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Late Cenozoic Volcanism in the Baikal Rift System: Evidence for Formation of the Baikal and Khubsugul Basins due to Thermal Impacts on the Lithosphere and Collision-Derived Tectonic Stress

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Abstract

To constrain the timing of uplift and basin subsidence related to the formation of the South Baikal and Khubsugul lake basins, we present new $^{40}Ar/^{39}Ar$ and K-Ar geochronology on basalts interbedded occasionally with rift-related sedimentary rocks. Based on the new results and previous data, the late Cenozoic magmatism in the Baikal Rift System is considered to be an expression of four important thermal events in the lithosphere at 22-17 Ma, 16-12 Ma, 12-8 Ma, and 4-0 Ma. It is inferred that tectonic instability was first imparted at 22-17 Ma by a deep thermal event beneath the South Baikal basin, followed at 10-8 Ma by a similar event beneath the Khubsugul basin. These events resulted from tectonic stress associated with the Indian-Asian collision, 3000 km to the south, which was focused along a lithospheric-scale boundary, and in turn triggered upwelling of hot mantle material. Episodes of continued extension at 16-12 Ma and 4-0.6 Ma contributed to the development of the deep lake basins and also led to extensional faulting along the whole length of the rift system.

Key words: Baikal Rift System, volcanism, Baikal Basin, Khubsugul Basin, tectonic stress, K-Ar geochronology, Late Cenozoic

1. Introduction

Many large lakes occupy large intracontinental fault-bounded basins (e.g. Baikal, Khubsugul, Tanganyika, Malawi) located in tectonically reactivated areas where the lithosphere has been strongly affected by extension and associated magmatic activity. The development of rift basins is the upper crustal response to deeper lithospheric processes. In this respect, the temporal and spatial record of volcanic activity and associated faulting can provide important insight into the thermal and tectonic evolution of the lithosphere.

Two broad time intervals of magmatic activity have been recognized in the Baikal Rift System, the late Mesozoic through middle Cenozoic and the late Cenozoic. Available K-Ar dates of ca 53-26 Ma on volcanic rocks from the Western Transbaikal area (Rasskazov, 1994; Ivanov et al., 1995), related to the first (late Mesozoic through middle Cenozoic) time interval, are consistent with biostratigraphic data on sedimentary rocks interbedded with lavas. Taking into account large variations of K-Ar ages for the Paleogene and Cretaceous basalts as compared more tightly constrained $^{40}Ar/^{39}Ar$ and paleomagnetic data (Hofman et al., 1997; Bragin et al., 1999; Rasskazov et al., 2000), additional geochronological work is required to fully constrain the timing of the Paleogene volcanism in the Western Transbaikal.

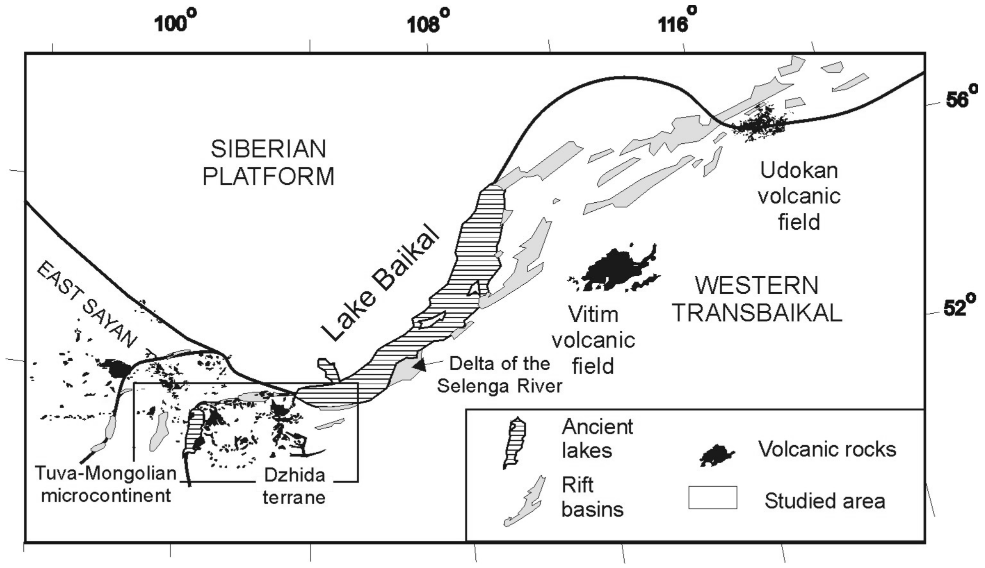

Fig. 1: Location of the late Cenozoic volcanic fields in the Baikal Rift System.

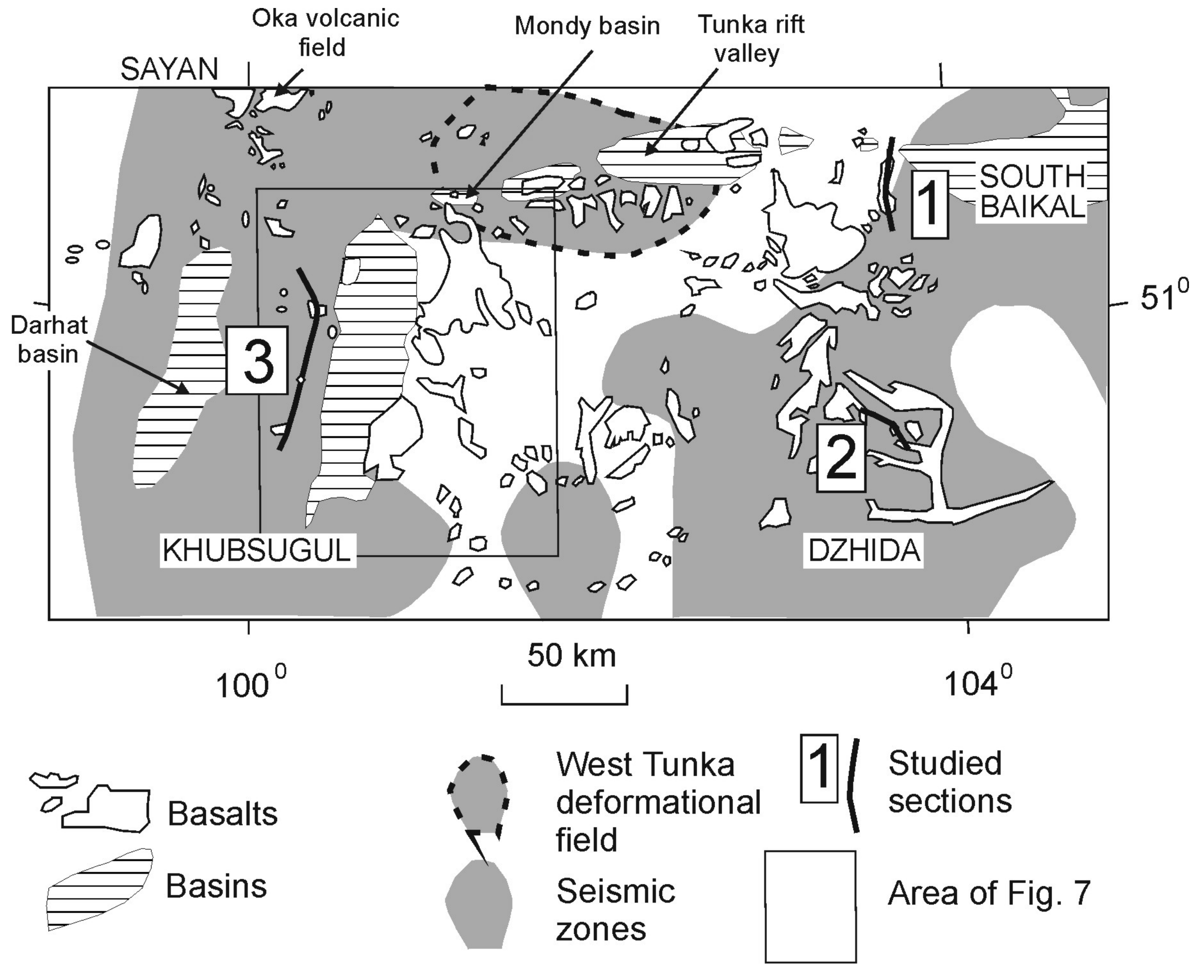

Fig. 2: Late Cenozoic basalts, basins, and seismic deformational structures in the southwestern part of the Baikal Rift System. The seismic deformational zones and the West Tunka seismic field are shown after Golenetskii (1998) and Klutchevskii & Demyanovich (2002). The line of the cross section 1 corresponds to the crest of the Khamar ridge.

