Petrology, Vol. 5, No. 6, 1997, pp. 550–569. Translated from Petrologiya, Vol. 5, No. 6, 1997, pp. 614–635.

Petrological–Geochemical Model for Genetic Relationships between Basaltic and Andesitic Magmatism of Klyuchevskoi and Bezymyannyi Volcanoes, Kamchatka

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Received January 27, 1997

Abstract—The paper reports data on the deep structure and feeding system of Klyuchevskoi and Bezymyannyi volcanoes, distinctive features of their eruptive activity, and new geochemical data on their basalts and andesites. The materials are used to discuss the concept of a common deep-seated source of the volcanoes. The fractionation products of the source underwent a complex evolution during their ascent along the system of volcanic conduits. The magmas of the Klyuchevskoi and Bezymyannyi volcanoes are thought to have originated in notably different geodynamic and thermodynamic environments and, thus, yielded two "reduced" volcanic series: the predominantly basaltic series of Klyuchevskoi volcano and the basaltic andesite–dacite series of Bezymyannyi volcano. Both of the series experienced crystal fractionation with a subordinate role of other petrogenetic processes. According to the concept, the two volcanic series compose a single evolutionary series (a specific geochemical system), whose source was upper mantle peridotitic material and whose derivatives encompass a broad spectrum of volcanics ranging from mafic to acid rocks.

INTRODUCTION

Klyuchevskoi and Bezymyannyi volcanoes, distinctive features of their eruptive activity, structure, and magmatic evolution continue attracting the attention of volcanologists and petrologists. These volcanoes are among the world's most active ones. They are spaced only 9.5 km apart (Fig. 1) and belong to the Klyuchevskoi group of volcanoes. The group comprises twelve large eruption centers, which are restricted to the Central Kamchatka depression at the junction zone between the Kuril–Kamchatka and Aleutian island arcs. Klyuchevskoi and Bezymyannyi volcanoes were described in a series of monographs by Soviet and foreign scientists (Vlodavets, 1940; Naboko, 1947; Piip, 1956; Gorshkov and Bogoyavlenskaya, 1965; Ermakov, 1977; Anosov, 1978; Balesta, 1981; Kadik *et al.*, 1986; Ivanov, 1990; Rittmann, 1960; MacDonald, 1972, Rast, 1980; *Glubinnoe stroenie i seismichnost'* ..., 1976; *Deistvuyushchie vulkany* ..., 1991) and in numerous papers.

Having a typical composition of rocks of the calc-alkaline series, which are common among island-arc volcanics, the volcanic products of Klyuchevskoi and Bezymyannyi volcanoes are principally different in mineral and chemical composition. Magnesian and aluminous basalts are widespread on Klyuchevskoi volcano, whereas the rocks of Bezymyannyi are more silicic: from basaltic andesite to dacite. The character of eruptive activity, a feature definitely correlated with the compositional differences between the respective rocks, is also principally different at these two volcanoes. This seems to be the main reason why Klyuchevskoi and Bezymyannyi volcanoes were usually considered separately, although many authors emphasized their spatial closeness but, ignoring experimental evidence of the principal possibility of andesite and dacite origin from basalt magma, expressed very cautious notions that the rocks of these large volcanic centers could be related genetically (Ivanov, 1976; Kadik *et al.*, 1986). Possible genetic relationships between these rocks are, thus, one of the key problems in the petrology of the Klyuchevskoi and Bezymyannyi volcanic system. The resolution of this problems will be petrologically significant in the context of a more general problem concerning the genesis of island-arc andesite.

GENESIS OF ISLAND-ARC CALC-ALKALINE SERIES

The genetic problem of calc-alkaline series involves the following aspects: (1) mechanisms and conditions that resulted in the origin of andesite–dacite series; (2) the nature of possible genetic links between andesites and accompanying highly aluminous basalts; and (3) mechanisms leading to the origin of highly aluminous basalts, which are commonly considered to be the

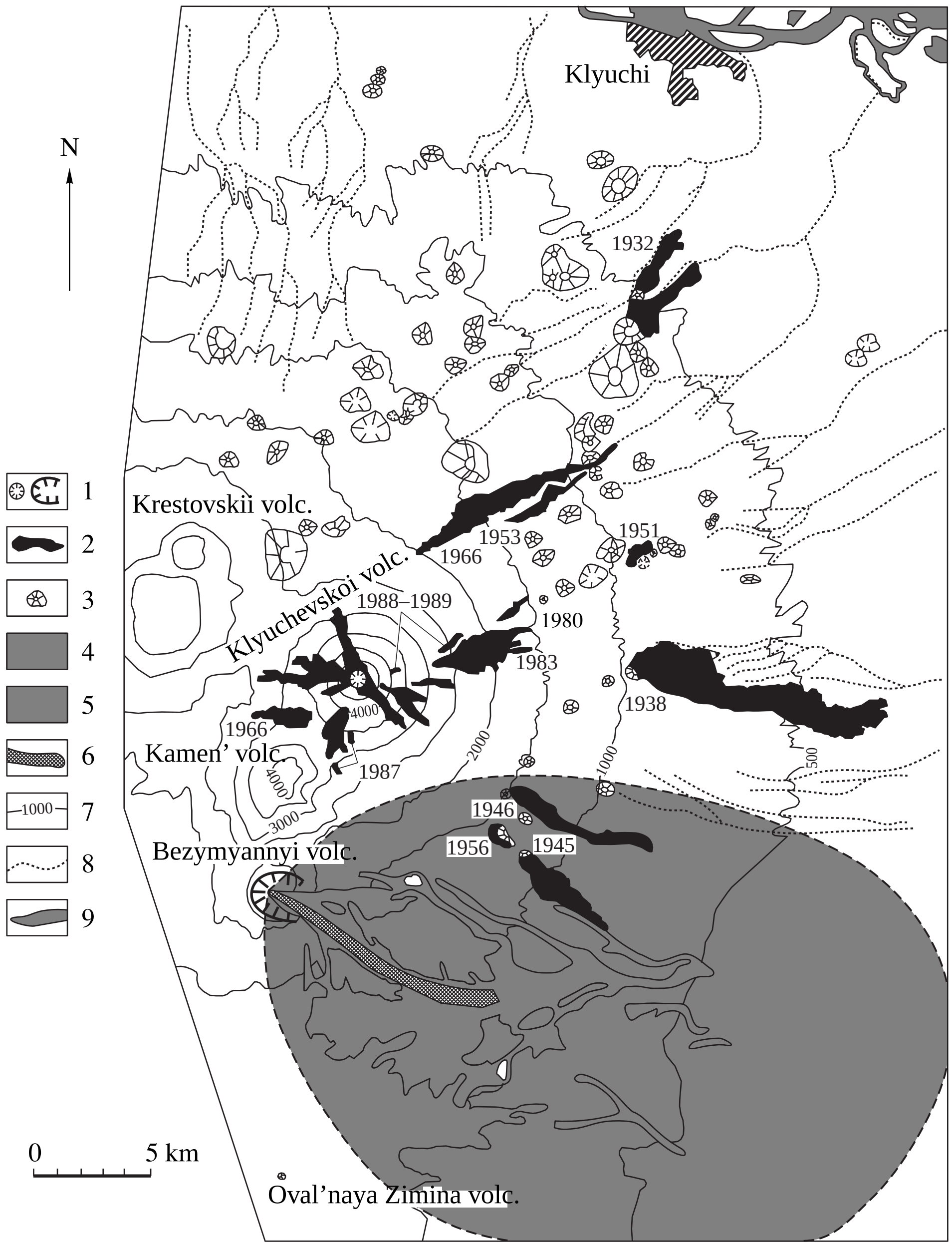

Fig. 1. Schematic map showing the deposits of historical eruptions of Klyuchevskoi and Bezymyannyi volcanoes (prepared by A.Yu. Ozerov using materials of G.E. Bogoyavlenskaya and V.N. Dvigalo of the Institute of Volcanology, Far East Division, Russian Academy of Sciences).

(1) Craters of the volcanoes Klyuchevskoi (circle) and Bezymyannyi (semioval); (2) lava flows of historical (1932–1990) eruptions of Klyuchevskoi volcano and their eruption years; (3) cinder cones; (4) pyroclastic flows of the 1956 eruption of Bezymyannyi volcano; (5) deposits produced by the pinpoint explosion of the 1956 Bezymyannyi eruption; (6) courses of pyroclastic flows from 1957 to the present time, Bezymyannyi volcano; (7) contours; (8) dry river valleys; (9) Kamchatka River.

initial (parental) magmas for the association of andesites and dacites.

A number of hypotheses were developed to account for the two former problems. These hypotheses involve the idea that andesitic melts can be melted immediately from water-bearing material of the upper mantle or from the subducted oceanic crust, metasomatic transformations of mantle material under the effect of fluid flows, assimilation of sialic crustal material by basaltic magmas, separation of immiscible mafic liquids, and the fractionation of the basaltic source accompanied by the settling of magnetite- and amphibole-bearing mineral assemblages [detailed reviews of these concepts were presented by Kadik *et al.* (1986) and Bogatikov and Tsvetkov (1988)]. A thorough analysis of the reasoning in support of certain concepts is beyond the scope of this paper; however, in our opinion, it is only the concept of *crystal fractionation of a highly-alumina basaltic magma* that has received the necessary experimental support (Grove *et al.*, 1982; Babansky *et al.*, 1983; Kadik *et al.*, 1986; Grove and Baker, 1984; Grove and Kinzler, 1986; Sisson and Grove, 1993).

The very first lines of evidence for this concept were developed by Osborn, who demonstrated that an increase in the oxygen fugacity (f_{O_2}) expands the stability field of magnetite in silicate systems, and, as a result, the residual melts become strongly enriched in SiO_2 (Osborn, 1959). This conclusion was later confirmed by numerous experiments with natural basalts. However, there is no consensus among petrologists concerning the conditions and main phases that control the development of calc-alkaline trends. This is explained by the fact that the melt can also enrich in SiO_2 in response to an increase in the water pressure, which shifts the proportions of olivine, plagioclase, and pyroxenes (± amphibole) toward the fields of more acid differentiates (Sisson and Grove, 1993).[1] Thus, the assessment of the effect of magnetite and amphibole crystallization in the presence of water is of crucial importance for understanding the conditions under which the andesite and dacite of calc-alkaline series develops. The presence of magnetite and the wide occurrence of amphibole in the lavas of Bezymyannyi volcano make these rocks useful for petrological and geochemical studies dealing with the origin of andesitic and dacitic associations.

