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Calderas and Ignimbrites in the Uzon–Semyachik Area of Kamchatka: New Data from Field Work on the Shirokoe Plateau

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New evidence is reported on the geologic structure of the southern side of the Uzon–Geizernaya depression (Shirokoe Plateau). As a result of detailed geological mapping, the rocks composing the plateau were divided into six members of different depositional environments. It is concluded that before the formation of the present-day Uzon–Geizernaya Depression, there existed a large depression which obviously was combined with the Bolshoi Semyachik caldera which is now located southward. A detailed study of the stratigraphy and mineralogy of the ignimbrites in the Uzon–Geizernaya Depression suggested that their emplacement had been a long, complex, multiphase process. There are three ignimbrite units separated by lava flows and lake deposits. The ignimbrites of a basaltic andesite composition are suggestive of the participation of water in their formation and of the fact that an important role in the origin of the Uzon–Geizernaya Depression was played by relatively small explosions in pre-existing depressions that were partially filled with water.

INTRODUCTION

Volcanologists have long since been interested in the areas where calderas and associated ignimbrites are developed, because calderas are believed to be the surface manifestations of extensive but shallow magma chambers and to control hydrothermal activity and ore deposition [20], [23], [24], [26]. As far as Kamchatka is concerned, calderas are most widespread in the central segment of the East-Kamchatka volcanic belt (Fig. 1), where they are spaced 20–25 km apart and occur as a chain of a SW–NE direction. The calderas located in the southern end of this chain are merged to form one extensive subsidence

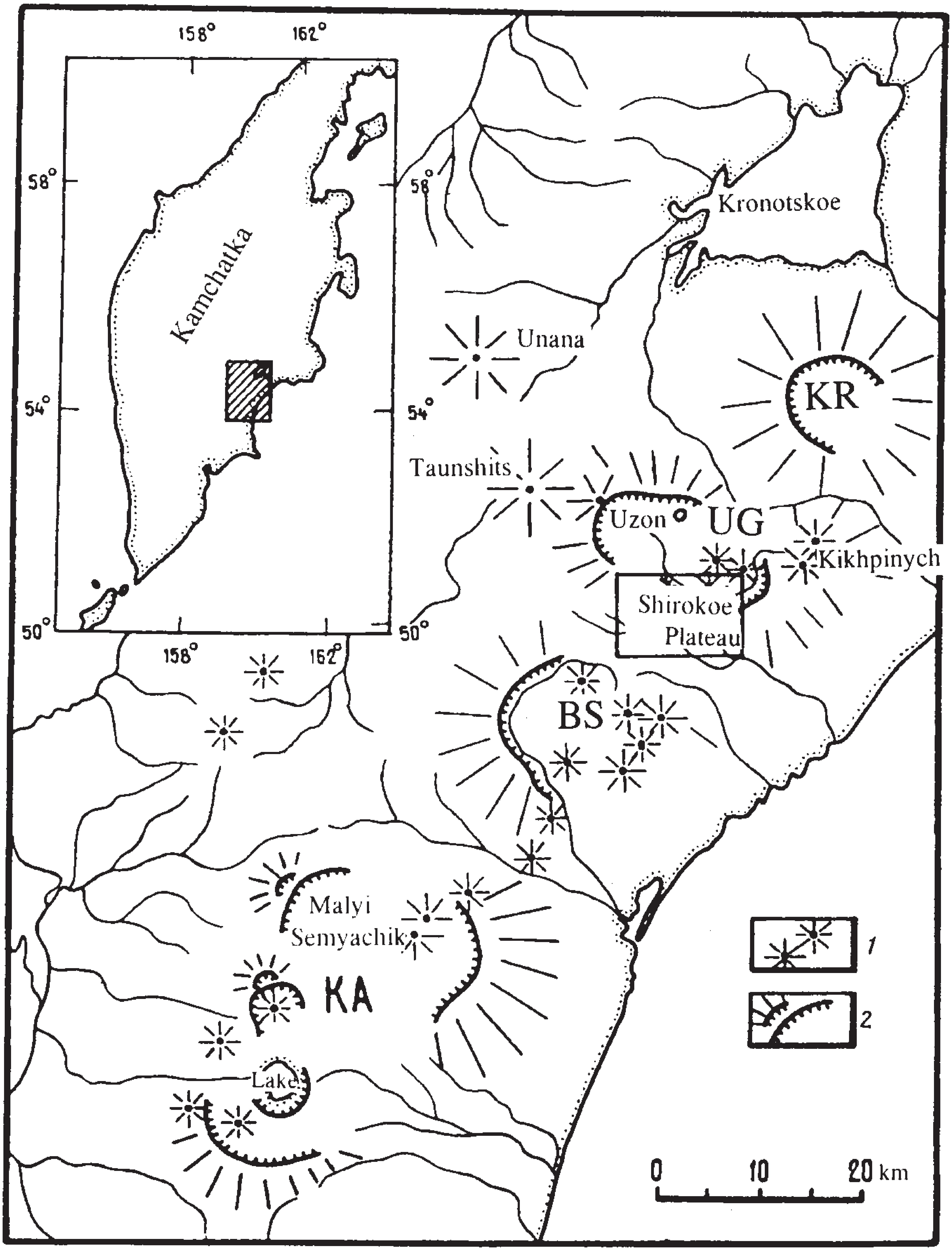


Figure 1 Location of major volcanic centers and calderas in the central segment of the East-Kamchatka volcanic belt: *1* – volcano; *2* – caldera. Volcanic centers: KA – Karymsky, BS – Bolshoi Semyachik, UG – Uzon-Geizernyi, KR – Krasheninnikov. Boxed area is region of study (see Fig. 2).

zone (Karymsky–Semyachik caldera system [14]). These calderas have a late Quaternary age: the Karymsky–Semyachik caldera system was dated 130–140 thousand years [14], the Bolshoi Semyachik caldera, ~80 thousand years [5], and the Uzon–Geizernaya caldera, 40 thousand years [15]. The ignimbrites associated with these calderas overlap successively one another: the Karymsky ignimbrites are overlain by the Semyachik ones, which in turn are covered by the Uzon ignimbrites, the latter being overlain by the pumice associated with the Krasheninnikov caldera. We agree with Erlikh *et al.* [19] that in this region, calderas were successively formed in the NE direction during the Pleistocene. This trend was possibly related to gradual magma migration at depth [11].

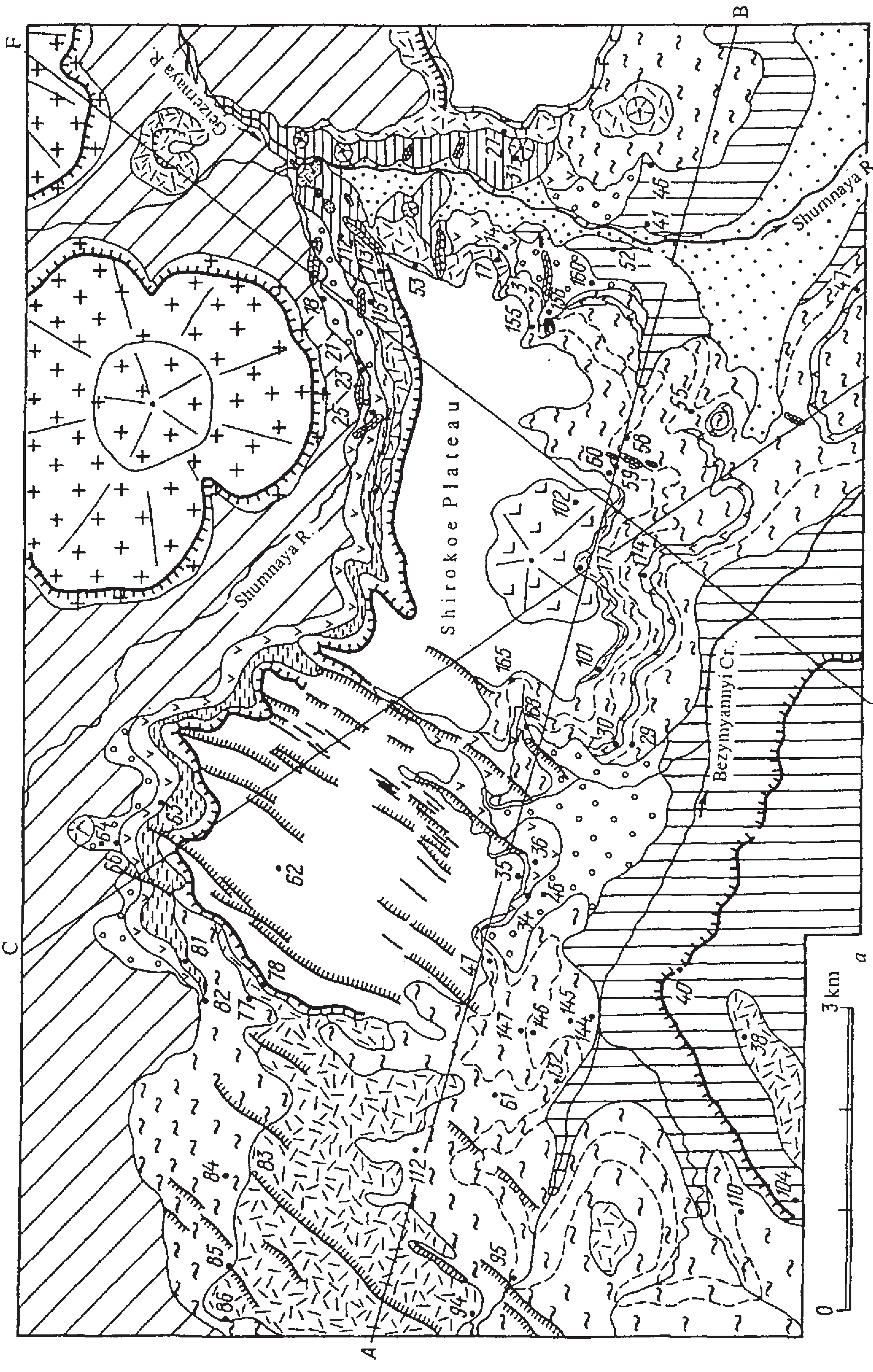
In this paper we discuss the new data that we obtained while investigating the geologic structure of the southern side of the Uzon–Geizernaya Depression (Shirokoe Plateau). This depression has a size of $\sim 8 \times 4$ km and is an isolated upland with a plateau-shaped top with elevations of ~900–950 m above sea level. Thanks to its good exposure and the large thickness of the outcropping rock sequences (max. 500–600 m), this area was chosen as a key site for the study of the formation of calderas and ignimbrites in this segment of the East-Kamchatka volcanic belt.

