シベリアの新生代火山活動

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Cenozoic Volcanism in Siberia : A review

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Key Words : Siberia, Cenozoic volcanism, Plateau lava, Scoria cone

1. Introduction

Volcanic fields are distributed within Asian part of the Eurasian continent, despite their remote locations from convergent plate boundaries where most active volcanoes on earth are found [Whitford-Stark 1987 : 1-28]. Some volcanoes including Udalianchi of northeastern part of China have historic record of eruptions [1719-1721 A. D. ; Feng and Whitford-Stark 1986 : 1-3]. Thus these inland volcanoes did not necessarily terminate their activities. Evaluations of size and characteristics of volcanism in these areas are important not only for the mitigation of volcanic disasters but also for understanding the energy and material circulations in the earth's system including crust and mantle.

Published geological information on volcanism from inland Siberia is quite limited. Whitford-Stark's [1986 : 1-74] compilation of volcanoes from mainland Asia is still one of the most comprehensive English literatures for Siberia. Most petrological (and geological) works of the region, which appeared after Whitford-Stark, dealt with mantle xenoliths [e. g. Ionov et al. 1992 : 235-247 ; 1995 : 174-190], whereas descriptions on the host volcanic rocks are few. Therefore, it is difficult to have an overview of volcanism in Baikal region.

This paper reviews present knowledge of volcanism in Siberia, especially that of Baikal rift zone, including distribution, volcanic form, eruption mode, and age of volcanoes. We will introduce volcanological works by Russian scientists, summarize them, and look for future research topics necessary for a comprehensive understanding of the volcanism of the area.

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2. Distribution of Cenozoic volcanism in Siberia

Figure 1 shows the distribution of Cenozoic volcanism in the Baikal rift zone. Figure 2 shows the details of its southwestern part. We will group them into four provinces : Udokan, Vitim, Khobsogol-Khamardaban, and East Sayan. The first two are distinct from others, while the last two include several volcanic areas clustered closely together in the southwestern Baikal rift zone. Khobsogol-Khamardaban provinces includes Khamar-Daban Range, Dzhida Basin, Tunka Depression and Khobsogol (Prikhubsugulye, Khubsugul) area. Khobsogol and its southern extension belong to Mongolia. Lastly, East Sayan province includes Oka plateau (east) and Azas plateau (west).

The following list clarifies the names of volcanic provinces and volcanic areas mentioned above, and also indicate the section number where descriptions of each volcano appear.

I . Udokan province	A) Udokan Plateau	… 3
II . Vitim province	B) Vitim Plateau	… 4
III . Khobsogol-Khamardaban province	C) Khamar-Daban Range	… 5
	D) Dzhida Basin	… 6
	E) Tunka Depression	… 7
	F) Khobsogol area	… (not included in this paper)
IV. East Sayan province	G) Oka Plateau	… 8
	H) Azas Plateau	… 9

The areas of volcanism occur along the Baikal rift zone, which formed as the result of collision between Indian and Eurasian plates [Molnar and Tapponnier 1975 : 419-426]. Such spatial relationship suggests tectonic influence on volcanism. However, in local scale, they do not coincide with those of the tectonic depressions [Figs. 1 & 2]. An exception is the northern part of Tunka depression. Other volcanic areas now form plateaus and mountain ranges, where tectonic uplift took place. Moreover, Kononova et al. [1987 : 644-659] pointed out that the peak in the magmatic activity and that in tectonic activity were not coeval.

Another factor which might have caused the volcanism of the Baikal region is hot spots or hot fields, as proposed by Zorin [1981 : 91-104], Yarmolyuk et al. [1991 : 69-83 ; 1995 : 41-67], Zonenshain et al. [1991 : 165-192], and Kiselev and Popov [1992 : 287-295]. Baikal rift zone has lithospheric mantle having a thickness of less than 100 km. This thinning of lithosphere suggests a protrusion of anomalous mantle, or upwelling of asthenospheric diapir. Volcanic fields in Mongolia, not associated with any tectonic depressions, probably result from such hot spots alone.

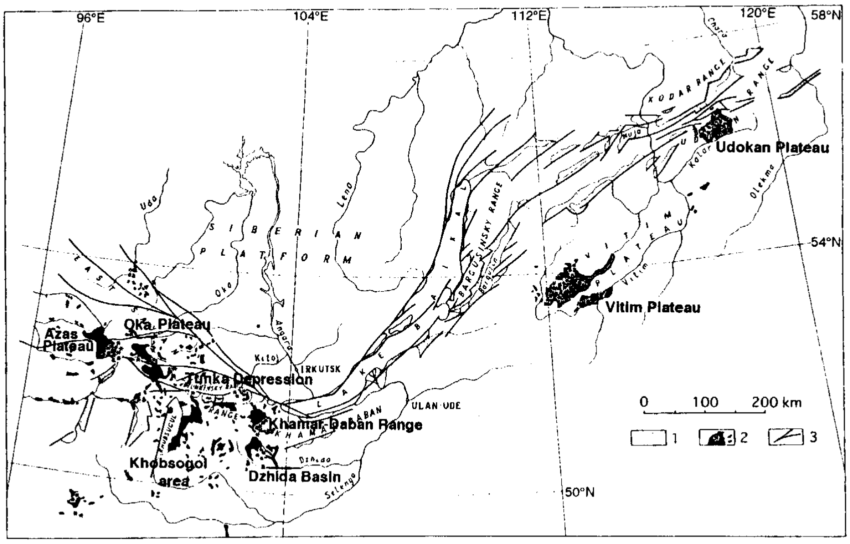

Fig. 1. Distribution of Cenozoic volcanism in Baikal rift zone after Kiselev [1987 : 236].
1 : rift depressions, 2 : basaltic lava flow plateaus and volcanic centers (stars), 3 : faults.