The problem of the nature of highly-aluminous basalt as a probable source of island-arc andesites was first formulated by Kuno, who hypothesized that highly-aluminous basalts represent a primary magma that originated by the partial melting of mantle peridotite (Kuno, 1960). An alternative concept, which was advanced shortly after that by Yoder and Tilley (1962), is that the Al_2O_3 enrichment in such magmas can be caused by the delay in plagioclase crystallization from water-bearing picrite–basaltic magmas. In this connection, it seems to be particularly important to take into consideration the fact that many island-arc volcanic centers pervasively produce both highly-aluminous and highly-magnesian basalts.[2] Such associations were encountered, for example, on Okmok and Makushin volcanoes on the Aleutian Islands (Nye and Reid, 1986; Gust and Perfit, 1987) and on Klyuchevskoi volcano (Khrenov *et al.*, 1989; Ozerov and Khubunaya, 1992; Kersting and Arculus, 1994). In spite of the fact that highly-magnesian basalts are relatively scarce, they were discussed as the possible parental rocks of highly-aluminous basaltic melts, whose source is upper mantle peridotitic material.

The hypothesis was further developed in a number of experimental works aimed at studying phase equilibria in highly-magnesian island-arc basalts under pressures from 1 atm to 20 kbar (Gust and Perfit, 1987; Kadik *et al.*, 1989, 1990; Draper and Johnston, 1992). These studies have established that, under pressures above 8 kbar and dry conditions, highly-magnesian basalts fractionate to melts with 16–18 wt % Al_2O_3. Their contents of major components are close to those of natural highly-aluminous basalts. However, some characteristics of highly-aluminous basalts, for example, the CaO and MgO proportions, have no analogues among synthetic chilled glasses (Draper and Johnston, 1992). A solution of this problem was proposed based on the example of lavas from Klyuchevskoi volcano (Ariskin *et al.*, 1995; Ozerov *et al.*, 1996a) and using methods of computer simulation of the polybaric fractionation of basaltic magma (Ariskin *et al.*, 1993).

According to the model, highly-aluminous basalts result from the high-pressure fractionation of parental picrite–basalt magma in the presence of water and under gradually decreasing pressure (decompression). In application to the Klyuchevskoi lavas, this model suggests the decompressional crystallization of the *Ol* + *Cpx* + *Opx* + *Sp* assemblage from the initial high-Mg magma at depths from 57 to 21 km (19–7 kbar), temperatures of ~1350–1110°C, and 2–3 wt % water in the melt (Ariskin *et al.*, 1995). The enrichment of the melt in H_2O results in a notable delay of plagioclase crystallization and the origin of highly-aluminous differentiation products, which contain more than 18 wt % Al_2O_3. The aluminum enrichment trend terminates when plagioclase appears on the liquidus at $P = 7$ kbar and $T = 1110$°C. The compositional range of the model liquids produced by this moment covers the whole diversity of the Klyuchevskoi lavas, from highly-magnesian to highly-aluminous varieties (Table 1).

Our petrological model implicitly involves the fractionation dynamics of the Klyuchevskoi lavas by using a parameter characterizing the decompression rate of the magmatic melt, dP/dF, where F is the crystallization degree. According to our evaluations, this parameter for the Klyuchevskoi magma feeder should be approximately 0.33 kbar/% of the initial magma crystallization. Apparently, this value is related to the rate of ascent of the magmatic material, and the model itself assumes that, beneath the volcano, there are no large peripheral magma chambers in which isobaric fractionation could occur. Hence, the results of our petrological simulation of the origin of the Klyuchevskoi highly-aluminous basalts can be considered an indirect indication of that the roots of the volcanic feeding system penetrate as deep as the magma-generating zone in the upper mantle.

This paper presents materials on the deep-seated structure of the magma feeding system of Klyuchev-

[1] Symbols for minerals and end-members: *Ol*, olivine, *Pl*, plagioclase, *Cpx*, clinopyroxene (*Aug*, augite), *Opx*, orthopyroxene, *Sp*, chrome spinellid, *Mt*, titanomagnetite, *Fo*, forsterite, *An*, anorthite.

[2] These are basalts with >10 wt % MgO (Perfit *et al.*, 1980) and forsterite-rich olivine phenocrysts (Fo_{88-92}) (Kay and Kay, 1985).

skoi and Bezymyannyi volcanoes, distinctive features of their eruptive activity, and new geochemical data, which are employed in discussing the concept of a deep-seated source common for both volcanoes. The material from this source underwent a complex evolution during its ascent and migration through magma conduits.

DEEP-SEATED STRUCTURE OF THE KLYUCHEVSKOI GROUP OF VOLCANOES

This problem will be discussed starting from analysis of the deep-seated structure of the Klyuchevskoi group of volcanoes and proceeding to the consideration of the upper portions of the system feeding Klyuchevskoi and Bezymyannyi volcanoes.

The crust and upper mantle beneath the Klyuchevskoi group of volcanoes was thoroughly examined by deep seismic sounding (Anosov *et al.,* 1978; Balesta *et al.,* 1991). According to these data, no Moho discontinuity, as it is traditionally understood, was recognized within the Central Kamchatka depression, but a thick transition zone with a complicated distribution of velocities was detected at depths from 28–32 to 40–42 km. This zone is overlain by the so-called "basaltic" layer 8–10 km in thickness. According to data of these geologists, the Conrad discontinuity beneath the Klyuchevskoi group of volcanoes is pronounced poorly and occurs at a depth of 18–20 km. The "granitic" layer has a thickness of 14–16 km, and its roof is situated at a depth of 6 km. The "granitic" layer is thought to be composed of Paleozoic sequences which are compositionally similar to the metamorphic complexes of the Sredinnyi and Ganal'skii ranges and the Khavyven Highland.

Seismic data make it possible to estimate the depth of younger rocks beneath the Klyuchevskoi group of volcanoes (Balesta *et al.,* 1991). These data indicate that the sedimentary cover has a complex structure, with the horizontal attitude of the rocks disturbed by numerous normal faults, and an *en echelon* structure that seems to be situated immediately underneath Klyuchevskoi volcano has a net slip of up to 1.5–2 km. According to this, the thicknesses, strikes, and dips of cover sequences vary within the area. The overall thickness of the Cretaceous succession was evaluated at approximately 3–4 km. It is overlain by a Paleogene volcanic–sedimentary sequence, whose thickness beneath the Klyuchevskoi group of volcanoes is about 1 km. The Neogene rocks (alternating terrigenous and volcanic rocks of varying composition) have roughly the same thickness. Hence, the earth's crust beneath the Klyuchevskoi group of volcanoes has a thickness of at least 28–30 km and is of the continental type. Its original structure was disturbed by normal faults and younger geologic structures.

Data obtained by deep seismic sounding provide valuable information for understanding the structure of the feeding volcanic system. The use of the "magma chamber sounding" method (Balesta, 1971) made it possible to determine that there are no seismic boundaries over the depth interval 20–60 km beneath Klyuchevskoi volcano because of the strong absorption of seismic waves (Anosov *et al.,* 1978 and a personal communication by G.I. Anosov in 1996). The "seismic shadow" zone suggests that there is a nearly vertical anomalous zone beneath the volcano. The zone is a magma conduit with a diameter of no more than 2 km. This structure is thought to cut through the lower crust, transition zone between the crust and mantle, and penetrate the upper mantle. The upper boundary of the zone cannot be traced based on seismic data, and its lower limit was not detected. Nevertheless, the geometry of this zone makes it identical to a long-living magma conduit, through which magma arose from its deep-seated source beneath the crust. Moreover, seismic data (diffracted waves related to the depth interval 40–60 km) give grounds to believe that no structures that could be interpreted as magma chambers occur within this depth range.

Unlike Klyuchevskoi volcano, a 6- to 7-km-thick anomalous zone with lower seismic wave velocities was definitely recognized beneath Bezymyannyi volcano at depths of 10–20 km. The zone was identified with a peripheral crustal magma chamber, which is not connected immediately with the upper mantle (Utnasin *et al.,* 1976). This is clearly indicated by reflecting seismic boundaries which can be traced immediately beneath the chamber zone of Bezymyannyi volcano at depths of 28–40 km. Nevertheless, the results of numerical simulation of the wave field registered by the seismic sounding of the whole Klyuchevskoi volcanic group indicate that a regional anomalous zone runs between Klyuchevskoi and Bezymyannyi volcanoes. The zone is characterized by variations in its seismic parameters along the strike. This suggests that the anomalous zone of Bezymyannyi volcano plunges beneath Kamen' and Klyuchevskoi volcanoes (Fig. 2), where it is connected with the anomalous zone of the Klyuchevskoi magma conduit (Utnasin *et al.,* 1976) probably at a depth of 30–40 km.

Further information on the deep structure of the Kluichevskoi group of volcanoes is obtained from natural sources of seismic waves: earthquakes, which occur both within the seismic focal layer and immediately underneath the volcanoes. Studies of the propagation of body waves from distant (in Japan) earthquakes indicate that the morphology of the "magma chamber" beneath Klyuchevskoi volcano resembles a flat lens, and it is situated at depths of 50–60 km (Gorshkov, 1956). It is pertinent to comment that an unambiguous interpretation of seismic data obtained using distant earthquakes is complicated by the necessity of taking into account numerous factors that can affect the damping of seismic waves. Because of this, it was proposed to use closer earthquakes to obtain more reliable depth estimates for magma chambers (Fedotov and Farberov, 1966). In particular, Firsov and Shirokov (1971) revealed, using earthquakes in the vicinity of the Klyuchevskoi group of volcanoes in the seismic focal layer of the Vadati–Zavaritsky–Benioff zone, that seismic waves are shielded at depth of 70–150 km beneath Klyuchevskoi and Bezymyannyi volcanoes. This phenomenon was interpreted as caused by the propagation of seismic waves through a magma-generating zone. However, other interpretations are also possible. For example, a similar result can be produced by high-velocity layers within the crust–mantle transition zone (Anosov *et al.,* 1978).

The upper portion of the feeding system of Klyuchevskoi volcano proper (to a depth of 25–30 km) was described in detail on the basis of seismic data (Fedotov *et al.,* 1988). Volcanic earthquakes are known to be generated around magma conduits and chambers during the emplacement of intrusions, dikes, sills, and other processes that bring about changes in the pressure within magmatic reservoirs. Analysis of these earthquakes made it possible to establish that a highly seismic area is located immediately beneath Klyuchevskoi volcano, and single earthquakes and their swarms usually reach a depth of 25–30 km and occasionally (as during the 1986–1989 eruptions) reach as low as 35–40 km (Zharinov *et al.,* 1990, 1991). It should be noted that numerous observations indicate that, before eruptions, earthquakes arise from a depth of about 25 km to the volcanic edifice with a velocity of 3–5 km per month. These observations suggest that a vertical seismically active zone (which was identified with a magma feeder) occurs in the upper portion of the Klyuchevskoi volcano feeding system. The zone continues from the bottom of the summit crater to depths of 25–30 km (Fedotov *et al.,* 1988).

