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Synchronous fluctuations of glaciers in the Alps and Altai in the second half of the Holocene

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Abstract

The Altai Mountains occupy the northwestern part of the Central Asian collision belt. The late-Holocene behavior of glaciers in the Altai Mountains was reconstructed for the Khaidun river valley in the western part of the Russian Altai. We report here 17 new radiocarbon datings from wood remains buried by moraines, from peat layers and lacustrine sediments. The glaciers' advance took place in 2500–2200 BC, 1100 BC, 500 BC, AD 400, AD 1200–1300 and AD 1500–1850. It is the first time that material which separates the so-called Historical stage of cooling into three stages has been collected in the Altai Mountains. The comparison of time of moraine formation in the Altai with glacier activity in the Alps is evidence of the simultaneity of these processes.

Keywords

Altai Mountains, glacier, Holocene, moraine, radiocarbon dating, stratigraphy

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Introduction

Almost all explorers of the Altai Mountains mentioned the glacier fluctuations in the late Holocene. A review of the research history of Holocene glaciation in the Altai was recently presented by Agatova et al. (2012). But until recently, the paleoglaciological construction was poorly provided with radiocarbon dating. The lack of statistically significant radiocarbon dating of the Altai moraine complexes resulted in varying interpretations of the time of their formation. For instance, the A Shnitnikov's 1900-year rhythms were used for moraine timing.

A founder of Siberian glacial geomorphology, LN Ivanovsky defined three stages of glacial advance in the Altai Mountains after the Holocene Climate Optimum (HCO): Akkem (AM), Historical (HS) and Aktru (AS; Ivanovsky, 1967). The dating of the Altai moraine complexes undertaken over the last decade has allowed us to understand more about the Holocene cold stages. But, so far, the exact period of glacier advance in the second half of the Holocene was defined with radiocarbon and lichenometric dating only for the North-Chuisky ridge (Agatova et al., 2012; Galakhov et al., 2008). The advance of glaciers in the Akkem stage took place here around 4200–4900 BC. The Historical stage lasted for 1000 years, and was on the border of the old and new eras (500 BC–AD 400). The Aktru stage corresponds to the 'Little Ice Age' according to the alpine chronology.

However, the alpine chronology includes many more stages after the climatic optimum (Wilhelm, 1975); that is, Larstig/Misox (4500–4000 BC), Piorphase (2900–2300 BC), Lebbenschwankung (1500–1100 BC), Gletscherkaltphase 1 (700–200 BC), Gletscherkaltphase 2 (AD 200–700), advance of the Aletschgletscher (AD 1200), and Fernau (AD 1600–1850).

As evidenced by thorough research carried out in the Aktru basin (North-Chuisky ridge), the Maly Aktru glacier moraines correspond to two alpine stages; that is, Fernau AD 1500–1800 (AS_2) and the preceding Fernau AD 1200–1300 (AS_1). The Fernau stage moraine covers the previous moraine complex with radiocarbon dating of organic residues found in these moraines, clearly demonstrating their chronological separation (Galakhov et al., 2008, 2009) as had been previously suggested by Dushkin (1965) and by Ivanovsky et al. (1982).

Geomorphologically, the moraine of the Historical stage (HS) in the Aktru basin is hard to define. The studies made in the basin have allowed us to divide the moraines of this cold stage into three complexes and attribute them approximately to 1600 years ago (HS_3), 2500 years ago (HS_2) and 3100 years ago (HS_1; Galakhov et al., 2005). These phases of glacier fluctuation were revealed based on the rate of lichen growth. The larger growth gradient along the valley axis corresponds to glacier tongues stabilization and the appropriate phase of glacier fluctuations.

In order to study more thoroughly and to date the moraines of the Historical stage as well as to separate them into phases, it was necessary to find a suitable mountain glacial basin in the Altai.

Material and methods

The Altai Mountains occupy the northwestern part of the Central Asian collision belt and include large mountain massifs in the south of Siberia, northern China, Mongolia and northeastern Kazakhstan. Most of the area is characterized by an arid climate because of its inland location; however, areas subject to humid western winds get larger amounts of precipitation (up to 2000 mm/yr).