Late Cenozoic volcanic rocks occur in a vast area at the southwestern end of the Baikal Rift system, as well as in smaller areas of the Vitim and Udokan volcanic fields of its northeastern part (Fig. 1). In this paper, we present geochronolgoical constraints on the evolution of the late Cenozoic rift-related volcanic activity near the Baikal and Khubsugul lake basins. The former began subsiding as early as the Paleocene and continued through the Cenozoic. The timing of the Khubsugul basin development has not been dated previously, but in general is believed to be younger than the Baikal basin (Logatchev, 2001). So far, few K-Ar and $^{40}Ar/^{39}Ar$ ages are available for the area between the two basins. This study is based on the dating of volcanic rocks from the South Baikal-Dzhida area located near the South Baikal basin and on volcanic rocks from the Lake Khubsugul area.

2. Geologic Background and Structural Control of Rifting

The Khubsugul and South Baikal lake basins spatially correspond to the eastern boundary of the Neoproterozoic Tuva-Mongolian microcontinent and the southern boundary of the Siberian Platform, respectively (Fig. 1). Between these lake basins lies the Tunka rift valley (Fig. 2). Vasilev et al. (1997) and Rasskazov et al. (2000b) have argued that the latter is located at a suture between the Tuva-Mongolian microcontinent and the Dzhida terrane, which was accreted to the former in the Early Paleozoic. If so, both the Khubsugul and Tunka rifts mark boundaries of the same microcontinent.

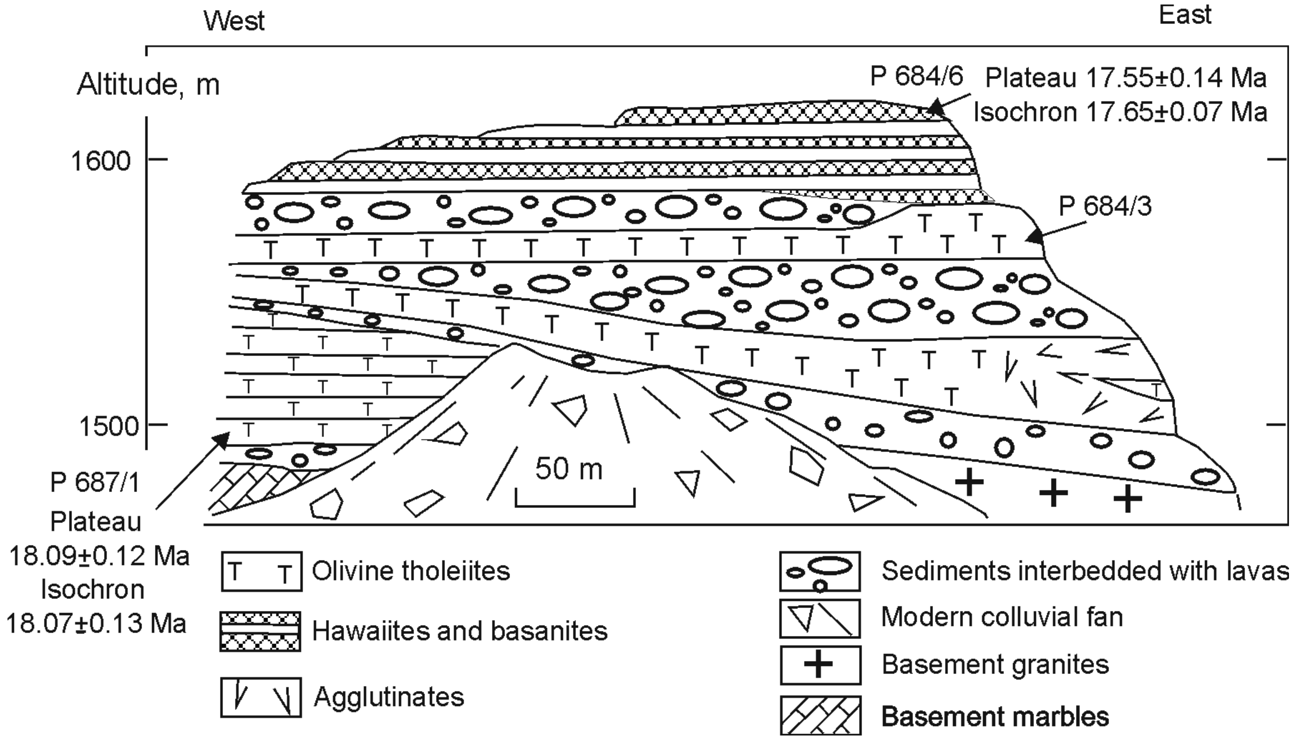

Fig. 3: Outcrop near the weather forecast station. Location is shown in the cross section 1 of Fig. 4.

The Baikal Rift system shows an irregular spatial distribution of modern seismicity. The earthquake epicenters (Golenetskii, 1998) and different focal mechanism solutions (Klutchevskii & Demyanovich, 2002) were used to distinguish both relatively small seismic fields as well as large seismic zones. One field of strong seismic activity occurs, for example, at the delta of the Selenga River. A larger seismic zone extends from this the Selenga delta southwestwards along the South Baikal Rift to the Dzhida River area. The Khubsugul basin is located in another seismic zone, which extends over a distance of 450 km from central Mongolia through the Khubsugul basin to the East Sayan mountains. A field of strong seismicity is situated in the western part of the Tunka rift valley. It is connected with the Khubsugul-Sayan seismic zone and separated from the South Baikal-Dzhida seismic zone by an area of seismic quiescence (Fig. 2).