The most active part of the vertical seismically active zone has a shape of an elongated cylinder about 5 km in diameter. Within this zone, an aseismic area less than 3 km in diameter was recognized at depths from 5 to 20 km. The area is interpreted as a zone of plastic rocks around the main magma conduit of the volcano. This is compatible with data calculated based on the inferred temperatures of the feeding system (Fedotov *et al.,* 1988). The temperature of the walls of the main feeding conduit is 1200–1100°C and gradually decreases away from them to the ambient temperature in the host rocks. The rocks are most plastic near the conduit at a temperature of 1100–700°C, and, thus, the number of earthquakes there decreases or they are totally absent.

It should be stressed that no aseismic zones 5 km across or more that could be interpreted as large intermediate magma chambers were detected to depths of 25–30 km within the above-mentioned seismically active zone. The same conclusion follows from an analysis of the variations in the number of earthquakes with depth: the stress field varies with approximately the same intensity in the upper part of the feeding system of Klyuchevskoi volcano over the depth interval 0–25 km (Fedotov *et al.,* 1988). This indicates that no large heterogeneities (magma chambers) occur in the feeding system within this depth range. It seems to be hardly possible that any significant amounts of basaltic magma could be accumulated at depths more than 20 km. This is evident from calculations based on estimated variations in excess magma pressure with depth: magma with a density of 2.5–2.6 g/cm^3 and under a pressure of hundreds of bars should be actively squeezed from deeper parts of the feeding system without forming intermediate chambers (Fedotov, 1993).

The following considerations should be taken into account in discussing the problem of intermediate magma chambers. The age of Klyuchevskoi volcano is approximately 7000 years (Braitseva *et al.,* 1994); i.e., it is too young for any large crustal or peripheral chambers to form on the magma feeder (Fedotov, 1980). The volcano has no caldera (and shows no traces of its development), a fact that would be indicative of the existence of a shallow magma reservoir beneath the volcano. The relatively even delivery of large magma volumes to Klyuchevskoi volcano (about 6×10^7 t/year) seems to mean that it is not connected with any large crustal magma reservoir. At the same time, the discontinuous supply of magma to the Bezymyannyi feeder implies that a large intermediate magma chamber possibly exists in the roots of its feeding system.

In closing the analysis of the deep structure of the volcanoes, let us formulate two principal conclusions, which are important for discussing possible genetic links between the basalts and andesites of Klyuchevskoi and Bezymyannyi volcanoes.

(1) Both volcanoes have the same mantle source, which continuously generated magma. The magma arose to the surface first along a single conduit and then, from depths of 30–40 km, along two channels. The evolution of the magmatic material parental for both volcanoes proceeded during this stage under polybaric conditions (predominantly, under decompression).

(2) No large peripheral magma chambers in which isobaric crystallization could proceed exists near the feeder of Klyuchevskoi volcano at depths less than 40–30 km, i.e., the fractionation of the magma continued under decompression. Bezumyannyi volcano most probably possesses an intermediate magma chamber at depths of 10–20 km. In this chamber, large volumes of high-aluminum magma could undergo significant transformations by nearly isobaric fractionation.

These features of the crustal evolutionary regimes are important for understanding the differences in the composition of the eruption products of Klyuchevskoi and Bezymyannyi volcanoes and related distinctive features of their eruptive activity.

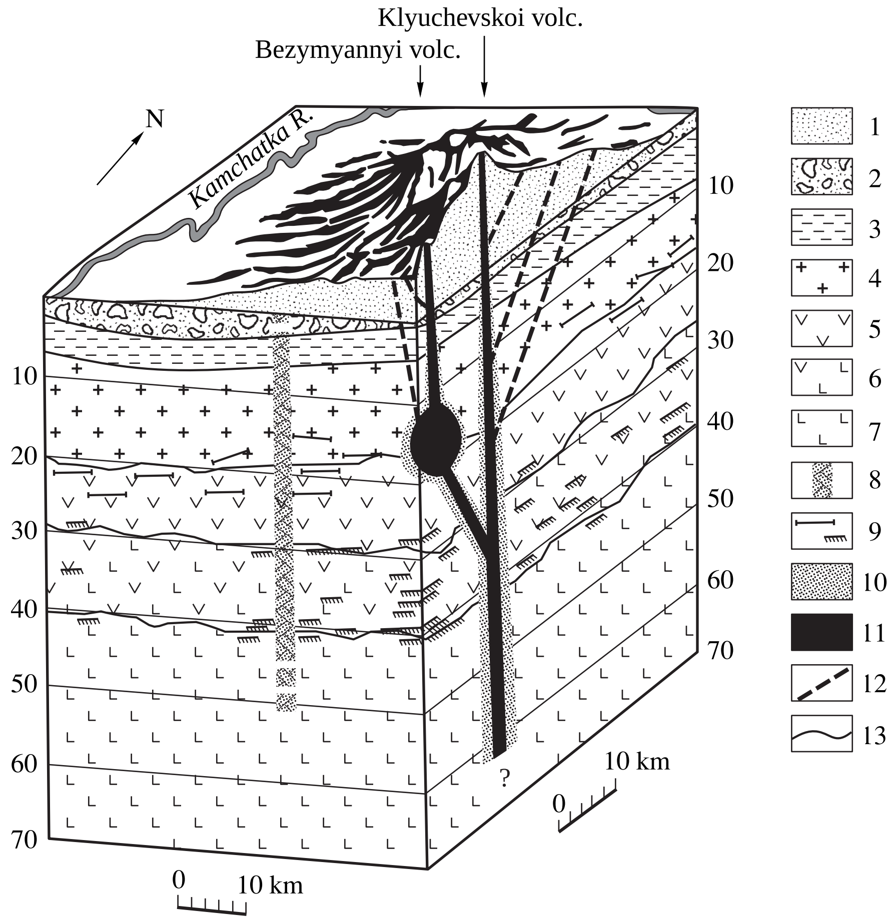

Fig. 2. Schematic seismological–volcanological model for the deep structure of the Klyuchevskoi and Bezymyannyi volcanoes [modified by A.Yu. Ozerov and G.I. Anosov, Institute of Volcanology, Far East Division, Russian Academy of Sciences, after Utnasin *et al.* (1976)].

(1) Quaternary volcanic edifices; (2) Paleogene–Neogene volcanic–sedimentary rocks; (3) Cretaceous volcanic–sedimentary rocks; (4) "granitic" layer; (5) "basaltic" layer; (6) transition zone between the "basaltic" layer and the upper mantle; (7) upper mantle; (8) deep fault; (9) reflecting seismic surfaces; (10) zone of heated rocks; (11) volumes of liquid magmatic melts; (12) monostage magmatic dikes; (13) boundaries between seismic sequences.

COMPARATIVE CHARACTERIZATION OF ERUPTIVE ACTIVITY AT THE KLYUCHEVSKOI AND BEZYMYANNYI VOLCANOES

Klyuchevskoi Volcano

At a magma discharge of 6×10^7 t/year, the Klyuchevskoi volcano accounts for nearly a half of the juvenile material that is delivered to the surface within the Kuril–Kamchatka volcanic area (Fedotov *et al.*, 1987). The volcano began to develop 6000–7000 years ago (Braitseva *et al.*, 1994) on a slope of the preexisting Kamen' volcano. Its intense eruptive activity shaped the Klyuchevskoi volcano into an almost ideal truncated cone 4822 m high (as of August 3, 1993; Ozerov *et al.*, 1996c). Now, it is a typical central stratovolcano with an active crater 750 m in diameter. The volcanic edifice consists of lava flows intercalating with layers of pyroclastic material and ice, with the volume of pyroclastics notably exceeding that of lava flows. More than 50 auxiliary fissures cut the slopes of the volcano, and its numerous parasitic cinder cones range from a few dozen meters to 200 m in height.

It is difficult to reconstruct in detail the eruptive activity of the volcano because the active growth of its central cone hampers the development of deep ravines. Nevertheless, the results of historical observations and geological studies indicate that from the late 17th century until 1932, Klyuchevskoi volcano had grown owing only to summit eruptions. A change in its eruptive activity occurred in 1932: as the central crater activity proceeded, auxiliary eruptions began to develop on the slopes.

The modern summit eruptions of the volcano differ in duration and intensity. Sometimes, they last two, three, and even more years or are as brief as a few weeks or months. The calm interludes range from one to two months to five to ten years and are usually correlated with fumarolic activity. The eruptions are diverse and can be classified with different types (Vulcano, Strombolian, or sub-Plinian) but often switch from one type to another. The Vulcano type is specific to weak and moderately powerful eruptions, when ash without hot fragments is ejected in the crater. The Strombolian type is characteristic of more powerful eruptions with lava fountains, sheaf-shaped ejections of incandescent bombs, and outpouring lava flows. Extremely powerful (paroxysmal) eruptions are very rare and can be classified with the sub-Plinian type, when a thick eruption column arises for a height of about 10 km above the volcano, and ash covers are as long as several dozen kilometers.

Lava flows of terminal (summit) eruptions do not extend beyond the central cone and usually do not descend lower than the elevation of 3000 m. The structure of the summit crater depends on the character of the eruptive activity. Eruptions of the Strombolian and Volcano types fill the terminal crater and lead to the growth of a cinder cone in it, which can rise higher than the brim of the main crater, and the summit of the volcano becomes acute in shape. Sub-Plinian eruptions destroy, completely or partly, the inner cinder cone. Deep collapse fault scarps form during pauses between eruptions, which are caused by the descent of the magma column.

Adventive fissures were observed within the northeastern, eastern, southeastern, southern, and southwestern sectors of the volcano (Fig. 1). The elevations of lava exposures vary from 450 to 4400 m, with the fissures generally following radial fractures. Single eruption centers are more rare, and multivent adventive fissures were detected only twice. Lava flows from adventive fissures range from 1.3 to 11.2 km in length and from 2 to 25 m in thickness. The number of craters developing during a single auxiliary eruption varies from one to ten. The briefest eruption lasted for seven days, and the longest one was 1.5 years. Some adventive eruptions were attended by strong explosive activity, which produced cinder cones from a few dozen meters to 200 m high. Sometimes, cinder cones did not develop at all, and only lava flows were erupted. The most widespread lavas have a blocky fragmented surface (aa lava), whereas ropy lava (pahoehoe) is very rare. We estimated the overall volume of the lava flows produced by adventive eruptions since 1932 at ~1 km^3.