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Our knowledge of Holocene cold stages in the Altai has come mostly from the study of the glacier tongue fluctuations in the inner part of the mountain territory characterized by less moisture than the Alps. To study the moraines of the Historical stage (HS) in detail, we investigated the Khaidun river basin (Figure 1) where, according to Krencke (1982), the index of ablation/accumulation on the firn line reaches 300–350 g/m^2. Here, the precipitation is three times higher than, for example, in the southeastern Altai. The Khaidun river basin is situated within the Kholzun ridge at the border of the Republic of Altai and Kazakhstan. The ridge forms a watershed for the basins of the Ob and Irtysh rivers. Rivers and tributaries of the River Koksa (River Khaidun is one of them) run through the Russian part of the ridge. The Khaidun basin is situated in the Russian part, in the so-called Turgusun junction that is a circular watershed of rivers Turgusun, Khaidun, Chernaya Uba, Belaya Uba and Malaya Ul'ba. Sometimes it is considered as an individual orographic unit which merges with the Kholzun ridge in the southeast. Formerly, Obruchev (1915) noted that the Kholzun is characterized by extremely snowy winters, when the thickness of snow cover in some areas can exceed more than 8 m. VB Sochava, who visited the area in 1939, wrote that the observations at high mountain weather stations in the upper reaches of the Malaya Ul'ba and Gramotukha rivers revealed an average amount of precipitation of 1600 mm/yr (observations for nine years) but that in some years it could be as high as 2227 mm. About half of the total annual precipitation falls as snow (Sochava, 1946).

In 1920 Tronov and Tronov revealed that the height of the snow line in this part of the Altai is lower in comparison with other regions and reaches as low as 2300 m a.s.l. Nowadays only small hanging glaciers are observed on the kar walls of Kholzun ridge, but back in the AD 1970s–1980s their number reached 38, and the total area was 2.3 km^2 (Revyakin and Mukhametov, 1987).

The late-Holocene terminal-moraine complexes are well-defined morphologically in the Khaidun valleys and tributaries. In 2009–2011 the morphology of existing moraine complexes in the Khaidun valley was studied. The moraines were mapped, and the morphometric characteristics were specified (Figure 2; Table 1). Fifteen samples of subfossil remains of wood and peat were taken for radiocarbon dating (by Orlova from the V Sobolev Institute for Geology and Mineralogy SB RAS). Another two samples were taken in the River Multa basin, in front of the moraine of the Akkem stage (AS) as identified by Ivanovsky et al. (1982).

Results and discussion

Modern glaciers and moraines of the Aktru stage

Small snow-ice formations left in the relief of some moraine complexes of the 16th to 19th centuries are easy to observe in the field and from satellite images. Actually, modern glaciers in some valleys of Khaidun tributaries are small snow-ice formations several hundred kilometers in width and length.

The glacier tongue in the left bank of Khaidun tributary lies about 20–25 m lower in comparison with the moraine crest of the Aktru stage and this may be due to an ice core under the moraine. The fact that this moraine belongs to the Aktru stage is proved by an upper profile made approximately 1 km away from the glacier: the radiocarbon age of a peat interlayer in the basement makes up 270±45 years (278±50 cal. yr BP; 1940 m a.s.l. SOAN-7829 counted from 1950).

Approximately 500 m down the valley a sample from a dead Siberian cedar found on the surface of the well-formed moraine from the last phase of the Historical stage (HS_3) was taken for radiocarbon dating (1930 m a.s.l., SOAN-7827). According to the growth rings, the cedar's age was 313 years (measured by NV Malysheva). The radiocarbon age of the outer part of the sapwood constitutes gave 135±50 yr uncal. BP. This might suggest that the occupation of this moraine by trees started during the Medieval Climatic Optimum (c. AD 1500) and perhaps the death of the tree was caused by the cold period during the Aktru stage which correlates with the 'Little Ice Age' in Western Europe. Opposite the front edge of the moraine complex, on the southeastern slope of the glacial valley (40–45°) and 40–50 m above the moraine, there is an ancient pine-larch wood.

