblage (zone Brd2a) from the same site was attributed to the Late Pleistocene–early Holocene transition, which is generally characterised by wetter conditions than the previous period (White et al., 2013). The transitional molluscan assemblage was characterised mainly by freshwater species and few terrestrial species.

4.1.2. Mongolian area

Vegetation data. Late Pleistocene (Late Glacial) palynological data in the Mongolian area were derived from lacustrine bottom sediments of the Hoton, Achit, Huh, Daba, Dood-Tsagan, and Yamant Lakes, and the data are summarised by Dorofeyuk (2008) (Figs. 1 and 3). According to the radiocarbon dating, the palynological data can be presented as follows:

For the interval 15,000–12,210 yrs BP, treeless vegetation with steppe associations dominated the western, central, and northern plains of Mongolia (*Artemisia*, Amaranthaceae, and Poacea); tundra elements also occurred at elevations of >2000 m above modern sea level (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008) (Table 3).

Starting from 12,000 cal BP, desert-type vegetation occurred in the intermountain depression occupied by Achit Lake (compared to modern vegetation represented by dry steppes in this area) (Dorofeyuk, 2008).

Palaeozoology data. Struthio camelus Linnaeus, 1758 remains were identified from the Tolbor-4, Tolbor-15, and Tolbor-16 archaeological sites. The ostrich eggshells were dated by AMS: Tolbor-15: 14,056 ± 81 cal BP (AA-84136), 14,930 ± 70 cal (Beta-263,742); Tolbor-4: 14,547 ± 730 cal BP (AA-93139); Tolbor-16: 15,660 ± 40 cal BP (MAMS-14938) (Derevianko et al., 2013) (Table 4).

4.2. Holocene (11,700 cal BP–recent): palynological and palaeozoological data of the Baikal region and Mongolia

4.2.1. Early Holocene (11,700–8200 cal BP)

4.2.1.1. Baikal region. Vegetation data. Early Holocene palynological data have been derived from the bottom sediments of Kotokel, Baikal (Vipper, 1962; Bezrukova et al., 2011a,b), Zun-Soktui (Bazarova et al., 2011), Arakhlei (Reshetova et al., 2013), and Ochaul Lakes (Kobe et al., 2020), as well as from lacustrine and underlying deposits from drilled borehole cores from the Krivoe Lake bog, Duliha bog, Bolshaya Rechka bog, Arangatui bog, Chivyrkui Bay, exposure 2, Chivyrkui Bay, Krohalinaya Bay bog, Bolshoi Chivyrkui River bog, Duguldzeri River bog, Tompuda bog, Froliha River, and Tompuda end moraine (Krivonogov et al., 2004) (Figs. 1 and 2; Table 3).

Sparse tree and shrub vegetation appeared in the central part of the Trans-Baikal area during 13,500–12,850 yrs BP, which formed areas of forest tundra and shrub tundra. Steppe landscapes with cryoxerophytic herbaceous vegetation were partly widespread (Reshetova et al., 2013).

Climate cooling occurred in the Trans-Baikal area during 11,700–10,500 yrs BP, which resulted in the expansion of semi-desert-steppe vegetation (Reshetova et al., 2013).

Kobe et al. (2020) inferred a relatively open landscape around Ochaul Lake during 11,600 yrs BP, and forest vegetation began to spread during the Late Glacial–Holocene transition (ca. 11,650 yrs BP), which occurred ca. 1000 years earlier than that around Kotokel Lake (Fig. 4) (Kobe et al., 2020).

According to Bezrukova et al. (2011a,b), precipitation increased in the Baikal region during the early Holocene to the early mid-Holocene. For the south-eastern Trans-Baikal area, extreme flooding was typical between 8480 ± 130 cal BP (Lu-8068) and 7090 ± 120 cal BP (Lu-8065) (Bazhenova et al., 2017) (Table 2).

In the Dauria territory (Trans-Baikal subregion), pine forests appeared at the beginning of the early Holocene in response to permafrost degradation. Moreover, Vipper (1962) and Neishtadt (1957) did not identify the growth of pines in the eastern area of Baikal Lake before the early Holocene. In response to the slight warming and increased humidity in the second half of the early Holocene, pine forests enlarged, and larch–birch forests were abundant with dwarf-birch-alder understories; ferns were also present in the ground cover, and *Pinus* s/g *Haploxylon* (most probably *Pinus sibirica*) and spruces were scarce. In response to the subsequent short-term cooling at the end of the early Holocene, pine forests shrank, and cold steppes with fairly abundant xerophytes enlarged (Bazarova et al., 2011).

Palaeozoology data. There are faunal remains correlated to the early Holocene at Sagan-Zaba II, Gorelyi Les, Ust-Khaita, Basovo, Shamanka-2, and Lokomotiv-Raisovet sites (Cis-Baikal subregion), Burdukovo and Studenoe-2 sites, and Fofanovo cemetery (Trans-Baikal subregion) (Savel'ev et al., 2001; Henzyhenova et al., 2005; Lbova et al., 2008; White et al., 2008, 2013; Nomokonova et al., 2015; Khenzykhenova et al., 2016a; Losey and Nomokonova, 2017) (Tables 4 and 5).

Nomokonova et al. (2015) conducted a faunistic study of a multi-layered Holocene settlement in Sagan-Zaba II. The fauna was represented by modern species only and included 8 species of fishes, 5 species of birds, and 10 species of mammals (Table 4). The groups of layers and their chronological framework applied to the study of faunal remains were dated to 9020–8650 cal BP (Losey and Nomokonova, 2017).

Ust'-Khaita fauna consists of two mollusc species—*Fruticicola schrenckii* (Middendorf, 1850) and *Discus ruderatus* (Hartmann, 1821)—nine species of small mammals (Henzyhenova et al., 2005), and nine species of large mammals (Savel'ev et al., 2001) (Table 4). AMS-dates corresponded to layers X–VI covering 11,155–10757 cal BP (OxA-27238) and 9267–9022 cal BP (OxA-27354) (Losey and Nomokonova, 2017).

