

Upper Age Boundary of the Accretion of Terranes in the Northwestern Part of the Eastern Segment of the Central Asian Foldbelt

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Received November 8, 2006

DOI: 10.1134/S1028334X07040137

Different concepts have been proposed for the sequence and character of the accretionary and collisional processes during formation of mosaic structures in the northwestern part of the eastern segment of the Central Asian Foldbelt (CAFB) framing the Siberian Craton [1–5]. According to one of the latest models [1], these events started with the formation of the accretionary Caledonian superterrane, which was later softly amalgamated to the craton along the strike-slip boundary [1]. The large-scale accretion of different terranes and their collision with the craton are traditionally considered as nearly simultaneous processes. However, it is suggested that individual terranes were preliminarily amalgamated or accreted into large tectonic units (composite terranes) [2]. The upper age boundary of the accretionary–collisional processes is determined with great uncertainty (450–490 Ma) [1, 3, 4]. According to different data, the formation of the accretionary–collisional mosaic structure of the considered part of the CAFB beginning from amalgamation of individual tectonic units to accretion with the Siberian Craton continued from the Cambrian to terminal Ordovician or initial Devonian [1, 4, 5].

The upper age limit of the amalgamation or accretion of certain terranes can be reliably constrained by the age of the overlying and (or) crosslinking complexes. In the considered part of CAFB, such complexes are represented by the Munkusardyk granitoid massif located southeast of the eastern Sayan–Northern Khubsugul area. The massif intrudes rocks of the

Khamardaban, Tunka, and Tuva–Mongolia terranes at their junction (Fig. 1).

The Munkusardyk Massif is mainly composed of medium- to coarse-grained biotite and biotite–hornblende tonalite, trondhjemite, and granodiorite, which show gradual transitions. These granitoids are characterized by a gneissic or coarse-banded structure, which is most expressed near the contacts of massifs and is parallel to them. All granitoids have a hypidiomorphic granular or granitic texture, while subhedral plagioclase often has reverse zoning. All features indicate the magmatic origin of directive structures. The granites lack signs of superimposed structural–metamorphic reworking.

It should also be noted that the Munkusardyk Massif is crosscut by numerous granite veins of at least four texture and age groups ranging from the oldest fine-grained plagiogranites to light gray and pink fine-grained microcline-rich granites, aplites, and pegmatoid granites. The thickness of vein bodies is typically no more than 0.5–2 m.

At significant variations of the SiO₂ content (from 63 to 73 wt %), total alkalis (5.75–7.66 wt %), K/Na ratio (0.32–0.86), and color index (from 3–5 to 15–20), the figurative points of the tonalites, trondhjemites, and granodiorites of the Munkusardyk Massif are grouped into compact fields in different petrochemical diagrams. In terms of the Al₂O₃ content (>15 wt %), they are peraluminous rocks with the corresponding geochemical features [6]. They are characterized by low HREE contents, a high (La/Yb)_n ratio (30–51), the virtual absence of an Eu anomaly ((Eu/Eu*)_n = 0.79–1.17), and very high contents of Ba (710–1800 ppm) and Sr (320–1717 ppm). In terms of geochemical features, such as elevated CaO and Sr contents, lowered K₂O and Rb contents, and CaO–alkali–Al₂O₃ proportions, the tonalites, trondhjemites, and granodiorites of the considered massif correspond to type I granitoids.

