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Ignimbrite Differentiation and Estimation of the Volume of Magma Ejected during Ignimbrite Forming Eruptions in East Kamchatka

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This study was carried out in the central segment of the East Kamchatka volcanic belt, known for its wide development of ignimbrites which cover an area of ~4000 km^2. Ignimbrites fill several calderas located in the central parts of three major volcanic centers: Karymskii, Bolshoi Semyachik, and Uzon-Geizernyi. They range from 35 to 180 thousand years in age. Ignimbrites were examined in the Novyi Semyachik R. valley stretching along a boundary between the Karymskii and Bolshoi Semyachik volcanic centers, where their sequences were described in detail. The study of their mineral compositions revealed differences between the rocks produced by different volcanoes. As a result, the limits of the ignimbrite fields were defined more exactly, and the ignimbrite volumes were calculated. The total volume of the rhyodacite magma ejected during the eruptions that had occurred in East Kamchatka during the last 180 000 years was estimated as 1.2 km^3/thou. years.

INTRODUCTION

Many volcanic regions of the world include calderas associated with thick strata of pyroclastic deposits which cover vast areas. Examples are the long-studied volcanic fields of Southwestern Nevada [23], the San Juan volcanic field in Colorado [26], and the central segment of the Taupo volcanic zone in New Zealand [25], [31]. The volcanologists working there face the problems of differentiating complex pyroclastic sequences, identifying individual covers, and tracing them to some or other calderas. The work done to cope with these problems helps to substantiate the modeling of a magmatic evolution, study geothermal activity and ore-formation processes, and even to discover new, previously unknown structures [26], [27]. The central segment of East Kamchatka, where ten Middle–Late Quaternary calderas are situated in a relatively small area (120 × 50 km), is another example. Here, calderas form a compact group elongated in a NE direction (Fig. 1). These calderas are restricted to the central parts of major volcanic centers and are surrounded by extensive fields of pyroclastic deposits associated with their formation. Most abundant among these deposits are ignimbrites which are interlayered with pumice, cinder, lake beds, and glacier deposits. Many volcanologists were engaged in the study of these calderas and ignimbrites [2], [3], [4], [5], [6], [7], [8], [9], [10], [12], [13], [14], [15], [16], [17], [18], [19], [20]. They located three major centers of ignimbrite formation: Karymskii, Bolshoi Semyachik, and Uzon-Geizernyi. The ignimbrites associated with these centers are usually referred to as Karymskii, Semyachik, and Uzon, respectively. All of them have fairly complicated sequences, indicative of a long and multiphase history of their deposition [5], [6], [7], [8], [15], [19], [20]. In spite of the extensive literature on these rocks, the areas of their distribution, relations among them, and potential volumes are still uncertain and are treated in different ways by different volcanologists. Most complicated is the area of the Novyi Semyachik River (Fig. 2), where the ignimbrites of all three sequences are interlayered and, at the same time, can be investigated comprehensively because of their good exposure. Until recently the ignimbrites in this region had either been not differentiated at all [12], [13], [14], [19] or the boundaries between the individual sequences were drawn conventionally along the rivers separating these volcanic centers [5], [15], [17]. Special surveys were conducted in this region in the last years in order to differentiate the ignimbrites into individual sequences and determine their characteristic features and differences. The results of this work are described below.

PREVIOUS DATA

The geological structure of the caldera formations in the Uzon-Geizernyi, Bolshoi Semyachik, and Karymskii volcanic centers had been studied fairly well [2], [3], [4], [5], [8], [9], [10], [11], [14], [15], [16], [17]. Some most complicated localities were mapped on scales 1 : 10 000 and 1 : 25 000, and the ignimbrite sequences were investigated comprehensively [6], [7], [8], [19], [20]. The characteristic features of some ignimbrites were discovered. It was found, in particular, that the oldest ignimbrites from the Bolshoi Semyachik region had a rhyolite composition and contained quartz and that their accessory pumiceous tuff contained quartz and biotite [6], [20]. The study of the ignimbrites of the Bolshoi Semyachik caldera complex revealed a distinct correlation tag – the content of manganese in the pyroxenes [6]. On this basis the ignimbrite sequence had been differentiated and different ignimbrite portions had been compared [11]. Recently we had a chance to examine the most typical sequences of the Karymskii ignimbrites which had

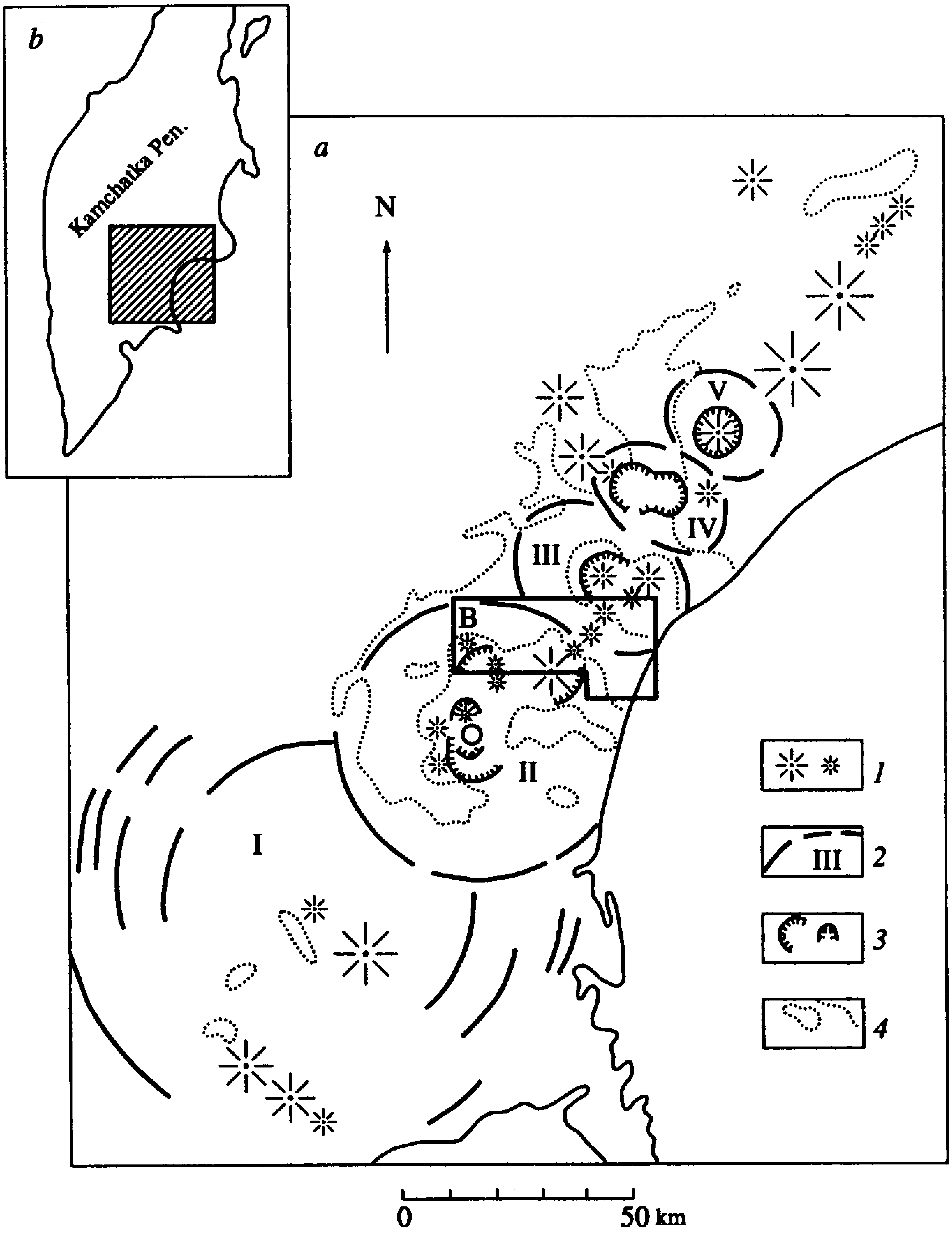


Figure 1 Map (*a*) of major volcanic centers and fields of Late Quaternary ignimbrites in the central area (*b* – location of the study area): *1* – volcanoes; *2* – inferred outlines of major volcanic centers: I – Nalachevskii, II – Karymskii, III – Bolshoi Semyachik, IV – Uzon-Geizernyi; *3* – calderas, *4* – fields of Late Quaternary ignimbrites; B – location area of the map presented in Fig. 2.