Braitseva *et al.* [3] were the first to describe the geologic structure of this area. These authors interpreted most of the deposits that make up the Shirokoe Plateau as a pre-caldera complex, that is, as the rocks composing the basement of the Uzon–Geizernaya Depression. They identified the ignimbrites associated with the formation of the depression as a thin cover at the top of the sequences examined. Their general conclusion was that *the plateau had a simple structure with the lava flows gradually pinching out southward* being replaced by a pyroclastic material. Later the eastern slopes of the plateau were investigated by Leonov [8], who found its structure to be more complex: the older rocks had been replaced by the younger ones northward, and the replacement was not gradual but abrupt with the sudden termination of the older rocks and their replacement by the younger varieties. Peculiar deposits were discovered in the extreme NE part of the Shirokoe Plateau and on the adjacent slopes of the Gornoe Plateau. These deposits were separated by major unconformities both from the underlying and from the overlying rocks and were named the Ustie member [8].

As a result of the surveys we carried out in the last years, we prepared a geological map of the Shirokoe Plateau, refined the stratigraphy of the rocks composing it, and reconstructed the conditions of their deposition.

STRATIGRAPHY

We divided the rocks of the study area into a number of members (units), which are separated by major unconformities (Fig. 2). The oldest rocks (Unit 1) occur in the south of the area and in the areas adjacent to the Shirokoe Plateau. The rocks of Units 2 and 3


Shirokoe Plateau
Shumnaya R.
Shumnaya R.
Geizernaya R.
Bezymyannyi Cr.
A
B
C
D
E
F
0
3 km
a

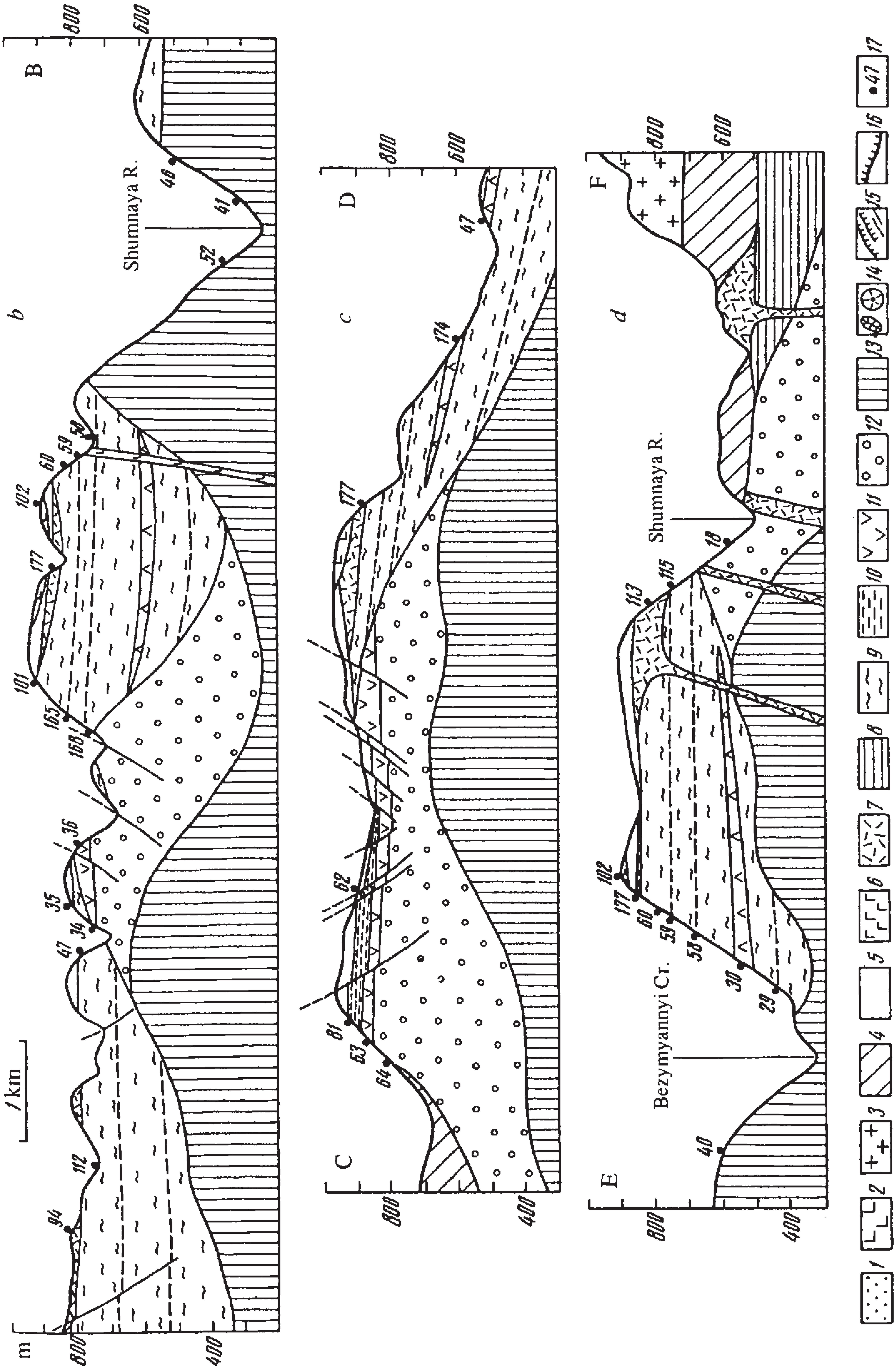


Figure 2

make up the plateau itself. They were described partially in [3], where they are referred to as the upper and lower members. The rocks attributed to Unit 4 are exposed at the surface in the extreme NE part of the plateau. Earlier [8] they were described as the Ustie member. Unit 5 comprises the lavas and ignimbrites that rest on the rocks of Unit 4. The rocks of Unit 6 fill the Uzon-Geizernaya Depression and crop out in the north of the study area (see Fig. 2).

Unit 1 was described in detail earlier [7] from the canyon of the Shumnaya River. Here we will note merely that in the area discussed its most abundant rocks are andesitic lavas which are overlain everywhere by the ignimbrites associated with Bolshoi Semyachik caldera situated south of the study area. The ignimbrites do not vary in bedding dipping NE at an average angle of 10–12° [8]. These rocks were obliterated by erosion from the larger part of the study area. Now merely some isolated outliers remained from the once extensive Bolshoi Semyachik ignimbrite plateau.

Unit 2 was described earlier [3] as the lower member of the Shirokoe Plateau. The distinctive features of these rocks are that they are dominated by volcanogenic sediments, often stratified, containing unequally rounded lava fragments and intercalated with thin-bedded silt and silty pelite. Interbedded stratified sandy agglomerate tuffs and tuffstones of green color were mapped at Sites 64 and 66 on the NW cliffs of the plateau. The sequence is crowned by tuffstones with occasional pumice fragments 1–2 cm across and a few silty tuff interlayers. The total thickness of this sequence is 75 m. These rocks are overlain by andesitic lavas (Table 1) ~15 m thick. Sedimentary deposits (interbedded sandy tuffs and tuffstones) were found above the andesitic lavas at a distance of 1 km westward (Site 81).

A very similar sequence is exposed on the SW slopes of the plateau (Site 46), the bottom of which consists of lake deposits: tuffstone and tuffaceous gravel layers ranging between 3 and 10 cm in thickness. The total thickness of the sedimentary rock sequence is 50 m. These deposits are overlain by pillow andesite lavas. A thick sequence of light yellow or pinkish agglomerate pumice tuff is exposed in the deep canyon of a tributary

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Figure 2 Schematic geological map (*a*) and cross sections (*b*, *c*, *d*) of the Shirokoe Plateau: *1* – alluvium and diluvium; *2* – lava and scoria of basaltic andesite and andesite composition; *3* – rhyodacitic lava (post-caldera volcanic domes: Plateau Krugloe and Mount Geizernaya); *4* – lake deposits (Unit 6) filling Uzon-Geizernaya Depression; *5* – pumice and tephra (explosive deposits armoring Shirokoe Plateau surface); *6* – andesitic lava; *7* – lava, tuff, and ignimbrite of dacitic and rhyodacite composition (Unit 5); *8* – lake deposits (Unit 4); *9* – ignimbrite and tuff associated with Uzon-Geizernaya Depression (Unit 3); *10–12* – deposits of Unit 2 (*10* – psephitic tuff and tuffstone, *11* – lavas of andesite and basaltic andesite composition, *12* – lake deposits (tuffstones and tuffaceous siltstones) and tuffs); *13* – andesitic lava, tuff, and ignimbrite associated with Bolshoi Semyachik caldera (Unit 1); *14* – necks, dikes, lava domes; *15* – faults; *16* – erosion scarps; *17* – sample site and number. Plotted on the sections are sample sites from the section lines and aside.

