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Structural Control of Volcanism and Hydrothermal Activity on the Bol'shoi Semyachik Volcanic Massif, Kamchatka, Russia

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ABSTRACT

We provide new evidence that bears on the geological structure, history of evolution, and structural setting for the Bol'shoi Semyachik Volcanic Massif in Kamchatka. The new Ar–Ar results for dating of volcanic rocks allowed significant advances in updating the stratigraphy and history of the evolution of the area of study. We discuss the distribution of centers of volcanic and hydrothermal activity in the Bol'shoi Semyachik Massif area. The distribution suggests that the volcanism in the area is progressively migrating southeastward. It is shown that all thermal occurrences, such as sets of steam jets, thermal springs, and heated patches (evidence of present day activity), are also displaced into the southeastern part of the massif. It was concluded that these patterns are not accidental, but are controlled by dipping magma conducting and fluid-conducting faults that bound a major basement low on the southeast. The low had been identified earlier from geophysical observations. The dip gives the result that the magma and fluids rise to the surface and simultaneously deviate eastward and southeastward, where the youngest occurrences of volcanic activity and present-day thermal features are found today.

1. INTRODUCTION

The Bol'shoi Semyachik Volcanic Massif is a volcanic edifice with a complex structure that is situated in the central part of eastern Kamchatka (Fig. 1). The massif consists of numerous volcanoes whose bases have coalesced; it bears a variety of names: "Bol'shoi Semyachik volcanic cluster," "Bol'shoi Semyachik volcanic center," "Bol'shoi Semyachik volcanic massif," or just "Bol'shoi Semyachik Volcano."

The name Bol'shoi Semyachik Volcano is properly applied to the highest mountain in the area, Mount Zubchataya (Novograblenov, 1932; Vlodavets, 1949, 1958; Yastrebov, 1953; Svyatlovskii, 1959). The numerous smaller volcanoes around Mount Zubchataya received names of their own: Burlyashchii, Tsentral'nyi Semyachik, Problematichnyi, Ivanova, Popkova, Vostochnyi Baranii, Zapadnyi Baranii, Kulakova, and Plosko-Kruglen'kii (Vlodavets, 1958) (Fig. 2). Apart from the above volcanoes, there are many small extrusive domes in the area that received names of their own as well: Polukupol, Kupol "so shchitom," Kupol "s pemzoi," Korona, Yuzhno_Tsentral'nyi, Peremychka, Ezh, Kupol "s kraterom," Chernyi, Krutoi, Skalistyi, and Oval'nye (Vlodavets, 1958).

In the 1960s workers of the Institute of Volcanology, Siberian Branch, of the USSR Academy of Sciences carried out comprehensive investigations in the area of study. The net result of this work was to find out that the main geologic structure in the area where the Bol'shoi Semyachik volcanic cluster is situated is a major volcano-tectonic depression (caldera) and that its generation was caused by a powerful burst of acid volcanism during Pleistocene time (Aver'ev et al., 1971). It was also shown that the area contains one of the largest (in Kamchatka) high-temperature hydrothermal systems, the Semyachik system; its features were identified, the total heat power was calculated, and it was suggested that there is a deep-seated source of heat, viz., a magma chamber in the interior of the caldera (Aver'ev et al., 1971; Vakin, 1976). The general features of caldera structures were identified for the central part of eastern Kamchatka: it was shown that the structures progressively become younger in the northeastern direction from the Bol'shoi Semyachik caldera toward the Uzon–Geizernaya Depression and further toward the Krasheninnikova Volcano caldera accompanied by a definite pattern in the variation of the associated pyroclastic deposits (Erlikh et al., 1974). All of this work led to the understanding that it was caldera generating processes that have been the main agents in the evolution of volcanism in the region and the history of each structure began to be viewed in individual phases, identifying the pre-caldera phase, the caldera generating phase, and the post-caldera one (Aver'ev et al., 1971; Sheimovich et al., 1973; Braitseva and Melekestsev, 1973; *Vulkanizm…*, 1974).

Work was conducted during the 1980s in the Bol'shoi Semyachik area to refine the geological structure and structural setting of hydrothermal activity. Some of the results were published in the *Active Kamchatka Volcanoes* atlas (Leonov and Grib, 1991), as well as in several papers (Murav'ev and Egorov, 1989; Grib and Leonov, 1993; Leonov, 1993; Leonov and Grib, 1999). In recent years new Ar–Ar data were acquired in the dating of volcanogenic rocks in Kamchatka (Leonov et al., 2008; Bindeman et al., 2010). The dating was carried out at a laboratory at the University of Wisconsin in Madison, USA. The rocks that were sampled for this analysis were discharged during the larger and best known caldera-generating eruptions in Kamchatka; among other samples, the ignimbrites related to the Bol'shoi Semyachik caldera were dated. This work gave much that was new in the stratigraphy of rocks that compose the Bol'shoi Semyachik area, resulting in a new stratigraphic column and a map of the geological structure for the area of study, which is to be described below.

2. GEOLOGICAL STRUCTURE OF THE AREA OF STUDY

The basement for the volcanoes standing in the Bol'shoi Semyachik Massif is mostly composed of Cretaceous/Paleogene and Oligocene/Miocene sedimentary rocks that are exposed within the Vostochnyi Range of Kamchatka (the folded basement), as well as of a complex of volcanogenic–sedimentary deposits that fill the East Kamchatka Depression (the upper structural level)

(Shantser et al., 1980). These rocks are not exposed at the surface in the Bol'shoi Semyachik Massif area. The rocks that compose the upper structural level, which consist of the Shchapino terrigenous volcanogenic deposits, as well as of the Storozh volcanogenic deposits, are exposed at the surface 30 km west of the Bol'shoi Semyachik Massif, in the junction zone between the East Kamchatka Depression and the uplift of the Valaginskii Range. The deposits of the Shchapino and Storozh Formations were previously supposed to be of Pliocene age (Shantser et al., 1980) and this was corroborated by the Ar–Ar dating: the age of the ignimbrites that were exposed on Mount Stol (these were previously classed as belonging to the Storozh Formation) turned out to be 3.71 Ma (Leonov et al., 2008; Bindeman et al., 2010).

