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The extent of Late Pleistocene glaciations in the Altai and Khangai Mountains

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Summary

The current state of research concerning the extent of Late Pleistocene glaciations in Mongolia and the Russian Altai is summarised. Pleistocene moraines resulting from valley glaciers, plateau glaciers, cirque glaciers and ice streams can be found. The most extensive Late Pleistocene glaciation occurred in the western part of the Altai. However, the extent of Late Pleistocene ice in the Russian Altai is still under debate. In the eastern Altai and especially in the northern part of the Mongolian Altai, Pleistocene glaciers were restricted to several isolated mountain systems. To show the variations in the ice extent, the modern and Late Pleistocene equilibrium-line altitudes (ELAs) and the glaciated area are presented in two cross-sections through the Altai and Western Mongolia. The ELAs are relatively low in the more humid outermost ranges of the arid and semi-arid regions of Central Asia and rise towards the central part of Mongolia. The limited extent of present and Pleistocene glaciers in the eastern part of the Russian Altai and in the Mongolian Altai is the result of decreasing precipitation from west to east. This results in a rise of both the present-day and Pleistocene ELAs towards the east. However, it was more pronounced during the Pleistocene than today. There is an essential lack of absolute dating of glacial sediments in this particular region. Nevertheless, on the basis of present knowledge, most Late Pleistocene glacier advances in Mongolia and in the Russian Altai took place during Marine Isotope Stages (MIS) 2 and 4.

Introduction

This paper presents first the extent of Late Pleistocene ice in the Russian Altai and Western Mongolia, and second the current state of research concerning the timing of different glacier advances in this region. The focus is on the Altai Mountain system and the Khangai Mountains. These mountains are situated at the northern border of the Central Asia, between the Siberian taiga in the north, and the steppe to desert steppe regions in the south (Fig. 1). Based on the different geomorphological settings and climate conditions the Altai Mountains (82° - 95° E; 46° - 52° N) can be divided into the western Russian Altai and the eastern Mongolian Altai. The southern regions, which belong to the territory of China, are also called the Chinese Altai. In the north-east, the Altai Mountains are bounded by the Sayan Mountains. The south-eastern Altai extend into the Gobi Altai. East of the Altai, the so-called 'Valley of Great Lakes' lead over to the Khangai Mountains. The Khangai Mountains trend from north-west to south-east and occur in central Mongolia (96°-103° E; 46°-50° N, Fig. 1), approximately 100 km east of the Altai Mountains.

The extent of the Last Glacial Maximum (LGM) in the eastern Altai and the Khangai is often clearly determinable by using the morphology of glacial sediments identified on air photographs, satellite images and topographic maps. On the other hand, intensive fieldwork is required to examine glacial relics and sediments, especially in the steep and narrow valleys of the western Altai, and in a few regions of the Mongolian Altai and Khangai, respectively. The Altai Mountains fall into the territories of four different countries: Russia, Mongolia, China and Kazakhstan. Therefore, research work in the Altai is always restricted to a part of these mountains. The different regions are discussed separately in the literature and until today there is no comprehensive of the entire Altai Mountains region.

In several areas of this region the extent and especially the timing of glaciers during the Last Glacial Maximum is still a matter of debate. Some relative chronologies exist for mountain glacier fluctuations, but the timing is poorly understood because of the lack of absolute ages for moraines. However, field evidence in Mongolia and Russia demonstrates that there is a considerable difference between the Late Pleistocene moraines and their associated outwash plains and those of the penultimate glaciation. The extent and distribution of ice is summarised in two profiles including the present and Late Pleistocene ELAs.

The underlying topography and the climatic conditions control the extent of modern and Pleistocene glaciations. In the western and southern Altai the alpine relief is dominated by steep V-shaped valleys. At the margins of the Russain Altai and in Mongolia the highest parts of the mountains comprise flat mountain tops, which are shaped by a main planation surface rising from 2,000 m a.s.l. in the north-western Altai to elevations between 3,000 and 3,500 m a.s.l. on the eastern fringe of the Altai. The summits,

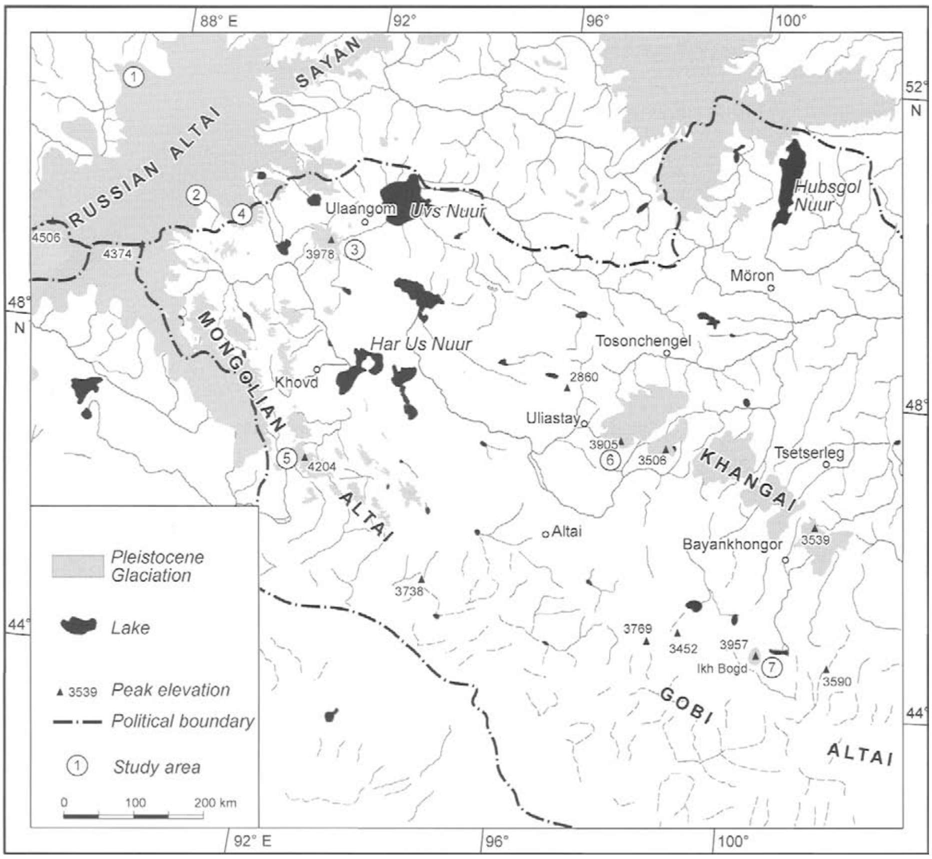


Fig. 1. Pleistocene glaciated areas in the Altai and Khangai Mountains (compiled according to Budvylovski, 1993, Kotljakov et al., 1997; Shi, 1992).

which stretch above the main mountain surface, reach elevations of more than 4,000 m a.s.l., including mountains up to 4,506 m a.s.l. as the Belucha and the Tavan Bogd (4,374 m a.s.l.). In contrast, in the eastern Altai intramontane basins which include widespread alluvial fans, fanglomerates and lakes that divide the various isolated mountain systems. The mountain systems of the eastern part of the Altai, especially in Mongolia, wide and extensive flat surfaces comprise their central parts. They have been dissected by deep glacial cirques and U-shaped glacial troughs in the higher areas of the mountains. At the outer margins of the mountains these flat areas give way to broad flat ridges. Whereas in the central part of the Khangai three main planation surfaces (peneplains) can be recognised (Klimek, 1980), whilst in the northern part of the Altai two to three main planation surfaces also exist. As a consequence of the more active fault scarps and tectonics they can be divided into smaller patches.

