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GEOLOGY

Late Cenozoic Volcanism at the Northeastern Flank of the South Khangai Volcanic Region (Central Mongolia): Geochronology and Formation Conditions

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The South Khangai volcanic region holds a special place within the Cenozoic intraplate province of Central Asia due to a long evolutionary history continuously traced within the range of the last 100 Ma [1] and a south-to-north elongated shape. Such a configuration of the region is related to a sequential northward shift of centers of volcanism for more than 800 km and is considered as a trace of the South Khangai hot spot of the mantle imprinted in the structure of the lithosphere during its passage over a mantle plume [2]. The position of the volcanic region in the modern structure of the province coincides with the boundary between the Amur and Mongolian microplates [3] (Fig. 1) formed in the Late Cenozoic [4] as the result of disintegration of inner areas of Central Asia caused by collision between the Indian and Asian lithospheric plates [3].

In the Late Cenozoic, volcanic processes were apparently autonomous on both sides of the lithospheric boundary. Such processes were manifested mainly within the Mongolian microplate. They occupied the entire Khangai Upland and incorporated a large group of volcanic fields distinguished as the Khangai volcanic area (Fig. 1). Volcanic processes within the Amur microplate were less extensive. They occupied an area of about 15 000 km^2 in the middle part of the Orkhon River basin and southern tributaries of the Selenga River, resulting in the formation of a series of separate (mainly small) lava fields united in our work as the Orkhon–Selenga volcanic area (Fig. 1). This area is spatially separated from Late Cenozoic volcanic fields of the Khangai Upland, which raises the problem of its relation to the development of the South Khangai hot spot of the mantle and, as a consequence, sources of volcanism on both sides of the lithospheric boundary. The problem is considered in this work on the basis of geochronological data illustrating the timing and structural evolution of volcanism in the Orkhon–Selenga volcanic area, as well as on the basis of its correlation with volcanism in the Khangai volcanic area. Geochronological studies of volcanism in the Orkhon–Selenga area were carried out as far back as the early 1970s [5]. However, the data obtained were scarce, nonsystematic, and unreliable in terms of dating of the youngest (Late Pliocene and Pleistocene) volcanic events because of the absence of essential techniques and procedures at that time.

The *Orkhon–Selenga volcanic area* encompasses the middle mountainous area, which is bounded by a latitudinal valley traced by the Ugiinur depression and the Khara–Bukhyn-Gol River valley in the south and by a system of narrow fault-related valleys extending along the watershed of the Orkhon, Khanui, and Selenga rivers in the north (Fig. 2). The territory is crosscut by sublatitudinal, meridional, NW-striking faults, which control the location of river valleys and intermontane depressions. The sublatitudinal faults, which were responsible for the formation of two sublatitudinal (Ugiinur and Orkhon–Khanui) grabens, are particularly important in terms of structure formation and magma control. The Ugiinur graben looks like a relatively narrow intermontane depression (up to 15 km wide) that extends from west to east for more than 100 km between the Orkhon and Tola rivers (Figs. 1, 2). The Orkhon–Khanui graben is represented by a chain of wide hilly valleys, which extends from the Settlement of Tsetserleg in the west to the Settlement of Orkhon in the east for more than 150 km (Fig. 2). Both grabens played the role of major magma-controlling structures that determined the distribution of Late Cenozoic volcanism within the Orkhon–Selenga volcanic area.