A large and steep cirque with basal area of 0.58 km^2 is situated in the upper reaches of the Khaidun. There is now no glacial ice here and well-shaped moraine complexes are absent. Glacial sediments

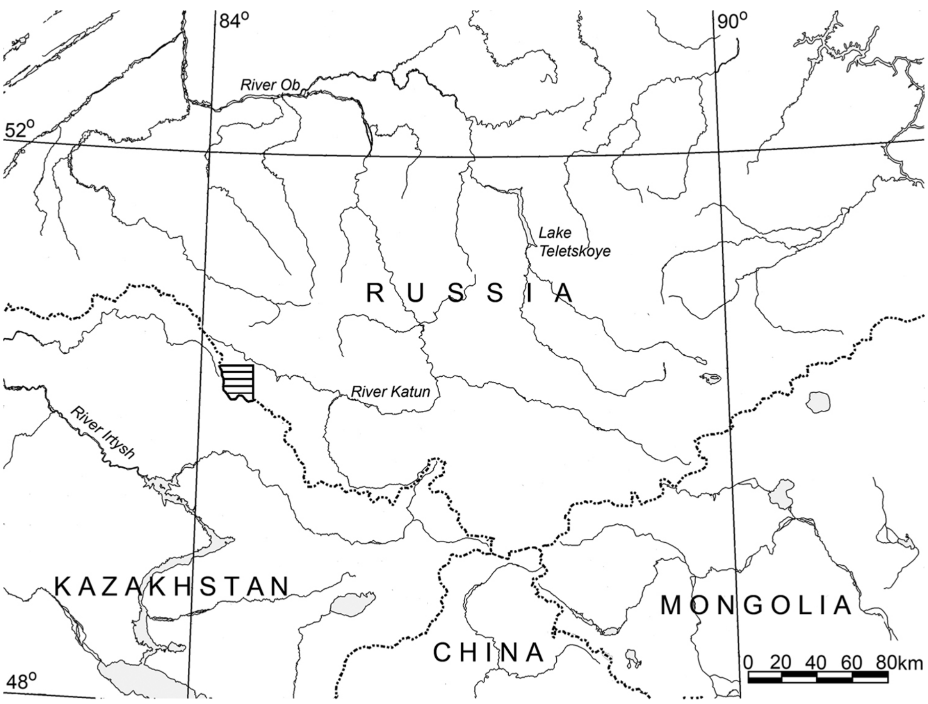

Figure 1. Study area in Central Asia.

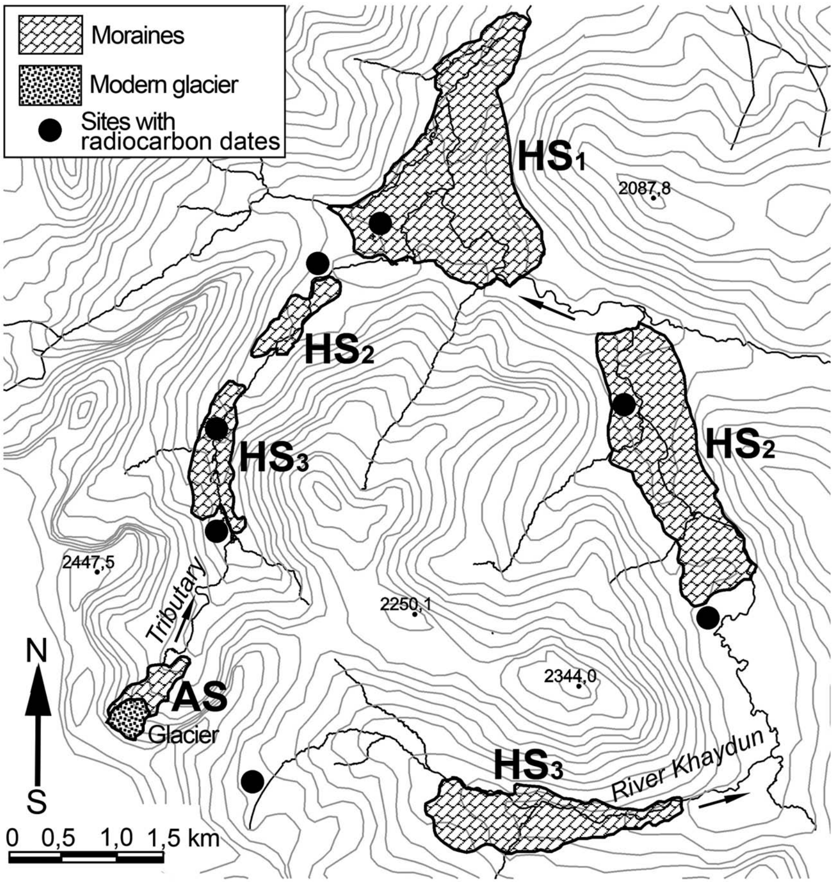

Figure 2. The sites in the Khaidun study area with radiocarbon dates.

