ISSN 0742-0463, Journal of Volcanology and Seismology, 2010, Vol. 4, No. 1, pp. 1–33. © Pleiades Publishing, Ltd., 2010.
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This work is dedicated to the memory of the outstanding volcanologists
Georgii Stepanovich Gorshkov, Artur Nikolaevich Sirin,
Klara Mikhailovna Timerbaeva, and the seismologist Pavel Ivanovich Tokarev

The Magmatic System of the Klyuchevskaya Group of Volcanoes Inferred from Data on Its Eruptions, Earthquakes, Deformation, and Deep Structure

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Received October 21, 2009

Abstract—The study of magmatic plumbing systems of volcanoes (roots of volcanoes) is one of the main tasks facing volcanology. One major object of this research is the Klyuchevskaya group of volcanoes (KGV), in Kamchatka, which is the greatest such group that has been found at any island arc and subduction zone. We summarize the comprehensive research that has been conducted there since 1931. Several conspicuous results derived since the 1960s have been reported, emerging from the study of magma sources, eruptions, earthquakes, deformation, and the deep structure for the KGV. Our discussion of these subjects incorporates the data of physical volcanology relating to the mechanism of volcanic activity and data from petrology as to magma generation. The following five parts can be distinguished in the KGV plumbing system and the associated geophysical model: the source of energy and material at the top of the Pacific Benioff zone at a depth of about 160 km, the region of magma ascent in the asthenosphere, the region of magma storage in the crust–mantle layer at depths of 40–25 km, magma chambers and channelways in the crust, and the bases of volcanic edifices. We discuss and explain the properties of and the relationships between these parts and the mechanisms of volcanic activity and of the KGV plumbing system as they exist today. Methods for calculating magma chambers and conduits, the amount of magma in the system, and its other properties are available.

DOI: 10.1134/S074204631001001X

INTRODUCTION: THE PROBLEM OF VOLCANIC ROOTS AND STUDIES OF THE KLYUCHEVSKAYA GROUP OF VOLCANOES

Volcanism is one of the most powerful planetary geologic processes. Volcanoes are known to exist, apart from Earth, on the Moon, Venus, Mars, and on the Jovian moons. Volcanic activity has been largely responsible for the Earth's crust, the hydrosphere, and the atmosphere. The origin of volcanic activity, its sources, the movement and storage of magmas, and the structure of the roots or plumbing systems of volcanoes were among the first and largest issues to be discussed in volcanology when it first established itself as a science. These issues are studied in different volcanic regions that involve onshore and offshore types of volcanic activity. These studies are conducted using a wide range of methods available in geology, geophysics, geochemistry and related sciences, seismology, geodesy, petrology, mathematical simulation, as well as physical and chemical volcanology, if we adhere to V.I. Vlodavets' terminology [8].

Knowledge of the magmatic plumbing systems of volcanoes is set forth in books which contain connected accounts of complicated volcanic phenomena. Among these are the books by A. Rittman [35], I.V. Luchitskii [28, 29], H. Williams and A. McBirney [80].

A history of and evidence for volcanic roots can be found in Luchitskii's book *Paleovolcanology (vol. 2, Chapter "Volcanic Roots")* [29]. This is an impressive review of how opinions on the relationships between volcanoes and deep-seated chambers evolved from the latter half of the 18th century until 1971, information on the root zones of present-day and ancient volcanoes, and the mechanisms responsible for the generation of ring structures, dikes, and sheet deposits. Several books are specifically devoted to plumbing systems [56, 77, etc.].

Significantly, the General Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI), which was held in Reykjavik, Iceland August 22–27, 2008 was entitled "Understanding Volcanoes."

One of the main objects in the study of volcanic roots or plumbing systems is the Klyuchevskaya group of volcanoes (KGV), which is the largest that has been found at any island arc or subduction boundary worldwide. This group is situated in the northern part of the Kuril–Kamchatka volcanic belt near the intersection of the Kuril–Kamchatka and Aleutian island arcs. This great activity of the KGV is due to the intensity of the geodynamic processes that are occurring in the region [38, 39, etc.].

The KGV contains four active central-type volcanoes, see Fig. 1: the basaltic stratovolcano Klyuchevskoi, which is the largest active volcano in Eurasia, standing 4.8 km high; the well-known andesitic Bezymyannyi volcano; as well as the basaltic Ploskii Tolbachik volcanoes, with heights of 3.1 km and Ushkovskii, with a height 4.1 km. A general view of the KGV can be seen in Fig. 2. On the summits of Ploskii Tolbachik and Ushkovskii large calderas are found, while their slopes contain linear zones of cinder cones that are similar to the summit calderas and rifts of Hawaiian volcanoes. The active Tolbachik zone of cinder cones and fissure eruptions extends for 40 km southwest from the Ploskii Tolbachik summit. The Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik volcanoes, as well as the Tolbachik zone of cinder cones, are aligned along the KGV axial line (see Fig. 1). Apart from these, the KGV contains extinct volcanoes, hundreds of monogenic cinder cones, and lava extrusions. The KGV area of volcanoes, cinder cones, and lava extrusions is a 100 × 55 km ellipse.