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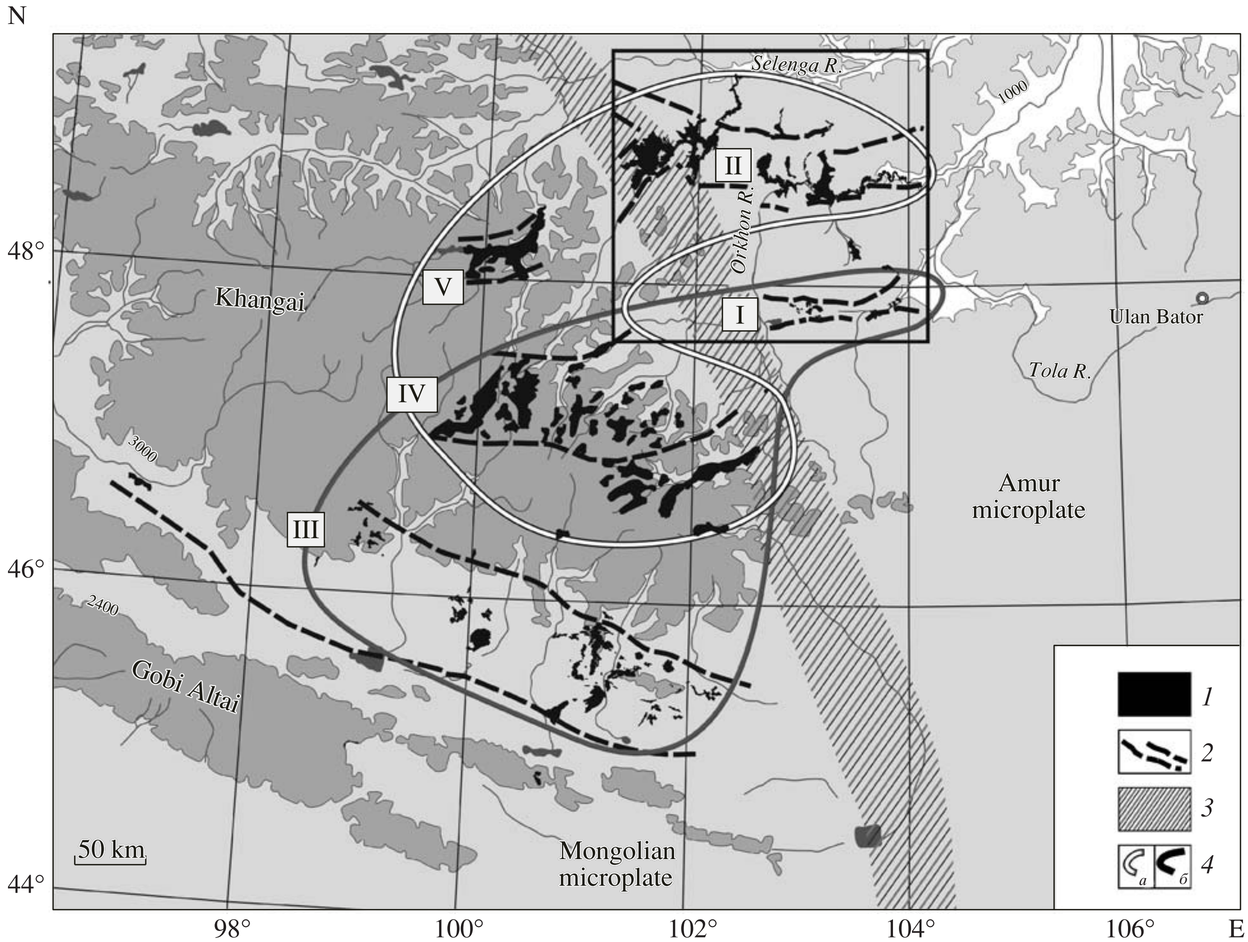

Fig. 1. Scheme of Late Cenozoic volcanism within the Khangai and Orkhon–Selenga volcanic areas. (*1*) Lava fields; (*2*) grabens; (*3*) boundary between the Amur and Mongolian microplates [3]; (*4*) areas of volcanic rocks with an age of (a) <10 and (b) 17–10 Ma. Grabens: (I) Ugiinur, (II) Orkhon–Khanui, (III) Dolinoozero, (IV) Vodorazdel, (V) Taryat.