As numerical simulations indicate, dikes separated from the main conduit that fed auxiliary eruptions when the excess magma pressure reached 100–200 bar; such conditions can be expected to occur from a height of ~3 km within the volcanic edifice to a depth of ~25 km, mainly within the range from 1–2 km in the edifice to a depth of 10–12 km (Fedotov, 1993). It was determined that dikes form shortly before eruptions and stopped developing shortly after them (Fedotov, 1976).

Bezymyannyi Volcano

Bezymyannyi volcano started to form 10 000–11 000 years ago, when the pre-Bezymyannyi volcano appeared on the southern slope of the older Kamen' volcano. Preserved relics of its edifice consist of coarse-grained agglomerate tuff intercalating with scarce lava flows (Bogoyavlenskaya *et al.*, 1991). The pre-Bezymyannyi volcano was active for 3000–4000 years, and the subsequent hiatus lasted for approximately 3000 years. The second period of its activity began about 5–5.5 thousand years ago. Young Bezymyannyi volcano is now a typical stratovolcano, which consists, in addition to thick pyroclastic layers, of lava flows. Morphologically, it is a complex massif somewhat elongated westward with an absolute height of 2900 m (Fig. 1). Its summit is an oval crater 1.3 by 2.8 km, whose central part is occupied by a volcanic dome.

Volcanic flows that armor the slopes range from 500 to 2000 m in length at a width of a few hundred meters and a thickness of 10–30 m. Periodical catastrophic explosive eruptions produced thick pyroclastic flows, whose overall volume attains ~0.35 km^3. Twelve volcanic domes are situated near the base and on the slopes of the volcano in its southern sector. In terms of age, they are classified into two groups: domes that formed before the origin of the main volcano (15–20 thousand years ago) and younger domes, which were emplaced simultaneously with the development of the "young" Bezymyannyi volcano. The height of the domes varies from 10–15 to 280 m (Bogoyavlenskaya *et al.*, 1991).

Over historic time, from the discovery of Kamchatka in 1697 to the middle of the XX century, Bezymyannyi volcano was considered dormant. Its new eruptive cycle began in late 1955 and has continued to the present. The cycle can be classified into three periods: (I) explosive, (II) a period of a paroxysmal explosion, and (III) a period when the volcanic dome developed (Gorshkov and Bogoyavlenskaya, 1965).

Period I (from October 22, 1955, to March 29, 1956). The activity of the volcano in October–November 1955 was highly explosive. A thick gas–cinder column was almost continuously ascending from the crater to a height from 0.5 to 4 km. Ash falls were detected within several hundred kilometers around the volcano. Then, from December of that year until the end of the period, the eruptive activity became gradually weaker. The gas–ash activity above the crater was more sluggish, with volcanic material ejected to a height of no more than 1–1.5 km and less active ash falls. Simultaneously, a volcanic dome began to develop. This process was accompanied by the surge eruptions. The total volume of volcanic products of this stage was estimated at 0.4–0.5 km^3.

Period II (till March 30, 1956). The period lasted for only a few hours. A pin-point explosion destroyed the summit of the volcano, and its absolute height decreased from 3085 to 2900 m. As a result, an ellipsoidal crater almost 3 km across, 700 m deep, and breached in its eastern part originated at the summit. Voluminous pyroclastic flows poured through the breach and filled river valleys within the range up to 18 km from the volcano. An eruption cloud arose for a height of 35 km above the crater, and an ash blanket formed 50 km wide and up to 400 km long. The vast masses of ejected hot material caused active snow melting on the slopes of the volcano and the development of lahars, which extended, crushing woods crossing their path, for about 80 km up to the Kamchatka River. The overall volume of the ejected material was about 3 km^3.

Period III (from April, 1956 to the present time). The period is characterized by the development of the large Novyi volcanic dome (Alidibirov *et al.,* 1988; Belousov *et al.,* 1996; Bogoyavlenskaya and Kirsanov, 1981; Ozerov *et al.,* 1996b). During this period, one or two eruptions occurred yearly in the form of fresh blocks of viscous lava that were squeezed from the dome. As a result, the dome has attained a height of about 1.5 km and become ~2–2.5 km in diameter during the 40-year period of its evolution. The dome growth was associated with explosive activity, and pyroclastic flows descended along the volcano slopes during stronger eruptions. Flows of different age vary from 2 to 12 km in length. Over recent decades, short (no more than a few hundred meters long) lava flows were poured from the upper part of the dome.

Conclusions. Analysis of papers dealing with the activity of Bezymyannyi and Klyuchevskoi volcanoes and our own observations led us to conclude that there was no simultaneous activation of their eruptive processes. Even paroxysmal eruptions of one of them did not affect significantly the activity of the other. For example, the period of time from 1955 till 1963 was one of the most active for Bezymyannyi volcano and included the paroxysmal eruption of March 30, 1956. However, no notable changes in eruptive activity were detected at Klyuchevskoi volcano (Gorshkov and Bogoyavlenskaya, 1965). In turn, neither the activation of these processes at Klyuchevskoi volcano in 1994 nor the paroxysmal eruption on October 1 correlated with any enhancement of the activity at Bezymyannyi, which was then characterized by only weak fumarolic jets (Ozerov *et al.,* 1996b).

The main cause of these differences in the eruptive activities of Klyuchevskoi and Bezymyannyi volcanoes seems to be related to the compositional differences and the conditions of the evolution and delivery of differentiation products into the magma feeder. We believe that highly-aluminous basalt magma fractionated isobarically in the magma conduit beneath Bezymyannyi volcano. The magma was produced by the differentiation of compositionally uniform picrite-basalt melts, which came from a depth of 40–30 km along a feeder branching from the main magma conduit of the Klyuchevskoi–Bezymyannyi system (Fig. 2). The fractionation proceeded under conditions close to water saturation and resulted in amphibole-bearing andesite and dacite magmas. The richness in volatiles and more acid composition of the differentiates were, on the one hand, favorable for paroxysmal eruptions and, on the other, were responsible for the high viscosity of the "dried" derivatives and the related development of volcanic domes at Bezymyannyi volcano.

Let us now discuss mineralogical and geochemical arguments in support of our concept of genetic links between the basalts and andesites of Klyuchevskoi and Bezymyannyi volcanoes.

COMPOSITIONAL EVOLUTION OF ROCKS AND MINERALS

To carry out a comparative analysis of the chemical features of the igneous rocks, we used data newly obtained on the geochemistry of 13 basalt varieties of Klyuchevskoi volcano (8 adventive eruptions over the period of time from 1945 to 1988, 1 summit eruption in 1993, and 3 ancient fissures that produced magnesian basalt) and 11 andesite varieties from Bezymyannyi volcano (8 eruptions in 1956–1991 and 1 ancient eruption with an age of ~1000 years).[3] The analytical studies were performed at the geochemical laboratory of the Technological Institute of New Mexico in Socorro, New Mexico. Major oxides were determined by XRF in samples obtained by fusing analytical charges with lithium borate. Rare and trace elements were analyzed by INNA and XRF techniques (Hallet and Kyle, 1993).

Normative Composition and Crystallization Order

A general idea of the chemistry of the associations in question can be obtained from Table 1, which lists averaged analyses of the principal basalt groups (recognized on the basis of their major-element composition) from Klyuchevskoi volcano (Ariskin *et al.,* 1995) and a series of lavas from Bezymyannyi volcano (Bogoyavlenskaya *et al.,* 1991).

As follows from these data, Klyuchevskoi volcano is characterized by a monotonous transition from highly magnesian to highly-aluminous basalts with a systematic increase in the contents of SiO_2, TiO_2, Al_2O_3, Na_2O, K_2O, and P_2O_5 and a decrease in the concentrations of MgO and CaO. The FeO contents remain at approximately the same level (Khrenov *et al.,* 1991; Ozerov and Khubunaya, 1992), and hence, the magnesium numbers of the rocks, MGN = Mg/(Mg + Fe) decrease monotonically from 0.7 in the high-Mg basalt to 0.5 in the most aluminous compositions. These chemical features are correlated with changes in the normative composition of the rocks: an increase in the contents of the plagioclase components and a decrease in the contents of olivine and diopside (Table 1). The

[3] Most samples are from the collection of the authors, three samples of magnesian basalt from Klyuchevskoi volcano were provided by the courtesy of S.A. Khubunaya of the Institute of Volcanology, Far East Division, Russian Academy of Sciences.

latter observation is indicative of that the series of Klyuchevskoi lavas could evolve by means of olivine and clinopyroxene fractionation at a subordinate role of plagioclase settling.

This conclusion finds support in the mineralogy of the Klyuchevskoi basalts. These are usually porphyritic rocks with abundant phenocrysts and glomeroporphyric aggregates (up to 10 mm across) of olivine and clinopyroxene. Their amount decreases in more aluminous varieties, which systematically contain plagioclase grains (they are also sometimes present in the magnesian basalts). Orthopyroxene is rare: occasional grains, sometimes in aggregates with plagioclase and clinopyroxene, were detected only in the aluminous and highly aluminous basalts. Microprobe studies reveal orthopyroxene inclusions in the olivine and clinopyroxene (Ozerov, 1993; Khubunaya *et al.,* 1993). Chromium-rich spinel (picotite) was also detected in the form of tiny inclusions in the olivine, in particular, in this mineral in ancient flows of highly magnesian basalt. The highly-aluminous basalt commonly contains fine titanomagnetite dust.

Detailed microprobe studies of mineral assemblages in the Klyuchevskoi basalts allowed us to establish the general evolutionary sequence of minerals during the fractionation of the hypothetical parental magma (Ariskin *et al.,* 1995; Ozerov *et al.,* 1996a):

$$\begin{gathered} Ol(Fo_{90-92}) + Aug(MGN_{89-91}) \pm Sp(CRN_{70-72}) \\ \longrightarrow Ol(Fo_{87-88}) + Aug(MGN_{86-87}) \\ \pm Opx(MGN_{88-89}) \longrightarrow Sp(CRN_{65-70}) \\ \longrightarrow Ol(Fo_{75-77}) + Aug(MGN_{79-80}) \\ + Opx(MGN_{78-79}) + Sp(CRN_{20-30}) + Pl(An_{65-77}), \end{gathered}$$

where $CRN = Cr/(Cr + Al + Fe^{3+})$, and the ± sign refers to the situation when minerals do not form cotectic aggregates and are identified only as inclusions. The most important feature of these relationships is the high magnesium number of the initial assemblage of clinopyroxene (MGN = 87–91) and olivine (MGN = 88–92). Grains of these highly magnesian minerals were encountered not only in the most magnesian basalts (Khubunaya *et al.,* 1993) but also in the highly aluminous rocks (Ozerov, 1993). Comparing the compositions of coexisting olivine and augite from the Klyuchevskoi basalts with those synthesized in experiments on the melting of natural samples, we arrived at the conclusion that the assemblage crystallized at high pressures (more than 15 kbar; Ariskin *et al.,* 1995).