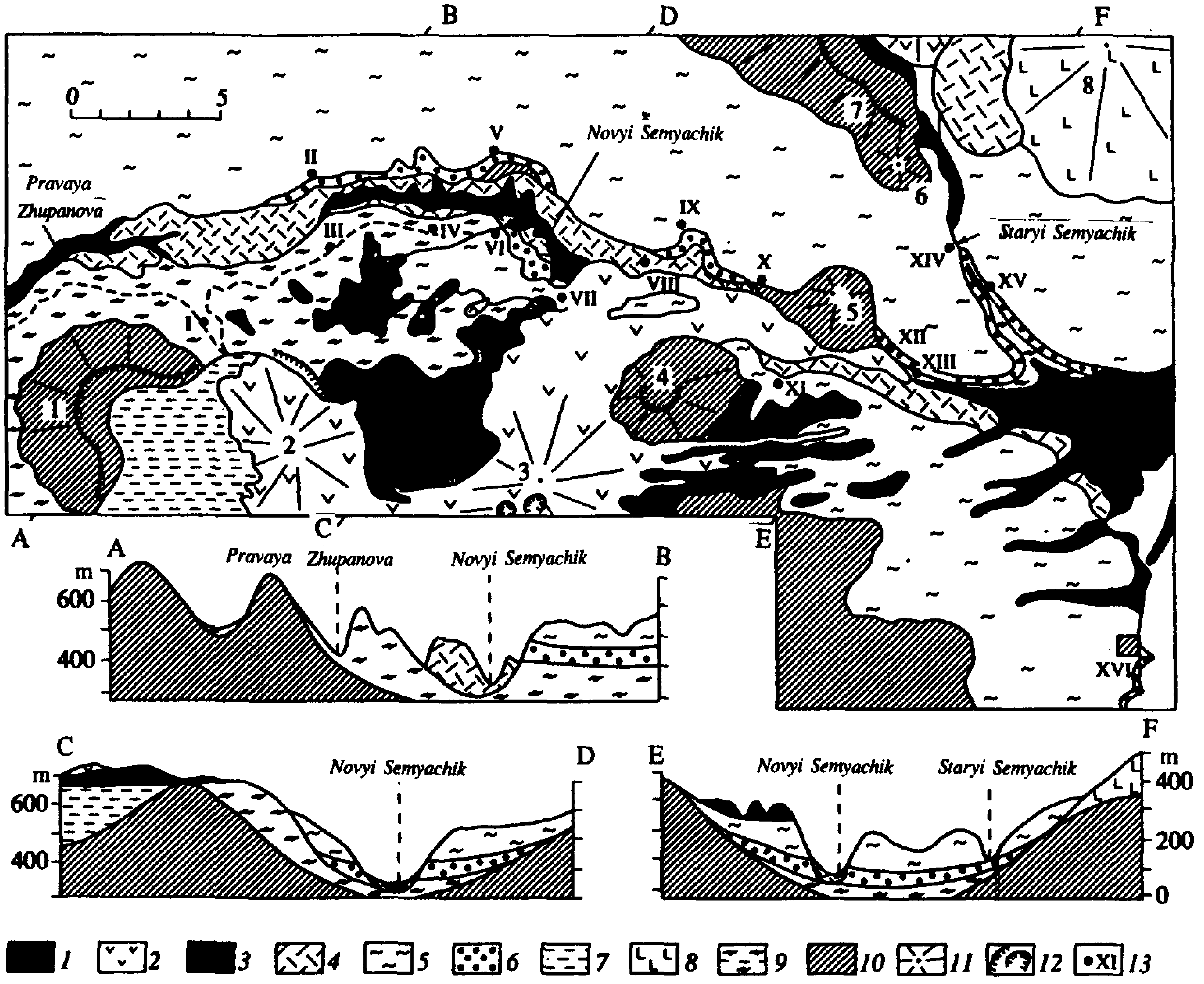


Figure 2 Geological map of the Novyi Semyachik R. basin (plotted with the use of O. B. Selyangin data [15]): *1* - alluvium (Q_4); *2* - basaltic andesite and basalt lavas, volcanic breccias, and cinder (Q^4_3-Q_4); *3* - agglomerate cinder tuff (Q^4_3); *4* - agglomerate pumice tuff and ignimbrite (emplaced in the valleys of the Novyi Semyachik and Pravaya Zhupanova rivers, undifferentiated) (Q^4_3); ignimbrites associated with the Uzon-Geizernyi volcanic center (Q_3); *6* - agglomerate pumiceous quartz-biotite tuff associated with the Bolshoi Semyachik volcanic center (Q_3); *7* - sandstones, siltstones (lake beds in the caldera of Sobolinyi Volcano) ($Q_{2\text{-}3}$); *8* - andesitic lavas (Q_2); *9* - ignimbrites associated with the Karymskii volcanic center (Q_2); *10* - basaltic andesite and basaltic lavas, volcanic breccias, and tuff of precaldera volcanoes ($Q_{1\text{-}2}$); *11* - volcanoes (1 - Sobolinyi, 2 - Stupenchatyi Bastion, 3 - Malyi Semyachik, 4 - Berezovyi, 5 - Dvukhyurtochnyi, 6 - Nezametnyi, 7 - Bort, 8 - Problematichnyi); *12* - erosion scarps of calderas and craters; *13* - location and numbers of sections.

previously been investigated comprehensively by other volcanologists [5], [8], [15]. Therefore, prior to our own survey we had a sufficiently representative database on all (Karymskii, Semyachik, and Uzon) ignimbrites and identified the characteristic features of their sequences, as well as criteria to be used for their correlation.

METHODS OF STUDY

We carried out a detailed survey of the sequences of pyroclastic deposits that were exposed on the sides of the valley of the Novyi Semyachik River, where, as followed from the previous work, the ignimbrites of all three sequences were exposed. We located and traced along the valley sides a typical marker - a layer of quartz-biotite pumiceous tuff of rhyolite composition. We correlated ignimbrite sequences from different localities, collected ignimbrite samples and made their chemical, mineralogic, and petrochemical analyses. The compositions of mineral phases and residual glasses from the ignimbrite samples were determined using a Camebax microprobe.

RESULTS

Description of geologic sections. Figures 2 and 3 show our geological map of the Novyi Semyachik River basin and the geological sections of the deposits that are exposed in the study area. One can see that the ignimbrites and the related pumice and cinder tuffs compose the larger part of the study area. They crop out on the sides of the river valleys, where they make up extensive plateaus, and also on the floor of the valleys where they have a valley-in-valley cross profile. We identified two units of ignimbrite deposits: a valley-side unit (plateau ignimbrites) and a valley-floor unit (valley ignimbrites). The rocks of the former are more abundant and were subdivided into three sequences thanks to the presence of a distinct marker - a bed of pumiceous quartz-biotite tuff. One of them (lower) is exposed mainly in the west of the study area, on the slopes of the caldera of Sobolinyi Volcano (Fig. 2). Earlier the ignimbrites of this sequence had been investigated by B. V. Ivanov [8] in the upper reaches of the Pravaya Zhupanova River, who associated these ignimbrites with the Karymskii volcanic center. The next sequence is made up of agglomerate pumiceous quartz-biotite tuff associated with the beginning of caldera-forming activity in the Bolshoi Semyachik volcanic center [6]. This tuff rests on the ignimbrite of the lower sequence (Fig. 2). It was found in all sections on the northern side of the Novyi Semyachik R. valley, and also at the base of section VI on its southern side (Fig. 3). The third (upper) sequence of the valley-side ignimbrites occurs everywhere above the pumiceous quartz-biotite tuff and is most widely spread in the area. These ignimbrites make up an extensive plateau in the north and east of the area, which extends as far as the coast where the ignimbrites occur as gently dipping capes extending far into the ocean (Fig. 2). It was not difficult to trace the ignimbrites of the lower and middle sequences to their parental volcanic centers (Karymskii and Semyachik, respectively). The tracing of the upper ignimbrite sequence to the Uzon volcano, as it is shown in Fig. 2, required more detailed mineralogic studies which will be discussed below.