The Ugiinur graben comprises a series of intensely eroded volcanic fields. Their more or less isometric shape and large area (approximately 80 km in width) suggest that the lava sheet was distributed initially over the whole graben. The largest field located directly east of Lake Ugiinur includes fragments of, at least, four shield volcanoes. Lava sheets of volcanoes consist of series of four or more lava flows with a total thickness of 15–40 m. Eruption centers are recorded by relicts of lapilli–bomb cones (with intravent dikes) and lava plugs (necks). Volcanic products are mainly composed of phonotephrites and shoshonites. The table presents results of the K–Ar dating of volcanic rocks of different volcanoes. The age of the Ikh-Togo-Obo Volcano is estimated at 15.2 ± 0.4 Ma; the neck of an anonymous volcano, at 14.6 ± 0.4 Ma. These data are in agreement with data obtained by Saltykovskii et al. [7] for other volcanic centers (15.5–14 Ma) of the Ugiinur graben. Therefore, we can assume that volcanic processes in the graben took place between 16 and 14 Ma ago.

The structure of the Orkhon–Khanui graben is determined by two separate (Orkhon and Khanui) volcanic regions with a total area of about 2500 km^2.

The Orkhon volcanic region evolved in several eruption stages recorded by relicts of shield volcanoes and their lava pedestals, which formed lava terraces of different hypsometric levels. The early stage of volcanism is characterized by the activity of several volcanoes confined to the axial zone of the Orkhon–Khanui graben and traced by shield volcanic edifices. The volcanic centers are represented by differently preserved lapilli–bomb cones (with intravent dikes) and slopes composed of lava flows dipping sideways from these centers. The lava sheets grade into lava plateaus with the observed sections represented by series of basalt flows with a thickness of 50 m or more. Volcanic products of volcanoes and plateaus are mainly composed of shoshonites. Trachybasalts (hawaiites and potassic trachybasalts) and basanites are less common. The rocks make up the upper lava terrace, fragments of which are retained in the Settlement of Saikhan and along the valleys of some northern tributaries of the Orkhon River. The age of volcanoes and lavas of the upper lava terrace varies within 7.1–5.3 Ma (table). Hence, volcanism of the early stage took place in the Late Miocene. It is likely that the activity of the stage was completed by

