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IGNIMBRITES OF THE BOLSHOI SEMYACHIK CALDERA, KAMCHATKA: COMPOSITION, STRUCTURE, AND ORIGIN

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Three periods of emplacement of petrochemically different ignimbrites have been recognized. Each of them began with the eruption of rhyolite-dacite pyroclastic flows and was concluded by the formation of andesite and basaltic andesite ignimbrites. Compositions of minerals and residual glasses were determined on a Camebax electron microprobe; a mineralogical criterion was employed to correlate geologic sections. Temperatures of the ignimbrite-forming melt were calculated by mineralogical thermometers. The gases occluded in the minerals were qualitatively analyzed on a mass spectrometer. The character of the chemical evolution of the ignimbrites, different mineral assemblages, and chemically varying glasses indicate that in middle Pleistocene time a zoned magma chamber existed in the crust beneath the Bolshoi Semyachik caldera.

INTRODUCTION

Ignimbrites are widely developed in eastern Kamchatka. They are associated with many late Pleistocene calderas and volcano-tectonic depressions. The Kronotskiy Bay is one of the areas where extensive ignimbrite outcrops are easily accessible for study (Figure 1). The ignimbrites are associated with three large caldera centers: Karymskiy, Bolshoi Semyachik, and Uzon-Geyser. Accordingly, we will refer to them as the Karymskiy, Semyachik, and Uzon ignimbrites. This paper presents new data on the structure, composition, and origin of the Semyachik ignimbrites (Bolshoi Semyachik caldera). These ignimbrites lie on the similar rocks of the Karymskiy volcanic center, which is situated to the south from Bolshoi Semyachik, and are in turn overlain by the Uzon ignimbrites. Figure 2 shows the summarized stratigraphic column for the ignimbrites of the study area. The geolo-

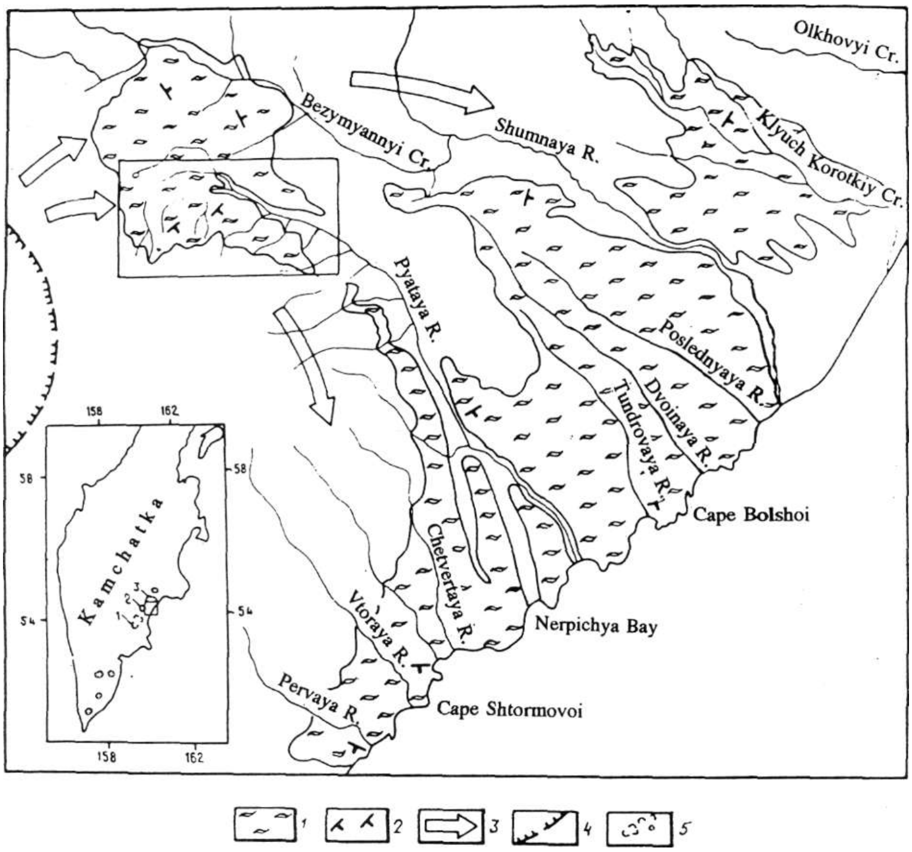

Figure 1 Location map of study area. 1 - ignimbrites related to the Bolshoi Semyachik caldera; 2 - measured strikes and dips of ignimbrite layers; 3 - reconstructed directions of pyroclastic flows; 4 - structural boundaries of the Bolshoi Semyachik caldera; 5 - calderas (in the inset map): 1 - Karymskiy, 2 - Bolshoi Semyachik, 3 - Uzon-Geysernaya. Boxed area in the left top corner is the area shown in Figure 3.

gic section of the Semyachik ignimbrites is composed of intercalating ignimbrites, pumices, and lake beds or glacial deposits. The detailed descriptions of the section were given in [1], [2], [3], [5], [8], and [9]. The stratigraphical column in Figure 2 shows the way the ignimbrites were differentiated before [8], [9] and the way we differentiate them. We studied the ignimbrites and their relations with the other rocks in the upper course of the Pyataya River (Figure 3). One can see that south of that locality the ignimbrites are overlain by younger lavas and are inaccessible for examination. We can only imply from the available data that the pyroclastic flows parental for the ignimbrites were emplaced as two broad branches. They flowed initially out of the caldera to the northeast and then gradually deviated to the east and southeast, and on the coast, south and southwest (see Figure 1).