Analysis of the average compositions of the Bezymyannyi lavas (Table 1) indicates that this association is characterized by a strong enrichment in SiO_2 at insignificant variations in Al_2O_3 contents and Mg-numbers. The MgO and CaO contents continue decreasing but, unlike the Klyuchevskoi basalts, in which a moderate enrichment in TiO_2 contents at a constant FeO concentrations is observed, the Bezymyannyi basalts are depleted in these components. This is reflected in variations in the normative composition: the rocks become quartz-normative, and the contents of plagioclase components decrease (because of an increase in the contents of orthoclase and albite and a decrease in the content of anorthite) from the basaltic andesite to dacite, whereas the abundances of diopside, hypersthene, and ilmenite decrease monotonically.

Such relationships provide evidence for the important role of magnetite crystallization, which was favorable for the transition from olivine-normative to quartz-normative compositions; widespread magnetite phenocrysts in the Bezymyannyi lavas confirm that this process was quite feasible (Kadik *et al.,* 1986). However, the minerals crystallizing in the melts were dominated by plagioclase and Fe–Mg silicates such as clinopyroxene, orthopyroxene, and hornblende. The Bezymyannyi andesite can be classified into three principal mineralogical types: two-pyroxene andesite, hornblende–pyroxene andesite, and hornblende andesite (Gorshkov and Bogoyavlenskaya, 1965; Timerbaeva, 1967). The absence of data on the composition of coexisting minerals and mineral inclusions in these rocks does not allow us to reconstruct in detail the crystallization order during the fractionation, as we managed to do for mineral assemblages in the Klyuchevskoi lavas (Ariskin *et al.,* 1995; Ozerov *et al.,* 1996a).

Nevertheless, geological observations demonstrated that the same evolutionary pattern of the composition pervasively occurs within every eruption cycle throughout the history of Bezymyannyi volcano: the most acid hornblende andesites (up to dacite) formed during the initial stages of eruptions and gave way to pyroxene–hornblende and two-pyroxene andesites during the closing stages. This regularity and reaction textures with clino- and orthopyroxene replaced by hornblende (observed in thin sections) led scientists to conclude that, in the andesite–dacite evolutionary sequence, the amphibole-bearing rocks are the lowest temperature and the most evolved derivatives, and the two-pyroxene andesite is the least differentiated, "relatively primitive" material (Kadik *et al.,* 1986).

Comparison between Major-Element Trends

The average compositions of the above-mentioned major-element rock groups listed in Table 1 are portrayed in classification diagrams SiO_2–FeO/MgO (Miyashiro, 1974) and ($Na_2O + K_2O$)–FeO–MgO (Irvine and Baragar, 1971) (Fig. 3). Apparently, the Klyuchevskoi basalts and the basaltic andesite–dacite association of Bezymyannyi volcano are plotted in the field of typical calc–alkaline series, with the relationships between the trends not contradicting the idea that both of the "reduced" (Frolova *et al.,* 1985) series are members of a single genetic rock sequence derived from the same source.

This hypothesis is also supported by data presented in the diagrams of Fig. 4, in which variations of major

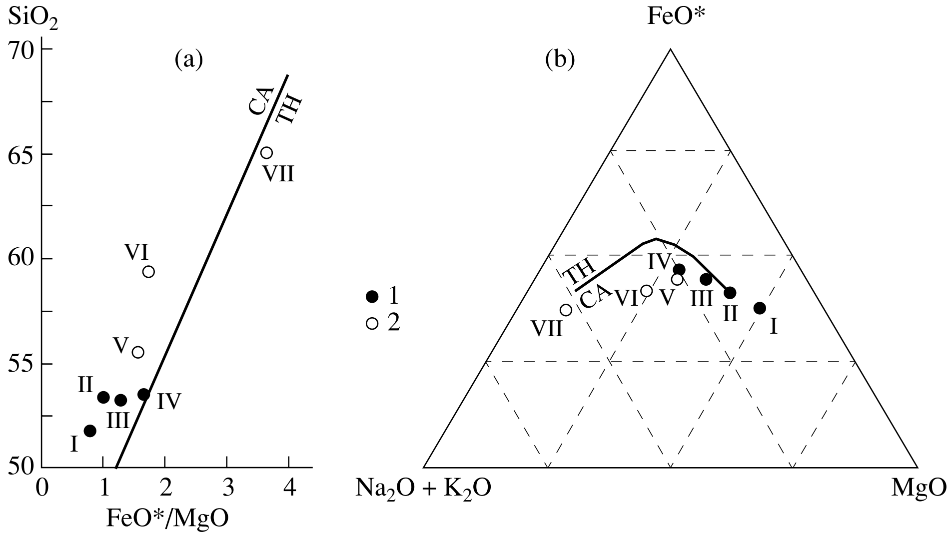

Fig. 3. Discriminant diagram to distinguish between rocks of the tholeiitic (TH) and calc-alkaline (CA) series.
(a) After Miyashiro (1974); (b) after Irvine and Baragar (1971). Roman numbers present the average compositions of the petrochemical types given in Table 1. (1) Klyuchevskoi volcano; (2) Bezymyannyi volcano.

components are shown as functions of the MgO and SiO_2 contents (the initial compositions are presented in Tables 2 and 3). Diagrams in terms of these two components accentuate petrochemical similarities between the associations (see the trends of Na_2O, K_2O, and CaO) and illustrate the different directions of trends caused by changes in the assemblages of settling minerals (see trends of Al_2O_3 , FeO, and TiO_2). In particular, the termination of enrichment in Al_2O_3 or a small decrease in its concentration is natural to relate to the onset of plagioclase fractionation after the long-lasting crystallization of mafic silicates (Ariskin *et al.*, 1995). A strong decrease in the contents of FeO and TiO_2 implies that magnetite began to be fractionated in the system nearly simultaneously with plagioclase crystallization. However, the diagrams do not allow us to distinguish between the consequences of pyroxene or amphibole fractionation.

Evolution of Trace-Element Contents

Although the relationships between major-element trends of the Klyuchevskoi and Bezymyannyi lavas are compatible with the concept of a single genetic sequence and do not contradict the idea of different fractionation regimes in the magma feeders of the volcanoes, genetic links between the volcanics can be established more reliably by using additional data on the minor-element composition of the rocks.

Diagrams showing the evolution of the contents of the most incompatible elements such as Rb, Cs, and Th as functions of the MgO and SiO_2 contents are presented in Fig. 5. As follows from these plots, the minor-element evolutionary trends for the Bezymyannyi andesites definitely inherit some regularities in the evolution of incompatible elements in the Klyuchevskoi lavas. It should be stressed that these elements show an enrichment by a factor of approximately three with transition from the high-Mg basalts of Klyuchevskoi volcano to the andesites of Bezymyannyi volcano. This means that the latter rocks could be produced by the ~70% fractionation of the high-Mg magma, and the content of any incompatible element can be used as an indicator of the fractionation degree of the initial magmatic melt.

Figure 6 illustrates the evolution of the Sc, Cr, Ba, Zn, La, and Yb contents as functions of the Th concentrations. These trends are also quite consistent with the concept of crystal fractionation: the behavior of Sc is definitely controlled by clinopyroxene crystallization, the contents of Cr are determined by clinopyroxene and spinellid, the trend of Ba enrichment terminates with the onset of plagioclase crystallization, and the transition from Zn enrichment to depletion in this element can be accounted for by magnetite fractionation [see the review of experimental results on crystal–melt partition coefficients presented by Green (1994)]. La is one of LREEs, which do not behave as “ideally incompatible” elements. The maximum coefficient of La enrichment for the andesite–basalt pair is no higher than 2.5 (Tables 2, 3). An even lower enrichment degree was determined for Yb: the contents of this element first somewhat increase from the high-Mg to high-Al basalts and then decreases again with the transition to the andesites (Fig. 6). These facts are generally consistent with data available on the partition coefficients of HREEs between pyroxenes, amphiboles, and basaltic andesite melt (Green, 1994).

Concluding the discussion of the minor-element relationships, it should be stressed that, when speaking

Table 1. Chemical (wt %) and CIPW normative compositions of the main petrochemical types of lavas from Klyuchevskoi and Bezymyannyi volcanoes

Component	Klyuchevskoi				High-Al basalt	Bezymyannyi		
	I	II	III	IV		V	VI	VII
	15*	46	50	131		29	50	4
SiO_2	51.76	53.39	53.22	53.50	53.23	55.66	59.51	65.14
TiO_2	0.86	0.84	0.95	1.09	1.13	0.74	0.60	0.51
Al_2O_3	13.86	15.29	16.79	18.26	18.16	18.06	17.79	18.25
FeO*	8.83	8.52	8.83	8.67	9.10	7.55	6.18	4.02
MnO	0.17	0.17	0.17	0.16	0.15	0.15	0.13	0.13
MgO	11.55	8.58	6.89	5.24	5.29	4.90	3.58	1.10
CaO	9.73	9.41	8.91	8.22	8.14	8.26	6.96	5.17
Na_2O	2.47	2.72	3.11	3.45	3.65	3.18	3.51	4.00
K_2O	0.63	0.90	0.96	1.20	0.93	1.26	1.51	1.68
P_2O_5	0.15	0.18	0.18	0.20	0.22	0.23	0.23	–
Mg/(Mg + Fe)	0.700	0.642	0.582	0.509	0.509	0.537	0.508	0.328
Ca/(Ca + Al)	0.390	0.359	0.325	0.290	0.290	0.294	0.262	0.205
CIPW, wt %								
Qzt	–	–	–	–	–	3.88	9.90	19.63
Or	3.72	5.32	5.67	7.09	5.50	7.46	8.95	9.95
Ab	20.90	23.01	26.31	29.19	30.88	26.89	29.69	33.83
An	24.88	26.86	29.02	30.80	30.40	31.25	28.29	25.65
Di	18.18	15.24	11.54	7.20	7.09	6.81	3.93	–
Hy	17.93	25.04	21.96	21.15	19.71	21.70	17.52	9.51
Ol	12.42	2.52	3.28	2.02	3.70	–	–	–
Ilm	1.63	1.60	1.80	2.07	2.15	1.41	1.14	0.97
Ap	0.36	0.43	0.43	0.47	0.48	0.50	0.50	–

Note: Analyses of the petrochemical types are recalculated to anhydrous basis, Fe was not recalculated to FeO and Fe_2O_3. Petrochemical types: (I) highly-magnesian basalt, (II) magnesian basalt, (III) aluminous basalt, (IV) highly-aluminous basalt (Ariskin *et al*., 1995), (V) basaltic andesite, (VI) andesite, (VII) dacite (Bogoyavlenskaya *et al*., 1991). The high-Al basalt represents the composition of a model derivative for P = 7 kbar, T = 1110°C, and 3.0 wt % H_2O in the melt after the 36% decompressional fractionation of the parental high-Mg magma (Ariskin *et al*., 1995).