The present continental climatic conditions are characterised by large temperature ranges with winter temperatures below -20°C and summer temperatures up to more than 20°C (for example: January mean temperature of Ulaan Gom, Western Mongolia: -32.9°C, July: 19.2°C, annual average: -3.7°C). The highest annual rainfall is measured in the western Altai, which is influenced by westerly winds (Lydolph, 1977). The eastern part of the Altai is situated in a rain shadow and is consequently more arid. However, there are only a few meteorological stations, most of which are restricted to valleys and basins below 2,000 m a.s.l. In the north-western Russian Altai the amount of precipitation is estimated to exceed 1500 mm/a in the mountains, but this decreades and reduces to less than 300 mm/a in the south-eastern Altai region (Komitet Geodesii I Kartografii SSSR, 1991). For western Mongolia the precipitation is about 200 mm in 2000 m a.s.l. and it is estimated to reach over 300 mm in the higher mountain areas. In the Valley of Great Lakes precipitation decreases to less than 50 mm/a. Further to the east, in the Khangai Mountains, the recent annual precipitation increases to over 400 mm/a, whereas precipitation in the basins is below 100 mm/a (Academy of Sciences of Mongolia and Academy of Sciences of USSR, 1990; Barthel, 1983). The modern altitudinal vegetation belts, the soils and the geomorphological processes, including the distribution of glaciers, are controlled by these general climatic conditions.

Extent of present and Late Pleistocene glaciations

In the Russian Altai even today many glaciers exist. Information concerning the modern glaciation in the Altai and Khangai Mountains is given by Academy of Sciences of Mongolia & Academy of Sciences of USSR (1990), Klinge (2001), Klinge *et al.* (2003) Kotljakov *et al.* (1997) and Lehmkuhl (1999). The present glaciation in the eastern Altai is restricted to the highest peaks in the central parts of various mountain systems. Plateau-glaciers, cirque-glaciers, many isolated ice-patches and several smaller valley

Fig. 2. Cirques and glacier lakes north of the Aigulak Range (3,400 m a.s.l.), north of the Chuja Basin, in the upper catchment of the Bashkaus River. While the glaciers south of this range terminate in the vicinity of the settlement Aktasch at c. 1160 m a.s.l. (Fig. 4), the northern parts contributed to an ice sheet downstream to c. 500 m a.s.l.

glaciers occur. The size of the present glaciated area exceeds 900 km^2 in the Russian Altai (Bussemer, 2000), about 300 km^2 in the Chinese Altai (Shi, 1992) and about 850 km^2 in the Mongolian Altai (Klinge, 2001). In the Khangai Mountains, only one small modern glacier occurs. The first reports on Pleistocene glaciation in the Altai were gathered by the expeditions of Granö (1910). Evidence on Pleistocene glaciers in the Altai and Khangai was presented by von Klebelsberg (1948) and Murzaev (1954).

Russian Altai

The extent of Pleistocene glaciations in the north-western Russian Altai is in dispute. For example, according to Rudoi (2002) Pleistocene ice reached the foothill of the Altai close to Gorno Altaisk (about 300 m a.s.l.) in the Katun valley. In contrast, Budvylovski (1993) concluded that the terminal moraines are about 100 km further upstream. Bussemer (2000) compiled the various descriptions in Russian literature on the extension of the last maximum glaciation in the north-western Russian Altai. The extent of the Pleistocene glaciated area in the Russian Altai varies between 32,000 km^2 to 35,000 km^2 (Bussemer, 2000). On the basis of the compiled maps the writers estimatie an extent of Pleistocene ice in the Russian Altai of at least 80,000 km^2.

However, most researchers argue that valley glaciers of a limited ice cap reached at least to Lake Teleski at 430 m a.s.l. (Fig. 1, No. 1; e.g. Baryshnikov, 1992; Budvylovski, 1993; Bussemer, 2000). This indicates a Pleistocene ELA of lower than 2,000 m a.s.l. However, the extent of ice was much larger in the western parts of the Altai than in the eastern regions. The Pleistocene glacial landforms mainly comprise cirques, U-shaped valleys, hanging glaciers and small ice caps (Fig. 2 and 3). In the ablation areas different types of moraines occur. The southern limit of this small ice sheet can be shown north of the Chuja Basin (Fig. 1, No. 2 and Fig. 4). Several moraines reach the foothills of the mountains surrounding this tectonic basin. On the basis of the geomorphology, weathering, and the overlying deposits, several moraine stages can be mapped especially at the south-western part close to the settlement Beltir. This is one of the areas where valley glaciers descended to the basin and dammed the main rivers. The extensive outflow from the resulting ice-dammed lakes probably produced very large mega-floods (Glacier Outburst Floods – GLOFs) (Baker *et al.*, 1993; Carling *et al.*, 2002; Rudoi, 2002).

Mongolian Altai

Three areas with geological evidence for Pleistocene glaciations are found in the Mongolian Mountains: the

Fig. 3. U-shaped valley of the Bashkaus River (valley bottom: 700 m a.s.l., close to Fig. 1 No. 1) indicating a huge ice stream network at the northern part of the Russian Altai.

Khentey, the Khangai and the Mongolian Altai. In addition, there are traces of Pleistocene glaciations in a fourth area, the mountains surrounding Lake Khovgul (Hovsgol Nuur) in Northern Mongolia (Devjatkin, 1981; Kotljakov *et al.*, 1997). The Pleistocene glaciated area in the Mongolian Altai (western Mongolia) is calculated to occupy about 28,750 km^2 (Devjatkin, 1981), and 20,700 km^2 (Klinge, 2001), respectively. Florensov & Korzhnev (1982) compiled the Russian work on glaciations in Mongolia and produced a map showing the extent of a widespread Pleistocene ice-sheet in the Mongolian Altai. However, the distribution of passive Pleistocene glaciers proposed by these authors could not be confirmed during fieldwork by the writers (Klinge, 2001; Lehmkuhl, 1998).