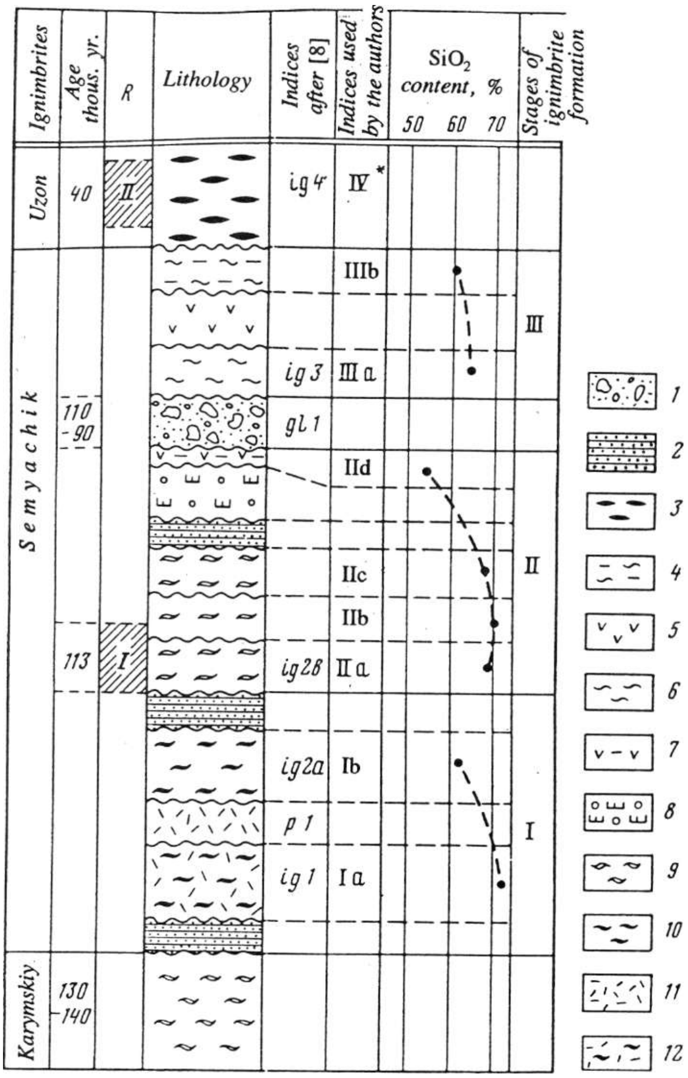

Figure 2 Stratigraphic column for the ignimbrites outcropping in the study area. *R* - zones of reversed polarity: I - Blake (113 thousand years), II - Alby-Lasham (35-44 thousand years). IV* - ignimbrites of the 4th solidified unit [8] from the coast, which in contrast to the previous investigators are regarded as the Uzon ignimbrites (see the text); 1 - glacial deposits, boulders and pebbles; 2 - stratified lake beds: the layer between the Blake and Alby-Lasham zones contains tuff breccias; the layer underlying the Blake zone bears pumices and soil slags; 3 - ignimbrite; 4 - andesite ignimbrite; 5 - andesite and dacite lavas; 6 - dacite ignimbrite; 7 - andesite-basalt ignimbrite-like rocks; 8 - agglomerate scoria tuff; 9 - rhyodacite ignimbrite; 10 - andesite-dacite ignimbrite; 11 - unwelded pumice; 12 - rhyolite ignimbrite.

Previously the age of the Semyachik ignimbrites was placed in a rather wide range (from middle to late Pleistocene [8], [9]). We dated it more precisely on the basis of paleomagnetic data. The rock samples of unit Ila showed reversed polarity. Only one polarity reversal took place in the period between 130-140 thousand years (age of the lates* Karymskiy ignimbrites, [6]) and 40 thousand years (age of the Uzon ignimbrites, [7]). It occured 113 thousand years ago. So that was the time when unit Ila was formed. The deposits of the first stage of the late Pleistocene glaciation occurring between units II and III, have according to Zubakov's data [4], an age of 110-90 thousand years, the age of the maximum glaciation in the high latitudes of the Northern Hemisphere. The age of unit II ignimbrites can thus be fairly precisely dated as 110 to 130 thousand years. The 3d stage ignimbrites (Ilia and Illb) are slightly younger, 90 to 80 thousand years.

DESCRIPTION OF IGNIMBRITE SEQUENCES

Ignimbrites from the coast. The oldest rocks are rhyolitic ignimbrites (first consolidated unit after [8]). They are intermittently seen in the base of the coastal cliffs from the Pyataya River to the northern cape of the Dvoinaya Bay (see Figure 1 and Table 1). These are light-grey, whitish, relatively highly crystalline rhyolitic rocks (Table 2) with typical quartz phenocrysts and unevenly distributed crystals. The groundmass is composed of hyaline ash particles, which have a complicated form in the slightly agglutinated tuff at the top of the sequence and are flattened and fine-fibrous in the highly welded zones. The ignimbrites show a high devitrification grade. Rare pumiceous fiamme are entirely recrystallized to form quartz-feldspar aggregates. These ignimbrites seem to be coeval with the quartz- and biotite-bearing pumices, occurring in the base of the coastal cliffs, and with the poorly welded ignimbrites of the same composition from the southwest of the area (V. Stan River).

Dark-grey, massive andesite-dacite ignimbrites with disk-like fiamme (see Tables 1 and 2) overlie the rhyolitic ignimbrites on the southern cape of the Pyataya River Bay, in a small bay between the Pyataya and Tundrovaya Rivers, and on the northern cape of the Dvoinaya Bay. The size of the fiamme varies from fractions of mm to "pies" up to 30 cm across and 10 to 15 cm thick. They are composed of brown or dark-brown nontransparent glass with a large amount of crystals. Especially aboundant are pyroxenes whose accumulations are seen on weathered surfaces. These ignimbrites were previously assigned to the lower flow of unit II [8J. However, their composition and a close spatial relation to the quartz-bearing ignimbrites allow one to attribute them to the 1st stage of the ignimbrite formation, which started with the eruption *of* the rhyolite products (la) and terminated with the andesite-dacite ignimbrites (lb).

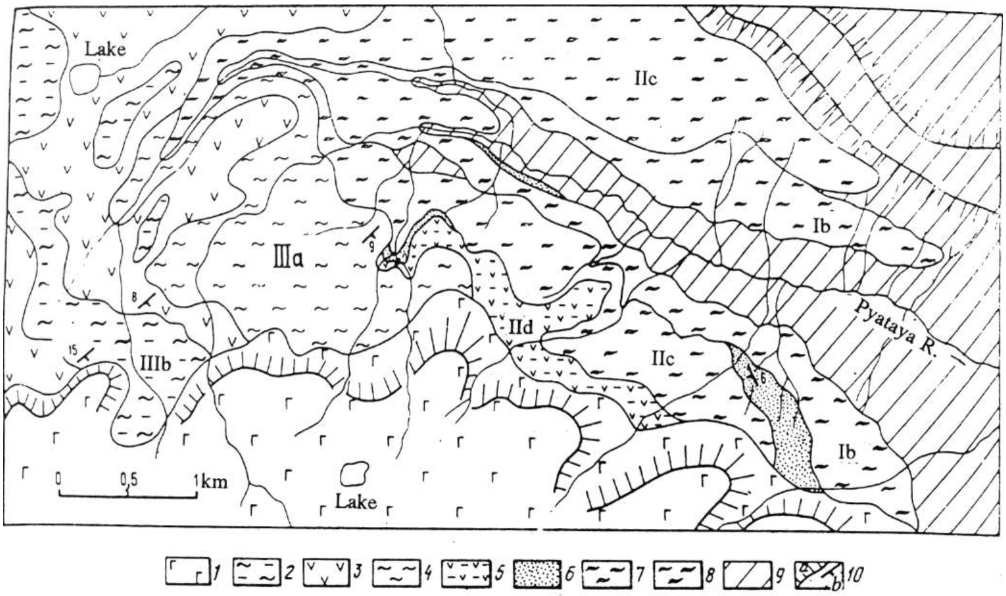

Figure 3 Schematic map showing the distribution of ignimbrites in the upper reaches of the Pyataya River. 1 - basalt lavas erupted by postcaldera Bolshoi Semyachik (Zubatka) Volcano; 2 - IIIb ignimbrites; 3 - andesite and dacite lavas separating the upper ignimbrite layers; 4 - IIIa ignimbrites; 5 - andesite-basalt ignimbrite-like rocks (IId); 6 - bedded tuffs, tuffaceous sandstones, and tuffaceous siltstones separating ignimbrite layers; 7 - IIc ignimbrites; 8 - Ib ignimbrites; 9 - rocks underlying the ignimbrite sequence (basalt and andesite lavas and tuffs); 10 - large erosion scarps (a), strike and dip (b).