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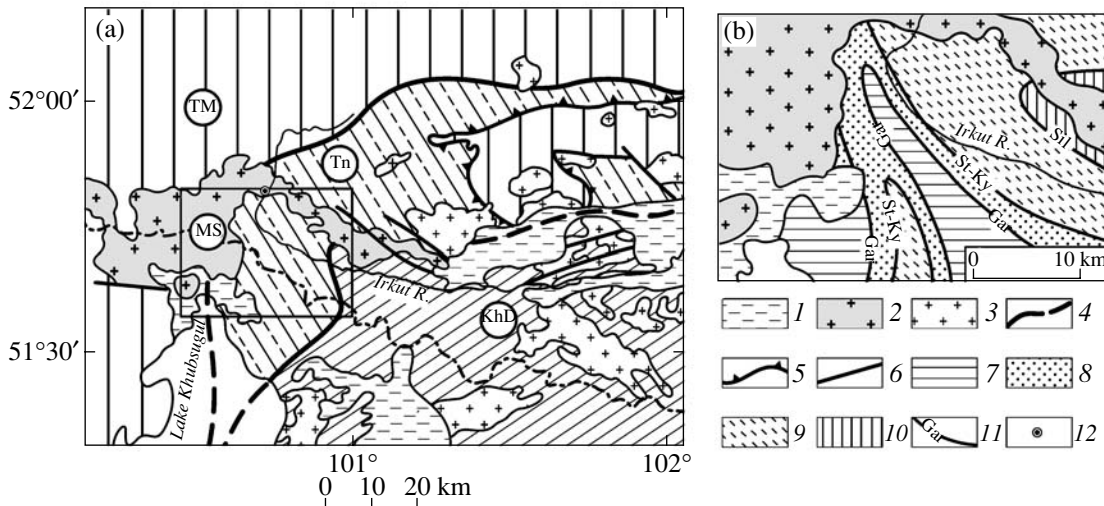


Fig. 1. (a) Geological position of the Munkusardyk Massif and (b) relations of its contacts with metamorphic zoning. (1) Cenozoic basalts and Quaternary deposits; (2) granitoids of the Munkusardyk Massif; (3) other Paleozoic granitoids; (4) boundaries of terranes; (5) tectonic window; (6) faults; (7–10) metamorphic zones: (7, 8) biotite–chlorite and almandine–chlorite subfacies, respectively, of the greenschist facies, (9, 10) kyanite–staurolite–biotite and sillimanite–staurolite–biotite subfacies, respectively, of the staurolite facies; (11) metamorphic isogrades: (Gar) garnet, (St–Ky) staurolite and kyanite, (Sil) sillimanite (fibrolite); (12) locality of sample THA-16. (MS) Munkusardyk granitoid massif; terranes: (TM) Tuva–Mongolia, (Tn) Tunka, (KhD) Khamardaban.

In the spider diagrams, they demonstrate distinct Ti, Nb, and Ta minimums.

The aforementioned terranes of CAFB are described in detail in [5]. In composition and rock associations of premetamorphic protoliths, the Tunka and Khamardaban terranes are most similar to the fragments of island-arc systems, in particular, back-arc basins. The Tuva–Mongolia terranes, which have a two-unit structure (heterogeneous Precambrian basement and subplatformal Vendian–Cambrian sedimentary cover), existed as a microcontinent prior to incorporation into collisional–accretionary mosaics of the CAFB. The Tunka and Khamardaban terranes were affected by zonal metamorphism of a wide range of facies.

In the Tunka Ridge area, the metamorphic isogrades intersect the Vendian–Cambrian cover of the Tuva–Mongolia terrane [8, 9]. Thus, zoned metamorphism occurred after or in the course of accretion of the considered terranes.

The massif is situated in a relatively low-grade area with lower greenschist to moderate-temperature amphibolite facies (from biotite–chlorite to sillimanite–staurolite–biotite subfacies after metapelites). The absence of a contact effect of the granites on the host rocks at the present-day erosion level allowed us to trace the metamorphic isogrades up to the massif boundary (Fig. 1b, inset). Distinct intrusive contacts of the massif with metamorphic rocks and preservation of magmatic granitic textures unambiguously indicate its postmetamorphic formation. Thus, the geochronological dating of the Munkusardyk Massif makes it possible to constrain the upper age boundary of the accretion

and metamorphism in the terranes of the analyzed segment of CAFB.

According to different studies, the estimates of the age of the Munkusardyk Massif range from Upper to Middle Paleozoic and even Mesozoic. In the 1980s, most researchers supported the Early Paleozoic (Ordovician–Silurian) age based on the Rb–Sr whole-rock dating (452 ± 16 Ma) [7]. However, this isochron was based on major rock types of the granitoid massif and cross-cutting vein granites, making interpretation somewhat incorrect.

We conducted more accurate dating of the Munkusardyk Massif using the U–Pb zircon method. Zircon was separated from the typical rock of the massif represented by melanocratic granodiorite (sample THA-16, Table 1).