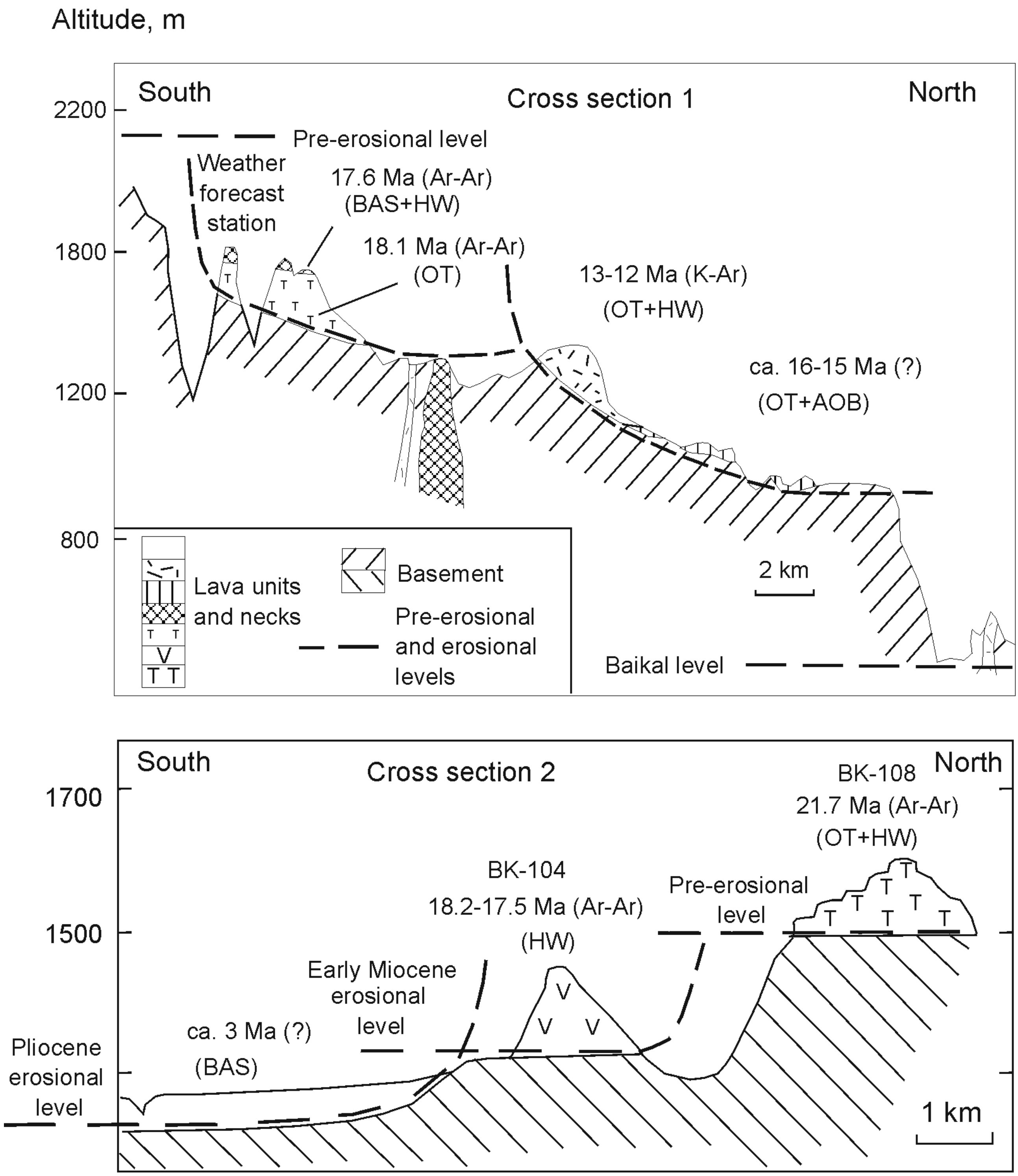

Fig. 4: Cross sections 1 and 2 (Khamar ridge and Dzhida River area). Locations of the cross sections are shown on Fig. 2. BAS – basanites, HW – hawaiites, OT – olivine tholeiites, AOB – alkali olivine basalts.

3. Volcanic sequences and $^{40}Ar/^{39}Ar$ and K-Ar ages

The studied volcanic sequences are presented along three cross sections shown on Fig. 2. In the South Baikal-Dzhida seismic zone, volcanic sequences have been studied along cross section 1 on the southwestern shoulder of the South Baikal basin (Figs. 2, 3, and 4a) and cross section 2 in the Dzhida River area (Figs. 2 and 4b). In the Khubsugul-Sayan seismic zone, volcanic rocks were studied along cross section 3 on the western shoulder of the Khubsugul basin (Figs. 2 and 5).

Volcanic rocks have been dated in laboratories of the Institute of the Earth's crust, Irkutsk, Russia (K-Ar method), the Vrije Universiteit Brussel, Brussels, Belgium ($^{40}Ar/^{39}Ar$ method), and the USGS, Reston, USA ($^{40}Ar/^{39}Ar$ method). Details of techniques used in these laboratories are described by Rasskazov et al. (2000) and Ivanov et al. (this issue). In Reston and Brussels $^{40}Ar/^{39}Ar$ laboratories, fast neutron flux was monitored using Fish Canyon sanidine (Cebula et al., 1986) and TC 85 G003, respectively. Ages of both monitors were recalculated to GA-1550 primary standard of Renne et al. (1998).

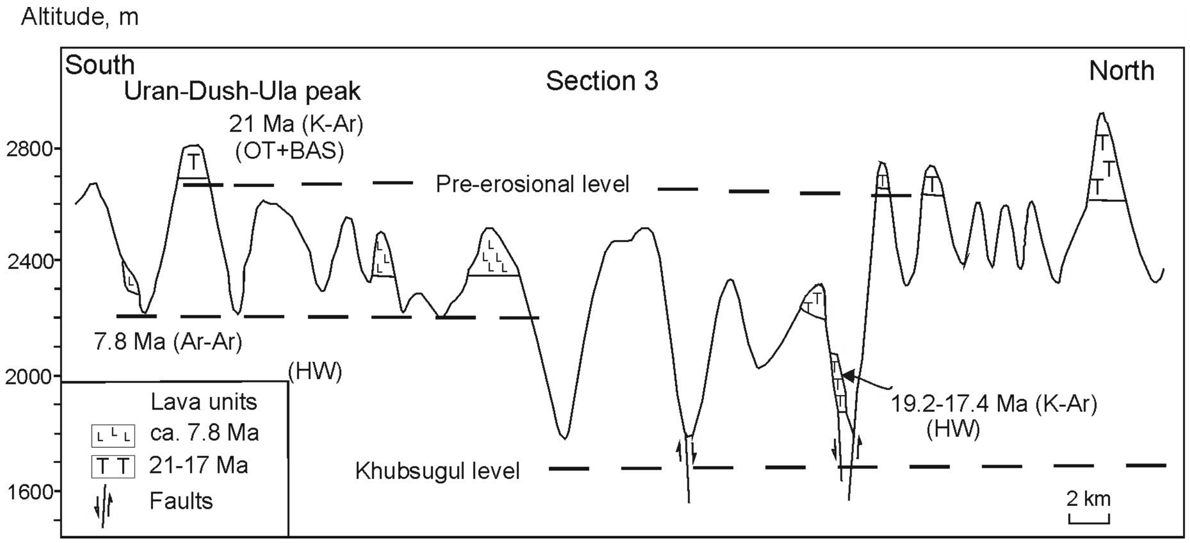

Fig. 5: Cross section 3 directed along the western shoulder of the Khubsugul basin. Location of the cross section is shown on Fig. 2. Three levels in relief are shown by dashed lines.

3.1. Cross Section 1

Fig. 3 gives details for a representative outcrop situated near the weather-forecast station at the southern end of cross section 1, shown in Fig. 4a. In the outcrop, a volcanic-sedimentary succession is capped by a unit of hawaiite and basanite lava flows. In the lower and middle parts of the outcrop, dark-gray olivine tholeiite lavas are interbedded with coarse-grained alluvial sediments. Layers of the sediments are as thick as 30 m. A local volcanic vent is marked by agglutinates. Lava flow P-687/1 from the base of the sequence (Fig. 3, coordinates: 51° 35.51'N 103° 30.5'E) has been dated in the Brussels laboratory, and yielded a $^{40}Ar/^{39}Ar$ plateau age of 18.09 ± 0.12 Ma. The isochron age is 18.07 ± 0.13 Ma (MSWD 1.1) with a $^{40}Ar/^{36}Ar$ ratio of contaminating argon component of 296.1 ± 8.8, equal to the atmospheric value. The coincidence of the plateau and isochron ages indicates high quality in the age determination (Fig. 6).