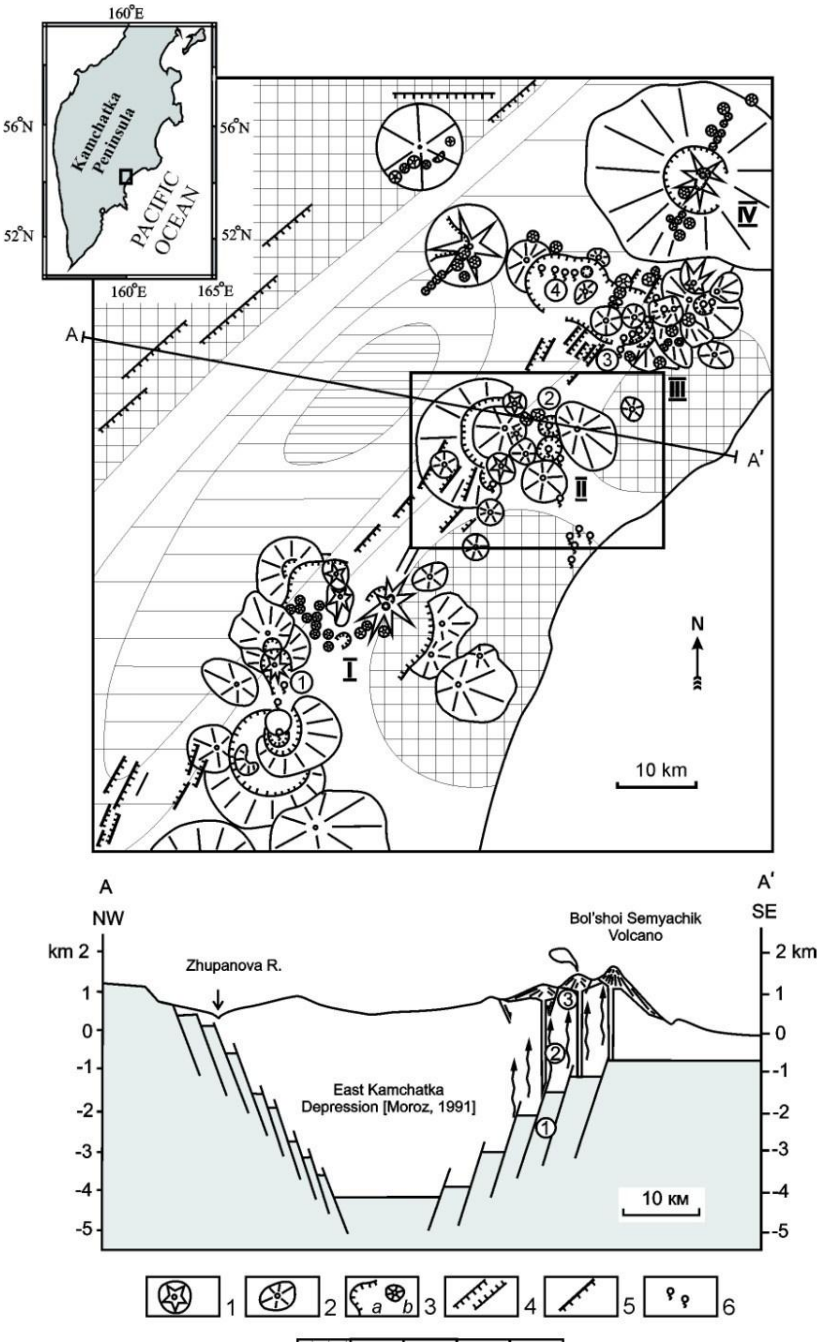

Figure 1: A map and a section showing the location of the basement low, volcanoes, and high-temperature hydrothermal systems in the central part of eastern Kamchatka (Leonov, 2001). (1) Late Pleistocene to Holocene volcanoes, (2) Middle to Upper Pleistocene volcanoes, (3) calderas (*a*), smaller volcanoes and cinder cones (*b*), (4) major faults striking northeast, (5) Late Pleistocene to Holocene fissures and normal faults, (6) thermal features, (7) depth to top of Cretaceous basement, km (Moroz, 1991): *a* below 1, *b* 1–2, *c* 2–3, *d* 3–4, *e* over 4. I–IV volcanic centers: I Karymskii, II Bol'shoi Semyachik, III Uzon–Geizernaya, IV Krasheninnikova. Numerals in circles mark high-temperature hydrothermal systems (*1*—Karymskii, *2*—Semyachik, *3*—Geizernaya, *4*—Uzon). A–A' section line. The hatching in the section denotes the basement (pre-Cenozoic complex), numerals in circles mark zones: (1) fault zone that bounds the low and is a deep-seated trap for magma and hydrothermal fluids, (2) zones of ascent of magma and hydrothermal fluids to the ground surface, (3) zone of Late Pleistocene fissures and normal faults at the ground surface.

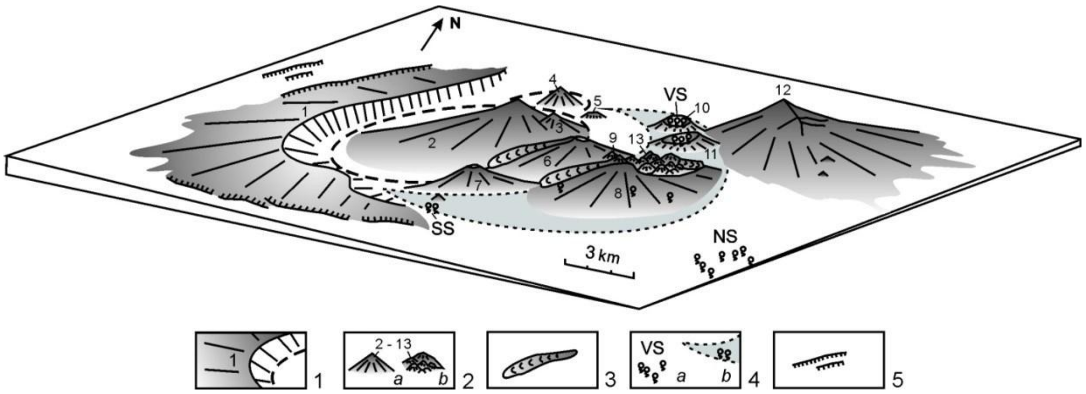

Figure 2: A block diagram for the Bol'shoi Semyachik Volcanic Massif. (1) Khrebet Bort (remains of the caldera edifice), dashed line shows the structural boundary of the caldera, (2) volcanoes (*a*) and extrusive domes (*b*) of the post-caldera phase (*2* Zapadnyi Baranii, *3* Vostochnyi Baranii, *4* Kulakova, *5* Opal'nyi, *6* Popkova, *7* Plosko-Kruglen'kii, *8* Problematichnyi, *9* Ivanova, *10* Burlyashchii, *11* Tsentral'nyi Semyachik, *12* Zubchatka (Bol'shoi Semyachik), *13* set of extrusive domes), (*3*) lava flows, (*4*) thermal features (thermal springs and steam jets) (*a*), arcuate zone where the thermal features near the caldera concentrate (*b*), letters mark sets of steam jets and springs: VS Verkhnesemyachikskie, SS Srednesemyachikskie, NS Nizhnesemyachikskie, (*5*) faults.

The Bol'shoi Semyachik Volcanic Massif is mostly composed of volcanogenic rocks with ages ranging between the Eopleistocene and the Holocene (Figs. 3, 4). One can discern the pre-caldera, the caldera-generating, and the post-caldera rock complexes in the massif structure.

The rocks of the *pre-caldera complex* are exposed in the western part of the massif, on the slopes of the Bort Range (a remnant of the pre-caldera structure), and in the northeastern part of the area of study, in the Promezhutochnyi Range. At these locations one finds fragments of stratovolcanoes with predominantly basic basaltic, basaltic andesitic and andesitic composition of the volcanic rocks involved. The northern part of the Khrebet Bort, which is the largest volcanic edifice of the pre-caldera phase, is composed of dacite lavas. The eastern part of that edifice has subsided along the faults that bound the Bol'shoi Semyachik caldera and is hidden beneath younger volcanic rocks.

The rocks that belong to the *caldera-generating complex* are mostly ignimbrites, which occupy extensive areas around the Bol'shoi Semyachik Massif (Fig. 5). They were built by major caldera-generating explosions and by the formation of the Bol'shoi Semyachik caldera. The first investigator to detect and describe the caldera was V.I. Vlodavets (1958); while the western boundary was evidently along the foots of the Bort Range, the eastern edge was tentatively identified by Vlodavets as passing through the craters of two destroyed volcanoes, Burlyashchii and Tsentral'nyi Semyachik. He was also the first to describe the rocks that are labeled ignimbrites today, although he called them tuff lavas and did not link their generation to the Bol'shoi Semyachik caldera (Vlodavets, 1953, 1957, 1958).

Subsequent detailed studies of the ignimbrite sections that are exposed on the shore of the Kronotskii Bay (near the eastern foot of the Bol'shoi Semyachik Massif) and in the basin of the Verkhnii Stan River (near the western base of the massif) were carried out by V.S. Sheimovich, O.A. Braitseva, and T.S. Kraevaya (Sheimovich et al., 1973). They showed that the ignimbrite sequence consists of several independent horizons of different ages ("cooled units") and that the ignimbrites proper contain members of agglomerate pumice tuffs, tephra, buried soils, as well as deposits of glacial and fluvioglacial genesis. It was also remarked that all "cooled units" typically involve well-defined zonal structures, with abundant transitions from unconsolidated, unbaked varieties to baked, frequently homogenized, lava-like rocks. In all, Sheimovich et al. (1973) identified five "cooled units," with the three lower ones being thought to originate from the formation of the Bol'shoi Semyachik caldera, while the two upper ones were believed to be related to post-caldera volcanism, although no associated eruptive centers have been identified.