Zircon in this sample is represented by euhedral to subhedral transparent, rarely semitransparent or turbid colorless, light pink, and pinkish yellow thinly zoned crystals of long-prismatic and prismatic habit (Fig. 2, inset). The turbid grains contain fractured metamict cores of irregular or prismatic shape with dissolution traces, which are surrounded by transparent zoned rims with high birefringence. The crystals occur as prism {100}, {110} and bipyramid {101}, {111}, {211}. The grain size varies from 50 to 300 μm ($K_{\text{el}} = 2.5\text{--}3.0$).

Five aliquots of the most transparent and euhedral zircons were taken from $-100+85$ and $-150+100$ μm fractions for U–Pb geochronological dating (Table 2). Table 2 and Fig. 2 show that zircon from the $-100+85$ μm fraction has a concordant age of 479 ± 2 Ma (MSWD = 1.2, probability 0.28), while zircon from the

Table 1. Chemical (wt %) and trace-element (ppm) composition of granodiorite THA-16

Component	Content	Component	Content	Component	Content
SiO ₂	62.26	U	1.86	Cr	57
TiO ₂	1.02	Th	9.12	V	150
Al ₂ O ₃	16.55	Li	55	Ni	51
Fe ₂ O ₃	1.19	Rb	86	Co	15
FeO	3.86	Ba	1400	Sc	12
MnO	0.06	Sr	1100	La	63.46
MgO	2.51	Ta	1.01	Ce	115.78
CaO	4.80	Nb	15.57	Pr	11.34
Na ₂ O	4.24	Y	14.63	Nd	41.88
K ₂ O	2.45	Zr	244.33	Sm	7.36
P ₂ O ₅	0.35	Hf	5.29	Eu	1.74
L.O.I.	0.82	Be	3	Gd	4.36
F	0.08	Cu	61	Tb	0.52
Total	100.19	Zn	510	Yb	1.05
		Pb	11	Lu	0.15

Note: The content of major oxides was determined by chemical analysis (G.V. Bondareva, analyst); trace elements were analyzed by emission spectroscopy and ICP-MS (V.V. Shcherban, L.V. Vorotynova, S.V. Panteeva, and V.V. Markova, analysts). The analyses were made at the Analytical Center of the Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences.

–150 + 100 μm fraction is weakly discordant (discordance degree 1–2%). Given the magmatic origin of the studied zircon, its average ²⁰⁷Pb/²⁰⁶Pb age of 481 ± 2 Ma (MSWD = 0.81) can be taken as the most accurate crystallization age of the granitoids of the Munkusardyk Massif.

The model Sm–Nd age of the granitoids is 1.8 Ga ($\epsilon_{\text{Nd}}(T) = -7.1$). The initial ⁸⁷Sr/⁸⁶Sr ratio is close to 0.705 [7].

The Early Proterozoic Sm–Nd model age and low ϵ_{Nd} value testify to the significant contribution of the ancient continental crust, possibly from deep-seated horizons of the basement of the Tuva–Mongolia microcontinent. The melting could be initiated by the accretion of terranes, as is inferred for the Caledonian magmatism in huge areas of the CAFB [2, 3]. In this case, the interval between metamorphism and emplacement of the Munkusardyk granitoids could be insignificant.

It should be noted that, according to some data [5], zoned metamorphism of the Khamardaban and Tunka terranes also occupied the adjacent southern region of the Dzhida island-arc terrane. Hence, its amalgamation with the Khamardaban terrane predated the emplacement of the Munkusardyk Massif.

Thus, the Munkusardyk Massif is the crosslinking complex, which intrudes the Tuva–Mongolia, Tunka, and Khamardaban terranes. This massif is discordant relative to metamorphic zoning, which embraces the aforementioned terranes and northwestern part of the

Table 2. Results of U–Pb isotopic studies of zircons from the Munkusardyk Massif (sample THA-16)