Another precise $^{40}Ar/^{39}Ar$ age has been obtained in the same laboratory for a basalt P-684/6 from the top of the same outcrop (Fig. 3). Again, the plateau age of 17.55 ± 0.14 Ma is very close to the isochron age of 17.65 ± 0.07 Ma (MSWD 1.8). The $^{40}Ar/^{36}Ar$ ratio of the contaminating component at 280.6 ± 1.2 is lower

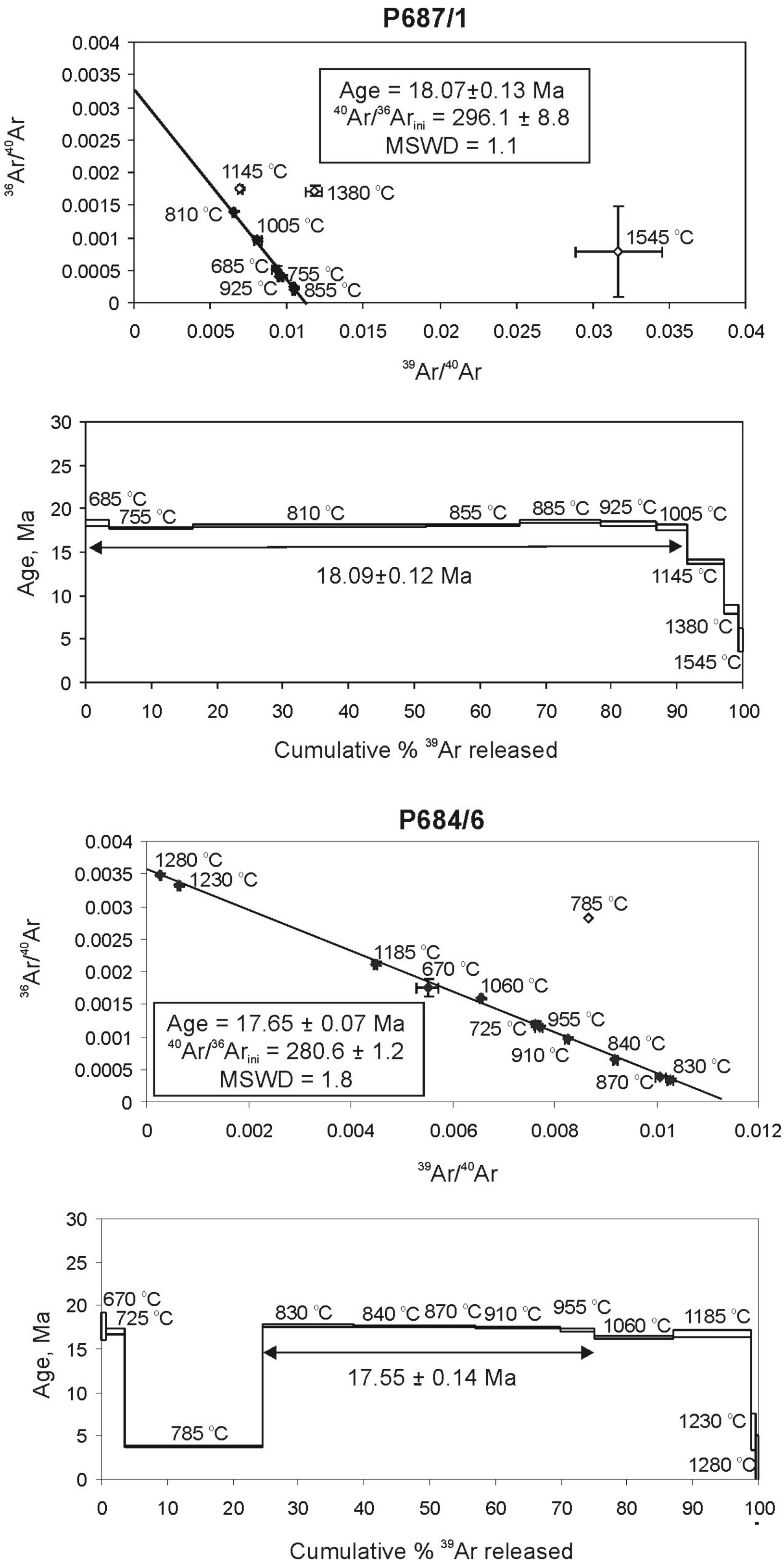

Fig. 6: Isotope-correlation and ^{40}Ar/^{39}Ar step-heating diagrams for samples P687/1 and P684/3 from the outcrop near the weather forecast station (Fig. 3). The error bars are two sigma. Open symbols in the isotope-correlation diagrams are excluded from calculations of isochrones.

than atmospheric. The ages of these two samples demonstrate that the entire volcanic sequence at the southern end of the Khamar ridge erupted during the narrow time interval of 18.1-17.6 Ma. In an attempt to determine the age of a mid-level lava in the same outcrop, a ^{40}Ar/^{39}Ar age was measured at the Brussels laboratory on a basalt P-684/3 (Fig. 3). The results obtained are less robust (not shown in Fig. 6). This sample yielded a plateau age of 17.34 $\pm$ 0.32 Ma and an isochron age of 18.18 $\pm$ 0.41 Ma (MSWD 0.75). The relatively low ^{40}Ar/^{36}Ar ratio of a contaminating component (285.4 $\pm$ 2.8) is similar to that in overlying basalt P-684/6. Although the plateau and isochron ages of basalt P-684/3 are comparable within error with those measured for samples from the base and the top of the succession, their relative imprecision provides no additional constraints on the time interval of the volcanic-sedimentary unit.

Cross section 1 extends northward from the weather-forecast station for a distance of over 10 km, exposing the 200-m thick volcanic-sedimentary succession along the crest of the Khamar ridge. At the northern end, two units are distinguished that differ compositionally from those near the weather-forecast station at the southern end (Rasskazov, 1993). At an elevation of 970-1090 m, black alkali olivine basalt and olivine tholeiite lavas occur. At the higher elevation of 1090-1310 m, dark-gray porphyritic hawaiite and olivine tholeiite lavas predominate. In the northern Khamar ridge, the upper unit was dated by K-Ar method in the Irkutsk lab to a range of 13.4-11.7 Ma (Fig. 4a). Based on lava compositions and positions in erosional paleovalleys, lavas from the lower elevation of this area appeared to be contemporaneous with lavas flooded the central part of the Tunka rift valley at 16-15 Ma (Rasskazov et al., 2000).

3.2 Cross Section 2

Cross section 2 includes three volcanic units at different elevations in the Dzhida River area (Fig. 4b). The unit of olivine-tholeiite and hawaiite lavas lies atop a flat pre-erosional level at 1500 m. It is called a “summit” unit. Sample BK-108 (coordinates: 50° 45.74N 103° 27.56E) was dated at the USGS laboratory using a plagioclase separate. The isochron age deduced from the first five steps of the age spectrum, which contain 76.3% of the ^{39}Ar released suggest an age of 21.89 ± 0.2 Ma, with an initial $^{40}Ar/^{36}Ar$ (291.2 ± 5.8) equal to that of modern-day atmospheric argon (MSWD = 0.988). The isochron age coincides within error with a plateau age of 21.86 ± 0.05 Ma (Fig. 7).