The KGV formed during Quaternary time; it is several hundreds of thousands of years old and the volume of its volcanic rocks is over 6500 km^3. The discharge of magma in the KGV was at its greatest during the past 50000 years. Klyuchevskoi Volcano alone discharges an average of 60×10^6 t/yr of basalts, which equals half of the annual discharge of juvenile products and one quarter of the discharge of all erupted products due to the 70 active volcanoes in the Kuril–Kamchatka belt. (The data on the volumes of the products that have been discharged by Klyuchevskoi, Ploskii Tolbachik, and Bezymyannyi for the period from 1930 to 2008 can be found below.) The Klyuchevskoi and Ploskii Tolbachik volcanoes and the cinder cones over the entire KGV area and in the Tolbachik Dol all discharge basalts, which prevail in the KGV, while andesites are the dominant rocks in the middle of the KGV and on Bezymyannyi Volcano. Information on the structure, age and history of the evolution, eruptions, products, petrology, earthquakes, deformation, and the mechanisms of volcanic activity for the KGV can be found in the book *Active Volcanoes of Kamchatka* [19].

The KGV has been the foremost object of volcanological research in this country since the early 1930s. The beginnings of this research were associated with the names of such outstanding scientists as academicians F.Yu. Levinson-Lessing, A.N. Zavaritskii, V.I. Vlodavets, corresponding member of the USSR Academy of Sciences B.I. Piip, S.I. Naboko, and others. Several volcanological expeditions worked in the KGV during the period from 1931 to 1935; the Kamchatka Volcanological Station of the USSR Academy of Sciences was inaugurated in the village of Klyuchi near the northern foot of Klyuchevskoi Volcano on September 1, 1935. The Station has been conducting continuous valuable observations of the KGV volcanoes since that time. This research has expanded since the Laboratory of Volcanology of the USSR Academy of Sciences with its Kamchatka Volcanological Station were set up in 1945–1962 and afterward successfully continued in the 1960s after the Institute of Volcanology of the Siberian Branch (SB) of the USSR Academy of Sciences was set up in the city of Petropavlovsk-Kamchatskii [9]. By the present time the study of the KGV volcanoes has been conducted for nearly 80 years. Fundamental scientific results have emerged from the comprehensive study of major eruptions. These include the paroxysmal summit eruption of 1944–1945 on Klyuchevskoi [33], the disastrous eruption and directed explosion of the andesitic volcano Bezymyannyi in 1955–1956 [17], and the Great Tolbachik Fissure Eruption GTFE of 1975–1976, which is the greatest basaltic eruption to have occurred in Kamchatka during historical time [6].

Some general knowledge of the magma sources for the KGV was derived between 1931 and the 1960s from the study of the geological structure, volcanic eruptions, petrography and petrochemistry of erupted rocks, and the evolution of the KGV volcanic activity during Holocene time and in previous periods. These results are set forth in the works of the fathers of Russian volcanology A.N. Zavaritskii [24], V.I. Vlodavets [7], B.I. Piip [33], and others.

The KGV began its activity during the Upper Quaternary time about 300000 years ago and has passed through several phases during its evolution. Areal volcanic activity took place in the beginning. Later, large shield volcanoes, hundreds of monogenic cones, and 12 central-type volcanoes arose. Four of these (Krestovskii, Kamen', Bol'shaya Udina, and Malaya Udina) ceased erupting in the Holocene, but new volcanoes formed, viz., Bezymyannyi and Klyuchevskoi, Figs. 1 and 2 [30, 42, 43, etc.].

The KGV eruption products belong to two series or formations, viz., a basalt–basaltic andesite formation and an andesitic formation. The KGV rocks lying above sea level occupy a volume of about 5000 km^3. The rock composition in the first series varies from high magnesian basalts to basaltic andesites; the range for the second is from basalts to dacites. The rock volume of the second series is smaller compared with that of the first, and is approximately equal to 1000 km^3.