Table 1. Some of the quantitative characteristics of the late-Holocene moraine complexes in the upper reach of River Khaidun.

	Khaidun			Tributary				
	HS_1	HS_2	HS_3	HS_1	HS_2	HS_3	AS	Glacier
Meters above sea level	1635–1750	1720–1800	1810–1940	1635–1750	1720–1780	1800–1960	2090–2180	2180–2270
Distance to a glacier or cirque, km	12.0	8.3	3.9	6.5	4.0	2.8	0.5	–
Length, km	2.0	2.2	2.0	–	1.1	1.1	0.5	0.3
Maximum width, km	1.5	0.7	0.5	–	0.3	0.3	0.3	0.3
Area, km^2	1.78	1.23	0.71	–	0.15	0.29	0.11	0.07

Table 2. Stratigraphy of a left bank swampy tributary of the River Khaidun.

Unit no.	Unit description	Depth (m)
1	Slightly decomposed light-brown peat with a considerable amount of roots, compactly bound by sedge and grass turf	0–0.04
2	Dark-brown peat	0.04–0.13
3	Solid and lamellar dark-brown peat	0.13–0.48
4	Pale yellow-grey and slightly brown silt with organic inclusion of slightly decomposed debris of herbaceous plants	0.48–0.52
5	Brown moderately decomposed peat	0.52–0.55
6	Grey dove-colored silt with inclusions of sand and gravel, small inclusion of organic matter inter-layers with more organic matter at the depths of 0.61 m and 0.71 m	0.55–0.78
7	Brown moderately decomposed peat with sand and silt inclusions	0.78–0.83
8	Sand-gravel-pebble deposits with fuzzy layering and considerable inclusion of well-preserved sedge leaves	0.83–0.95
9	Silt with inclusions of fine sand, moderately decomposed leaves of herbaceous plants, wood fragments	0.95–1.08
10	Slightly rounded large pebbly deposits	1.08–>1.20

are represented solely by some boulders and small fragments of a ground moraine. The cirque has four steps defined by well-marked terraces. From the southwestern wall of the cirque, on the surface of the upper terrace, there is a blocky ground that, most likely, was a landslip which occurred in the final phase of the glacier's degradation since its frontal wall is steep, and in the lower part the trail is absent. The wall of separation (where snow is preserved until mid-August) is well observed above this terrace. On each terrace there are tarns connected by channels. Sedge-cottongrass (*Eriophorum*) bogs and sedge-grass swampy meadows are formed on lake terraces under hydromorphic and semi-hydromorphic conditions. The wettest and previously totally occupied by a tarn is the second cirque step. The thickness of lake silt in some places reaches 0.3 m. Here, excavation revealed a profile showing swampy peat-gley soil and we obtained two radiocarbon dates from samples taken from 0.42–0.45 m depth (the onset of sedimentation) and 0.22–0.25 m depth (the onset of waterlogging and peat-depositing). The radiocarbon date for the upper sample was 240±30 (290±30 cal. yr BP) (SOAN-8223), the age of the lower one was 270±45 (375±105 cal. yr BP; SOAN-8224). These dates suggest that the glacier in the Khaidun valley either vanished at the end of the 'Medieval Warm Period' or disintegrated into some relict dead-ice fragments located in the rear part of the upper terrace and buried under the slope sediments. During the second cold period in the Aktru stage, the swamp was already forming on the lake terrace of the second cirque step (2193 m a.s.l.).

Moraine complexes of the Historical stage

In comparison with less wet parts of the Altai (Katunsky, North-Chuisky and South-Chuisky ridges), the moraines of the Historical stage of cold events are well expressed in the relief of the River Khaidun basin and all three phases are well presented (HS_1-HS_3, Figure 2).