Ordinal no.	Size (μm) and characteristics of fraction	Sample, mg	Content, $\mu\text{g/g}$		Isotope ratios		
			Pb	U	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb ^a	²⁰⁸ Pb/ ²⁰⁶ Pb ^a
1	–100 + 85	1.11	31.7	386	5024	0.0565 \pm 1	0.1808 \pm 1
2	–150 + 100	0.93	59.5	715	6734	0.0568 \pm 1	0.2099 \pm 1
3	–150 + 100	1.25	57.2	687	10291	0.0567 \pm 1	0.2088 \pm 1
4	–150 + 100	1.86	58.5	705	10424	0.0567 \pm 1	0.2056 \pm 1
5	–150 + 100	1.75	52.8	634	10653	0.0567 \pm 1	0.2094 \pm 1
Ordinal no.	Size (μm) and characteristics of fraction	Isotope ratios		<i>Rho</i>	Age, Ma		
		²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U		²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb
1	–100 + 85	0.6012 \pm 12	0.0771 \pm 1	0.86	478 \pm 1	479 \pm 1	474 \pm 2
2	–150 + 100	0.5943 \pm 12	0.0759 \pm 1	0.93	474 \pm 1	472 \pm 1	482 \pm 1
3	–150 + 100	0.5960 \pm 12	0.0762 \pm 1	0.95	475 \pm 1	473 \pm 1	482 \pm 1
4	–150 + 100	0.5950 \pm 12	0.0762 \pm 2	0.92	474 \pm 1	473 \pm 1	478 \pm 1
5	–150 + 100	0.5960 \pm 12	0.0762 \pm 1	0.96	475 \pm 1	473 \pm 1	481 \pm 1

Note: (a) Isotope ratios were corrected for procedure blank and total lead. The errors correspond to the last significant digits. Accessory zircons were separated using the standard heavy liquid technique. The chemical decomposition of zircons and extraction of U and Pb were made using a modified Krogh technique [1]. Isotope analysis was conducted on a Finnigan MAT-261 mass spectrometer. The measurement accuracy of U and Pb contents was 0.5%. The procedure blank was no more than 0.1 ng for Pb and 0.005 ng for U. Experimental data were processed with the PbDAT [11] and ISOPLOT [12] programs. Ages were calculated using generally accepted U decay constants [13]. Common lead was corrected in accordance with model values [14]. All errors are given at the 2 σ level.

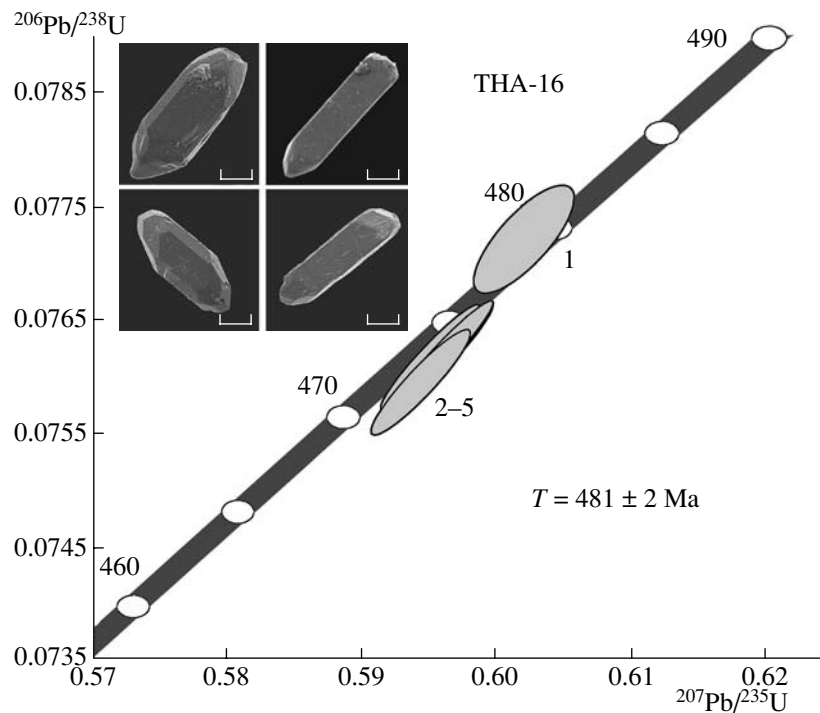


Fig. 2. Concordia diagram for zircons from the granodiorite of the Munkusardyk Massif. The number of data points corresponds to the ordinal numbers in Table 2. Inset shows microimages of zircons from sample THA-16. The scale is 33 μm .

Dzhida terrane. The age of the Munkusardyk granitoid massif (481 ± 2 Ma) defines the upper age limit of the accretion and metamorphism of the terranes of the CAFB.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 04-05-64320) and the Division of Earth Sciences of the Russian Academy of Sciences (programs "Isotope Systems and Isotope Fractionation in Natural Processes" and "The Central Asian Foldbelt: Geodynamics and Formation Stages of the Earth's Crust").

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