Our work that was later conducted in the area suggested that the youngest ignimbrites that were previously classified as belonging to the two upper "cooled units" (Sheimovich et al., 1973) really are "Uzon" ignimbrites (Grib and Leonov, 1993; Leonov and Grib, 1999; Leonov et al., 2001). They can be followed from exactly the wall of the Uzon–Geizernaya Depression southward as far as the Bol'shoi Semyachik Massif. We use our previous results to give a brief review of the distribution of Semyachik ignimbrites and the structure of their sections.

The pyroclastic flows related to the generation of the Bol'shoi Semyachik caldera propagated east toward the ocean, as well as to the south and west of the caldera (see Fig. 5). They filled the valleys of rivers nearby, where one can see thick sequences of ignimbrites inside the paleorelief in the valley slopes. A study of available exposures shows that the Bol'shoi Semyachik ignimbrites (to be referred to as Semyachik ignimbrites) overlie those related to the Karymskii Volcanic Center (or Karymskii ignimbrites) and are in turn overlain by the ignimbrites related to the Uzon–Geizernaya Depression (Uzon ignimbrites). The section of the Semyachik ignimbrites consists of a sequence of lava-like ignimbrite beds separated by layers of pumice, and of lacustrine and glacial deposits.

Three ignimbrite generation phases have been identified (Grib and Leonov, 1993). The main factors brought to bear in comparisons of pyroclastic deposits include the stratigraphic position of ignimbrites in the section, their textural and structural characteristics, in particular, the degree of baking, as well as rock composition and the mineralogic compositions of phenocryst associations. The correlation of isolated sections of pyroclastic deposits especially relied on the relationship between the degree of iron content (Fm) in pyroxenes and that of manganese (Grib and Leonov, 1993; Leonov and Grib, 1999; Leonov et al., 2001).

The first phase began with an eruption of rhyolite (72–74% SiO_2) agglomerate tuffs and moderately baked ignimbrites with quartz and biotite, which are encountered south and west of the Bol'shoi Semyachik Massif. These give way to ignimbrites of rhyodacite (72–73% SiO_2) composition, which compose the bases of the shore cliffs in the Kronotskii Bay. These ignimbrites typically involve a quartz–pyroxene association of phenocrysts and a higher degree of baking. These last are in their turn overlain by massive ignimbrites of dacite andesitic (63–64% SiO_2) composition with disk-shaped fiamme involving a large amount (2–3% of rock volume) of pyroxene phenocrysts (Grib and Leonov, 1993).

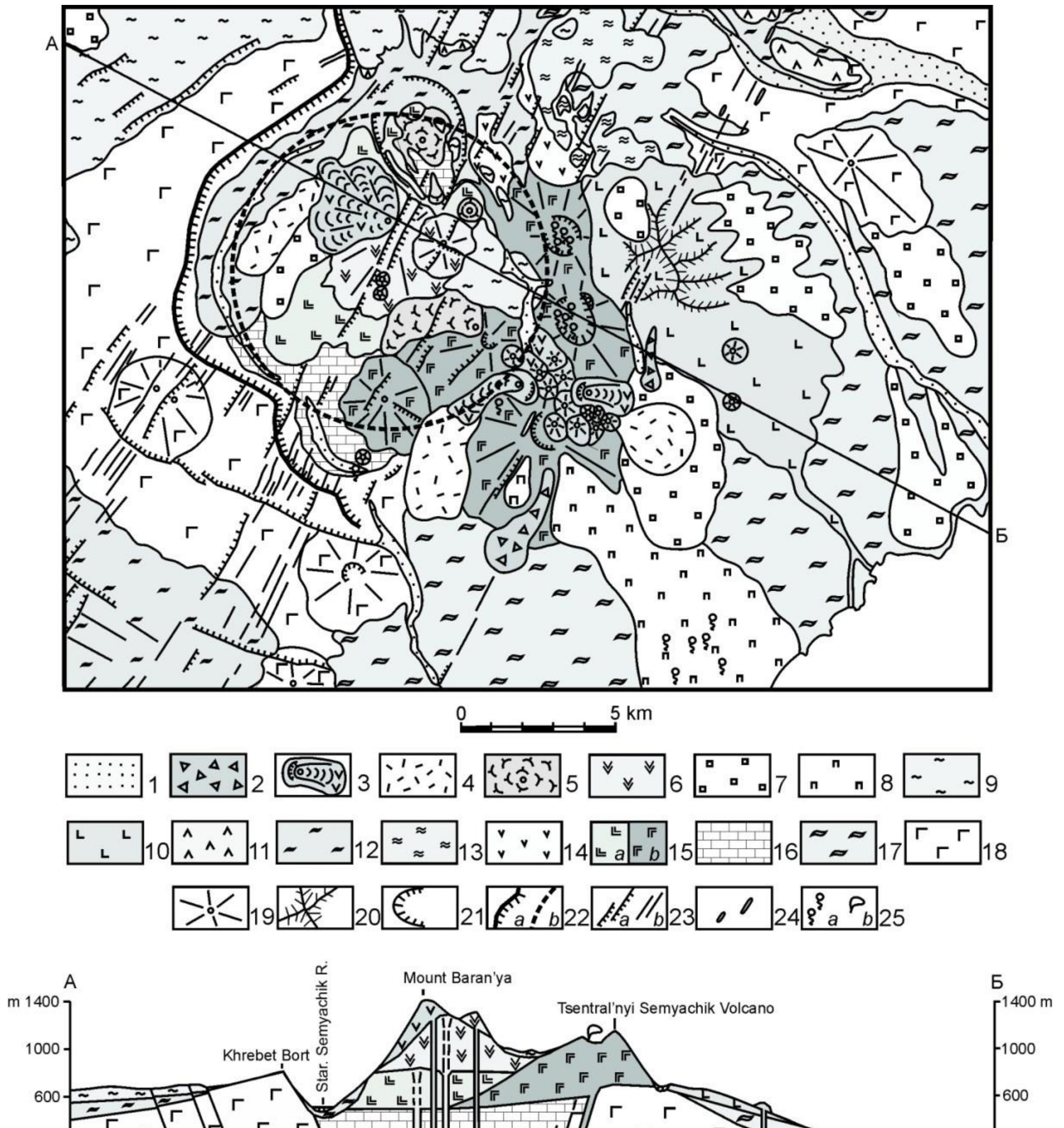

Figure 3: A schematic geological map of the Bol'shoi Semyachik Volcanic Massif. (*1*) alluvial deposits (Q4), (*2*) landslide deposits (Q4), (*3*) andesitic and basaltic andesitic lavas that compose the extrusive domes and associated lava flows (Q4), (*4*) explosion deposits related to extrusive domes (Q4), (*5*) rhyolitic lavas (Q4), (*6*) andesitic and dacite andesitic lavas, their tuff and tuff breccias (Zapadnyi Baranii Volcano), (*7*) glacial deposits, (*8*) pyroclastic pumice deposits related to Problematichnyi Volcano (Q3), (*9*) ignimbrites related to the Uzon–Geizernaya Depression (the "upper Uzon" ignimbrites) (Q3), (*10*) basaltic and basaltic andesite lavas and tuffs related to Zubchatka (Bol'shoi Semyachik) Volcano (Q2), (*11*) andesitic and dacitic lavas lying in the sequence of "Uzon" ignimbrites (Q2), (*12*) ignimbrites related to the Uzon–Geizernaya Depression (the "lower Uzon" ignimbrites (Q2), (*13*) ignimbrite-like rocks (Q2), (*14*) andesitic lavas (Q2), (*15*) andesitic and basaltic andesite lavas that compose the base of Zapadnyi Baranii Volcano (*a*), basaltic and basaltic andesite lavas that compose Burlyashchii, Tsentral'nyi Semyachik, Popkova, and Problematichnyi volcanoes (*b*) (Q2), (*16*) sandstones, gritstone, and tuffs—lacustrine deposits that fill the Bol'shoi Semyachik caldera (Q1–2), (*17*) ignimbrites related to the generation of the Bol'shoi Semyachik caldera (Q1), (*18*) basaltic, andesitic, and dacitic lavas and tuffs—pre-caldera complex (QE), (*19*) centers of major volcanic edifices, (*20*) mountain ranges of Mount Zubchatka, (*21*) volcanic craters, (*22*) erosional (*a*) and structural (*b*) boundaries of the Bol'shoi Semyachik caldera, (*23*) normal faults (*a*) and fissures (*b*), (*24*) dikes, (*25*) thermal springs and steam jets: *a* in map view, *b* in section.