In 2009, nearby the field camp (1740 m a.s.l.), in a Khaidun's left bank swampy tributary at the distance of 50–70 m from the bank, a 1.2 m hole was excavated, and four samples were taken for radiocarbon analysis. The stratigraphy is given in Table 2. Radiocarbon dating from the profile gave the following results listed in Table 3. The radiocarbon dates confirm that the latest phase of the Historical stage occurred 1900 years ago (for the Aktru basin it is about 300–400 years AD).

In 2010 some samples were taken, the dating of which allowed the time of the second phase of the Historical stage's cold period (HS_2) to be characterized. One of the samples from (HS_2) inter-morainal depression in the valley of the River Khaidun (1750 m a.s.l.; SOAN-8225) has a radiocarbon age of 2250±65 (2230±130 cal. yr BP). Two other samples (1780 m a.s.l.; SOAN-8227 and SOAN-8228, radiocarbon age 2200±40 [2230±110 cal. yr BP] and 2280±65 [2265±145 cal. yr BP], respectively) were taken from a bed of the open-cast with lake and marsh sediments behind this moraine complex. The stratigraphy is given in Table 4.

It should be noted that these dates mark not the period of the glacier's existence, but the period of post-degradation and the beginning of the formation of inter-morainal and drift-dammed lakes. We believe that the second phase of the Historical Stage (HS_2) took place about 2500 years ago.

The moraine of the early phase of the Historical stage (HS_1) is also well marked in the relief and it is common in the Khaidun river valley and its tributary. In 2011 an attempt to date it was made. Within the large intra-moraine depression, occupied by grass-sedge cottongrass swamp, an examination pit of 1.52 m in depth was made and the stratigraphy is given in Table 5.

Two samples were used for dating: a tree trunk from the depth of 1.45 m which gave a date of 7750±125 (8675±325 cal. yr BP; SOAN-8527) and an organic-mineral mass which included fragments of tree trunks, plant remains and bug elytra at a depth of 1.45–1.5 m which gave a date of 9400±90 (10,700±400 cal. yr BP; SOAN-8528). As we can see, these dates are much older than would be expected for HS_1. However, it should be noted that there was clear evidence of disturbance and possible inter-layer movement in this complex stratigraphic profile. At a depth of 0.91–1.02 m

Table 3. Radiocarbon dating from the profile of a left bank swampy tributary of the River Khaidun.

Depth (m)	^{14}C age (cal. yr BP)	Laboratory no.
0.52-0.55	1040±45 (1071±85)	SOAN-7831
0.78-0.83	1545±55 (1591±130)	SOAN-7832
1.05-1.08	1890±45 (1947±95)	SOAN-7833

Table 4. Stratigraphy from the lake-and-marsh surface behind the HS_2 moraine complex in the Khaidun valley.

Unit no.	Unit description	Depth (m)
1	Brown peat, penetrated by plant roots	0–0.08
2	Friable, moderately decomposed brown peat	0.08–0.18
3	Organic-mineral mass consisted of thin inter-layers of grayish dove-colored silt and peat; the layer's depth varies because of the cryoturbation	0.18–0.86
4	Soft grey-brown silt with peat inter-layers	0.86–0.94
5	Multicolored (from grey-white colored to brown) organic-mineral mass with twigs	0.94–1.26
6	Grey silt with inclusions of herb leaves	1.26–1.42
7	Moderately rounded gravel deposits	1.42–1.50

Table 5. Stratigraphy from the large intra-moraine (HS_1) depression within Khaidun River.