* Number of analyses.

about “the initial magma,” “a common genetic sequence,” “major-element series,” “fractionation degree,” etc., we do not assume by any means that rocks of Klyuchevskoi and Bezymyannyi volcanoes were produced by the same source magma. Using these terms, we only mean that high-Mg melts of relatively constant composition were generated for a geologically long period of time in a mantle chamber zone below Klyuchevskoi and Bezymyannyi volcanoes. During the early stage of their evolution, the melts were affected by similar fractionation processes, and the resultant derivatives inherited certain minor-element signatures of the common source.

Isotopic Relationships between Pb, Nd, and Sr

Isotopic data provide information important for establishing possible genetic links between rocks. The first work dealing with this aspect of the Klyuchevskoi basalts was the paper by Kersting and Arculus (1995). No such data are now available on the andesites of Bezymyannyi volcano.

Kersting and Arculus were the first to obtain data on the Pb isotopic composition of the Klyuchevskoi basalts. Analyzing the $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ ratios, they concluded that the Klyuchevskoi lavas consist of isotopically homogeneous material whose geochemical signatures are close

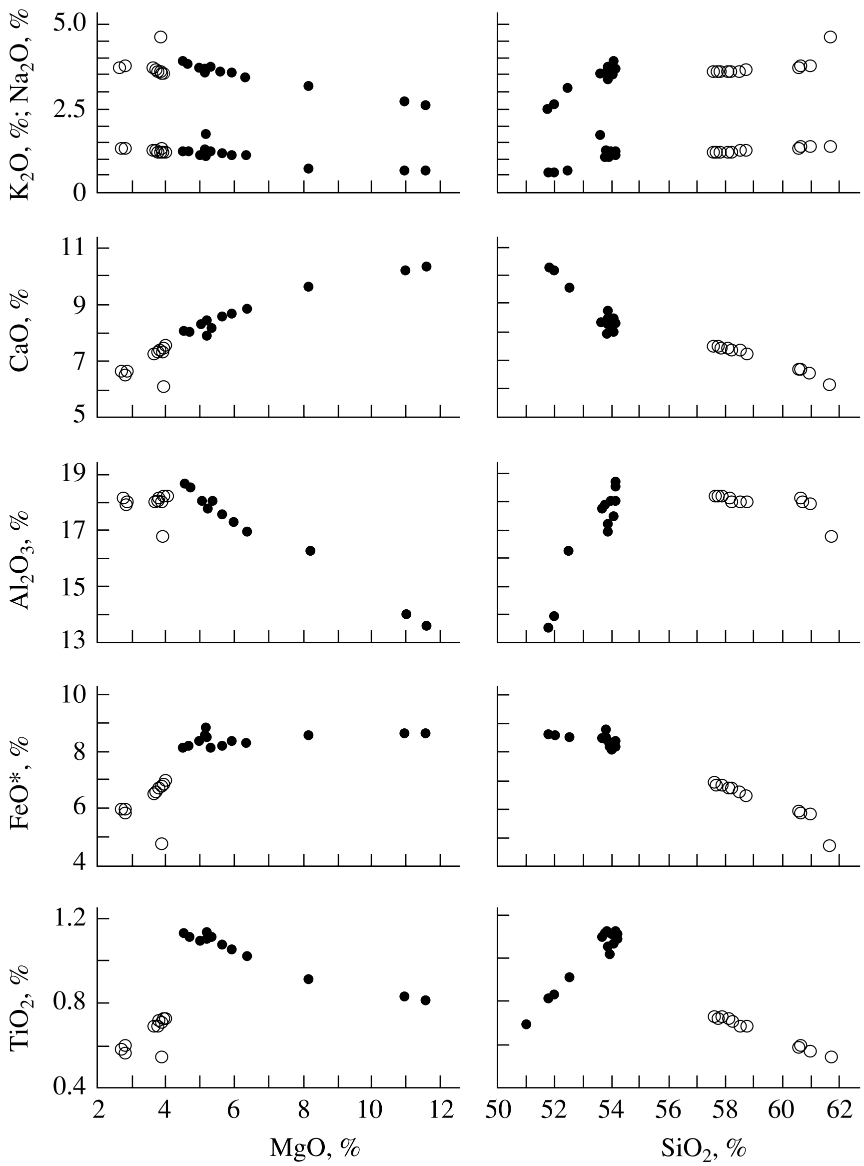

Fig. 4. Major-element variation diagrams. See Fig. 3 for symbol explanations.

to those of the Pacific MORBs (Kersting and Arculus, 1995). No evidence was gleaned that the magma source could involve some material identical to sediments from the North Pacific Ocean. Another important conclusion, which followed from the lead isotopic ratios, was that the magnesian and aluminous basalts of Klyuchevskoi volcano do compose a continuous genetic sequence produced from a single source.

This conclusion is also supported by the Nd and Sr isotopic ratios (Kersting and Arculus, 1995). For example, the fairly narrow range of ε_{Nd} from +8.1 to +9.3 overlaps the compositional field of Pacific MORB (Table 4). At the same time, $^{87}Sr/^{86}Sr$ = 0.70354–0.70369 is somewhat higher than usual, and the compositional field of the Klyuchevskoi basalts is slightly displaced to the right of the main mantle trend in a ε_{Nd}–ε_{Sr} plot (Fig. 7) (Faure, 1986). This feature of Kamchatkan rocks was extensively discussed in the literature (Kersting and Arculus, 1995; Tatsumi *et al.,* 1995; Volynets *et al.,* 1996).

In the context of this work, we measured, using a mass spectrometer, the Nd and Sr isotopic ratios in two samples of the high-Al Klyuchevskoi basalts (Samples KL-1, K-1956) and two andesite samples from Bezymyannyi volcano (Samples B-1987, B-1990). The chemical treatment of the samples, separation of Nd for mass-spectrometric analyses, and the isotopic analyses themselves were carried out at the Vernadsky Institute

Table 2. Major- (wt %) and trace-element (ppm) compositions of basalts of Klyuchevskoi volcano

Component	Khu-1* (1)	Khu-2 (2)	Khu-3 (3)	K-1945 (4)	K-1946 (5)	K-1951 (6)	K-1953 (7)	K-1956 (8)	K-1966 (9)	K-1983 (10)	K-1988 (11)	K-1993 (12)	KL-1 (13)
SiO_2	51.78	51.99	52.49	53.88	54.04	53.96	54.01	54.08	53.87	53.61	53.75	54.12	53.79
TiO_2	0.81	0.83	0.91	1.02	1.07	1.11	1.11	1.13	1.05	1.10	1.12	1.09	1.13
Al_2O_3	13.58	13.96	16.26	16.96	17.52	18.04	18.55	18.65	17.27	17.75	17.93	18.03	17.93
FeO*	8.61	8.58	8.51	8.24	8.19	8.13	8.19	8.16	8.32	8.47	8.59	8.40	8.81
MnO	0.17	0.17	0.16	0.16	0.17	0.15	0.15	0.15	0.16	0.16	0.17	0.17	0.16
MgO	11.60	10.98	8.16	6.33	5.62	5.31	4.65	4.52	5.91	5.17	5.15	4.98	5.17
CaO	10.29	10.18	9.60	8.78	8.52	8.20	8.00	8.05	8.64	8.33	8.44	8.27	7.90
Na_2O	2.49	2.60	3.11	3.37	3.55	3.70	3.82	3.86	3.52	3.54	3.60	3.67	3.65
K_2O	0.55	0.59	0.66	1.07	1.12	1.20	1.20	1.20	1.07	1.70	1.07	1.09	1.22
P_2O_5	0.12	0.12	0.13	0.19	0.20	0.21	0.21	0.21	0.19	0.19	0.19	0.19	0.23
Cr	810	751	259	109	60	53	19	20	120	41	27	25	54
Sc	37.7	36.9	32.9	30.4	28.9	24.4	23.9	23.9	29.0	27.3	27.9	26.8	30
Zn	66	68	79	92	78	95	91	86	98	88	91	85	–
Ba	193	234	249	326	362	427	401	396	404	451	392	383	450
Rb	10.0	9.8	10.0	12.6	20.0	18.5	15.7	17.1	14.9	17.5	10.6	16.8	16
Cs	0.31	0.30	0.27	0.48	0.49	0.55	0.57	0.55	0.52	0.55	0.48	0.49	–
Hf	1.8	2.0	2.0	2.5	2.6	2.9	2.8	2.8	2.7	2.8	2.7	2.7	–
Ta	0.35	0.44	0.56	0.44	0.65	0.64	0.51	0.85	0.61	0.53	0.56	0.53	–
Th	0.37	0.38	0.37	0.67	0.67	0.72	0.80	0.70	0.60	0.71	0.73	0.70	–
U	0.16	0.21	0.18	0.47	0.38	0.46	0.40	0.53	0.21	0.64	0.39	0.32	–
La	4.0	4.3	5.0	6.6	6.9	7.5	7.5	7.4	7.0	7.3	7.1	7.4	9.0
Ce	11.0	10.9	13.3	17.1	17.5	18.5	18.5	18.0	17.5	17.6	17.4	17.3	17.9
Sm	2.6	2.6	2.8	3.4	3.5	3.6	3.7	3.8	3.6	3.7	3.7	3.7	3.8
Eu	0.83	0.87	0.96	1.10	1.14	1.17	1.18	1.20	1.16	1.18	1.19	1.18	1.27
Tb	0.46	0.50	0.50	0.58	0.63	0.63	0.65	0.62	0.61	0.66	0.64	0.64	–
Yb	1.8	1.9	1.9	2.0	2.1	2.2	2.3	2.2	2.3	2.4	2.4	2.4	2.6

Note: Analyses 1–3 are highly-magnesian and magnesian basalts (samples from the collection of S.A. Khubunaya); the numbers of samples listed as analyses 4–12 correspond to the years of eruption; analysis 13 (Sample KL-1) is highly-aluminous basalt from the Piip Fissure (eruption of 1966). The contents of major elements are recalculated to anhydrous basis. The first 12 samples were analyzed at the geochemical laboratory of the Technological Institute of New Mexico in Socorro, New Mexico: major elements were analyzed by XRF; trace elements were determined by neutron activation and XRF. Sample KL-1 was analyzed at the Central Analytical Laboratory of the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences (Ariskin *et al.*, 1995): major elements were analyzed by XRF, Ba was determined by ICP, Cr was determined by atomic absorption, Rb was analyzed by flame photometry, and REEs and Sc were determined by neutron activation.

