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Petrochemistry of Kamen Volcano: A Comparison with Neighboring Volcanoes of the Klyuchevskoy Group

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Abstract—The data on geology, petrography, mineralogy and petrochemistry for Kamen volcano in the Central Kamchatka Depression are presented. A study of the volcano's rocks and comparison with rocks of neighboring active volcanoes of the Klyuchevskoy group allow the establishment of some relationships. The rocks and minerals of Kamen and Ploskie Sopky volcanoes show systematic differences in the chemistry of rocks and minerals such that they obviously could not be formed from the same primary melts. The rocks of dykes and Kamen stratovolcano on one hand and the rocks of the Klyuchevskoy Volcano on the other hand form differently directed trends on petrochemical diagrams and differ in their compositions of rock-forming minerals, such they also could not originate from the same primary melts. The lavas of the monogenetic cones of Kamen volcano and moderately magnesian basalts of Klyuchevskoy volcano are derivates of the same melts, i.e., the cones situated on the slopes of Kamen are cones of Klyuchevskoy. The rocks of Kamen and Bezymianny stratovolcanoes form a single narrow trend in all petrochemical diagrams in which the lavas of Bezymianny volcano show a silica-rich part, thus indicating a genetic relationship between these two volcanoes.

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INTRODUCTION

Among actual problems related to magma formation in subduction zones, one of the most critical is the problem of the petrochemical and geochemical variety of igneous rocks. In full measure this applies to the Klyuchevskoy group of volcanoes (KGV), which is situated in the Central Kamchatka Depression (CKD). The KGV is of particular importance among Kamchatka volcanoes due to its activity and colossal scale. The results from studying eruption products of this volcanic center have been considered in many publications in recent years [Khrenov et al., 1989, 1991; Kersting and Arculus, 1995; Pineau et al., 1999; Ozerov, 2000; Dorendorf et al., 2000; Mironov et al., 2001; Churikova et al., 2001, 2007; Portnyagin et al., 2007; Turner et al., 2007]; almost all the papers examine only active volcanoes (Klyuchevskoy, Bezymianny, and Tolbachik). However, to understand the space-and-time development of this volcanic cluster it is also important to include data on volcanoes that were active in the past, but which possibly derived magma from the same sources as the present-day volcanoes and in most cases created the basement of the modern edifices.

Kamen volcano (Fig. 1), which is situated in the center of the KGV between Klyuchevskoy, Bezymianny, and Ploskie Sopky volcanoes (Fig. 1a) is one such volcano. In spite of its closeness to other active volcanoes and the huge size of its edifice (its height is 4579.6 m, just 250 m lower than the neighboring Klyuchevskoy volcano) Kamen remains poorly studied compared to its famous neighbors. Investigations of Kamen volcano were carried out in the 1970s. During that period V.A. Ermakov compiled a detailed geological map of the volcano and provided the first petrographical and petrochemical descriptions of the rocks [Ermakov, 1969, 1977]. Interest in Kamen volcano arose after a major Holocene landslide that occurred on its eastern slope (Fig. 1b) [Melekestsev, 1980; Melekestsev and Braitseva, 1984; Ponomareva et al., 2006].

Investigation of Kamen volcano is very important because it may throw light on not only the history of this volcano and its close neighbors, but also on the development of the entire immense KGV cluster. Kamen volcano is located on a shield volcano whose center was beneath Ploskie Sopky; Kamen volcano itself is a pedestal of the presently active Klyuchevskoy and Bezymiannyi volcanoes, which formed on its

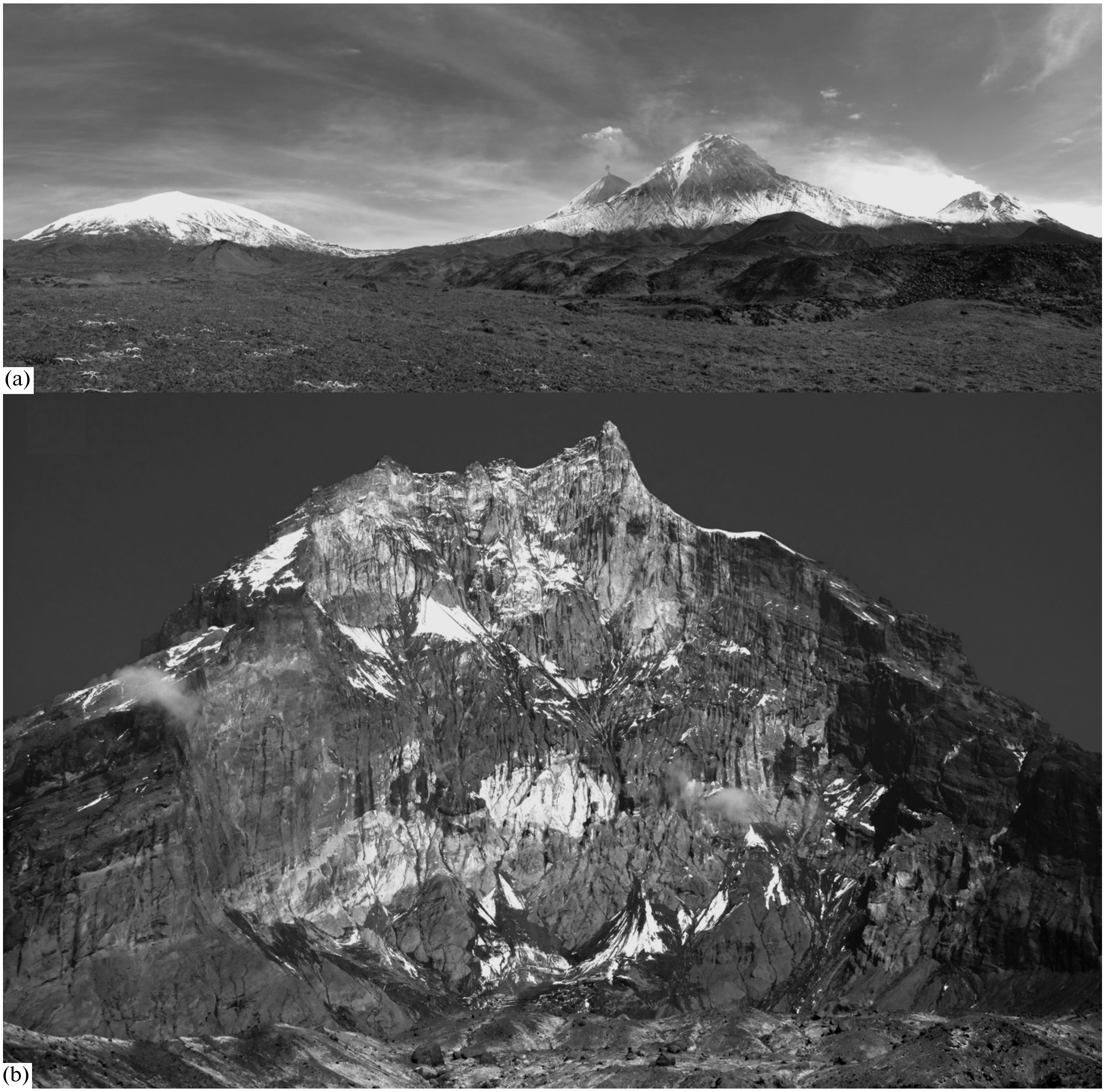

Fig. 1. Kamen volcano. (a) General view of the four neighboring volcanoes from the southwest, from the Studenaya River valley, from left to right: Ploskie Sopky, Klyuchevskoy, Kamen, Bezymiannyi. Klyuchevskoy is erupting, Bezymiannyi shows fumarole activity, dark hills in the foreground is Bogdanovich Glacier, photo by the authors, August 31, 2010; (b) pyroclastic deposits at the eastern landslide wall of Kamen volcano. Original photo in color was published in [Churikova, et al., 2010], photo by the authors.

northern and southern slopes, respectively. The distances between the Kamen–Klyuchevskoy and Kamen–Bezymianny summits are 5 km each (Fig. 1a). The closeness of these volcanoes in space and time and the single zone of anomalous seismic attenuation [Tokarev and Zobin, 1970] may indicate a genetic relationship. However, the lavas of the neighboring volcanoes are radically different: Klyuchevskoy volcano produces high-magnesian and high-alumina olivine–pyroxene–plagioclase basalts and basaltic andesites, while Bezymianny typically discharges hornblende andesites and dacites. Ploskie Sopky volcano , which is located 10 km NW of Kamen volcano (Fig. 1a), produces intermediate- and high-potassium subalkaline lavas. Any attempt to find and explain the causes of these differences will inevitably raise the issue of the rock types of Kamen volcano, which stands almost in the middle of these three volcanoes.

In the course of the 2007–2009 field work the authors studied the geology and petrology of Kamen

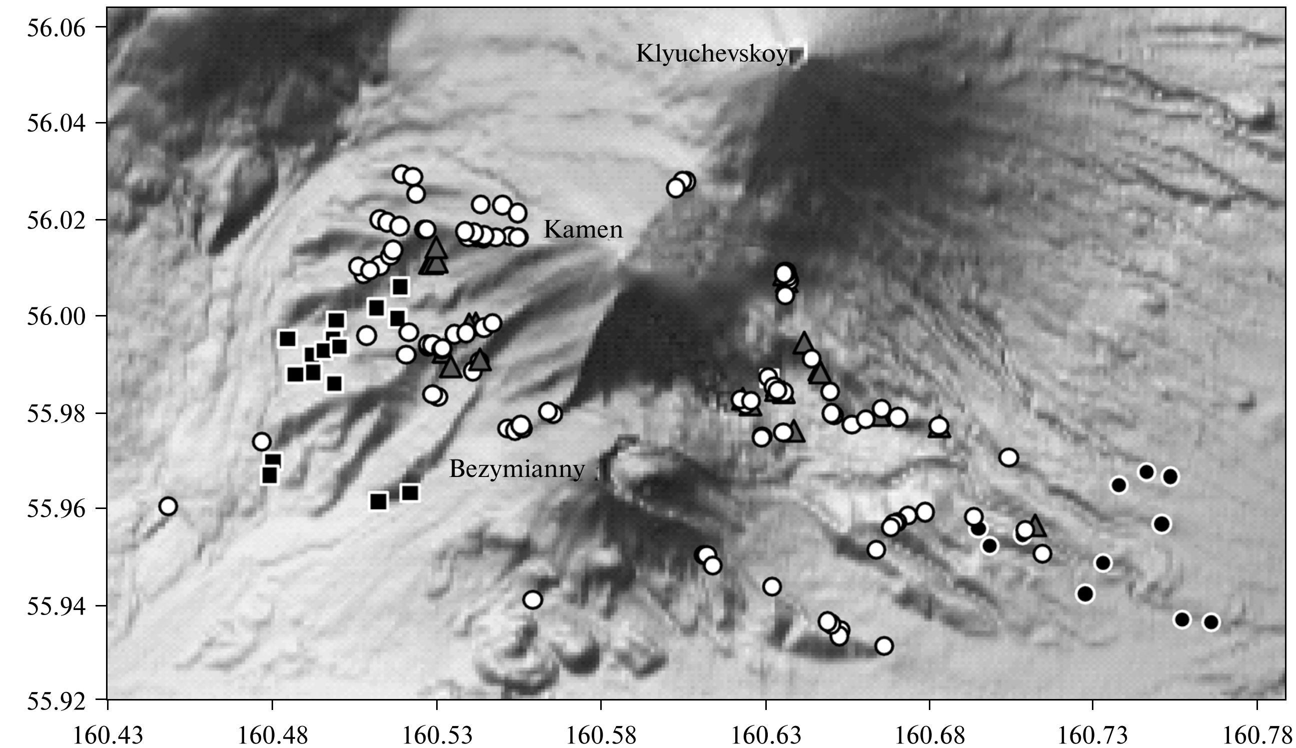

Fig. 2. Map of sample collection in Kamen volcano area. Symbols denote sampling sites: white circles mark stratovolcano rocks; triangles are dykes; squares are lavas of monogenetic cones; black circles are samples of the Ambon rock deposits.

volcano and sampled rocks of the stratovolcano's edifices, the dyke complex, and monogenetic cones (Fig. 2). This paper presents data on the geology, petrography, mineralogy, and petrochemistry of these rocks.

