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RADIOCARBON CHRONOLOGY OF THE LATE PLEISTOCENE–HOLOCENE PALEOGEOGRAPHIC EVENTS IN LAKE BAIKAL REGION (SIBERIA)

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ABSTRACT. New radiocarbon dates obtained from Late Pleistocene and Holocene deposits of the southern, eastern, and northern shores of Lake Baikal in 1995–2001 are presented, and the most important results of paleoenvironmental studies based on ^{14}C data are discussed. The following paleogeographic events were verified with the help of ^{14}C dating: 1) first Late Pleistocene glaciation (Early Zyryan); 2) Middle Zyryan interstadial; 3) loess formation during the Late Zyryan (Sartan) deglaciation; 4) warm and cold events in the Late Glacial; and 5) vegetation changes and forest successions during the Late Glacial and Holocene.

INTRODUCTION

The international research program being conducted in the Lake Baikal region since 1993 (Baikal Drilling Project) concerns mainly the sedimental and environmental records in the lake cores. In addition, some projects dealt with the surroundings of Lake Baikal. One of these was a joint Russian-Japanese project, "The climate and vegetation changes in the Lake Baikal area during the last 15,000 years" (1995–2001). The project's main task was to investigate bogs and small lakes around Lake Baikal in order to obtain detailed paleoenvironmental information for the Late Glacial and Holocene, and to compare these results with those from the lacustrine sediments of Lake Baikal.

The principal results of the project were recently published in a series of articles (Bezrukova et al. 1998, 2000, 2002; Kataoka et al. 2003; Krivonogov and Takahara 2003; Takahara et al. 2000, 2001). We discovered that the climate and vegetation history of the region is better represented in the bog and small lake sediments surrounding Lake Baikal, rather than in Lake Baikal itself. The reasons for this are 1) greater thickness of the Late Glacial and Holocene sediments allows higher temporal resolution of environmental reconstructions; and 2) high biogenic content of the sediments provide good possibilities for ^{14}C dating. For example, the sedimentation rate in Lake Baikal (Akademichesky Ridge) in the Holocene was about 40 mm/1000 yr (Kuzmin et al. 2000), and in the surrounding small lakes and bogs, it was up to 500 mm/1000 yr according to our research. This permits a 10 times better resolution of paleoclimatic events. In this paper, we present a series of ^{14}C dates and discuss their importance for determining the age of paleogeographic events.

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MATERIALS AND METHODS

The area of our investigation covers the southern, eastern, and northern shores of Lake Baikal (Figure 1). In total, 25 boreholes were drilled and a few dozen outcrops were also investigated. Boreholes and outcrops with ^{14}C dates are shown in Figure 1. Fifty-one ^{14}C dates have been generated from several boreholes and outcrops (Table 1). Some outcrops have large series of ^{14}C dates with up to 15 values. Dates mainly correspond to the last 14,000 ^{14}C yr (the Late Glacial and Holocene). Earlier ^{14}C dates, about 46,000–23,000 BP, were obtained from the 2 deepest boreholes, Duliha and Bolshaya Rechka.