Unit no.	Unit description	Depth (m)
1	Brown moderately decomposed solid peat penetrated by plant roots; there is water under pressure	0–0.30
2	Brown moderately decomposed peat with inclusions of whitish grains of sand; there is no water under pressure	0.30–0.42
3	Organic-mineral mass; the mineral part is represented by dark grey dove-colored silt with inclusions of grains of sand; organic part is silt penetrated by moderately decomposed vegetable remains	0.42–0.59
4	Coarse sand-silt grey depositions with organic inclusions of herbaceous plant leaves (sedge); single pebble inclusions	0.59–0.75
5	Silt-coarse sand light grey depositions with inclusions of gravel, pebbles and organic residues (up to 10%)	0.75–0.91
6	Sandy-gravel depositions with vegetable remains (up to 10%)	0.91–1.02
7	Silty lamellar grey-white colored depositions with inclusions of vegetable remains (up to 10%); there is a peat inter-layer 5 mm thick at a depth of 1.08 m	1.02–1.15
8	Silty organic-mineral brown mass; there are numerous inclusions of tree trunks	1.15–1.30
9	Brown organic-mineral mass with numerous inclusions of pebbles and roughly rounded small boulders, and fragments of tree trunks; the amount of pebbles increases with depth	1.30–1.52

Table 6. Second part of the Holocene cool phases in the Alps and Altai.

According to research statistics	Second part of the Holocene cool phases (based on the study of the Alps and Altai)					
Alps (Wilhelm, 1975)	Piorphase (2900–2300 BC)	Lebbenschwankung (1500–1100 BC)	Gletscherkaltphase 1 (700–200 BC)	Gletscherkaltphase 2 (AD 200–700)	Aletschgletscher (AD 1200)	Fernau (AD 1600–1850)
Central Alps (Maisch et al., 1998)	Piora II (3800–3350 BC)	Löbben BC (1900–1350 BC)	Göschener I (1100–450 BC)	Göschener II (AD 350–900)	'Little Ice Age' AD 1250–1850	
Alps and Swiss Plateau (Haas et al., 1998)	CE-6 (2600–2200 BC)	CE-7 (1500–1200 BC)	CE-8 (900–400 BC)	Not considered		
Swiss Alps (Holzhauser et al., 2005)	Not considered		1000–600 BC	AD 500–600, AD 800–900 (?)	AD 1100–1200	AD 1300–1860
French NW Alps (Chapron et al., 2005)	3200 BC		800 BC	AD 400		AD 1800
Western Italian Alps (Deline and Orombelli, 2005)	Early Neoglacial (2800–2600 BC)		500 BC	AD 600–900	'Little Ice Age' (AD 1250–1860)	
SE Altai, North Chuya range (Agatova et al., 2012)	Akkem stage (2900–2200 BC)		Historical stage (300 BC–AD 300)		Aktru stage (AD 1200–1850)	
Authors' data	Akkem stage (2500–2200 BC)	HS_1 (1100 BC)	HS_2 (500 BC)	HS_3 (AD 400)	AS_1 (AD 1200–1300)	AS_2 (AD 1500–1850)

silty lake deposits are covered by a layer of sand and gravel deposits, above which there is a layer of silt again. The burial and preservation of plant remains under basal moraine in depressions is not uncommon in mountain areas. For example wood with a radiocarbon age of c. 3000 years (SOAN-5631; Galakhov et al., 2005) was found not far from the Maly Aktru glacier tongue, although this location had definitely been covered by the glacier during the Fernau stage. In the Stubai Alps, in the Tyrol, there is an interesting swamp called Bunte Moor (Mayer, 1964). Here, Mayer has noted a 'layer-cake' of peat and ground moraine. In his opinion, these deposits were formed about 1400–1300 BC. Fernauferner glacier has repeatedly buried Bunte Moor, then retreated creating a layer-cake stratigraphy. Thus there is nothing unusual in the fact that the dates obtained from the profile pre-date the beginning of the Historical stage. Nowadays we do not think of an advancing glacier as a bulldozer which has to strip off all friable deposits in depressions. The dates obtained (c. 7750 and 9400 years) are of course evidence that no glacier occurred at that time (in the early–mid Holocene) in the area under consideration.

As for the Akkem stage (as defined by Ivanovsky), the moraines are not marked in the Khaidun valley. This is probably because at that time the glacier tongue was buried in the existing lake. Therefore the dates of lake-and-marsh deposits in the Multa River basin in front of the moraine of the Akkem stage have demonstrated ages of c. 4000 years (1700 m a.s.l., 4160±150 [4875±475 cal. yr BP; SOAN-7825] and 3890±90 [4525±325 cal. yr BP; SOAN-7826]). This phase of glacier advance is dated to be c. 4500 years old.