1. HISTORICAL AND GEOLOGICAL INFORMATION

Kamen volcano formed, like the other KGV volcanoes, on a plateau composed of a giant shield volcano [Flerov and Ovsyannikov, 1991] with its center beneath Ploskie Sopky and its lavas outcropping in the valleys of the Studenaya and Khapitsa rivers, in the villages of Kozyrevsk and Klyuchi. The age of these lavas is 270 Ka [Galkins, 2004]. The edifice of Kamen stratovolcano formed during two periods that differ in the characters of their eruptions and types of erupted products. The first period eruptions were of an explosive character with an accumulation of a thick deposition cone that mostly consists of tuffs and tuff breccias. The second and final period involved effusive activity and produced mostly thin lava layers that occupy extensive areas and cover the previously formed deposition cone with a thin veneer. Numerous dykes that served as conduits of lava effusions were probably also formed during this period. The Klyuchevskoy [Khrenov, 2003] and Staryi Shiveluch stratovolcanoes [Melekestsev et al., 1991] were formed in the same way.

The composition of the stratovolcano rocks attests to homodromous development: the earliest lava portions are predominantly olivine; higher in the section Ol–Cpx–Pl rocks occur with dark-colored minerals decreasing from bottom to top. The top sections of the stratovolcano consist of olivine-less rocks; some flows contain hornblende in phenocrysts. Nonetheless, some exceptions to this pattern are known. Thus, at the base of the landslide wall of the volcano at an altitude of 1680 m a series of lava flows that are composed of hornblende andesites occurs.

Dykes of radial and ring structures are found in all sectors of the edifice; these are 1–5 m thick and as long as 1.5–2 km. Most of the dyke complex rocks are macroscopically similar to those of the stratovolcano. In addition, on the eastern slope of the volcano coarse crystalline olivine basalts (up to 20–25% olivine) are found and the southwestern slope was found to contain hornblende andesite dykes.

The activity of Kamen volcano supposedly terminated at the end of the Pleistocene [Melekestsev and Braitseva, 1984]. After the termination of volcanic activity the geological processes on the volcano did not cease: since the Late Pleistocene, disintegration of the volcanic edifice commenced via numerous rockfalls [Ponomareva et al., 2006]. These are Toreva blocks, which are large parts of the edifice that moved down from the slopes for significant distances [Reiche, 1937], and fracturing on a smaller scale. Volcanic activity continued on the relief that arose after landslides and collapses. About 11 ^{14}C ka [Braitseva et al., 1990] on the southern slope of Kamen volcano, the new pra-Bezymianny volcano formed, whose edifice later became a part of Bezymianny volcano; at about 5.9 ^{14}C ka [Melekestsev, 1980] Klyuchevskoy volcano arose on the northern slope. West of Kamen a series of cinder and cinder–lava cones originated (about 2 ^{14}C ka, (as reported by V.V. Ponomareva, personal communication). In many cases the cones consist of cinder material exclusively, in the other cases their lava flows extend for 3–5 km. The rocks of the cones are largely Ol–Cpx–Pl varieties.

The latest of the known events is a major Holocene landslide with a volume of up to 6 km^3 that occurred on the eastern slope of Kamen 1200 years ago [Melekestsev, 1980; Melekestsev and Braitseva, 1984; Ponomareva et al., 2006]. At the present time the original topography of the edifice remains only in the north–northwestern sector of the volcano completely covered by a glacier.

This large Holocene landslide cut the edifice almost into two halves, opened its interior, and provided a unique possibility to observe the cross section of the stratovolcano on a practically vertical wall that is 2.5 km high. During the field season of 2009 these authors managed to approach the landslide wall very closely and several rare (at this location) days with an unusually transparent atmosphere made detailed visual examination possible.

It became clear that 80% of the wall consists of well-stratified pyroclastic deposits that are everywhere cut by numerous dykes; rare thin lava flows occur largely in the upper part of the edifice, i.e., they arose during the final stage of the stratovolcano development. The pyroclastic deposits are usually very thick (some tens and hundreds of meters) and consist of cemented volcanic breccias, cinder, agglomerate tuffs, lapilli, and volcanic bombs up to 2 and more meters across.

Representative cross sections of such deposits (Fig. 3) may occur in the bedrock position in many parts of the edifice, viz., at the base of the landslide wall (Fig. 3a), in some Toreva blocks of Severnaya Griva, and on two nameless Toreva blocks that are located on both sides of the lower part of Schmidt Glacier. The great thicknesses of the substantially pyroclastic strata attest to the fact that the volcano operated in an explosive manner for a long period of time.

The color of the pyroclastic deposits on the landslide wall systematically changes from the flanks of the cut edifice to its center: the freshest dark-gray and black deposits are exposed on the flanks (Fig. 1b and the color photo in [Churikova et. al., 2010]). The closer we come to the central part of the edifice the more these deposits become ocherous-yellow, then gray-green, and finally red at the center. The variation in the color of pyroclastics from the flanks to center is probably due to increased heat and/or hydrothermal flows that formerly existed in the central part that resulted in regular secondary alterations of the rocks.

It is such contrasted and variegated pyroclastic deposits that compose the landslide that occurred 1200 years ago (the Ambon rock deposits). This consists of volcanic breccias and tuff breccias with a sand–clay filler. Their colors form a spectrum that is similar to the colors of pyroclastic rocks in the landslide wall (see color photos in [Churikova et al., 2010]). The blocks of the Ambon deposits may consist of either solely pyroclastic material or complex blocks that involve pyroclastics and fragments of lava flows or dykes. These blocks are very resistant to weathering and fracturing. For example, the well-known Ambon stone (after which the landslide deposits are named) with an apparent thickness of 18 m, includes large blocks of lava, making it resistant to fracturing. Two Toreva blocks in the lower part of the Schmidt Glacier that were located near the landslide axis are preserved because they are armored by long (2.5 km) dykes of olivine–pyroxene basaltic andesites and lava flows. At the same time, on the landslide axis one may observe remains of completely destroyed pyroclastics in the form of cone-shaped hills a few meters in size, which are composed of sand-and-block material.

2. RESEARCH TECHNIQUE

Concentrations of trace elements were measured by X-ray fluorescence analysis using a S4 PIONEER wave disperse X-ray fluorescence spectrometer using the GEO-QUANT program. This instrument is installed at the Institute of Volcanology and Seismology at the Far East Branch of the Russian Academy of Sciences in Petropavlovsk-Kamchatskii. The analytical errors for major elements were less than 1%.

The composition of rock-forming minerals of the stratovolcano was analuzed by a JEOL JXA 8900RL microprobe equipped with five WDS detectors, at an accelerating voltage of 15kV, a probe current 15 nA, and a beam diameter of 5–10 μm. The microprobe is installed in the Geochemistry Department of the Geological Science Center at Göttingen University, Germany. Measurements were carried out using a set of synthetic and natural standards. The precision of analyses of major elements was better than 5%, and 7% for K and P. A detailed description of the technique can be found in [Ginibre et al., 2002; Churikova et al., 2007].

The compositions of minerals and glasses from monogenetic cones and dykes were carried out using a microprobe set based on a Jeol JSM-6480LV scanning electron microscope with a combined system of X-ray spectrometry microanalysis that includes an INCA-Energy 350 energy dispersive spectrometer and an INCA-Wave 500 four-crystal wave diffraction spectrometer. The instrument set is installed in the

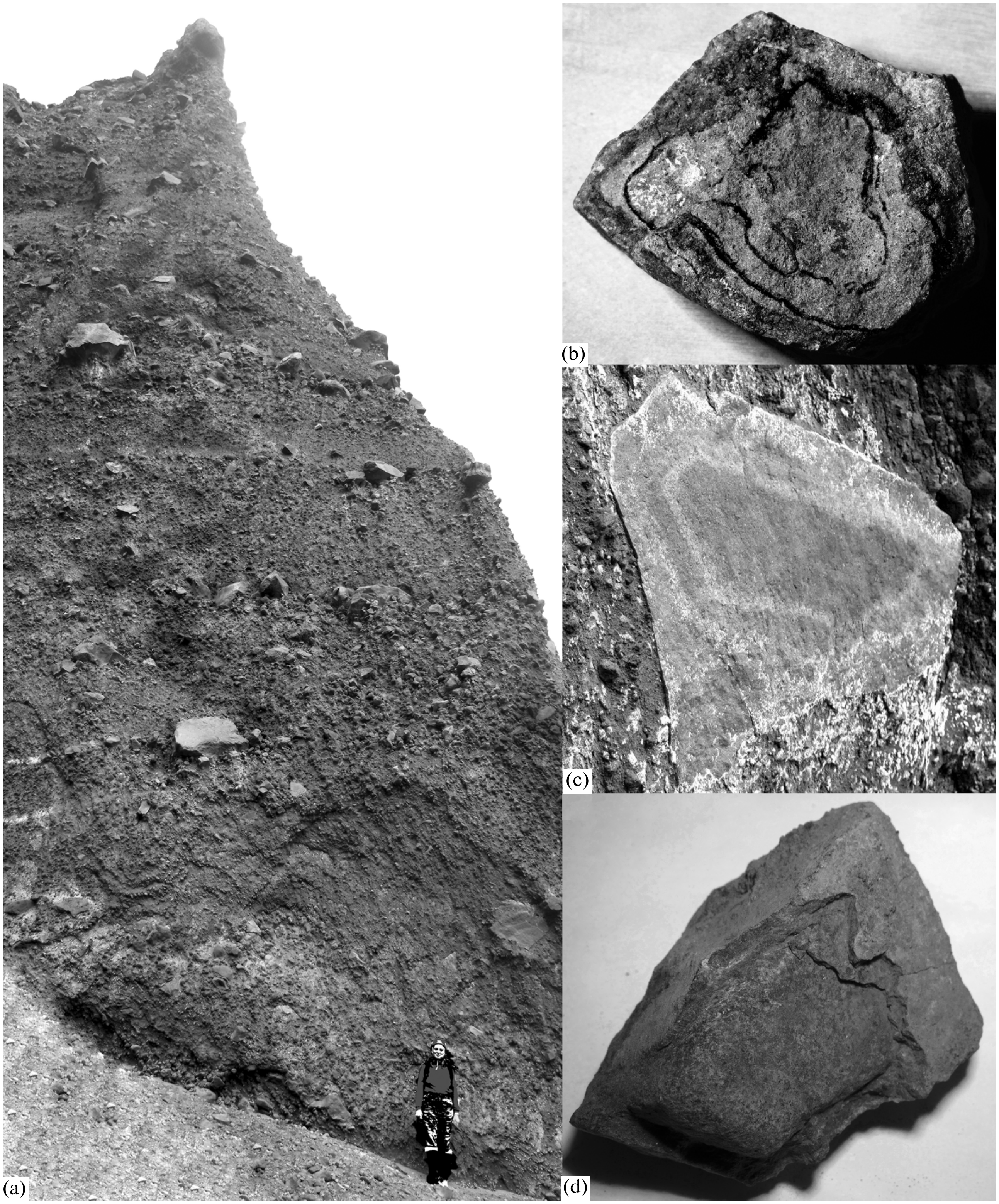

Fig. 3. Fragments of pyroclastics and the Ambon rock deposits of Kamen volcano. (a) Pyroclastic deposits on the right side of the landslide wall; (b) Liesegang rings in a sample of size 5 cm from the Ambon rock deposits; (c) Liesegang rings in a sample of size 50 cm from the pyroclastic deposits on the right side of the landslide wall; (d) rock foliation along ring textures resulting from deep inner alteration, the sample size is 8 cm.

Laboratory of Local Methods of Material Analysis at Moscow State University; the operators were N.G. Zinov'eva and N.N. Korotaeva. The specimens were studied under carbon sputtering of 30 μm at an accelerating voltage of 15 kV and a probe current of 15 nA. The results were processed using professional licensed software, viz., the SEM Control User Interface, version 7.11 (Jeol Technics LTD) and INCA, version 17a (Oxford Instrument). The current calibration was based on cobalt. The uncertainty of the measurements of the concentrations of elements by the energy dispersive method did not exceed the permissible limits for this analysis: at concentrations 1–5 wt %, 10 rel %; from 5 to 10 wt %, up to 5 rel %; and above 10 wt %, up to 2 rel %.

3. PETROGRAPHIC FEATURES OF ROCKS

The rocks of Kamen volcano can be seen to consist of lavas of various porosities and with different levels of phenocrysts. The rock textures vary from subaphyric and serial-porphyritic to coarse- and mega-porphyritic. At the same time, mega-plagiophyre rocks that are similar to the plateau lavas beneath Klyuchevskoy group of volcanoes and occur in some volcanoes of the Central Kamchatka Depression were not found. The main phenocryst minerals in the stratovolcano rocks are olivine, clino- and ortho-pyroxene, plagioclase, ilmenite, magnetite, and rarely, hornblende.