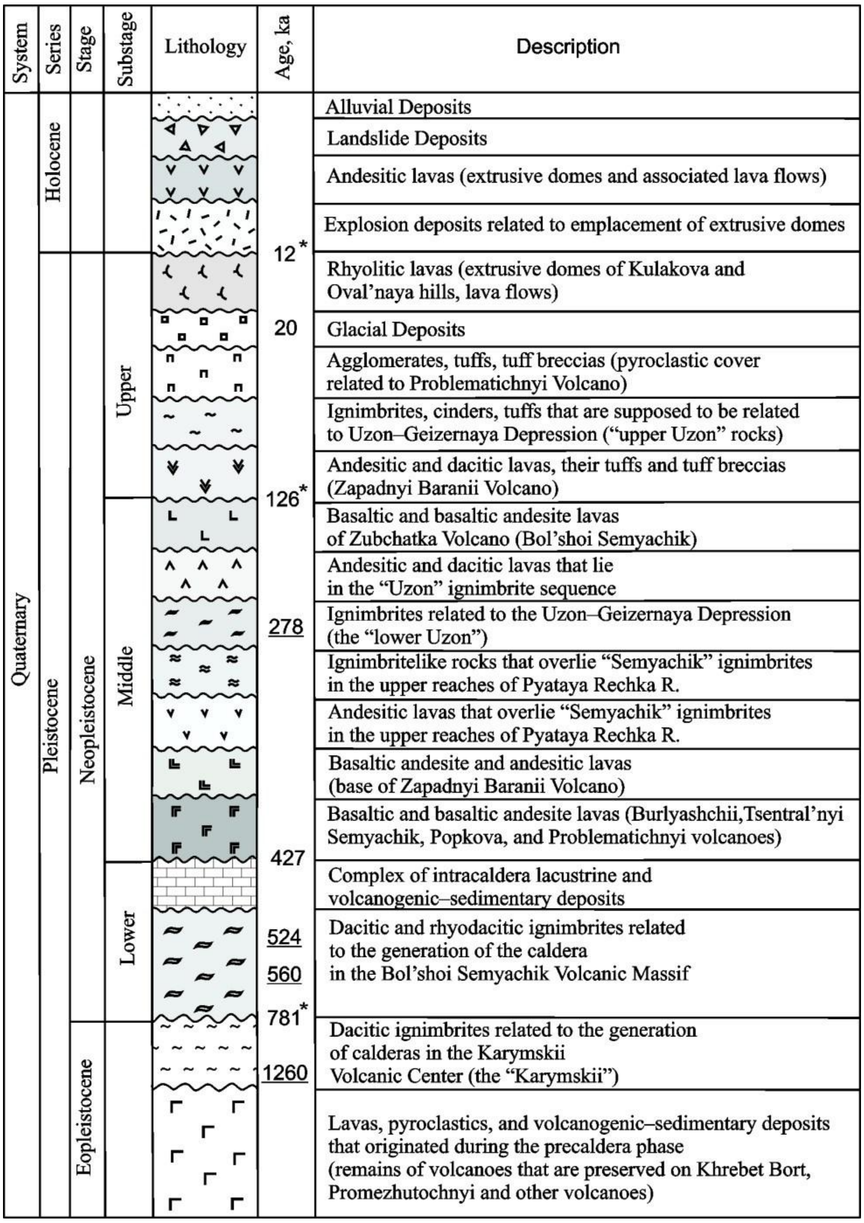

Figure 4: Stratigraphic column of deposits that are exposed in the Bol'shoi Semyachik Volcanic Massif area. Age datings are after the International Stratigraphic Scale (*Mezhdunarodnaya …*, 2012) – dates with stars, after Ar–Ar datings from (Bindeman et al., 2010) – underlined dates, and after (Borisov, 2010).

The next (second) phase is notable in that pyroclastic deposits of predominantly rhyodacite composition (69–71% SiO_2) were coming to the surface. One can identify at least three pyroclastic flows of lava-like ignimbrites with the trend of decreasing silicic acid in the last flow.

The phenocrysts contain plagioclase, pyroxene, and titanomagnetite. The second phase terminated in an eruption of ignimbrite-like rocks with a composition like that of basic andesite and basaltic andesite (54–59% SiO_2) that propagated in a thin layer (1–2 m) to considerable distances. These have an aphyric aspect, very fine porosity, and low specific weight for rocks of this composition.

The third phase of caldera generation began after glaciation, whose imprint (glacial deposits) is found in the sections. The first pyroclastic flows were of dacitic composition (64–65% SiO_2). Near the eastern wall of the caldera these gave way to andesitic ignimbrites (61–62% SiO_2) that are considerably inhomogeneous, containing inclusions of basaltic andesite cinder. One typically encounters a plagioclase–pyroxene–titanomagnetite association of phenocrysts.

The age of the Semyachik ignimbrites was previously determined to be Middle to Upper Pleistocene based on indirect evidence (Sheimovich et al., 1973; Grib and Leonov, 1993). In recent years new Ar–Ar dates were obtained to change that view, so that the age of the Semyachik ignimbrites was determined as 0.56 Ma for the first phase and 0.53 Ma for the second (Leonov et al., 2008; Bindeman et al., 2010). The age of the underlying ignimbrites that are related to the Karymskii Volcanic Center (and exposed at the Korneva River) was determined to be 1.26 Ma, while the age of the overlying ignimbrites related to the Uzon–Geizernaya Depression (and exposed on the Shirokoe plateau) was 0.278 Ma (see table).