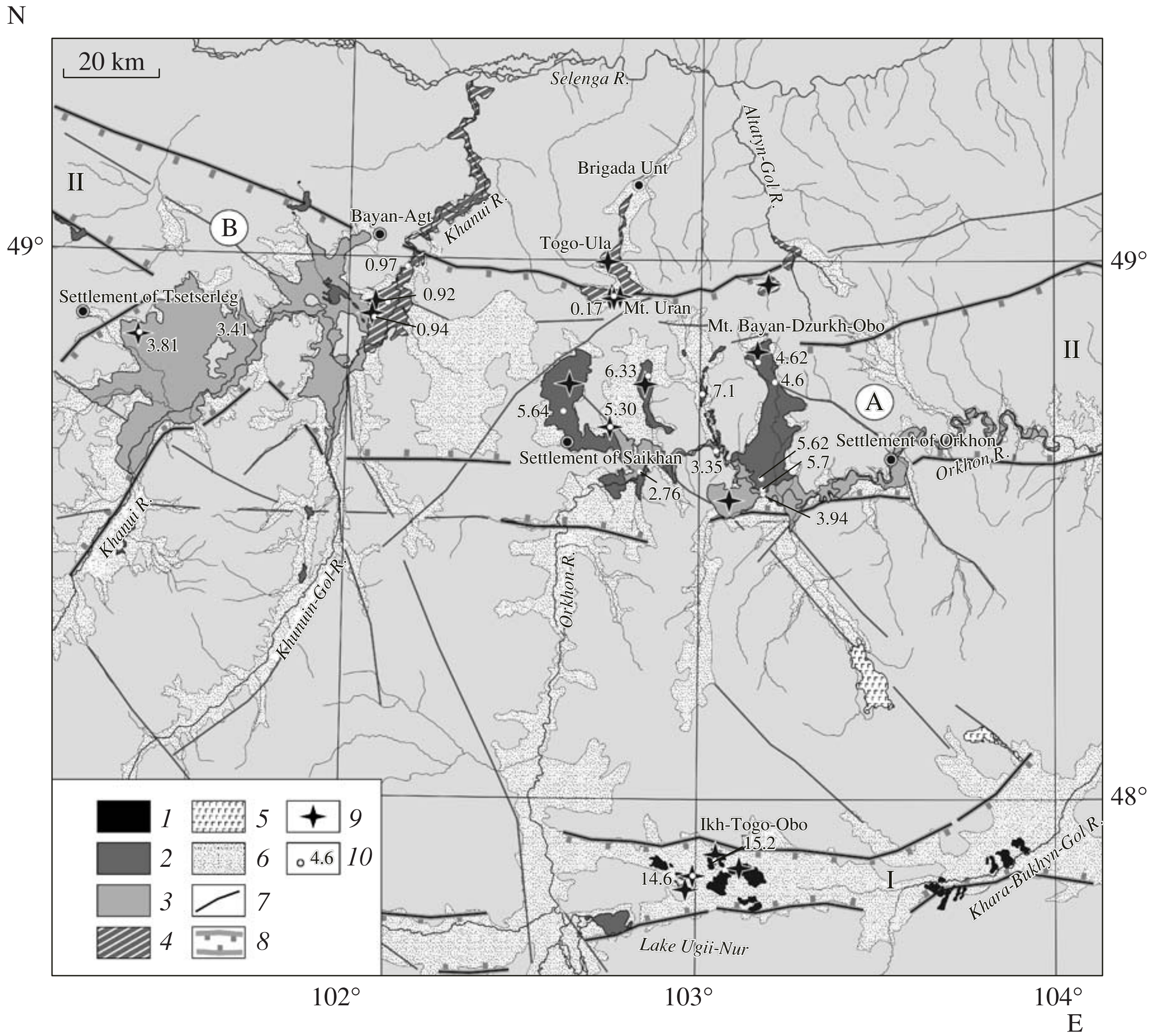

Fig. 2. The structure of the Orkhon–Selenga volcanic area. (*1–5*) Lava fields of different ages: (*1*) Middle Miocene, (*2*) Late Miocene, (*3*) Pliocene, (*4*) Pleistocene, (*5*) undefined age; (*6*) recent valleys and depressions; (*7*) faults; (*8*) graben boundaries; (*9*) volcanic eruption centers; (*10*) sampling sites and age, Ma. Grabens: (I) Ugiinur, (II) Orkhon–Khanui. Volcanic regions: (A) Orkhon, (B) Khanui.

eruption of shoshonite lavas from the well-preserved Bayan-Dzurkh-Obo Volcano. Their K–Ar age is estimated at 4.6 ± 0.2 Ma (table), which corresponds to the Early Pliocene. Lava flows of the volcano filled up a wide valley on the left bank of the Orkhon River and constituted the upper lava terrace.

The second stage of volcanic eruptions is represented by rocks of the lower lava terrace. Its formation was related to valley lava flows, which extended as a narrow strip along the Orkhon River from the Settlement of Saikhan and further downstream for more than 100 km. The lava terrace (100 m thick) is composed of a series of shoshonite flows and less common mugearites. Eruption centers have not been established. Therefore, it is not improbable that volcanism of this stage was controlled by fissure channels of eruptions. The age of terrace rocks varies within 3.9–2.7 Ma (table).

The latest stage of volcanic activity is represented by the small Unt and Altatyngol lava fields. Their location is controlled by a system of narrow fault-line valleys extending along the Orkhon–Selenga watershed. The Unt lava field includes well-preserved lapilli cones of the Uran and Togo volcanoes, which are complicated by central craters. A lava flow of these volcanoes is traced along the valley for more than 25 km. The lava flow is composed of basanites estimated at 0.17 ± 0.04 Ma by the K–Ar method (table).