Based on petrographic and mineralogical features, all the rocks of Kamen volcano can be classified into seven types that make up four groups. These are groups of olivine-bearing (Ol–2Px and Ol–Cpx), olivine-free (2Px–Pl and essentially Pl), subaphyric, and hornblende-bearing varieties. All the four types of rocks are found in the stratovolcano edifice. The lavas of monogenetic cones are olivine-bearing and subaphyric varieties; the dyke complex contains olivine-bearing and, in one case, hornblende-bearing volcanic rocks. Olivine-bearing rocks occur in all the volcanic complexes. Olivine-free rocks are observed only in the stratovolcano edifice. Subaphyric rocks are present in the stratovolcano edifice in the flows and bombs of monogenetic cones. Hornblende-bearing rocks are very rare. The rocks of the Ambon rock sequence on the eastern landslide wall of the volcano deserve a separate description.

3.1. Olivine-Bearing Rocks

3.1.1. Olivine–clinopyroxene rocks are most abundant on Kamen volcano. They occur in all the stages of its activity: they compose the larger part of the edifice, are found in the dyke complex, and form most of the rocks in the monogenetic cones. The rock textures are usually porphyritic and serial-porphyritic. Mafic minerals compose 5–20% of the total. The ratios of olivine and clinopyroxene vary greatly; plagioclase phenocrysts occur often. Olivine and clinopyroxene grains are well facetted and are frequently zonal. Olivine grains are often surrounded by a fringe of fine-grained clinopyroxene aggregate. In olivines of this rock group, as well as in olivines of twopyroxene varieties, well-crystallized melt inclusions are often observed. The groundmass notably differs not only in color, from light to almost black, but also in texture; in some rocks the groundmass is strongly crystallized, in others it includes a large amount of pure brown glass. Plagioclase phenocrysts occur periodically in these rocks; they often show well-pronounced features of resorption in growth zones or in the entire inner part, have a sheath-shaped texture, and often form twins.

In rocks of the monogenetic cones olivine generally dominates over clinopyroxene, while in the rocks of the stratovolcano and the dyke complex clinopyroxene dominates and olivine is much finer and of subordinate importance. In the rocks of monogenetic cones olivine often forms large crystals up to 1 cm, while large crystals and/or growths of clinopyroxene are typical of rocks of the edifice and the dyke complex.

3.1.2. Olivine–twopyroxene rocks are found more rarely at the volcano. They may be observed both in the stratovolcano body and among rocks of the dyke complex, less often in lavas of the monogenetic cones. In the stratovolcano edifice they compose the lower parts. Rock textures are usually series-porphyritic, medium- and coarse-grained; the structures are porphyritic. The rocks are typically abundant in mafic minerals, from 10 to 25%; the highest amounts of mafic minerals are observed in dykes within two Toreva blocks east of the volcano. The ratios of olivine and pyroxene vary greatly from substantially olivine to mainly pyroxene varieties. In the former, olivine forms large well-facetted crystals with numerous in-situ-hardened and crystallized melt inclusions and spinel ingrowths. In substantially pyroxene lavas orthopyroxene is found in sub-phenocrysts that are larger than those of olivine; clinopyroxene often forms large growths. Clino- and orthopyroxene often form large glomeroporphyritic growths up to 10–15 mm across. Clinopyroxene grains are sometimes zonal and partly show features of resorption in growth zones. The groundmass is oxidized and crystallized to different degrees. Rocks in dykes are crystallized more strongly than those in lava flows. Plagioclase is found largely in the groundmass; rare isolated grains are observed also among phenocrysts of some rocks.

Olivine-Free Rocks

3.2.1. Twopyroxene–plagioclase rocks are only found in a few samples in the northwestern sector of the stratovolcano edifice. Plagioclase is the dominant mineral; none the less orthopyroxene grains are of large size, making up to 30% of rock. Pyroxene is zonal and forms glomeroporphyritic growths. These rocks are very strongly resist splitting and form armoring flows in the sections.

3.2.2. Clinopyroxene–plagioclase rocks are only found among the stratovolcano rocks. They may occur in different sectors of the volcano but they are very similar in terms of petrography. Their texture is largely porphyritic. The content of mafic minerals is 5–8%. In addition to clinopyroxene and plagioclase, small very rare sub-phenocrysts of olivine are observed. Clinopyroxene forms large often zonal elongated tabular phenocrysts up to 8–10 mm. Plagioclase forms elongated prisms; the crystal are smaller (2–3 mm), but in dominating quantities. Plagioclase crystals are also zoned quite often and not infrequently show features of resorption.

3.2.3. Essentially plagioclase rocks, in a similar manner to the two previous rock types, only occur in the body of the stratovolcano edifice and are not found in the other rock complexes. In addition to plagioclase phenocrysts, these rocks contain dark-colored minerals (olivine and clinopyroxene), although their total presence does not exceed 1%. Mafic minerals are always fine grained, not larger than 1–3 mm. Plagioclase grains that are different in size form the series-porphyritic texture of the rocks.

3.3. Sub-Aphyric Rocks

Sub-aphyric rocks occur in the stratovolcano, bombs, and the lava flows of monogenetic cones. They are characterized by the presence of fine-grained structures, different degrees of crystallization of groundmass, and an almost complete absence of phenocrysts. Microlites of olivine, pyroxenes, and plagioclase may occur in the groundmass in different amounts. The sub-aphyric rocks of the top layers of the stratovolcano do not include olivine, not even as microlites. All the minerals are usually well facetted. Glass in the groundmass in non-crystallized spots varies between practically white and brown, probably due to different degrees of the oxidation of the rocks.

3.4. Hornblende-Bearing Rocks

Hornblende-bearing rocks in the outcrops occurrence are found on rare occasions: a compact series of small, strongly disintegrated dykes in the southwestern sector of the volcano, one lava flow at the base of the eastern landslide wall, and a lava flow at an altitude of 3000 m on the northwestern slope. In addition, on the left side of the Ambon rock deposits, large blocks of light-colored dacites with hornblende are found. These rocks were not observed in the outcrops.

All the hornblende in the volcano rocks possesses a thick opacite–magnetite fringe; in many cases the presence of hornblende is detected by the preserved shapes of crystals, although the entire mineral has been replaced by secondary products. In rocks of the destroyed flow on the northwestern slope phenocrysts of mafic minerals (olivine and clinopyroxene) were found. The concentration and size of hornblende grains vary greatly. In some rocks hornblende grains may be as large as 2–3 cm and its content may reach 5–7%, in other cases, only single small grains may occur.

Hornblende was found in two other places: Tyuya Kulich in the southwestern sector of the volcano and the Kroshka extrusion on the Severnaya Griva. These formations consist of Pl–Hb andesites that are macroscopically and petrographically similar to the rocks of the neighboring Bezymianny volcano. Hornblende makes up about 10% in Tyuya Kulich and up to 30% in the Kroshka extrusion. In Tyuya the hornblende is almost entirely opacitized, while in the extrusion it is altered much less. Plagioclase phenocrysts are 4–5 mm in size. In the extrusion, about 30% quartz is found, which is occasionally as large as 1 cm.

3.5. Rocks of the Ambon Rock Deposits and the Landslide Wall

We now provide some notes on the rocks that compose the Ambon rock deposits and on the pyroclastic deposits in the landslide wall. These are actually the same rocks as those that formerly composed the inner parts of the volcano. In terms of petrography, the blocks from the pyroclastic deposits and the Ambon rock deposits are identical and contain three varieties: olivine–clinopyroxene, olivine–twopyroxene, and clinopyroxene–plagioclase rocks.

It is of interest that all the deposits of the Ambon rock mass and pyroclastics that are colored to varying degrees are altered differently. Judging from the character of these alterations, the rocks underwent strong temperature and/or hydrothermal alteration. The alteration becomes stronger from the flanks to the center or from the edges of the landslide to its axis. At the axis of the landslide, different fragments in the breccia may be of absolutely different colors and form contrasted variegated rock (see color photos in [Churikova et al., 2010]). The alteration is obvious not only in small fragments (Fig. 3b) but also in large lava blocks (Fig. 3c). Fragments of different sizes with Liesegang rings are often found (Figs. 3b–3d) attesting to hydrothermal rather than thermal reworking of the rocks (Fig. 3d). The rock frequently decomposes on these rings, acquiring the shape of an egg as a result, with clearly observed and detachable shells (Fig. 3d). Due to the fact that lava fragments from the Ambon rock deposits, as well as pyroclastic fragments in the central parts of the volcano, are strongly altered they are not suitable for petrologic and geochemical studies.

Farther from the central parts of the volcano the lava fragments of pyroclastic deposits become less altered. Although when macroscopically considered the samples frequently looked fresh; microscopic study indicated strong oxidation. Oxidation in these samples affects not only the groundmass but also the fringes of mafic rock-forming minerals; therefore, it is not always possible to find the unaltered nuclei of phenocrysts. Only samples taken from pyroclastic strata at the extreme flanks of the volcano are fresh, do not contain traces of secondary alteration, and can be used for further geochemical studies.

4. THE MINERALOGY OF THE ROCKS

To conduct a microprobe analysis of mineral phases (Fig. 4) we selected five representative samples: two samples from the stratovolcano edifice, two samples from monogenetic cinder–lava cones, and one sample from an olivine–clinopyroxene dyke. Altogether, 200 olivine phenocrysts, 145 clinopyroxene phenocrysts, and 49 plagioclase grains were analyzed; representative analyses are given in Table 1. The diagrams also include previously published data [Al'meev, 2005; Ivanov, 2008].

4.1. Mineralogy of the Stratovolcano Rocks

Olivine compositions in Kamen stratovolcano vary from Fo_{60} to Fo_{83}, having a unimodal distribution with a peak at $Fo_{77–79}$ (Fig 4a). Trace elements in olivines vary greatly: NiO varies from 0.009 wt % to 0.48 wt %, Cr_2O_3 varies from 0.007% wt % to 0.06% wt %, and CaO from 0.1% wt % to 0.278% wt %. The NiO/Cr_2O_3 and NiO/CaO ratios are rather low, 3.5 and 0.38, respectively (Fig. 5a). Due to the low magnesium number of olivine and the low content of nickel in the olivine, Kamen olivines do not fit the mantle array suggested in [Ozawa, 1984]; consequently, these basalts underwent significant fractionation.

The composition of Kamen clinopyroxenes corresponds mainly to augite with magnesium number (Mg#) (Mg# = 100*Mg/(Mg + Fe)), which varies in the same range as the olivine magnesium number and which also has a unimodal distribution with a peak at Mg#79 (Fig. 4b). The concentrations of trace elements in clinopyroxenes vary in the following intervals: Cr_2O_3 varies from 0.01% to 0.76%, MnO varies from 0.09% to 0.60%, Na_2O varies from 0.02% to 0.50%, and TiO_2 varies from 0.25% to 1.07%. The concentrations of Cr_2O_3 decrease regularly but the content of TiO_2 increases as the Mg# of clinopyroxene decreases, while the values of MnO and Na_2O remain practically constant (Fig. 5b).

The plagioclases in the stratovolcano edifice have high values of the anorthite component, with maximums at $An_{87–93}$. Some samples demonstrate bimodal distributions that peak at An_{50} and An_{90} (Fig. 4c). The bimodal distribution probably recorded two stages of crystallization of this mineral during melt evolution. We emphasize the low magnesian and high iron presence in all the plagioclases.

In the studied rocks of the volcano edifice no high-Cr spinel was found; the oxides are high-Al spinel, magnetite, and titanomagnetite. Al_2O_3 positively correlates with MgO, while TiO_2 correlates positively with FeO in the oxide phase.

The similar distributions of Fo in olivine and Mg# in clinopyroxene suggest that these minerals are in equilibrium in the studied rocks. The low values of Mg# in olivine and clinopyroxene and low concentrations of Ni and Cr in them indicate significant fractionation of the melt from which the minerals crystallized. This conclusion is also supported by the absence of high-Cr spinel in olivines.