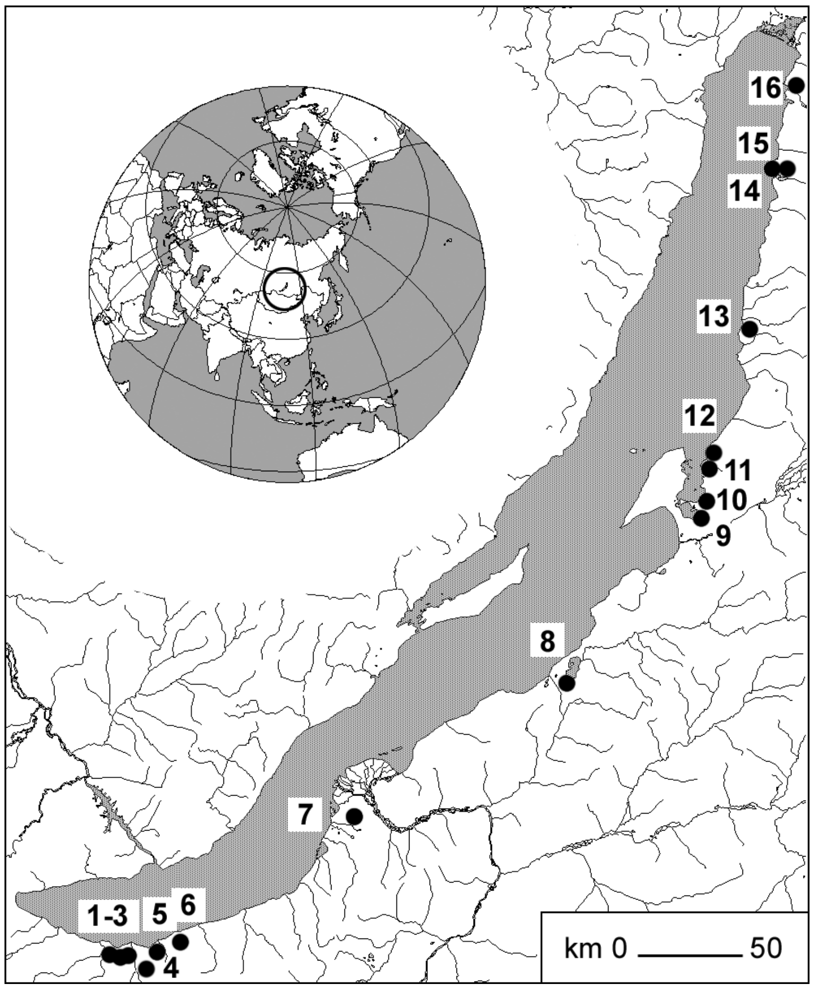

Figure 1 The area under investigation: location of the ^{14}C-dated sites (numbers correspond to those in Table 1).

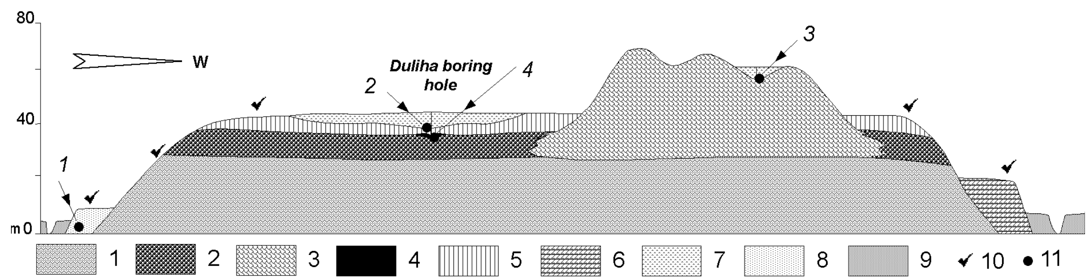

Figure 2 Generalized geological section of the Tanhoi Plain watershed. 1 – the Tanhoi group (N_1): clay, coal, sand; 2 – denudation cover (Q): boulders, pebbles; 3 – end moraine ($Q_{3/1}$); 4 – peat ($Q_{3/2}$); 5 – loess ($Q_{3/3}$); 6 – fluvioglacial terrace ($Q_{3/3}$): boulders, pebbles; 7 – peat (Q_4); 8 – high floodplain (Q_4): sand, peat; 9 – low floodplain (Q_4): sand, pebbles; 10 – exposures; 11 – ^{14}C dates verifying stratigraphic units: *1* – 4590 ± 70 BP (Beta-88092), Pankovka; *2* – 11,110 ± 120 BP (NUTA-5616), Duliha; *3* – 11,400 ± 200 BP (KEEA-170), Krivoe Lake; *4* – 46,700 ± 2800 BP (AA-37975) and 29,820 ± 710 BP (Beta-098423), Duliha.

Table 1 ^{14}C dates obtained by the joint Russian-Japanese expedition in the Lake Baikal area.