A sequence of hawaiite lavas covers an erosional surface 200 m lower than the base of the “summit” unit. The groundmass of hawiite BK-104 (Fig. 4b, coordinates: 50° 45.66'N 103° 27.57'E) was also analyzed by the $^{40}Ar/^{39}Ar$ technique at the Reston laboratory. The apparent age spectrum steps down from 20.15 to 17.58 Ma with increasing temperature of release. Inverse isotope correlation analysis of the data indicates two linear arrays. The first three steps of 60.5 % of ^{39}Ar release have an isochron age of 18.91 ± 0.17 Ma with MSWD 0.21 and an initial $^{40}Ar/^{36}Ar$ ratio 337.4 ± 8.9 significantly higher than that of modern-day atmospheric argon. The final four steps in the age spectrum define an isochron 19.25 ± 0.25 Ma with lower initial $^{40}Ar/^{36}Ar$ ratio of 219.4 ± 19.7. These four steps contain only 39.5% of the ^{39}Ar released in the age spectrum. The two isochron ages overlap within error. The first three steps reveal high K/Ca 0.68-0.87, the

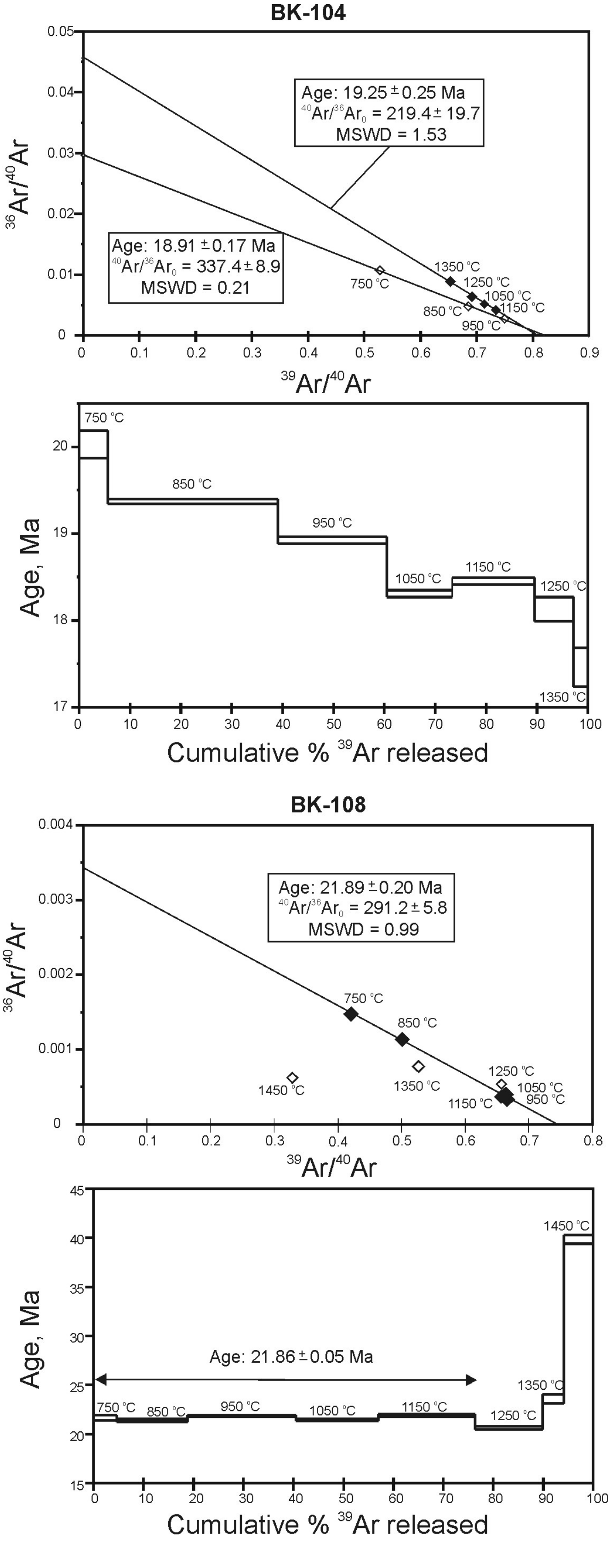

Fig. 7: Isotope-correlation and $^{40}Ar/^{39}Ar$ step-heating diagrams for samples BK-104 and BK-108 from the Dzhida River area (Fig. 4b) (explanation in the text).

final four steps demonstrate the decreasing K/Ca from 0.44 to 0.04. Therefore, a possible interpretation is that the lower temperature steps record extraction of argon from K-feldspar while the higher temperature steps record argon released mainly from plagioclase. In spite of irregular pattern of the ^{39}Ar release diagram, the overlapping isochron dates of ca. 19 Ma suggest an eruption age of around 19 Ma. Similarly, two or three distinct trapped-argon components with different initial $^{40}Ar/^{36}Ar$ but with the same age have been recognized through inverse isochron analysis of minerals and matrix from magmatic rocks elsewhere (Heizler and Harrison, 1988; Rasskazov et al., 2003). The obtained ages of the Dzhida basalts (21.9 Ma and 19.0 Ma) are older than those from the outcrop near the weather-forecast station (18.1 Ma and 17.6 Ma).

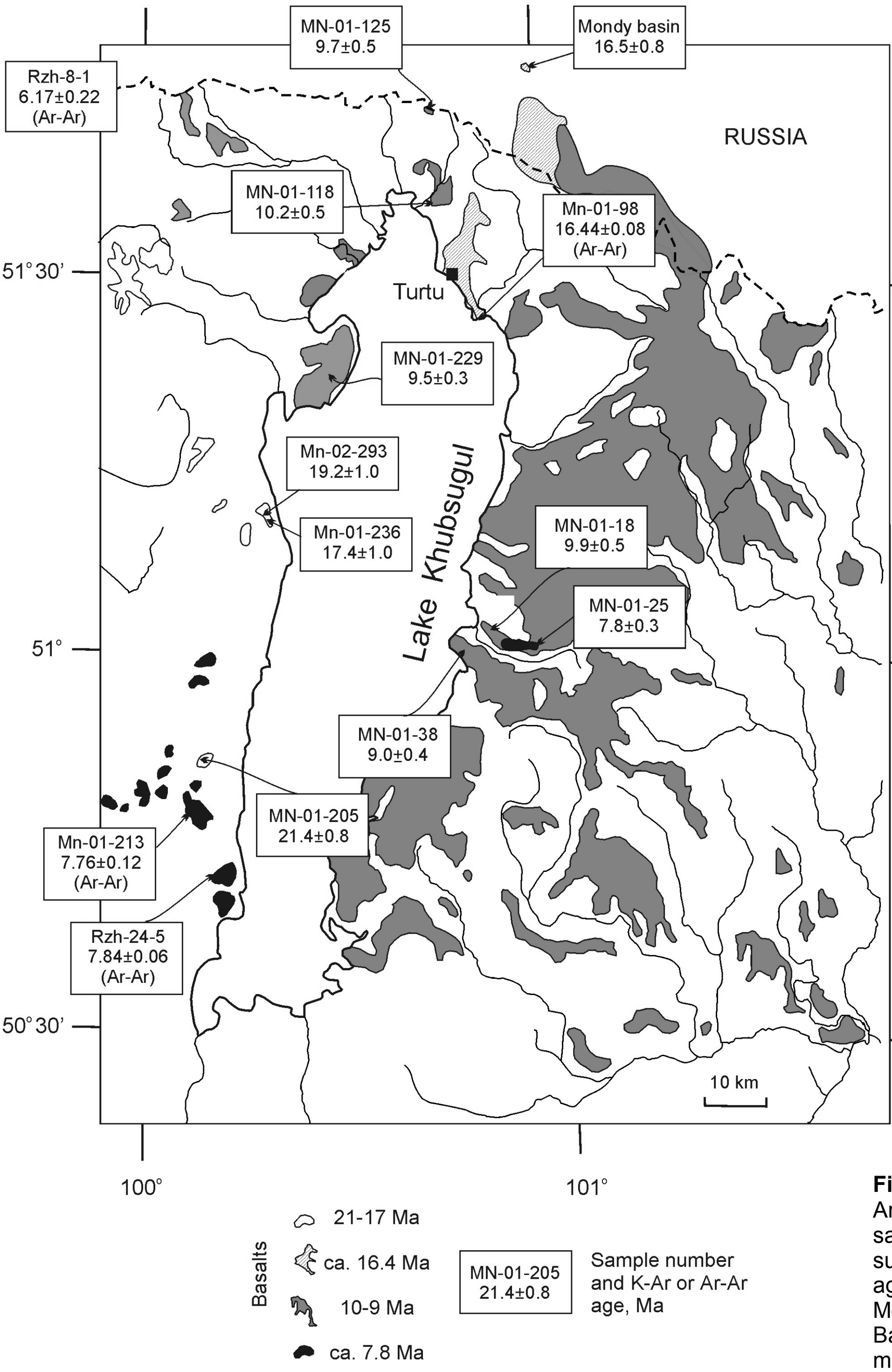

Fig. 8: Spatial variations of K-Ar and $^{40}Ar/^{39}Ar$ ages of basalts in vicinity of Lake Khubsugul. A potassium-argon age of a basalt from the Mondy basin is shown after Bagdasaryan et al. (1981). A major volcanic episode is suggested to be at 10-9 Ma.