4.2. Mineralogy of Rocks of the Dyke Complex

In the rocks of the dyke complex, the olivine composition varies from Fo_{66} to Fo_{80}, i.e., in the same range as in the rocks of Kamen stratovolcano. The olivine distribution in the studied KAM-08-A1 sample is bimodal with peaks at Fo_{70} and Fo_{78} (Fig 4d). This behavior probably attests to two levels of the generation of this mineral: first, as phenocrysts formed during fractionional crystallization of the melt, and second, as sub-phenocrysts that resulted from groundmass cooling. The CaO content in olivines varies from 0.15% to 0.27%.

The compositions of clinopyroxenes in the dyke complex largely correspond to augite. Their magnesium number varies from 74 to 78 and is in the same range as the magnesium number of olivines, suggesting equilibrium conditions of crystallization of these two minerals. The distribution of the pyroxene Mg# is unimodal with a peak at Mg#76 (Fig. 4e). The concentrations of trace elements in clinopyroxenes are in the following intervals: MnO from 0.28% to 0.45%, Na_2O from 0.27% to 0.61%, and TiO_2 from 0.36% to 1.00%. In a similar manner to pyroxenes from the stratovolcano edifice, the content of TiO_2 increases with decreasing clinopyroxene Mg#, while the values of MnO and Na_2O are practically constant.

The plagioclases of the dykes vary from An_{78} to An_{88} and show a unimodal distribution with a maximum at $An_{84–86}$ (Fig. 4f). These plagioclases contain somewhat more sodium compared to plagioclases of the stratovolcano rocks.

In general, the compositions of minerals in the stratovolcano and the dykes are rather similar and could have crystallized from the same melts at similar P–T conditions.

4.3. Mineralogy of Rocks of the Monogenetic Cones.

The compositions of minerals in the monogenetic cones systematically differ from those of the dykes and the stratovolcano. In two studied samples the olivines vary from Fo_{70} to Fo_{92} with a unimodal distribution and a maximum at Fo_{88} (Fig. 4g). The presence of a large amount of high-Mg olivine indicates that the

Table 1. Representative analyses of minerals in the rocks of Kamen volcano

Olivines

	Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	NiO	Cr_2O_3	Total
Stratovolcano	2310	37.51	0.01	0.01	29.75	33.19	0.54	0.20	0.04	0.02	101.27
–	2310	38.22	0.05	0.03	24.99	37.47	0.42	0.15	0.04	0.00	101.37
–	2310	38.50	0.03	0.01	22.81	39.22	0.39	0.13	0.03	0.03	101.15
–	2310	39.29	0.02	0.01	19.86	41.66	0.29	0.12	0.08	0.05	101.38
–	2310	39.73	0.01	0.05	16.43	44.17	0.25	0.15	0.10	0.03	100.91
–	KAM-08-07	37.96	0.00	0.00	27.61	34.51	0.29	0.19	0.00	0.00	100.55
–	KAM-08-07	37.28	0.00	0.00	24.69	36.53	0.44	0.17	0.00	0.00	99.12
–	KAM-08-07	37.66	0.00	0.20	22.67	37.71	0.25	0.21	0.00	0.00	98.70
–	KAM-08-07	38.14	0.00	0.00	20.73	39.64	0.25	0.20	0.48	0.00	99.44
–	KAM-08-07	38.53	0.00	0.00	19.75	39.62	0.40	0.00	0.00	0.00	98.30
Dyke	KAM-08-A1	37.14	0.00	0.00	28.61	32.65	0.49	0.00	0.00	0.00	98.88
–	KAM-08-A1	39.06	0.00	0.00	19.48	41.20	0.28	0.00	0.00	0.00	100.02
–	KAM-08-A1	38.56	0.00	0.00	19.99	40.36	0.24	0.22	0.00	0.00	99.36
–	KAM-08-A1	37.89	0.00	0.00	25.84	35.71	0.52	0.00	0.00	0.00	99.97
–	KAM-08-A1	38.45	0.00	0.00	20.75	39.80	0.00	0.14	0.00	0.00	99.14
Cones	KAM-08-01	38.71	0.00	0.00	20.03	40.85	0.00	0.24	0.00	0.00	99.83
–	KAM-08-01	37.01	0.00	0.00	26.07	34.70	0.36	0.24	0.00	0.00	98.38
–	KAM-08-01	39.53	0.00	0.00	17.34	43.72	0.00	0.31	0.36	0.00	101.25
–	KAM-08-01	41.12	0.00	0.00	9.46	49.69	0.00	0.15	0.47	0.00	100.89
–	KAM-08-01	40.57	0.00	0.00	12.04	47.38	0.36	0.00	0.00	0.00	100.35
–	KAM-08-67/1	40.61	0.00	0.00	11.67	47.49	0.00	0.18	0.46	0.00	100.42
–	KAM-08-67/1	38.09	0.00	0.00	21.19	39.50	0.29	0.21	0.00	0.00	99.29
–	KAM-08-67/1	40.89	0.00	0.00	9.47	49.69	0.00	0.29	0.00	0.00	100.33
–	KAM-08-67/1	40.26	0.00	0.00	13.15	45.93	0.00	0.19	0.40	0.00	99.93
–	KAM-08-67/1	39.61	0.00	0.00	15.62	43.94	0.27	0.16	0.00	0.00	99.59

Clinopyroxenes

	Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	NiO	Cr_2O_3	Na_2O	K_2O	Total
Stratovolcano	2310	51.03	0.74	2.70	11.43	15.11	0.37	17.73	0.00	0.01	0.40	0.00	99.5
–	2310	49.71	0.91	4.52	8.69	14.97	0.24	20.44	0.02	0.03	0.34	0.02	99.9
–	2310	50.62	0.54	4.80	6.88	15.35	0.17	21.04	0.01	0.25	0.39	0.02	100.1
–	2310	51.33	0.55	3.47	6.00	16.14	0.14	21.89	0.04	0.45	0.21	0.03	100.2
–	2310	52.26	0.30	2.78	5.19	16.94	0.15	21.15	0.02	0.70	0.33	0.00	99.8
–	2310, Opx	53.01	0.41	1.35	19.97	20.76	0.66	4.13	0.00	0.04	0.25	0.02	100.6
–	KAM-08-07	49.07	0.72	5.13	9.56	12.78	0.32	21.10	n.d.	0.00	0.47	0.00	99.2
–	KAM-08-07	49.09	0.71	5.75	8.90	14.43	0.35	19.05	n.d.	0.00	0.94	0.00	99.2
–	KAM-08-07	50.57	0.72	4.12	7.74	15.06	0.00	21.57	n.d.	0.27	0.29	0.00	100.3
–	KAM-08-07	49.28	0.55	5.15	6.98	15.21	0.00	20.02	n.d.	0.47	0.60	0.00	98.3
–	KAM-08-07	51.26	0.31	3.57	6.23	16.23	0.00	21.11	n.d.	0.28	0.45	0.00	99.4
Dyke	KAM-08-A1	48.33	0.90	6.61	9.36	13.58	0.28	20.08	n.d.	0.00	0.47	0.00	99.6
–	KAM-08-A1	50.00	0.81	5.27	9.53	15.10	0.00	19.11	n.d.	0.00	0.61	0.00	100.4
–	KAM-08-A1	50.68	0.58	3.18	9.14	15.39	0.35	20.24	n.d.	0.00	0.45	0.00	100.0
–	KAM-08-A1	50.78	0.53	4.49	8.34	15.49	0.00	20.13	n.d.	0.00	0.39	0.00	100.1
–	KAM-08-A1	49.20	0.83	5.61	7.66	14.74	0.00	21.08	n.d.	0.00	0.42	0.00	99.5
Cones	KAM-08-67/1	51.91	0.61	2.90	9.07	17.16	0.00	17.86	n.d.	0.39	0.28	0.00	100.2
–	KAM-08-67/1	52.89	0.46	2.13	8.57	18.05	0.46	17.65	n.d.	0.27	0.31	0.00	100.8
–	KAM-08-67/1	51.94	0.29	2.20	8.36	18.17	0.24	16.97	n.d.	0.43	0.49	0.00	99.1
–	KAM-08-67/1	52.66	0.33	2.28	8.05	17.98	0.39	17.56	n.d.	0.67	0.36	0.00	100.3
–	KAM-08-67/1	52.84	0.00	2.03	7.64	17.66	0.37	18.40	n.d.	0.47	0.25	0.00	99.7
–	KAM-08-01	51.73	0.59	2.88	9.78	16.90	0.28	17.72	n.d.	0.00	0.41	0.00	100.3
–	KAM-08-01	52.83	0.53	2.10	9.26	18.34	0.32	16.86	n.d.	0.36	0.38	0.00	101.0
–	KAM-08-01	52.28	0.68	2.56	8.61	17.56	0.30	17.77	n.d.	0.41	0.38	0.00	100.6
–	KAM-08-01	52.85	0.44	2.10	8.26	17.84	0.29	18.38	n.d.	0.32	0.36	0.00	100.9
–	KAM-08-01	52.38	0.51	2.53	7.70	17.70	0.00	18.13	n.d.	0.62	0.28	0.00	99.8

Table 1. (Contd.)

Plagioclases									
	Sample	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Total
Stratovolcano	2310	56.38	26.18	0.84	0.09	9.31	6.09	0.43	99.5
–	2310	54.81	27.55	0.33	0.03	10.41	5.55	0.24	99.0
–	2310	50.00	30.68	0.82	0.10	14.53	3.26	0.21	99.8
–	2310	47.01	32.51	0.73	0.06	16.65	2.04	0.08	99.1
–	2310	45.37	33.50	0.72	0.05	17.84	1.28	0.05	98.8
–	KAM-08-07	47.67	31.80	0.85	n.d.	15.99	2.27	0.15	98.7
–	KAM-08-07	45.63	32.80	0.57	n.d.	16.80	2.02	0.15	98.0
–	KAM-08-07	45.50	32.78	0.65	n.d.	17.11	1.78	0.00	97.8
–	KAM-08-07	46.11	33.46	0.42	n.d.	17.34	1.58	0.00	98.9
–	KAM-08-07	44.62	33.62	0.72	n.d.	18.05	1.28	0.00	98.3
Dyke	KAM-08-A1	46.96	32.27	0.77	n.d.	16.06	2.38	0.00	98.4
–	KAM-08-A1	47.31	33.10	0.52	n.d.	16.96	2.21	0.00	100.1
–	KAM-08-A1	47.49	33.29	0.57	n.d.	16.87	1.99	0.00	100.2
–	KAM-08-A1	46.61	33.11	0.72	n.d.	17.32	1.78	0.00	99.5
–	KAM-08-A1	46.23	34.12	0.61	n.d.	17.75	1.46	0.00	100.2
Cones	KAM-08-01	53.97	28.72	0.80	0.00	12.08	4.66	0.32	100.5
–	KAM-08-01	53.09	29.26	0.77	0.00	12.54	4.56	0.35	100.6
–	KAM-08-01	53.59	29.29	0.77	0.23	12.74	4.30	0.25	101.2
–	KAM-08-01	52.46	30.11	0.52	0.36	13.54	3.91	0.21	101.1
–	KAM-08-01	50.97	31.37	0.60	0.00	14.67	3.44	0.31	101.4
–	KAM-08-67/1	53.44	28.47	0.89	0.23	11.57	4.33	0.29	99.2
–	KAM-08-67/1	52.82	29.16	0.71	0.22	12.74	4.23	0.22	100.1
–	KAM-08-67/1	52.42	29.26	0.55	0.23	12.76	4.11	0.24	99.6
–	KAM-08-67/1	52.20	29.27	0.60	0.21	13.00	4.00	0.14	99.4
–	KAM-08-67/1	51.23	29.76	0.56	0.18	13.39	3.75	0.24	99.1

Oxides											
	Sample	SiO_2	TiO_2	Al_2O_3	FeO	MgO	MnO	CaO	NiO	Cr_2O_3	Total
Stratovolcano	2310	0.10	11.37	9.75	67.70	4.33	0.39	0.03	0.05	1.66	95.38
–	2310	0.33	7.13	9.61	74.50	2.52	0.50	0.47	0.01	1.08	96.21
–	2310	0.36	18.55	1.24	72.37	2.16	0.50	0.37	0.00	0.08	95.63
–	2310	0.28	2.69	18.54	67.42	8.85	0.50	0.35	0.00	0.29	98.93
–	2310	0.20	1.40	49.34	31.69	12.68	0.21	0.03	0.10	2.61	98.25

beginning of crystallization occurred from a high-Mg melt. Analoguous olivines were repeatedly described in the rocks of Klyuchevskoy Volcano, [Mironov, 2009] among many others. In both studied samples from monogenetic cones the concentrations of trace elements in olivines are also similar: NiO varies from 0.35% to 0.6% and CaO varies from 0.15% to 0.35%.