Site name and coordinates	Type[a], nr from Figure 1	Depth (cm)	Material dated	Lab code and nr	^{14}C date (BP)
Pankovka River	S, 1	90–92	peat	Beta-88090	1520 ± 60
51°28′N, 104°30′E		187–190	seeds	NUTA-4749	2950 ± 60
		302–305	peat	Beta-88091	4000 ± 70
		393–398	peat	Beta-88092	4590 ± 70
Bolshoe bog 51°28′N, 104°30′E	Bh, 2	238–240	peat	NUTA-4781	5330 ± 70
Yanvarskoe bog 51°27′N, 104°30′E	Bh, 3	268–269	peat	NUTA-4750	5680 ± 70
Tabachnye Lakes bog 51°29′N, 104°53′E	Bh, 4	187	plant fragment	Beta-149297	7070 ± 40
Krivoe Lake bog	Bh, 5	50	seed (*Pinus sibirica*)	NUTA-5444	1655 ± 140
51°29′N, 104°50′E		210	seed (*Pinus sibirica*)	NUTA-5455	8060 ± 115
		235–245	peat	KEEA-169	8520 ± 120
		301–304	seed	NUTA-5616	9260 ± 120
		341–351	peat	KEEA-170	11,400 ± 200
Duliha bog	Bh, 6	300–302	seeds	NUTA-5615	7620 ± 115
51°31′N, 105°00′E		399	peat	AA-37974	9185 ± 55
		474–475	peat	NUTA-6038	11,110 ± 120
		612–613	peat	NUTA-6039	35,890 ± 945
		618	wood	AA-37975	46,700 ± 2800
		663	wood	AA-37976	35,740 ± 850
		679–680	peat	Beta-098423	29,820 ± 710
		682	wood	AA-37977	30,110 ± 360
Bolshaya Rechka bog	Bh, 7	71–73	wood	NUTA-5450	940 ± 70
51°57′N, 106°20′E		508–510	peat	Beta-098421	8380 ± 40
		745–746	peat	Beta-098422	22,810 ± 280
Cheremushuka bog 52°45′N, 108°05′E	Bh, 8	366–367	peat	Beta-115297	12,100 ± 60
Arangatui bog 55°32′N, 109°08′E	Bh, 9	474	wood	Beta-113968	9400 ± 60
Chivyrkui Bay, exposure 1[b]	S, 10	35–40	peat	SOAN-3803	1450 ± 75
53°40′N, 109°12′E		75–80	peat	SOAN-3804	3720 ± 185
		115–120	peat	SOAN-3805	3500 ± 90
		155–160	peat	SOAN-3806	4795 ± 80
		195–200	peat	SOAN-3807	5400 ± 125
		215–220	peat	SOAN-3808	6605 ± 130
Chivyrkui Bay, exposure 2	S, 10	185–190[c]	peat	SOAN-3809	5645 ± 85
53°40′N, 109°12′E		165–170	peat	SOAN-3810	6105 ± 220
		145–150	peat	SOAN-3811	7025 ± 230
		105–110	peat	SOAN-3812	8340 ± 300
		65–70	peat	SOAN-3813	9165 ± 150
		25–30	peat	SOAN-3828	9600 ± 130
		0–5	peat	SOAN-3829	10,810 ± 150
	Bh, 10	–25 to –50[d]	peat	SOAN-3830	10,420 ± 200
Chivyrkui Bay 53°40′N, 109°12′E	Bh, 10	–50	wood	Beta-113969	9700 ± 70
Krohalinaya Bay bog	Bh, 11	260	peat	AA-37976	8550 ± 70
53°46′N, 109°12′E		426	peaty clay	AA-37968	10,980 ± 65
Bolshoi Chivyrkui River bog 53°49′N, 109°12′E	Bh, 12	365–366	peat	Beta-136811	9650 ± 40
Duguldzeri River bog	Bh, 13	90	wood	AA-37969	4515 ± 40
54°27′N, 109°32′E		193	seed	AA-37970	8020 ± 45
		323	gyttja	AA-37971	11,295 ± 55
		378	gyttja	AA-37972	12,950 ± 90
Tompuda bog	Bh, 14	273–274	peat	Beta-136813	10,150 ± 40
55°08′N, 109°46′E		515–516	gyttja	Beta-136814	14,090 ± 50
Tompuda end moraine 55°09′N, 109°42′E	S, 15		woody peat	SOAN-4266	9875 ± 45
Froliha River 55°30′N, 109°55′E	S, 16	170	wood	AA-37973	8010 ± 70

[a] S – section; Bh – borehole.
[b] For the detailed description of the sampling scheme for the sites of the Chivyrkui Bay, see Kataoka et al. (2003).
[c] Elevation above the Lake Baikal level.
[d] Negative value indicates the sample position below the Lake Baikal level.