Mollusc shells (*Anodonta* sp.), fish bone remains (*Acipenser* sp. and *Esox lucius*), and bird and mammal remains were excavated at the Shamanka-2 cemetery (early Neolithic grave) (Losey and Nomokonova, 2017) (Tables 4 and 5).

The fauna of the Locomotiv-Raisovet graves included one mollusc (*Anodonta* sp.) and bird and mammal remains (Losey and Nomokonova, 2017) (Table 4).

The Basovo site contains data on early Holocene molluscs (White et al., 2008) (Table 5). The mollusc assemblage (Bsv2) indicates a shift towards drier conditions from the base to the middle of the zone and a reverse to wetter conditions towards the top (from 11,195 to 11,260 to 9435 to 9025–9430 to 10,553 cal BP) (White et al., 2008).

In the Trans-Baikal subregion, the early Holocene fauna (layer 2) from the Studenoe-2 multilayer archaeological site consists of the rodents *Myopus schisticolor, Eutamias sibiricus*, (Laxmann, 1769), and *Alexandromys fortis* (Khenzykhenova et al., 2016a) (Table 4).

According to Martynovich (Lbova et al., 2008), the birds remains from the Fofanovo site were identified as *Anas platyrhinchos* Linnaeus, 1758, *Circus* cf. *aeruginosus* (Linnaeus, 1758), *Larus* cf. *ichtyaethus* Pallas, 1773, *Aquila* sp., and *Cygnus* sp.

Molluscan assemblages have been identified in the fluvial deposits of the Burdukovo site and consist of both terrestrial and freshwater species (zones Brd2b-c) (White et al., 2013) (Table 5). The mollusc composition is indicative of drier conditions at the beginning and wetter conditions at the end of this period. Radiocarbon dates of 9210 to 10,550 cal BP and 8180 to 11,668 cal BP suggest that the deposits are early Holocene in age (White et al., 2013).

4.2.1.2. Mongolian area. Vegetation data. Early Holocene palynological data on the Mongolian area have been derived from the lacustrine bottom sediments of the Hoton, Achit, Huh, Daba, Dood-Tsagan, Yamant, Terhiin-Tsagan, Shiret, and Gun Lakes, as well as the Khoit-Gol site;

the data are summarised by Dorofeyuk (2008) (Figs. 1 and 3; Table 3). All vegetation changes were correlated with the chronological table based on radiocarbon dating (Table 1).

During 11,500–10,580 yrs BP, steppe vegetation dominated on low and middle mountain regions in western Mongolia, cold steppes (tundra-steppe) covered surfaces at elevations of >2000 m, and dry steppes and semi-desert steppes occurred in the intermountain depressions. Coniferous forests with *Picea* were only noted in the north of Mongolia (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008).

At ~10,000 yrs BP, the surroundings of Dood-Tsagan and Gun Lakes in the northern part of Mongolia were covered by taiga forests, which replaced the steppe vegetation that dominated during the Late Glacial; however, steppe and desert vegetation began to dominate again at 9500 cal BP in the north and northwest of Mongolia (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008). Flat watersheds were covered by desert vegetation, and taiga and boreal-leaved forests only occurred in the north of Mongolia (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008).

Palaeozoology data. There are no known faunal data for Mongolia during this time.

4.2.2. Middle Holocene (8200–4200 cal BP)

4.2.2.1. Baikal region. Vegetation data. The data for this period were obtained from the sediments of the Tanga, Arey, Balzino (Vipper and Golubeva, 1976), Arakhley (Reshetova et al., 2013), Baikal, Kotokel (Bezrukova et al., 1996), and Zun-Soktui Lakes (Bazarova et al., 2011); the sediments of Verkhnyaya Zaimka and Ukhta peat bogs (Bezrukova et al., 2006); the floodplain sediments of the Ilya River (Bazarova et al., 2008, 2014); and the terrace deposits of the Chikoy River (Reshetova et al., 2008) (Figs. 1 and 2; Table 3).

From 7000 to 5000 cal BP (the Holocene climatic optimum), vegetation in the Trans-Baikal subregion was dominated by polydominant coniferous taiga, with highest abundances of *Abies* and *Pinus sibirica*. Thermophile species (*Tilia*, *Corylus,* and *Ulmus*) were also in high abundance (Bezrukova et al., 1996). On the south-eastern part of the Trans-Baikal area, this interval was marked by a significant increase in *Pine-Betula-Larix* forests and a decrease in the area of steppes (Bazarova et al., 2011).

From 6350 to 6615 cal BP, *Pinus-Betula* forests spread to the border of the forests and steppe zones. *Pinus sibirica-Larix* and *Pinus sibirica* forests with undergrowths of *Juniperus* and *Alnus* occurred in the more humid depressions of the alpine (high mountainous) zone, and *Picea-Larix* and *Picea-Abies* forests with a *Betula* admixture occurred in the canyon-like mountain valleys. *Artemisia* associations with Cyperaceae and Poaceae dominated the plain areas (Bazarova et al., 2008). *Quercus mongolica* appeared in the floodplain forests of the forest-steppe and steppe zones of the south-eastern Trans-Baikal area (Bazarova, 2011, 2014). In the central Trans-Baikal subregion (ca. 6500 yrs BP), *Betula-Larix* forests were replaced by *Pinus-Larix* forests, with insignificant contributions from *Abies, Quercus,* and *Ulmus* (Reshetova et al., 2008, 2013).

During 4800–4550 cal BP, the area of *Pinus sibirica-Picea* forests expanded in the northern coast of Lake Baikal (Bezrukova et al., 2006).