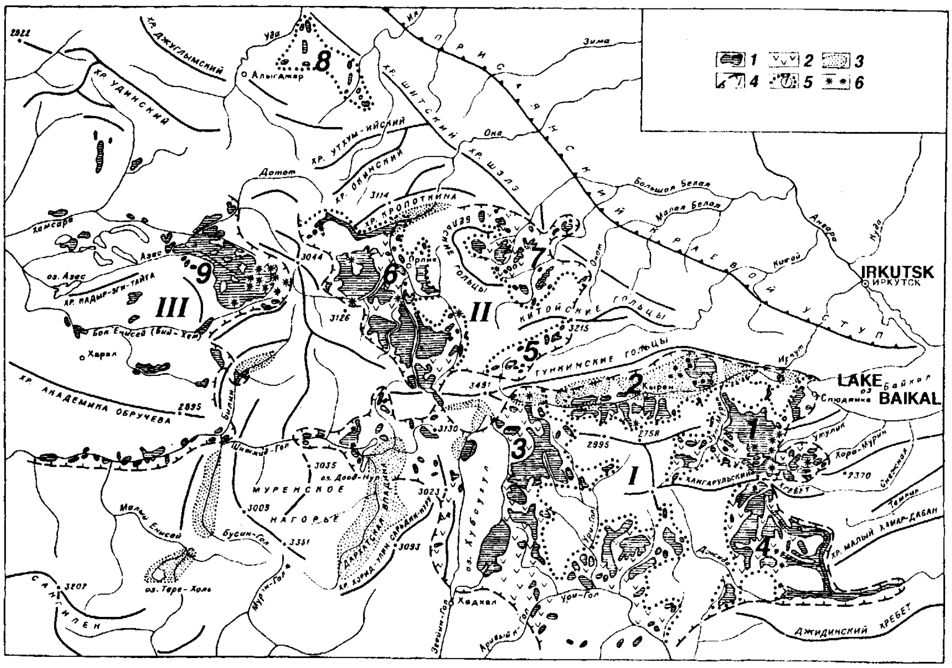

Fig. 2. Distribution of Cenozoic volcanism in southwestern Baikal rift zone after Kiselev et al. [1979 : 50]
1 : Neogene-Quaternary lava flows and covers, 2 : Supposed extension of lava covers, 3 : Cenozoic depressions, 4 : boundaries of volcanic regions as defined by Kiselev et al. [1979], 5 : boundaries of volcanic areas as defined by Kiselev et al. [1979], 6 : volcanic centers and scoria cones. Volcanic provinces : I =Khobsogol-Khamardaban, II & III =East Sayan (divided into East Sayan and East Tuva in Kiselev's original figure). Volcanic areas : 1=Khamar-Daban Range, 2=Tunka depression, 3=Khobsogol area, 4=Dzhida basin, 5=Kitoi River, 6=Oka Plateau, 7=Urik-Belaya field, 8=Iya-Uda field, 9=Azas Plateau (The area 9 is not specified in Kiselev's original figure).

The following sections describe the volcanism of each volcanic areas in Baikal rift zone.

3. Udokan Plateau

3.1 Locations and age of volcanism

Udokan plateau lies on the northeastern margin of the Baikal rift zone, 400 km east from the northern edge of Baikal Lake. It occupies the central part of the Udokan range at an altitude of 1500-2000 m. The volcanic activity of the plateau spans from Miocene to Holocene [Kiselev 1978: 49-50; 1987: 235-238].

3.2 Three major lines of volcanic centers

Stupak [1987 : 65] grouped volcanic centers into three major lines, Khangura-Issakachan (K-I), Syni-Vakat (S V), and Sakukan-Ingamakit (S-I), as shown by Fig. 3. The S-V line is parallel to the rift structures to the north.

Volcanoes of the S-I line, one of the best studied, include scoria cones ranging in height from 25 to 150 m, covering an area of 0.1 to 1.5 km^2, with estimated eruption volume of 0.001 to 0.05 km^3. Outcrop sections of eroded cones show interlayering of lavas and pyroclastics. Latest age determinations by Rasskazov et al. [1997 : 123] and Rasskazov et al. [1998 : 380] showed that the volcanoes from the S-I line did not make synchronous eruptions. Northern group (the S-V line) is the oldest for the Udokan Plateau (13-14 Ma), whereas, others are much younger (less than 4 Ma). Major part of the volcanic plateau formed between 4 and 3.5 Ma by fissure eruptions. Central eruptions are characteristic for the oldest volcanoes (14 Ma) and those younger than the plateau formation (2.7-0.002 Ma).

3.3 Syni

Volcano Syni [No. 3, hereafter these numbers denote volcanoes in Fig. 3] [56.2° N, 117.35° E] is described by Whitford-Stark [1987 : 26] as a Holocene central vent along fissure with seismic activity. The volcano is located on the left slope of the Syni River canyon about 450 m above water level, and 250 m above its base. The length of major basaltic scoria wall is about 800 m, whereas the entire length is more than 3 km. The width varies from 70-80 to 150-200 m (area 4 km^2, volume 0.15 km^3). The extrusions of basaltic lavas flowing into the Syni valley was followed by mostly explosive eruptions of the second and third stages [Stupak 1987 : 66]. The volcano is composed of alkaline olivine basalt.

3.4 Eimnakh, Lurbun, Dvoinoi and West Sakukan

Volcano Eimnakh [No. 12] is located SW from the Lurbun volcano [No. 13], both of which are scoria cones of similar size. Crater diameter is 200 m and 300 m, respectively. Eimnakh has a rounded crater rim, flat floor slightly inclined to SW, and well preserved crater walls at its NE side [Kiselev et al. 1979 : 52]. Lurbun volcano (200 m high) has completely eroded crater walls, and is composed of aphrolithic lavas with volcanic bombs and agglutinates [Kiselev et al. 1979 : 51].