Table 1 Chemical analyses of lavas, scoria, and ignimbrites from Units 2–5, Shirokoe Plateau, wt.%.

Sample no.	*Index*	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
					Unit 2						
34	–	56,34	1,09	17,80	3,07	5,93	0,18	3,49	7,07	3,76	1,30
63	–	56,97	1,16	17,68	0,62	8,26	0,17	3,43	7,02	3,54	1,15
36	–	58,05	1,28	16,88	2,23	6,89	0,26	3,36	7,53	2,63	0,89
					Unit 3						
54	*i*	58,20	1,02	17,34	4,28	4,69	0,22	3,17	6,70	3,93	0,45
55	*h*	68,47	0,67	15,40	0,67	3,40	0,15	1,03	3,33	4,79	2,06
47	*g*	63,15	1,11	16,19	2,45	4,18	0,13	1,51	5,26	4,00	2,02
29	*g*	66,72	1,01	14,53	0,52	7,15	0,16	1,03	3,93	3,50	1,45
30	*g*	67,60	0,67	15,16	0,15	6,00	0,17	0,97	3,98	3,78	1,52
58	*d*	56,74	1,17	16,31	1,43	8,38	0,17	3,56	7,41	3,86	0,97
168	*d*	59,77	1,49	15,72	2,09	6,37	0,27	2,87	6,22	4,30	0,90
3	*c*	64,09	0,58	16,76	2,49	3,25	0,18	2,11	4,21	4,44	1,89
59	*c*	64,65	1,04	15,74	3,04	3,03	0,16	1,48	4,26	4,71	1,89
35	*c*	65,05	0,98	16,61	1,65	3,82	0,14	1,30	4,59	3,94	1,92
					Unit 5						
177	*a*	68,18	0,83	14,01	2,11	2,83	0,19	1,35	3,72	4,78	2,00

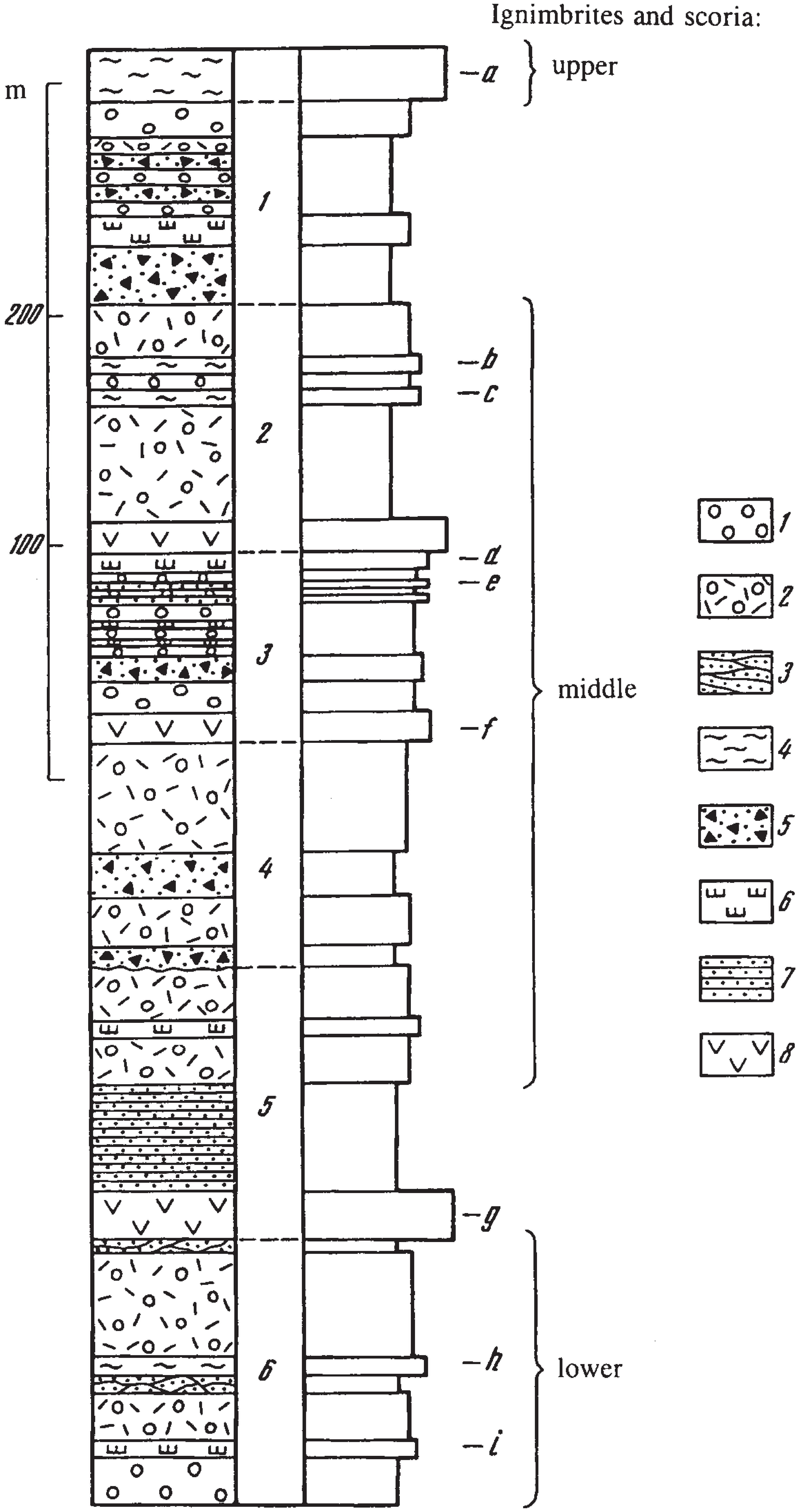
Note. Sample numbers correspond with the data points numbered in Fig. 2. Analyses were made at the Central Chemical Laboratory of the Institute of Volcanology, DVO RAN, Far East Division, Russian Academy of Science. Analysts T. G. Alekseeva, L. T. Braitseva, and L. A. Kartasheva.

of the Bezymyannyi Creek 1 km east of Site 46. This sequence was described earlier in [3]. Its total thickness is as large as 200 m. The presence of numerous rounded lava fragments and thin silt layers in the tuff indicates that they were deposited in an aqueous environment.

Fragments of this section were observed on the eastern slopes of the plateau at Sites 18, 21, 22, 25, 156, and 160. At Site 160 the tuff contains lava fragments (as large as 2 m across) arranged in a lenticular manner.

In spite of the fact that the deposits of Unit 2 are exposed in random outcrops (in the NW, SW, and E parts of the plateau), they are easily recognizable and definitely belong to the same sequence that accumulated in an aqueous environment, most likely in a large lake. They are obviously stratified and dip NE everywhere, their dip angle varying from 9–11 to 24–26°. A characteristic feature is the presence of andesitic lavas. The lavas are restricted to the western part of the plateau being exposed on its northern and southern slopes. They have a very uniform composition (56% SiO_2). The vents of their issue were not established.

Unit 3 rests on the rocks of Unit 2 with a distinct unconformity (see Fig. 2). The deposition of the Unit-3 rocks was preceded by a significant hiatus, during which part of the underlying deposits were eroded. In the eastern part of the plateau, there existed a


Ignimbrites and scoria:
upper
middle
lower
m
200
100
1
2
3
4
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8

deep canyon, the prototype of a modern valley in the lower course of the Shumnaya River. The deposits of Unit 3 filled this canyon to the brim; they also filled a deep valley located west of the plateau.

The most complete sequences of these rocks are exposed in the southeast, where their total thickness is as large as 600 m. The rocks are rather loose, easily washable agglomerate pumice tuff with lava fragments ranging between 2 and 10 cm in size. They contain occasional breccia lenses. Distinctive structural elements of this unit are relatively thin scoria, lava, and ignimbrite layers traceable along the plateau's slopes over long distances as well-expressed scarps. Figure 3 shows a stratigraphic column of the Unit-3 deposits exposed on the SE slope of the plateau (Sites 55, 58–60 in Fig. 2). We divided the sequence into six members separated by small hiatuses and the small scours of the underlying rocks. Generally, the boundaries between the members are marked by lavas or coarse breccias occurring in the pockets of the underlying rocks. The lowermost member (*6*) consists of poorly cemented agglomerate pumice tuff which includes two denser layers. Layer *i* consists of coarse welded scoria with fragments as large as 30 cm and with a thickness varying from 1.5 to 4–5 m. This rock differs from ordinary scoria by its ignimbrite structures (fiamme-like lenses), pseudofluidal texture, ash particles (discernable under high magnification), and small inclusions of foreign material. Layer *h* consists of black vitreous ignimbrite containing obsidian fiamme and having a thickness of 1–1.5 m. Toward the top of this layer, the agglomerate pumice tuff contain more fragments and are replaced by thin unstratified sandy deposits (possibly ash-cloud deposits [2]).