The next stage began with the eruption of rhyodacite ignimbrites, which compose the larger part of the coastal cliffs (upper flow of the 2nd consolidated unit [8]). The transition from the 1st to the 2nd phases can be seen in the outcrops on the southern cape of the Pyataya River Bay and at the Dvoinaya Bay. At least two flows of similar composition can be recognized among the ignimbrites of this stage. They overlap on the Bolshoi Cape. Gray lava-like ignimbrites with a distinct fluidal texture (IIa) predominate. The groundmass of these ignimbrites consists of flattened and welded ash particles. They are almost completely devitrified at the base of the sequence and are less devitrified upward, where flattened ash fragments are represented by pseudofluidal shards of fine-dispersed brown glass. The almost invariable size of the ash particles (0.3 to 0.5 mm) accounts for the lava-like appearance of the Semyachik ignimbrites [1], [2]. The amount of a xenogenic material does not exceed 5-8%, and the maximal size of the inclusions is 2 to 3 cm. The rare fiamme in the lower flow are almost completely devitrified. Black obsidian-like glass is preserved in large fiamme but is surrounded with a gray devitrified rim.

The younger IIb flow consists of a dark-gray, massive, glassy rock with < 10

Table 1 Average chemical compositions of the Semyachik ignimbrites.

Oxides	Ip	Ia	Ib	IIa	IIb	IIc	IId
SiO_2	71.62	72.93	63.27	69.57	71.00	68.61	54.32
TiO_2	0.40	0.39	0.86	0.66	0.63	0.71	1.31
Al_2O_3	14.68	14.30	17.05	15.37	14.76	15.25	15.74
Fe_2O_3	0.85	1.10	2.76	1.48	1.46	1.72	7.37
FeO	2.09	2.04	3.19	2.26	2.25	2.66	5.09
MnO	0.13	0.05	0.13	0.12	0.10	0.13	0.24
MgO	0.62	0.84	1.81	0.84	0.75	0.90	3.90
CaO	2.62	1.78	5.03	2.80	2.14	3.09	7.99
Na_2O	4.23	3.78	4.27	4.82	4.57	4.92	3.07
K_2O	2.76	2.76	1.64	2.07	2.33	2.01	0.96
n	2	6	6	9	4	4	1
Oxides	IIIa	IIIb	*Heterotaxic pumices*		IV	*Fiamme*	
			Light bands	*Dark bands*		Ib	Ia
SiO_2	64.97	61.36	67.11	58.08	70.98	64.80	71.91
TiO_2	0.89	1.02	0.81	1.09	0.66	0.86	0.62
Al_2O_3	15.30	15.60	13.45	16.89	14.71	15.41	14.06
Fe_2O_3	3.65	3.90	1.16	2.58	1.82	2.34	1.23
FeO	3.37	4.27	2.98	5.10	2.24	3.50	2.22
MnO	0.14	0.15	0.12	0.16	0.12	0.10	0.10
MgO	1.44	2.44	2.69	3.30	0.74	1.76	1.13
CaO	4.38	5.72	4.89	8.50	2.00	4.39	3.86
Na_2O	3.80	3.70	4.22	3.05	4.58	4.94	4.88
K_2O	2.06	1.84	2.54	1.28	2.14	1.89	2.57
n	6	3	1	1	3	2	1

Note. Ip - pumice with quartz and biotite; la, lb,...IV - indices of ignimbrite flows; n - number of analyses.

percent of small xenogenic inclusions. The rock is similar in the composition and amount of phenocrysts to the earlier portions, but is less altered. The glass from the groundmass of these ignimbrites is dense, brown and almost not devitrified.

In the Nerpichiya Bay, the dark-gray ignimbrites of the 2nd stage are sequentially overlain by a glacial material and a layer of unwelded pumiceous dacite tuff with heterotaxic pumice intercalatons (see Table 1). This layer begins the 3rd stage of the ignimbrite formation. The ignimbrites of this stage (3rd consolidated unit after

[8]) occur in the coastal cliffs between the Piataya and Tretiya Rivers. They lie on the light-gray fluidal ignimbrites of unit IIa in the north and are overlapped by a pumiceous pyroclastic flow of Problematichnyi Volcano in the south. These are lilac or lilac-gray ignimbrites with a large amount of clastic material (15 to 20%). The clastic material comprises altered and oxidized andesite and basalt xenoliths, abundant swelled and scoria-like black glasses, ignimbrites, and pumices, thus being more diversified compositionally than the previous ignimbrites, which contain mainly lava fragments. The less welded varieties bear oval and flattened pumice inclusions with notched margins, ranging from fractions of mm to several cm. The ash particles of the groundmass are very small (max. 0.1 mm) and occur in a fine, almost isotropic volcanic dust. The larger pumice inclusions are transformed to fiamme of red-brown, obsidian-like glass with a relict fibrous pumiceous texture. The amount of fragments diminishes in the welded varieties.

The rhyodacite ignimbrites of the 4th stage (4th consolidated unit after [8]) are the youngest (see Table 1). They occur in the north of the area from the Bolshoi Cape to the mouth of the Shumnaya River and are mostly represented by dark-brown, poorly welded rocks with small pumiceous fiamme. The most welded varieties were found in the base of the sequence at the southern cape of the Dvoinaya Bay, where they drape the IIa ignimbrites. They are represented by thin-platy, lava-like rocks with lenses of homogenized porous glassy ignimbrites and rare fiamme of brown glass. These ignimbrites are distinguished by the lowest amount of crystalline phase (see Table 2) and are almost undevitrified. Foreign inclusions are rare (3 to 5%), small (not large than 1 cm), and are largely composed of andesite lava and scoria-like glass with scarce fragments of felsite.

Ignimbrites in the middle-course of the Pyataya River (see Figures 1 and 3). The pyroclastic flow deposits extending toward the ocean are most deeply dissected by the Pyataya River. The ignimbrites of the 1st and the 2nd stages build the coastal cliffs of the Kronotskiy Bay and extend 7 km upstream. Further upsteam they are eroded and outcrop again in the upper course of the Pyataya River (see Figure 3), where five layers are clearly distinguishable topographically.