Palaeozoology data. Bones of vertebrates and mollusc shells in the Cis-Baikal subregion were obtained from the Basovo, Sagan-Zaba, Bugul-deika II, Gorelyi Les, and Shamanka-2 cemetery (early Bronze Age), as well as the Ust'-Ida cemetery (Neolithic and early Bronze Age graves); in the Trans-Baikal subregion – from Burdukovo site (White et al., 2008, 2013, 2013; Lozej et al., 2014; Losey and Nomokonova, 2017) (Figs. 1 and 2; Tables 4 and 5).

A Russian-Canadian expedition obtained the following radiocarbon dates of animal bones from the Sagan-Zaba site (layer IV): 8160–7880 cal BP, 6750–6310 cal BP, and 5590–4870 cal BP (Losej et al., 2014) (Table 2).

Lozej et al. (2014) conducted radiocarbon dating and faunistic research from the Buguldeika II multi-layered site. The fauna from this site included fish (*Acipenser* sp. and *Esox lucius*) and seven species of wild mammals (Table 4); the domestic animals were represented by *Equus caballus* and *Bos* sp. A *Bos primigenius* bone was dated to 5740–5600 yrs BP, and 42 new Holocene chronological dates were obtained by Losej et al. (2014) and Losey and Nomokonova (2017).

Several layers in the Gorelyi Les archaeological site were dated to the mid-Holocene, including layer VI dated to 7976–7842 cal BP (OxA-20576), 7947–7791 cal BP (OxA-20575), and 7850–7681 cal BP (OxA-31920); and layers V and Va dated to 7167–6974 cal BP (OxA-31848) and 7158–6912 cal BP (OxA-31849) (Losey and Nomokonova, 2017). The fauna of layer VI includes the fish *Esox lucius* and several mammals, including Rodentia gen. indet., *Ursus arctos, Capreolus pygargus,* and *Bison* sp./*Bos* ssp. The fauna of layer V and layer Va was represented by *Lepus* sp., Rodentia gen. indet., and *Capreolus pygargus* (Losey and Nomokonova, 2017) (Tables 2 and 4).

The shells of *Anodonta* sp., the bone remains of the bird *Gavia* sp., and several mammals were identified at the Shamanka-2 site (early Bronze Age) (Table 4). The mollusc *Anodonta* sp., the bird *Cygnus* sp., and several mammals (Table 2) were excavated from the late Neolithic graves (5466–5313 cal BP, OxA-23963) of the Ust'-Ida site; *Anodonta* sp. Shells were also excavated from early Bronze Age deposits (Losey and Nomokonova, 2017).

The Basovo site contains data on mid-Holocene molluscs (White et al., 2008) (Table 5). The mollusc assemblages inferred the occurrence of small ephemeral pools on the floodplain and relatively wet conditions (mollusc assemblage Bsv3 has no direct radiocarbon dates; however, the underlying deposits were dated to 9025–9430 to 10,553 cal BP), which transitioned to moderately dry conditions (part of Bsv4; 7200–7420 to 10,973 cal BP) (White et al., 2008).

A terrestrial molluscan assemblage (zone Brd 3) was identified in the Burdukovo site in the upper limit of the zone dated to 6810 cal BP (White et al., 2013) (Table 5). The mollusc composition indicated increasing aridity in the site vicinity.

4.2.2.2. Mongolian area. Vegetation data. Mid-Holocene palynological data from the Mongolian area have been determined from the lacustrine bottom sediments of the Hoton, Achit, Huh, Daba, Dood-Tsagan, Yamant, Terhiin-Tsagan, Shiret, Urmiin-Tsagan, Hovsgol, Khudo, Dund, Tolbo, and Gun Lakes, as well as the Khoit-Gol site; the data are summarised by Dorofeyuk (2008). Additionally, data from terrace deposits of the Uldza and Togootyn gol Rivers in north-eastern Mongolia were used for the analysis (Golubeva, 1976; Bazarova et al., 2019) (Figs. 1 and 3; Table 3).

Taiga and boreal-leaved forests occurred in limited areas of the northernmost part of Mongolia at ~8000 cal BP (Dood-Tsagan, Yamant, and Gun Lakes surroundings). Steppes dominated across most of the country, and deserts continued to occur in the wide depressions of north-western Mongolia (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008) (Table 3).

Dorofeyuk and Tarasov (1998) and Dorofeyuk (2008) identified significant vegetation changes in Mongolia at 7000 and 6000 cal BP. At ~7000 cal BP, taiga vegetation replaced steppes in the north and west of Mongolia (surroundings of Horgon, Dood-Tsagan, and Gun Lakes surroundings), and desert vegetation was slowly replaced by steppes (surroundings of Achit Lake and the Khoit-Gol site). At ~6000 yrs BP, taiga forests dominated by *Picea, Pinus sibirica*, and *Abies* covered a wider area in Mongolia than the present day. Forest-steppe vegetation with small forests of *Larix, Picea*, and *Pinus sibirica* occurred at elevations of 1700–2500 m above sea level in the central and western parts of Mongolia (Mongolian Altai and Khangai Mountains).

During 5500–4900 BP, pine-larch forests with an admixture of spruce and fir were widely distributed in the Khentii Mountains. *Tilia, Corylus*, and *Ulmus* pollen were identified in mid-Holocene sediments in the Onon, Khalkh Gol, and Idar Rivers valleys (Vipper et al., 1978; Malaeva and Murzaeva, 1987). Moreover, oak (*Quercus mongolica*) penetrated the valleys of the Uldza and Kerulen Rivers (Golubeva, 1976; Vipper et al., 1976).

Palaeozoology data. The Neolithic Togootyn gol site and the Dzotol'skoe and Bayan-Sayr faunistic localities contain faunal remains.