* Sample number.

of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, on a modified TSN 206SA spectrometer equipped with a three-filament ion source (Karpenko *et al.*, 1984). The isotopic ratios measured in the samples were normalized to $^{150}Nd/^{142}Nd$ = 0.209627 at the assumed CHUR $^{143}Nd/^{144}Nd$ ratio of 0.511847 (Wasserburg *et al.*, 1981).

Our data are summarized in Table 4 and Fig. 7. Apparently, in spite of certain differences in the techniques (see caption to Table 4 for details) and taking into account the analytical uncertainties of the order of ±1 for ε_{Nd} and ±2 for ε_{Sr}, the isotopic compositions of the Klyuchevskoi basalts and Bezymyannyi andesites cluster within a fairly compact field in an $\varepsilon_{Nd}-\varepsilon_{Sr}$ plot (Fig. 7). This can be interpreted as another argument for genetic relations between volcanic rocks erupted from the two volcanic centers. The somewhat higher $^{87}Sr/^{86}Sr$ ratio of the Bezymyannyi andesite (Sample B-1990)

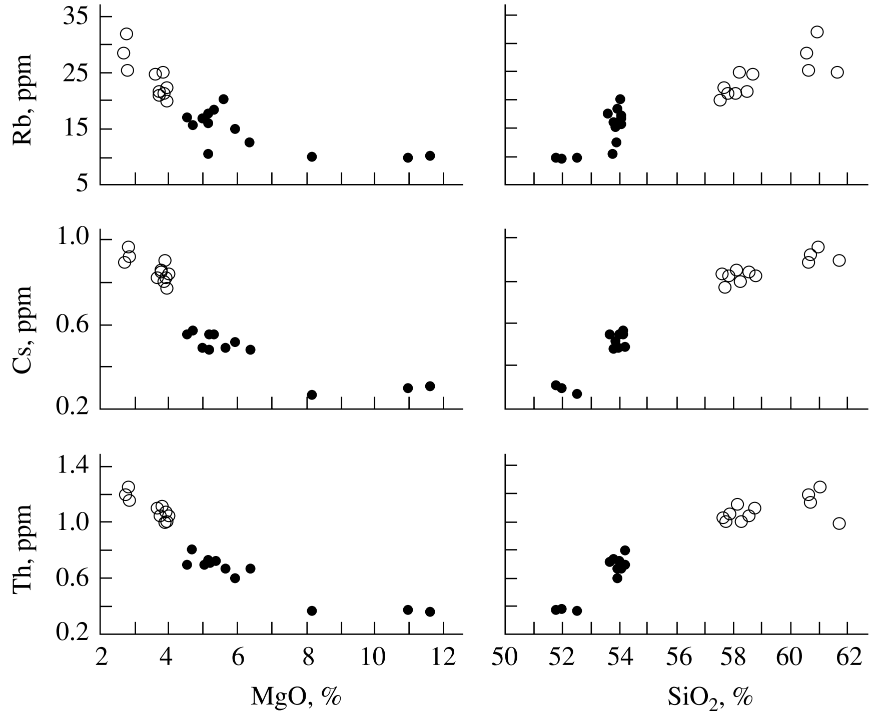

Fig. 5. Concentrations of incompatible elements as functions of MgO and SiO_2 contents. Symbols are the same as in Fig. 3.

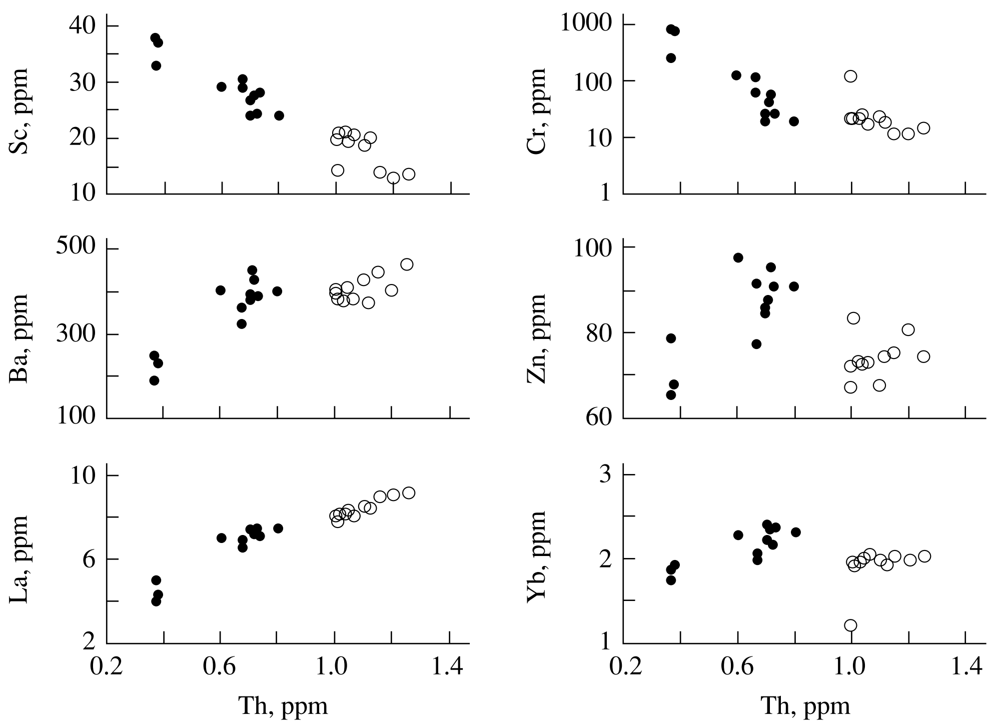

Fig. 6. Concentrations of trace elements as functions of Th contents. Symbols are the same as in Fig. 3.

can be accounted for by additional Sr input in the magmatic system owing to the partial assimilation of crustal rocks (the wall rocks of the magma feeder). However, we believe that this effect is not significant enough to topple the hypothesis of a single magmatic source of the Klyuchevskoi and Bezymyannyi volcanoes. Of course, this problem calls for further studies of the isotopic compositions of the rocks.

Table 3. Major- (wt %) and trace-element (ppm) compositions of andesites of Bezymyannyi volcano

Component	B-1956[1]	B-1956[2]	B-1977	B-1981	B-1986	B-1987	B-1989[1]	B-1989[2]	B-1990	B-1991	B-0000
SiO_2	60.97	60.66	58.74	58.51	58.22	60.59	57.70	57.57	57.83	58.09	61.71
TiO_2	0.57	0.60	0.69	0.69	0.71	0.59	0.72	0.73	0.73	0.72	0.55
Al_2O_3	17.93	18.05	18.01	18.05	18.00	18.16	18.21	18.22	18.19	18.17	16.81
FeO*	5.82	5.88	6.51	6.61	6.77	5.93	6.85	6.93	6.85	6.76	4.76
MnO	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.10
MgO	2.79	2.81	3.64	3.72	3.85	2.69	3.95	3.96	3.90	3.77	3.86
CaO	6.53	6.65	7.24	7.32	7.36	6.69	7.55	7.55	7.46	7.44	6.11
Na_2O	3.75	3.74	3.66	3.60	3.58	3.72	3.53	3.55	3.55	3.55	4.61
K_2O	1.32	1.30	1.22	1.21	1.20	1.29	1.18	1.17	1.19	1.20	1.32
P_2O_5	0.17	0.17	0.16	0.16	0.16	0.18	0.16	0.16	0.16	0.16	0.16
Cr	15	11	23	24	21	12	21	21	18	18	112
Sc	13.8	13.9	18.8	19.4	19.9	13.0	20.9	21.2	20.5	20.0	14.4
Zn	75	76	68	73	72	81	84	74	73	75	67
Ba	464	445	426	408	405	402	385	380	385	375	397
Rb	32.0	25.4	24.6	21.6	24.9	28.2	22.1	19.9	21.1	21.0	24.7
Cs	0.96	0.92	0.82	0.84	0.80	0.89	0.77	0.83	0.82	0.85	0.90
Hf	3.1	3.1	2.9	2.9	2.8	3.2	2.8	2.7	2.7	2.8	2.9
Ta	0.54	0.44	0.55	0.72	0.57	0.37	0.43	0.49	0.40	0.41	0.69
Th	1.25	1.15	1.10	1.04	1.00	1.20	1.01	1.03	1.06	1.12	1.00
U	0.94	0.86	0.70	0.86	0.81	0.92	0.83	0.83	0.56	0.77	0.80
La	9.2	9.0	8.5	8.3	8.1	9.1	8.1	8.2	8.1	8.4	7.8
Ce	20.9	20.7	19.2	19.7	19.3	21.0	18.5	18.2	18.6	19.0	18.5
Sm	3.2	3.2	3.1	3.1	3.1	3.2	3.1	3.1	3.1	3.1	2.7
Eu	1.00	0.99	0.99	1.01	0.98	1.02	0.97	0.97	0.96	0.97	0.81
Tb	0.52	0.50	0.50	0.53	0.54	0.50	0.53	0.50	0.51	0.48	0.35
Yb	2.0	2.0	2.0	2.0	2.0	2.0	1.9	2.0	2.1	1.9	1.2

Note: Numerals in sample numbers correspond to eruption years (superscript indices mark samples from the same flows). Sample B-0000 is andesite of an ancient eruption. The contents of major elements are recalculated to anhydrous basis. Samples were analyzed at the geochemical laboratory of the New Mexico Technological Institute in Socorro. New Mexico: major elements were analyzed by XRF; trace elements were determined by neutron activation and XRF.