Palynological and plant macrofossil analyses were conducted according to standard procedures (cf. Berglund and Ralska-Jasiewiczowa 1986). The ^{14}C liquid scintillation dating (SOAN Lab, Novosibirsk, Russia; and KEEA Lab, Fukuoka, Japan) follows the general procedure for peat samples (cf. Taylor 1987; Orlova and Zykina 2003). The ^{14}C accelerator mass spectrometry (AMS) dating (Beta Lab, Miami, Florida, USA; NUTA Lab, Nagoya, Japan; and AA Lab, Tucson, Arizona, USA) was carried out according to general pretreatment and measurement protocols (cf. Tuniz et al. 1998).

Paleogeographic Events in the Lake Baikal Region and Their ^{14}C Ages

The ^{14}C dates were used as geochronological markers for stratigraphical and palynological analyses. Except for the directly dated levels, the age of paleoenvironmental boundaries and palynozones was estimated by linear interpolation between ^{14}C-dated levels. The following paleogeographic events have been verified using ^{14}C dates: 1) the first Late Pleistocene glaciation (Early Zyryan, corresponding to the Early Weichselian in Europe and Early Wisconsin in North America); 2) the Middle Zyryan interstadial (corresponding to the Middle Wisconsin); 3) loess formation in the Tanhoi Plain, southern Lake Baikal shore, in the Late Zyryan (Sartan in Siberia, or Late Wisconsin in North America) deglaciation period; 4) warm and cold events in the Late Glacial; and 5) vegetation changes and forest successions during the Late Glacial and Holocene.

The glacial events in the northern, northeastern, and southern mountainous surroundings of the Lake Baikal region are recorded in broadly distributed end moraines. A wide range of ^{14}C dates generated by previous investigators was described by Back and Strecker (1998) as evidence of asymmetric and asynchronous glaciation of the Lake Baikal mountain system. Moraines of the eastern shore were created by glacier advances at more than 50,000 BP; 40,000–35,000 BP; and 26,000–13,000 BP. Careful examination of the moraine exposures revealed a lack of any organic matter, such as wood and peat, in the basal and supraglacial layers. We interpret this as an indication that temperatures were too cold during glacial times in Siberia for tree growth, and, thus, glacial tongues did not reach the tree belt in the piedmonts and did not incorporate any wood into moraines. Nevertheless, one can find wood and peat in the uppermost and distal parts of the moraine ridges. For example, the end moraine of the Tompuda Valley (Figure 1, #15) has a ^{14}C date of 39,240 ± 1780 BP (Mats et. al. 2001). We also found a woody peat layer in the northern part of this outcrop which was dated to 9875 ± 45 BP (SOAN-4266). Neither of these dates can be correlated with any significant glacial events. We suggest that the dated layers represent a drift of the post-glacial thermokarst flows which resulted from the reworking of frozen moraines or dead-ice massifs. Thus, such dates can only indicate that the glaciation itself is older; we assume it is of Early Zyryan age, older than about 39,000 BP. More obvious evidence that it is of the Early Zyryan end moraines was found on the southern shore of Lake Baikal on the Tanhoi Plane. The end moraine ridge of the Duliha River (Figure 1, #6) is related to the surrounding sediments, as shown in Figure 2. ^{14}C dates of 46,000–30,000 BP (Table 1) were obtained for the peat that lies stratigraphically above the glacial sediments, and their age is, therefore, older than approximately 46,000 BP.

The presence of the Middle Zyryan interstadial (about 50,000–21,000 BP) in the sediments of the Lake Baikal region is still questionable. We occasionally found peat of this age at 2 sites, Duliha and Bolshaya Rechka bogs (Figure 1, #6 and #7). In the Duliha bog (Figure 2), the Middle Zyryan peat, dated to about 46,700–30,100 BP, lies on the layer of outwash pebbles which correlate with the end moraine ridge situated at a distance of 300 m from the drilling site. The peat is lens-shaped with a width of less than 10 m and a maximum thickness of about 0.5 m according to the drilling tests. We suggest that this lens occupies a small depression on the intersection of 2 melted ice wedges (tundra polygons). This allows us to explain the age differences and inversions of the ^{14}C dates (about

30,110 BP on the bottom versus about 35,900 BP and about 46,700 BP on the top) as a result of subsidence or collapse of the peat during the long time development of the ice wedge system. Pollen analysis indicates a cool but relatively mild climate typical for the Middle Zyryan in southern Siberia (Bezrukova et al. 2000).