The results of these new studies of the terminal-moraine complexes and the corresponding deposits in the valleys of the Aktru and Khaidun rivers have allowed us to expand our notions of the chronology and nature of late-Holocene cold periods in the Altai and to identify the relationship between the glacier advance in the Altai and other mountain systems, particularly in the Alps.

Table 6 presents some of the schemes of periodization of cooling and the advance of glaciers in the late Holocene based on the study of the Alps and Altai. As the table shows, the periods of glacier advance in the Altai and Alps are similar. The age of the alpine Fernau stage corresponds with the age of the Aktru stage in the Altai. We also propose that the surge of Aletschgletscher glaciers in the Alps (about 1200 years AD) corresponds to the glacier advance in Altai preceding the Fernau stage which is included in the Aktru stage. Gletscherkaltphase 2 in the Alps (200–700 years AD) corresponds with the latest phase of the Historical Stage in Altai (HS_3). Gletscherkaltphase 1 in the Alps (200–700 years BC) corresponds with the core of the Historical stage (HS_2) and the Lebbenschwankung advance in the Alps (1100–1500 years BC) corresponds to the early phase of the Historical stage in the Altai (HS_1). This stage in the Aktru basin was dated earlier not only through lichenometry, but also through the dating of lake deposits in front of the moraine of the Akkem stage (2950±120 uncal. BP, SOAN-5636). Finally we also propose that the Pior phase in the Alps (2300–2900 years BC) corresponds to the Akkem stage proper (sensu Ivanovsky).

Recent studies on the Great Aletsch and Gorner glaciers in the Alps of Valais, as well as on the Lower Grindelwald glacier in the Bernese Alps (Holzhauser et al., 2005) and Miage morainic amphitheatre (Mont Blanc massif, Italy), have shed light on glacier fluctuations during the last 3500 years. These new data are also in line with our findings.

Whilst these correlations remain provisional we believe that this study has shown that there is more correspondence between the glacial chronology of the Altai Mountains and thus Central Asia and Western Europe than had previously been thought and this has implications for climatic connections between the two regions.

Conclusion

(1) The studies received 15 new radiocarbon datings from wood remains buried by moraines, from peat layers and lacustrine sediments in the Khaidun valley at the Kholzun ridge, in the Russian Altai. Two more dates are obtained for the Mul'ta valley at the Katunsky ridge. Thus the Kholzun ridge is the second in the Altai after the North-Chuisky ridge for which the stages and phases of glacier advance in the late Holocene have been characterized in detail. It is the first time that material which separates the so-called Historical stage of cooling into three stages has been collected in the Altai Mountains.

(2) The comparison of time of moraine formation in the Altai with glacier activity in the Alps is evidence of the simultaneity of these processes. This is despite the position of these mountain systems in the areas with different continentality. The results obtained provide further evidence that the causes which led to the cool snaps in the late Holocene were global.

(3) At the same time, the dynamics of glaciation in the late Holocene against a background of weak short-term fluctuations of meteorological parameters was

largely determined by the position-geographical characteristics and the self-development of glaciers and adjacent landscapes. Even in the two adjacent valleys, the Khaidun valley and the valley of its tributary, the glacier evolution had its own peculiarities. The comparative analysis of the late-Holocene moraine complexes shows that the initially larger glacier in the Khaidun valley degraded more rapidly as compared with the one in the valley of its tributary. The main reasons are the 'failed' orientation of the Khaidun valley and its considerable width, and therefore the valley is insolated and blown better. Nowadays the glacier in the Khaidun head is not found. In the tributary valley, the glacier experienced the warming of the medieval optimum, intensified in the Aktru Stage, and remains unchanged until now despite the lower hypsometric position of the circus.

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References

Agatova AR, Nazarov AN, Nepop RK et al. (2012) Holocene glacier fluctuations and climate changes in the southeastern part of the Russian Altai (south Siberia) based on a radiocarbon chronology. *Quaternary Science Reviews* 43: 74–93.

Chapron E, Arnaud F, Noel H et al. (2005) Rhone River flood deposits in Lake Le Bourget: A proxy for Holocene environmental changes in the NW Alps, France. *Boreas* 34: 404–416.