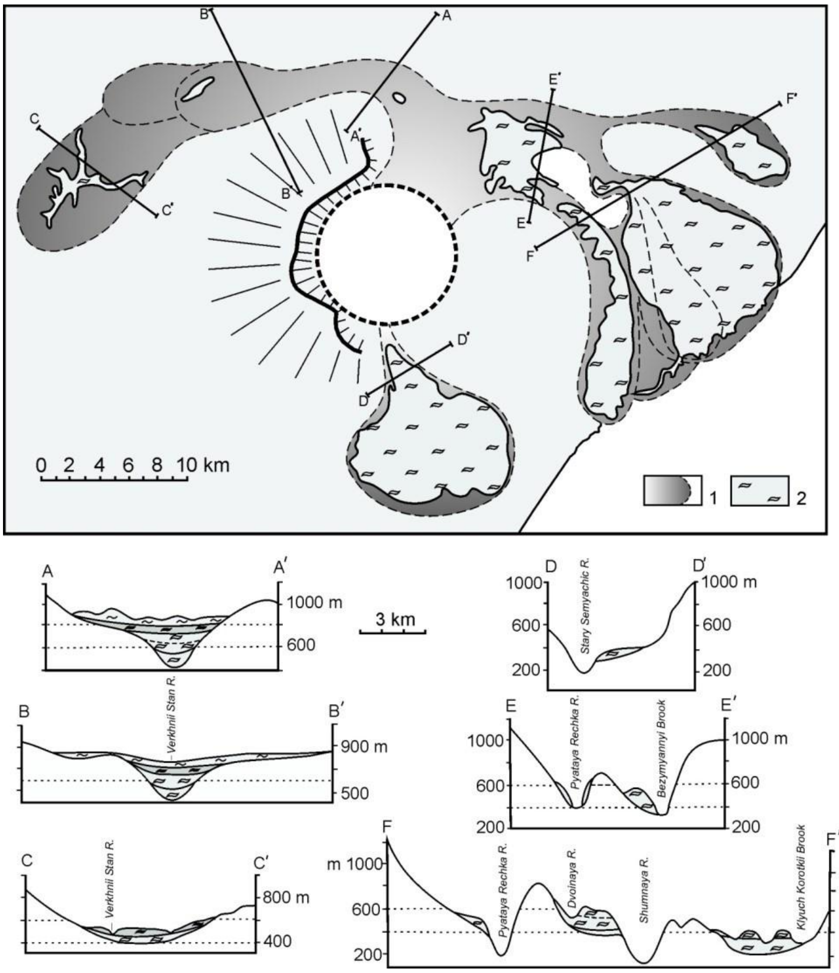

Figure 5: A map showing the distribution of pyroclastic flows related to the generation of the Bol'shoi Semyachik caldera (top) and sections that cut across the trend of individual flows (bottom). (1) inferred distribution of pyroclastic flows, (2) areas where Semyachik ignimbrites are exposed at the surface. For the other notation see Fig. 3.

Table. Results of Ar-Ar dating of volcanic rocks (Leonov et al., 2008)

Sample number	Sampling site	Rock	Ar-Ar age, Ma
1990L-101	Shirokoe plateau	"Uzon" ignimbrite	0.278 ± 0.017
1990L-8	Pyataya Rechka R.	"Semyachik" ignimbrite	0.53 ± 0.110
1990L-80	Verkhnii Stan R.	Welded "Semyachik" tuff	0.56 ± 0.045
509-1	Korneva R.	"Karymskii" ignimbrite	1.26 ± 0.01

The post-caldera complex. The bulk of the Bol'shoi Semyachik Massif is composed of post-caldera features that are situated both outside of the caldera, mostly to the east of it, and also inside and near it.

One especially notes five volcanoes from among the oldest volcanoes of the post-caldera period, viz., Problematichnyi, Tsentral'nyi Semyachik, Popkova, Plosko-Kruglen'kii, and Burlyashchii. They have much the same features, all having comparatively small dimensions (the base is 2 to 4 km in diameter and the relative heights range between 200 and 500 m) and are isolated cone-like elevations.

Problematichnyi Volcano occupies the southernmost part of the Bol'shoi Semyachik Massif and is one of the most dilapidated volcanoes in this set. Its southern part is in good preservation and the northern is overlain by younger extrusive domes. The summit is an arcuate ridge that is probably the edge of the crater. Outliers of the volcano's basaltic edifice are encountered in the form of local exposures in the southeastern sector of the massif. They consist of alternating lava flows 1 to 5 m thick and poorly stratified tuff breccia. Above the basaltic section is a layer of tuff breccia, tuff gritstone, and tuff sandstone containing fragments of lava froth, 2 m thick. These are overlain by a series of andesitic flows and their tuff breccias as thick as 100 m in places. The lava flows make a shield on the eastern and southern slopes of the volcano. They are in turn overlain by agglomerate pumice flows.

Tsentral'nyi Semyachik Volcano stands between Zubchatka and Problematichnyi volcanoes. Its north-eastern part is preserved, the eastern and the southern are less so. The western part was destroyed by erosion whose effect was aided by intensive hydrothermal and fumarole activities. An extrusive dome of dacitic composition (Polukupol) stands on the northern slope of the volcano; the southern and eastern parts contain a group of Upper Pleistocene to Holocene andesitic domes. Intensive hydrothermal activity is currently observed in the central destroyed part, as well as on the volcano's southeastern slope (Vakin, 1976).

Popkova Volcano is situated between a small dome called "Ivanova Volcano" and Vostochnyi Baranii Volcano. The Popkova western and southwestern slopes are gentle and the northern and eastern slopes are steep. There is a large cirque-like depression in the central part of the volcano. The depression is an extended and deepened (by erosion) crater. It gets narrower at the base of the northeastern slope and terminates in an alluvial cone.

Burlyashchii Volcano is situated near the western foot of Zubchatka Volcano. When viewed from the south, the volcano has the outlines of a gentle hill divided by the valley of the Fumarol'nyi Brook, which cuts across it from east to west. The central part of the volcano is today an arena of powerful fumarole activity (Vakin, 1976).

Plosko-Kruglen'kii Volcano is a cone-shaped stratovolcano with a truncated summit and a shallow crater. It is situated in the southern part of the Bol'shoi Semyachik Massif, somewhat apart from the main set of volcanoes. Morphologically, the volcano is a cone-shaped mountain whose slopes are cut through by shallow barrancos. One can clearly see a series of regional fissures that traverse the volcano's summit.

There is a younger set of volcanoes consisting of Zapadnyi Baranii, Vostochnyi Baranii, and Zubchatka (Bol'shoi Semyachik).

Zapadnyi Baranii Volcano is situated at the center of the Bol'shoi Semyachik caldera and fills it practically completely. The base of the volcano is 6–7 km across and the summit has an absolute altitude of 1426 m. The volcano has a complex structure including a pre-glacial basement that forms a plateau southwest of the volcano's summit, the cone of the main edifice, as well as a series of lava flows in the western part of the cone, which occurred during post-glacial time. The base of the volcano is exposed on the southwestern side from the summit in the left wall and in the bed of the Staryi Semyachik River. The base is a series of plateau-shaped lava flows consisting of basaltic andesite and their tuff breccias, which are alternating in the upper part of the section with thin-layered ash and lacustrine psephite tuffs that fill the caldera. The present-day cone of the volcano is mostly composed of subaphyric dacites. The lava flows are separated by members of agglomerate tuffs 5–10 m thick. Extensive fields of hydrothermally altered rocks lie in the near-summit part of the volcano. Two small extrusive domes can be seen on the southern slope; the eastern slope contains **Vostochnyi Baranii** Volcano, which is a side product of Zapadnyi Baranii Volcano. The domes are mostly composed of andesitic lavas and tuff breccias.

Zubchatka Volcano (Bol'shoi Semyachik) is situated in the northeastern part of the massif and is the largest, both by height and base diameter. The fresh aspect of the lavas and the young relief forms provide evidence of its younger age compared with the other volcanoes in the Bol'shoi Semyachik Massif. At the same time, the volcano dates back to preglacial time, because its edifice is heavily destroyed by glacial erosion, resulting in a series of corries on the slopes. The volcano section is exposed in the corrie walls, showing alternating lava flows and pyroclastic material.

All the stratovolcanoes described above have identical structures; the sections consist of thin (1–3 m) lavas and thick members of poorly stratified tuff breccias and tuff agglomerates. The products of explosive activity prevail over the lava material. The explosivity index is 60–70%. Thicker members of pyroclastic deposits are confined to the bottoms of the sections, while nearer the top these deposits alternate more uniformly with the lava flows. The lavas from Tsentral'nyi Semyachik, Popkova, Zubchatka, and Problematichnyi volcanoes mostly consist of high-silica bipyroxene–plagioclase basalts and, to a lesser degree, of bipyroxene–olivine–plagioclase ones. The rock has a porphyric texture, the groundmass is intersertal.

The extrusive domes. This set includes numerous small volcanic edifices, mostly lava domes. Among these one especially notes, on the one hand, Upper Pleistocene to Holocene domes with an andesitic composition. They are situated east of the caldera and outside it. On the other hand, there is a set of domes and associated lava flows situated at the edge of the caldera. These volcanic edifices have a rhyodacite composition. Most domes in the first set are situated compactly between Problematichnyi and Tsentral'nyi Semyachik volcanoes (Fig. 6). The first investigator to describe them was V.I. Vlodavets (1958). The domes are steep structures with smoothed slopes and coalescing bases. Their diameters vary between 500 and 700 m, the relative elevations are 100–150 m.