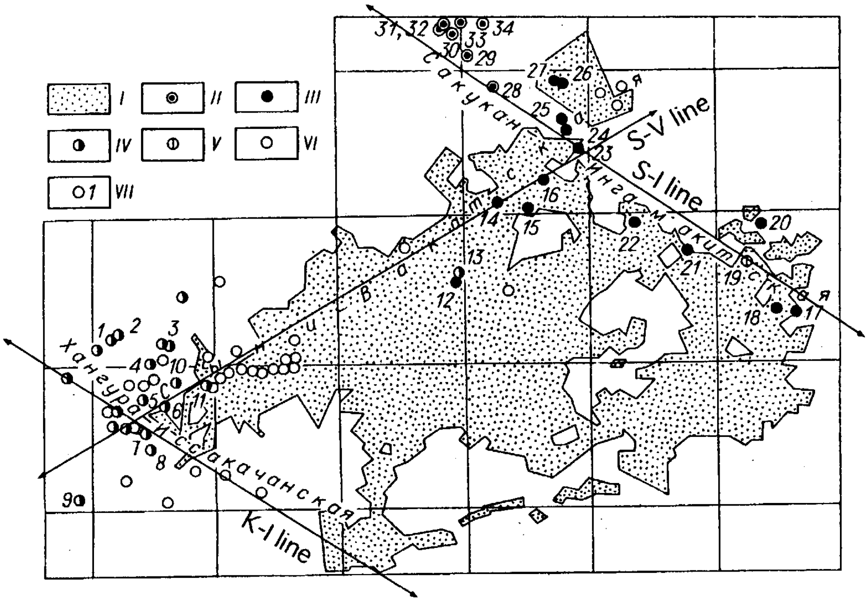

Fig. 3. Distribution of volcanoes and extrusions of lavas from Udokan plateau
Taken from Stupak [1987 : 66]. I-pre-Pleistocene volcanics ; II-VII-Pleistocene volcanoes and extrusions composed of (II) olivine melaleucitites, (III) basanites, (IV) hawaiites, (V) mugearites, (VI) not studied, (VII) with bulk major element data in Stupak [1987 : 66]. Coordinates are not shown in original map. The area is probably between 56° N and 57° N, and 117° E and 119° E. Major lines of volcanoes include K-I (Khangura-Issakachan) line, S-V (Syni-Vakat) line, and S-I (Sakukan-Ingamakit) line.
Names of volcanoes:1. Khangura (Hangura), 2. Ust'-Khangura (Ust-Hangura), 3. Syni (Sini), 4. A fragment of volcanic center in the Syni valley near the Trachytovyi volcano, 5. Unnamed volcano on the Syni-Turuktak watershed, 6. Unnamed neck on the right bank of the Tupil'gun river, 7. Unnamed volcano on the right bank of the Turuktak river, 8. Left Tupilgun (Tupil'gun), 9. Unnamed neck near the Dzhelo lake, 10. Unnamed volcano between Syni and Turuktak rivers, 11. Unnamed volcano (upper streams of the Turuktak river), 12. Eimnakh, 13. Lurbun, 14. Burichi, 15. Extrusion near the upper streams of the Verkhnii Ingamakit river, 16. Dike in a canyon of the Verkhnii Ingamakit river between the Burichi and Amutychi lakes, 17. Dvoinoi, 18. West Sakukan, 19. Yakutskii (Yakutsk, Yakutskiy, Yakutskij) 20. Extrusion near the upper streams of the Levyi Munkudyak river, 21. Dike across the Chukchudu river, near the Cholomdyk tributary, 22. Cholomdyk (Cholomdik), 23. Amutychi, 24. Neozhidannyi, 25. Vakat (located on the left bank of the Vakat river), 26. East Verkhne-Ingamakitskii, 27. West Verkhne-Ingamakitskii, 28. Munduzhyak, 29. Peremychka, 30. Pravyi Lurbun (Right Lurbun), 31. Extrusion Nizhnii Lurbun-1, 32. Extrusion Nizhnii Lurbun-2, 33. Ingamakit (located near 29), 34. Extrusion Levyi Ingamakit.

Volcano Dvoinoi [No. 17] has two rounded dome peaks (one, 15 m high) separated by 200 m and surrounded by a 0.1 km^2 lava field. It has an irregular basal shape with long axis extending 500 m in the E-W direction. Explosive eruption produced pyroclastics, followed by effusion of lava flows that extends 250 m toward WNW. The lava is mostly dense, black nepheline-bearing analcime basalt [Whitford-Stark 1987 : 26 ; Kiselev et al. 1979 : 53].

Volcano West Sakukan [No. 18] is a scoria cone located 3 km NW from Dvoinoi [No. 17] on the flat and narrow watershed between River West Sakukan and its tributary Spuskovoi. It is 30 m higher than the watershed and has an elliptical plan shape (600 m by 250 m) extending NNW-SSE. The cone rests on the middle portion of the plateau section. Basanitic lavas effused in the early stage. Final stage eruption produced three well exposed lava flows extending NW, SW and NE (length, 190, 85, 100 m, respectively ; width near expected crater, 5-10, 5-10, 15-20 m, respectively ; width in frontal part, 2-3, 2-3, 5-10 m, respectively). Crater is not pronounced and is estimated from the position of agglutinates. Nepheline-bearing analcime basalts and kulaite (or nepheline basanite) lavas containing xenoliths of pyroxene peridotite, granite and gneiss are reported. [Stupak 1987 : 68-70 ; Kiselev et al. 1979 : 53].

3.5 Yakutskii, Neozhidannyi, Vakat and Munduzhyak

Volcano Yakutskii (Yakutsk, Yakutskiy, Yakutskij) [No. 19] is located at the upper streames of River Yakutskii (left tributary of River Chukchudu). It is more eroded than Dvoinoi and West Sakukan volcanoes. The volcano has gently sloping sides and an oval shape (600 m by 350 m), rises 30 m above the watershed, and covers an area of 0.35 km^2. The first stage product is alkaline basalts ; final effusive stage, hornblende alkaline basalts [Stupak 1987 : 71]. The latter was described by Stupak [1978a : 87-94 ; 1978b : 26-34] as analcime kulaites and analcime basalts.

Volcanoes No. 22 through No. 27 [Fig. 3] are well-formed scoria cones (100-150 m high) with associated small lava flows, very similar both in morphology and volcanic products. K-Ar age of 2.4 Ma is reported for Neozhidannyi volcano [No. 24] whose lava flows extend 750 m [Stupak 1987 : 71]. Vakat volcano [No. 25], located on the left bank of the Vakat river, is exceptionally eroded among these 6 volcanoes with K-Ar age of 2.7 Ma. Lava flows extend as far as 2 km from the eruption center. The 50-70 m thick section show interlaterel lava flows. The most thick one is the lowermost flow (about 20 m). Uppermost flows are thin (2-3 m) and often contain pyroxenite and lherzolite xenoliths. Lavas are mostly basanites. [Stupak 1987 : 72-73].

Volcano Munduzhyak [No. 28] is located near the upper streams of Munduzhyak River just on the edge of main lava plateau. A fragment of scoria cone (1 km^2, 100 m high) and two remainders of lava dome occur. The crater is not preserved. River-cut exposure of scoria cone shows an interlayering of lava flows and pyroclastics of approximately equal volumes. Volcanic products are basanites, hawaiites, melaleucitites, and melanephelinites. Ivanov

[1997 : 44] reported different lava compositions between cinder cone and lava domes: the former is composed of alkaline basalts, whereas the latter are melanephelinites and melaleucitites. In the lava dome fragments and scoria bombs, abundant pyroxene and phlogopite megacrysts and lherzolite xenoliths were found. Reported K-Ar ages are 13-14 Ma, two independent determinations by Sharygin [unpublished data] and Rasskazov et al. [1997 : 123]. [Stupak 1987 : 73; Litasov 1992 : 17-18 ; Rasskazov et al. 1997 : 123]

3.6 Peremychka, Ingamakit, Pravyi Lurbun, Nizhnii Lurbun and Trachitovyi

Peremychka [No. 29], Ingamakit [No. 33] and Pravyi Lurbun (Right Lurbun) [No. 30] volcanoes are located on the low watershed between the Lurbun and Ingamakit rivers. They show extensive erosions by glaciers. These three volcanoes differ from others in the absence of pyroclastic materials. The only remainder of scoria bank was observed on top of Ingamakit lava dome. Multiple lava flows of the Ingamakit are observed. Scattered xenoliths of pyroxenites and pyroxene megacrysts were found at the base of some flows. The lavas of all three volcanoes are melanephelinites and melaleucitites. [Stupak 1987 : 73 ; Litasov 1992 : 18]. Reported K-Ar ages are 15 Ma for Peremychka [Ivanov 1997 : 44], 13-14 Ma for Pravyi Lurbun [Rasskazov, unpublished data], and 15 Ma for Ingamakit [Ivanov 1997 : 44].

Extrusion Nizhnii Lurbun-1 [No. 31, K-Ar age of 13-14 Ma] produced olivine melanephelinites [Rasskazov, unpublished]. Volcano Trachitovyi (Trachytic), not listed in Fig. 3, is located in the Syni river valley near the middle streams. It broke a steep right bank of the Syni river 400 m above a water level. Crater is about 400 m in diameter. Small amount of viscous trachytic lava, 10 m thick, was effused towards the river. [Stupak 1987 : 86-87].

3.7 Chepe, Aku and Inarichi

Volcano Chepe is a Holocene-age volcano with a summit crater, located 6 km ENE from the Aku crater (56. 18° N, 117. 55° E). Elliptical crater (650 m by 700 m), extending in the NE direction, is composed of two rounded sommas. The SW somma is larger ; 500 m in diameter and 100 m deep. The volcano rises 380 m above its base (1200 m in diameter, $H/W_{co}=0.32$). Eruption started from benmoritic lava flows filling up the valley towards the Eimnakh river. Final stage was an explosion of trachytic scoria. [Whitford-Stark 1987 : 26; Stupak 1987 : 88 ; Kiselev et al. 1979 : 60-63].