On the basis of geomorphological criteria, the degree of erosion and preservation of deposits, Devjatkin (1981) differentiates three separate Pleistocene glacial advances in Mongolia. The most extensive advance occurred during the Middle Pleistocene, whereas the two younger moraines belong to the Late Pleistocene. This chronological classification was confirmed by correlation of fluvial and alluvial sediments with the different end moraine stages and the radiometric dating of overlying peat, fossil soil and aeolian sediments (Grunert *et al.*, 2000; Klinge, 2001; Lehmkuhl, 1999; Lehmkuhl & Lang, 2001). The correlation between the different Late Quaternary glacier advances in the Altai and Khangai Mountains and the glaciations in northern Asia (Arkhipov *et al.*, 1986) and Europe is shown in Table 1.

During several expeditions to western Mongolia between 1996 and 1999, detailed glacio-geomorphological fieldwork was undertaken by the authors at various sites in the Khangai and Mongolian Altai. In western Mongolia several systems of terminal moraines can be separated using geomorphological criteria. These are surface morphology, weathering and different types of soil development. Two types of carbonate crusts, which develop under arid climate conditions on the underside of stones, can be differentiated: a younger one of Holocene origin has a bright white colour and mostly lies in its initial position; the older one has a light yellow colour, has been weathered and turned upside down by fluvial or periglacial processes. Old carbonate crusts are often distributed as fossil soils and/or gravel in older till (Table 1).

In the northernmost part of the Mongolian Altai at least some Pleistocene glaciers reached the intramontane basins (Figs 5 and 6), but they are restricted to the central part of the mountains in the southern parts of the Mongolian Altai (Fig. 7). The detailed geomorphology of the Turgen-Kharkhiraa Mountains (Fig. 1: No. 3; Fig. 5) is presented by Lehmkuhl (1998). Downstream of the modern glaciers, U-shaped valleys (troughs) indicate that smaller Pleistocene ice stream nets occurred on the northern, southern and western slopes of the Turgen-Kharkhiraa Mountains. Cirque levels, mainly in 2,900 to 3,100 m a.s.l. on the surrounding mountains, are further clear geological evidence for Pleistocene glaciations. The maximum extent of Pleistocene ice marginal landforms was mapped on all slopes of the Turgen-Kharkhiraa mountains. Here, there are five main valleys where Pleistocene valley glaciers end at elevations of 1,950 to 2,250 m a.s.l. (Fig. 5). Each of these ice margins is connected to glacial outwash trains composed of rounded gravels and pebbles, into which the modern streams are incised. Fig. 6, from the neighbouring Ikh Turgen Mountain (Fig. 1: No. 4) shows a similar situation as on the western slope of the Turgen-Kharkhiraa. The Pleistocene glaciers here reached the western part of the basin of the Achit Nuur from the Ikh Turgen Mountains and the eastern part of the basin from the Turgen-Kharkhiraa Mountains.

Figure 7 shows a detailed map of a local mountain glaciation at the Munkh Khayrkhan Mountains in the southern Mongolian Altai (Fig. 1: No. 5). The ages of the moraines can be divided into Late Holocene (Little Ice Age) and Middle to Late Pleistocene. Late-Glacial moraines are rare and indistinct in the Mongolian Altai (Klinge, 2001), while there are more in the Khangai (Richter, 1961; Florensov & Korzhnev, 1982; Devjatkin, 1981; Lehmkuhl, 1998). This morphostratigraphical system (Table 1) is confirmed by optically-stimulated luminescence (OSL) dating of overlying aeolian sediments that yield ages of 57 ka BP and 17 ka BP (Klinge, 2001; Lehmkuhl & Lang, 2001). The clearly-identifiable Late Pleistocene end moraines M_1 derived from large valley glaciers. Most of them are marked by two morainic ridges, which indicate two main glacial advance periods during the Late Pleistocene (M_{1a}: 14/15-32 ka BP, M_{1b}: 50-70 ka BP). The morainic stages can be combined with glaciofluvial outwash plains and terraces, which are connected with alluvial fans and fanglomerates in the basins. In some areas in the region relics of older, deeply weathered moraines (M_2) can be found close to the Last Glacial ice-margins. They probably belong to a slightly more extensive Middle Pleistocene-age glaciation.

Together the geological and tectonic situation predominantly influences the nature of glacial erosion and accumulation landforms. The volume of moraines is

Table 1: Stratigraphy of Late and Middle Pleistocene and Holocene glacier advances in the Altai and Khangai Mountains.

Terminal moraine stage	Glacier advances	Marine Isotope Stage	Siberian chronostratigraphy	Alpine chronostratigraphy	Pedological environment of the specific till
M_{LIA}	16th – middle of 19th centuries AD	1		Little Ice Age	Fresh till without any sediment and soil cover
M_0	10-15 ka BP	1		Late-glacial Würmian	aeolian sediments and castanosem soil with carbonate horizon
M_{1a}	15 / 20-32 ka BP	2	Sartan	Late Würmian	aeolian sediments and castanosem soil with carbonate horizon
		3	*Karginsky Interstadial*		*Higher lake levels*
M_{1b}	50-70 ka BP	4	Early Zyrianka	Early Würmian	aeolian sediment and castanosem soil with carbonate horizon; erosion, older carbonate crusts are common
		5	*Kazantsevo Interglacial*	*Eemian*	
M_2	> 132 ka BP	>5	Taz, Somarovan	Rissian	intensively-eroded; relics
		>9 /16	Shaitan	Early to Middle Pleistocene	no glacial deposits

determined by the quantity of crystalline bedrock. In addition, the morainic landform character is influenced by the elevation of the snowline and the intensity of neotectonic movements (Fig. 6). In regions with minor tectonic activity the different Quaternary end moraines stages are horizontally separated. By contrast, in mountains which have experienced strong tectonic uplift the moraines occur more or less in the same place one above the other. However, if the uplift is weaker, younger fluvial and glacial sediments bury the older moraines.

Fig. 8 shows a cross-section of two valleys from the Ikh Turgen Mountains. In the lower part of the eastern valley (Fig. 8A) many fault lines are found that indicate recent neotectonics. As a result the block-like steps created by the fault lines Pleistocene moraines of different ages are deposited close together and even on top of one another. In contrast, the western valley (Fig. 8B) ends on a more a less flat and stable area. Therefore the end moraines are more widespread and frequently include glacial lakes (Fig. 6).

Khangai

The six centres of Pleistocene glaciation in the Khangai Mountains cover an area of *c.* 12,900 km² according to Florensov & Korzhnev (1982) and Lehmkuhl (1998). Richter (1961) and Klinge (2001) have described Pleistocene glaciers and end moraines from the western Khangai, near Otgon Tenger Uul (Fig. 1: No. 6). Two Last Glaciation stages have also been reported from the southern side of the Khangai in the Tsagan-Turutuin-Gol drainage basin by Klimek (1980). In addition, information on Pleistocene glaciations from the upper catchment area of Baydragiyn Gol, in the central part of the Khangai, is given by Lehmkuhl (1998), Lehmkuhl & Lang (2001), and Walther (1998). On the highest peaks with elevations up to 2,928 m a.s.l. in the Khan Khukhiyn Mountains, south of Uvs Nuur, glacial erosion landforms have been identified in the field.