Clinopyroxenes in rocks from the monogenetic cones have a magnesium number that is notably lower than the Mg# of olivines; it varies from 72 to 80 with a unimodal distribution and maximum at Mg#79 (Fig. 4h). This suggests that clinopyroxene crystallized much later and with some intermission relative to olivine from a melt that had already considerably fractionated. The trace element concentrations in clinopyroxenes from the cones vary greatly: MnO, from 0.24% to 0.46%; Na_2O from 0.21% to 1.08%; and TiO_2, from 0.27% to 0.75%.

Plagioclases in the monogenetic cones rocks contain more sodium than those in the dyke complex

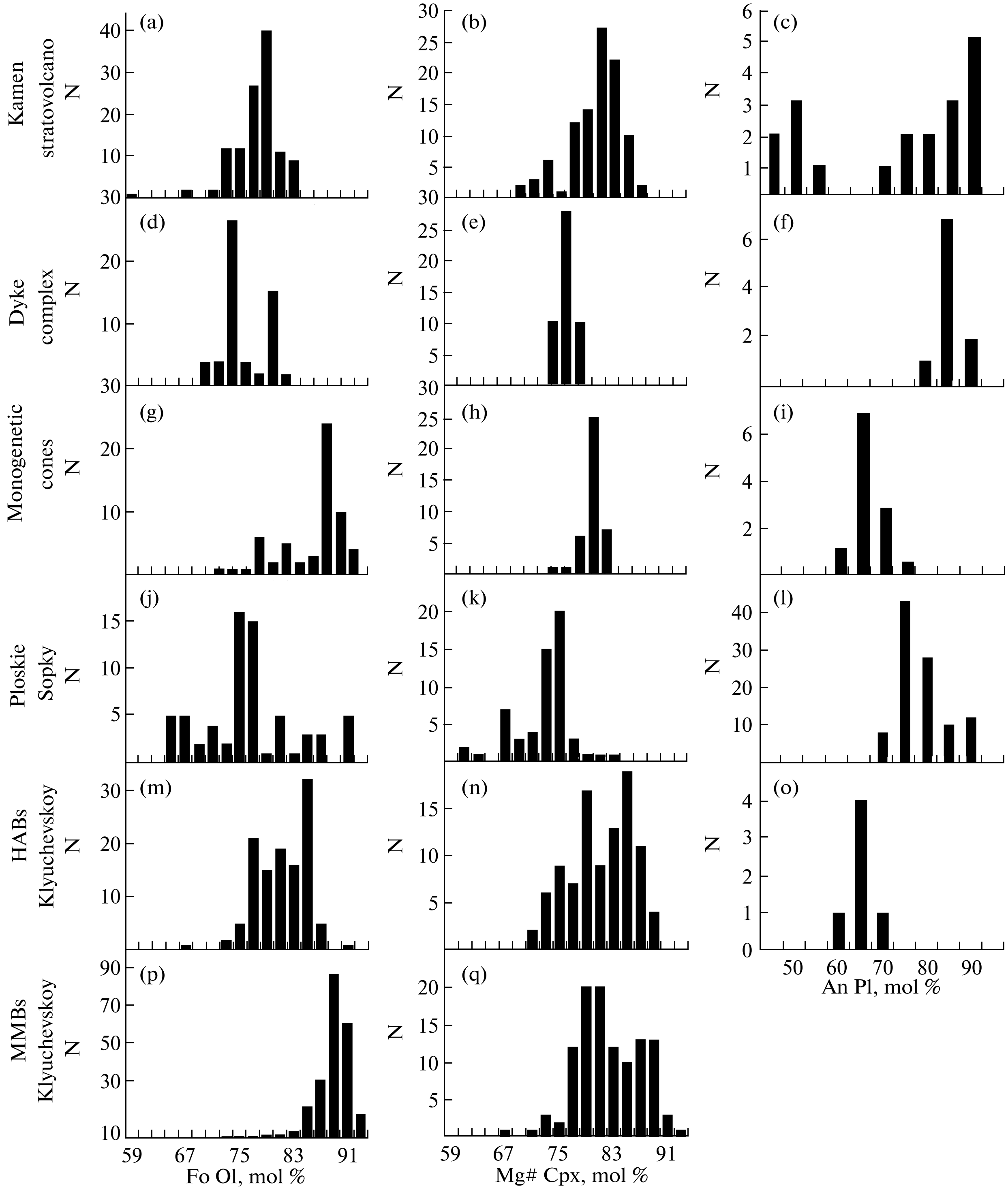

Fig. 4. Mineral compositions in rocks from different complexes of Kamen volcano and from basalts of neighboring volcanoes. For rocks of Kamen volcano: (a–c) stratovolcano, (d–f) dykes, (g–i) monogenetic cones. Rocks of Ploskie Sopky volcano (j–l). For rocks of Klyuchevskoy volcano: high-alumina basalts (HABs) (m–o), moderately magnesian basalts (MMBs) (p–q). Plots a, d, g, j, m, p show the distribution of olivines in relation to their composition; b, e, h, k, n, q the distribution of clinopyroxenes in relation to their magnesium number; c, f, i, l, o the distribution of plagioclases in relation to their anorthite component. Fo Ol olivine composition; Mg# Cpx = 100*Mg/(Mg + Fe) magnesium content in clinopyroxene; An PI denotes the composition of plagioclase.

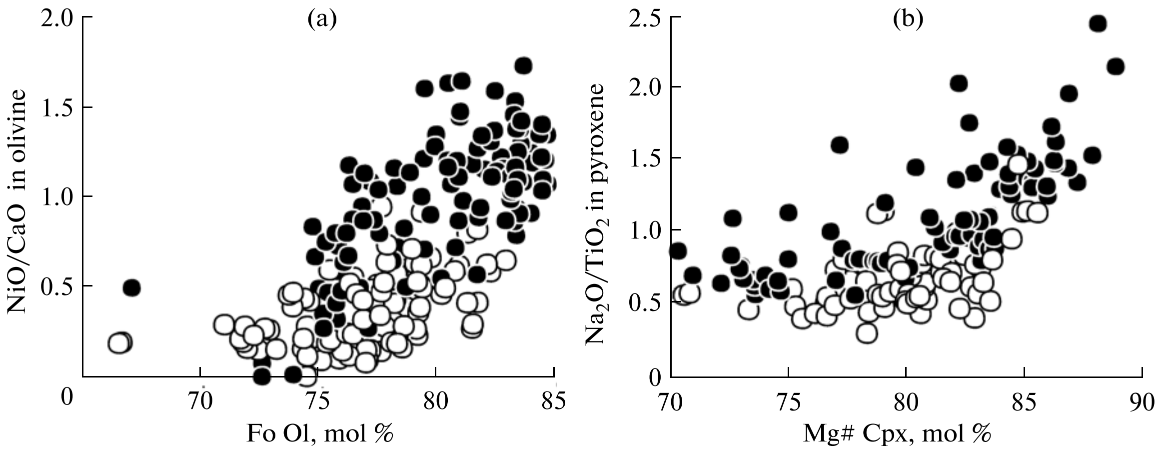

Fig. 5. Relationships between trace elements in olivines and pyroxenes from the basalts of Kamen stratovolcano and high-alumina basalts of Klyuchevskoy volcano. (a) Dependence of the NiO/CaO ratio in olivine on the magnesium number of olivine; (b) the dependence of the Na_2O/TiO_2 ratio in pyroxenes on the magnesium number of pyroxenes. Symbols: open circles are the minerals of Kamen volcano, filled circles are minerals of HABs of Klyuchevskoy volcano. Fo stands for olivine composition and Mg# = 100*Mg/(Mg + Fe) for magnesian content in clinopyroxene.

rocks, varying from An_{55} to An_{75} with a unimodal distribution and a maximum at An_{65} (Fig. 4i). This indicates a late crystallization of plagioclase in the monogenetic cones rocks. Late crystallization of plagioclase was also noted in the rocks of Klyuchevskoy volcano [Mironov, 2009].

5. THE DISTRIBUTION OF MAJOR ELEMENTS IN ROCKS

All the three rock complexes of Kamen volcano, viz., the stratovolcano edifice, the monogenetic cones, and the dykes, belong to a moderate-K subalkaline basalt—andesite-basalt series (Fig. 6). At the same time, significant systematic differences between these three complexes are obvious on the Harker diagram. The rocks of the stratovolcano edifice are high-alumina, low-magnesian (Mg < 6%) varieties of basalt—andesite-basalt series and form persistent trends on most diagrams with rising K_2O (Fig. 6a) and decreasing TiO_2, Al_2O_3, CaO, FeO, and MgO (Figs. 6b–6e, 6g) as SiO_2 increases. However, the concentrations of Na_2O and P_2O_5 (Figs. 6f and 6h) remain almost the same. The range of SiO_2 in the stratovolcano edifice rocks is the greatest compared to the other complexes. The most acid rock varieties with silica contents of 53–56% are found exactly in the stratovolcano lavas, which probably caused the wide occurrence of olivine-free varieties in this rock complex. On the Harker diagrams the dyke rocks are located in the field of the stratovolcano rocks and are derivates of the same mantle source as the edifice (Fig. 6).

The monogenetic cone lavas differ from the complexes described above. They form a separate field on the diagrams that is often entirely distinct from the field of the edifice. Compared to the rocks of the stratovolcano and dykes, the monogenetic cones lavas possess a similar SiO_2 content but are enriched in MgO and CaO and poorer in FeO, TiO_2, Al_2O_3, and P_2O_5. In general, this complex is less alkaline, which is vividly exposed in the Na_2O distribution (Fig. 6f) and is less clear in the K_2O distribution (Fig. 6a). The monogenetic cones rocks do not show clearly expressed trends on the Harker diagram but form fields of dots with certain variations in different elements. It is this complex that involves the most magnesian rocks among those studied (Fig. 6g).

6. COMPARISON WITH THE ROCKS OF THE NEIGHBORING VOLCANOES

6.1. Comparison between Kamen and Ploskie Sopky

Compared to the rocks of Kamen volcano, those of Ploskie Sopky volcano are systematically enriched in potassium (Fig. 7a) and phosphorous (Fig. 7b). The differences in the concentrations of these elements are so significant that the fields of those two volcanoes do not even overlap. Although the respective diagrams are not given here, we note that the rocks of the Ploskie Sopky volcano contain less Al_2O_3 and MnO compared to the rocks of Kamen volcano.