Volcano Aku of Holocene age is located on the watershed between the Aku and Syni rivers, 8 km SE from the Syni Volcano (56.18° N, 117.45° E). The height (H) is 220-260 m and basal diameter (W_{co}) is about 1 km ($H/W_{co}=0.24$). Near the somma to SW is a trachytic dome ("sommatic cone", Solonenko [1966 : 102-127], reference from Kiselev et al. [1979 :

57]). It has a rounded shape, flat double summit and steep slopes. The dome is 110-140 m high with 800-950 m basal diameter ($H/W_{CO}=0.14$). The volcanic products are composed of basalt, trachybasalt, and andesite. [Whitford-Stark 1987 : 26; Stupak 1987 : 88 ; Kiselev et al. 1979 : 56-57].

Volcano Inarichi, a completely eroded scoria cone, is located in the basin of Inarichi river (left tributary of the River Eimnakh). Lava flows are covered by Holocene pyroclastics and sediments. (The youngest rocks at the basement correspond to Quaternary age) Sharygin [unpublished data] gives K-Ar age of 4-2.6 Ma. The volcano once covered an area up to 15 km^2, and produced 3 km^3 of erupted materials. A 300-m-high volcanic neck of elliptical shape (1.5-0.75 km) extends in the N-S direction. It is composed of porphyritic trachyte to trachytic andesite. The thickness of lava flows after erosion does not exceed 60 m. The lavas are trachytic andesites and mugearites.

All the Holocene volcanoes compose a line extending in the direction of ENE for a distance of 15 km. This line is located within the SW end of the S-V line, near No. 11 volcano [Fig. 3], and includes volcanoes of Trachitovyi, Aku, Chepe, Kislyi Klyuch, Uchuchei, Turuktak, and Inarichi [Rasskazov personal communication; Stupak 1987 : 86-98]. The radiogenic carbon dating of the wood from Inarichi scoria is 2100 ± 80 years [Devirts et al. 1981 : 1250-1253], and 2230 ± 50 years measured at the Uralian Education Institute [Stupak 1987 : 88].

3.8 Turuktak, Dolinnyi, Kislyi Klyuch and Uchuchei

Volcano Turuktak at the upper streames of Rivers Syni and Turuktak is rather small (covered area, 3 km^2, volume of erupted materials, 0.25 km^3). It is located 5 km WSW from Volcano Inarichi. The eruption center was also eroded to a neck remainder composed of trachytes. No pyroclastics were found. A few lava flows are composed of mugearites. [Stupak 1987 : 58-59]. Unnamed volcano near the Turuktak river belongs to the Pleistocene [Stupak 1987: 88].

Volcano Dolinnyi, 2 km east from Aku, has an elliptical shape (1350 m by 1000 m) extending in the NW direction. Lowermost benmorite and trachyte lava flows and pyroclastic cover directly overlie the granitic basement. Two craters are 350-370 and 250-300 m in diameter. Early lavas are benmorites and trachytes. Final stage explosion products are trachytic scoria from the upper crater [Stupak 1987 : 90 ; Kiselev et al. 1979 : 59-60]. Age determination result for the Dolinnyi volcano is 7940 ± 110 years [Stupak, 1987 : 98].

Kislyi Klyuch (area 0.15 km^2, volume 0.2 km^3) and Uchuchei are possibly Holocene volcanoes. Unpublished K-Ar ages appear in Rasskazov et al. [1998 : 380] without descriptions; hawaiite lavas from Volcano Kislyi Klyuch, 1.8-0.002 Ma [Polyakova unpublished data], comagmatic pyroxenite xenolith from Volcano Uchuchei, 1.8-0.002 Ma [Polyakova unpublished data; Rasskazov unpublished data].

4. Vitim Plateau

4.1 Location and age of volcanism

The volcanic field of Vitim Plateau [7000 km^2] is located along Vitim river, 200 km east of Lake Baikal, and also 200 km from the rift axis [centered around 54° N, 114° E, Fig. 4]. It is the only area of the Baikal rift system foregone by the Early Cretaceous basaltic volcanism. Three stages of volcanic activity were established by Rasskazov et al. [1996 : 56]. Mapping of 86 volcanic centers from the Vitim Plateau revealed that they form clusters. The NW line volcanoes are the most ancient and correspond to Late Miocene [Rasskazov et al. 1996 : 56-58].

4.2 The first stage

A pit between 75 and 76 km from Romanovka toward Bagdarino macadam road [Fig. 4], exploited for a road construction, exposes a volcanic sedimentary stratum with layers of abundant volcanic bombs. Enclosed in picritic basalt host of such bombs are nodules of mantle peridotites including pyroxenites, megacrysts, and crustal rocks [Litasov 1996 : 17-18]. This stratum lies directly on the granite basement of the Angara-Vitim batholith. It contains agglutinate layers at the lower part, and unconsolidated volcanic conglomerate with clear cross bedding at the upper part. K-Ar ages, obtained by various authors from the groundmass, range from 14.4 to 17.3 Ma [Esin et al. 1995 : 49]. Drilling core samples also give similar ages. For example, the age of leucobasalt from the depth of 286 m in the central part of the plateau is 14-15 Ma [Rasskazov and Batyrmurzaev 1985 : 26; Rasskazov et al. 1996 : 56]. Rasskazov et al. [1996 : 56-58] interpreted picritic basalt bombs as explosive (subaqueous ?) eruption products, and leucobasalts, as those of fissure eruptions. Drilling core data show evidences that the first stage lavas filled deep erosive valleys, interlayered with sediments, and reached a thickness of 200 m [Rasskazov et al. 1996 : 56-58]. These lavas were piled up to a height of 960 m (the thalweg of the palaeo-Amalat river is 850 m in altitude).

4.3 The second stage

Probable fissure eruptions were the most extensive. The lava flows comprise a main volcanic sequence of the plateau and cover an area up to 7000 km^2. Age determination results range from 11 to 6 Ma [Esin et al. 1995 : 49; Rasskazov et al. 1996: 56]. Rasskazov et al. [1996 : 56-57] discovered about 18 volcanic centers under the lava shields by drilling. Distinction between fissure and central eruptions is difficult. The volcanic rocks are represented by basanites, trachy-basalts, alkaline basalts and rare nephelinites, olivine tholeiites, and picrites.

4.4 The third stage

The lava flows, possibly originated from fissure eruptions, filled up the river valleys on the surface of partly eroded volcanic plateau. Some upper flows clearly belong to certain volcanic centers, suggesting their central eruption origin. Reported ages vary between 1.1-0.8 Ma [Rasskazov et al. 1996 : 56], 4-0.8 Ma [Ashchepkov 1991 : 27], and 5-0.8 Ma [Esin et al. 1995 : 41].