According to the palaeozoological analysis of the Neolithic Togootyn gol site in eastern Mongolia (Bazarova et al., 2019), the Brandt's vole *Lasiopodomys brandti* was the dominant species of small mammal, which together with pika *Ochotona* sp. are characteristic steppe inhabitants. The favoured habitats of the toad *Strauchbufo* sp. living close to the Mongolian *Strauchbufo raddei* (Strauch, 1876) are forest-steppe landscapes and river and lake floodplains. An animal bone in the main cultural layer was AMS dated to 5087 ± 0.300 cal BP (AAR-22181).

Recovered palaeozoological material was correlated with data from the Dariganga Plateau (Dzotol'skoe site) in the same province (Sukhbataar Province; Dinesman et al., 1989). A rich species composition of late Holocene small mammals—inhabitants of mainly dry steppes and semi-deserts—was determined in the Dzotol'skoe locality: hare-tolai *Lepus tolai* Pallas, 1778, Daurian pika *Ochotona daurica* (Pallas, 1776), jerboa *Allactaga sibirica* (Förster, 1778), Daurian hamster *Cricetulus barabensis* (Pallas, 1773), Djungar hamster *Phodopus sungorus* (Pallas, 1773), Daurian ground squirrel *Spermophilus dauricus* (Brandt, 1844), tarbagan *Marmota sibirica*, Mongolian gerbil *Meriones unguiculatus* (Milne-Edwards, 1867), silvery mountain vole *Alticola argentatus* (Severtzov, 1879); narrow skull vole *Lasiopodomys gregalis*, and Brandt's vole *Lasiopodomys brandti* (Dinesman et al., 1989) (Table 4).

Dinesman and Knyazev (1984) identified a horn fragment of the red deer *Cervus elaphus* in the wood remains of the Bayan-Sayr tract in the Gobi Altai, which was dated to 4500–3500 yrs BP.

The species composition of mammals in the Mongolian area indicated the dominance of dry steppes and the presence of forests.

4.2.3. Late Holocene (4200 cal BP to the present)

4.2.3.1. Baikal region. Vegetation data. Late Holocene palynological data for the Baikal region have been derived from the bottom sediments of the Tanga, Arei, Balzino, Kotokel, Arakhlei, Nozhiy, and Zun-Soktui Lakes (Vipper and Golubeva, 1976; Bezrukova et al., 2011b; Reshetova et al., 2013; Ptitsyn et al., 2010); the peat of Verkhnya Zaimka, Ukhta, and Khanda bogs (Bezrukova et al., 2006, 2011a); and the terrace deposits of the Aga and Ilya Rivers (Bazarova et al., 2011, 2015) (Figs. 1 and 2; Table 3).

During ca. 3300–3400 yrs BP, moisture supply promoted the forestation of river valleys in the steppe zone of the Trans-Baikal subregion (Bazarova et al., 2015). In the forest zone at 2600 yrs BP, Vipper and Golubeva (1976) inferred the widespread development of *Picea* and *Abies* in the Trans-Baikal subregion. Vegetation began to change at 2500 yrs BP around the Lake Baikal area, with increasing tree composition of both *Larix* and *Pinus* (Bezrukova et al., 2011a, b).

On the northern coast of Lake Baikal during 1700–1200 yrs BP, *Larix* forests expanded and were later replaced by *Pinus sibirica* and *Pinus sylvestris* forests. A signal of the Medieval Warm Period was detected during 1200–800 cal BP, which coincided with the enhanced coverage of *Abies* in the middle-mountain taiga zone (Bezrukova et al., 2006).

Ptitsyn et al. (2010) identified two phases of vegetation development in the central part of the Trans-Baikal subregion over the last 1900 years: the first phase was marked by the contribution of *Larix* and *Picea*, and the second phase was marked by the contribution of *Larix* and *Betula*.

During 1755–1855 AD (the Little Ice Age, XIV–XVIII centuries), Bazarova et al. (2015) inferred steppe associations in the southern part of the Trans-Baikal subregion.

Paleozoology data. Late Holocene faunas have been identified in the Basovo and Ust'-Khaita site (layer IV) sites (Cis-Baikal subregion) (White et al., 2008), Xiongnu Fortress (Trans-Baikal subregion) (Davydova, 1985; Savel'ev et al., 2001; Henzyhenova et al., 2005; Losey and Nomokonova, 2017; Khenzykhenova et al., 2020) (Figs. 1 and 2; Tables 4 and 5).

The Basovo site contains data on late Holocene molluscs (White et al., 2008) (Table 5). The mollusc assemblages indicated moderately dry conditions, but conditions were sufficiently moist for the growth of wet-ground species such as *Vallonia pulchella* (part of Bsv4; 3550–3695 to 9433 cal BP). Wet-ground taxa later dominated, indicating the presence of moist open meadows and marsh habitats on the floodplain (Bsv5; 2430–3360 to 9431 cal BP; 2710–2780 to 9436 cal BP; 2950–3080 to 10,554 cal BP); the dry conditions later followed the wet conditions (Bsv6; 1290–1350 to 10,556 cal BP; 1415–1615 to 10,557 cal BP) (White et al., 2008).

The fauna of Ust'-Khaita site (layer IV) included *Arvicola terrestris, Castor fiber, Ursus arctos*, and *Cervus elaphus* (Henzyhenova et al., 2005; Savel'ev et al., 2001; Losey and Nomokonova, 2017) (Table 4).