The domes are composed of comparatively acid (59–63% SiO_2) grey andesites; the andesites are remarkable for containing partially molten, cracked quartz grains, large (as large as 6–8 mm) plagioclase crystals, pyroxene, and rounded basalt inclusions a few tenths of a centimeter to 10 cm among the phenocrysts. These features are not characteristic for andesites in the Yuzhno-Tsentral'nyi dome. By petrographic features, mineral composition (an absence of quartz phenocrysts), and the spatial position, the lavas of this dome are nearer to the Problematichnyi andesites and possibly are a fragment of this volcano separated by a fault.

Among the domes one especially notes a set of Late Holocene neoformations. These are Ezh, Korona, Skalistyi, Chernyi, Krutoi, and Ivanova. The last four are steep-walled lava monoliths surrounded by a breccias mantle. There are deposits of a directed explosion related to Skalistyi Dome, with giant boulders dispersed over an extensive area on its southeastern side. The age of Skalistyi Dome is estimated as a few hundred years (V.V. Ponomareva, personal communication). There are thick (occasionally as thick as 100 m) lava flows 2 km long related to the volcanic edifices of Ezh and Korona, the flow surface showing ridges and furrows of the flow. The young Holocene domes are composed of andesites that are more basic in composition compared with the Upper Pleistocene domes (57–59% SiO2, and 61–63% on Korona Dome). These are dark grey rocks with porphyric exhalations of plagioclase, pyroxene, titanomagnetite, and rare olivine phenocrysts in highly basic varieties. The groundmass texture is microlitic and pilotaxitic. No visible basaltic inclusions occur, but the groundmass occasionally shows some inhomogeneity.

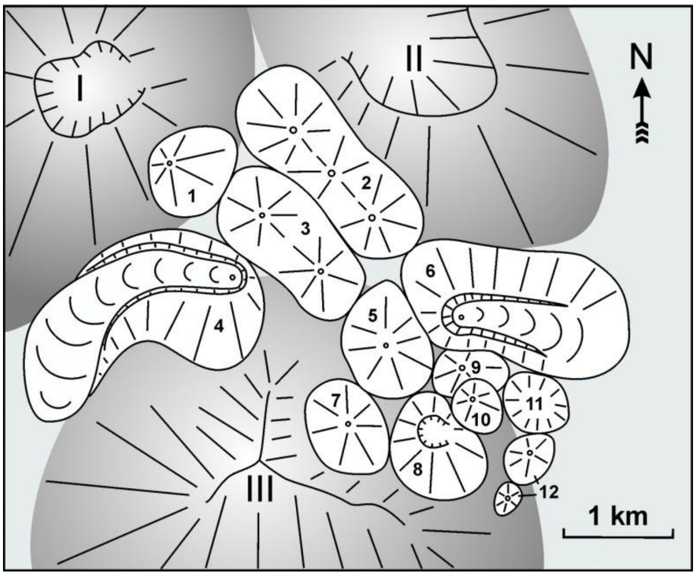

Figure 6: Set of volcanic domes that are situated in the southeastern part of the Bol'shoi Semyachik massif. I–III volcanoes: Popkova (I), Tsentral'nyi Semyachik (II), Problematichnyi (III). Arabic numerals mark domes (the names are after [Vlodavets, 1958]): (1) "Ivanova Volcano," (2) Kupol "so shchitom" and its series, (3) Kupol "s pemzoi" and its series, (4) Korona, (5) Peremychka, (6) Ezh, (7) Yuzhno-Tsentral'nyi, (8) Kupol "s kraterom," (9) Chernyi, (10) Krutoi, (11) Skalistyi, (12) Oval'nye.

The volcanic edifices that are connected with the caldera include the dacite domes and rhyodacite lava flows on the caldera walls (the Kulakova and Opal'nyi extrusive domes, as well as the lava flows on the north-western slope of Popkova Volcano).

The Kulakova dome is situated in the northern part of the Bol'shoi Semyachik Massif on the ring fault that serves as the boundary to the caldera. It is a cone-shaped structure with a highest absolute altitude of 1226 m and a relative elevation of about 600 m (Fig. 7). The dome summit is composed of grey massive rhyodacite with large quartz and plagioclase crystals. The phenocryst minerals (15–20% of rock volume) include plagioclase, pyroxene, hornblende, and titanomagnetite. The groundmass has a xenomorphic-granular and microgranophyric texture. Fragments of a lava flow (15–25 m thick) have been preserved near the southern base of the dome; they consist of rose–grey fluidal, sugary grained rhyodacite with banded structures that are typical of acid flows. There is much less hornblende in the flow lavas than in the dome rocks. The rhyodacites contain considerable amounts of basaltic inclusions. The amount of hornblende in the flow lavas is considerably lower. The emplacement of summit rhyodacites was accompanied by uplifting of earlier structures and by the generation of a resurgent dome about 3 km in diameter. The lacustrine deposits that filled the caldera after the ignimbrite eruption and the overlying lavas of Zapadnyi Baranii Volcano (basaltic andesites and black aphyric andesites) turned out to be uplifted by a few hundred meters (see Fig. 7). Psephite and aleuropelite tuffs have periclinal bedding with dip angles of 30–40° around the perimeter of the dome. The blocks of lacustrine tuffs and black aphyric andesites dip as steeply as at 60–70° in the near-summit part of the dome and in deep incisions of a brook, on its northern slope. These blocks are penetrated with feather-shaped rhyodacite emplacements with a microgranophyric texture. The massive rhyodacites were evidently emplaced in the form of a stock about 1 km in diameter and this uplifted the deposits that fill the caldera.

The Opal'nyi dome has a round shape; it is situated on the northeastern slopes of Vostochnyi Baranii Volcano, near the Kulakova dome (see Figs. 2, 3). Its base has a diameter of about 1 km and is composed of yellowish–grey sugary grained rhyodacites 20 to 150 m thick that contain a great amount of plagioclase phenocrysts, with occasional quartz and hornblende phenocrysts. The rock structure is poorly porous, the texture is porphyric (15% of rock volume), the groundmass has a glassy texture that is occasionally spherulitic.

The rhyodacite flow of Popkova Volcano is situated on its northwestern slope (see Figs. 2, 3). The lavas have penetrated into the near-summit part of the volcano and descended to the base in the form of a broad tongue, with some lavas propagating southward for a distance of 3 km at most. The maximum lava thickness on the northwestern slope reaches 100 m; it is 50 m in its frontal part. The flow surface is step-shaped in profile and little touched by erosion. The lavas have a fluidal structure that is banded at the top; foamed beds alternate with glassy and spherulitic varieties. The base of the flow is composed of greenish–grey massive rhyodacites that contain numerous basaltic inclusions. The phenocrysts consist of plagioclase, pyroxene, and titanomagnetite, with rare olivine subphenocrysts being encountered in basaltic inclusions.

3. THE STRUCTURAL SETTING OF THE VOLCANOES AND THERMAL OCCURRENCES IN THE BOL'SHOI SEMYACHIK VOLCANIC MASSIF

Our previous work (Leonov, 1992) demonstrated that hydrothermal activity, including that observed in the Bol'shoi Semyachik area, concentrates, as it were, the long-lived directional processes of tectono-magmatic activity that best manifest themselves in major fault zones striking northeast and cutting through the volcanic belts at acute angles. The work of Yu.F. Moroz (1991), who used his interpretations of deep electromagnetic sounding data combined with all the geophysical evidence acquired in recent years to demonstrate the topography of a surface that is identified with the pre-Cenozoic (Upper Cretaceous) complex, allowed us to refine our knowledge of the structural setting of the volcanoes and hydrothermal systems in the area of study. It has become evident that the setting of volcanoes in the central part of eastern Kamchatka is controlled by the faults that bound the East Kamchatka Depression on the southeast (see Fig. 1) (Leonov, 2001).