The first layer is composed of dark-grey, massive, glassy dacite ignimbrite, largely welded, with a large amount of crystals, including pyroxenes. They are chemically comparable with the andesite-dacite ignimbrites that terminated the 1st stage (Ib).

The second layer consists of dark-grey, lava-like rhyolite ignimbrites with a small amount of xenogenic inclusions and a pronounced fluidal structure. They either overlap the first layer or lie on the stratified lake beds. These ignimbrites correlate with flows IIa and IIb of the second stage in the coastal localities and are distinguished here as flow IIc.

The third thin layer (1 to 2 m) comprises ignimbrite-like rocks of andesite and basaltic andesite composition (see Table 1). These are dark-grey subaphyric rocks

Table 2 Quantitative mineralogical composition of the Semyachik ignimbrites, %.

Index of ignimbrite flow	*Ground-mass*	*Pl*	*Cpx*	*Opx*	*Mag*	*Qtz*	*Crys-tals*
Ia	65	26	1.5	2.0	2.0	3.6	35
Ib	59	30	4.0	4.0	3.0	-	41
F	75	17	2.0	3.0	3.0	-	25
IIa	72	22	1.2	2.8	2.0	-	28
F	79	16	1.0	2.0	2.0	-	21
IIb	74	20	1.5	2.3	2.2	-	26
IIc	79	15	1.7	2.6	2.7	-	21
IId	93	4	0.6	1.4	1.0	-	7
IIIa	70	19	3.7	3.5	2.8	-	30
IIIb	61	28	3.5	4.2	3.3	-	39
IV	86	10	0.5	1.5	2	-	14

Note. F - fiamme.

consisting of frothy fine-dispersed glass and rare microlites. Scarce phenocrysts are represented by plagioclase, pyroxene, and more rare olivine. Typical of these rocks are small (< 2 mm) discolored fragments of a recrystallized quartz-feldspar aggregate, slightly altered fragments of andesite and less common basalt, and deformed andesite nodules. Stratified tuff occurs between the 2nd and the 3d ignimbrite layer; it grades locally to unwelded pumice and scoria. The tuff layer is 4 to 5 m thick. The ignimbrite-like subaphyric rocks are distributed over a wide area as a thin layer, which is used as a marker bed. Similar rocks occur as a 1-m bed within the ignimbrite sequence on the Gornoe Plateau in the upper course of the Kronotskiy Creek; they conclude the eruptive stage of the rhyolite ignimbrites. This layer is indexed IId.

The 4th ignimbrite layer lies on the ignimbrite-like rocks. In the middle course of the Pyataya River it consist of lilac-gray dacite ignimbrites with thin fiamme of black porous glass. The glass is distinguished by a "stellate" crystallization pattern of mafic minerals. These ignimbrites build areas between the right-hand tributaries of the Pyataya River. They are compositionally similar to the pooly welded lilac ignimbrites with pumice fiamme (IIIa), which occur in the coastal cliffs between the Pyataya and Vtoraya Rivers.

The uppermost, 5th, ignimbrite layer is thin and occurs near the caldera rim (heads of the Pyataya River and Bezymyannyi Creek). It contains fiamme-like inclusions of brown dacitic glass along with nodules of andesite-basaltic scoria, which determine the motley appearance and andesite composition of the rocks. Small scoria inclusions are often flattened. This flow was assigned the index IIIb (see Table 1). Pyroclastic flows IIIa and IIIb are separated by andesite and dacite lava flows.

DISTRIBUTION AND CHEMISTRY OF MINERALS

Constituents of pyroclastic flows are redistributed in the course of eruption and transportation; for example, lighter glassy ash is separated to enrich the ignimbrites in phenocrysts [15]. The highest contents of crystalline phase (30-40%) was noted in the andesitic ignimbrites of the 1st and 2nd stages (see Table 2), the amount of phenocrysts increasing toward the end of each stage. The crystallinity of the 2nd stage rhyolitic ignimbrites is lower (21-28%) and decreases in each successive flow.

Phenocrysts are unevenly distributed and often form clusters, which are especially typical of the Ia and Ib ignimbrites. Salic minerals concentrate in the rhyolitic ignimbrites, whereas the overlying andesite varieties contain clusters of large pyroxene phenocrysts, which are visible to the unaided eye in the discolored and devitrified groundmass.

A more correct assessment of the content of crystals in the melt is provided by fiamme, which represent its relatively large and undisturbed fragments. We calculated, where possible, a difference between the amount of phenoctyst contents in the fiamme (la and Ila) and in the groundmass. It amounts to 7-16%, and points to a noticeable segregation of phenocrysts in the ash flow. The ignimbrite-like andesite-basaltic rocks of unit lid and the ignimbrites of unit IV contain the least amounts of phenocrysts (7-14%).

The assemblage plagioclase + orthopyroxene + clinopyroxene predominates in the phenocrysts, though the compositions and proportions of these minerals vary throughout the sequence. The exception is the earliest Ia ignimbrites and the related fiamme containing quartz in addition to plagioclase. The ignimbrite of unit IIIa contains single grains of green hornblende, whereas the mafic mineral of the quartz-bearing pumices *is* biotite. The andesite *ignimbrites* and ignimbrite-like rocks of unit IId also contain nonequilibrium olivine grains. The compositions of *the* minerals were determined on a Camebax electron microprobe.

Plagioclase is the leading mineral among the phenocrysts. It chemically ranges from 26 to 87% An, oligoclase-andesine (25-35% An) dominating in the rhyolite and rhyodacite flows, and andesine-labradorite and labradorite (45-60% An) in the dacite and andesite flows. It is worth noting a narrow compositional range of phenocrysts from the 1st stage ignimbrites, both in the quartz-bearing rhyolites and in the andesites (Figure 4). The phenocrysts are unzoned or poorly zoned crystals.