The mineralogical composition of mafic minerals from the magnesian basalt of the Ploskie Sopky volcano is very similar to that of Kamen stratovolcano: olivines vary from Fo_{70} to Fo_{90} and have a unimodal distribution with a maximum at Fo_{80} (Fig. 4j). The magnesium number of clinopyroxenes varies from 60 to 88 and also follows a unimodal distribution with a maximum at 75 (Fig. 4k) [Churikova, 1993; Churikova

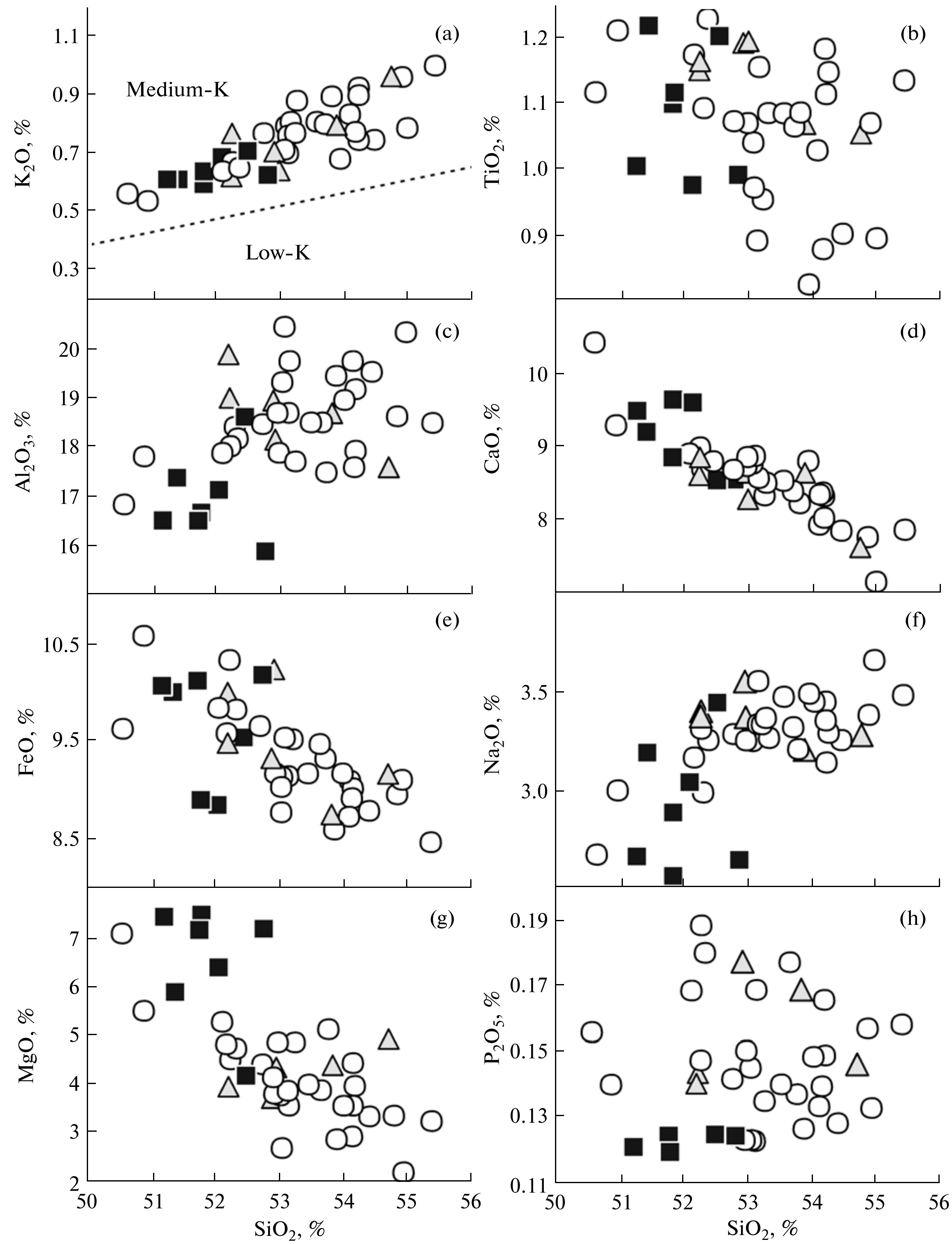

Fig. 6. Harker diagram for Kamen volcano rocks. For legend, see Fig. 2.

et al., 2009]. In spite of the similarity of major element compositions, the olivines of the Ploskie Sopky volcano differ systematically and significantly, not only from the olivines of the rocks of Kamen volcano, but also from olivines of all the rocks of the Central Kamchatka Depression, in a high content of Ca with the same values of forsterite. Similar high concentrations of Ca appear only in the most ferrug-

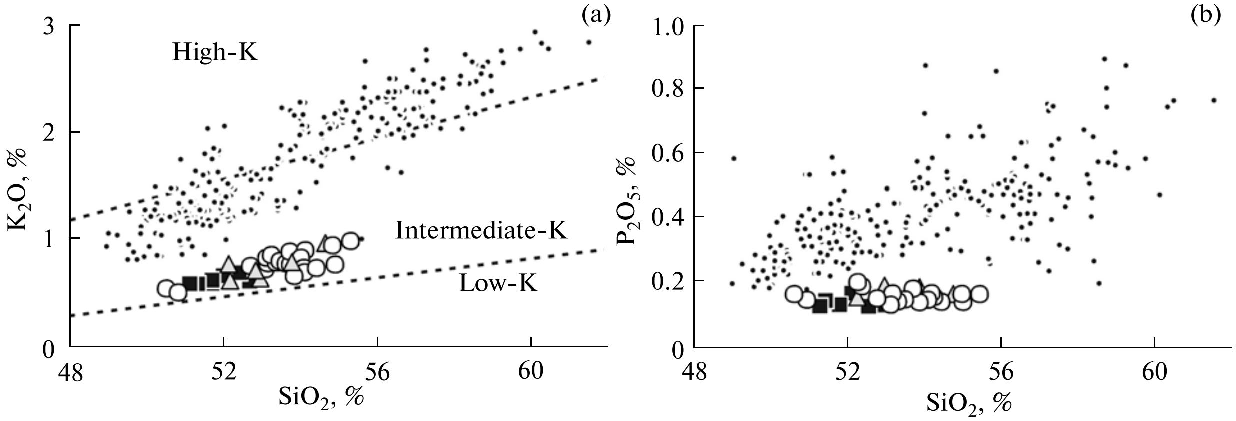

Fig. 7. Diagrams of relationships of K_2O (a) and P_2O_5 (b) to SiO_2 in rocks of Kamen and Ploskie Sopky volcanoes. Dots indicate compositions of Ploskie Sopky volcano rocks according to [Churikova, 1993]. The other symbols are the same as in Fig. 2.

inous olivines of Kamen and Bezymianny volcanoes (Fig. 8).

The above data on the major elements in rocks and minerals suggest that the rocks of Kamen and Ploskie Sopky volcanoes could not have been derived from the same primary melt.

6.2. Comparison of the Rocks of Kamen and Klyuchevskoy Volcanoes

Based on the concentrations of MgO and Al_2O_3 all the rocks of Klyuchevskoy volcano may be classified into three major groups (see, e.g., [Khrenov et al., 1991; Mironov, 2009 and many others]): high-alumina basalts (HABs), moderately magnesian basalts (MMBs), and high-magnesian basalts (HMBs). These three groups separate well on most petrologic diagrams (Fig. 9).

The crystallization trend of Kamen stratovolcano and dykes crosses that for Klyuchevskoy volcano ; only at SiO_2 = 53–55% do the rocks from Kamen edifice fall in the HABs field of Klyuchevskoy volcano (Fig. 9). The intersection of the trends is clearly seen in Figs. 9b and 9c, but closer inspection reveals it in all the diagrams. In the rocks of Klyuchevskoy volcano MgO decreases very rapidly with decreasing SiO_2, with the decrease being from 12% to 3.5% in the interval of SiO_2 from 51% to 54.5%, while in the lavas of Kamen volcano MgO decreases insignificantly, diminishing twice (from 7% to 3.5%) in a wider SiO_2 interval (from 50% to 56%, Fig. 9c). Titanium behaves in an opposite manner: in the lavas of Klyuchevskoy volcano titanium increases during fractional crystallization, while in the rocks of Kamen volcano it drops (Fig. 9b).

Two trends intersect in the field of the HABs of Klyuchevskoy volcano (Figs. 9b and 9c), which might suggest the similarity of rocks of Kamen stratovolcano and the HABs of Klyuchevskoy volcano. The compositions of olivines (Figs. 4a and 4m) and pyroxenes (Figs. 4b and 4n) in these rocks are also similar in their contents of major oxides. None the less, the rocks of Kamen stratovolcano and the HABs of Klyuchevskoy volcano systematically differ in the concentrations of trace elements in minerals: olivines of the Kamen stratovolcano have lower NiO/CaO ratios compared to the HABs of Klyuchevskoy volcano (Fig. 5a). Analogous differences are also noted in the concentrations of trace elements in pyroxenes for two rock groups: the pyroxenes of Kamen stratovolcano have lower Na_2O/TiO_2 ratios compared to the pyroxenes of the HABs of Klyuchevskoy volcano (Fig. 5b).

No rocks similar to the HMBs of the Klyuchevskoy volcano have been found at Kamen volcano. As to the MMBs of the Klyuchevskoy volcano, the rocks of the monogenetic cones of Kamen volcano fall in the MMBs of the Klyuchevskoy volcano in all the dia-

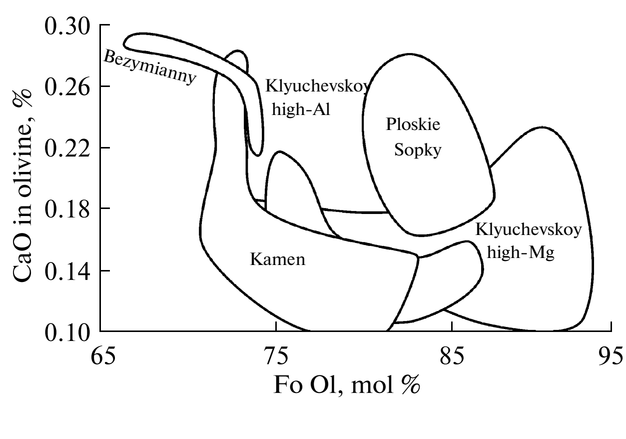

Fig. 8. CaO–Fo diagram for olivines of the Klyuchevskoy group of volcanoes. A clear trend from Klyuchevskoy volcano via Kamen volcano to Bezymianny volcano is observed. The olivines of the Ploskie Sopky volcano do not fit this trend. Fo denotes olivine composition (mol %).

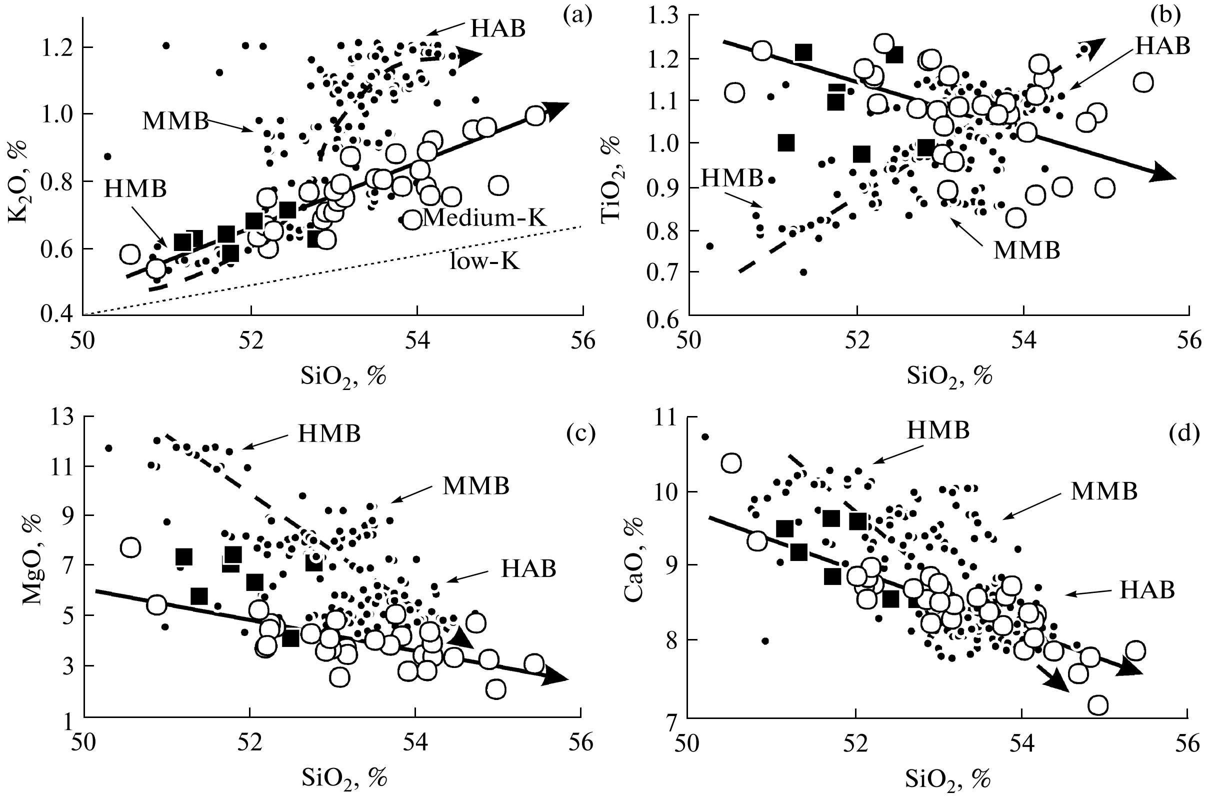

Fig. 9. Diagrams of the relationships of SiO_2 to other major elements in the rock of Kamen volcano and Klyuchevskoy volcano es. Dots show compositions of rocks of Klyuchevskoy volcano taken from the database [Portnyagin et al., 2007]. HABs denotes high-alumina rocks of Klyuchevskoy volcano, MMBs, moderately magnesian basalts of Klyuchevskoy volcano , and HMBs denotes high-magnesian rocks of Klyuchevskoy volcano. For the other symbols see Fig. 2.

grams. We demonstrated above that the compositions of minerals in the monogenetic cones significantly differ from those of the rocks of Kamen stratovolcano. However, the compositions of the minerals in the rocks of Kamen monogenetic cones and the MMBs of Klyuchevskoy volcano are rather similar: the MMBs of Klyuchevskoy volcano contain olivine Fo_{75-92} with a maximum at Fo_{88-91} (Fig. 4p) and clinopyroxenes with $Mg\#_{75-91}$ and maximums at $Mg\#_{81}$ and $Mg\#_{87}$ (Fig. 4q); lavas of monogenetic cones of Kamen contain olivine Fo_{70-92} with a maximum at Fo_{88} (Fig. 4g) and clinopyroxenes with $Mg\#_{72-80}$ and a maximum at $Mg\#_{79}$ (Fig. 4h).