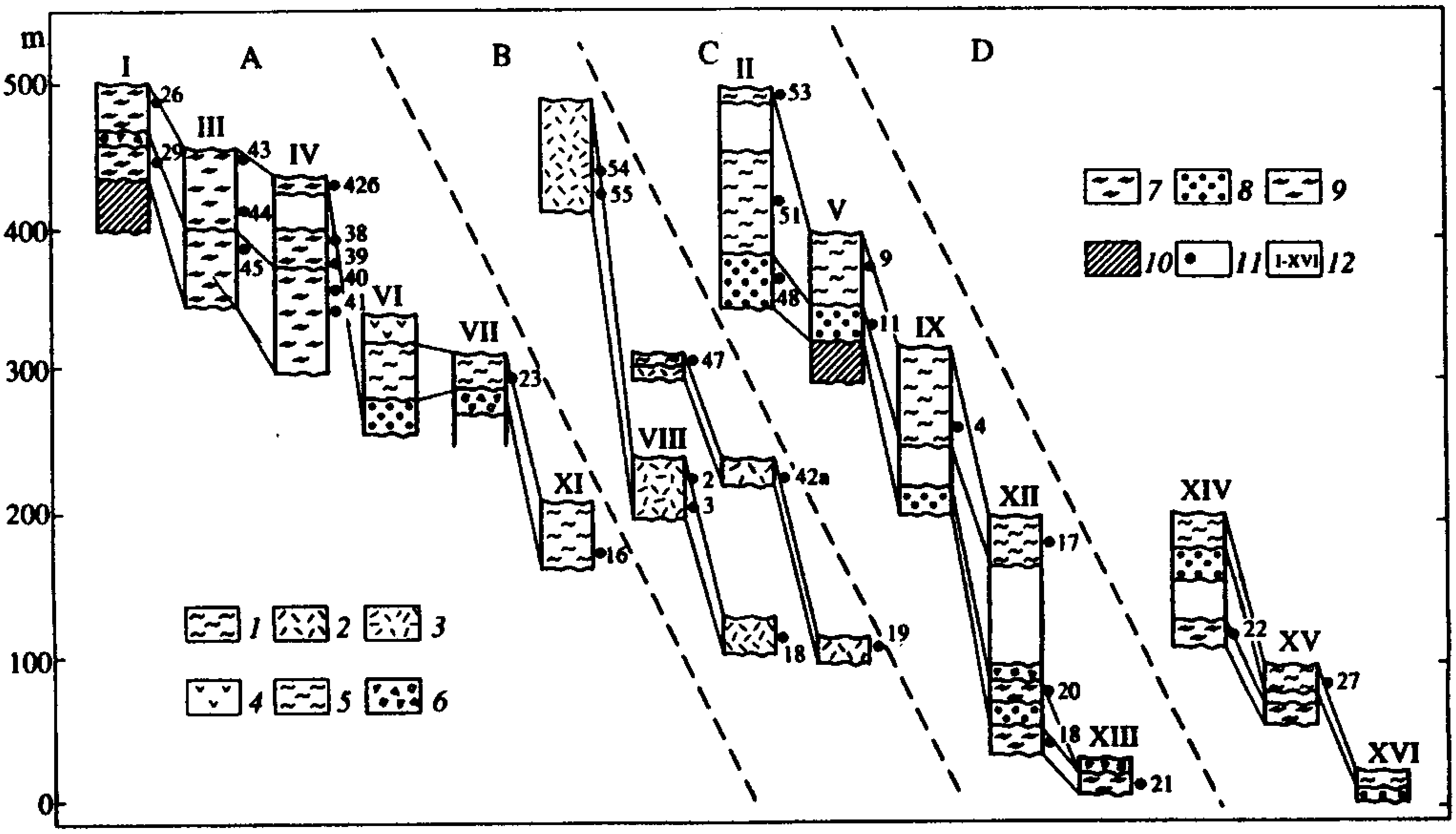


Figure 3 Correlation of ignimbrite deposits exposed in the basin of the Novyi Semyachik River and adjacent areas: *1-3* - deposits emplaced in the Novyi Semyachik R. valley (*1* - ignimbrite, *2* - agglomerate andesite tuff, *3* - agglomerate dacite tuff); *4* - basaltic andesite lava; *5* - Uzon ignimbrite; *6* - glacial (boulder) deposits; *7* - Semyachik ignimbrite; *8* - Semyachik agglomerate pumiceous quartz-biotite tuff; *9* - Karymskii ignimbrite; *10* - precaldera deposits (tuffstones, tuffaceous siltstones, and basaltic andesite and basalt lavas); *11, 12* - numbers of samples and sections, respectively (see the text). A - deposits on the right (southern) side of the Novyi Semyachik R. valley. B - deposits emplaced in the valley. C - deposits on the left (northern) side of the Novyi Semyachik R. valley. D - deposits exposed along the Staryi Semyachik River (XIV, XV) and near Zhupanova Village on the ocean shore (XVI).

The ignimbrites and tuffs of the second unit, emplaced into the valley floors of the Novyi Semyachik and Pravaya Zhupanova rivers, are less abundant (Fig. 2). They had been deposited much later than the plateau ignimbrites exposed in the sides of the valleys. Based on the mode of their occurrence and compositional features, we differentiated them into two sequences: an older one composed of agglomerate pumiceous dacite tuff and a younger one consisting of psephitic cinder tuff and andesite ignimbrite. The deposits of the former are as thick as 100 m and fill almost completely the valley of the Novyi Semyachik River in its upper course (section along line A-B in Fig. 2). In the middle and lower segments of the valley much of these deposits had been eroded except for ubiquitous outliers. The deposits of the younger sequence occur at the floors of ravines and washouts produced in the deposits of the older sequence. They have a thickness as small as 20-30 m. The outliers of these deposits, which had previously filled the whole of the Novyi

Semyachik R. valley, occur at the present time as isolated outcrops in many places of its middle and lower parts (Sites 19, 42a, and 47 in Fig. 3).

Ignimbrite deposits of the lower (Karymskii) sequence of the valley-side unit. As mentioned above, the most complete sequences of these deposits are exposed in the upper reaches of the Novyi Semyachik and Pravaya Zhupanova rivers, on the slopes of the caldera of Sobolinyi Volcano (Fig. 2). The following rocks are exposed in Section IV (Figs 2 and 3), downward:

1. Gray ignimbrite with thin winding fiammes of black glass, 20 m;
2. Black ignimbrite with abundant black fiammes, 8 m;
3. Dark gray dense fine-clastic ignimbrite with fine cleavage and fiammes as thin glass layers, 2 m;
4. Light gray baked tuff with numerous, slightly flattened fragments of light gray pumice and cinder, 3 m;
5. Brick-red dense, lava-like ignimbrite, 7 m;
6. Lilac-colored ignimbrite with thin, winding fiammes of dark brown crystallized glass and numerous fragments of brown-red color, 3m.

A similar sequence with the repetition of layers 1–4 is exposed westward near the Golubichnyi Pass (Section III in Figs 2 and 3).

Ignimbrites similar to those described above (Section I in Figs 2 and 3) are abundant farther westward in the upper reaches of the Pravaya Zhupanova River. Here, a thick sequence of precaldera thin-bedded tuffaceous sandstones, tuffaceous gritstones, and psephitic tuffs is overlain by (downward):

1. Gray ignimbrite with thin winding fiammes of black, partially crystallized glass, 30 m;
2. Brick-red ignimbrite with numerous cinder fragments, 15 m;
3. Agglomerate tuff with lava and glass fragments, 2m;
4. Light brown, earthy ignimbrite with numerous slightly flattened fragments of black cinder and glass, 6 m;
5. Conglomerate with boulders, 10 to 30 cm in size, made up mainly of compositionally varying lavas, 6 m;
6. Dark-gray dense ignimbrite with abundant fiammes of black glass, 6 m;

A distinctive feature of the above ignimbrites is that they include rocks of reddish brown or lilac colors. As mentioned in [5], the reddish tint of many ignimbrites from the Karymskii volcanic center can be explained by the presence of numerous stone bubbles filled with an earthy aggregate of brick-red color. Rims of this material were found on some fragments present in the rocks. Because the rocks with a red or lilac tint were very rare among the ignimbrites of the Bolshoi Semyachik and Uzon-Geizernyi volcanic centers, which had been studied by us earlier [6], [7], the wide development of these rocks among the ignimbrites of the Karymskii center can be used as an extra marker for correlations in the study area.

To have a mineralogic characteristic of the Karymskii ignimbrites, we collected samples from Sections III and IV located in the upper reaches of the Novyi Semyachik River (Figs 2 and 3), and also two samples (nos. 60 and 61) from a section located on the Karymskii River below the mouth of Uglovoi Creek (beyond the limits of the area shown in Fig. 2). The ignimbrites exposed along the Karymskii River had been described earlier by many volcanologists [5], [8], [15] and were used in our study as a standard of the Karymskii ignimbrite. The results of our bulk chemical analyses and mineral phase analyses are listed in Tables 1 and 2. They suggest that we collected samples from two fields of the Karymskii ignimbrites, which we labelled conventionally as the lower and upper fields. The ignimbrites of the lower field showed a rather uniform dacite composition (63.6–64.4 SiO_2) with an insignificant growth in SiO_2 in its lower part. The ignimbrites of the upper field were found to be more silicic, their composition ranging from rhyodacite at the base to dacite at the top.

Using a Camebax microprobe we studied the mineral assemblages in all of the ignimbrite varieties. Figure 4 shows relationships between the Mn and Fe contents in all of the studied samples. This figure also shows the fields of the data points of the orthopyroxenes we had studied earlier from the ignimbrites of the Bolshoi Semyachik and Uzon-Geizernyi volcanic centers (Semyachik and Uzon ignimbrites). One can see that the iron content of orthopyroxenes from the studied samples of the Karymskii ignimbrites varies very little from 28 to 31% (in some grains to 32–33%). The manganese concentration varies from 0.7–1.2% in the low-Si dacite to 1.2–1.9% in more silicic rocks. Generally, the data points of the orthopyroxenes from the Karymskii ignimbrites produce a compact isolated region which does not coincide with the similar regions of the Semyachik or Uzon ignimbrites, being lower in Fe and higher in Mn.

Figure 5 presents histograms of plagioclase phenocryst distribution in the studied ignimbrite samples. For the Karymskii ignimbrites we plotted data for the bottoms and tops of two studied fields. One can see that the lower (earlier) ignimbrites differ by their more homogeneous composition and a unimodal distribution of anorthite in the phenocrysts, and the upper, by its more complex composition and a bimodal anorthite distribution (Fig. 5, *a–d*). The plagioclase composition also varies along the section of each pyroclastic field. The base of the lower field is dominated by andesine–labradorite (45–55% An), its plagioclase growing more calcic (Fig. 5, *a* and *b*). The upper pyroclastic field is dominated by andesine (40–45% An) which is replaced upward by andesine–labradorite.

The results of studying the compositions of titanomagnetites from the same ignimbrite samples are plotted in the Al_2O_3–MnO–MgO diagram of Fig. 6 which also shows the data points of the Semyachik and Uzon ignimbrites. The data points of the titanomagnetites from the Karymskii ignimbrites generally occur as an isolated group and are distinguished by their high Al, moderate Mg, and low Mn concentrations. At the same time the titanomagnetites from the last portion of the upper field of the Karymskii ignimbrites are

Table 1 Compositions of ignimbrites exposed in the valleys of the Karymskaya and Novyi Semyachik Rivers.