The predominant composition of the plagioclases from the ignimbrites of unit lb is 50 to 58% An in the cores and 30 to 48% An in the margins. Some crystals have the cores compositionally similar to phenocrysts from the quartz-bearing

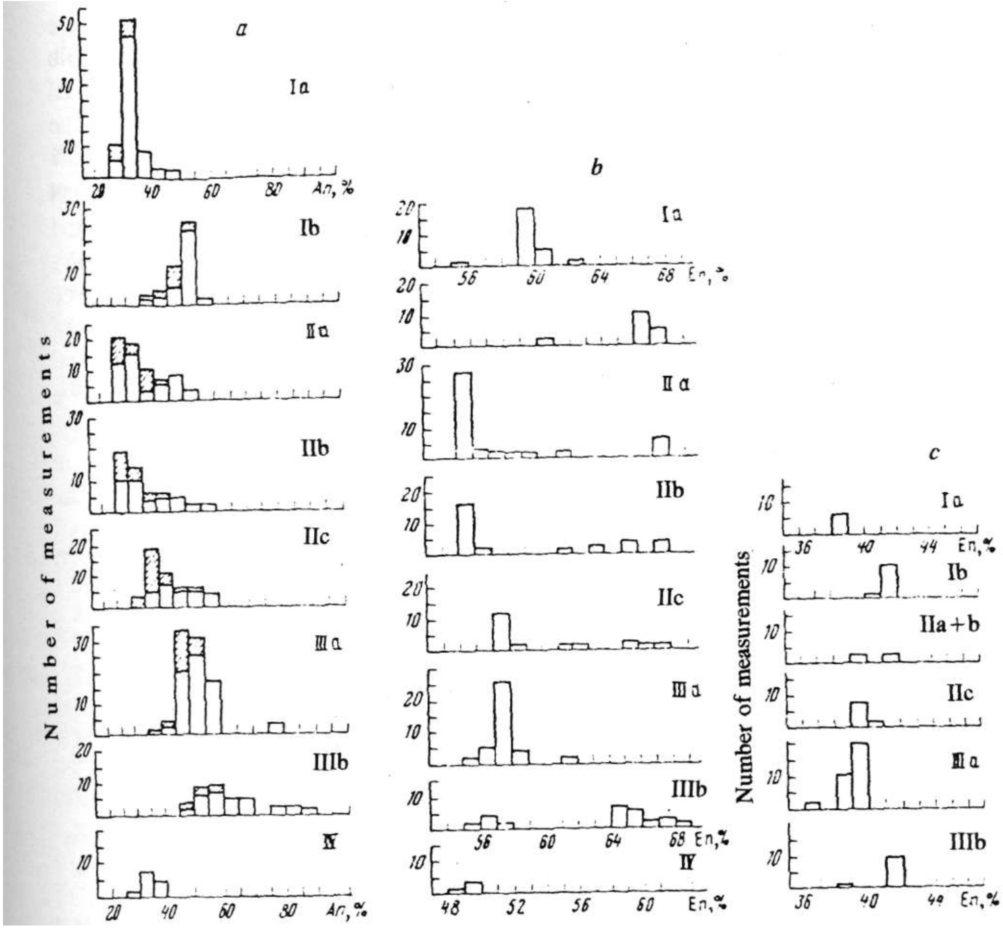

Figure 4 Frequency distribution of mineral compositions: *a* - plagioclase, % An; *b* orthopyroxene, % En; c - clinopyroxene, % En.

ignimbrites (30 to 36% An). Plagioclases from the 2nd stage rhyodacitic ignimbrites compositionally expand into the Na- and Ca-rich regions and comprise three compositional groups with the cores of: (1) 29-35% An; (2) 39-45% An; and (3) 52-57% An. Their margins consist of andesine with 30-44% An. The 2nd group phenocrysts predominate in the IIc flow in the head of the Pyataya River. Sometimes they exhibit reverse zoning. The average plagioclase composition becomes more calcic in each subsequent flow, 35, 38, and 44% An respectively.

A bimodal compositional pattern is typical of the plagioclases from the 3d stage ignimbrites (see Figure 4, *a):* in addition to the predominating plagioclases with 45-60% An, more anorthitic plagioclases appear (75-87%). Their amount increases in flow IIIb, obviously due to nodules of andesite-basalt scoria. The zoning pattern becomes more complex: whereas the plagioclases in the previous ignimbrites are characterized by a poor or simple zoning, some phenocrysts from the IIIa and IIIb flows display an intricately repeated zoning throughout the whole compositional range. High-Ca plagioclase occurs in the cores and intermediate zones. The average composition of the plagioclases from the 3rd stage flows is 54 and 60% An, respectively. So the average anorthite content increases in each subsequent flow beginning from the 2nd stage.

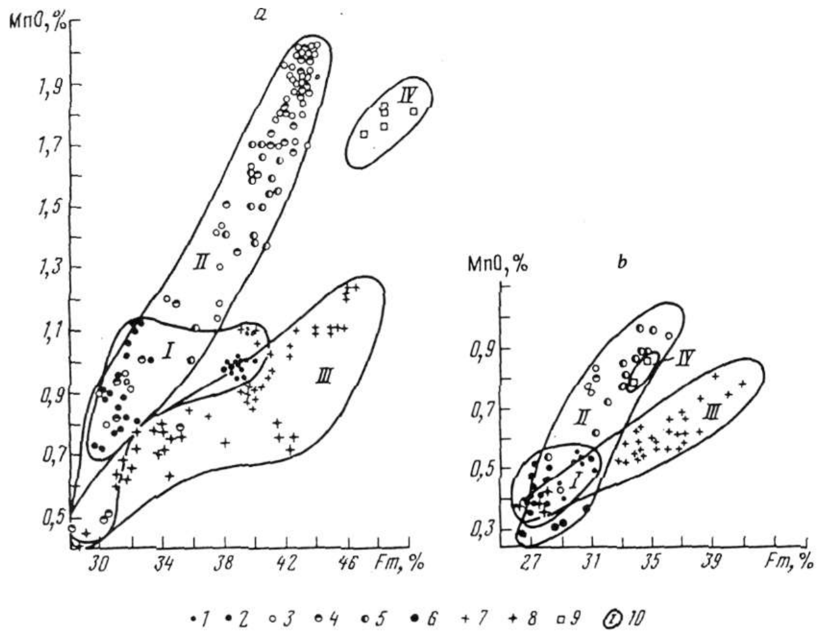

Figure 5 MnO content vs. *fm* values for orthopyroxenes (*a*) and clinopyroxenes (*b*). I to IV - ignimbrite-forming stages. Pyroxenes from: 1 - rhyolitic unit Ia; 2 - andesite-dacitic unit Ib; 3 to 5 - rhyodacitic unit IIa+c; 6 - andesite-basalt ignimbrite-like rocks, IId; 7 - dacitic unit IIIa; 8 - andesitic unit IIIb; 9 - rhyodacitic unit IV; 10 - boundaries of the pyroxene fields during different ignimbrite-forming stages.

Quartz occurs in the earliest and most acid ignimbrites. It is associated with biotite in the pumice tuff and with pyroxene in the la ignimbrites. The margins of the quartz phenocrysts may contain xenomorphic inclusions of titanomagnetite and pyroxene.

Pyroxene is unevenly distributed in the ignimbrite sequence: it is essentially more abundant in the dacite (IIIa) and andesite (Ib and IIIb) flows (see Table 2). Orthopyroxene is mainly represented by hypersthene, which is the primary mafic mineral in the acid *ignimbrites (see Figure* 4, *b).* In *the 1st stage ignimbrites,* it is compositionally restricted to a range of Mg and Fe-rich hypersthene (59-61% En,

Table 3 Average compositions of glasses (microprobe data).