These results demonstrate that the rocks of Kamen stratovolcano and Klyuchevskoy volcano are not derivates of a common primary melt, while the monogenetic cones and MMBs of the Klyuchevskoy volcano may have the same primary melt. Therefore, the monogenetic cones situated in the west–southwestern sector of Kamen volcano are the lateral cones of the Klyuchevskoy volcano . This inference is supported by their age, about 2 ^{14}C ka, as reported by V.V. Ponomareva (personal communication) and by their location in the zone of areal volcanism of the Klyuchevskoy volcano , with the distance from its summit to the cones being 9–14 km.

6.3. Comparison of Rocks of Kamen and Bezymianny Volcanoes

The rocks of Kame and Bezymianny stratovolcanoes form a common trend in all petrologic diagrams. The lavas of Kamen stratovolcano constitute a more basic part of this trend, as shown by basalts and andesite–basalts, while the rocks of the Bezymianny volcano form a more acidic extension, as shown by andesite–basalts, andesites, and dacites (Fig. 10).

The compositions of the mafic minerals of the Bezymianny volcano occupy a more ferruginous area compared to minerals of Kamen rocks. Thus, on the diagram of CaO in olivines as plotted against forsterite, the compositions of the minerals of the Bezymianny volcano also extend the trend of the mineral compositions of Kamen volcano, forming its highest-calcium segment (Fig. 8).

The close affinity of Bezymianny and Kamen volcanoes is also supported by the appearance of hornblende rocks at the late evolutionary stages of Kamen volcano among both the later lavas of the stratovol-

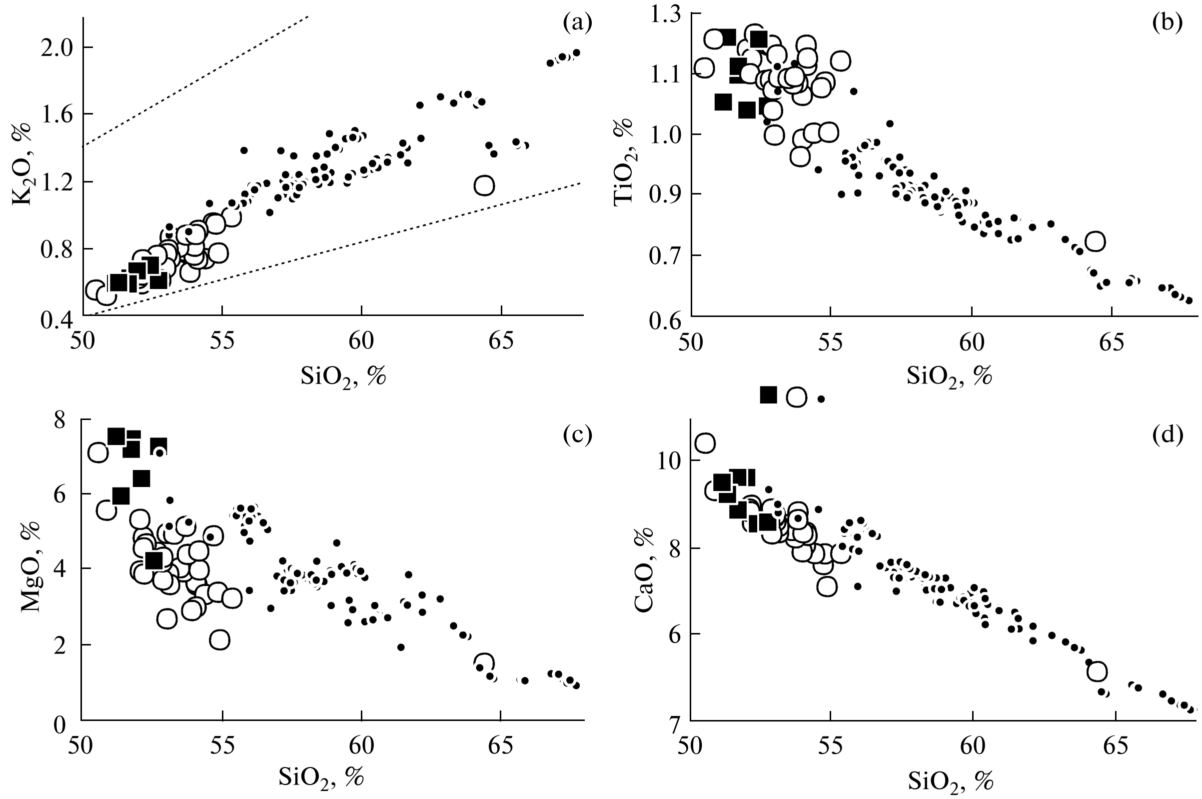

Fig. 10. Diagrams of the dependence of SiO_2 on other major elements in the rocks of Kamen and Bezymianny volcanoes. Dots show the compositions of the rocks of Klyuchevskoy volcano taken from the database [Portnyagin et al., 2007]. The symbols are the same as in Fig. 2.

cano and in the rocks of the dyke complex. Hornblende andesites occur widely in the rocks of Bezymianny volcano.

Interconnections between volcanoes of Klyuchevskoy group are also observed in the *P–T* diagram based on CKD whole-rock compositions (Fig. 11). Crystallization temperatures were calculated using the model due to [Albarede, 1992] and pressure after [Putirka, 2008]. The diagram clearly demonstrates that the rocks of Ploskie Sopky volcano occupy a special place among all of the CKD volcanic rocks and that they crystallized at higher pressures. The HABs, MMBs, and HMBs of Klyuchevskoy volcano occupy three areas; HMBs that crystallized at the highest temperatures and pressures (T = 1320–1350°C, P = 10–12 kbar) and MMBs and HABs that crystallized at similar depths (P = 6–8 kbars) but at different temperatures (T = 1200–1270 for MMBs and T = 1000–1200°C for HABs). The data points of the monogenetic cones occur in the field of the MMBs of Klyuchevskoy volcano, thus supporting their genetic affinity. The rocks of the dykes and Kamen stratovolcano follow the same trend, with Kamen volcano rocks corresponding to higher temperatures and pressures (T = 1100–1200°C, P = 4–8 kbars) than those of Bezymianny volcano (T = 1050–1150°C, P = 1–4 kbars) (Fig. 11).

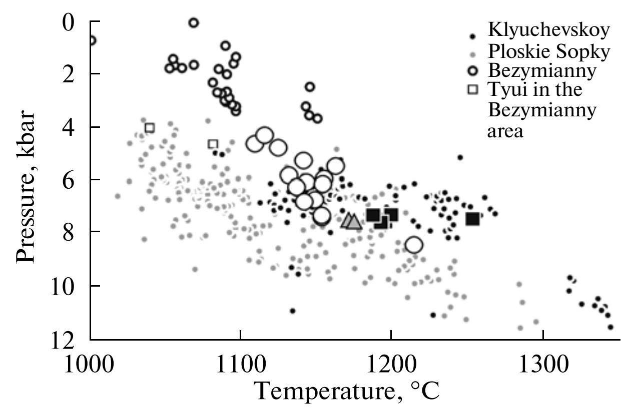

Fig. 11. *P–T* diagram for the rocks of volcanoes in the Central Kamchatka Depression. The temperature was calculated in accordance with the model in [Albarede, 1992] and pressure using the model in [Putirka, 2008] based on whole rock composition. The other symbols are the same as in Fig. 2.

Table 2. Major elements in the rocks of Kamen volcano

Sample	2311	KAM-07-03	KAM-08-14	KAM-08-01	KAM-08-68	KAM-08-20
Complex	cone	cone	cone	cone	cone	cone
Latitude (N)	55°57′54″	55°58′4.2″	55°59′59.7″	56°0′1.9″	55°59′50.5″	56°0′7″
Longitude (E)	160°27′8.7″	160°31′32.1″	160°29′19.3″	160°30′46″	160°29′58.5″	160°20′15.8″
SiO_2%	51.82	52.90	51.80	52.20	50.90	51.00
TiO_2 %	0.97	1.10	1.19	0.98	1.10	1.21
Al_2O_3%	17.13	17.80	18.60	15.90	16.70	17.40
Fe_2O_3%	6.65	3.01	3.95	3.75	2.95	4.64
FeO%	2.84	6.12	5.90	6.70	6.12	5.76
MnO%	0.17	0.15	0.15	0.16	0.16	0.16
CaO%	9.61	8.71	8.56	8.57	9.65	9.21
MgO%	6.41	5.18	4.21	7.21	7.44	5.90
Na_2O%	3.04	3.05	3.46	2.65	2.54	3.19
K_2O%	0.68	0.50	0.71	0.62	0.59	0.61
P_2O_5%	0.16	0.14	0.13	0.12	0.12	0.14
L.O.I.	0.43	0.57	0.69	0.74	0.80	0.56
Total	99.91	99.23	99.35	99.61	99.06	99.78
Sample	KAM-08-15	KAM-08-67/1	KAM-08-11	KAM-08-50	KAM-08-A1	KAM-08-84
Complex	cone	cone	dyke	dyke	dyke	dyke
Latitude (N)	56°0′14.8″	55°59′47.5″	56°0′11.4″	56°0′56.5″	55°58′54.2″	55°57′39.8″
Longitude (E)	160°31′20.2″	160°29′46.3″	160°32′45″	160°31′57.1″	160°41′12.6″	160°42′57.4″
SiO_2%	50.80	51.50	54.20	53.60	52.20	52.60
TiO_2%	1.00	1.09	1.04	1.06	1.17	1.18
Al_2O_3%	16.50	16.50	17.50	18.60	18.90	18.10
Fe_2O_3%	3.50	4.25	2.32	3.35	3.55	4.11
FeO%	6.85	6.26	6.98	5.68	5.97	6.45
MnO%	0.16	0.15	0.15	0.16	0.15	0.17
CaO%	9.51	8.86	7.58	8.61	8.58	8.25
MgO%	7.48	7.19	4.89	4.35	3.69	4.31
Na_2O%	2.66	2.89	3.27	3.18	3.55	3.35
K_2O%	0.61	0.63	0.95	0.78	0.69	0.63
P_2O_5%	0.12	0.13	0.15	0.17	0.18	0.16
L.O.I.	0.75	0.65	0.87	0.60	0.61	0.77
Total	99.93	100.10	99.89	100.14	99.24	100.07
Sample	KAM-08-52	KAM-08-85	KAM-08-30	2310	KAM-08-13	KAM-08A3
Complex	dyke	dyke	dyke	stratovolcano	stratovolcano	stratovolcano
Latitude (N)	56°1′8.4″	55°57′39.8″	55°59′50″	55°57′54″	55°57′54″	55°59′7″
Longitude (E)	160°32′1.6″	160°42′57.4″	160°32′9.6″	160°27′8.7″	160°27′8.7″	160°40′9.9″
SiO_2%	51.90	51.90	63.80	50.52	50.40	52.56
TiO_6%	1.15	1.14	0.54	1.11	1.20	1.03
Al_2O_3%	18.90	19.80	17.10	16.82	17.80	17.90
Fe_2O_3%	3.89	4.36	5.72	6.93	4.20	4.54
FeO%	6.41	5.47		3.40	6.70	5.04
MnO%	0.16	0.16	0.10	0.19	0.17	0.16
CaO%	8.82	8.56	5.08	10.41	9.31	8.72
MgO%	3.88	3.88	1.50	7.10	5.54	4.88
Na_2O%	3.35	3.37	3.85	2.68	3.01	3.33
K_2O%	0.75	0.61	1.18	0.56	0.53	0.78
P_2O_5%	0.14	0.14	0.13	0.16	0.14	0.15
L.O.I.	0.75	0.62	0.68	0.33	0.72	0.44
Total	100.11	100.01	99.68	100.19	99.72	99.52

Table 2. (Contd.)