4.5 Bereya area

Bereya area is the best studied in Vitim Plateau, and comprises volcanoes of 1.1-0.8 Ma ages [Fig. 4 ; Rasskazov et al. 1996 : 56]. Volcano Kandidushka is a scoria cone with heavily eroded crater located just at the roadside [86 km from Romanovka toward Bagdarino, Fig. 4, 53°50.1'N, 113°21.2'E]. The basal diameter is 450-500 m. Crater rim is preserved at E, NE and W parts having a height of 15-20 m ($H/W_{co}=0.04$). Several small lava flows extending

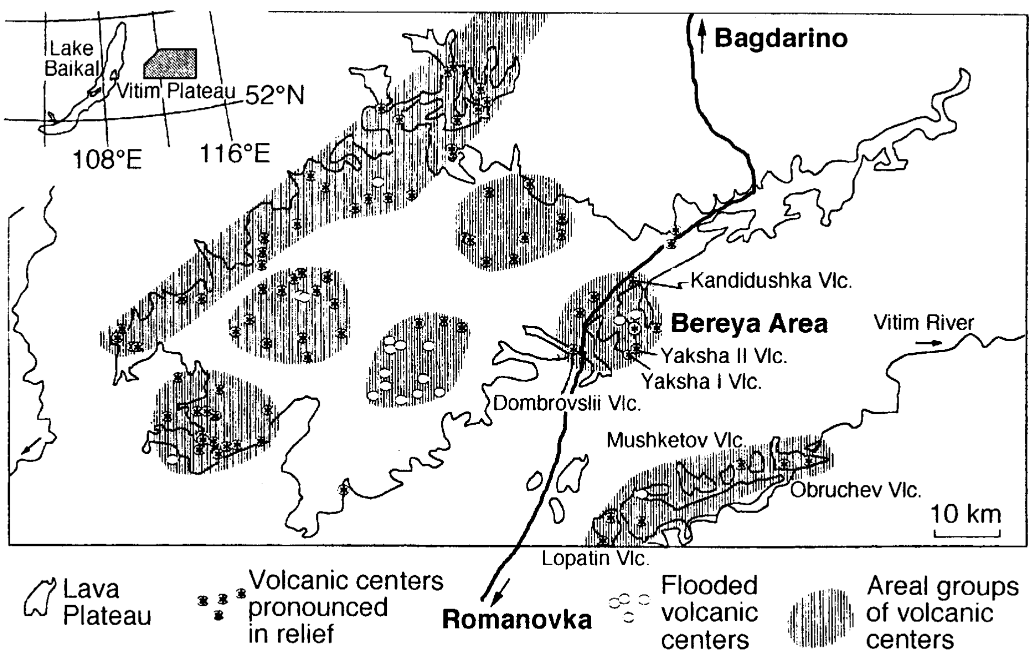

Fig. 4. Distribution of volcanoes and areal groups of volcanic centers from Vitim plateau after Rasskazov et al. [1996 : 57]

NW towards the Dzhilinda river belong to the Kandidushka. The volcanic rocks are basanites. [Kiselev et al. 1979 : 68 ; Litasov 1996 : 18].

Volcano Yaksha I is a poorly preserved scoria cone about 3 km WSW from the Yaksha II. The northern and southern parts of crater rim is preserved, having a height of 60 m. The basal diameter is about 1 km, the crater diameter is 350-400 m ($H/W_{co}=0.06$, $W_{cr}/W_{co}=0.38$). The volcanic rocks are basanites [Kiselev et al. 1979 : 68].

Volcano Yaksha II is a scoria cone located at 53° 43.0'N, 113° 20.7'E, about 5 km east from the road. The SE part is well preserved having a height of 100 m. Other parts are offset by a normal fault and eroded. The crater diameter is about 450-500 m. Crater walls are composed of vesicular basalts with fluidal structure. Several basanite lava flows are associated with the cone. Reported K-Ar age is 0.83 Ma [Ashchepkov, unpublished data ; Kiselev et al. 1979 : 68 ; Litasov 1996 : 18-19].

Several basanitic flows of undetermined origin corresponding to the third stage volcanic activity are exposed along Bulykhta River.

4.6 Southeast Area (Vitim Plateau)

Volcano Obruchev (Obrucheva) is located on the watershed between the Kokyrda and Slyunda rivers (right tributaries of the Vitim river). It is a scoria cone 80 m high with a crater eroded at the western rim. The basal diameter is 750-800 m ($H/W_{co}=0.10$), the diameter of crater bottom is 400 m, the height of crater wall is 20-30 m. The volcanic rocks are basalts [Kiselev et al. 1979 : 67].

Volcano Mushketov (Mushketova) is located on the watershed between the Ingura and Talaya rivers, 4.5 km west from the Ingur (Ingura) village. It is an 80-m-high scoria cone with a rounded crater lake. The basal diameter is about 1 km, and diameter of crater bottom is 400 m. Northern part of crater wall is eroded. Basalts are found [Kiselev et al. 1979 : 68].

Volcano Lopatin (Lopatina) is one of the best preserved. It is located on the watershed between the Endondin and Sherbakhta rivers, 5.2 km NE from the Endondin village. It is a 120 m high scoria cone. The basal diameter is about 800 m ($H/W_{co}=0.15$), the crater diameter is 450 m ($W_{cr}/W_{co}=0.56$), crater walls are 50-60 m. The lavas are basalts [Kiselev et al. 1979 : 68].

5. Khamar-Daban range

The Khamar-Daban range stretches along the southern shore of Lake Baikal, east of Lake Hubsugul [Fig. 5]. The volcanic activity continued from Oligocene to Quaternary period, and was most widespread and abundant during Miocene period. Contrasting occurrences of basaltic lava flows are found for those with different ages. The Oligocene Miocene basaltic lava flows were uplifted in the last 3-4 Ma during the rifting of Baikal area, and form the "summit" or plateau basalts. In contrast, the Pliocene-Pleistocene basalts form "valley" basalts in modern river valleys.

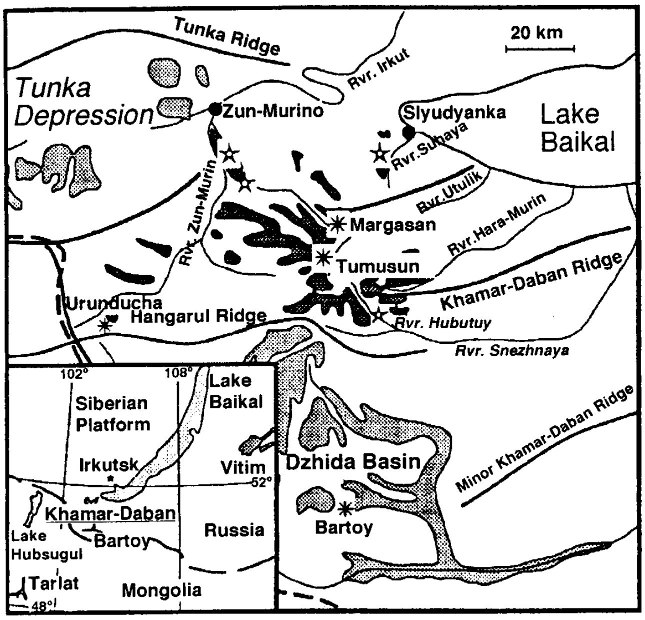

Fig. 5. Distribution of volcanoes and extrusions of lavas from Khamar-Daban ridge and its vicinity after Ionov et al. [1995 : 175]. The Khamar-Daban volcanic field is shown by darkly filled area, other volcanic fields by lightly filled area. Representative volcanoes are shown as large stars, known xenolith occurrences as small stars.