Present and Late Pleistocene ELA reconstructions

Palaeoclimatic reconstructions based on the limits of former glaciers often make use of estimates of the associated equilibrium-line altitudes (ELAs). The equilibrium line marks the position where, over a period of one year, accumulation of snow and ablation is exactly balanced. There is a very close connection between the ELA and local climate, particularly solid precipitation and air temperatures. The ELA is sensitive to perturbations in either of these two variables, and rises in response to decreasing snowfall and/or increasing frequency of positive air temperatures, and *vice versa*. Fluctuations in the ELA therefore provide an important indicator of glacier response to climate change and allow reconstructions of former climates, as well as the prediction of future glacier behaviour (Benn & Lehmkuhl, 2000).

Frenzel (1959) reconstructed the Pleistocene snowline in Eurasia. He includes the Russian references and shows

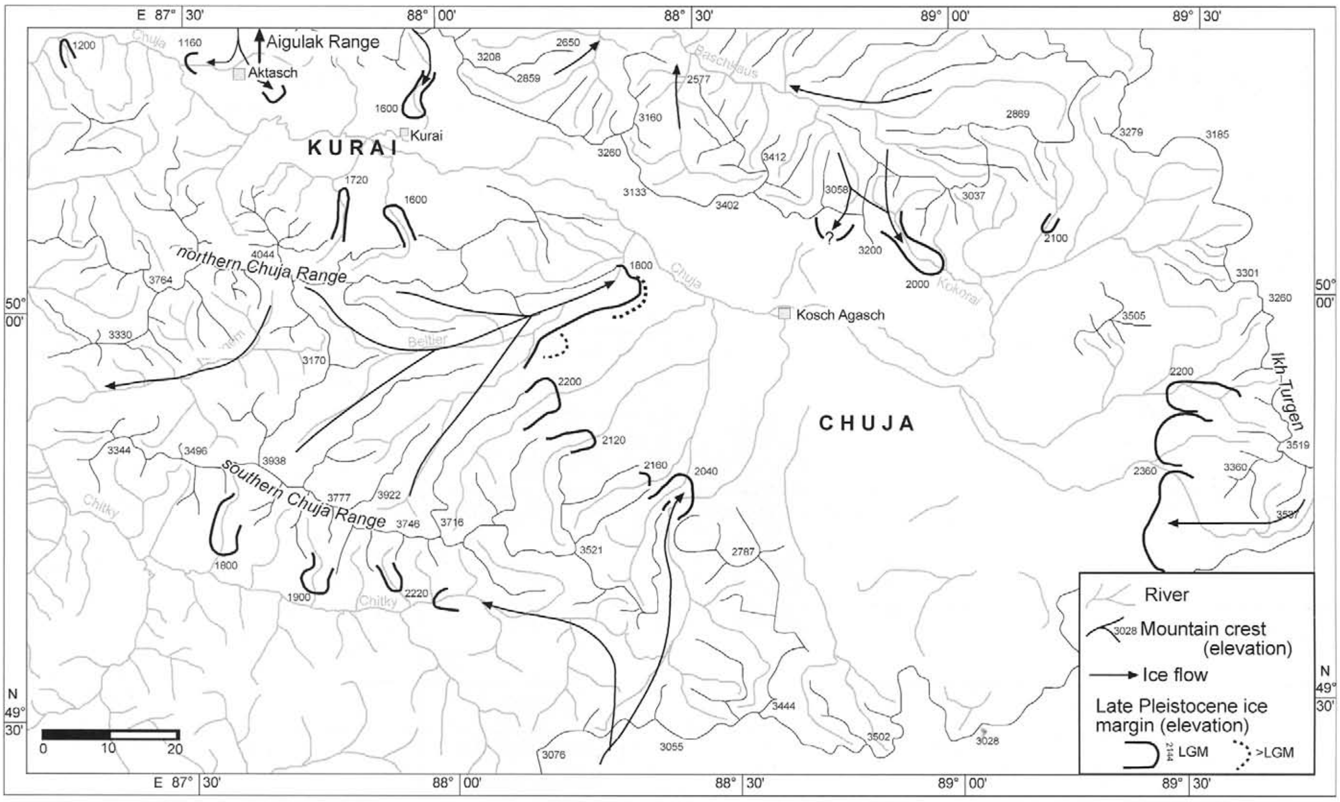


Fig. 4. Extent of selected ice margins surrounding the Chuja basin (compiled according to Budvylovski and the authors' observations, see Fig 1, No. 2).

Pleistocene snowlines for the Russian Altai with a steep west – east increase of about 1,500 m from about 1,250 to 2,750 m a.s.l. A map of Pleistocene glaciations in southern Siberia, presented by Kotljakov *et al.* (1997), is based on information from Grosswald (1980) and shows an increase of the Pleistocene snowline from 1,800 m a.s.l. in the north-western Russian Altai to 2,600 m in the central Mongolian Altai, while it decreases again to 2,600 m a.s.l. in the south-eastern Mongolian Altai. In contrast, Klinge (2001) calculates a steady increase of the Pleistocene snowline from 2,900 m a.s.l. in the centre to over 3,100 m a.s.l. in the south-eastern Mongolian Altai. For the Turgen-Kharkhiraa Mountains (91.5°E, 49.6°N), which are situated in the northern Mongolian Altai, Kotljakov *et al.* (1997) propose a Pleistocene snowline of about 2,700 m a.s.l. In contrast, Lehmkuhl (1998, 1999), Stauch (2002) and Grunert *et al.* (2000) report a Pleistocene snowline of 2,900 to 3,000 m a.s.l. for the Turgen-Kharkhiraa. These differences between the snowline altitudes of 200 to 300 m can be caused by unequal snowline calculation methods (Benn & Lehmkuhl 2000).

For the Pleistocene glaciation in the southern Altai region, which occurs in Kazakhstan and China, Kotljakov *et al.* (1997) and Shi (1992) have reported glacial snowline altitudes between 2,350 and 2,500 m a.s.l. In this study the authors use the detailed description of the Pleistocene glaciated area by Kotljakov *et al.* (1997). For the Chinese Altai the extent of Pleistocene ice is estimated to be *c.* 23,000 km².

To show the variations in ice extent, the modern and Late Pleistocene equilibrium-line altitudes (ELAs) for this area are presented in two cross-sections (Fig. 8). The ELAs are relatively low in the more humid outermost ranges of the Russian Altai and rise towards the central part of Mongolia (Fig. 1). The limited extent of present and Pleistocene glaciers in the eastern part of the Russian Altai and in the Mongolian Altai is the result of decreasing precipitation from west to east. This results in a rise of present and Pleistocene ELAs towards the east. However, this general increase of the ELAs towards the more arid regions was more evident during glacial times. Two major Pleistocene glaciations can be separated on the basis of their differing degrees of weathering of sediments and the connection with different meltwater gravel spreads and terraces. There is an essential lack of absolute dating in this particular region. However, the present knowledge indicates that most Late Pleistocene glacier advances in the Russian Altai and Mongolia took place during the maximum cooling periods of the Last Glacial cycle, equivalent to the Marine Isotope Stages (MIS) 2 and 4.