Sample	KAM-08-37	KAM-08-54	KAM-08-08	KAM-08-10	KAM-08-07	KAM-07-23
Complex	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano
Latitude (N)	55°59′52.5″	56°1′26.9″	56°0′4.1″	56°0′11.3″	56°0′2.9″	55°59′3.4″
Longitude (E)	160°32′8.8″	160°31′8.5″	160°32′34.4″	160°33′4″	160°32′22.2″	160°34′10.1″
SiO_2%	53.50	52.50	55.10	53.50	51.90	50.80
TiO_2%	1.08	0.96	1.13	1.10	1.14	1.17
Al_2O_3%	17.50	19.30	18.50	17.60	18.10	19.40
Fe_2O_3%	3.61	4.36	3.48	4.12	3.72	4.88
FeO%	6.05	5.04	5.32	5.26	6.91	5.40
MnO%	0.15	0.15	0.15	0.15	0.17	0.17
CaO%	8.21	8.81	7.86	8.35	8.75	9.03
MgO%	5.14	3.75	3.26	4.45	4.82	4.85
Na_2O%	3.21	3.25	3.49	3.15	3.00	3.25
K_2O%	0.89	0.70	0.99	0.90	0.65	0.49
P_2O_5%	0.14	0.12	0.16	0.17	0.15	0.14
L.O.I.	0.84	0.57	0.57	0.82	0.76	0.57
Total	100.32	99.51	100.01	99.56	100.06	100.14

Sample	KAM-08-05	KAM-08-02	KAM-08-39	KAM-08-40-1	KAM-08-24	KAM-08-22
Complex	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano
Latitude (N)	55°59′55.5″	56°0′47.7″	56°1′21.3″	56°1′21.3″	56°1′15″	56°1′1.7″
Longitude (E)	160°31′53″	160°30′42.2″	160°31′48.8″	160°31′52″	160°32′53.7″	160°31′11.8″
SiO_2%	51.90	52.80	54.00	53.80	54.40	54.30
TiO_2%	1.22	1.15	1.18	0.89	0.89	1.06
Al_2O_3%	18.10	18.70	19.10	19.50	20.30	18.60
Fe_2O_3%	4.58	3.35	4.33	4.00	3.55	3.26
FeO%	5.62	6.48	5.04	5.11	5.83	5.96
MnO%	0.17	0.16	0.16	0.16	0.15	0.15
CaO%	8.79	8.56	8.04	7.85	7.11	7.77
MgO%	4.69	3.87	3.58	3.36	2.17	3.38
Na_2O%	3.26	3.33	3.35	3.26	3.66	3.39
K_2O%	0.64	0.80	0.74	0.75	0.78	0.95
P_2O_5%	0.18	0.17	0.14	0.13	0.13	0.16
L.O.I.	0.67	0.69	0.59	0.58	0.75	0.87
Total	99.82	100.06	100.24	99.38	99.72	99.85

Sample	KAM-08-16	KAM-08-06	KAM-08-29	KAM-08-26	KAM-08-61	KAM-08-04
Complex	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano
Latitude (N)	56°0′4.5″	55°59′55″	56°1′15.9″	56°1′16.2″	56°1′33.4″	55°59′54.2″
Longitude (E)	160°31′31.9″	160°31′58.2″	160°32′36.9″	160°32′41.5″	160°33′31.4″	160°31′53.3″
SiO_2%	53.40	51.70	53.80	52.80	53.30	51.90
TiO_2%	1.13	1.08	0.87	0.81	1.08	1.17
Al_2O_3%	17.90	18.40	19.70	19.40	18.50	17.90
Fe_2O_3%	3.11	4.15	4.95	3.55	4.19	4.75
FeO%	6.19	5.75	4.25	5.26	5.40	5.54
MnO%	0.15	0.16	0.15	0.15	0.16	0.16
CaO%	8.28	8.98	8.35	8.79	8.52	8.89
MgO%	3.99	4.54	2.96	2.88	4.02	5.28
Na_2O%	3.30	3.31	3.45	3.49	3.47	3.18
K_2O%	0.91	0.66	0.76	0.67	0.80	0.63
P_2O_5%	0.15	0.19	0.13	0.13	0.14	0.17
L.O.I.	0.87	0.61	0.75	0.55	0.64	0.61
Total	99.38	99.53	100.13	98.48	100.22	100.18

Table 2. (Contd.)

Sample	KAM-08-60	KAM-08-38	KAM-08-31	KAM-08-64	KAM-08-43	KAM-08-23
Complex	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano
Latitude (N)	56°1′39.5″	56°0′53.6″	55°59′51.5″	56°1′33.7″	56°1′15.2″	56°1′6.1″
Longitude (E)	160°33′14.8″	160°30′36.3″	160°32′7.4″	160°33′31.5″	160°33′31.6″	160°31′14.9″
SiO_2%	52.80	53.50	52.90	53.60	52.50	52.50
TiO_2%	0.95	1.06	1.08	1.02	0.88	1.06
Al_2O_3%	19.70	18.50	17.70	18.90	20.40	18.70
Fe_2O_3%	3.90	4.35	3.75	4.21	3.99	3.75
FeO%	5.62	5.54	6.10	5.33	5.11	5.76
MnO%	0.15	0.16	0.15	0.16	0.14	0.15
CaO%	8.31	8.38	8.48	7.89	8.73	8.84
MgO%	3.59	3.88	4.88	3.61	2.68	4.21
Na_2O%	3.37	3.32	3.27	3.45	3.56	3.26
K_2O%	0.76	0.79	0.88	0.83	0.75	0.71
P_2O_5%	0.12	0.18	0.14	0.15	0.12	0.15
L.O.I.	0.60	0.44	0.82	0.64	0.58	0.68
Total	99.88	100.10	100.14	99.78	99.45	99.77
Sample	KAM-08-59	KAM-08-97	KAM-08-88	KAM-08-98	KAM-08-87	KAM-08-92
Complex	stratovolcano	stratovolcano	stratovolcano	stratovolcano	stratovolcano	Ambon
Latitude (N)	56°1′48.2″	55°57′49.7″	55°57′46.5″	55°57′47.3″	55°57′33″	55°57′40.8″
Longitude (E)	160°31′40.3″	160°40′57.8″	160°41′51″	160°40′38.8″	160°42′44.5″	160°45′16.7″
SiO_2%	52.50	52.60	54.40	50.90	54.00	62.50
TiO_2%	1.07	0.98	1.06	1.15	1.09	0.72
Al_2O_3%	18.40	19.80	18.30	19.30	18.90	17.30
Fe_2O_3%	4.87	3.55	3.12	4.10	3.36	3.97
FeO%	5.26	5.54	6.12	5.95	6.48	1.94
MnO%	0.16	0.15	0.15	0.16	0.15	0.10
CaO%	8.66	8.66	8.24	9.12	7.28	5.28
MgO%	4.42	2.96	3.21	3.99	3.58	2.56
Na_2O%	3.29	3.48	3.37	3.12	3.53	3.37
K_2O%	0.76	0.80	1.02	0.59	0.84	1.25
P_2O_5%	0.14	0.14	0.18	0.13	0.16	0.15
L.O.I.	0.54	0.69	0.63	0.75	0.67	0.68
Total	100.07	99.34	99.79	99.26	100.04	99.82
Sample	KAM-08-94	KAM-08-93	KAM-07-01	KAM-07-04	KAM-07-11	
Complex	Ambon	Ambon	Tyuya Kulich	stratovolcano	cone	
Latitude (N)	55°57′24.9″	55°56′48.8″	55°57′57.8″	55°58′52.7″	55°59.899″	
Longitude (E)	160°42′8.4″	160°43′53″	160°30′58.9	160°33′20.3″	160°30.275″	
SiO_2%	51.70	54.20	60.10	55.80	52.08	
TiO_2%	1.04	1.13	0.59	0.93	0.98	
Al_2O_3%	17.80	17.50	18.22	17.93	16.06	
Fe_2O_3%	4.86	4.26	2.88	3.41	4.00	
FeO%	5.47	5.26	4.10	4.75	5.62	
MnO%	0.16	0.15	0.16	0.15	0.15	
CaO%	8.63	8.48	6.59	7.76	8.95	
MgO%	5.17	4.21	1.79	4.21	8.52	
Na_2O%	3.22	3.24	3.79	3.21	2.59	
K_2O%	0.87	0.95	0.89	0.84	0.51	
P_2O_5%	0.13	0.15	0.26	0.17	0.13	
L.O.I.	0.68	0.62	0.46	0.44	0.58	
Total	99.73	100.14	99.83	99.60	100.16	

CONCLUSIONS

Our studies provided data on the petrologic and geochemical classification of the rocks of Kamen volcano and improved our understanding of its relationship with the neighboring volcanoes. The first data on the concentration of major and trace elements in the rocks and minerals of Kamen indicated that the stratovolcano and dykes had no common primary melts with Ploskie Sopky and Klyuchevskoy volcanoes. At the same time, the genetic relationship between the rocks of Kamen volcano and the rocks of Bezymianny is quite obvious. This might be explained by the fact that the magma chamber of Kamen volcano moved to the south, occupied a near-surface position, and was inherited by Bezymianny volcano .

The origins of the numerous monogenetic cinder–lava cones that are abundant on the western and southwestern slopes of Kamen volcano were also unclear. Our results provide evidence that these cones are actually cones of Klyuchevskoy volcano and correlate in composition to its MMBs.

Below, we present a short summary of the results.

Based on petrographic features, the rocks of Kamen volcano are classified into four groups that involve seven rock types. They are olivine-bearing (types 1 and 2), olivine-free (types 3–5), sub-aphyric (type 6), and hornblende-bearing (type 7) rocks.

Olivine-bearing rocks are found in all the volcanic complexes. In contrast, rocks without olivine occur only in the edifice of the stratovolcano and are absent from the other volcanic complexes. The greatest diversity of rocks is found in the stratovolcano edifice; all the rock types are present here. The lavas of the monogenetic cones are composed of olivine-bearing and sub-aphyric rocks, and the dyke complex consists of olivine-bearing and hornblende-bearing varieties.

All the rocks of Kamen volcano belong to the moderate-K, subalkaline, basalt–andesite-basalt series.

The lavas of the stratovolcano are high-alumina low-magnesian ($MgO \leq 7\%$, $SiO_2 \sim 50–56\%$) varieties of basalt-andesite–basalt series and form persistent trends in petrochemical diagrams.

The rocks of the dyke complex are located in the petrochemical diagrams in the field of the stratovolcano rocks; they have a mineral composition that is similar to the stratovolcano minerals and are derivates of the same mantle sources as the edifice of the stratovolcano.

The lavas of the monogenetic cones are high-magnesian andesite–basalts ($MgO > 6\%$, $SiO_2 \sim 52–53\%$) and systematically differ from the stratovolcano rocks in their compositions of major elements and rock-forming minerals.

The rocks of Kamen and Ploskie Sopky volcanoes systematically differ in the chemistry of their rocks and minerals; they could not be formed out of common primary melts.

The lavas of the monogenetic cones of Kamen volcano and the moderately-magnesian basalts of Klyuchevskoy volcano are derivates of common melts.

The rocks of dykes and the Kamen stratovolcano and the rocks of Klyuchevskoy volcano form differently directed trends on petrochemical diagrams and differ in the compositions of their rock-forming minerals, i.e., they do not show a genetic affinity.

The rocks of the Kamen and Bezymianny stratovolcanoes on all the petrochemical diagrams form a common narrow trend in which the lavas of Bezymianny compose a branch that is rich in SiO_2, thus suggesting the genetic affinity of these volcanoes.

The initial period of evolution of the edifice of Kamen volcano was related to explosive activity, which resulted in the formation of a large deposition cone; at later evolutionary stages effusive activity prevailed.

The inner parts of the volcanic edifice underwent intense secondary alterations that increase towards the center and diminish towards the flanks. This was probably due to active heat and/or hydrothermal flows through the central conduit of the volcano.

The Ambon rock deposits consists of disintegrated material of the inner fragments of the edifice that have undergone secondary alteration.

Fresh unaltered material of the initial stage of Kamen volcano evolution occurs only on its extreme flanks.

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