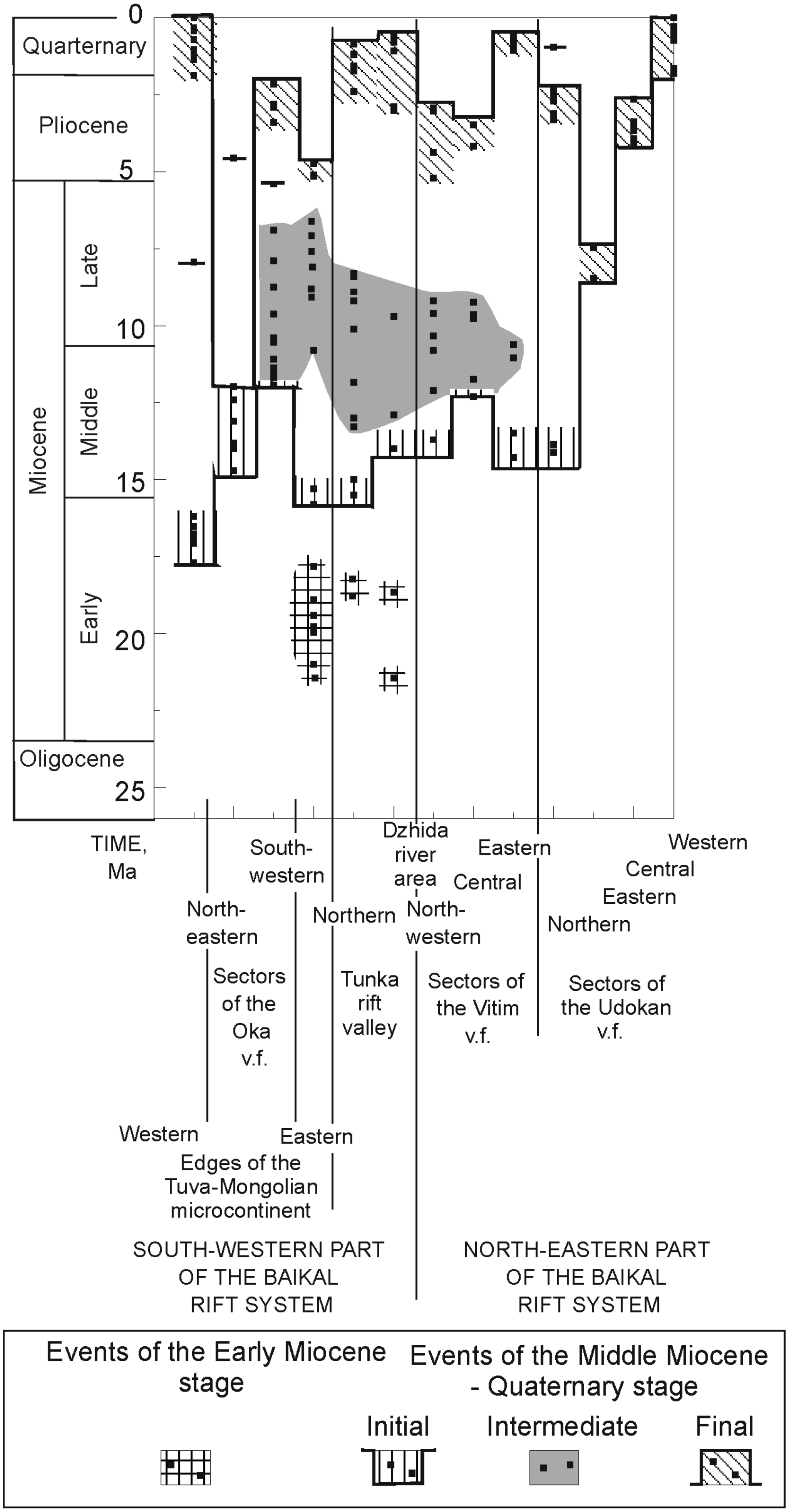

Fig. 9: Correlation of the Late Cenozoic volcanic events in the southwestern and northeastern Baikal Rift System. Modified after (Rasskazov et al., 2000). Symbols with horizontal line are individual episodes of relatively weak volcanic activity.

A volcanic unit from the lowest elevation in cross section 2 are basanite lavas that form part of the volcanic-sedimentary sequences exposed in modern river valleys. Although this basanite was not dated, we are confident that it correlates with other Pliocene-Quaternary valley-filling basanite lavas of the Dzhida River area that have been constrained by $^{40}Ar/^{39}Ar$ dating within narrow time interval from 1.2 to 0.6 Ma. Although some K-Ar ages up to 3 Ma are available (Rasskazov et al., 2000), they have not been confirmed by $^{40}Ar/^{39}Ar$ technique so far.

3.3. Cross Section 3

Two basalt-capped levels are identified on the high western shoulder of the Khubsugul basin where basalts occupy a pre-erosional levels at an elevation of more than 2600 m ("summit" unit) and an erosional level at ca. 2300 m ("valley" unit) (Fig. 5). Some basalts similar to those from the "summit" unit are found as low as 1800 m due to relative subsidence of tectonic blocks.
The oldest age of 21.4 $\pm$ 0.8 Ma (sample MN-01-205, Table 1) was obtained by K-Ar method in Irkutsk for a mantle xenolith-bearing basanite dome located on the top of Uran-Dush-Ula peak (Fig. 5). For these basanites, Ivanenko et al. (1988) reported K-Ar ages of 24.4 $\pm$ 0.5 Ma and 24.1 $\pm$ 0.6 Ma. The discrepancy between the previous and new results may reflect inhomogeneous distribution of excess argon in the xenolith-bearing rocks. Accordingly, the younger age is accepted as the preferred one. The "summit" volcanic remnants occupy mountain tops in the western shore of the Khubsugul in a distance of 40-80 km to the north of Uran-Dush-Ula peak (Figs. 5 and 8). K-Ar ages of 19.2 $\pm$ 1.0 Ma (sample MN-02-239) and 17.4 $\pm$ 1.0 Ma (sample MN-01-236) were obtained for basalts from the subsided block. No sedimentary rocks were found interbedded with the lavas.

Ivanenko et al. (1988) published K-Ar ages of 8.8 $\pm$ 0.2 and 8.1 $\pm$ 0.2 Ma obtained for the "valley" basalts sampled south of Uran-Dush-Ula peak (coordinates: 50^o 45.87'N 100^o 09.37'E). Similar age has been measured by the $^{40}Ar/^{39}Ar$ method at Brussels for a sample Rzh-24-5 taken from an outcrop situated near the lake (coordinates: 50^o 39.75'N 100^o 17.36'E). Its plateau age of 7.89 $\pm$ 0.09 is statistically identical to the isochron age of 7.84 $\pm$ 0.06 Ma (MSWD 0.93) with $^{40}Ar/^{36}Ar$ ratio of a contaminating component at 298.7 $\pm$ 2.5. Basalt MN-01-213 sampled from the upper part of the outcrop previously dated by Ivanenko et al. showed a slightly disturbed argon spectrum. Seven steps with 85% of released ^{39}Ar yielded a mean age of 7.52 $\pm$ 0.33 Ma. An isochron age of 7.76 $\pm$ 0.12 Ma (MSWD 1.8) with $^{40}Ar/^{36}Ar$ ratio of a contaminating component 292.4 $\pm$ 1.7 is within error similar to the age of sample Rzh-24-5 (7.84 $\pm$ 0.06 Ma). The latter is accepted as the most reliable age. We infer that volcanic eruptions took place at the western shore of Lake Khubsugul during a short episode of the Late Miocene at about 7.84 Ma.