The next member of the sequence (*5*) begins with a dacitic lava layer as thick as 30 m (denoted by index *g*). These lavas extend for a distance of >5 km along the slopes of the plateau (Sites 30, 47, 156, and 174 in Fig. 2). They are overlain by lakebeds consisting of rhythmically interbedded silty, psammitic, and psephitic tuffs, their layers being 3–5 cm thick. Upward follows pumice tuff which also composes the entire next member (*4*). These deposits accumulated as a result of the successive deposition of several pyroclastic flows which eventually produced a thick tuff sequence where individual solidified units are difficult to isolate. We believe that at least five pyroclastic flows piled one upon another in this interval of the sequence.

The next member (*3*) also begins with dacitic lavas (denoted by index *f*). They are overlain by agglomerate pumice tuff which is followed further by coarse-bedded scoria

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Figure 3 Stratigraphic column of Unit 3 exposed on the SE slope of Shirokoe Plateau (Sites 58, 59, 60 in Fig. 2). The column on the right shows beds of different densities (*b*–*i*) (bed *a* belongs to Unit 5): *1* to *6* are members of Unit 3. The legend: *1* – pumice, *2* – pyroclastic flow deposits, *3* – pyroclastic surge deposits, *4* – ignimbrite, *5* – breccia, *6* – scoria, *7* – lake deposits (tuffstone and tuffaceous siltstone) and tuff, *8* – lava.

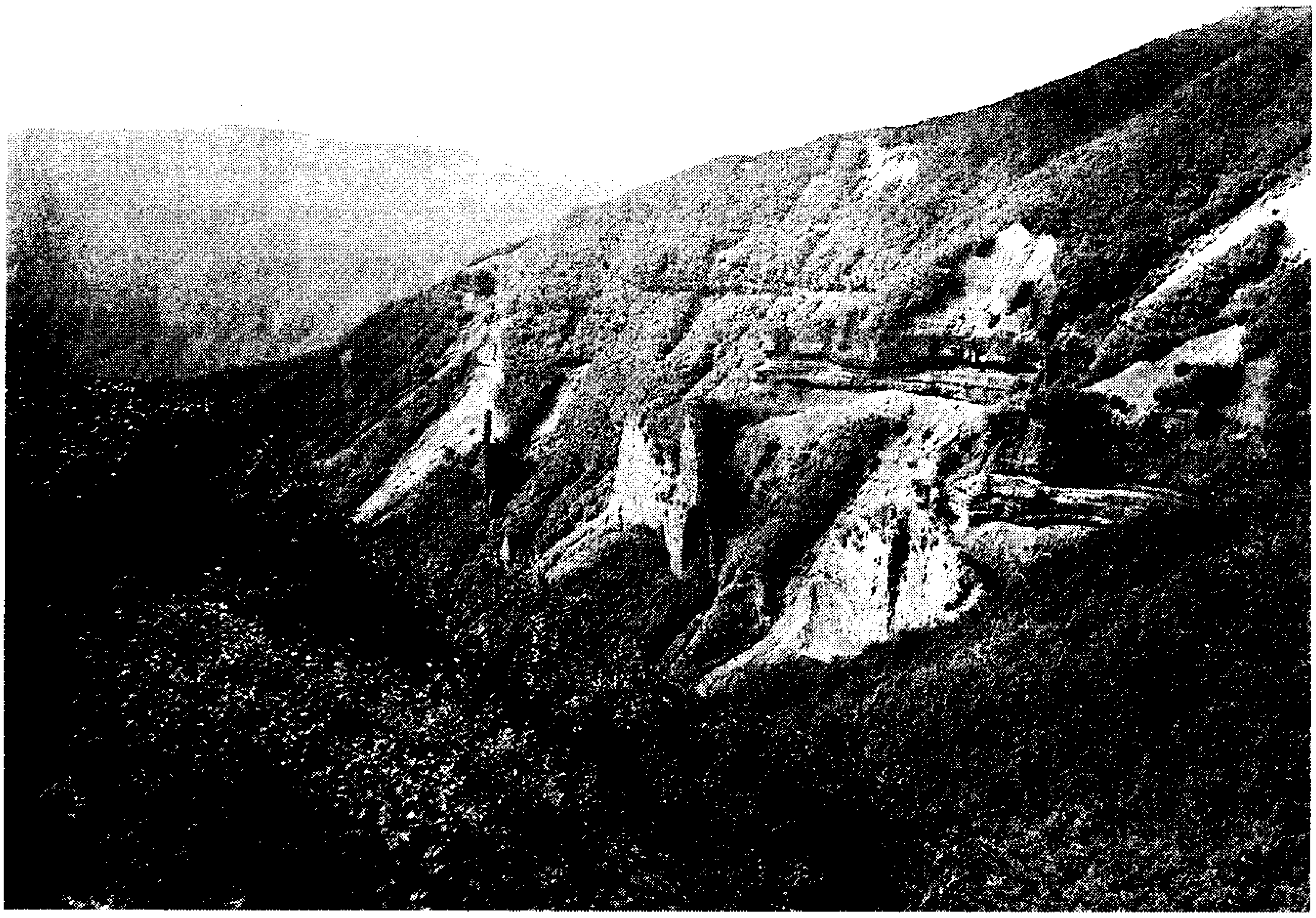

Figure 4 General view of Unit-3 deposits exposed on the SE slope of the Shirokoe Plateau. Layers of welded scoria and tuffstone (*e* and *d* in Fig. 3) are seen in the middle of the section as a scarp. Photo by V. L. Leonov.

tuff with lakebeds at the top. The lakebeds are 15–20 cm to 1 m thick and consist of tuffstone and also silty and psephitic tuffs. These deposits are distinctly horizontally bedded, have a small thickness (1.5–2 m), and form, together with the overlying layer of welded scoria tuff, a low scarp traceable along all of the SE slopes of the plateau (Fig. 4). These two well-defined layers are denoted by indexes *e* and *d*, respectively.

The overlying member (*2*) is made up predominantly of agglomerate and psephitic pumice tuff, with andesitic lavas, 10–15 m thick, occurring locally at the base. The tuff shows generally a poor horizontal bedding with two extensive layers of denser rocks denoted by indexes *b* and *c*. The lower layer (*c*) is black ignimbrite 1.5 m thick, with outstanding obsidian fiamme. The upper layer (*b*) is highly welded ignimbrite without fiamme having the same thickness.

The uppermost member (*1*) consists mostly of coarse-bedded deposits containing numerous fragments which fall out of the rock easily. A layer of black psephitic scoria tuff, 1 m thick, occurs in the middle. The uppermost rocks are represented by a layer of dense ignimbrite denoted by index *a*. We attributed these ignimbrites to Unit 5 and described in detail below. They are widely developed in the south of the plateau (Sites 101 and 177 in Fig. 2) and pinch out west- and eastward. They are as thick as 10 m at Site 177.

Table 2 Chemical composition of mineral phases and residual glass in ignimbrites and scoria in the Shirokoe Plateau. wt.%.

Sample no.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Σ	O_2	Ab	An	W_0	E_n	F_s	F_m
1	58,17	-	26,21	0,15	-	-	8,66	6,51	0,18	99,98	1,03	57,05	41,92	-	-	-	-
2	58,14	-	27,13	0,18	-	-	9,60	5,12	0,18	100,35	1,10	48,57	50,33	-	-	-	-
3	55,04	-	28,32	0,30	-	-	11,25	4,29	0,03	99,22	0,19	40,73	59,07	-	-	-	-
4	45,59	-	34,89	0,31	-	-	18,60	0,68	0,00	100,08	0,00	6,24	93,76	-	-	-	-
5	53,72	0,18	0,44	21,45	1,58	21,75	1,38	-	-	100,50	-	-	-	2,85	62,54	34,61	35,63
6	53,59	0,30	0,80	21,34	1,14	21,55	1,44	-	-	100,17	-	-	-	3,00	62,37	34,63	35,70
7	52,77	0,16	0,48	23,71	1,48	19,97	1,59	-	-	100,15	-	-	-	3,33	58,02	36,55	39,98
8	54,19	0,22	0,94	17,44	0,68	25,28	1,58	-	-	100,32	-	-	-	3,14	69,83	27,03	27,90
9	52,81	0,26	0,94	9,74	0,66	14,03	21,33	0,25	-	100,03	-	-	-	44,03	40,28	15,69	28,04
10	53,24	0,35	1,03	9,96	0,38	14,40	21,02	0,21	-	100,58	-	-	-	43,05	41,03	15,92	27,96
11	51,93	0,28	0,83	12,97	0,89	13,09	19,20	0,02	-	99,22	-	-	-	40,39	38,30	21,31	35,74
12	52,44	0,36	1,41	8,65	0,30	14,91	20,48	0,07	-	99,13	-	-	-	43,28	42,78	13,93	24,57
13	55,98	1,34	15,58	10,73	-	3,32	7,74	3,48	1,34	99,51	-	-	-	-	-	-	-
14	59,54	1,01	15,88	8,29	0,05	3,04	6,70	4,00	1,42	99,93	-	-	-	-	-	-	-
15	73,34	0,40	13,80	2,29	0,01	0,34	1,75	4,35	2,80	99,08	-	-	-	-	-	-	-
16	64,35	0,97	15,60	5,73	0,03	1,84	5,01	4,43	1,35	99,30	-	-	-	-	-	-	-

Note. Samples 1-4 - plagioclase (1-3 - from ignimbrites, 4 - from scoria); 5-8 - orthopyroxene (5-7 - from ignimbrites in layers *h*, *c*, *a*, respectively, 8 - from scoria); 9-12 - clinopyroxene (9-11 - from ignimbrites, 12 - from scoria); 13-16 - glass (13-14 - from scoria, 15-16 - from ignimbrites). Analyzed using Camebax microprobe, analyst V. M. Chubarov.