The area of "summit" basalts is estimated to be 3,000 km^2 [Whitford-Stark 1987 : 27]. The thickness of plateau basalts reaches 400-550 m on the watersheds between the Margasan, Tumusun, Urugudei, Utulik, and Zun-Murin rivers [Fig. 5]. Upwarping of the Khamar-Daban range and intensive river erosion resulted in partial inversion of relief. Cone like summits (2200-2400 m a. s. l.) extrude above the flat surface of the basalt plateau along the watershed between the Utulik and Zun-Murin rivers. These are possible volcanic centers, as lava thickness decreases away from them. Estimated vertical movement of the lava plateau is as great as 3500 m. Kiselev et al. [1979 : 25-26] first reported the findings of pyroclastic layers and lenses from different parts of area.

Volcano Tumusun (Tumusunskii, 2369 m) located on the watershed between upper streames of the Tumusun and Utulik rivers is one of the largest eruption centers of this region. The thickness of basalts reaches 500 m, the altitude of base surface is 1880 m. Two 6-8 m thick pyroclastic layers were found between lava flows 60-80 m below the summit. The volcanic center is cut by numerous basaltic dikes. The basaltic flows underlying the volcano are 16-17 Ma [Ashchepkov, unpublished data].

6. Dzhida Basin.

The Dzhida volcanic basin is located on the southern slopes of Khamar-Daban range and on the Dzhida ridge [Fig. 5]. The largest lava covers is located on the watershed between Tsakirka, Nuda and Sangino rivers and on the Kupchinskii plateau (Dzhida ridge). Main lava field is Miocene in age. Younger "valley" lava flows along the Dzhida, Khamnei, Darkhintui, Sangino rivers correspond to the Late Pliocene-Pleistocene. Well preserved volcanoes are reported from the valleys of Bartoi, Barun-Khobol, Zun-Khobol, Khurai-Tsakir, and Khubutui rivers. Miocene lava flows reach 400-500 m in thickness at erosive depressions, and form thick shields indicated by high mountainous relief. The main sequences were probably formed by fissure eruptions, however only few vents were found. The "valley" lava flows reach 140-160 m in thickness and lie over an eroded surface of the Miocene lava field. In addition to the "valley" flows, several groups of Pleistocene volcanoes and associated small lava flows occur within the Dzhida river basin. [Kiselev et al. 1979 : 28-29; Obruchev 1929: 1-207; Bozhinskii 1941 : 50-59 ; Belov 1963 : 244-249 ; Antoshchenko-Olenev 1975 : 1-123].

The largest area of volcanism is Bartoi group in the valley of Bartoi river 18-20 km NW from the river mouth. Scoria cones 50-60 m in height form a chain around swamped round hollows [boccas - Kiselev et al. 1979 : 28-29] probably related to earlier eruptions. The lava field is 20 km long, with thickness decreasing down to the valley. Six cones are preserved within the lava field, whereas one is located on the slope of watershed. These cones have a breached shape as the result of destruction of crater walls by issuing lava flows. Antoshchenko-Olenev [1975 : 101-120] counted up to 10 phases of eruptions. The Bartoi river cut the basaltic plateau and formed a wide valley with several terrace planes with 10-25 m high scarps.

The Khobol group includes three volcanoes. Barun-Khobol volcano, the largest one, is a 230-240 m high stratovolcano on the watershed between the Barun-Khobol balka and Naryn-Gol river. Two other cones, Vershinnyi Barun-Khobol and Levyi Barun-Khobol, are small cinder cones. The Barun-Khobol valley downcut the lava field to 20-40 m depth.

Volcano Khurai-Tsakir and associated lava field is located in the Khurai-Tsakir river valley 9 km from the mouth. This cone is 155-160 m high. Three craters, 140, 30, and 22 m in diameter, make a lineament in the ENE direction. The Khurai-Tsakir basaltic lavas overlie those of the Dzhida field in the Dzhida river valley [Belov 1963 : 244-246]. Unnamed 15-20 m high cinder cone without a crater is located on the flat watershed (2050 m a. s. l.) between Tsakirka and Khubutui rivers. Its western slope is eroded to expose the central neck at the basement of cone. The cinder cone is obviously younger than the last effused lava flows of the Khurai-Tsakir (?) lava field [Kiselev et al. 1979 : 28-31].

7. Tunka Depression (Tunka Valley, Tunkin Depression)

Basaltic lava flows and tuffs of the Miocene to Pliocene and Quaternary age are found from drill cores [Belov 1958 : 80-91]. Whitford-Stark's [1987 : 27] descriptions include cones of Pleistocene to Holocene age from five distinct groups, three of which are Talaya, Kuntinskaya and Khobok. Svyashchennaya Gora (meaning Holy Mountain), located in the zone of maximum sinking of the depression, is a volcanic cone 30 to 40 m high, with a flat-floored crater 45 m in diameter (H/Wco=0.18, Wcr/Wco=0.22, Fig. 6). Khara-Boldok (Ulyaborskiy) cone of Khobok group is the highest (120 to 125 m) and best preserved with a summit crater 85 to 90 m in diameter (Wcr/Wco=0.72). Whitford-Stark [1987 : 27] also described destroyed cones as represented by rafted fragments. The volcanic rocks in this area include olivine basalt, palagonite basalt, and carbonatite basalt [Belov 1958 : 80-91].

To the west of the Tunka Depression is a small E-W-trending basin (Mondinsk Depression) forming a northernmost part of the Khubsugul (Khobsogol) volcanic region mostly located in Mongolia. It contains an explosion vent of Khulugayshi volcano, probably of Quaternary age [Belov 1958 : 80-91].

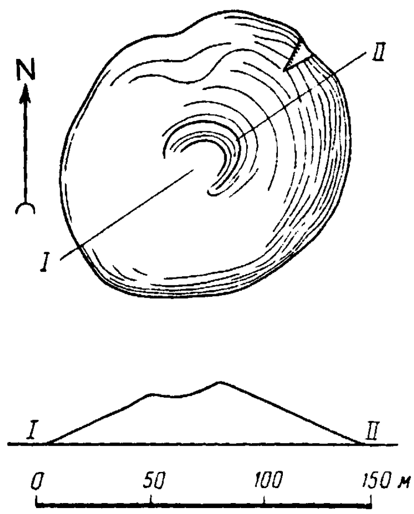

Fig. 6. Plan view and cross section of a volcanic cone, Svyashchennaya Gora (Holy Mountain) after Belov [1963 : 242].