Ignimbrites	Karymskii										Semyachik	Uzon		Emplaced in river valleys	
N	61	60	45a	45b	45c	41	44	39	38	42c	20	16	17	18	42a
SiO_2	64.24	63.08	63.89	64.39	63.87	63.65	69.15	69.46	63.00	62.95	67.10	67.20	67.36	64.86	62.40
TiO_2	0.57	1.01	1.08	1.07	1.05	0.99	0.77	0.77	0.88	0.96	0.52	0.80	0.77	0.68	1.05
Al_2O_3	15.21	15.54	15.79	15.52	16.14	15.56	15.50	15.10	16.08	17.00	16.03	15.07	15.16	16.76	16.36
Fe_2O_3	1.83	3.38	2.85	2.97	2.36	3.14	1.57	1.63	2.32	2.08	2.84	1.92	1.84	2.15	2.68
FeO	4.99	4.68	3.50	4.17	4.76	3.05	2.50	2.39	4.80	4.50	3.90	3.30	3.19	2.97	4.08
MnO	0.17	0.17	0.18	0.17	0.18	0.13	0.07	0.12	0.17	0.17	0.17	0.15	0.14	0.15	0.15
MgO	1.80	1.64	2.19	1.68	1.26	2.00	0.98	1.15	2.27	1.74	0.54	1.22	1.65	2.63	1.67
CaO	3.82	4.59	3.96	3.56	4.13	4.63	2.76	1.79	4.17	4.46	2.16	2.98	3.17	5.20	5.14
Na_2O	5.12	4.05	4.17	4.26	4.33	4.30	4.72	4.76	4.33	4.23	4.12	4.70	4.43	2.83	4.18
K_2O	2.24	1.85	2.38	2.20	1.92	2.54	1.94	2.96	1.97	1.91	2.61	2.61	2.28	1.74	2.29

Note. Analyses were made at the Central Chemical Laboratory of the Institute of Volcanology, Far East Division, Russian Academy of Sciences, analysts L. A. Kartasheva and V. V. Dunun-Barkovskaya. Location and numbers of the samples are given as in Fig. 3

Table 2 Compositions of ignimbrites exposed in the valleys of the Karymskaya and Novyi Semyachik Rivers.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	54.48	56.07	57.79	55.22	57.47	55.97	53.55	52.73	53.47	53.94	54.32
TiO_2	-	-	-	-	-	-	-	0.45	0.24	0.24	0.20
Al_2O_3	28.13	26.42	25.91	27.97	26.61	26.20	28.45	0.67	0.73	0.47	0.70
FeO^*	0.59	0.57	0.45	0.73	0.24	0.57	0.61	19.77	18.86	18.66	18.04
MgO	-	-	-	-	-	-	-	23.90	23.73	23.63	24.26
CaO	10.73	11.19	8.25	10.62	9.38	8.91	11.48	1.86	1.83	1.28	1.29
Na_2O	4.98	4.45	5.73	5.64	5.57	7.68	4.58	-	-	-	-
K_2O	0.20	0.33	0.34	0.24	0.29	0.41	0.13	-	-	-	-
MnO	-	-	-	-	-	-	-	1.08	0.87	1.50	1.04
Σ	99.16	99.23	98.54	100.52	99.61	99.85	98.99	100.47	99.60	99.79	99.90
Or	1.21	2.01	2.16	1.37	1.75	2.08	0.80	-	-	-	-
Ab	45.10	41.01	54.47	43.37	50.9	59.68	41.61	-	-	-	-
An	53.68	56.98	48.32	50.31	47.35	38.25	57.50	-	-	-	-
fm	-	-	-	-	-	-	-	31.70	29.87	30.69	29.44
Wo	-	-	-	-	-	-	-	3.68	3.70	2.63	2.63
En	-	-	-	-	-	-	-	65.79	66.80	67.48	68.70
Fs	-	-	-	-	-	-	-	30.53	29.50	29.89	28.67

	12	13	14	15	16	17	18	19	20	21	22
SiO_2	52.74	53.15	52.85	53.80	-	-	-	-	-	-	-
TiO_2	0.24	0.16	0.30	0.32	11.44	7.90	10.19	11.04	18.86	7.96	8.02
Al_2O_3	0.39	0.13	0.54	1.10	2.38	2.74	1.04	1.89	1.55	1.47	2.79
FeO^*	26.31	21.54	18.77	17.47	83.81	87.19	86.03	85.56	87.59	89.47	88.67
MgO	17.31	20.77	24.27	24.69	1.19	0.28	0.98	0.53	1.56	0.78	1.60
CaO	1.81	0.84	1.36	1.52	-	-	-	-	-	-	-
Na_2O	-	-	-	-	-	-	-	-	-	-	-
K_2O	-	-	-	-	-	-	-	-	-	-	-
MnO	1.05	1.60	1.38	0.39	0.63	0.41	1.28	0.52	0.87	0.78	0.33
Σ	99.85	98.87	99.55	99.30	99.76	99.28	99.20	99.66	100.47	100.53	101
Or	-	-	-	-	-	-	-	-	-	-	-
Ab	-	-	-	-	-	-	-	-	-	-	-
An	-	-	-	-	-	-	-	-	-	-	-
fm	46.03	36.78	30.26	28.42	-	-	-	-	-	-	-
Wo	3.89	1.81	2.73	3.07	-	-	-	-	-	-	-
En	51.87	62.07	67.84	69.38	-	-	-	-	-	-	-
Fs	44.24	36.12	29.43	27.55	-	-	-	-	-	-	-

Note. 1–7 – plagioclase (1, 2 and 3, 4 – Karymskii ignimbrites from the lower and upper plateaus, respectively; 5 – Semyachik ignimbrite; 6, 7 – Uzon ignimbrite); 8–15 – orthopyroxene (8, 9 and 10, 11 – Karymskii ignimbrites from the lower and upper plateaus, respectively; 12 – Semyachik ignimbrites; 13, 14 – Uzon ignimbrite; 15 – ignimbrite emplaced into the valley of the Novyi Semyachik River; 16-22 – titanomagnetite (16, 17 and 18, 19 – Karymskii ignimbrites from the lower and upper plateaus, respectively; 21 – Uzon ignimbrite; 22 – ignimbrite emplaced in the valley of the Novyi Semyachik River). Analyses were made on a Camebax microprobe at the Institute of Volcanology, Far East Division, Russian Academy of Sciences.

distinguished by their higher Mn content, and their data points occur as an isolated region located at the boundary between the Semyachik and Uzon ignimbrite regions (Fig. 6).

Ignimbrite deposits of the middle sequence of the valley-side (Semyachik) unit. As mentioned above, this sequence is mainly composed of agglomerate pumiceous quartz-biotite tuff which was encountered in all sections examined on the northern side of the Novyi Semyachik R. valley, and also at the base of Section VI on its southern side