A rich collection of molluscs, fish, reptiles, amphibians, birds, and wild mammals was retrieved from late Holocene deposits of the famous Ivolga Xiongnu Fortress in the vicinity of Ulan-Ude city (Khenzykhenova et al., 2020). The identified molluscs were both terrestrial and freshwater species (Table 5). The fish species composition included *Hucho taimen* (Pallas, 1773), *Brachymystax lenok* (Pallas, 1773), *Thymallus brevipinnis* Svetovidov, 1935, *Coregonus migratorius* (Georgi, 1775), *C. pidschian* (Gmelin, 1788), *Acipenser baerii baikalensis*, *Leuciscus idus* (Linnaeus, 1758), *Perca fluviatilis*, *Rutilus rutilus*, *Carassius gibelio* (Bloch, 1782), *Lota lota*, and *Esox lucius*. Amphibia were represented by *Strauchbufo raddei*, *Hyla* sp., and *Rana* cf. *amurensis* Boulenger, 1886, and Anura gen. indet. Among the Reptilia, one species was identified as *Elaphe* cf. *dione* (Pallas, 1773). The birds included *Alauda arvensis* (Linnaeus, 1758), *Emberiza* sp., Emberizidae gen. indet., Passeriformes gen. indet., *Perdix daurica* (Pallas, 1811), *Coturnix coturnix* (Pallas, 1758), *Tetrao tetrix* (Linnaeus, 1758), and Aves gen. indet. The mammal fauna was rich and included *Sorex* sp., *Lepus timidus*, *Ochotona dauurica*, *Eutamias sibiricus* (Laxmann, 1769), *Spermophilus undulatus*, *Marmota* sp., *Cricetulus barabensis*, *Lasiopodomys gregalis*, *Microtus oeconomus* (Pallas, 1776), *Alexandromys fortis*, and *Microtus* sp. Large mammals included *Vulpes* sp., *Ursus arctos* Linnaeus, 1758, *Mustela* sp., *Sus scrofa*, *Alces alces* (Linnaeus, 1758), and *Capreolus pygargus* (Davydova, 1985) (Table 4). The new AMS-date 2029 ± 37 cal (OxA-38662) from coal of the dwelling of Ivolga Xiongnu Fortress, does not contradict the known reliable date 2037 ± 30 cal (Ua-47734) obtained from the bone of a dog from this site (Lozey et al., 2018) (Table 2).

4.2.3.2. Mongolian area. Vegetation data. Late Holocene palynological data on the Mongolian area have been determined from the lacustrine bottom sediments of the Hoton, Achit, Huh, Daba, Dood-Tsagan, Yamant, Turhiin-Tsagan, Shiret, Urmiin-Tsagan, Hovsgol, Khudo, Dund, Dayan, Danyagiin-Khara, Khar, Tolbo, Tsagan, Buir, and Gun Lakes, as well as the Khoit-Gol site; the data are summarised by Dorofeyuk (2008) (Figs. 1 and 3; Table 3).

At ~4000 cal BP, the area of taiga forests in the north of the country (Mongolian Altai) slowly decreased (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008), which continued at 3000 cal BP when steppe associations began to dominate (surroundings of Dood-Tsagan, Hovsgol, and Gun Lakes) (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008). Bazarova et al. (2019) inferred the displacement of forest vegetation by steppe ecosystems at the foothills of the Khentii Mountains. Moreover, desert plant associations began to dominate in the Khoit-Gol site surroundings (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008).

Paleozoology data. Late Holocene faunistic remains were obtained in Mongolia from a late Neolithic site (Barga els), several burial grounds (Khankh, Khashat, Dulaan uul, Zenchermandal, Tsagaan Chulut, Ulaan Suukh, Sharkhad, and Southern Gobi), and an ancient city of Mongolia (Avarga balgas) (Khenzykhenova et al., 2016b) (Figs. 1 and 3; Table 4). Tsydenova (Khenzykhenova et al., 2016b) collected faunistic remains from the archaeological sites, the species compositions included Amphibia (*Rana* sp.), small mammals (*Lepus* sp., *Ochotona* cf. *dauurica*, *Spermophilus undulatus*, *Marmota sibirica*, *Allactaga* sp., *Cricetulus barabensis*, *Meriones* sp., *Lasiopodomys brandti*), and large mammals (*Vulpes* sp. and *Equus* sp). The faunal material was not rich, as interpreted by the presence of open steppe spaces and forest areas.

5. Discussion and summary of palaeoenvironmental changes

5.1. Late Pleistocene (Late Glacial, 15,000–11,700 cal BP): palaeoenvironment and climate of the Baikal region and Mongolia

During the Late Glacial, the landscape of the Cis-Baikal subregion was dominated by steppes and forest-steppes with isolated forests in the valley regions (Tarasov et al., 2007; Bezrukova et al., 2011a, b). Moreover, open steppes dominated the landscapes of the Trans-Baikal subregion (Reshetova et al., 2013). Bezrukova et al. (2005, 2011b) recorded the development of permafrost and its subsequent thawing in summer on the eastern coast of Baikal Lake.

Moderate warming and increasing humidity at 12,000 yrs BP expanded the forest area across the whole territory of the Lake Baikal area (Demske et al., 2005; Bezrukova et al., 2009, 2011b), Altai Mountains (Blyakharchuk et al., 2007), and Northern Mongolia (Prokopenko et al., 2007).

During the Late Glacial, steppe landscapes generally dominated the entire area of Mongolia, and the area of tundra also expanded in the depressions of mountains and desert landscapes (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008). Steppe landscapes dominated at the northern and north-eastern borders of Mongolia, as well as in the territory adjacent to the Tuva area and the Altai Mountains (Blyakharchuk et al., 2007) (Figs. 1 and 3).

During the Late Pleistocene to Holocene transition (12,700–10,000 yrs BP) in the territory of eastern Kazakhstan close to the western boundary of Mongolia, Tarasov et al. (1997) inferred the widespread distribution of treeless steppe landscapes. Winkler and Wang (1993) inferred the distribution of dry steppes on the territory of northern China located south of the Mongolian border. Van Campo and Gasse (1993) inferred desert landscapes in the Tibetan Sumxi Lake basin, southwest of Mongolia.

Faunal remains obtained from the Baikal region and Mongolia provide general information on the local landscapes.

In the Cis-Baikal subregion, the species composition of fauna from the Ust'-Khaita and Bely Yar sites inferred the presence of broad-leaved and taiga forests, and open spaces were covered by steppes and forest tundra (Shchetnikov et al., 2015).