Fig. 9 shows the distribution of present and Pleistocene ice in two profiles (modified from Lehmkuhl, 2003). Because there are only a few absolute dates available related to the age of formation of the end moraines within the last glacial cycle the Late Pleistocene stage was termed the local Last Glacial Maximum (cf. Lehmkuhl & Owen, 2002). The first profile (Fig. 9A) is from the Russian Altai in the north-western part of the Altai towards the southern

Fig. 5. Glaciation in the Tugen-Kharkhiraa Mountains, northern Mongolian Altai (modified according to Lehmkuhl, 1998; Fig. 1, No. 3).

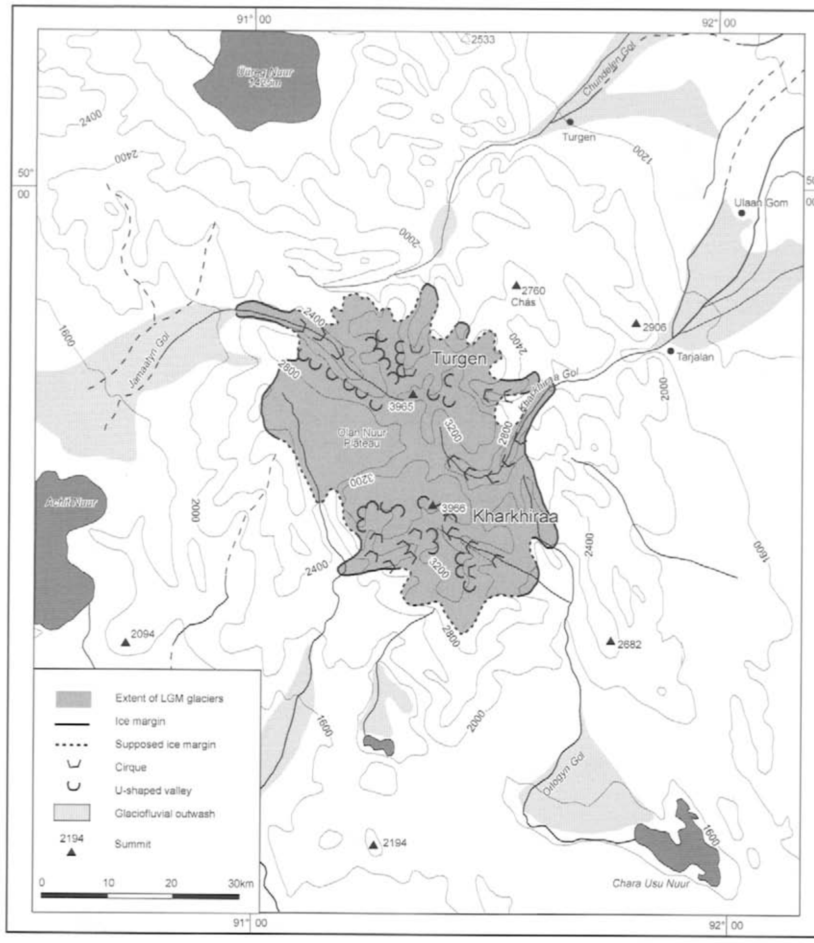
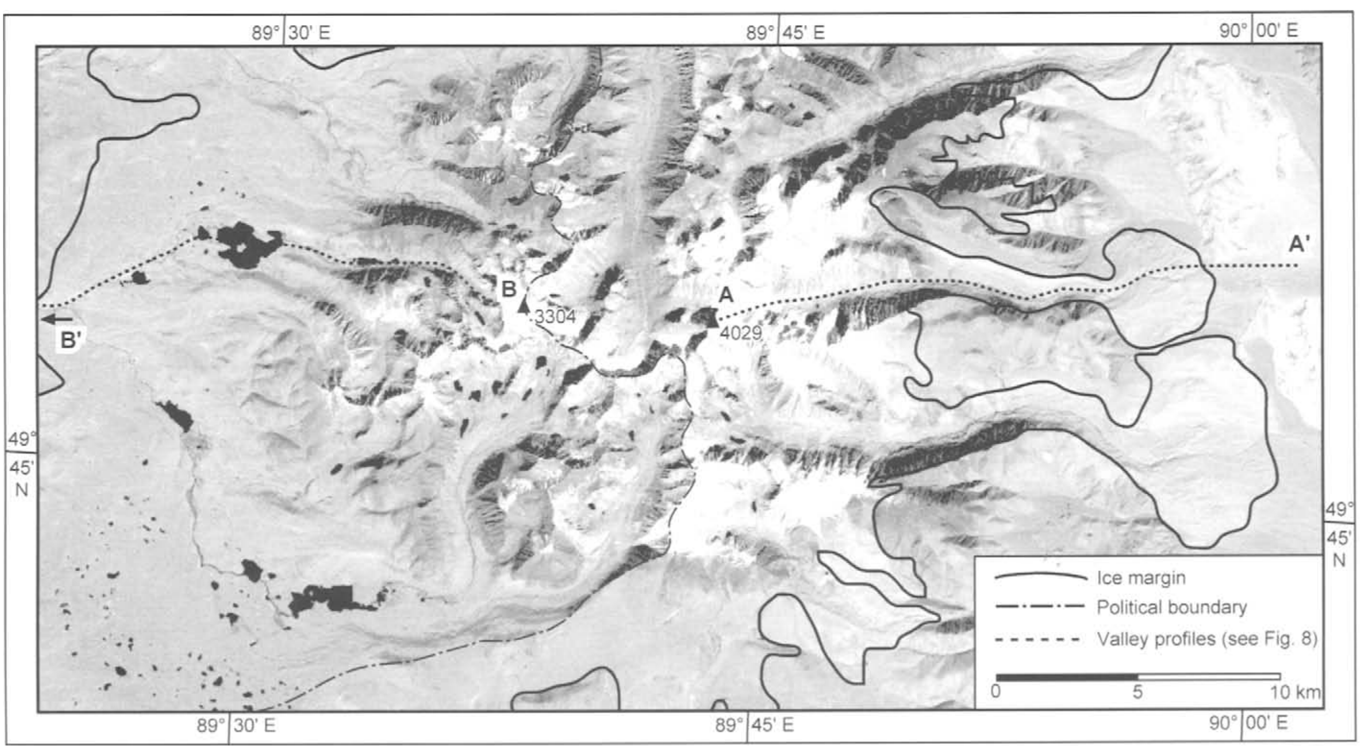


Fig. 6. Satellite image from the eastern slope of the Ikh Turgen (Western Mongolia); Fig. 1, No. 4.