8. Oka Plateau.

The Oka plateau is located at the upper streames of the Oka river. It is bounded on the north by the Sentsa fault, on the west by Sentsa-Tissa highland, on the southwest by the Sarkhoi massif, on the south by the highest ridge of the East Sayan (Munku-Sardyk), and on the east by the combination of the Kalandarashwili ridge, Sorokskie Goltsy and Garganskii massif. The basaltic cover, distributed mainly within the basins of left tributaries of the Oka river (Sentsa, Tissa, Zabit, Dibi, Bokson, etc.), reaches 200 m in thickness. The flat basaltic plateau remains only on watersheds between these rivers. Only three volcanic centers within the plateau were marked on the map of Kiselev et al. [1979 : 31-38]. One of them is the Khiripsa volcano, completely destroyed by erosion to reveal numerous dikes and welded host rocks. The upper flow of volcanic sequence near the Zabit river has a K-Ag age 10.4 Ma [unpublished data by Rasskazov].

In the upper streames of the Khi-Gol (Khikushka) river, the right tributary of the Zhom-Bolok (Dzhom-Balyk) River, occur two Holocene scoria cones composed of olivine basalt, Kropotkin and Peretolchin (52.6° N, 98.9° E). They are located to the north from the main plateau. The flows from these volcanoes extend 15 km down to the mouth of Khi-Gol river with the thickness about 150-200 m. Along the Zhom-Bolok, the lava flows extend about 55 km to Oka river. Belov [1963 : 250] suggested their origin from these two volcanoes despite clear evidences. The surface of the upper flows is "wave-like" with the length of "waves" 10-15 m and a height difference of 2-3 m. The Kropotkin is 90 m in height and has a basal diameter of 490 m ($H/W_{co}=0.18$). The crater diameter is 200 m and the depth is 60 m ($Wcr/Wco=0.41$). The Peretolchin is 120 m high with a basal diameter of 530 m and crater diameter of 140 m (25-30 m deep) ($H/W_{co}=0.23$ and $Wcr/Wco=0.26$). The scorias of both volcanoes lie over the "valley" flows. Pyroclastics occur on the valley slopes near the Peretolchin and the mouth of Gurba-Nurta, the right tributary of the Khi-Gol [Adamovich et al. 1959 : 82-85].

Another volcano, Staryi (Old), located 500 m SW from the Kropotkin, is also composed of Holocene-age olivine basalt. The Staryi has an oval shape, 480 m by 390 m, extending in the NNE direction. It is composed of three combined scoria cones with craters divided by narrow walls. Two southern cones are heavily eroded. The northern cone has a somma with a summit cone inside. This summit cone is 15 m high with 15-20 degree slope angles and a crater 25 m in diameter. The width of an atrium between the summit cone basement and somma walls is about 50 m. The somma walls are eroded and vary 5-10 to 50-60 m in height and 20-25 degree in slope. The volcanic activity is divided into two stages. The first-Staryi volcano and Gurba-

Nurta pyroclastics, the second-Kropotkin and Peretolchin volcanoes and associated lava flows. Both stages started from effusion of lavas and terminated by explosive eruptions to form scoria cones [Adamovich et al. 1959 : 88].

Whitford-Stark [1987 : 27] cited an existence of basaltic extrusions composed of scoria, lapilli, and bombs within an agglutinated mass on top of lava flows near the village of Orlik (52.5° N, 98.8° E), which was described by Belov [1958].

9. Azas Plateau

Within the area bounded by 52.16° N to 52.91° N, 97.83° E to 99.33° E exist a large volcanic field (1500 km^2), located between upper streames of the Khamsara and Bii-Khem (Biy-Hem, Bol'shoi Enisey) rivers [Fig. 7]. This volcanic field is called as several different names: Azas plateau, Khamsara-Bol'shoi Yenisei (=Upper Bol'shoi Enisei), East Tuva plateau, or Khamsara-Biykhem plateau. The plateau surface inclines to NW by 1-2 degrees, so that its altitude decreases from 2200 m to 1250 m. Several table-like mounts with escarp slopes and wide flat summits tower above the plateau surface: Derbi-Taiga (2605 m, 52.2° N, 98.15° E), Ulug-Art-Taiga, Soi-Taiga (2765 m), Sorug Chushku-Uzu ridge (up to 2516 m). The last two are doubled or tripled volcanoes with merged basal parts. These "tables" are composed of abundant "tuff" layers armoring basaltic flows [Grosvald et al. 1959 : 91; Grosvald 1965 : 1-166]. Yarmolyuk and Litasov [unpublished data] interpret these "tuff layers" as hyaloclastite. The surface of lava flows on the "tables" is complicated with numerous rounded hollows 40-80 m deep, 300-600 m in diameter, and small 50-60 m high scoria cones. Similar tuff-and-lava mounts were found apart from the main plateau to the east and southeast : Mt. Ploskaya, Mt. Kok-Hem, Mt. Priozernaya, Mt. Kadyr-Tayga. In addition, there are several mounts without armoring upper lava flows : Mt. Albine-Boldok, Mt. Sagan, etc. Three small 100-m-thick basaltic flows remain on the flat surfaces of the Ulug-Arga ridge, 600-700 m above the neighboring lava plateau [Grosvald et al. 1959 : 91].

The plateau surface and river valleys show signs of intensive glacial erosion. The valleys were deeply downcut to form troughs with wide floors, containing numerous moraines and other hydro-glacial deposits. The plateau basement is about 100 m above the Bii-Khem thalweg [Grosvald et al. 1959 : 93]. However, some basaltic flows on the valleys show Holocene morphology lacking glacial erosions [Litasov, unpublished data].

Volcano Derbi-Taiga is a shield volcano badly eroded by glacier, located about 10 km from the southern boundary of main plateau in the upper streames of the Mon-Dash-Khem river (2605 m, 52.2° N, 98.15° E). Major volcanic sequence includes hyaloclastites, which were formerly described as tuffs [Yarmolyuk and Litasov, unpublished data]. The thickness of hyaloclastite layers ranges from decimeter order to 5-8 m. Occasionally, 1-2 m thick lenses of olivine basalt lava occur. The size of angular grains ranges from mm order to meter order. In places, layers of basaltic pillows were found. The total thickness of the volcanics is estimated as 600 m, above which are the upper armoring lava flows composed of olivine basalt with a thickness of 100 m. Several necks and dikes expose on the southern and southeastern slopes [Grosvald et al. 1959 : 95 ; Litasov, unpublished data].