The species composition of fauna (birds and mammals) in the Trans-Baikal subregion corresponded to 12,230–11,375 yrs BP and was indicative of mosaic landscapes dominated by dry steppes, semideserts, taiga forests, meadow steppes, and near-water vegetation (Henzyhenova et al., 1991; Mlikovsky et al., 1997; Khenzykhenova et al., 2016a).

In Mongolia (Tolbor sites), the ostrich *Struthio camelus* corresponded to the interval 15,560–14,056 cal BP, indicating the occurrence of dry, treeless spaces (Derevianko et al., 2013). Therefore, the fauna of the Cis-Baikal region generally reflects global climate warming; however, two representatives of the mammoth faunistic complex, such as the mammoth and woolly rhinoceros, were also preserved, and typical inhabitants of tundra, such as the collared (*Dicrostonyx guilielmi*) and Siberian (*Lemmus sibiricus*) lemmings and the North Siberian (*Microtus hyperboreus*) and Middendorf' (*M. middendorfii*) voles (Khenzykhenova et al., 2016a), became extinct. The species composition of mammals in the Trans-Baikal area (such as the entire Baikal region) was mixed but significantly differed to the Cis-Baikalian composition due to the dominance of dry steppe inhabitants (*Ochotona daurica, Marmota, Meriones, Lagurus lagurus, Lasiopodomys brandti, Spiroceros kiakthensis*), similar to that of the Late Pleistocene.

Palaeontological data suggest that global climate changes caused different landscape changes in Mongolia and the Baikal region during the Late Glacial due to their different regional characteristics.

During the Late Glacial, the climatic conditions of the Baikal region were generally characterised by short-term and abrupt changes, leading to changes in landscape structure and vegetation composition. For this period, Bezrukova et al. (2011 b) assessed palynological data from Lake Kotokel bottom sediments (eastern coast of Baikal Lake) and determined five short intervals: 15,500–14,700, 14,700–14,300, 14,300–13,200, 13,200–12,500, and 12,500–11,700 cal BP. Bezrukova et al. (2011b) stated that climate during the Late Pleistocene to Holocene transition was sharply continental, shifting from dry/very cold to cold/humid to moderately cool/humid to moderately warm/humid (Fig. 4).

During the Late Glacial, the climate was inferred to be cold and dry in the Mongolian territory (Dorofeyuk, 2008) as well as in the northern part of China (Yang et al., 2004). This climate condition was attributed to the southward shift of the cold and dry southern branch of the Asian anticyclone ("winter monsoon") and the weak intensity of the summer Pacific monsoon. The cold and dry air masses from Mongolia and Siberia transported substantial amounts of sand and dust to China and contributed to the active formation of dunes, most of which had accumulated in the former lake basins (Qin and Yu, 1998; Yang et al., 2004).

Since 15,000 yrs BP (Late Glacial), Mongolian lakes in the Ubsunuur Basin, Mongolian Altai, and Khangai Mountains, as well as Hovsgol Lake had higher water levels than that of the present day, likely due to high summer insolation (higher than the present day) and the subsequent melting of snow and ice (Vipper et al., 1978, 1981, 1989, 1981; Tarasov et al., 1994, 1996, 1996; Grunert et al., 2000; Mischke et al., 2020). High lacustrine water levels were also observed in the adjacent territories of Mongolia, such as in Sumxi Lake (Tibetan mountains) (Van Campo and Gasse, 1993) and other Chinese lakes (Winkler and Wang, 1993); Baikal Lake also had higher water levels than that of the present day (Fedotov et al., 2000, 2004) (Figs. 1–3).

5.2. Holocene (11,700 cal BP–recent): palaeoenvironment and climate of the Baikal region and Mongolia

5.2.1. Early Holocene (11,700–8200 cal BP)

In the Trans-Baikal subregion, open steppes and forest-tundra landscapes were widespread, and the area of semi-desert-steppe vegetation and pine forests on sandy soils also expanded (Vipper, 1962). Vegetation showed several changes during this period in response to short intervals of cooling and warming at the end of the early Holocene (Bazarova et al., 2011).

At the beginning of the Holocene, treeless steppe vegetation (*Artemisia*, Amaranthaceae, Poaceae) prevailed over most of Mongolia. Dry and desert steppes prevailed in extensive depressions in the north-west of the country (Dorofeyuk and Tarasov, 2000; Dorofeyuk, 2008), and tundra (Cyperaceae, shrub forms of *Betula* and Alnus) elements occurred at elevations above 2000 m above sea level. At the beginning of the Holocene, coniferous forests with contributions from *Picea* were only recorded in the north of the country in the Hoit-Gol River floodplain (Sevast'yanov et al., 1993), in the Darkhat Basin, and in the catchment area of Lake Hovsgol (Prokopenko et al., 2007).

In the areas of Tuva and the south-eastern part of the Altai Mountains located north of Mongolia and west of the Baikal region, *Artemisia*-steppes with *Ephedra* in combination with tundra expanded during the early Holocene, and their central areas were predominantly occupied by tundra (Blyakharchuk et al., 2007). In Northern Kazakhstan situated north-west of Mongolia, *Artemisia*-Amaranthaceae communities and small birch forests were widely distributed, and treeless landscapes were common in eastern Kazakhstan (Tarasov et al., 1997).

During the early Holocene, the mammal fauna from the Cis-Baikal subregion only included modern species, but mammoth bones were recovered from Locomotiv-Raisovet grave sites (Nomokonova et al., 2015; Losey and Nomokonova, 2017). Generally, a mixed species composition indicates a mosaic landscape structure (taiga, steppe, tundra-steppe, and forests and meadows along river valleys) and a warmer climate after the Late Glacial.

The fauna of the Trans-Baikal subregion contains *Myopus* and *Eutamias*, which are forest inhabitants; their occurrence therefore reflects afforestation in the area, as well as a warmer and wetter climate after the Late Glacial.