The loess sediments, atypical for the Lake Baikal region, were found in the western part of the Tanhoi Plain (Figure 2). The different Pleistocene sediments shown in Figure 2 are labeled as Q, Q_3 (Late Pleistocene), and Q_4 (the Holocene). The nearest extensive loess deposits are situated on the Irkutsk-Cheremkhovo Plain, west of Irkutsk City and at least 150 km NW of the Tanhoi Plain. The age of the Tanhoi Plain loess is estimated as Late Zyryan, older than about 11,000 BP and younger than about 30,000 BP, based on the ^{14}C ages of underlying and overlapping biogenic sediments (Table 1, Duliha borehole). Specific "wind-shadow" conditions may have permitted loess accumulation in the piedmonts of the Khamar-Daban Range and deterred erosion.

Some boreholes drilled into the lacustrine and underlying soil layers revealed ^{14}C ages of about 14,000–11,000 BP. Different events, corresponding to the warm and cool phases of the Late Glacial, were established in these boreholes using pollen data. Unfortunately, we do not have a continuous record for this period; the younger events are better represented then the older ones. Thus, the basal layer of the Duliha peat bog at a depth of about 5 m—characterized by pollen of deciduous trees and steppe-and-meadow grasses and dated to about 11,100 BP—corresponds to the end of the Allerød warming. In contrast, paleosol at the bottom of the Krivoe Lake bog core (Figures 1, #5), situated in the depression on the top of the Vydrinnaya end moraine ridge, contains many *Betula nana* L. *s.l.* seeds and indicates cold conditions. Considering that the date of about 11,400 BP shows correspondence of this layer to the middle of the Allerød, this discrepancy might be evidence of a "compression" of the Older Dryas and Allerød events in the paleosol. Our only other conclusion would be that the Older Dryas vegetation survived in the Krivoe Lake depression at the Allerød. Based on these fragmentary data, we would conclude that the post-Last Glacial Maximum forest vegetation began to spread in the Lake Baikal area already at the end of the Late Glacial, and the periglacial tundra and forest tundra formations were rapidly replaced by forest formations.

Regularities in the vegetation changes and migration of the plant zones can be revealed by comparison of the data obtained at different localities. The appearance and predominance of major forest tree species since the Late Glacial, according to Bezrukova et al. (forthcoming), is shown in Figure 3. We can clearly observe the succession of larch (*Larix*) and spruce (*Picea*) assemblages by fir (*Abies*) and Siberian pine (*Pinus sibirica*) in the Boreal period of the Holocene. These formations were replaced by pine (*Pinus sylvestris*) in the post-Atlantic. Correlation of the pollen zones between the main localities for the last 30,000 yr is shown in Figure 4 (Takahara et. al. 2001).

DISCUSSION

The majority of the ^{14}C dates obtained are in good agreement with the sedimentation sequences and paleogeographic interpretations. However, at 2 sites we have inversions of the dates. The lowermost member of the Duliha core was accumulated in the specific conditions described above. The fluvioglacial plain of the Duliha site was developed as a tundra and forest tundra landscape over a long time, from the end of the Early Zyryan glaciation to the beginning of the Late Zyryan one. The formation and melting of ice wedges could have occurred over a prolonged period of time, resulting in mixing of the younger and older parts of the peat layer, downward migration of the organic material, and so on. An apparent inversion occurs in the upper part of the peat layer in the Chivyrkui Bay 1 outcrop: 3720 ± 185 BP (SOAN-3804) at a depth of 75–80 cm versus 3500 ± 90 BP (SOAN-3805)