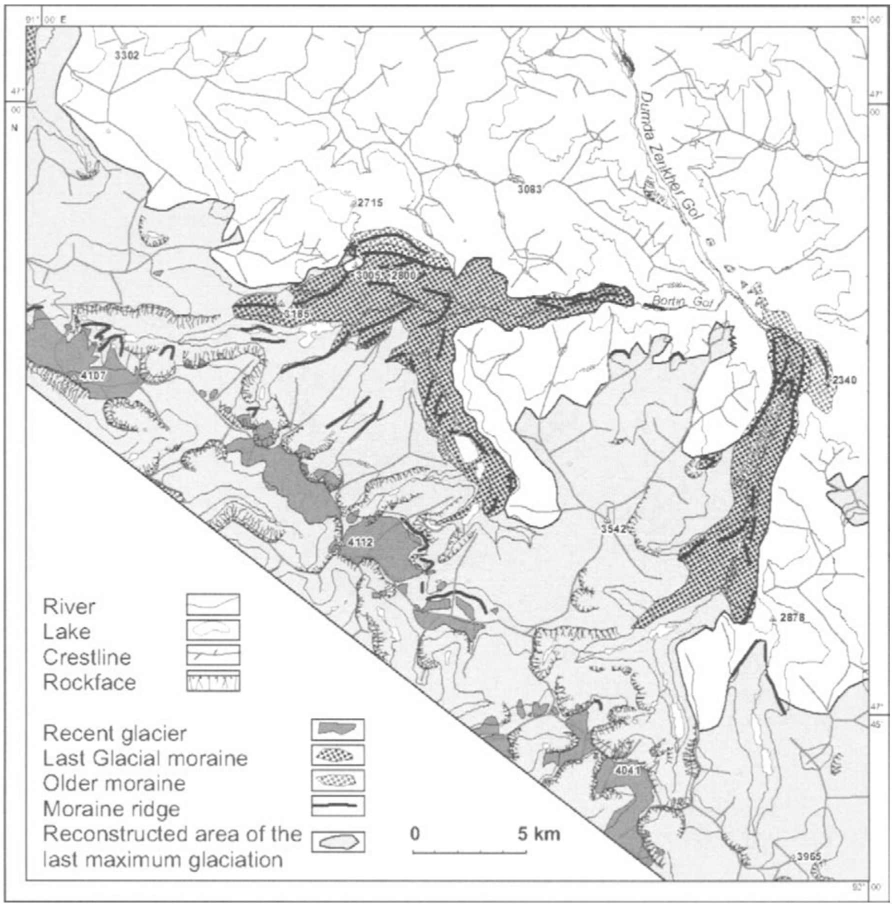


Fig. 7. Detailed map of glacial deposits in the Munkh Khayrkhan Mountains, southern Mongolian Altai (according to Klinge, 2001; Fig. 1, No. 5).

part of the Mongolian Altai. In the north-western part of the Russian Altai, the present ELA is below 2,600 m a.s.l., rising towards the east to 3,800 m a.s.l. The Late Pleistocene ELA is calculated to be *c.* 2,000 m a.s.l. in the north-western mountains ranges of the Russian Altai and >3,100 m a.s.l. in the southern parts of the Mongolian Altai.

Fig. 9B presents the ELAs from the Chinese and Mongolian Altai in the west towards the Khangai Mountains in the east. The present ELAs in the Chinese Altai and Mongolian Altai range between 3,000 and 3,600 m a.s.l., and about 3,900 m a.s.l. in the Khangai Mountains, respectively (Lehmkuhl, 1998; Klinge, 2001). In the Chinese Altai the Late Pleistocene ELA can be estimated at heights between 2,600 and 3,000 m a.s.l. In the Khangai Mountains the Pleistocene ELA is 2,700 to 2,800 m a.s.l.
The resulting ELA depressions are >1,000 m in the wettest parts of the western Russian Altai (today's annual precipitation: >1,000 mm/a) and between 800 to 500 m in the eastern part of the Russian Altai and in the Mongolian Altai, respectively. In the Khangai further to the east, the ELA depression is again >1,000 m. This may be the consequence of a strong monsoonal influence, which is also evident further east in the mountains of Northern China as the Qinling Shan or Wutai Shan (Lehmkuhl & Rost, 1993; Rost, 2000). This general increase of the ELAs towards the more arid regions was more evident during glacial times. The extent of present and Late Pleistocene glaciations in the

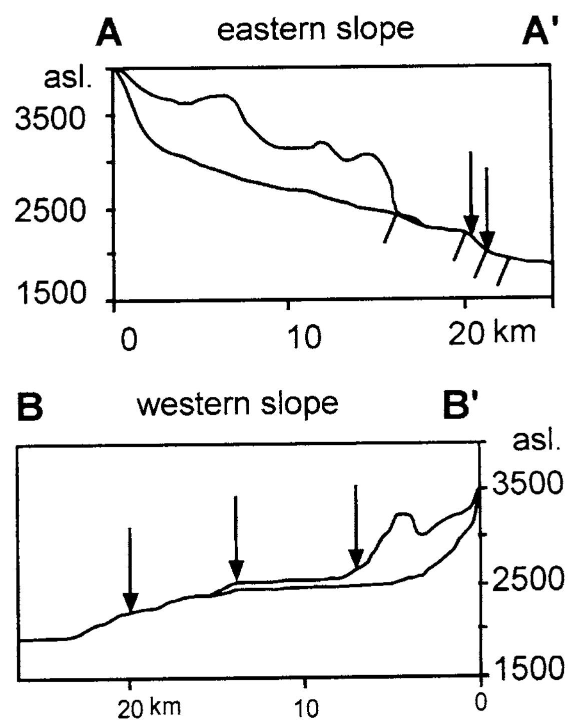


Fig. 8. Cross-section of two valleys from the Ikh Turgen Mountains, including the end moraines. A-A': Western slope, B-B': Eastern slope including the fault lines (cf. Fig. 6).