During the early Holocene, the continental climate continued to develop, which was characterised by mild winters, cool summers, significant snow cover, and relatively high average annual precipitation (Bezrukova et al., 2005, 2010). A short-term cooling at the end of the early Holocene was followed by slight warming and increased humidity in the Baikal region (Bazarova et al., 2011).

The water level of most lakes experienced maximum shallowing during the early Holocene in Mongolia and began to increase only during 8995–8776 yrs BP (Dorofeyuk, 2008). The lake basins also experienced a regressive phase in the Dauria area, which was accompanied by a decrease in water level or the disappearance of ponds (Bazhenova et al., 2017; Bazhenova and Cherkashina, 2018).

5.2.2. *Middle Holocene (8200–4200 cal BP)*

In general, the mid-Holocene was characterised by maximum afforestation across all territories of the Baikal region and north-eastern Mongolia (Malaeva and Murzaeva, 1987; Golubeva, 1976; Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008; Bazarova, 2011, 2014, 2019).

During the mid-Holocene, the borderline of the taiga-forest zone was distributed 250–300 km south of the modern borderline (Bazarova et al., 2019). Small quantities of the broad-leaved species *Tilia, Corylus,* and *Ulmus* were observed in mid-Holocene sediments in the valleys of the Onon, Khalkh Gol, and Idar Rivers. In the present day, the eastern border of broad-leaved species passes along the eastern foothills of the Greater Khingan Mountains (~125°E) (Bazarova, 2011, 2014).

In the Trans-Baikal subregion, the vegetation during the Holocene climatic optimum (7000–5000 yrs BP) consisted of polydominant coniferous taiga with an admixture of broad-leaved trees. The modern analogues of the subnemoral forests occurred on the western slopes of the southern Siberian Mountains (Bezrukova et al., 1996). The south-eastern part of the Trans-Baikal area during this time was characterised by widespread coniferous forests and decreasing steppe distribution. The presence of thermophile pollen was recorded in the forest-occupied floodplains in the forest-steppe and steppe zones (Bazarova et al., 2011). Bazarova (2011, 2014) noted that the single presence of broad-leaved pollen species in sediments of different genesis suggests that elements of broad-leaved flora did not form independent extensive forests, but only minorly contributed to the composition of *Betula-Pinus* and *Pinus sibirica* formations.

At the beginning of the mid-Holocene, the northern part of Mongolia was covered by forests, while the remaining area of the country was characterised by steppe landscapes. Desert landscapes were also common in the wide depressions (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008). During 7000–6000 yrs BP, taiga forests in Mongolia were more widely distributed than that of the present day; deserts were transformed in steppe landscapes, and mountains were occupied by forest-steppes.

Palaeozoological analysis of eastern Mongolia (Neolithic site Togootyn gol) inferred the widespread distribution of meadow-steppe and steppe landscapes on the terrace-like surfaces of the Togootyn gol River valley at ~5100 cal BP (Bazarova et al., 2019). The species composition of small mammals from the Dariganga Plateau (Dinesman et al., 1989) were indicative of dry steppe and semi-desert landscapes. In general, the palaeozoological data do not contradict the palynological data, which inferred steppe landscapes across most of Mongolia (Dorofeyuk, 2008). In the Cis-Baikal region, the mid-Holocene fauna only included modern species indicative of forest-steppe, taiga, and near-water landscapes.

The continental climate increased in the Cis-Baikal subregion at ~7000–2500 cal BP, which was inferred from a significant decrease in average annual precipitation, an increase in average summer temperatures, and a decrease in winter average temperatures.

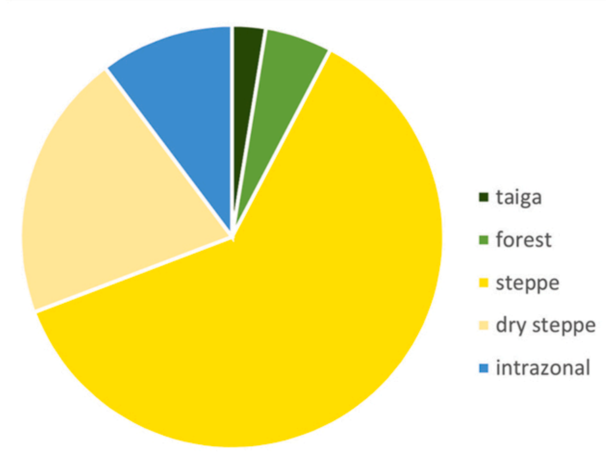

Fig. 5. The ratio of ecological groups of small mammals at the Ivolga Xiongnu Fortress (Trans-Baikal area, Russia).
Taiga is marked in dark green; forest-light green; steppe-yellow; dry steppe-pale yellow; intrazonal-blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this paper)

The increasing average summer temperatures enhanced the melting of mountain glaciers and snow caps, which increased the water level and moisture supply to the lakes of central Mongolia during 7900–4200 yrs BP (Schwanghart et al., 2008) and eastern Mongolia during 5500–4900 yrs BP (Dorofeyuk and Tarasov, 1998; Dorofeyuk, 2008; Dgebuadze, 2014). These conditions caused a transgressive phase of the lakes in Dauria, as well as extreme river flooding in the south-eastern Trans-Baikal region during 8480–7090 yrs BP, which ceased around 5000 yrs BP.

5.2.3. *Late Holocene (4200 cal BP to the present)*

According to the palynological data, the arid climatic stage in Mongolia and the Baikal region generally began at ~4000 yrs BP but was not synchronous across the entire area. During this period, the area covered by taiga forests reduced to its modern position, and steppe and desert landscapes began to dominate. For example, taiga forests of the Khangai Mountains significantly reduced and were replaced by steppe associations at ~4250–4000 yrs BP (Tarasov et al., 2004), but taiga forests in the Hoton Lake surroundings (Mongolian Altai) began to reduce earlier at approximately 4500 yrs BP (Tarasov et al., 2000). Moreover, taiga forests prevailed in the Gobi Altai until 3500 yrs BP and even 2000 yrs BP (Dinesman et al., 1989), and data from the Khoit-Gol site indicates forestation in the Ubsnuur depression during 4500–4200 yrs BP (Sevast'yanov et al., 1993).