Oxides	Ip	Ia	Ib	IIa	IIb
SiO_2	74.78	76.29	74.18	76.38	76.76
TiO_2	0.0	0.0	0.50	0.34	0.22
Al_2O_3	12.03	11.59	13.00	11.44	11.99
FeO	0.52	0.30	2.38	2.88	1.92
MnO	0.07	0.0	0.03	0.03	0.02
MgO	0.0	0.0	0.45	0.28	0.16
CaO	0.036	0.27	2.01	0.59	0.94
Na_2O	3.10	3.00	4.32	4.82	4.33
K_2O	5.35	6.03	2.96	2.58	3.55
Σ	96.98	97.48	92.83	99.35	99.89
Na_2O+K_2O	8.45	9.03	7.28	7.40	7.88
Oxides	IIc	IIIa	$IIIb_I$	$IIIb_{II}$	IV
SiO_2	76.49	71.83	72.67	67.70	73.99
TiO_2	0.55	0.52	0.53	0.55	0.34
Al_2O_3	13.29	13.68	14.85	14.63	12.98
FeO	2.16	3.58	2.23	5.08	2.20
MnO	0.08	0.12	0.11	0.10	0.07
MgO	0.26	0.41	0.26	1.46	0.23
CaO	1.56	2.43	2.83	3.23	1.07
Na_2O	5.28	4.50	4.71	5.02	4.40
K_2O	2.07	2.77	2.37	1.69	3.88
Σ	99.74	99.84	100.56	99.36	99.16
Na_2O+K_2O	7.35	7.27	7.08	6.71	8.28

Note. Roman numbers are indices of ignimbrite flows.

*f*m = 38-40%) in the quartz-bearing ignimbrites (Ia) and magnesian hypersthene (66-68% *En*, *fin* = 30-33%) in the andesite flow (Ib). Orthopyroxene from the rhyodacitic ignimbrites of the 2nd stage shows a bimodal distribution and variation of the enstatite content (55-68% *En*, *fin* = 30-44%), essentially iron-rich hypersthenes predominate. In the first two flows, they are compositionally close (55-56% En), the magnesian varieties predominating in the IIc flow.

The dacitic ignimbrite flow of the early 3rd stage contains mainly iron-rich hypersthenes (57-58% *En*, *f*m - 39-46%), similar to those in the last flow of the 2nd stage. The compositions of hypersthenes from the IIIa most basic ignimbrites, which close the 3rd stage, exhibit a bimodal distribution: along with iron-rich hypersthenes magnesian varieties, close to bronzite (68-69% En, *fm* = 29-30%), appear due to andesite-basalt scoria inclusions. The most Fe-rich hypersthenes (48-50% En, *fin* = 49-50%) occur as scarce crystals in poorly welded ignimbrites IV (see Figure 4, *b).* They are compositionally close to ferrohypersthene.

The orthopyroxenes from the Semyachik ingnimbrites vary significantly in the Mn content (Figure 5), which correlates with the *fm* values and the bulk chemistry of the ignimbrites. The manganese content decreases toward the end of each stage, this feature correlating with the bulk composition of the ignimbrites. The highest MnO contents (1.5-2%) and variation were noted in the orthopyroxenes from the rhyodacitic ignimbrites (IIa and IIb), with MnO decreasing in each subsequent flow. Though there is no data on the compositions of pyroxenes from the ignimbrite-like andesite-basalt rocks of the late 2nd stage (IId), the above regularity of the Mn distribution in the pyroxenes is confirmed by the clinopyroxene behavior.

The hypersthenes from the earliest quartz-bearing ignimbrites (Ia) are characterized by a fairly stable Mn content (0.95-1.1 %). These pyroxenes are more close to those from the dacite flows (IIIa), in spite of a more acidic (rhyolitic) bulk-rock chemistry. The hypersthenes from the andesite-dacite flows (Ib) are close to those from the dacite flows (IIIa) in Mn but are lower in the *fin* value, which is higher in the latter. The lowest Mn (0.40-0.50%) content was found in the hypersthenes from the rhyodacite flow IIb and the Illb andesite flow.

Most of the hypersthene phenocrysts are generally homogeneous but sometimes display a higher ferrosilite content in the margins, which is especially typical of the pyroxenes from the 3rd stage ignimbrites. The magnesian hypersthenes and the hypersthenes from the Ia ignimbrites are characterized by low wollastonite contents.

The clinopyroxenes are mainly augites; the proportions of their main component contents depend on the bulk rock chemistry. Augites from the rhyodacite (Ila-llc) and dacite (IIIa) flows are compositionally similar with the exception of higher *fin* values in the latter (see Figure 4, c). The clinopyroxenes from the flows of stage I and the end of stage III are higher in Ca and Mg and hence are identified as salite-augites *(fm* = 27-30%). The relations between the Mn contents and the *fin* values in the clinopyroxenes are identical to those in the hypersthenes (see Figure 5).

The opaque minerals are represented by titanomagnetite and ilmenite, which occur as individual grains and polymineral growths. The titanomagnetite is locally corroded and contains exsolution lamellae. The homogeneous grains of titanomagnetite and ilmenite contain 3-18% and 42-44% $Ti0_2$, respectively. Titanomagnetites with 9.5-13.0% $Ti0_2$ predominate. They occur largely in the rhyodacitic ignimbrites and are distinctly higher in Mn (0.8 to 1.4%). Both Ti and Mn are lower in Fe-Mn oxides from unit Ib and from the ignimbrites of the 3rd stage.

The accessories are represented by apatite, which crystallized in euhedral

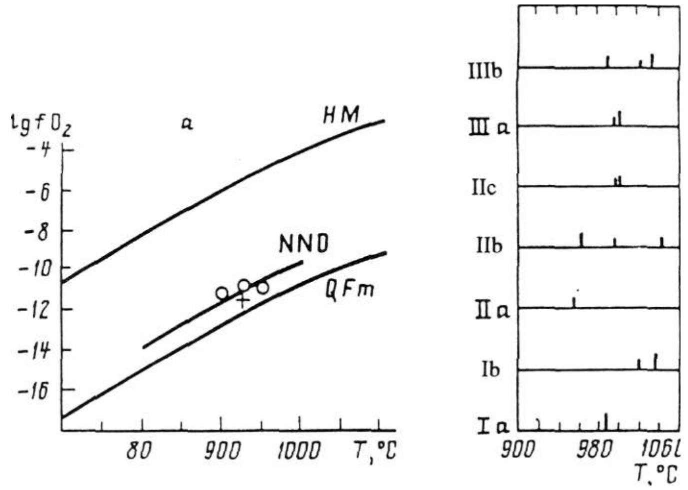

Figure 6 Ignimbrite temperatures calculated by: a - magnetite-ilmenite thermometer [11], [12]; *b* - orthopyroxene-clinopyroxene thermometer [16].

prismatic 0.04 to 0.06-mm crystals in the closing stages of melt crystallization. It occurs in the groundmass and grows on the faces of plagioclase, pyroxene, and magnetite phenocrysts in the ignimbrites of intermediate composition (Ia, IIIa, b). Zircon was found in the quartz-bearing ignimbrites of unit la.