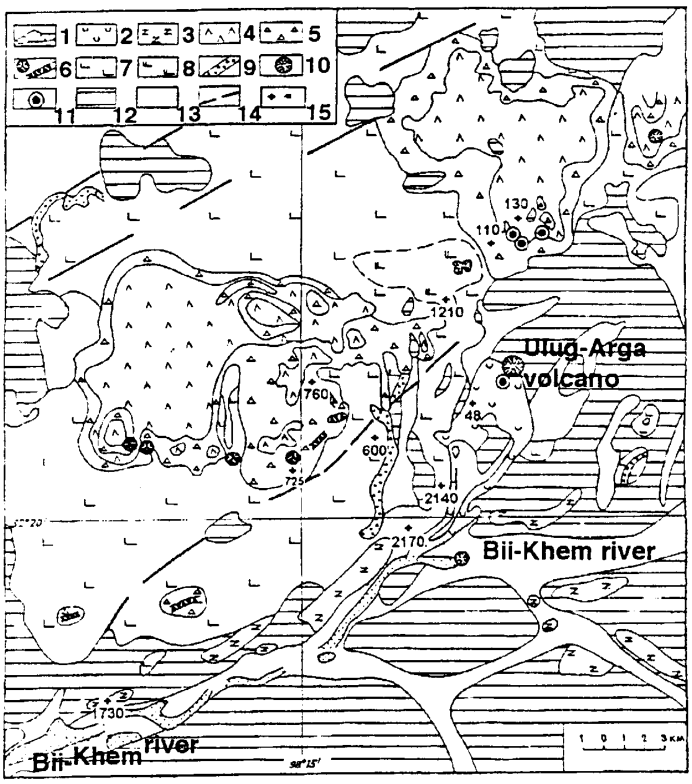

Fig. 7. Geologic map of Azas Plateau taken from Yarmolyuk et al. [in press] with permission. 1. Late Pleistocene-Early Holocene valley basalts, 2. Late Pleistocene-Early Holocene tephrites of the Ulug Arga volcano, 3. Early valley basalts, 4-5-Inner glacial volcanics : 4. Lava flows, 5. Chaotic complex (hyaloclastites, pillow-lavas, lahars, volcano-sedimentary lake deposits), 6. Subvolcanics (necks, dikes, domes) within chaotic complex, 7-9. Lava plateau volcanic complex : 7. Olivine basalts, 8. Tephrites, 9. Hyaloclastites, 10. Eruption centers (craters, cinder cones), 11. Maars, 12. Pre-Quaternary basement, 13. Quaternary sediments (morainal, alluvium), 14. Major faults, 15. Age dating results (in thousand years).

Plateau Soi-Taiga (about 2500 m) is 300 m higher than the main plateau, but has a similar structure in the north, where it is downcut by the Sorug river and its left tributaries [Grosvald et al. 1959: 98]. In contrast, the southern part is probably lower than the main plateau surface and contains Shivit-Taiga volcano.

Volcano Shivit-Taiga (2765 m), located on the watershed between the Shivit, Dalga-Khonug, and Kadyr-Sug rivers (52.27° N, 98.24° E), is a stratovolcano composed of numerous lava flows at high altitudes and hyaloclastites at its base. The crater walls are poorly preserved. The northern part is an elongated hill (140 m higher than the crater floor, with 250 m x 350 m base) extending E-W. The southwestern part is a triangle-shaped mount with a flatten summit (180 m higher than the crater floor, with 1 x 1.5 km base). The summit (750 m x 1000 m) shows a complicated morphology with two maars. The larger crater is 250 m across, 100 m deep, with 100 m wide flat floor. The smaller crater is 100 m across, and 30 m deep. Well-preserved surface of lavas on the crater floor and a short lava flowing out indicate an existence of lava lake and outpouring lava flows by breaking the NW rim. This event probably occurred during glaciation, thus did not undergo substantial glacial erosion. The Volcano Shivit-Taiga is one of dominant summits of this region. The section of the volcano is represented by hyaloclastites interlayering with rare lava flows at the lower part, and lava flows at the upper part. A single hyaloclastite layer is also exposed near the summit maar [Litasov, unpublished data].

Volcano Ulug-Arginskii, located in a SW kar (van) of the Ulug-Arga Mt. (52.23° N, 98.23° E, Fig. 7), is a crescent-shaped scoria cone with a maar to the south. The remaining cone is about 750-800 m across, 200 m in height. The maar is about 250 m in diameter, 25-30 m deep, with a 100 m wide lake on the flat floor. The SSW edge of the maar is composed of alkaline basalt flow. This basalt flowed down the valley of Shivit river as far as 10 km to reach the Bii-Khem valley. Several lava flows were observed in the middle part of scoria cone section. The age of volcano was earlier estimated as the Holocene. However, we found huge granitic boulders on the summit of scoria cone and glacial scores on the surface of lava flows. Also, the lava flows along the Shivit river are overlain by a moraine. On the other hand, the Ulug-Arginskii has a younger morphology than that of the main plateau which underwent glacial erosions. Thus, the age of volcano should correspond to Late Pleistocene [Litasov, unpublished data].

10. Compositions of lavas

Volcanic rock types, briefly mentioned above in each section of the volcanic area, indicate that most are alkaline basalts. Chemical compositions of lavas reported by Kiselev [1978 : 49-59], also indicate that majority of rocks are alkaline basalts. Petrography of some lavas reveal existence of phenocrystic nepheline, and occasional leucite. The Udokan Plateau is an exception to the predominance of basaltic rocks. There, differentiated rock types often occur.

Evidences for alkaline characters for these rocks mostly come from SiO_2 vs. alkali plot, and norm mineral calculations. These two, however, should be used carefully for judgement. Alteration and oxidation, as often observed among lavas from Baikal rift region, reduces their alkali contents and increases Fe_2O_3/FeO ratio to produce "apparent" subalkalic and silica-saturated rocks. Chondrite-normalized rare earth element (REE) patterns show that even "tholeiites" are enriched in light REE's [Kononova 1987 : 644-659 ; Esin et al. 1995 : 1-58]. Some of the "tholeiites" as appear in old petrological descriptions may need re-evaluations.

11. Summary of volcanism in Siberia

Scoria cones, maars, shield volcanoes, and lava flows were abundant in volcanic fields from Baikal rift zone, as described above. Although stratovolcanoes are also reported from these areas, majority of small volcanoes are scoria cones or volcanic necks, thus probably are monogenetic. The lava plateaus are composed of accumulation of thin lava flows produced by fissure eruptions or central eruptions (shield volcanoes). "Plateau" lava flows traveled a long distance (>10 km) and have low aspect ratios, reflecting undifferentiated characters of magmas with low viscosity. In contrast, Udokan lavas are mostly short due probably to their differentiated compositions and viscous properties. Subaqueous volcanic rocks are also found.

Geomorphological descriptions of monogenetic volcanoes often lack basic data such as cone height, basal diameter, crater diameter and cone slope angles. Kropotkin and Svyashchennaya Gora give H/W_{co} ratios representative for pristine scoria cones (0.18); others have smaller ratios resulting from degradation of cone, or unusually high ratios due probably to welding of cone or possible measurement errors. A number of Holocene and late Pleistocene volcanoes are found from Baikal rift zone.

The locations of volcanism do not coincide with the tectonic depressions, thus regional tectonic control on the eruption sites are difficult to envisage. However, local alignment of volcanoes are observed in some cases, especially for well-preserved Holocene volcanoes of Udokan. Such alignments suggest an influence of local tectonic stress fields on the magma passage near the surface.

Geomorphologically, the lavas are grouped into two stages. They are (1) "plateau" lavas that form plateau topography and (2) "valley" flows found at currently low-altitude places. Lava flows forming high terraces in the river valley may be included in (2), as well as topographically youthful scoria cones. "Plateau" lavas are older and more important in terms of volume than "valley" lava flows.

The geomophological difference between "plateau" lavas and "valley" lava flows suggests distinct magma transportation systems and physico-chemical features of magmas between the two, which will become an important factors to understand the volcanism of Baikal rift zone.

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