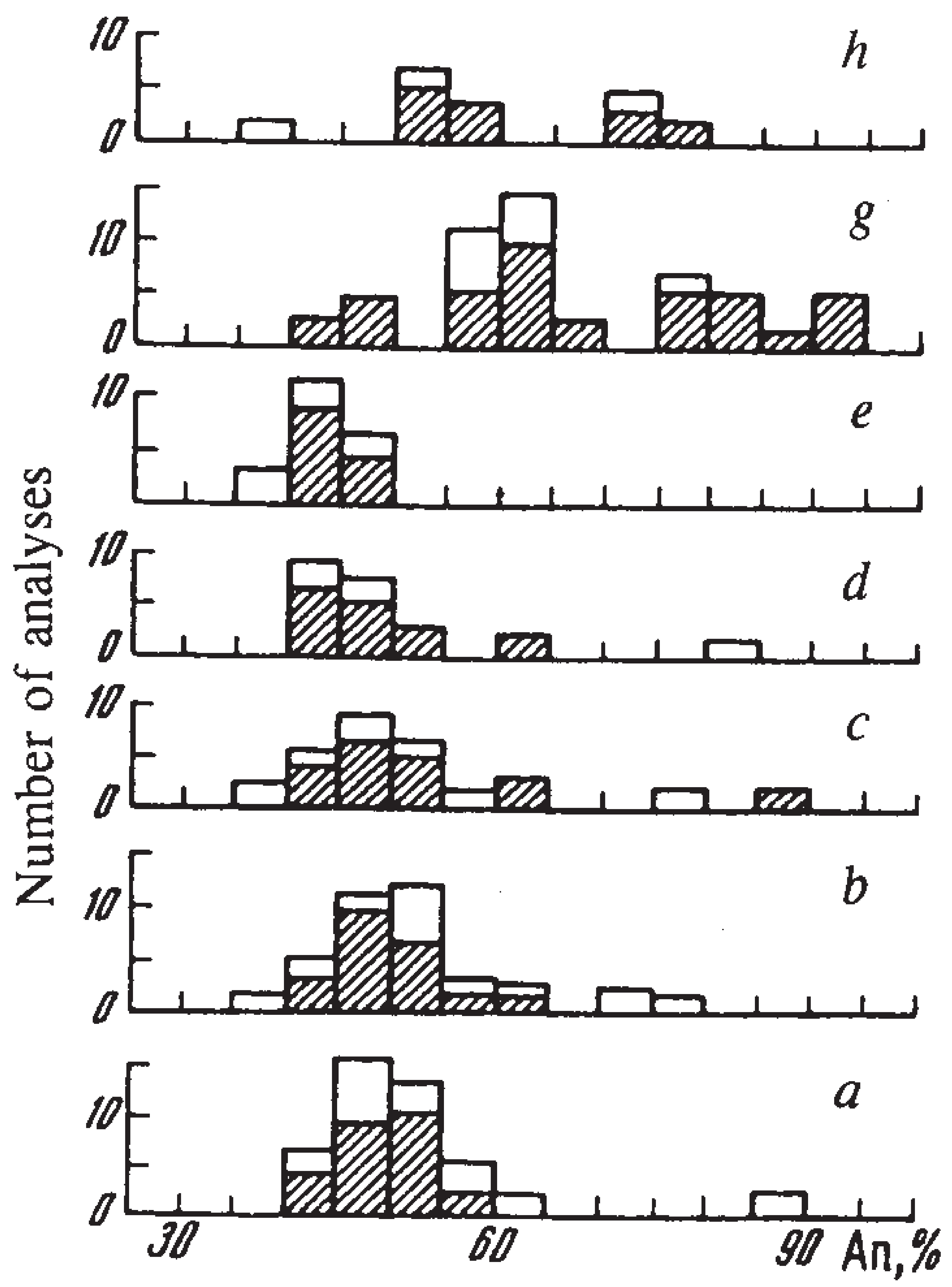

Figure 5 Histograms for the compositions of plagioclases in ignimbrites from the Northern field (*a*), southern field (*b*), and from layers *h* (*c*), *c* (*d*), and *a* (*e*) of the Shirokoe Plateau and in scoria (*g*) and lavas (*h*).

Random outcrops of this sequence were encountered on the N slopes of the plateau and west of it. A sequence beginning with layer *d* was investigated at Sites 113–115 in the NE part of the plateau, where layer *c* of black glassy ignimbrite, 1 m thick, is exposed 20 m up the section. The sequence of Unit 3 is crowned with light psephitic pumice tuff and a poorly cemented thick-bedded block breccia. The ignimbrites of layer *a* are missing there, and the breccia is overlain by rhyolitic lavas.

The deposits of Unit 3 are poorly exposed west of the plateau. There are no deeply cut river valleys. The ignimbrites that fill a deep depression are very thick and do not show distinct contacts between individual layers. The lowermost rocks of the sequence are exposed in the area of Sites 144–147. The section begins with a layer of black welded scoria tuff, 4–5 m thick. We identified it as layer *h* of the sequence described above. Upward follow psephitic to agglomerate bedded tuffs with a thickness as large as 200 m, which are followed by tuffstones and tuff gravels, 10 m thick, and a 3-meter layer of black scoria containing fragments of foreign rocks. We identified the latter as layer *d*. A thick layer (max. 100 m) of gray ignimbrite with black fiamme was traced at higher elevations along the canyon of the upper reaches of the Bezymyannyi Creek (Sites 47, 61, 132, 112, 95, and 100). This bed correlates with layer *c* of the sequence described above. Eastward, at Site 35, this ignimbrite decreases in thickness rapidly and vanishes at Site 36. A similar unconformable bedding of this layer was observed at Sites 81 and 82 on the NW slopes of the plateau, where the ignimbrite of layer *c* has a thickness of ~10 m, pinches out rapidly eastward, and vanishes at a distance of 1 km. Westward, on the contrary, its thickness grows rapidly and exceeds 100 m 2 km further west, where the base of this layer is concealed under younger lakebeds that fill the Uzon–Geizernaya Depression.

Unit 4 (Ustie member [8]) consists mainly of tuff and tuffaceous sediments. Its lower sequence is represented by agglomerate tuff, tuffaceous block breccias, and interlayers and lenses of psammitic and psephitic tuff. The lava blocks are not rounded, have a maximum size of 1–2 m, and usually form nest-like concentrations. These deposits show a notable thick stratification. Upward follow green bedded psephitic and psamitic tuffs. This interval is distinguished by its rhythmic bedding. The upper part of this unit sequence consists of psephitic or agglomerate bedded tuffs of green or brown color. Most of their fragments are rounded. In places these rocks grade to tuff gravels and tuffstones where unidentifiable flora remains were found. The total thickness of Unit 4 is ~600 m.

The rocks of this unit include numerous dikes, necks, sills, and lava domes and flows. Apparently they were emplaced simultaneously with the accumulation of sediments: the lava flows and sills alternate with the tuffs and tuff breccias whose fragments approximate the composition of the former (rhyodacite and dacite). The tuff sediments are highly silicified, the fact indicative of the material being erupted into a lake.

Most of the dikes are emplaced along a zone of arcuate faults that circumscribe the Uzon–Geizernaya volcano-tectonic depression in the southeast.

Unit 5 was identified and is described here for the first time. The rocks attributed to this unit are lavas and pyroclastic rocks (ignimbrites) that occur above the rocks of Unit 4. In the northeast of the plateau these deposits occur as a thick accumulation of rhyodacite and rhyolite lava flows with lava-like ignimbrites containing fiamme and elongated obsidian bands at the base. On the Gornoe Plateau, situated eastward, ignimbrites overlap rhyolite lavas and have the highest stratigraphic position among the deposits that compose the side of the Uzon–Geizernaya Depression. They drape topographic features dip steeply (up to 30°) on the slopes, often occur as lenses rapidly wedging on strike, and have an earthy (where thin) or a lava-like (where thick) habit.