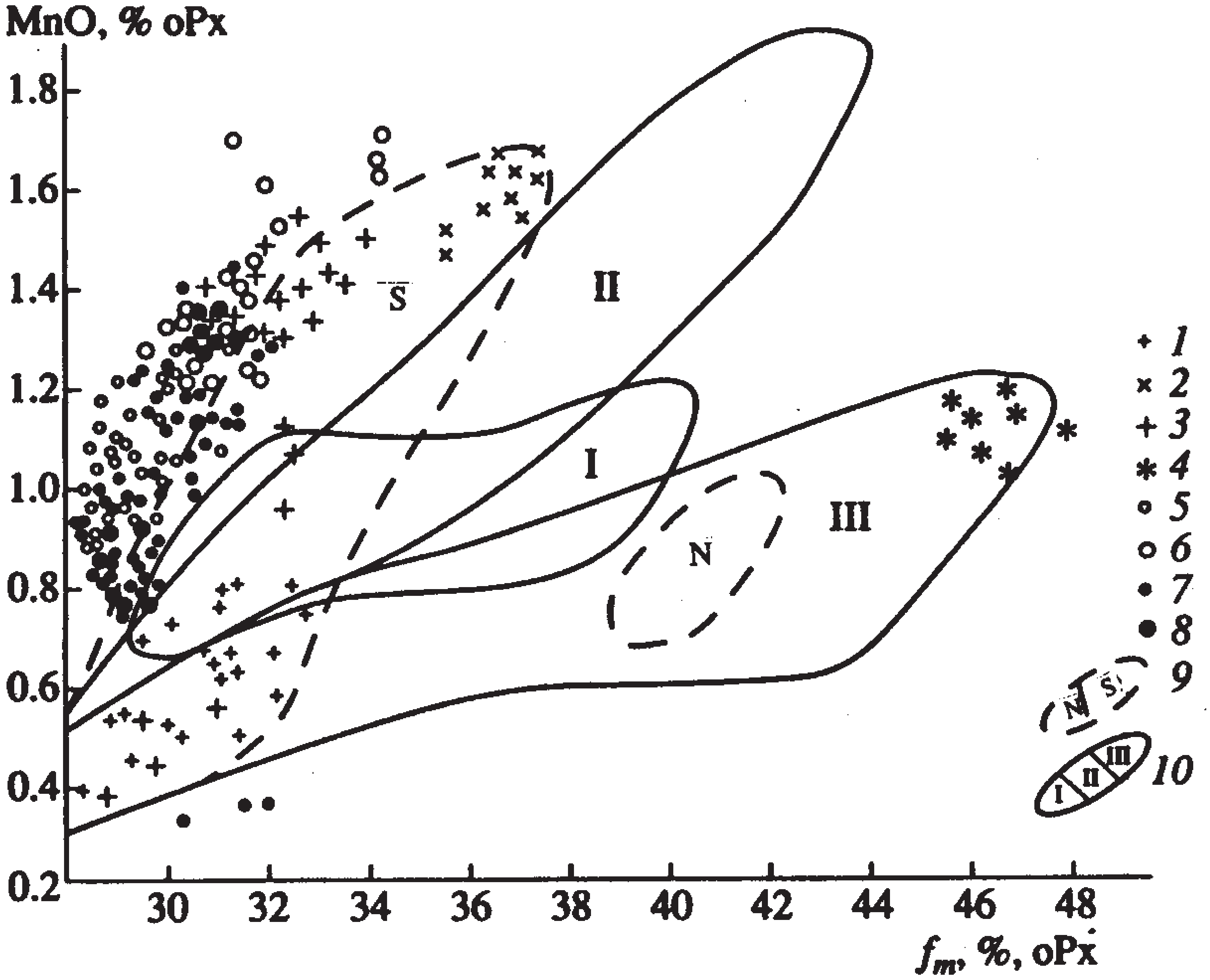


Figure 4 The distribution of MnO as a function of f_m in orthopyroxene phenocrysts from the samples under study: *1* – andesitic ignimbrites (emplaced in the valley of the Novyi Semyachik River); *2* – agglomerate pumiceous dacite tuff (emplaced in the valley of the Novyi Semyachik River); *3* – Uzon ignimbrite; *4* – Semyachik ignimbrite; *5-8* – Karymskii ignimbrites (lower (*5*) and upper (*6*) portions of the upper plateau); *7, 8* – lower and upper portions of the lower plateau, respectively; *9* – regions of orthopyroxenes from the previously studied Uzon ignimbrites of the northern (N) and southern (S) fields [7]; *10* – regions of the previously studied Semyachik ignimbrites emplaced during events I, II, and III.

(Figs 2 and 3). The ignimbrites that occur above this tuff and form extensive fields north of the Novyi Semyachik River had been interpreted by other volcanologists, including us, as the Semyachik formations [5], [10], [15], [17]. However the data on the composition of minerals from these rocks, given below, and the comparison of these data with the results of our earlier study of minerals from the Semyachik ignimbrites [6] prove these inferences to be erroneous. The Semyachik ignimbrites are distinguished by the higher Fe content of their pyroxenes [6]. This value varies from 28 to 47% depending on the composition of the ignimbrites. Earlier, based on the Fe number of the orthopyroxenes and on the Mn content in them, we plotted three isolated regions characterizing the composition of orthopyroxenes from the ignimbrites produced during three periods of ignimbrite formation in the Bolshoi Semyachik volcanic center (Fig. 4). Only one of the studied samples of the ignimbrites exposed in the Novyi Semyachik R. basin, the one that

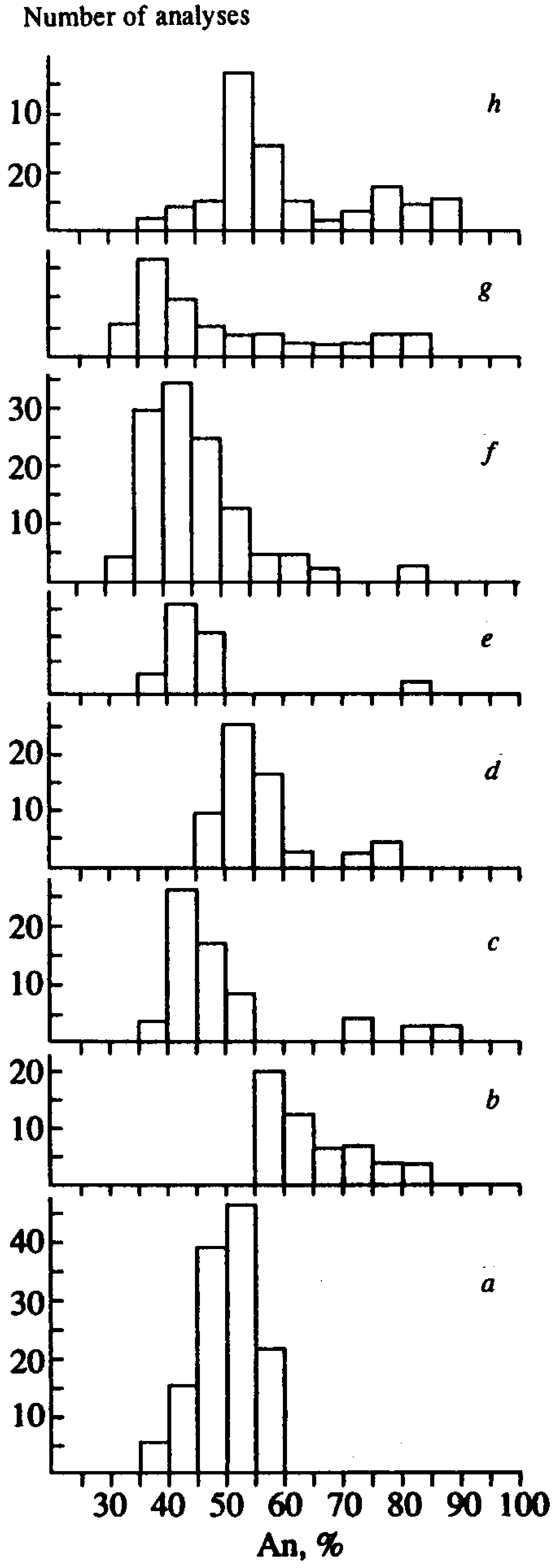


Figure 5 Histograms for the frequency distribution of plagioclase phenocrysts: *a*, *b* - Karymskii ignimbrites, bottom and top of the lower sequence, respectively; *c*, *d* - Karymskii ignimbrites, bottom and top of the upper sequence, respectively; *e* - Semyachik ignimbrite; *f* - Uzon ignimbrite; *g* - agglomerate pumice dacite tuff emplaced in the valley of the Novyi Semyachik River; *h* - andesitic ignimbrite emplaced in the valley of the Novyi Semyachik River.

was collected from the lower part of Section XII (Figs 2 and 3), contained high-Fe hypersthene (f_m 45–47%) and could be classified as a Semyachik ignimbrite.