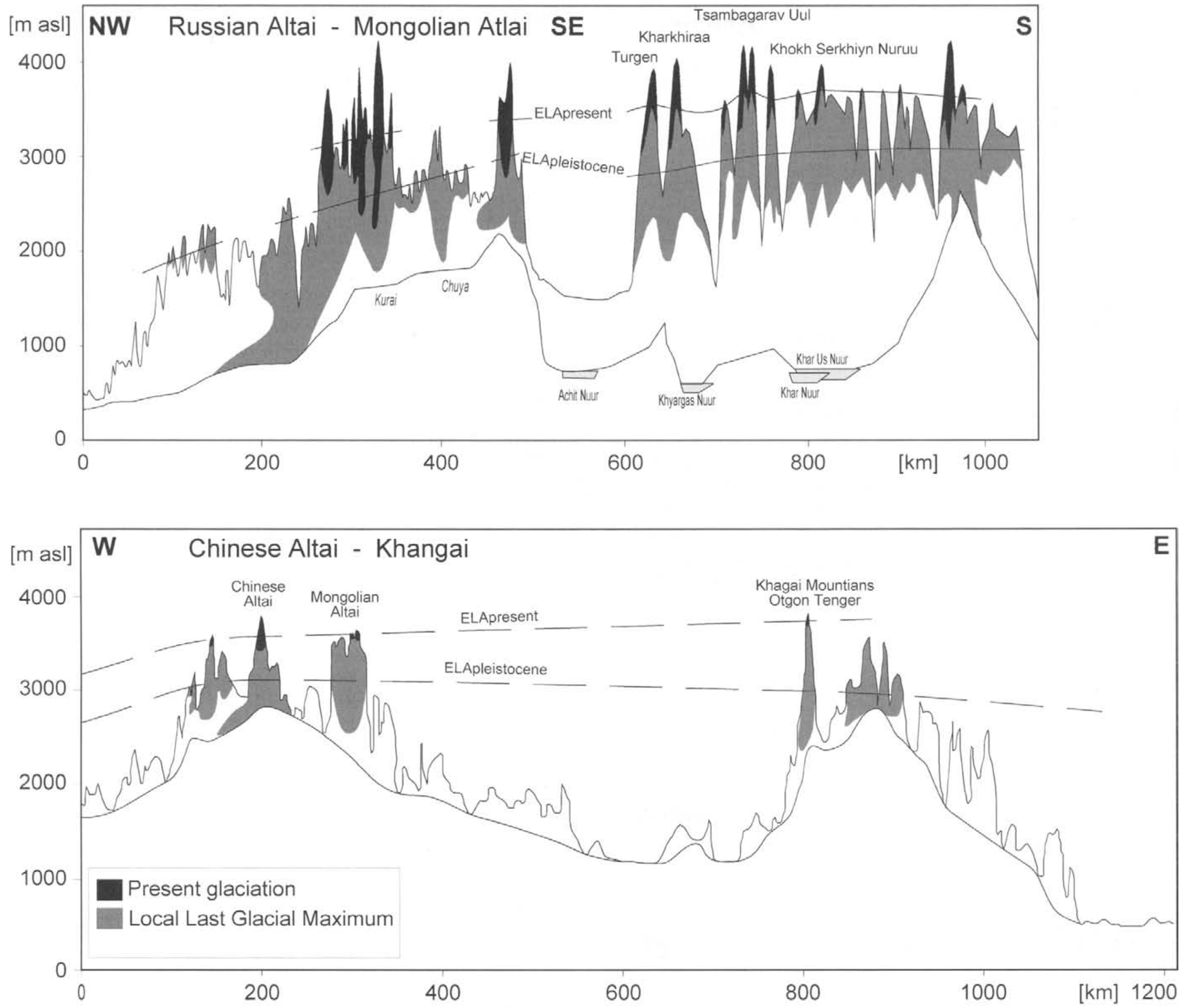


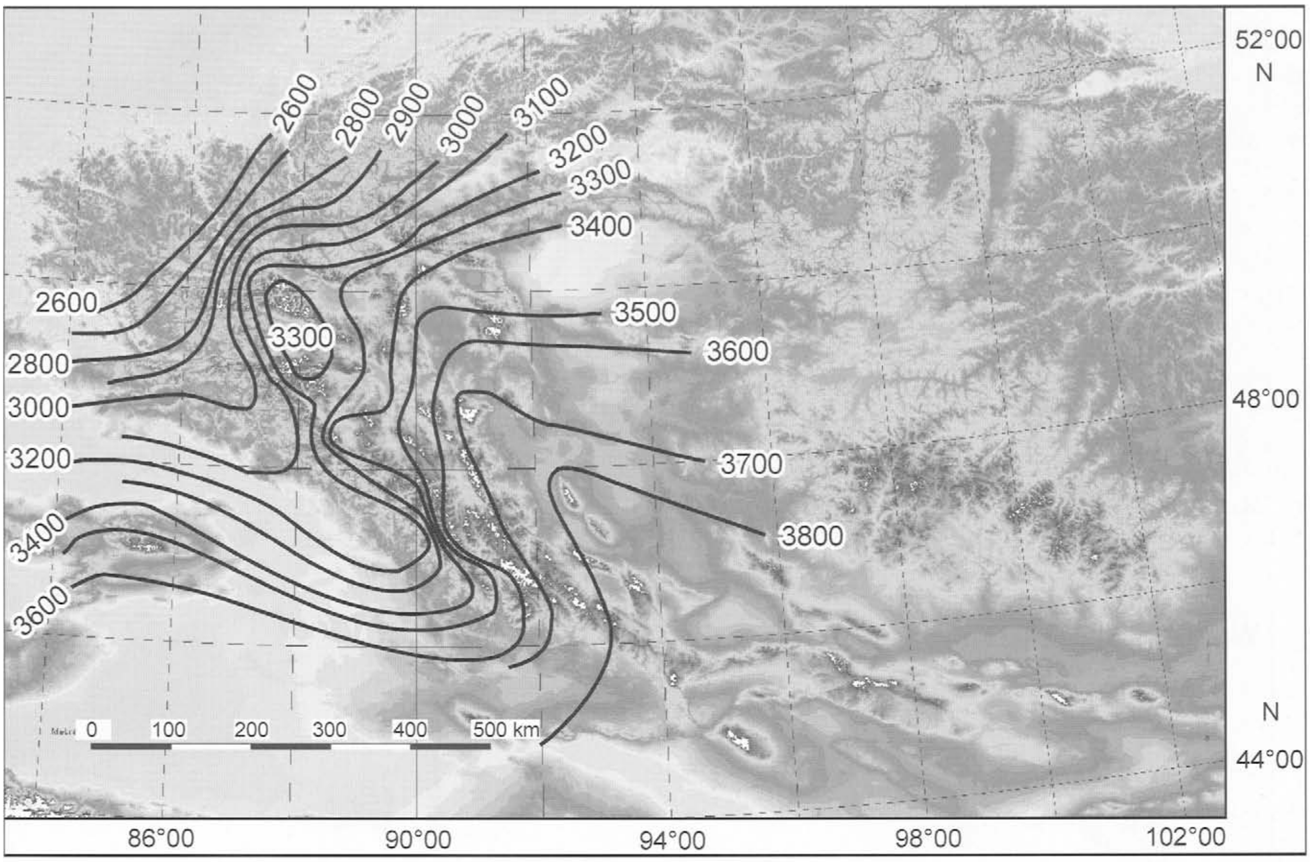
Fig. 9. Late Pleistocene ELAs in Mongolia and China. The two profiles include the present and (local) Last Glacial Maximum. The shaded areas are mountains above 3,000 m a.s.l. For further explanation, see text.

mountains of Mongolia (Khangai and Gobi Altai) towards the southern part of the Tibetan Plateau is published by Lehmkuhl (1998). Although there are no modern glaciers in the central part of the Khangai and Gobi Altai, Lehmkuhl & Lang (2001) calculated the Pleistocene ELA to be between 2,700 to 2,800 m a.s.l. in the Khangai. Lehmkuhl (1998) sug-gested that limited Pleistocene glaciers were also present in the Gobi Altai in the vicinity of the Ikh Bogd (3,957 m a.s.l., Fig. 1: No. 7) during glacial times. This implies that the ELA depression in the Khangai and Gobi Altai was *c.* 1,000 m, similar as on the northern slopes of the Qilian Shan in north-eastern Tibet (Lehmkuhl & Rost, 1993).