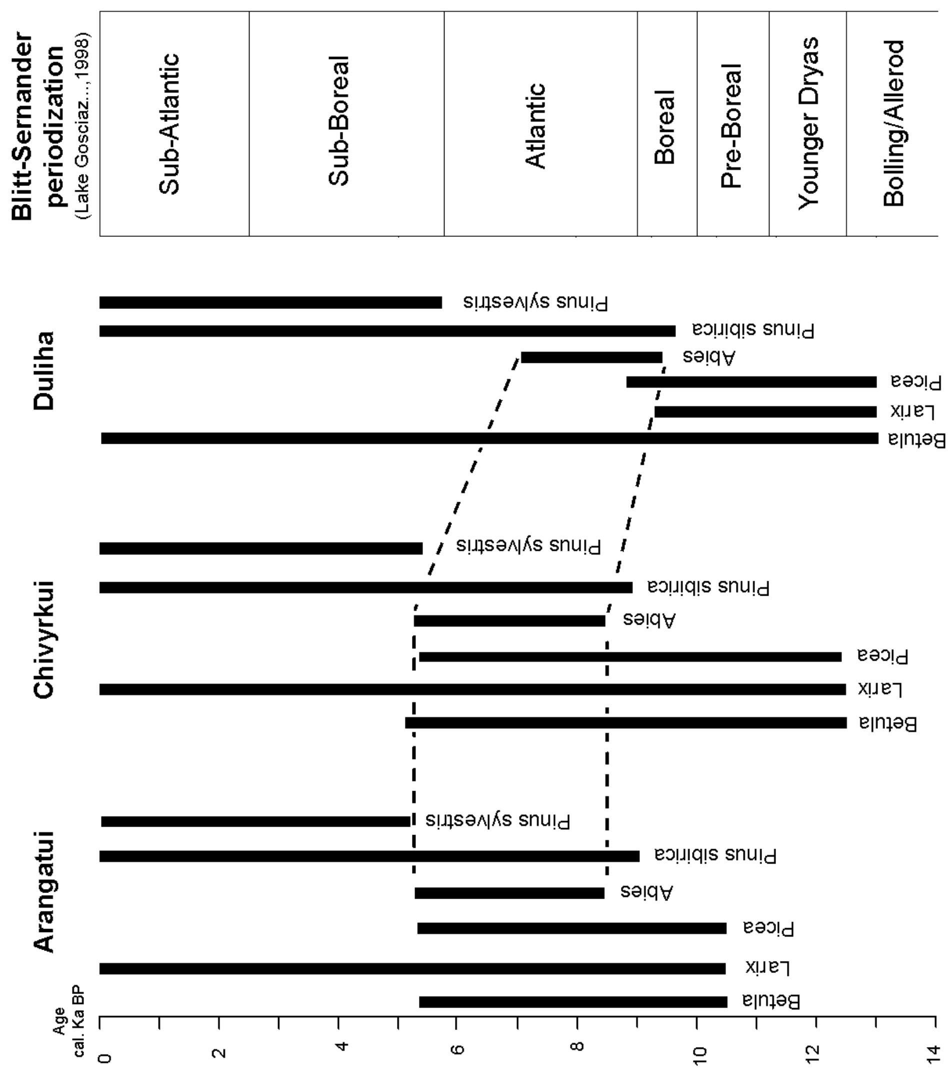

Figure 3 Expansion of the main forest trees and their predominance in the southern and eastern shores of Lake Baikal in the Late Glacial and the Holocene