Deline P and Orombelli G (2005) Glacier fluctuations in the western Alps during the Neoglacial, as indicated by the Miage morainic amphitheatre (Mont Blanc massif, Italy). *Boreas* 34: 456–467.

Dushkin MA (1965) Mnogoletnie kolebaniya lednikov Aktru i usloviya razvitiya molodyh moren [Long-term fluctuations of the Aktru glaciers and conditions for the development of young moraines]. *Glaciology of Alta* 4: 83–101.

Galakhov VP, Lovtskaya OV and Nazarov AN (2009) Statistichesky prognoz termicheskih izmeneniy blizhaishego buduschego (po materialam issledovaniy kolebaniy lednikov Tsentral'nogo Altaya [Statistical prediction of thermal changes in the near future (based on the studies of glacier fluctuations in Central Altai)]. *Izvestiya RGS* 141(5): 51–59.

Galakhov VP, Nazarov AN and Kharlamova NF (2005) *Kolebaniya lednikov i izmeneniya klimata v pozdnem golotsene po materialam issledovaniy lednikov i lednikovyh otlozheniy basseina Aktru (Tsentralny Altai, Severo-Chuisky hrebet)*.[Glacier Fluctuations and Climate Change in the Late Holocene Based on the Studies of Glaciers and Glacial Deposits in the Aktru Basin (Central Altai, North-Chuisky ridge)]. Barnaul: ASU Publishers.

Galakhov VP, Nazarov AN, Lovtskaya OV et al. (2008) *Hronologia teplogo perioda vtoroi poloviny golotsena Yugo-Vostochnogo Altaya (po datirovaniyu lednikovyh otlozheniy)* [Chronology of the Warm Period of the Second Part of the Holocene in the Southeast Altai (dating of glacial deposits)]. Barnaul: Azbuka Publishers.

Haas JN, Richoz I, Tinner W et al. (1998) Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. *The Holocene* 8(3): 301–309.

Holzhauser H, Magny M and Zumbuhl HJ (2005) Glacier and lake-level variations in west-central Europe over the last 3500 years. *The Holocene* 15(6): 789–801.

Ivanovsky LN (1967) *Formy lednikovogo rel'efa i ih paleogeograficheskoe znachenie na Altae*. [Glacial Relief Forms and their Paleogeographical Significance in Altai]. Leningrad: Nauka Publishers.

Ivanovsky LN, Panychev VA and Orlova LA (1982) Vozrast konechnyh moren stadiy 'Aktru' i 'Istoricheskoi' lednikov Altaya [Age of terminal moraines of the 'Aktru' and 'Historical' stages of Altai glaciers]. In: Logachev NA (ed.) *Late Pleistocene and Holocene in the South of East Siberia*. Novosibirsk: Nauka Publishers, pp. 57–64.

Krenke AN (1982) *Massoobmen v lednikovyh sistemah na territorii SSSR* [Mass Transfer in Glacier Systems in the USSR]. Leningrad: Hydrometeoizdat.

Mayer F (1964) Untersuchungen uber Ausmass und Folgen der Klima- und Gletscherschwankungen seit dem Beginn der postglazialen Warmezeit [Studies on the extent and consequences of climate and glacier fluctuations since the beginning of the post-glacial warm period]. *Zeitschrift fur Geomorphologie. Neue Folge* 8–3: 257–285.

Obruchev VA (1915) Altaiskie etyudy [Sketches of Altai]. *Geography* 4: 50–93.

Revyakin VS and Mukhametov RM (1987) Sovremennoe oledenenie Altae-Sayanskoy gornoi oblasti [Modern glaciation of Altai-Sayan mountain region]. In: Maloletko AM (ed.) *Glaciers and Climate of Siberia*. Tomsk: Tomsk State University, pp. 29–32.

Sochava VB (1946) K sovremennomu i drevnemu oledeneniyu Holzunskogo hrebta (Zapadny Altai) [On the modern and ancient glaciation of the Kholzunsky ridge (West Altai)]. *Bulletin of the Herzen Leningrad State Pedagogical Institute* 49: 164–178.

Wilhelm F (1975) *Schnee- und Gletscherkunde* [Snow and Glaciers Study]. Berlin, New-York: De Gruyter Publishers.