It follows from the results of Moroz (1991) that the top of the Cretaceous basement shows a subsidence of 3–4 km within the East Kamchatka Depression, with the figure for the crystalline basement being 6–7 km. The depression extends northeast for nearly 300 km, with the width varying between 30 and 50 km. The northwestern boundary of the depression has a well-defined expression in the relief, this being also the southeastern boundary of the Vostochnyi Range in Kamchatka where rocks of the pre-Cenozoic basement are exposed at the surface. The southeastern boundary of the depression is not seen in the relief. It is overlain by volcanogenic rocks (mostly Late Quaternary ones) that are abundant in the central part of eastern Kamchatka. The field of these rocks clearly exhibits young, Late Pleistocene to Holocene, faults that strike north–northeast, form several en echelon sets and extend as a whole in a northeast trending band that approximately coincides with the southeastern boundary of the depression. That band also contains the larger volcanic centers, which give rise to caldera complexes and extensive fields of pumice and ignimbrites (see Fig. 1). Three of these centers, viz., the Karymskii, the Bol'shoi Semyachik, and the Uzon–Geizernaya Center, are connected with high-temperature hydrothermal systems (the Karymskii, Semyachik, Geizernaya, and Uzon systems).

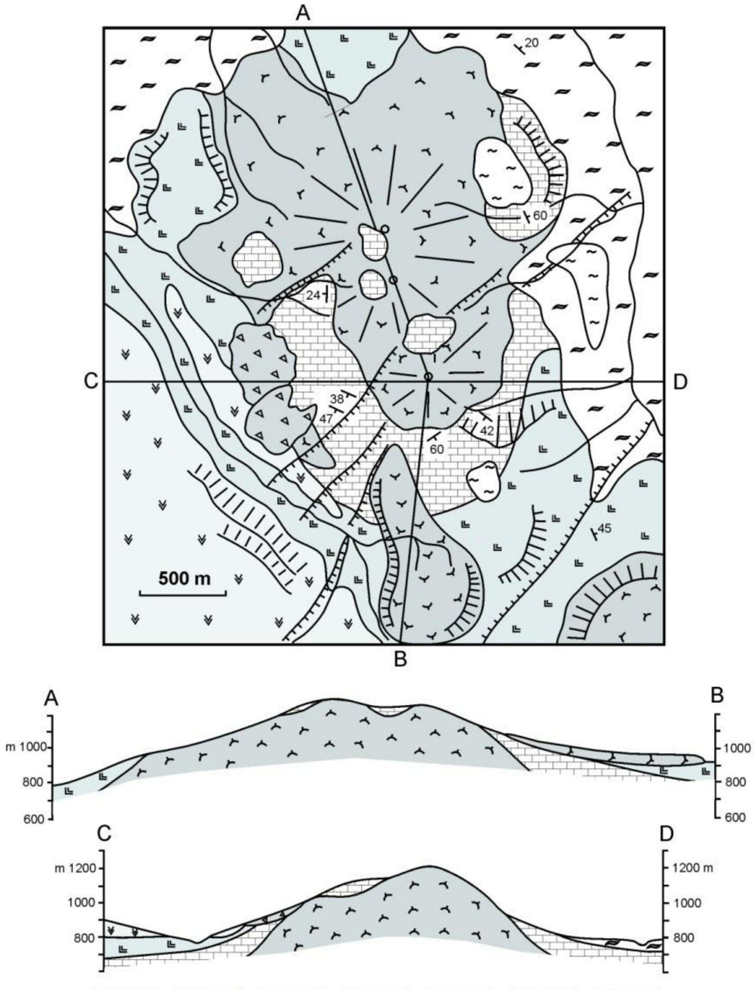

Figure 7: Geological structure of the Kulakova dome. (*1*) landslide deposits (*Q*4), (*2*) rhyolite lavas (Q4), (*3*) andesitic and dacite basaltic lavas, their tuffs and tuff breccias (Zapadnyi Baranii Volcano) ( ), (*4*) ignimbrites related to the Uzon–Geizernaya Depression (the "upper Uzon" ignimbrites) (Q3) (*5*) ignimbrites related to the Uzon–Geizernaya Depression (the "lower Uzon" ignimbrites) (Q2), (*6*) andesitic and basaltic andesite lavas that compose the base of Zapadnyi Baranii Volcano (Q2), (*7*) sandstones, gritstone, and tuffs—lacustrine deposits that fill the Bol'shoi Semyachik caldera (Q1–2), (*8*) centers of major volcanic edifices, (*9*) larger erosion scarps, (*10*) normal faults (*a*) and fissures (*b*).

The distribution of volcanoes and thermal features in the central part of eastern Kamchatka is also controlled by large structures that cut the depression-bounding faults at acute angles. This includes a north–south fault in the Karymskii Center (Vlodavets, 1947; Ivanov, 1970), a north–northwest-striking fault in the Bol'shoi Semyachik Center (Naboko, 1964; Vakin, 1976), and a nearly east–west fault in the Uzon–Geizernaya Center (Zavaritskii, 1937; Shantser, 1979). The locations where these faults intersect deep-seated permeable zones striking northeast harbor the most intensive volcanic and hydrothermal activity. The thermal features in the known hydrothermal systems situated at these locations, or nodes, form sets that are mostly extend along the cutting faults. In particular, the occurrence of thermal fields and hydrothermally altered rocks in a band striking north–northwest in the Bol'shoi Semyachik Massif was pointed out by E.A. Vakin (1976). Leonov (2001) came to the conclusion that the dip of the faults that bound the basement low controls the direction of lateral displacements in volcanic and hydrothermal activity, with the result that thermal occurrences may, in particular, be exposed at great distances from the associated volcanic edifices. The thermal occurrences in the Bol'shoi Semyachik area come to the surface both in the near-summit part of the edifice and at the base of the volcanic massif, where the Nizhne-Semyachikskie thermal springs are situated (see Figs. 1, 2).

We now discuss the structural setting of volcanic and hydrothermal activity in the Bol'shoi Semyachik Massif in more detail. Figure 8 shows the main structural elements, viz., the pre-caldera edifice (Khrebet Bort), the caldera, the volcanoes and extrusive domes that originated during the post-caldera phase. As appears from this figure, two chains of successive generation of the structures can be outlined. The one chain (numerals in circles from 1 through 4) reflects successive displacements of centers of volcanic activity along a zone of neotectonic faults (north–northeastward). The chain includes Khrebet Bort Volcano (1), the center of the Bol'shoi Semyachik caldera (2), Zapadnyi Baranii Volcano, which is the largest edifice in the caldera (3), and the Kulakova dome (4). It should be noted that a series of transverse scarps formed back of the chain, on the SSW slopes of the pre-caldera edifice; the scarps are expressed in the relief as scarps whose steeper side looks NNE (see Fig. 3). We believe that the generation of these scarps, as well as the NNE displacement of centers of volcanic activity, is related to a probable NNE migration of magma in the interior of the Bol'shoi Semyachik Massif.