The eastern shoulder of the Khubsugul basin is at a lower elevation than the western flank. Along the eastern and northern shores of the lake, basalts are found at elevations below the current water level (elevation 1645 m). Five samples from the northern and eastern shores of Lake Khubsugul dated in Irkutsk yielded K-Ar ages between 10.2 and 9.0 Ma, which are comparable to each other within error (Table 1). In the northern and eastern shores of the lake, basalts of 10-9 Ma represent volcanic remnants capped fragments of a flat relief. Having such a position, the lavas nevertheless are much younger than those of the 21-17 Ma unit from the western shore. An age of 7.8 $\pm$ 0.3 Ma was also measured for a basalt MN-01-25 sampled from the top of a volcanic sequence exposed in the eastern shore (Fig. 8).

Sample	Rock type	Coordinates	K, %	$^{40}Ar_{rad.}\times10^{-5}$, nmm^3/g	Air Ar, %	Age, Ma
MN-01-205	Basanite	50° 51.10N 100° 10.12E	1.726	144.7	66.0	21.4 ± 0.8
MN-02-239	Hawaiite	51° 11.20N 100° 19.15E	1.502	112.6	69.6	19.2 ± 1.0
MN-01-236	Hawaiite	51° 11.00N 100° 19.14E	1.320	89.8	71.4	17.4 ± 1.0
MN-01-125	Basanite	51° 41.25N 100° 41.33E	1.428	54.2	84.9	9.7 ± 0.5
MN-01-118	Hawaiite	51° 36.39N 100° 37.30E	1.779	70.9	87.4	10.2 ± 0.7
MN-01-229	Hawaiite	51° 23.65N 100° 25.90E	1.679	61.9	47.3	9.5 ± 0.3
MN-01-38	Olivine tholeiite	51° 00.39N 100° 42.27E	1.162	40.8	74.3	9.0 ± 0.4
MN-01-18	Olivine tholeiite	51° 04.49N 100° 43.23E	1.256	48.3	81.5	9.9 ± 0.5
MN-01-25	Olivine tholeiite	51° 03.38N 100° 46.26E	1.311	39.7	74.3	7.8 ± 0.3

Table 1: New K-Ar ages of volcanic rocks from the Khubsugul area: Constants: $\lambda_K = 0.581\times10^{-10}$ year^{-1}; $\lambda_\beta = 4.962\times10^{-10}$ year^{-1}; ^{40}K = 0.01167 at.% K. Location of samples is shown in Fig. 8.

In the northeastern part of the Khubsugul area, a lava flow from the top of the cliff situated southeast of Turtu settlement has been dated by the $^{40}Ar/^{39}Ar$ technique in Brussels (sample MN-01-98, coordinates: 51° 27.37'N 100° 41.97'E). A plateau age of 16.44 ± 0.08 Ma comprises 8 steps with 85% of released ^{39}Ar and overlaps with the isochron age of 16.41 ± 0.09 Ma is calculated with $^{40}Ar/^{36}Ar$ 297.1 ± 1.7 and MSWD 0.72. The age obtained is comparable to the K-Ar age of 16.5 ± 0.8 Ma reported previously by Bagdasaryan et al. (1981) for a basaltic lava from the Mondy basin, located 40 km to the north (Fig. 8). These two dated samples are both well-crystallized basalts that may belong to a single volcanic unit with an original extent at least as great as their current separation distance.

The youngest age yet determined for the Lake Khubsugul area is a new $^{40}Ar/^{39}Ar$ measurement performed in Brussels on sample Rzh-8-1 (coordinates: 51° 43.36'N 99° 40.10'E), from northwest of the northern lake tip. Its plateau age of 6.17 ± 0.06 Ma is identical to the isochron age of 6.17 ± 0.22 Ma (MSWD 0.82) with exactly the atmospheric $^{40}Ar/^{36}Ar$ ratio of 295.0 ± 1.4 as a contaminating component. Other young basalts in the range of 6.9-2.2 Ma are known to the northwest of the Khubsugul area, in the southern part of the Oka volcanic field (Fig. 2) (Rasskazov et al., 2000; 2000a).

4. Discussion

A synthesis of all available K-Ar and $^{40}Ar/^{39}Ar$ ages for basalts in the Baikal Rift system by Rasskazov et al. (2000) revealed four main stages of volcanic activity: (1) Early Miocene at 22-18 Ma (extended to 17 Ma), (2) Middle Miocene at 16-12 Ma (extended to 17 Ma), (3) Late Miocene at 12-8 (extended to 13.5 Ma and 7 Ma), and (4) Pliocene-Quaternary at the last 5-4 Ma (Fig. 9). These volcanic intervals are considered to be a reflection of four separate episodes of lithospheric extension and mantle magmatism.

Spatial separation of seismic zones at the western and eastern ends of the Tunka rift valley indicates that the South Baikal and Khubsugul basins have no tectonic present-day connection. Seismicity in the South

Baikal-Dzhida and Khubsugul-Sayan zones may represent short-term tectonic activity. A character of a changeable structural development of the southwestern Baikal Rift system can be demonstrated through a distribution of the volcanic activity in space and time.

4.1. Early Miocene and Late Miocene magmatism

Analysis of all geochrobological data show that initial volcanism in the South Baikal and Khubsugul took place simultaneously at 22-17 Ma, but then volcanic activity in each area was distinctly different. Volcanic eruptions lasted near the South Baikal until 12 Ma. At a structural junction between the Khubsugul basin and Tunka rift valley, a particular volcanic event occurred at the Early-Middle Miocene boundary (ca. 16.4 Ma) (Figs. 2, 8), but afterwards volcanism ceased. Its rejuvenation along the whole length of the Khubsugul began during the Late Miocene at 10-9 Ma.

Southwest of Lake Baikal, a flat pre-erosional surface could exist until the Early Miocene. In the Dzhida River area, lavas covered this surface at 22-21 Ma. The uplift and erosion was initiated before the volcanic episode of 19 Ma. Closer to the South Baikal, basaltic eruptions were accompanied with intensive erosional processes and accumulation of sediments in deep paleovalleys at 18.1-17.6 Ma (Fig. 4). Unlike the South Baikal, no direct evidence is available for any erosional events in the Khubsugul between 22 and 10 Ma. Uplift and erosion could begin only between 10 and 7.8 Ma. A similar scenario was suggested previously for adjacent area of the southern Oka volcanic field, where basalts occupied a pre-erosional level at 8.7 Ma and infilled erosional paleovalleys at 6.9-2.8 Ma (Rasskazov et al., 2000a). We infer, that although lava eruptions were widespread both in the South Baikal and Khubsugul between 22 and 17 Ma, tectonic reactivation, uplift, and erosion was delayed in the Khubsugal until 9-8 Ma (Fig. 10).