In the west of the Shirokoe Plateau, ignimbrites of this type occupy the top of the sequence as, e.g., at Sites 77, 83, 85, 86, and 94 (Fig. 2), where they have a small thickness (1.5–2 m), an earthy habit, and a black, locally red, color. They rest on the ignimbrites classed with Unit 3 and are separated from them by a layer of loose agglomerate pumice tuff. The ignimbrites that are exposed in the top of the sequence on the southern slopes of the Shirokoe Plateau (Sites 101 and 177) have their own

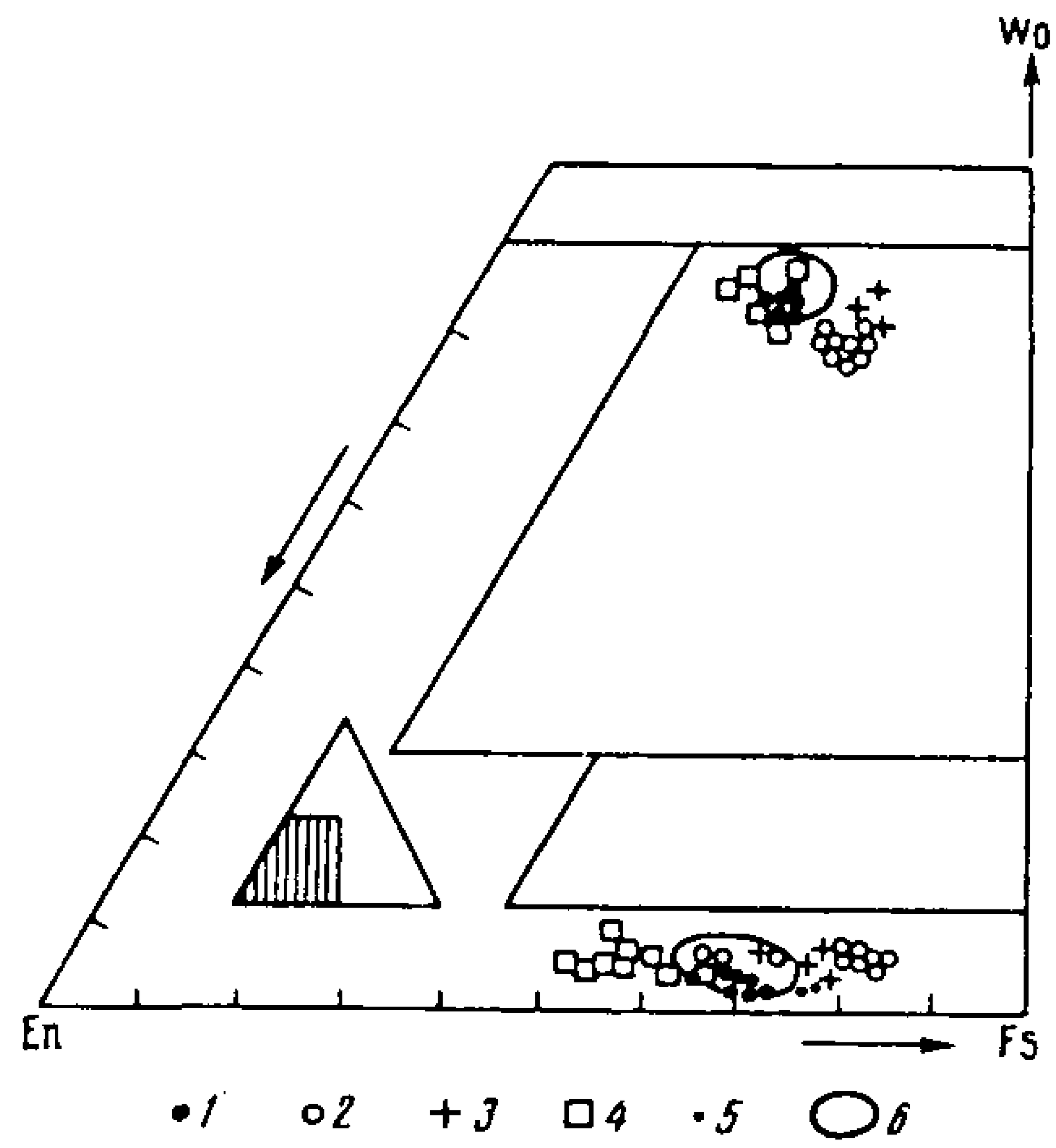

Figure 6 Ternary En–Wo–Fs diagram for compositions of pyroxenes: *1, 2* – from ignimbrites of the Southern and Northern fields, respectively, *3* – from ignimbrites of layer *a*; *4* – from welded scoria; *5* – from lava flows; *6* – regions of pyroxenes from ignimbrites of layers *h* and *c*.

characteristic features that allow them to be attributed to Unit 5: an earthy habit, occurrence as a lens that pinches out west and east, and specific mineralogy (see below).

Unit 6 includes the deposits that fill the Uzon–Geizernaya Depression and are exposed only at the foot of the northern slopes of the Shirokoe Plateau. They were described comprehensively in [1] and [3] and are dominated by lakebeds: tuffs, tuffstones, and tuff gravels. They also include lava domes and lava flows of rhyodacite or rhyolite compositions [1], [3]. The lake-tuff sequence of this unit is not differentiated in Fig. 2 even though it consists of several independent stratigraphic units separated by unconformities. Their total thickness is >500 m.

We conclude the description of the deposits composing the Shirokoe Plateau by mentioning the youngest volcanic formations made up of andesitic lavas. These are a small volcanic cone and a series of NNE-striking dikes in the south east of the plateau (Fig. 2).

MINERALOGY OF IGNIMBRITES

Earlier [3], the ignimbrites and lavas of a dacitic composition, exposed on the Shirokoe Plateau, were interpreted as relatively old rocks making up the foundation of the Uzon–Geizernaya Depression. Our study demonstrated that this interpretation was erroneous. The ignimbrites, scoria, and lavas of a dacitic composition, described above as constituents of Unit 3, constitute one rock complex, the emplacement of which was closely associated with the formation of the Uzon–Geizernaya Depression. They are correlatable with the ignimbrites widespread around the depression, which were described previously as the Kronotsky [13] or the Uzon [4] ignimbrites. These ignimbrites occur as two extensive fields: the Northern and the Southern field. Earlier they were investigated by many volcanologists [3], [6], [17], [18]. It was established that in addition to their spatial separation, the ignimbrites of these fields differed in outer appearance, mineral composition, and petrochemistry [6].

To compare the ignimbrites exposed on the slopes of the Shirokoe Plateau with the ignimbrites that had been examined earlier, we analyzed their minerals using a Camebax microprobe. The results of these analyses are listed in Table 2.

As regards their plagioclases phenocrysts (Fig. 5), the ignimbrites and welded scoria of the Shirokoe Plateau separate, based on the compositions of their cores, into three groups (one group for ignimbrites from layer *a*, Unit 3 (Fig. 3), described above). One group, represented by calcic andesine (An 40–48), is dominant in the ignimbrites. In layer *a*, all of the plagioclase phenocrysts are of this composition. The other group comprises sodic labradorite crystals (An 54–65). This plagioclase is dominant in the welded scoria and occurs in variable amounts in the ignimbrites of layers *h* and *c*. The third group of high-Ca plagioclases (An 80–96). Whereas bytownite is rather rare in the ignimbrites, this mineral and also anorthite are fairly common in the scoria. Comparison of our histograms with those reported earlier for the ignimbrites of the Uzon–Geizernaya Depression (Southern and Northern fields) shows that the plagioclases from the ignimbrites of the Shirokoe Plateau resemble the compositions of those from the latter, except that sodic plagioclases are more abundant in layer *a*.

More illustrative for correlation are pyroxenes. They have significantly different compositions in the ignimbrites from the Southern and Northern fields. On the ternary diagram of Fig. 6, the pyroxenes from the two lower ignimbrite layers of the Shirokoe Plateau sequence (*h* and *c*) are plotted in the field of the pyroxenes from the Southern field ignimbrites. The phenocrysts of the upper layer (*a*) are more ferrous and similar to the pyroxenes from the Northern field. Similar relations are seen in the MnO vs. the *f*-number of the orthopyroxenes (Fig. 7). The pyroxenes from the lower ignimbrite layer (*h*) show higher Mn concentrations than those from layer *c*. Being comparable in the *f*-number, the hypersthenes from the latest pyroclastic flow (layer *a*) differ from the phenocrysts of the ignimbrites from the Northern field by their higher Mn content.

The pyroxene phenocrysts from the welded scoria tuff are distinguished by their lower *f*-number and lower Mn content and at the same time are more magnesian. The ignimbrites and scoria contain minor phenocrysts that are not in equilibrium with the magma, their composition in the scoria being identical with the composition of pyroxenes from the ignimbrite of the lower layers, and vice versa.