Table 4. Nd and Sr isotopic ratios in lavas of Klyuchevskoi and Bezymyannyi volcanoes

Source	Sample numbers	SiO_2	MgO	Al_2O_3	Nd, ppm	$^{143}Nd/^{144}Nd$	ε_{Nd}	Sr, ppm	$^{87}Sr/^{86}Sr$	ε_{Sr}
(Kersting and Arculus, 1994, 1995)	K-21	52.27	8.88	14.27	15	0.513065	8.33	342	0.703543	–17.1
	K-51	52.29	6.26	26.72	10	0.513100	9.01	338	0.703543	–17.1
	K-256	53.01	7.05	15.68	16	0.513113	9.27	359	0.703632	–15.9
	K-5911	52.22	7.96	14.94	4	0.513055	8.13	334	0.703576	–16.7
	K-AXO3	52.85	5.07	17.25	10	0.513070	8.43	368	0.703689	–15.1
This paper	KL-1	53.79	5.17	17.93	11.8	0.51234	9.6	380	0.70334	–16.5
	K-1956	54.08	4.52	18.65	–	0.51235	9.8	–	0.70345	–14.9
	B-1987	60.59	2.69	18.16	–	0.51236	10.0	–	0.70343	–15.2
	B-1990	57.83	3.90	18.19	–	0.51228	8.5	–	0.70363	–12.3

Note: Samples with K and KL letters in their numbers are from Klyuchevskoi volcano; samples with the letter B are from Bezymyannyi volcano. The measured isotopic ratios are normalized to $^{146}Nd/^{144}Nd = 0.7219$ (Kersting and Arculus, 1995) and $^{150}Nd/^{142}Nd = 0.209627$ (this paper).

Table 5. Model for the evolution of the magma-generating and feeding system of the Klyuchevskoi and Bezymyannyi volcanic system

Depth, km	Main magma-generating processes (description and comments)	Conditions		Magma composition, wt %				Liquidus minerals				
		P, kbar	*T*, °C	SiO_2	MgO	Al_2O_3	H_2O	*Ol*	*Cpx*	*Opx*	*Pl*	*Sp*
150–30	**Common magmatic system**											
150–60	Zone of generation of the initial high-Mg magmas (horizontal size of the system was several dozen kilometers; water was possibly present in small amounts).	~50 ↓	>1400 ↓	~ 50 ↓	>12 ↓	<13 ↓	<2 ? ↓	*Fo*92 ↓	?	?	–	?
60–40	Primary melts ascended along the conduit and fractionated under decompression to produce less magnesian derivatives (the diameter of the magma column was ~1 km).	20 ↓	1350 ↓	51.8 ↓	11.6 ↓	13.9 ↓	~2.0 ↓	*Fo*90 ↓	+	–	–	+
40–30	Initial separation of the first differentiation products from the magma column and further movement of the melts along the slanted conduit toward Bezymyannyi volcano. Fractionation continued simultaneously with water enrichment in the melts (the melts could mix and partly assimilate the wall rocks).	~14 ↓	1250 ↓	52.5 ↓	8.6 ↓	15.5 ↓	2.3 ↓	*Fo*87 ↓	+	+	–	+
30–…	**Origin of two magma feeding systems**											
30–20	The magma moved upward along two separate conduits about 1 km in diameter diverging at a small angle; further fractionation resulted in high-Al magma; the products of different crystallization stages could mix (reverse zoning could develop in large phenocrysts).	~10	1170	52.7	6.6	17.0	2.6	*Fo*83	+	+	+	+
				Magma became highly aluminous								
		↓	↓	↓	↓	↓	↓	↓				
20–10	**The magma feeder of the Klyuchevskoi volcano** retained its size and direction; the magma continued to be constantly squeezed upward (the system could experience stratification, with the less dense high-Al basalts accumulating in the upper part; fractionation was relatively weak; dissolved water was partly released during decompression).	~7 ↓	1110 ↓	53.3 ↓	5.2 ↓	18.3 ↓	~3 ↓	*Fo*79 ↓	+	+	+	+
20–10	**The magma feeder of Bezymyannyi volcano** changed its morphology and developed into an intermediate magma chamber approximately 10 km in height and ~6–7 km in diameter in its broadest part; accumulation of high-Al melt was accompanied by water enrichment and crystallization under conditions close to water saturation; settling of magnetite- and amphibole-bearing assemblages led to the origin of andesitic and dacitic magmas.	~7 ↓	1110 ↓	53.3 ↓	5.2 ↓	18.3 ↓	~3 ↓	*Fo*79 ↓	+	+	+	+
		3–5	????	??.?	?.?	??.?	??	??	**Amphibole appeared**			
<10	**Summit craters of volcanoes**											
10–…	The feeding conduits had a diameter of <1 km: both volcanoes discharged their products through summit craters. **The magma conduit of Klyuchevskoi volcano** served for the ascent of mainly high-Al magma, which mixed with earlier derivatives, was depleted in water, and acquired a plagioclase porphyry composition (the magma viscosity is low, but its crystallinity increased because of partial water release). More viscous andesitic magma ascended, with several pauses and hiatuses, along **the magma conduit of Bezymyannyi volcano**. Water continued escaping simultaneously with the massive settling of plagioclase phenocrysts. The lowest temperature derivatives became compositionally close to dacite and contained hornblende phenocrysts. Excess magma pressure in the conduits of both volcanoes resulted in the branching of numerous dikes, which are now pronounced as adventive fissures on the slopes of Klyuchevskoi volcano and as volcanic domes on Bezymyannyi volcano.											

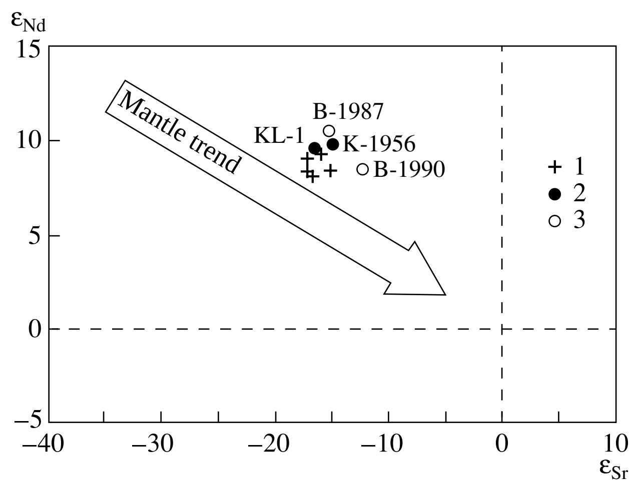

Fig. 7. Isotopic Nd and Sr ratios in lavas of Klyuchevskoi and Bezymyannyi volcanoes (Table 4).
(1) Kersting and Arculus (1995); (2) high-Al basalts of Klyuchevskoi volcano; (3) andesites of Bezymyannyi volcano.

CONCLUSION

Analysis of geological, geophysical, petrological, and geochemical data on the structure and distinctive features of magmatic processes of Klyuchevskoi and Bezumyannyi volcanoes led us to develop a model (Fig. 2, Table 5) for the deep-seated evolution and feeding system of the two volcanic centers. The petrological scheme involves three depth levels responsible for different regimes of the magmatic evolution.

(1) According to our scheme, the development of the magma-generating system of Klyuchevskoi and Bezymyannyi volcanoes over the depth interval from 150 to 30 km was governed by the same mechanism in the same mantle source. At depths from 150 to 60 km, the magma-generating processes involved the origin of initial highly magnesian melts in the presence of small amounts of water and their further fractionation under decompression conditions as the melts moved to the surface. At depths of 30–40 km, an auxiliary conduit branched out of the main magmatic column, and some of the less magnesian derivatives (basaltic melts, Table 5) were directed toward Bezymyannyi volcano along this conduit.

(2) Over the depth interval from 20 to 30 km, the magma ascended along two distinct conduits diverging at a small angle. The decompression-related magma fractionation continued, mainly by olivine and clinopyroxene settling. The process was attended by the enrichment of the melts in water, a resultant delay in plagioclase crystallization, and the enrichment of the younger derivatives in alumina (Tables 1, 5).

At depths shallower than 20 km, differentiation end-products (high-Al magmas) accumulated in the magma conduit of Klyuchevskoi volcano. The absence of a large magma chamber explains their weak fractionation: the process mainly involved the escape of volatiles and an increase in the crystallinity of the magmatic material. The conduit of Bezymyannyi volcano changes morphologically at depths of 20–10 km and becomes an extensive magma chamber. The chamber was a site of the isobaric fractionation of a water-saturated high-Al magma, a process that led to the origin of andesitic and dacitic melts.

(3) At depths less than 10 km, the feeding channels are no larger than 1 km in diameter, and the magmatic material was discharged mainly through the summit craters. The excess magma pressure caused the origin of dikes, which branched out of the magma conduits of both volcanoes. On the slopes of the volcanoes, these dikes are pronounced as adventive fissures of magnesian and aluminous basalts and as andesite volcanic domes at Bezymyannyi volcano.

Hence, the magmatic evolution of Klyuchevskoi and Bezymyannyi volcanoes proceeded in notably different geodynamic and thermodynamic conditions and resulted in two “reduced” magmatic series: a predominantly basaltic one at Klyuchevskoi volcano and a basaltic andesite–dacite series at Bezymyannyi volcano. The series developed by crystal fractionation at a subordinate role of other petrogenetic processes. According to this concept, both volcanic series compose a single genetic sequence, a peculiar geochemical system, whose source was upper mantle peridotite material and whose derivatives comprised the whole series of volcanics from mafic to acid differentiates.

Further development of the petrological–geochemical model should be aimed at refining the contributions of magnetite and amphibole crystallization to the origin of the calc-alkaline trend of the Klyuchevskoi–Bezymyannyi system. This problem can be resolved, in our opinion, by the numerical simulation of fractionation processes in basaltic magma in the presence of water with due regard for the crystallization of magnetite- and amphibole-bearing mineral assemblages (Al’meev and Ariskin, 1996). It seems to be very important to examine the compositional trends of minerals in the volcanics of Bezymyannyi volcano. This study should be based on microprobe analyses of rock-forming minerals and crystalline inclusions. New systematic studies of the isotopic compositions of volcanics in the system of Klyuchevskoi and Bezymyannyi volcanoes should be carried out.

ACKNOWLEDGMENTS

We thank G.I. Anosov (Institute of Volcanology, Far East Division, Russian Academy of Sciences) for useful comments concerning this paper and R.R. Al’meev (Moscow State University) for help in preparing the graphical materials. This work was supported by the Russian Foundation for Basic Research, projects no. 96-05-64231 and 97-05-64541 and a grant from the Ministry of Science (project “Petrology and Geochemistry of Island-Arc Magmatism of the Kuril–Kamchatka Area"). Analytical studies were carried out under a project of the National Science Foundation of the United States (grant EAR-9117815).

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