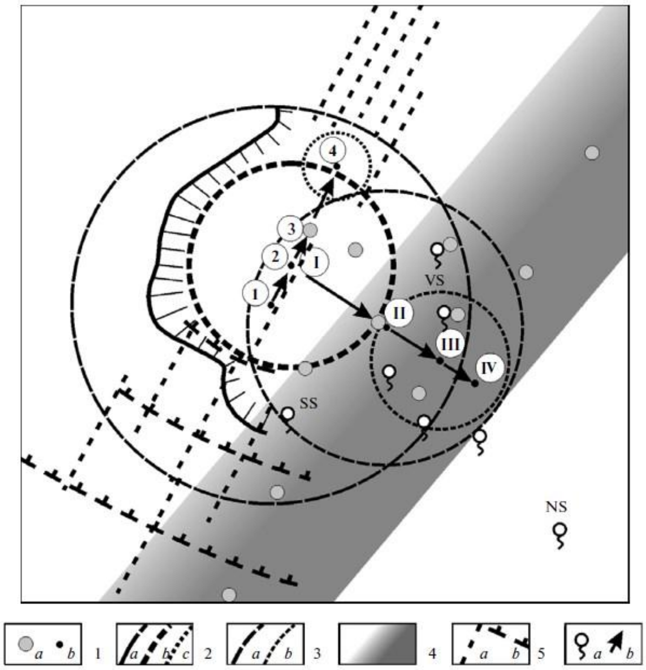

Figure 8: A map of structural localization for centers of volcanic and hydrothermal activity in the Bol'shoi Semyachik Massif area. (1) centers of volcanic edifices (*a*) and of volcanic fields or reconstructed edifices (*b*), (*2*) boundaries of a pre-caldera edifice (Khrebet Bort) (*a*), of the caldera (*b*), and of the post-caldera Kulakova Dome rise (*c*), (*3*) boundary of the area where the post-caldera volcanoes are situated (*b*), (*4*) zone where the locations of centers of volcanic activity are controlled by regional faults striking northeast, (*5*) neotectonic faults striking north–northeast (*a*) and west–northwest (*b*), (*6*) sets of thermal springs and steam jets (*a*), directions along which the centers of volcanic activity were migrating (*b*). Numerals in circles (1–4 and I–IV) mark two directions of migration, for detail see main text. For the other notation see Figs. 2 and 3.

The other chain is also clearly seen within the massif; it reflects the migration of centers of volcanic activity southeastward (numerals in circles from I through IV). This chain can be followed from the caldera (I) to the center of the area of post-caldera volcanoes (the area that contains Burlyashchii, Tsentral'nyi Semyachik, Problematichnyi, Popkova, Plosko-Kruglen'kii, Zapadnyi Baranii, and Vostochnyi Baranii) (II). It can be followed farther to the center of the area of the extrusive domes that formed during the terminal phase in the activity of post-caldera volcanoes (III) and to the youngest domes in the area (and the youngest occurrences of volcanic activity in the entire Bol'shoi Semyachik Massif), viz., the Chernyi, Krutoi, and Skalistyi domes (IV).

Zubchatka Volcano, as well as the smaller volcanoes that are situated in the south of the massif and to the northeast of it, on the Promezhutochnyi Range, do not occur in these chains and make their own zone of concentrated centers of volcanic activity trending northeast (see Fig. 8). That zone traverses the Bol'shoi Semyachik Massif and goes far beyond its boundary. In the north-east it can be traced in the direction toward Kikhpinych Volcano and in the southwest toward Malyi Semyachik Volcano (see Fig. 1). That zone seems to be related to the faults that bound the East Kamchatka Depression (described above) on the southeast (Moroz, 1991).

One distinctive feature of the present-day hydrothermal activity on the Bol'shoi Semyachik Massif consists in the fact that the activity occurs outside the caldera, with the thermal occurrences being situated either in dilapidated craters of minor volcanoes (Burlyashchii and Tsentral'nyi Semyachik) or at their bases (Plosko-Kruglen'kii and Problematichnyi). Overall, thermal features exhibit themselves in the arcuate sector southeast of the caldera (see Fig. 2). Fields of hydrothermally altered rocks widely occur inside the caldera on Zapadnyi Baranii and Vostochnyi Baranii volcanoes, but no present-day thermal features are preserved there. That is to say, it can also be said in respect of hydrothermal activity that it moved southeast as time went on, in the same direction in which the volcanic activity in the I–IV chain did.

The patterns described above are not accidental, in our opinion, and are controlled by the position of the Bol'shoi Semyachik Massif above a dipping zone of magma-conducting faults that bound the East Kamchatka Depression on the southeast. Being an upper crust volume with the highest permeability, that zone provides favorable conditions for magma ascent, controls the locations of magma-conducting channelways and magma chambers. The fact that the zone is a dipping one leads to the consequence that magma and fluids deviate to the east–southeast while rising to the surface; it is there that the youngest occurrences of volcanic activity and present-day thermal manifestations are found today. The north–northeast trending fault zone also exerted a great influence on the locations of centers of volcanic activity in the Bol'shoi Semyachik Massif. The volcanic activity was consistently migrating north–northeast along that zone during the period of caldera generation and subsequently, during the post-caldera phase of evolution. At the same time, the absence of Late Pleistocene to Holocene volcanism and present-day thermal occurrences in that zone provides indication that the magma chambers that are related to the caldera generation and to subsequent emplacement of extrusive rhyolite domes have by now cooled.

CONCLUSIONS

This paper sums up the results of numerous studies conducted by these authors in the Bol'shoi Semyachik Volcanic Massif, Kamchatka. Even though the area was investigated by many workers, there is still much to unravel in the history of its origin, with regard to the factors that helped to build the numerous and very different volcanic edifices that make the massif, and concerning the conditions of the origin for the associated high-temperature hydrothermal system, which is one of the larger ones in Kamchatka. The Ar–Ar datings of several volcanogenic rocks sampled in eastern Kamchatka gave new insights into the stratigraphy of the area, the history of the evolution of the massif, and provided materials for a new geological map. All this is reported in this paper.

The modern datings of volcanic rocks that were sampled in the area were used to reconstruct the history of the evolution of the Bol'shoi Semyachik Volcanic Massif over the period from the Eopleistocene to the Holocene. We obtained more exact estimates for the volumes of the pre-caldera, the caldera-generating, and the post-caldera rock complexes identified previously. We provide the first map showing the abundance of the rocks related to the caldera-generating phase. These rocks are mostly ignimbrites, which occupy extensive fields around the Bol'shoi Semyachik Massif. Three phases of ignimbrite generation have been identified. The age of the Semyachik ignimbrites was determined to be 0.56 Ma for the first phase and 0.53 Ma for the second.

We characterize the post-caldera features in detail, including two sets of volcanoes and a set of extrusive domes. We included five volcanoes in the set of the oldest volcanoes belonging to the post-caldera period: Problematichnyi, Tsentral'nyi Semyachik, Popkova, Plosko-Kruglen'kii, and Burlyashchii. The younger set includes Zapadnyi Baranii, Vostochnyi Baranii, and Zubchatka (Bol'shoi Semyachik). Among the minor volcanic structures we identify, on the one hand, the set of extrusive domes and associated lava flows, which are situated in the margin of the caldera and have a rhyodacitic composition and, on the other hand, the domes that are outside the caldera, southeast of it, whose age is Upper Pleistocene to Holocene and whose composition is andesitic.

The study of the distribution of centers of volcanic activity in the Bol'shoi Semyachik Massif area led us to the inference that the centers systematically moved both to the north–northeast and to the southeast. The former direction of motion can be inferred from the location of the caldera relative to a large pre-caldera volcano (Khrebet Bort) and from the locations of the centers of volcanic activity that came into being within the caldera during the post-caldera phase. The latter direction was found from the southeastward displacement of most of the post-caldera volcanoes and extrusive domes. It was in the same direction, to the south-east, that the centers of hydrothermal activity have moved. The main present-day thermal occurrences (groups of steam jets, thermal springs, and heated patches) are all of them situated in the southeastern part of the massif, while it is only the fields of hydrothermally altered rocks that have remained within the caldera (no present-day hydrothermal activity occurs within the caldera). It was concluded that these patterns are not accidental, but are determined by the dip of the magma-conducting faults. The dip is due to the fact that they bound on the southeast a large basement low that had been identified previously from geophysical data (Moroz, 1991). The dip causes the magma and fluids that are rising to the surface to deviate to the east-southeast, where the youngest manifestations of volcanic activity and present-day thermal occurrences are found.

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