The composition of the phenocrysts is notably stable and provides a useful mineralogical criterion for stratigraphic correlation.

Glass. The ash particles and fiamme are composed of glass, whose color and density are controlled by their composition, texture, and welding grade. In the acid ignimbrites, the homogeneous glass of the fiamme and ash particles is tinted pale or light yellowish-brown. The flattened ash particles are surrounded with a thin rim (fractions of mm) of opaque mineral dust. The glass becomes brown in more flattened and more welded particles, but its pseudofluidal texture remains. The glass of the fiamme from the andesite ignimbrites is dense, opaque and brown.

The composition of the glass fragments was determined on an electron microprobe. It does not always correspond to the original composition of the melt because of the loss of volatiles, the secondary chemical alteration of the glass, and the pneumatolitic crystallization of feldspar and quartz in the pores. The most variable are the concentrations of alkalis and $Si0_2$. Table 3 lists the average chemical analyses of the homogeneous, undevitrified glasses, which may reflect their compositional variation throughout the ignimbrite sequence. The acid glasses are usually poor in FeO, $Ti0_2$, and $A1_20_3$, the $Si0_2$ content ranging from 76.3 to 67.7%. The exception is the glass from the IIc ignimbrites, which is higher in $A1_20_3$ and is compositionally close to the ignimbrites produced by the closing of stage I. The minimum concentrations of these components were found in the glasses from the quartz-bearing rhyolitic ignimbrites.

Elevated *fin* values and alumina contents are typical of the residual ignimbrite melt of the 3d stage. Two types of glass were found in the last flow: (1) the more acid glass, which is compositionally close to the residual melts of the 1st flow (see Table 3); (2) the Fe and Mg-rich glass with a lower $Si0_2$ (67.7%). The latter is related to the inclusions of andesite-basalt scoria, which are distinguished macroscopically and impart a motley appearance to the rock.

The total alkalinity of the residual glasses ranges from 6.7 to 9.0% and decreases from stage I (with the most K-rich glasses) to stage III.

ORIGIN OF THE IGNIMBRITES

The temperature and oxygen fugacity of the parental melts were evaluated by means of mineral equilibria. Temperatures for the rhyolitic ignimbrites were calculated on the basis of the ilmenite-titanomagnetite pair in equilibrium with the melt [11]. They range between 875° and 950°C. Oxygen fugacities in these melts are 11.6 to 11.9. The data points group along the curve for the NNO buffer (Figure 6, *a).* Since this curve approximates acid volcanics with orthopyroxene [12], this testifies to a relative dryness of the melt. The two pyroxene thermometer [16] was employed to estimate the temperature of phenocryst crystallization, which ranges from 984° to 1046°C in almost all pyroclastic flows (see Figure 6, *b).* The lowest temperatures were obtained for the rhyodacite ignimbrites (they are comparable with the values obtained with the magnetite-ilmenite thermometer); the largest, 1020° to 1046°C temperatures were found for the andesitic ignimbrites. The coexistence of two melts of contrast composition, dacite and andesite-basalt, in the IIlb ignimbrites is supported by the occurrence of two pyroxene pairs: low-temperature and high-temperature ones. The latter are locally found in the IIb ignimbrites.

The composition of the volatiles. The plagioclase-pyroxene assemblage of the phenocrysts suggests a low content of readily soluble volatiles such as H_20 in the parental ignimbrite melt. A qualitative analysis of the gases occluded in quartz, plagioclase, and pyroxene was performed on a mass spectrometer by heating at 100°C steps to 1000°C (analyst A. Yu. Polyakov, Institute of Volcanology). The analysis has shown that the amount of volatiles was small on heating to 600° C and was dominated by H_20 and $C0_2$. The volatile release began to rise on heating from 600° to 900°C, and increased sharply at 1000°C (Figure 7). The composition of gases inverted, and the amounts of N_2 and CO increased. Since CO is usually present in magmatic gases merely as an admixture, this peak can be assigned to N_2. Nitrogen predominates in all experiments and in all minerals except for pyroxene from the Ib ignimbrite. Oxidized gases are more abundant in pyroxene and quartz than in plagioclase, whose water is either undetectable at all (Ib) or is present in a small amount. Small amounts of SO_2 were determined in quartz from unit Ia and in other minerals from unit IIIa.

The qualitative analysis of gases have thus shown that the fluid phase was fairly reduced in the early stages of the phenocrysts (mainly plagioclase) crystallization. The oxidation ratio was less than 1; it increased with a temperature drop and reached the maximum value during the pneumatolitic and hydrothermal stages. The role of CO_2 was significant.

The composition of the melt. The sequence of the ignimbrite layers separated by considerable time intervals suggests a long-lasted evolution of the Bolshoi Semyachik volcanotectonic structure. The ignimbrites are markedly inhomogeneous and compositionally evolve from rhyolites (71-73% SiO_2) at the early eruptive stages to andesites (59-61 % SiO_2). This evolution is also reflected in the succession of the mineral assemblages which are: (1) Qtz + Pl_{23-28} + Bt + Mag + IIm (pumice tuff and poorly welded ignimbrite at V. Stan River); (2) Qtz + Pl_{30-40} + Opx_{38-40} + Cpx_{29-31} + Mag + IIm (quartz-bearing ignimbrites, la); (3) Pl_{23-36} + Opx_{38-40} + Cpx_{33-35} + Mag + Ilm (rhyodacitic pyroclastic flows, IIa b, c); (4) Pl_{45-55} + Opx_{39-46} + Cpx_{33-41} + Mag + IIm (ignimbrites IIIa); (5) Pl_{45-55} + Opx_{30-35} + Cpx_{27-28} + Mag + Ilm (ignimbrites lb, Illb, and, partially, IIa, b); (6) Pl_{75-85} + Opx_{28-30} + Cpx_{26-28} + Mag (ignimbrites Illb and partially IIb).

The mineral assemblages seem to have crystallized out of chemically different melts. This is supported by Mn distribution between the pyroxenes which depends on the bulk chemistry of the rocks. The hypersthenes can be divided into three groups according to their Mn contents (see Figure 5): (1) the hypersthenes with the minimum Mn content (0.4-0.5%) related to the flattened andesite-basalt inclusions in the ignimbrites; (2) the hypersthenes with 0.6-1.1 % MnO from the andesitic and dacitic ignimbrites (lb, IIIa, b) and the ignimbrites containing quartz and pyroxenes similar to phenocrysts from the IIIa ignimbrites; (3) the hypersthenes with the maximum Mn content from the welded rhyodacitic tuffs (II, IIb, IIc).