Glasses from the ignimbrites are different in composition. Most abundant are rhyolite glasses that were found in all layers (Table 2). The ignimbrites of layers *h* and *c* contain

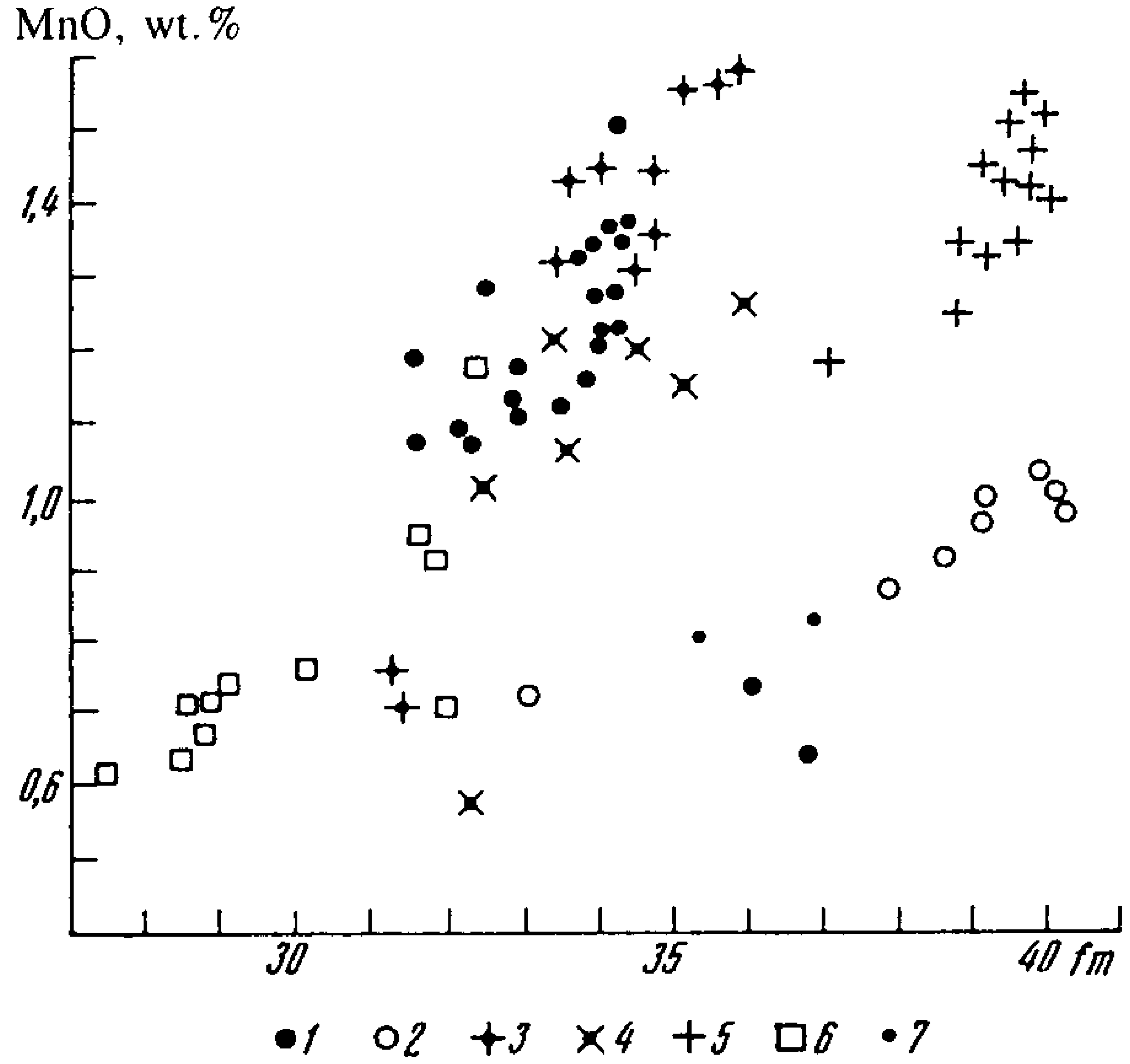

Figure 7 Variation of MnO vs. *fm* in orthopyroxenes from the ignimbrites of: *1* - Southern field, *2* - Northern field, *3* - layer *h*, *4* - layer *c*, *5* - layer *a*, *6* - scoria, *7* - lava.

fragments of glasses having a low-silica dacite (dacitic andesite) composition, some of which are surrounded by acid glass. Glasses from the welded scoria usually have an andesine composition and are high in Fe, Ti, and alkalis. Some of the scoria layers contain glasses of a basaltic andesite composition.

We analyzed the low-silica dacites from a lava flow lying between the ignimbrites of layers *h* and *c*. Based on the composition of their cores, the plagioclase phenocrysts fall into two groups (An 53–57 and An 73–78), comparable with groups 2 and 3 developed in the ignimbrites and welded scoria. Their orthopyroxenes are close to the pyroxenes from the ignimbrites of the Northern field in terms of the *f*-number and Mn concentration.

To sum up, the compositions of phenocrysts in the ignimbrites of the Shirokoe Plateau and in the ignimbrites developed near the Uzon–Geizernaya Depression, investigated earlier [6], indicate that the two lower layers of the plateau (*h* and *c*) are similar to the ignimbrites of the Southern field, and the youngest layer (*a*) to the ignimbrites of the Northern field. Based on the fact that two lower layers (*h* and *c*) have different Mn concentrations, we used this parameter to differentiate the ignimbrites developed south of the Uzon caldera. We found that the lower layer *h* correlated with a pyroclastic flow that reached the Bolshoi Semyachik caldera (upper reaches of the Bolshoi Semyachik River), and the intermediate layer (*c*), with the ignimbrites developed southwestward in the river valleys between the Bort Range and the Taunshits volcano.

CONDITIONS OF IGNIMBRITE EMPLACEMENT

The compositions and the modes of occurrence of the ignimbrites and other volcanic rocks on the Shirokoe Plateau suggest that all of them were emplaced in small depressions and valleys. In particular, this concerns the deposits of the Unit 2. At the present time it is difficult to reconstruct the configuration of a lake that existed during their accumulation, except for its southern and eastern sides which coincide roughly with the modern valley of the Bezymyannyi Creek and the canyon of the Shumnaya River. As to its northern and western sides, the lake seems to have extended 4–5 km farther, namely, as far as the northern sides of the modern Uzon-Geizernaya Depression. Evidence supporting this supposition is provided by the modes of occurrence of the thin-bedded lacustrine deposits of Unit 2, which dip NE at 24° even in the northernmost outcrops of the plateau (Sites 64 and 66), the fact suggesting that the center of the basin was located farther NNE.

The deposits of Unit 3 composing the SE part of the plateau accumulated in a small narrow depression, and the persistent thin-bedded tuffstones and tuffaceous siltstones, in a closed lake basin (or in a few neighboring basins). A lens of thin-bedded lacustrine deposits was reported from this interval of the sequence in [3].

The deposits of Unit 4 (Ustie member) composing the NE termination of the plateau, as well as all of the subsequent volcanogenic sediments filling the Uzon-Geizernaya Depression, accumulated in a closed lake basin too [1], [8]. The outline of this lake can be reconstructed with certainty only in its NW part, on the slopes of the Shirokoe and Gornoe plateaus, where all of the deposits dip NE at 50–70°. This suggests that the center of the lake basin was farther NE and is now hidden under the younger deposits.

To summarize, the deposits composing the Shirokoe Plateau and filling the Uzon-Geizernaya Depression situated north of it can be interpreted as a complex of volcanogenic sediments, pyroclastic rocks, and lavas that accumulated in similar environments, predominantly in lakes. All of these materials were deposited in deep depressions which seem to have been formed as a result of volcano-tectonic collapses and active erosion processes. Figure 8 shows the proved and inferred outlines of these depressions which can be classified in two groups: (1) depressions that were formed after the eruption of the Semyachik ignimbrites (which usually make up their sides) and (2) depressions that were formed after the Uzon ignimbrites. The depressions of group (1) stretch as a belt along a major NE-striking fault (volcanic spreading center [7]), depression III, in which the deposits of Unit 2 accumulated, being restricted to the intersection of this fault with a fault of a roughly NW–SE strike (Uzon–Valaginsky Fault [16]). The depressions of group (2) stretch as a belt along the Uzon–Valaginsky Fault. They were formed for a fairly long time. The oldest of them seems to be depression 1, in which the deposits of Unit 4 accumulated. The latest depression is a young explosion crater in the Uzon caldera (depression 6) [4].