As stated above, the ELA is determined by temperature and precipitation. Therefore, a general increase in ELA altitude from low to high latitude can be observed reflecting the lowering of temperature. However, according to the decreasing precipitation from west to east in the Altai mountain system, the recent snowline rises 1,200 m from 2,600 m a.s.l. in the north-western Altai to more than 3,800 m a.s.l. in the south-east (Fig. 10). Above the central Altai, the snowline changes its latitudinal (W-E) direction to a longitudinal direction, which arises from the maximum rainfall in the western mountain ranges. Therefore, a steep increase of the snowline from 3,100 m to 3,600 m a.s.l. occurs in the southern Chinese Altai. Only one recent glaciation exists in the Khangai at Otgon Tenger Uul and indicates a contemporaneous snowline of 3,700 m a.s.l.

Timing of Pleistocene glaciations in the Russian Altai and Western Mongolia

There are only a few results published constraining the dating of Late Pleistocene glaciations in this vast region



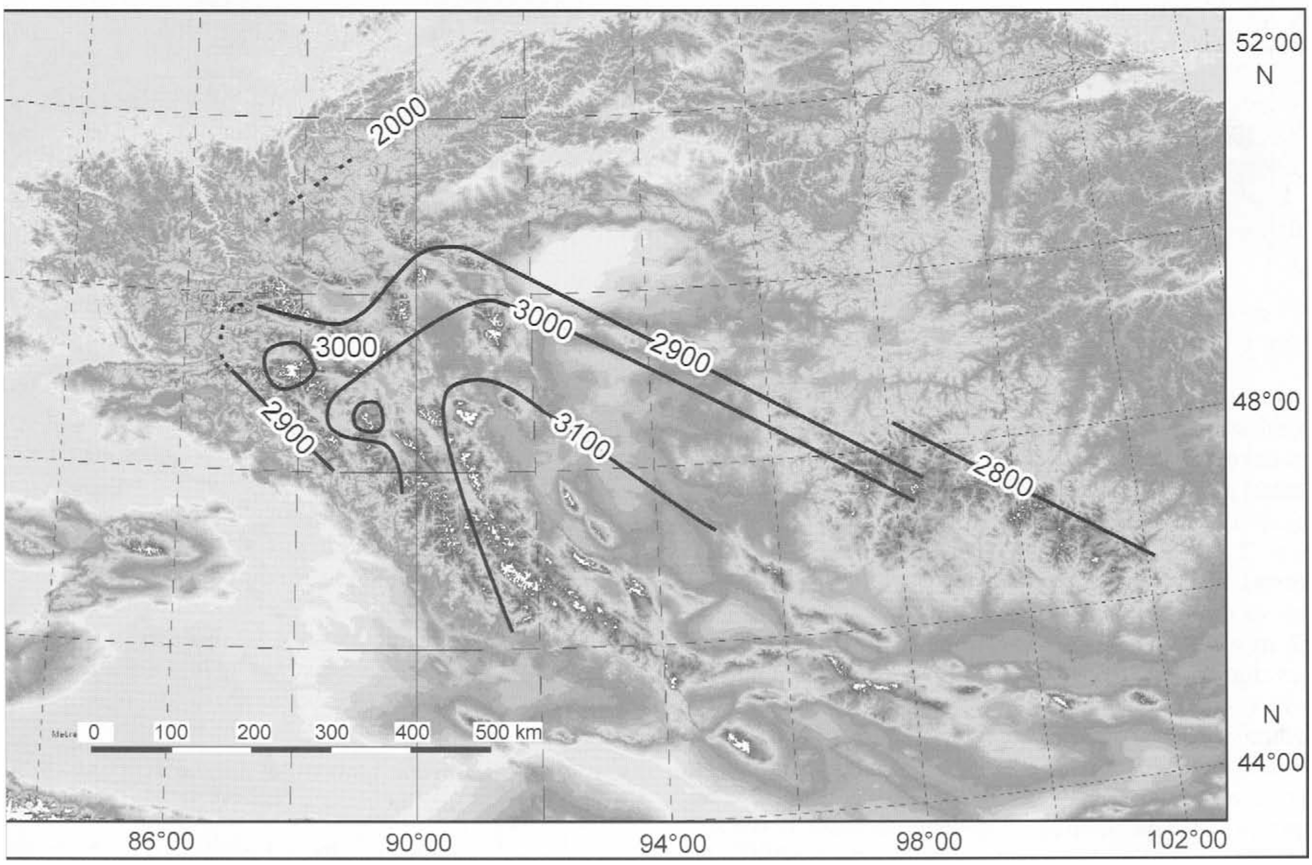


Fig. 10. Map of modern and Pleistocene ELAs in the Altai and western Khangai.

In the eastern part of the Russian Altai and the Mongolian Altai there is evidence for two to three major Pleistocene glaciations (Devjatkin, 1981; Florenzov & Korzhnev, 1982). However, the extent of two of the main stages is similar because the end moraines are close together (Lehmkuhl, 1998; Klinge, 2001). Russian scientists established a Pleistocene stratigraphy for this region using the local names from the Siberian stratigraphy (Arkhipov *et al.*, 1986; Lehmkuhl, 1998: Tab. 1). Accord-ing to this stratigraphy the Last Glaciation is divided into two glacial periods, the Sartan Glaciation (corresponding to MIS 2) and the Early Zyrianka Glaciation (MIS 4), inter-rupted by the Karginsky Interstadial (MIS 3). Remnants of these glaciations can be separated on the basis of the different degrees of weathering of their sediments and the connection with different gravel spreads and terraces (Lehmkuhl, 1998). Based on OSL dating of overlying aeolian sediments, huge alluvial fans and lake level variations, Grunert *et al.* (2000) support the view, that there are two major ice advances equivalent to MIS 2 and 4. In addition, Lehmkuhl & Lang (2001) published an OSL age of 21 ka for a sand deposit overlying the terrace deposits equivalent to the Last Glacial ice marginal position in the Khangai Mountains. Recent OSL dating, by A. Zander and M. Frechen from silt beds in four different moraines of the Russian Altai suggest ages ranging between 18.8 and 24.4 ka (personal communication).

In summary, the extent of glaciers during the local Last Glacial Maximum has more or less been determined. In contrast, knowledge concerning the timing and fluctuations of earlier Pleistocene glaciation is still very limited in this vast area. However, the application of modern geomorphological and sedimentological techniques, and the development of new dating techniques such as OSL and cosmogenic radio-nuclide (CRN) surface exposure dating have offered the possibility of regional and temporal correlations across this huge area.

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