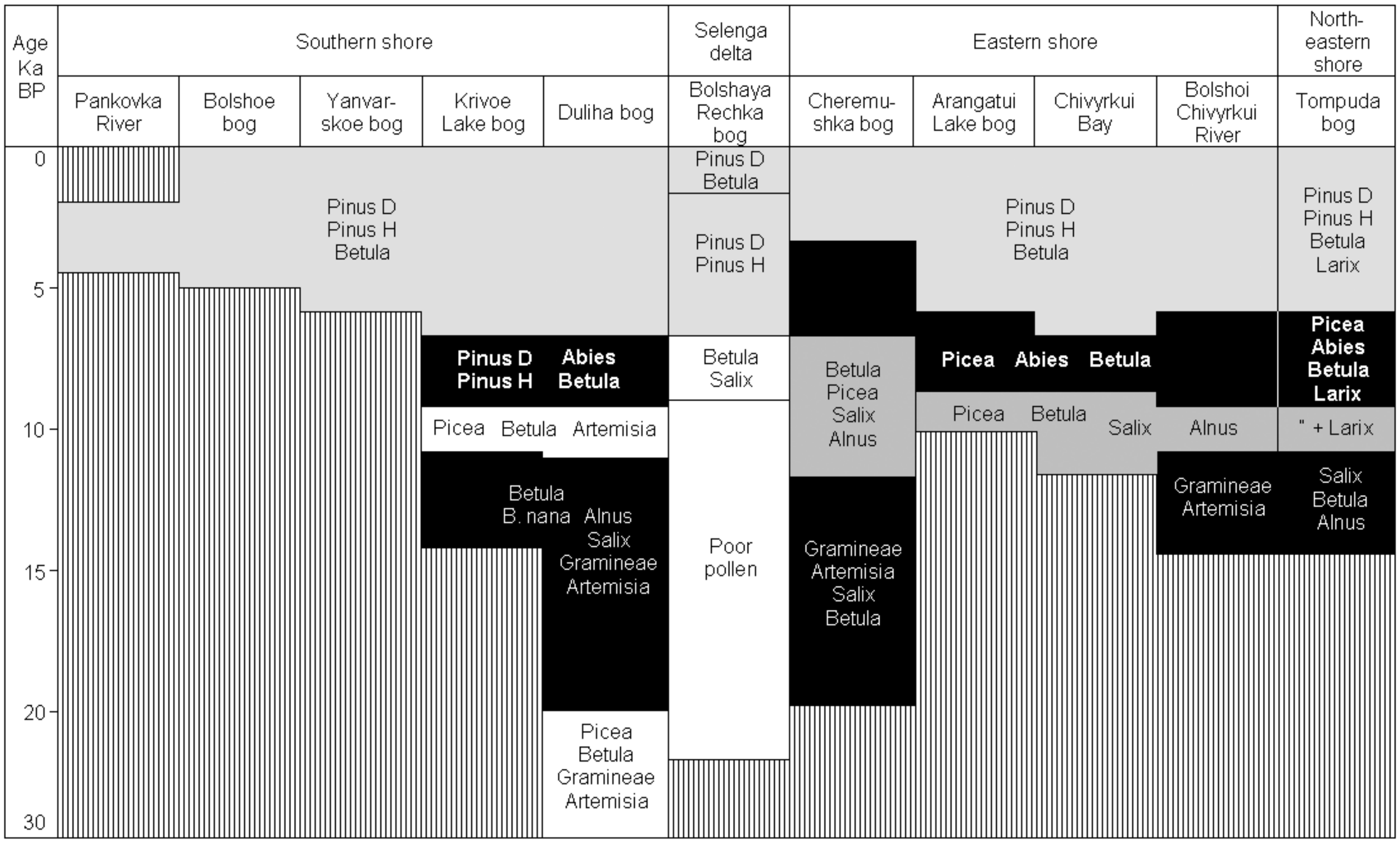

Figure 4 Correlation of the pollen assemblage zones in the cores from the Lake Baikal shore

at a depth of 115–120 cm. This bog is located in the permafrost area; erosion by the Lake Baikal waves causes melting of the exposed sediments and cracking and shifting of the peat blocks which would introduce the suggested migration. As a result, the maximum disturbance of sediments would have occurred only in the upper part of the exposure. In addition, the top of the bog is strongly influenced by the seasonal freeze-and-thaw processes up to a depth of 1 m.

We can only suggest what may cause the large difference between ^{14}C dates from the bottom layer of the Chivyrkui outcrop, exposure 2: 10,810 ± 150 BP (SOAN-3829), from peat collected at a height of 0–5 cm above the Lake Baikal shoreline versus 10,420 ± 200 BP (SOAN-3830) from peat at a depth of 25–50 cm below the Lake Baikal level. Both dates were obtained by the liquid scintillation technique. The AMS date of the wood fragments found at the depth of 50 cm below the lake level, 9700 ± 70 BP (Beta-113969), showed an even larger inversion. Several factors, such as redeposition, post-depositional contamination, and differences between labs using conventional and AMS methods, may be responsible for such differences.

CONCLUSION

Paleogeographic events of the Late Glacial and Holocene recorded in the terrestrial sediments around Lake Baikal are much more detailed (to at least one order of magnitude) compared with the records from the bottom sediments of Lake Baikal. Nevertheless, the phases of significant vegetation changes observed in the palynological analysis have a minimum duration of 150–250 yr. We consider that this is a technical limitation of the resolution of the environmental reconstructions in the palynological record within the last 12,000–10,000 yr. The topmost Holocene peat layers were investigated in a wide territory, and this allowed us to make reliable spatial environmental reconstructions. As for the Late Pleistocene events, such possibilities are significantly smaller.

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