Trees did not disappear during the late Holocene in Mongolia and the Trans-Baikal subregion, despite widespread aridisation at the end of the mid-Holocene; for example, pine and larch forests dominated the vegetation cover of Buryatia over the past 3000 years, reflecting the deterioration of moist conditions and an increase in continental climate (Dorofeyuk, 2008).

The occurrence of climate aridisation at the beginning of the late Holocene in Mongolia was inferred by Malaeva and Murzaeva (1987) and Chichagov (2006), which then intensified at ~3500–3000 cal BP (Dorofeyuk, 2008). A trend towards increasing continentality of climate in the Cis-Baikal subregion began at ~2500 cal BP and still prevails in the present day. According to Dinesman et al. (1989), the eastern part of Mongolia was covered by xerophytic steppes during the late Holocene.

Schwanghart et al. (2008) inferred prevailing arid conditions in central Mongolia during 4200–2800 yrs BP, followed by the transformation to a more humid phase up until the present day. The humid phase of the Trans-Baikal subregion (starting at 2600 cal BP) was characterised by milder winter temperatures and increased humidity, which favoured the widespread development of coniferous.

Climate aridisation was also observed in the adjacent area of southern and north-western China (Fig. 1); for example, Tarasov et al. (2019) identified a peak arid phase at ca. 4000 to 2000/1500 cal BP, followed by an interval of increasing humidity towards ca. 60 cal BP (Bosten Lake).

The beginning of anthropogenic influences on vegetation cover in Mongolia during the late Holocene is still under debate. According to palaeobotanical data, Dinesman et al. (1989) identified the first signs of pasture overloads in the dry steppes of Mongolia during 900 to 600 yrs BP; however, Grunert et al. (2000) inferred the intensification of anthropogenic influences during the last 2000 years based on the study of dunes in north-western Mongolia. According to Hilbig (1995), deforestation only began at the end of the 19th century.

The intensification of climate aridisation during the late Holocene in the Great Lakes Depression, the Valley of Lakes, and the Eastern-Mongolian steppe region was correlated with water level decreases in the water reservoirs (e.g. Khar, Khyargas, Dorgon, and Boon Tsagaan Lakes) (Fig. 3). At present, the water levels in the lakes continue to decrease due to the influence of anthropogenic activities (Dgebuadze, 2014).

During 1620–1800 AD (XIV–XVIII centuries), peak cooling was observed in eastern Mongolia (Chichagov, 1998; also referred to as the Maunder Minimum or Little Ice Age according to Eddy, 1976). This short period was characterised by catastrophic deflation processes, resulting in the significant deformation of fluvial complexes. The riverbeds of large rivers, such as the Onon and Uldza, became shallower. Extensive deflation basins were formed in the steppe zone of the Trans-Baikal subregion. In the south of Dauria, the Torey Lakes completely drained in response to decreased precipitation, lowered temperature, and strong winds during 1755–1855. On the steppe zone of the south-eastern Trans-Baikal region, deflation processes enhanced the accumulation of aeolian sands in the lake basins. In the steppe and forest-steppe zones of the Trans-Baikal subregion, climatic changes during the Little Ice Age led to the expansion of steppe landscapes, significant decreases in lake water levels, and the shallowing or draining of water from rivers.

At approximately 2000 cal BP, the vegetation of Mongolia became more similar to that of the modern day (Dorofeyuk, 2008).

The faunal species composition from archaeological sites in Mongolia inferred the dominance of open steppe landscapes (Khenzykhenova et al., 2016b).

The fauna species composition, palaeovegetation, and environmental data highlight the mosaic landscape characteristics surrounding the ancient settlement of the Ivolga Xiongnu Fortress (2029 ± 37, OxA-38662), including taiga and forests, steppe and forest-steppe biotopes, and meadows in the Selenga valley, with the prevalence of open steppe spaces (Fig. 5). In the era of the Xiongnu Empire (209 BC–48 AD), the climate was less arid than that of the present day (Khenzykhenova et al., 2020).

6. Conclusion

We summarised the palaeolandscape changes of the Mongolia and Baikal region by integrating (mainly) palaeontological and chronological data obtained over the past 50 years. The described materials from palaeobiotic studies inferred the diversity and uniqueness of plant and animal communities inhabiting various regions of Mongolia and the Baikal region, as well as their past developmental dynamics.

Based on the palynological and palaeozoological results of our study, we were able to determine the dominant natural environments of the Late Glacial and early, middle, and late Holocene, as well as their development in response to the relief and climatic changes of the entire region.

We reconstructed the palaeovegetation, palaeolandscape, and palaeoenvironment of Mongolia and the Baikal regions based on previously published studies of lacustrine bottom sediments, peat, and terrace deposits. This summary is particularly useful for understanding the processes that form modern and future landscapes, as well as the climatic development across the midcontinental territory.

Authors contribution

The original draft was completed by F. Kh. and all co-authors. N.D. contributed to the reconstruction of both Mongolian lake levels and palaeovegetation dynamics, and N.D. conducted the comparative analysis of our research results with the findings of other regions in Inner Asia. The lithological study was conducted by A.Sh.; the small mammal fauna was studied by F.Kh; the molluscs were studied by G.D.; and the palynology was conducted by V.B. All authors contributed to the writing, reviewing, and editing of the manuscript.

Data availability

The palaeontological collections are stored at the Institute of Geology UFRC RAS (Ufa) and Geological Institute of SB RAS (Ulan-Ude).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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