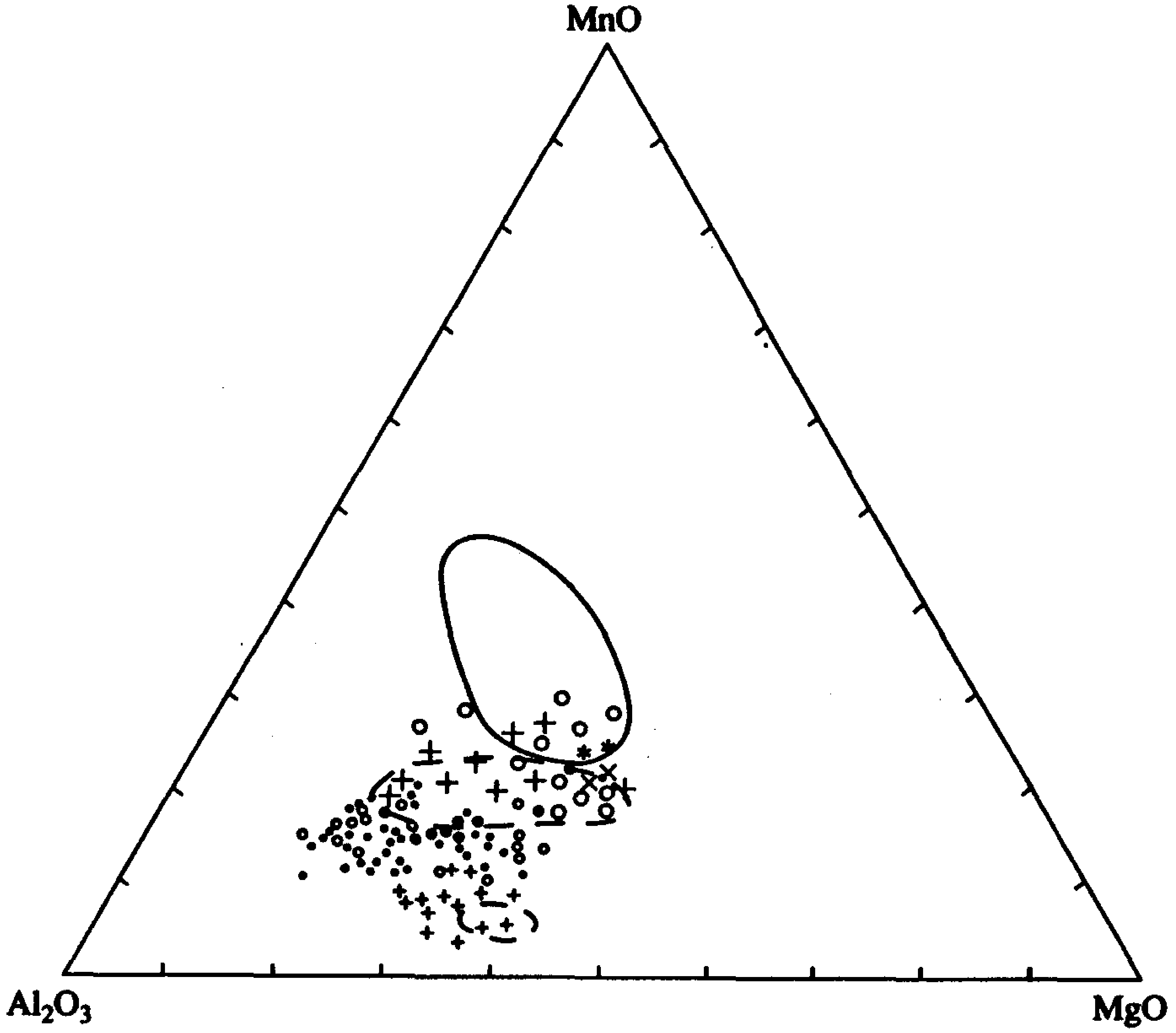


Figure 6 Al_2O_3–MnO–MgO diagram for titanomagnetite phenocrysts. See Fig. 4 for the explanation of symbols. For the Uzon ignimbrite: the upper oval – titanomagnetites from the ignimbrites of the southern and northern fields, the lower oval – phenocrysts from welded basaltic andesite cinder.

The following rocks are exposed in Section XII, where the tuffs and ignimbrites of the middle sequence from the valley-side unit are exposed most completely, downward:

1. Gray dense ignimbrite with poorly discernible fiammes of crystallized glass and numerous fragments, 30 m;
2. Unexposed portion, 60 m;
3. Rubble with boulders as large as 30–50 cm and even 1–2 m (occasional) of varying composition, mostly of lava and ignimbrite, 3 m;
4. Black dense ignimbrite with scarce small fragments welded into the rock, 15 m;
5. White pumiceous crystal-lithic tuff containing numerous quartz and biotite

phenocrysts, 10 m;

6. Gray, tinted red, ignimbrite containing numerous black glass fiammes, 15 m.

We attributed the lower ignimbrite layer from this section to the sequence of the Karymskii ignimbrites described above, the upper layer, to the Uzon ignimbrites to be described below, and layers 4 and 5, to the ignimbrites associated with the Bolshoi Semyachik volcanic center. The sample containing high-Fe hypersthenes was collected from layer 4. The fact that the data points of pyroxenes from this sample were plotted in the MnO-f_m diagram in the region of the Semyachik ignimbrites of the last third phase (Fig. 4) suggests that the ignimbrite exposed in Section XII belongs to one of the last pyroclastic flows associated with the formation of the Bolshoi Semyachik caldera. This inference is supported by the composition of the plagioclase phenocrysts from this sample (Fig. 5, *e*), which is in absolute agreement with the composition of plagioclase from the dacite ignimbrite emplaced at the beginning of the third event of ignimbrite formation in the Bolshoi Semyachik volcanic center [6].

The results of studying the compositions of titanomagnetites, plotted in the Al_2O_3–MnO–MgO diagram (Fig. 6), show that the titanomagnetites from the ignimbrite of layer 4 in Section XII are plotted in the lower part of the region of the previously studied pyroclastics of the Bolshoi Semyachik caldera, namely, in the part containing data points of phenocrysts from the dacite ignimbrite of the last (third) event of ignimbrite formation [6].

Pumiceous quartz–biotite tuff alone was attributed to the sequence concerned in all other sections of ignimbrites deposited in the Novyi Semyachik River drainage basin. This material had been deposited everywhere as loose, fine-grained pumiceous sand and is now represented by unstratified or agglomerate tuff consisting mainly of 10–15-cm fragments of white highly porous, fibrous pumice.

Ignimbrite deposits of the upper sequence of the valley-side (Uzon) unit. These deposits make up the upper parts of all sections on the northern side of the Novyi Semyachik R. Valley and were encountered in Sections VI, VII, and XI on its southern side as well as in the area of the Zhupanovo Village on the oceanic coast (Section XVI) (Figs 2 and 3). The ignimbrites of this sequence armor a plateau that extends north of the Novyi Semyachik R. Valley, being exposed almost ubiquitously in the edges of the cliffs bounding the valley. Almost in all investigated sections these ignimbrites rest on the pumiceous quartz-biotite tuff described above. Below we describe some characteristic sections. The following rocks are exposed in the upper reaches of the Novyi Semyachik River (Section II in Figs 2 and 3), downward:

1. Ignimbrite and agglomerate tuff with a great number of cinder fragments, 5 m;
2. Unexposed portion of the section, 30 m;
3. Gray ignimbrite containing scarce, poorly discernible, tightly welded fiammes of crystallized glass, 20 m;
4. Gray ignimbrite with abundant fiammes of black glass, 4 m;

5. Dark gray dense ignimbrite with light poorly discernible fiammes, 10 m;

6. Light brown layered psammitic and psephitic tuff, 3 m;

7. Gray and dark gray ignimbrite containing numerous black cinder fragments, some elongated as fiammes, 30 m;

8. White pumice and agglomerate crystal-lithic tuff containing quartz and biotite crystals, 30 m.

Similar sequences are exposed in the middle segment of the valley (V, IX, and X in Figs 2 and 3). The following rocks are exposed along Shirokii Creek (Section IX), downward:

1. Gray ignimbrite with scarce poorly discernible fiammes of crystallized glass showing block parting, 10 m;

2. Gray ignimbrite with fiammes of black glass and thick-plate parting, 12 m;

3. Gray, poorly welded, earthy ignimbrite with numerous slightly flattened fragments of black cinder, 8 m;

4. Yellow stratified psephitic pumiceous tuff, 5 m;

5. Black glassy, highly welded ignimbrite, 3 m;

6. Black poorly welded ignimbrite with numerous cinder and lava fragments, as large as 5-10 cm, showing columnar parting, 20 m;

7. Light gray dense, thick-platy ignimbrite with scarce black glass fiammes, 10 m;

8. Psephitic, pumice and agglomerate tuff with quartz and biotite, 5m.

Only the upper layers (1, 2, and 3) are exposed in Sections V and X.

Pumiceous quartz-biotite tuff was encountered only in one place (Section VI in Figs 2 and 3) along the right, southern side of the Novyi Semyachik R. Valley. This tuff is overlain by ignimbrite similar to the upper layers from the above section: gray with poorly discernible lighter fiammes. In the lower reaches of the river, along the right side of the valley (Section XI) we encountered ignimbrites similar to the above layers 1 and 2, but more welded and looking like lava. For the purpose of the mineralogic characterization of these deposits we collected ignimbrite samples from Sections XI and XII (Samples 16 and 17 in Fig. 3). These ignimbrites differ by their more lava-like habit, have fiammes of devitrified glass, and had been previously interpreted as Semyachik or Karymskii ignimbrites [5], [10], [15], [17]. Chemically they can be classified as high-Si dacite (Table 1). Earlier [6], [11], based on our large statistic material, we established that the Semyachik and Uzon ignimbrites differed in the Fe content of their pyroxenes and in the Mn content of the orthopyroxenes. We found that the Fe content varied from 28 to 47% in pyroxenes from the Semyachik ignimbrites and from 30 to 41% in pyroxenes from the Uzon ignimbrites. Furthermore, the Uzon ignimbrites showed significant differences in the pyroxene compositions in the major Northern and Southern fields of their distribution [7]. The pyroxenes from the ignimbrites of the northern field contain more iron (37-41%) and less manganese (0.7-1.0%), and the pyroxenes from the ignimbrites of the southern field contain less iron (30-34%) and more manganese (1.0-1.5%).

Moreover we found a difference between the lower and upper ignimbrite layers within the same southern field: the pyroxenes from the former are higher and those from the latter are lower in manganese [11].

As follows from Fig. 4, the orthopyroxenes from the ignimbrite samples collected from Sections XI and XII (Samples 16 and 17 in Fig. 3) are less ferriferous than the Semyachik ones. At the same time their data points exactly cover the region outlining the pyroxenes of the Uzon ignimbrites from the Southern field. Moreover, judging by the elevated Mn content in them, they are closest to the pyroclastics from the basal portions of the sections of the Uzon ignimbrites from the Southern field. Therefore the interpretation of these rocks as Semyachik ignimbrites was erroneous. Neither can they be interpreted as Karymskii ignimbrites because the latter lie, as has been shown above, under the quartz-biotite tuff and have an older age.

The composition of the plagioclase phenocrysts from the ignimbrites concerned is slightly more sodic than that from the other ignimbrites, although generally it is little different from that in the studied sample of Semyachik ignimbrite (Fig. 5). The compositions of titanomagnetites plotted in the Al_2O_3–MnO–MgO diagram lie mostly in the region of the Uzon ignimbrites and some at the boundary between the regions of the Uzon and Semyachik ignimbrites (Fig. 6).