The structure of the Khanui volcanic region is determined by two age groups of volcanic rocks. The early lava series is related to the activity of a shield volcano located near the Settlement of Tsetserleg in the western part of the volcanic region. Volcanic eruptions in this area produced a large (>700 km^2) lava plateau composed of a series of flows of basaltic trachyandesites (shoshonites and mugearites) and less common potassic trachybasalts. The total thickness of lavas estimated on the can-

Results of the K–Ar dating of lava sequences of the Orkhon–Selenga region

Stages	Sample	Rock	Sampling site		K, wt %	^{40}Ar, ng/g	Age (±2σ), Ma
			N	E			
Khanui volcanic region							
Pleistocene	YuKh-13/7	Basaltic trachyandesite	48°54.950′	102°06.748′	2.33	0.15	0.92 ± 0.04
	YuKh-13/2	The same	48°53.372′	102°04.521′	2.49	0.16	0.94 ± 0.04
	YuKh-13/8	″	48°59.109′	102°09.932′	2.20	0.15	0.97 ± 0.05
Pliocene	YuKh-13/15	″	48°50.773′	101°42.904′	1.28	0.30	3.41 ± 0.12
	YuKh-13/11	″	48°50.350′	101°23.987′	2.39	0.63	3.81 ± 0.11
Orkhon volcanic region							
Pleistocene	KhAN-23/2	Basanite	48°55.917′	102°45.188′	2.54	0.03	0.17 ± 0.04
Pliocene	YuKh-12/30	Basaltic trachyandesite	48°36.419′	102°49.820′	2.27	0.44	2.76 ± 0.08
	YuKh-12/20	The same	48°38.731′	103°02.762′	1.89	0.44	3.35 ± 0.12
	YuKh-12/9	″	48°33.916′	103°10.700′	1.92	0.53	3.94 ± 0.10
	YuKh-12/15	″	48°46.315′	103°12.551′	2.39	0.76	4.6 ± 0.2
	YuKh-12/7	″	48°48.686′	103°09.698′	2.95	0.95	4.62 ± 0.10
Late Miocene	YuKh-12/28	″	48°41.426′	102°44.773′	2.29	0.84	5.30 ± 0.15
	YuKh-12/11	″	48°35.697′	103°10.457′	2.41	0.94	5.62 ± 0.15
	YuKh-12/32	″	48°43.123′	102°36.851′	2.63	1.03	5.64 ± 0.14
	YuKh-12/10	″	48°34.336′	103°10.450′	2.14	0.85	5.7 ± 0.3
	YuKh-12/18	Trachybasalt;	48°47.116′	102°51.289′	2.64	1.16	6.33 ± 0.15
	YuKh-12/25	Basaltic trachyandesite	48°45.099′	103°00.392′	2.56	1.27	7.1 ± 0.2
Ugiinur graben							
Middle Miocene	YuKh-11/1	Phonotephrite	47°51.475′	102°59.558′	4.11	4.19	14.6 ± 0.4
	YuKh-11/2	The same	47°53.156′	103°03.322′	3.55	3.76	15.2 ± 0.4

Note: Analyses were made in the Laboratory of Isotopic Geochemistry of the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (Moscow) according to procedure [6].

yon wall at the edge of the lava field exceeds 50 m. Their K–Ar age is estimated at 3.8–3.4 Ma (table).

The later lava series is composed of shoshonites and subordinate mugearites, which filled up the Khanui River valley downstream of its confluence with the Khanui-Gol River. Valley lava flows were produced by the activity of two neighboring volcanoes. The lava flows are traced for about 90 km along the narrow Khanui River valley up to its confluence with the Selenga River. Depending on the depth of canyons, the thickness of the lava flow exceeds 70 m in some places. The age of eruptions of this stage is estimated at 0.97–0.92 Ma (table).

General regularities in the evolution of the area. The geochronological data obtained allow us to refine the evolutionary history of the volcanic area. Its evolution was related to the activation of latitudinal faults and formation of grabens. The earliest volcanic events took place in the Middle Miocene about 15 Ma ago when the major part of the Ugiinur graben, which originated probably at the same time, was covered by volcanic products erupted from a system of shield volcanoes.

After the Late Miocene, volcanic activity shifted to the northern linear system of wide hummocky depressions, which we interpret as the Orkhon–Khanui graben. Volcanic activity at 7.1 to 4.6 Ma ago confined to the Orkhon volcanic region was related to several shield volcanoes. Their lava flows extended along slightly dissected valleys of northern tributaries of the Orkhon River and formed a large lava sheet. Its relicts represented by exposures of the upper lava terrace are observed in different areas of the system of hummocky depressions, mainly along the northern flank of the Orkhon River.