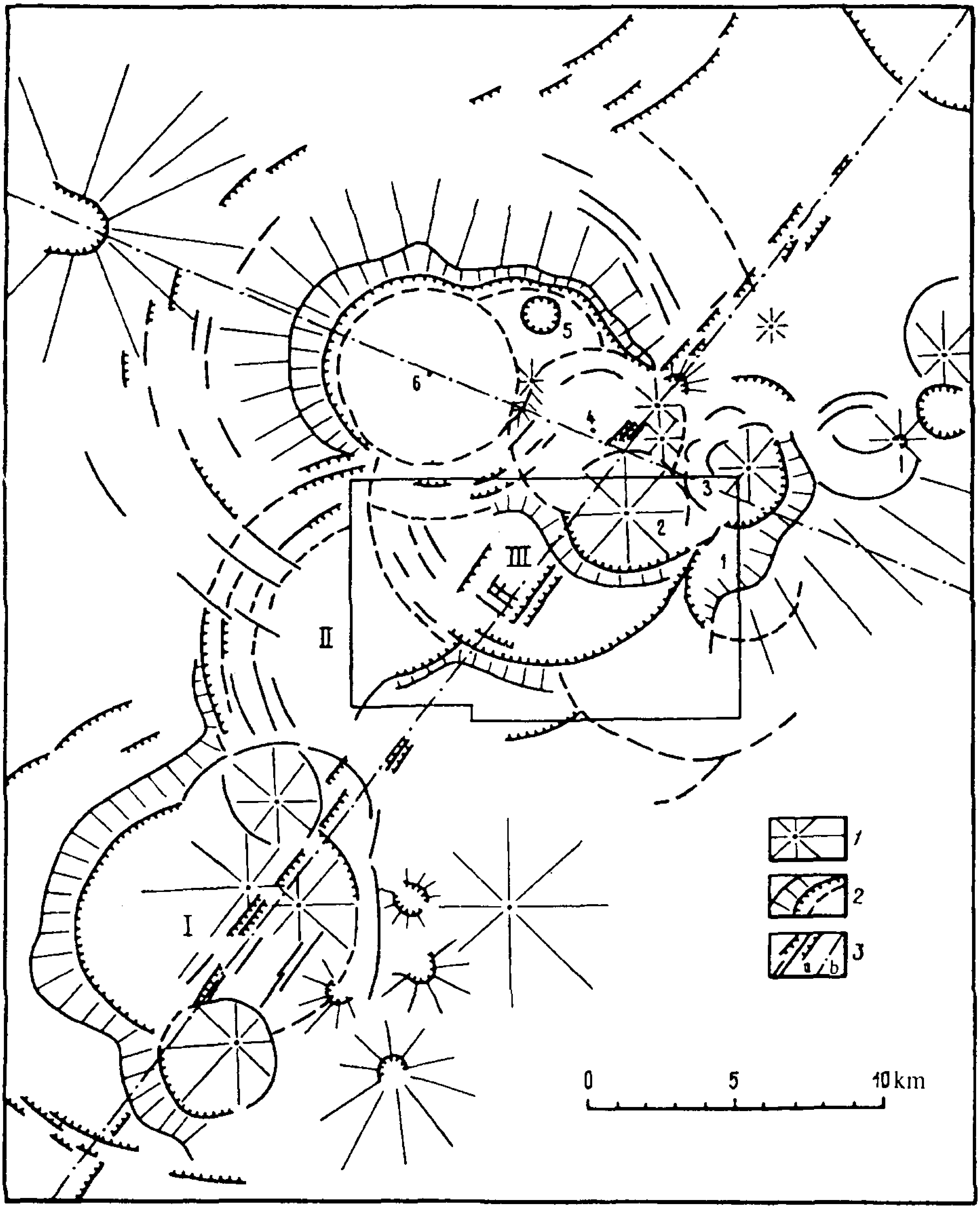

Figure 8 Proved and inferred outlines of the calderas and volcano-tectonic depressions which formed after the eruption of the Semyachik (I-III) and Uzon (1-6) ignimbrites: *1* - volcanoes; *2* - boundaries of calderas and volcano-tectonic depressions; *3* - faults (*a* - normal faults and fractures, *b* - axial lines of major faults: NE-striking pull-apart (spreading) fault and NW-SE Uzon-Valaginsky Fault). Boxed area is region described.

DISCUSSION OF RESULTS

The data reported here on the stratigraphy and modes of occurrence of the rocks composing the Shirokoe Plateau call for a revision of the view on the development of the caldera-forming and ignimbrite-producing processes in the area of study. The distribution and bedding of the deposits of Unit 2 suggest that a closed basin had existed in the area, now occupied by the Uzon–Geizernaya Depression, where lakebeds had accumulated, long before the eruption of the pyroclastics, the material from which the Uzon ignimbrites were produced. The stratigraphic positions of these deposits is identical with the position of the lakebed sediments filling the Bolshoi Semyachik caldera, situated 10 km SW of the Shirokoe Plateau. This caldera was formed ~80 thousand years ago after the eruption of a huge volume of pyroclastic material which was deposited around the volcano [5], [12]. Remnants of the pre-caldera cone (Bort Range) occur west of the caldera. The configuration of the range (consisting of three arcs) indicates that the caldera had a complex structure, consisting of several merged depressions stretching as a belt of a NNE strike (Fig. 8). The resulting basin was filled with lake deposits, a thick sequence of which is exposed at the present time in the deep cuts of the Staryi Semyachik River that flows east of the Bort Range. Similar to the deposits of Unit 2 on the Shirokoe Plateau, these lake deposits are interlayered with thick andesitic lavas. These deposits are covered by ignimbrites that fill the valley of the Staryi Semyachik River. In terms of their mineralogy, these ignimbrites are correlatable with the lower ignimbrite layer (*h*) from Unit 3 of the Shirokoe Plateau.

Therefore, there is enough ground to believe that the lake deposits that filled the Bolshoi Semyachik caldera and the lake deposits of Unit 2 from the Shirokoe Plateau accumulated simultaneously. Moreover, they were deposited in what might have been one depression which extended from the Bolshoi Semyachik caldera in the south to the area of the Shirokoe Plateau and the modern Uzon–Geizernaya Depression in the north (Fig. 8). It is difficult to reconstruct its outline in detail because in many localities the lake deposits are covered by ignimbrites that were emplaced later during the formation of the Uzon–Geizernaya Depression. At the same time the major features of its structure can be reconstructed with certainty. The depression was elongated in a NNE direction and broadened slightly northward. Generally it resembled, in outline and size, the more southern Karymsky–Semyachik caldera system [14]. Whereas in its southern part, where Bolshoi Semyachik Volcano stands, a depression was formed in the middle of the massif, approximately from where the ignimbrites were erupted [12], and can be interpreted as a caldera depression, the origin of its northern part is not as clear. No ignimbrite eruption centers preceding the formation of depressions are known in these areas. Therefore the depressions existing there cannot be interpreted as calderas and seem to be the results of volcano-tectonic cauldron subsidence that took place at the structurally weak intersection of the NE and NW-SE faults [10]. The general configuration of this extensive subsidence extending from Bolshoi Semyachik Volcano in the south to Uzon Volcano in the north is shown in Fig. 8. The subsidence limits are best defined in the west and north, its northern limit being the relatively upthrown northern wall of the NW-SE Uzon-Valaginsky Fault [16]. The fault served as a kind of a "barrage" which "dammed" the magma spread at depth to the northeast [11].

Our study revealed new mechanisms in the development of the ignimbrite formation process in this segment of the East-Kamchatka volcanic belt. An important discovery was that the most complete sequences of the ignimbrites associated with the Uzon-Geizernaya Depression are exposed southward from it instead of northward as believed previously [3]. The deposits Units 3 and 5 from the Shirokoe Plateau, described above, show that the formation of ignimbrites was a long multiphase process which might have lasted a few tens of thousand years. Basically, the ignimbrites occur as three lower, middle, and upper strata with significant time breaks between them, during which lava flowed and lenticular lakebeds were deposited. The ignimbrites developed north of the Uzon-Geizernaya Depression (previously interpreted as the main sequence of the Uzon ignimbrites [3]) are correlatable, on a mineralogic basis, with the upper member of the ignimbrite sequence on the Shirokoe Plateau. The study of pyroxenes from the ignimbrites developed north and south of the Uzon-Geizernaya Depression revealed that the pyroxenes from the "southern" ignimbrites had crystallized at high and those from the "northern" at low oxygen activity [6]. This indicates a slow decline of fluid pressure in the crustal magma reservoir, from which the pyroclastic material was erupted. The magma from which the late ignimbrites were derived (widely developed in the Northern field) was poorly saturated with volatiles.

Our conclusion that the ignimbrites developed north of the Uzon-Geizernaya Depression refer to the youngest upper sequence of the Uzon ignimbrites calls for a revision of the view on the age of the ignimbrites and on the dating of the Uzon-Geizernaya Depression. The previously reported date of 39-40 thousand years [15] is the age of the ignimbrites from the Northern field and cannot be referred to all of the Uzon ignimbrites. The lower and intermediate intervals of the ignimbrite sequence exposed on the Shirokoe Plateau and not found in the Northern field seem to be much older. Their lower age limit can approximate 80 thousand years, the age of the upper ignimbrite unit associated with the formation of the Bolshoi Semyachik caldera [5].

Of great importance for understanding the processes that took place during the emplacement of the Uzon ignimbrites and the formation of the Uzon-Geizernaya Depression was the identification of a specific type of pyroclastic rocks that were called "basaltic andesite ignimbrites" [22]. These rocks resemble the beds of coarse pyroclastics enriched in scoria on Santorin Volcano in Greece [25], and also the "red tuff with black scoria ignimbrite" of the Sabatini volcanic district in Italy [21]. Similar rocks were reported also from the Bolshoi Semyachik volcano [5]. We denoted these deposits as scoria beds in the pyroclastic sequence of Unit 3 from the Shirokoe Plateau shown in Fig.

3, where the thickest and longest of them are labeled *i* and *d*. The bottom of bed *d* contains thin stratified deposits consisting of several well-defined thin layers (max. 15–20 cm) of ash tuff and tuffstone (layer *e* in Fig. 3). The combined sequence of layers *e* and *d* is absolutely identical with the sequence of the Upper Scoria Bed reported from Santorin [25]. In both areas the scoria deposits are underlain by thin persistent layers of fine ash and tuffstone, which in [25] are interpreted as base surge beds. As demonstrated by Mellors and Sparks [25], a great role in the origin of these scoria deposits was played by water that was incorporated into the magmatic system. The eruptions that produced deposits of this kind can be classified as hydromagmatic events. Earlier [22] we associated the origin of these deposits with the injection of magma from the bottom of the reservoir in its top. It appears that both of these mechanisms contributed to the origin of these rocks. The incorporation of water proposed in [25] suggests that the eruptions that produced the above mentioned scoria beds, as well as all of the Uzon ignimbrites, occurred in depressions that contained significant amounts of water. The water and magma proportion controlled the character of eruptions and the deposition of different pyroclastic materials. Like during the eruption of Vesuvius in 79 A.D., here, too, the following activities seem to supercede one another: pumice ejections, hot dry surges, hot dry pyroclastic flows, mudflows, and lahars [27]. It is significant that there were no voluminous eruptions; individual explosions were comparatively small and did not lead to the complete withdrawal of magma from the near-surface reservoir and the collapse of its roof. In this context the Uzon–Geizernaya Depression can be interpreted as the result of the merging of several craters formed by these small explosions.

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