Proceeding from the above considerations, we arrived at the conclusion that the ignimbrites of the upper sequence of the valley-side unit were the Uzon ignimbrites. Earlier we traced the outcrops of similar ignimbrites continuously from the sides of the Uzon-Geizernaya Depression southward as far as the study area [7], [9], [10]. They cover almost the entire area north of the Novyi Semyachik River and also the area in its lower course where they armor flat plateaus gently dipping toward the ocean. Also they are exposed in the shore cliffs in the area of Zhupanovo Village (Section XVI in Figs 2 and 3). Many attempts were made to determine the absolute age of the ignimbrites exposed in the Zhupanovo Area [21]. The latest dating of soil collected from their base yielded a date of 35–37 thousand years (I. V. Melekestsev, personal communication). This indicates that the ignimbrites discussed in this section are close to the Uzon ignimbrites in chronological terms too (the age of the soil collected from the base of the Uzon ignimbrites near the Kronotskii Lake was found to be 39 thousand years [16]).

Ignimbrite deposits from the valley floors of the Novyi Semyachik and Pravaya Zhupanova rivers. These deposits which heretofore were referred to as the second or the valley-floor unit occur, as mentioned above, in the form of two sequences: an older sequence made up of agglomerate pumiceous dacite tuff and a younger one composed of psephitic cinder tuff and andesite ignimbrite. The most complete section of the pumiceous tuff of the older sequence is exposed in the middle course of the Novyi Semyachik River (Section VIII in Figs 2 and 3), where a uniform but not stratified sequence of light pumiceous psephitic tuff as thick as 100 m is exposed along the left side of the river. The fragments of the fibrous pumice are as large as 2 cm and fall out easily imparting a cavernous look to the rock. The tuff of this sequence that is exposed in the upper and lower reaches of the river (Samples 54, 55, and 18 in Fig. 3) is absolutely identical to the tuff described above. The bulk chemical analysis of this tuff (Sample 18 in Table 1) revealed its dacitic composition. Based on the compositions of its orthopyroxene and titanomagnetite corresponding data points were plotted in the region of orthopyroxenes and titanomagnetites from the Uzon ignimbrite of the Southern field (Figs 4 and 6). The composition of its plagioclase is also more close to the composition of plagioclase from the Uzon ignimbrite (Fig. 5).

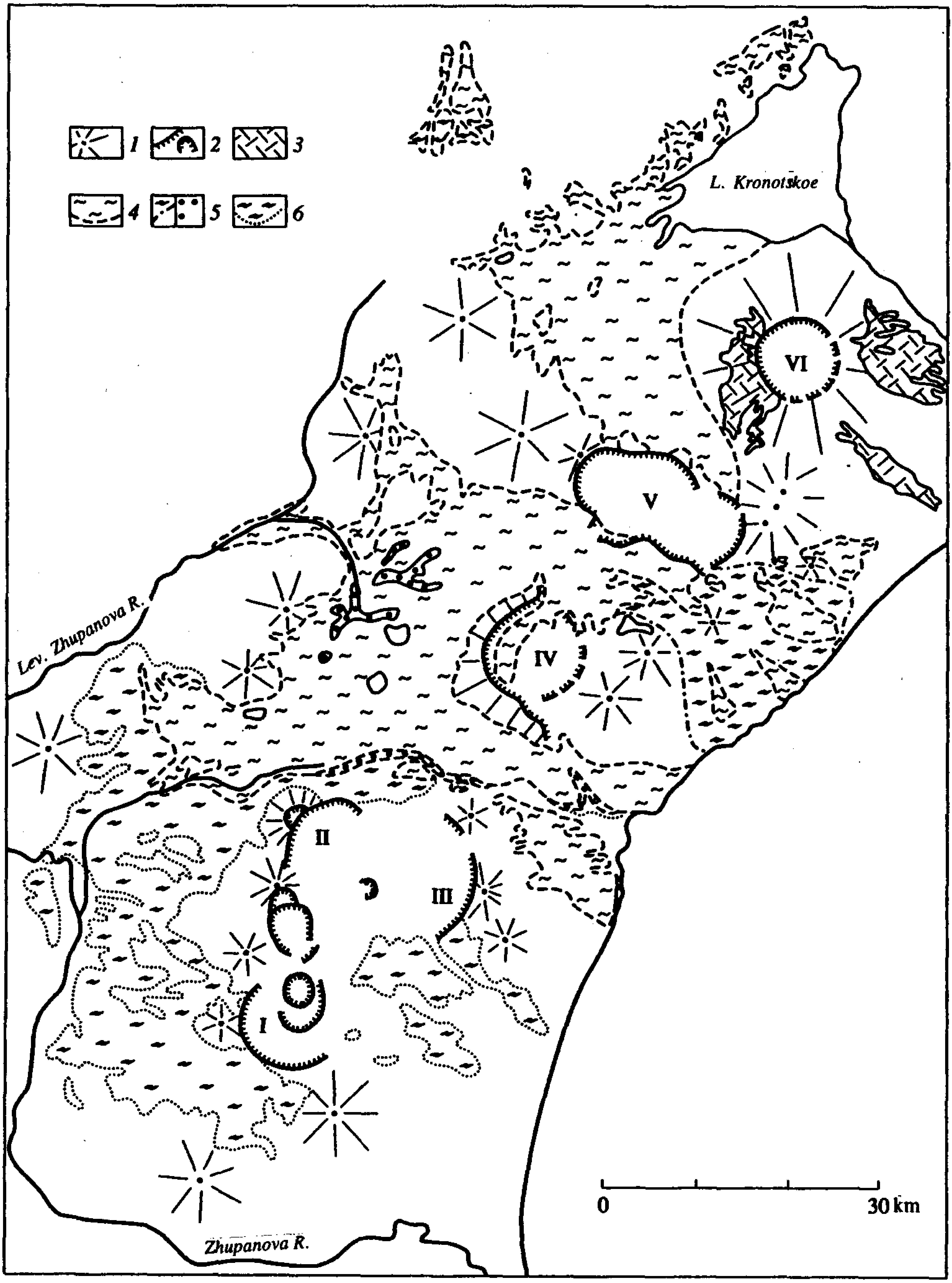
The other (younger) sequence is made up of psephitic cinder tuff and andesite ignimbrite and is much thinner ($<$ 30 m). Its most complete sections were encountered in the upper reaches of the Novyi Semyachik River, in the locality where the above mentioned Sections II and III were described in the valley sides (Fig. 2). Here, the following rocks are exposed in the valley floor in the terrace manner, downward:

1. Gray ignimbrite containing black glassy fiammes, 6 m;
2. Black psephitic tuff containing scarce fragments of black silky cinder, 20 m.

Psephitic tuff similar to the above was encountered in many places along the Novyi Semyachik River, where it makes up low terraces along the shores. The bulk chemical analysis of this tuff revealed its andesitic composition (Sample 42a in Table 1). Its orthopyroxene is distinguished by its very low Mn concentration (0.3–0.5%), which provide a good basis for correlating this tuff with the ignimbrite-like rocks from the Uzon ignimbrite exposed on the Shirokoe Plateau [11]. All data points of these pyroxenes were plotted in the MnO-f_m diagram within the region of the Uzon ignimbrite samples (Fig. 4). Its plagioclases are dominated by andesine–labradorite. This tuff is also distinguished by its high content of high-Ca microphenocrysts (Fig. 5, *h*). Its titanomagnetites are distinguished by their low Mn content and elevated Al and Mg concentrations (Table 2, Fig. 6). This is another feature which makes this tuff similar to the previously studied ignimbrite-like rocks of a basaltic andesite composition from the sequence of the Uzon ignimbrite on the Shirokoe Plateau [11].

As follows from the above, the ignimbrites deposited on the floors of the Novyi Semyachik and Pravaya Zhupanova rivers resemble the Uzon ignimbrite in many respects. It is clear that these rocks were deposited much later than the bulk of the ignimbrites exposed in the sides of the valleys. Their correlation with a certain volcanic center requires further more detailed work, although it appears that they were associated with the Uzon-Geizernyi center where the process of ignimbrite deposition had a long and complicated history.

More exact outlining of ignimbrite distribution areas and estimation of the volumes of magma ejected during ignimbrite-forming eruptions in East Kamchatka. The differentiation of the ignimbrites in the basin of the Novyi Semyachik River provided a good basis for refining the distribution areas of the Uzon, Semyachik, and Karymskii ignimbrites and estimating, at least roughly, the sizes of the ignimbrite-forming eruptions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that occurred during the middle–late Pleistocene in the volcanic centers of East Kamchatka. The distribution of these three ignimbrite sequences is shown in Fig. 7. The mapping of the *Uzon ignimbrites* is more exact because they are not covered by younger rocks and were least eroded. The total area of these ignimbrite field is roughly 2100 km^2. Their thickness varies from 4–10 m at a distance from the caldera to 50–70 m in the central parts of the pyroclastic flows. The assumption of the average ignimbrite thickness to be 20, gives the ignimbrite volume of about 40 km^3. Assuming the densities of the rhyodacite magma and the ignimbrite to be 2.4 and 1.2 g/cm^3, respectively, this gives a magma volume of 20 km^3. It is more difficult to estimate the volume of magma which was ejected during the caldera-forming eruptions as a fine pyroclastic material. Having been dispersed over distances of hundreds and thousands of kilometers from the eruption center, this material cannot be studied by direct methods at the present time. At the same time its volume can be estimated by analogy with other comprehensively studied eruptions. For instance, it was established that during the formation of the Crater Lake caldera in Oregon the volume of the fine pyroclastics had been 5 times greater than the volume of the pumice deposited near the caldera [22]. A similar proportion of the fine pyroclastics and the material of the pyroclastic flows was recently obtained from the study of the last caldera-forming eruption on Ksudach Volcano, Kamchatka [1]. These estimates are close to the values derived from the study of the tephra erupted in the Taupo volcanic center in New Zealand [29], [30]. The study of the concentration of crystals in these tephra showed that at a great distance from the volcanic centers commonly 60–80% of the material disperse. Proceeding from these data, we can assume that as much as 80 km^3 of fine pyroclastics had been erupted during the Uzon caldera-forming eruption. Assuming the densities of the magma and tephra to be 2.4 and 0.7 g/cm^3, respectively, this gives the magma volume of about 26 km^3. Therefore the total volume of magma ejected during the eruption of the Uzon ignimbrites can be estimated as 46 km^3.