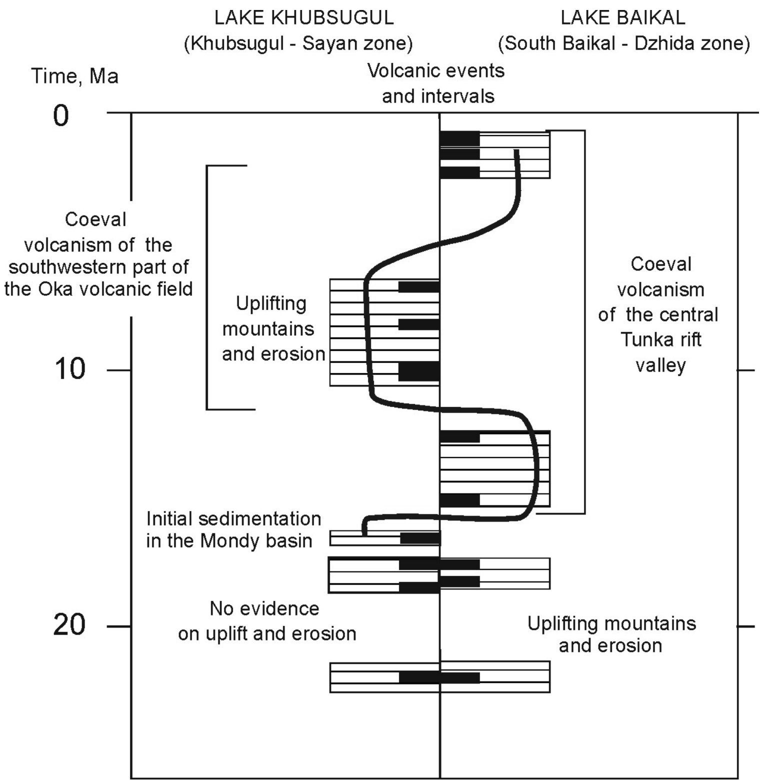

Fig. 10: Comparisons of volcanic events related spatially to the South Baikal and Khubsugul basins. Intervals of volcanic activity in the southwestern Oka volcanic field and in the central part of the Tunka rift valley are shown after (Rasskazov et al., 2000).

Late Miocene lava eruptions took place in the Hannuoba province of China, northeastern Shanxi Rift System. The volcanic interval between 8.8 and 5.8 Ma accompanied a reactivation of the SSW-NNE-trending Fen-Wei rift. The latter developed due to increasing influence of the Indian-Asian collision and anticlockwise rotation of the Precambrian Ordos massif and its motion in the NNE-direction (Xu et al., 1996). Volcanic episodes of 7.8 Ma and 6.2 Ma in Lake Khubsugul fall within this time interval. Potassium-argon age of ca. 7 Ma was measured also for a basalt from the Teciin-Gol volcanic field located 100 km southwest the southern end of Lake Khubsugul (Ageeva et al., 1988). So, similar to the Shanxi Rift System, the volcanic activity of 9-6 Ma in the Khubsugul could reflect increasing Indian-Asian collision-derived tectonic stress in Inner Asia.

We speculate that the 10-9 Ma voluminous lava eruptions around the Khubsugul were an important expression of extension and magmatism within the lithospheric mantle - a precursor to strong increasing tectonic stress in the crust and subsiding the Khubsugul basin. Similar mechanism of the initial thermal disturbance of the lithospheric mantle and the following manifestation of a collision-derived tectonic stress in the crust might be responsible also for development of the South Baikal basin between 22 and 17 Ma. The Early Miocene and Late Miocene thermal impacts caused extension of N-S and NE-SW trending weak zones in the lithosphere satisfied in orientation to increasing influence of Indian-Asian collision.

5.2. Middle Miocene and Pliocene-Quaternary magmatism

Unlike the Early Miocene volcanism, which was localized in the southwestern part of the Baikal Rift system, the Middle Miocene volcanism was distributed along the whole its length (Figs. 1, 9). The cross section of Fig. 4 exhibits a sufficient uplift and erosion between 17.6 and 16-15 Ma in the Khamar ridge area, where the Middle Miocene erosional level was 400 m lower than the Early Miocene. Coeval Middle Miocene volcanic sequences were recorded within deep paleocanyons in the central part of the Tunka rift valley as well as in volcanic fields of the Vitim and Oka plateaus (Rasskazov, 1993; Rasskazov et al., 2000).

In the Pliocene and Quaternary, lava eruptions occurred along the whole length of the Baikal Rift system. In the central part of the Tunka rift valley, volcanism began at 4 Ma contemporaneously with volcanic rejuvenation in the Udokan and Vitim volcanic fields. Taking into consideration no eruptions younger than 0.6 Ma in the Tunka-Dzhida area, the whole duration of the Pliocene-Quaternary extensional event is constrained between 4 and 0.6 Ma.

Similar to thermal events at 22-17 Ma and 10-6 Ma, the lithospheric extension at 16-12 Ma and 4-0.6 Ma is responsible for development of the deep lake basins, although extensional faulting and volcanism were dispersed along the whole length of the rift system. We suggest that rifting occurred in the Middle Miocene and Pliocene-Quaternary when influence of collision was negligible. As a result, new zones of weakness reactivated.

5.3. Volcanic Evolution of the Tunka Rift Valley

Collision-related and non-collisional magmatism are well manifested along the Tunka rift valley, which was developed between the Khubsugul-Sayan and South Baikal-Dzhida seismic zones during periods of reorientation of regional stress regimes.

The east-west orientation of the Tunka weak zone did not accomodate extension and volcanism at the initial collision-related Early Miocene thermal impact. A short volcanic event corresponding to transition from collisional to non-collisional stage took place at a structural junction between the Khubsugul basin and the Tunka rift valley at 16.4 Ma. Then, at 16-12 Ma, lava eruptions concentrated in an area between the South Baikal and the central part of the Tunka rift valley in the non-collisional conditions.

Due to increasing of intensity of collision-related deformation, volcanism was rejuvenated in the Khubsugul in the Late Miocene, at 10-6 Ma. Afterwards, lava eruptions did not occur in the Khubsugul but began again in the South Baikal-Dzhida area in the Pliocene-Quaternary, between 4 and 0.6 Ma (Fig. 10). Volcanism took place in non-collisional conditions. During the last 0.6 Ma, however, intraplate volcanic activity was strongly affected by increasing collision-derived stress (Rasskazov et al., 2000). Table 2 demonstrates important collision-related volcanic events in the Khubsugul at 16.4 Ma and 10-6.1 Ma and non-collisional events in the South Baikal-Dzhida area at 16-12 and 4.0-0.6 Ma.

Volcanic interval or episode, in Ma	Khubsugul – Sayan deformational zone (Khubsugul basin)	Tunka rift valley	South Baikal – Dzhida deformational zone
22-17	+	-	+
16.4	+	+	-
15-11	-	+	+
10-7.8	+	+	-
3-0.6	-	+	+
<0.6	-	-	-

(+) and (-) mean reactivation and quiescence of volcanism, respectively.

Table 2: Development of the Tunka rift valley in connection with activity of the Khubsugul – Sayan or South Baikal – Dzhida deformational zones as inferred from temporal evolution of volcanism

6. Conclusions

Both the Baikal and the Khubsugul ancient lake basins located at structural boundaries of Precambrian blocks. These zones of weakness allowed focusing of extensional stress in the lithosphere. Volcanic evolution in the Baikal Rift system indicates important thermal events in the lithosphere at 22-17 Ma, 16-12 Ma, 12-8 Ma, and 4-0.6 Ma. The events of 22-17 Ma and 10-8 Ma caused tectonic instability of the lithosphere, uplift and basin subsidence resulted in formation of the Baikal and Khubsugul lake basins, respectively. Extensional forces were concentrated in the lithosphere due to both upwelling of hot mantle material and a superimposed Indian-Asian collision-related tectonic stress. The magmatic episodes at 16-12 Ma and 4-0.6 Ma reflect extension along the whole length of the rift system.

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