Volcanic activity within the graben revived in the Middle Pliocene. The large Khanui lava plateau and lava flows along the Orkhon River valley were formed 3.9 to 2.7 Ma ago. Lava flows filled up the deep river valley that cut both lavas of the upper terrace and their basement by the moment of lava effusions. The timing of the river valley downcutting correlates well with the beginning of the growth of mountains in Central Asia and, particularly, the Khangai Upland, which formed west of the volcanic area during the last 4-Ma-long history of the region [8].

The final stage of volcanic activity in the Pleistocene was related to the next northward shift of volcanic centers to the boundary area of the Orkhon–Khanui graben. Valley lava flows from eruption centers of this stage spread beyond the graben along tributaries of the Selenga River.

Comparison with the Khangai volcanic area. The volcanic products of both areas are similar in composition. They are mainly composed of basic rocks (trachybasalts and basaltic trachyandesites) characterized by prominent potassic specificity (prevalence of rocks with K_2O + 2% > Na_2O). Such a specific composition is typical of rocks that should be identified as potassic trachybasalts and shoshonites [9]. Rocks of the Orkhon–Selenga volcanic area have a high silica content (mainly 50–54% SiO_2) and a relatively higher K_2O content. Hence, basaltic trachyandesites (shoshonites and mugearites) and phonotephrites predominate in this area.

The timing of manifestation of volcanic events in both areas also exhibits a great similarity, although volcanic events in the Khangai area were generally multiphase and more prolonged processes. The Middle Miocene lavas of the Ugiinur graben (16–14 Ma) are related to eruptions within the Dolinoozero and Vodorazdel grabens of the Khangai area between 17 and 12 Ma ago [10]. Since the end of the Late Miocene, the centers of volcanic activity shifted northward in both areas. The volcanic activity was localized in the Vodorazdel and Taryat grabens (Fig. 1) within the Khangai area and in the Orkhon–Khanui graben within the Orkhon–Selenga area. Between 7.6 and 4.5 Ma ago, upper lava terraces of compositionally similar rocks (shoshonites, potassic trachybasalts, and basanites) were formed in the eastern part of the Taryat graben [10] and within the Orkhon lava field. Nearly synchronous impulses of eruption of compositionally similar rocks were manifested in both areas in the Pleistocene (about 1 and 0.2 Ma ago) [10].

Let us also note another general regularity in the formation of both areas. Volcanism within them was related to formation of latitudinal grabens. The eastern areas of the Vodorazdel and Taryat grabens at the boundary between the Amur and Mongolian microplates acquired elements of northeastern orientation toward the coeval Ugiinur and Orkhon–Khanui grabens. Such a relationship of grabens is likely to indicate that processes of graben formation were common for boundary areas of microplates and independent of the position of the boundary between them.

In general, the data presented above suggest similarity of the Orkhon–Selenga and Khangai areas in terms of different (age, structure, and lithology) characteristics. Hence, these areas belong to a single region. We believe that the peculiarities of its structure and evolution are related to the South Khangai hot spot of the mantle (or mantle plume), the manifestation area of which in the lithosphere was complicated by the boundary between the microplates. Figure 1 demonstrates the projection of the mantle plume to the Earth' surface according to data on territories of active volcanism. More or less isometric (~250 × 250 km) areas of coeval volcanism correspond to this mantle plume (shown are projections for age intervals of 17–12 and <10 Ma) within the Mongolian microplate. Within the Amur microplate, we observe only peculiar appendices of these areas recorded by narrow zones of volcanic activity. These relationships are likely to indicate that the mantle plume is mainly located beneath the Mongolian microplate, and only its northeastern spur is traced beneath the Amur microplate where the plume controlled the formation of the Orkhon–Selenga volcanic area. It should also be noted that relative motions of the microplates might affect the distribution of Late Cenozoic volcanic fields in the region. It is not improbable that a shift of the Vodorazdel and Taryat grabens southward relative to the coeval Ugiinur and Orkhon–Khanui grabens might be related to the clockwise rotation of the Mongolian microplate.

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