The *Semyachik ignimbrites*, whose major field of distribution had been studied earlier [6], occupy an area of 350–400 km^2. Note that these ignimbrites had been eliminated by erosion over a significant area and in some localities are covered by younger lavas. An important fact is that they vary in thickness from 10 to 200. All this ranks the data on their volume given below as approximate. Assuming the average thickness of the Semyachik ignimbrites to be 40 m, their volume can be estimated as 16 km^3 (or 8 km^3

Figure 7 Distribution of ignimbrites and pumice tuffs associated with the formation of Middle and Late Pleistocene calderas in the central segment of East Kamchatka: *1* – precaldera volcanoes; 2 – calderas: IV – Krainyaya (Polovinka), II – Sobolinyi, III – Stena, IV – Bolshoi Semyachik, V – Uzon-Geizernyi, VI – Krasheninnikov; *3* – pumice tuff associated with the Krasheninnikov caldera (after A. O. Tsikunov); *4* – ignimbrite associated with the Uzon-Geizernyi depression; *5* – ignimbrite (a) and pumice tuff (b) associated with the Bolshoi Semyachik caldera; *6* – ignimbrites associated with the Stena, Sobolinyi, and Krainii (Polovinka) calderas in the Karymskii volcanic center (modified after [5] and [15]).

of magma). In addition to the ignimbrites, a significant volume of the pyroclastics produced in the Bolshoi Semyachik volcanic center during its caldera-forming eruption consisted of pumiceous quartz-biotite tuff described above. This material was erupted during the early phase of ignimbrite formation [6]. The tuff was distributed over a very large area; it is exposed almost ubiquitously in the deep valleys situated west, southwest, and south of the Bolshoi Semyachik center (Fig. 7). Because it is covered everywhere by the Uzon ignimbrites, the area of its occurrence cannot be outlined more or less exactly. A very rough estimate is 400 to 800 km^2. We will use the average value of 600 km^2 in our calculation here. Assuming the average tuff thickness to be 20 m, the tuff volume can be estimated at 12 km^3 (or 4 km^3 of magma). By analogy with the above data on the Uzon ignimbrites, we can find the volume of the magma which had been ejected in the Bolshoi Semyachik center as a fine pyroclastic material. The total pumice and ignimbrite volume was 28 km^3, and roughly 100 km^3 of fine pyroclastics were ejected, which gives a value of about 30 km^3 for the magma. Therefore the total volume of the magma erupted during the caldera-forming eruption in the Bolshoi Semyachik center might have been 42 km^3.

To estimate the volume of the *Karymskii ignimbrites* we used data from [5] and [15] to supplement those derived from our own observations. It should be noted that much of the Karymskii ignimbrites had been eroded or are covered by younger deposits. The data available suggest their area to be roughly 1100 km^2. This value and their average thickness of 50 m give the volume of 55 km^3. The volume of the fine pyroclastics disseminated away from the center was found to be about 220 km^3 by the analogy with the above calculations. The total volume of the pyroclastic material associated with formation of the Stena, Sobolinyi, and Krainii (Polovinka) calderas in the Karymskii volcanic center is thus roughly 275 km^3, the value close to the estimates reported in [5]. Taking the densities of the magma, ignimbrite, and fine tephra to be 2.4, 1.2, and 0.7 g/cm^3, respectively, this gives the approximate magma volume of 100 km^3.

The process of caldera formation and pyroclastic flows in the Karymskii center continued after the formation of the Stena, Sobolinyi, and Krainii (Polovinka) calderas. However this activity was much lower, and the pyroclastic material was dominated by an unwelded material. As follows from the data reported in [5], the volume of the resulting primarily rhyodacite pumice fields was as small as 15 km^3 (or roughly 5 km^3 of magma). Taking into account the volume of finely dispersed material estimated to be 60 km^3 (or 20 km^3 of magma), the total volume of magma erupted during that period was 25 km^3.

Apart from the calderas of the Karymskii, Bolshoi Semyachik, and Uzon-Geizernyi volcanic centers, Fig. 7 shows a caldera of the Krasheninnikov volcano. This caldera is surrounded by extensive fields of dacite pumice ejected during its formation. The volume of these deposits was estimated to be 6 km^3 [18], which gives roughly 2 km^3 of magma. Taking into account the fine pyroclastics, the total volume of magma ejected during that eruption was about 10 km^3. However this value can be underestimated because both the caldera and the deposits associated with its formation are still very poorly studied, and the volume of the pumice can be larger than 6 km^3.

The above data on the volumes of the pyroclastics ejected in the course of the caldera-forming eruptions during the middle–late Pleistocene (during the last 180 thousand years) in East Kamchatka are summarized in Table 3. The total volume of the rhyodacite magma erupted during that period in the form of ignimbrite, pumice, and tephra was about 220 km^3. The volume of the magma extruded as lava domes and lava flows was much smaller, apparently not more than 4–5 km^3, the largest rhyodacite extrusion in the Uzon–Geizernyi region having a volume of 2.38 km^3 [2]. It follows that the rate of the magma rise toward the surface was about 1.2 km^3/thou. years. This is slightly below the estimates derived for the same time interval in Japan, 2–3 km^3/thou. years [28], and seven times lower than the rhyolite magma eruption rate in the Taupo volcanic zone in New Zealand during the last 50 thousand years, 7 km^3/thou. years [24]. The volume of the magma erupted in the Taupo zone during the last 50 years is also much greater, 350 km^3 [24], and about 1000 km^3 for the last 200 thousand years [25].

CONCLUSIONS

1. The study of ignimbrite sections in the basin of the Novyi Semyachik River in East Kamchatka revealed that they consisted of three sequences (Karymskii, Semyachik, and Uzon ignimbrites) associated with the caldera-forming eruptions in the Karymskii, Bolshoi Semyachik, and Uzon–Geizernyi volcanic centers. Their depositions were not one-act events: the ignimbrite layers are interbeded with volcanogenic sedimentary layers, lake beds, and glacial deposits.

2. It was established that the extensive ignimbrite fields distributed in the lower reaches of the Novyi and Staryi Semyachik rivers and on the coast of the Gulf of Kronotskii in the area of Zhupanova Village consisted of the Uzon ignimbrites, rather than of the Semyachik or Karymskii ignimbrites as had been supposed earlier [5], [10], [15], [17].

3. We found that the Karymskii, Semyachik, and Uzon ignimbrite sequences overlapped one another successively. This and the data reported on their ages [5], [6], [15], [16] indicate that the process of ignimbrite formation in this segment of East Kamchatka had shifted gradually in an NE direction.

4. We confirmed the previously suggested difference [6], [7] among the ignimbrites of different sequences in the Fe and Mn contents of their pyroxenes. This correlation basis can be used to differentiate the complicated sequences of ignimbrites in other regions.

5. As a result of this survey we refined the deposition limits of the Karymskii, Semyachik, and Uzon ignimbrites. The reconstructed fields of their distribution were used to calculate their volumes, and also the volumes of the erupted magma. The latter were found to be 100, 42, and 46 km^3, respectively. The total volume of the rhyodacite magma erupted in this region of East Kamchatka during the last 180 thousand years was estimated to be 220 km^3, and the rate of its rise to the surface, to be 1.2 km^3/thou. years.

Table 3 Data calculated for ignimbrite-forming eruptions in East Kamchatka.

Ignimbrite, pumice tuff	S, km^2	h, m	V, km^3	V_t, km^3	ΣV, km^3	V_m, km^3
Karymskii center	1100	50	55	220	275	100
	400		15	60	75	25
Bolshoi Semyachik center	1000	20-40	28	100	128	42
Uzon-Geizernyi center	2100	20	40	80	120	46
Pumice tuff in Krasheninnikov caldera	600	10	6	24	30	10
All volcanic centers	5200		144	484	628	223

Note. S - area; h - average thickness; V - volume of ignimbrite and pumice tuff; V_t - volume of tephra; ΣV - total volume of ignimbrite, pumice tuff, and tephra; V_m - volume of magma. Two lines given for the Karymskii center indicate: upper line - ignimbrites associated with the calderas of the Stena, Sobolinyi, and Krainii (Polovinka) volcanoes: lower line - pumice tuff and ignimbrites associated with the calderas of the Odnobokii, Akademii Nauk, and Karymskii volcanoes.

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