The character of chemical variation of the ignimbrites in each stage, the succession of the mineral assemblages, and the compositionally different glasses and heterotaxic pumices suggest the existence of a crustal zoned magma chamber beneath Bolshoi Semyachik Volcano in Pleistocene time. The initial melt chemically corresponded to diorite, as evidenced by the predominance of andesite in the precaldera volcanic structure. The zoning of the magma chamber could result from fractional differentiation in the crystal-melt system [13]. By this mechanism, the crystallization of melt at the walls and in the roof of the chamber causes the squeezing out and floating of low-density residual liquids which form a cap of high-silica melts, rich in alkalis and water. The quartz-biotite pumice tuffs, the poorly welded ignimbrites in the V. Stan River area, and the quartz-bearing ignimbrites of unit la, composing the base of the Semyachik ignimbrites, all seem to reflect the composition of this zone. The aggregates of quartz, orthopyroxene, clinopyroxene, and magnetite, that occur sometimes in the la ignimbrites, may represent the crystalline fragments of a compositionally more basic solidified roof.

A layer of dacite and andesite-dacite melt occurred beneath the cap of high-silica melt, as seen from the subsequent eruption of the lb ignimbrites. Its composition is characterized by the disk-shaped fiamme with 64.8% SiO_2. Since both of these flows (Ia and Ib) are fairly homogeneous, and intermediate varieties are absent, the boundary between the layers was distinct, and they were drained separately. A relatively uniform composition of the plagioclase phenocrysts in the 1st stage ignimbrites indicates a quiet crystallization. A rather long interruption seems to have existed between the 1st and the 2nd stages during which the disturbed zoning of the chamber was restored, but the upper acid zone had become rhyodacitic by that time. A decrease of the silica content in the last Ila rhyodacite flow, a growth of plagioclase basisity, an increase of the magnesium content of the pyroxenes in each subsequent flow reflect theat progressively deeper zones of the chamberwere drained. The eruption of andesite-basaltic ignimbrite-like rocks (with 54% $Si0_2$) during the late 2nd stage suggests the existence of another, deeper, magma reservoir. A stratified crustal magma chamber usually acts as a density barier for basalts rising from a greater depth. Their breakthrough to the surface seems to have been caused by a vigorous gas lift effect (volatile withdrawal) and emptying of the upper acid zone. The volatile-rich basalt melt with an admixture of acid material was extremely mobile since it had covered a vast area by a thin layer. A wide compositional range of the phenocrysts in the 2nd stage ignimbrites may reflect magma mixing in the crustal chamber.

A relative depletion of the upper rhyolite layer during the first two stages and an active convection in the chamber after the basalt injection resulted in chemical homogenization of the magma and in the eruption of the compositionally intermediate dacitic ignimbrites in the early 3rd stage after the 1st phase of the Late Pleistocene glaciation. The ignimbrites are poorly stratified in chemistry. The lowermost layers (initial melt portions) are slightly higher in silica (66.7% SiO_2). The last flow declines in silica to the appearance of the andesite-basalt scoria. The composition of the layers in the crustal magma chamber is chemically reflected by the contrast layers in the heterotaxic pumices from the unwelded tuffs that preceded stage 3 (see Table 1). The bimodal mineral composition of the IIIb ignimbrites, the complex cyclic zoning of the plagioclases, and the coexistence of the acid glasses and the andesite-basalt scoria, suggest a magma mixing before and synchronous with the eruption.

The weak eruption of the IV rhyodacitic ignimbrite was probably the beginning of a new eruptive stage. However the absence of such ignimbrites near the Bolshoi Semyachik caldera and their occurrence in the Uzon-Geyzernaya depression suggest their genetical relation to the latter.

To sum up, the succession of the ignimbrite compositions within an individual stage and throughout the whole period of the ignimbrite formation, may indicate that magma was withdrawn successively from a zoned magma chamber. The chamber consisted of the upper rhyolitic layer and the lower part, where the composition varied from andesite-dacite to andesite. Basalts were injected into the bottom of the chamber from deeper reservoirs and stimulated eruptions of pyroclastic flows. Such

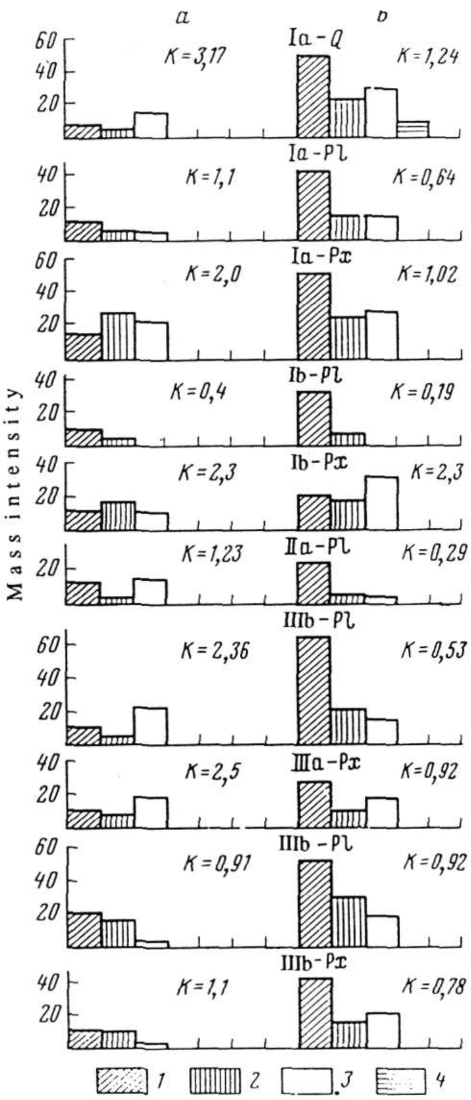

Figure 7 Composition of gases from the ignimbrite monomineral fractions at: *a* - 600°C, *b* - 1000°C; 1 - N_2, 2 - CO_2, 3 - H_2O, 4 - SO_2; *K* - oxidation ratio.

high-temperature basalt injections into acid crustal chambers seem to trigger vigorous explosive eruptions [14]. The homogeneity of the pyroclastic flows can be explained by a layer-by-layer emptying of the stratified magma chamber, like in the case of the Ia and Ib ignimbrites. A dynamic fluid model [10] can used to explain a successive chemical variation of the melt during the eruption. This model suggests the drawing up of magma from deeper zones of the chamber with an increasing heterogeneity of its properties (ignimbrites of unit II and partly unit III).

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