The rocks of the two series have certain patterns of abundance over the KGV area. High magnesian basalts erupted at the ends of the KGV axial line and basalts are found throughout the area, while andesites are concen-

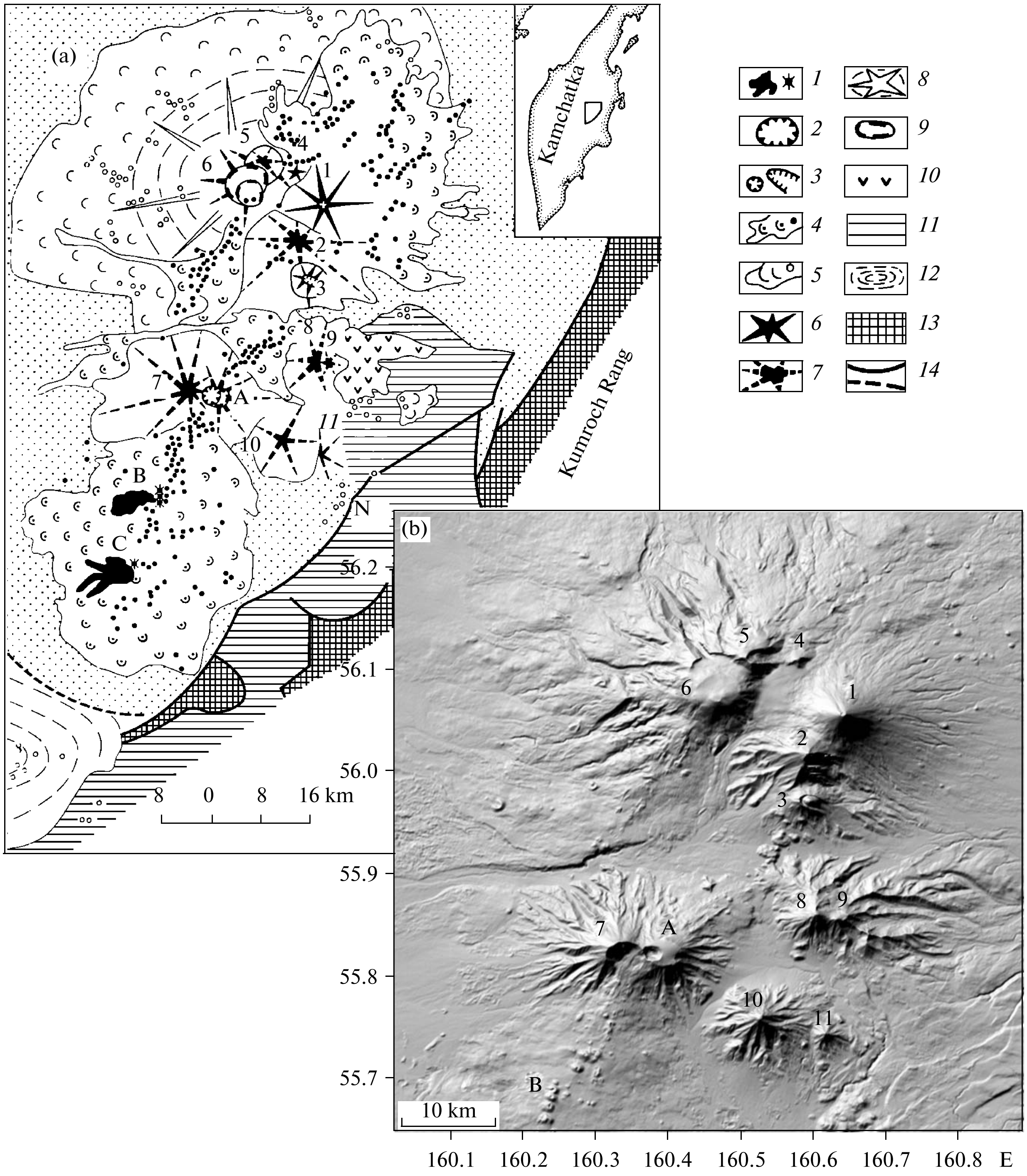


Fig. 1. A map of the Klyuchevskaya group of volcanoes (KGV). (a) locations of active and extinct volcanoes [6]: (*1*) lava flows from the North (B) and South (C) vents of the GTFE, (*2*) fresh collapse caldera on the summit of Ploskii Tolbachik which was generated during the GTFE (A), (*3*) larger craters, (*4*) Holocene cinder cones and lava flows from these, (*5*) Late Pleistocene cinder cones and lava flows from these, (*6*) major Holocene stratovolcanoes, (*7*) major Late Pleistocene volcanoes, (*8*) shield volcano at the base of Ushkovskii and Krestovskii volcanoes, (*9*) Holocene collapse calderas on the summits of Ploskii Tolbachik and Ushkovskii volcanoes, (*10*) strongly damaged Gornyi Zub Volcano, (*11*) lava plateaus, (*12*) Nikolka, shield volcano, (*13*) pre-Quaternary rocks of folded basement, (*14*) faults, those having relief expression and buried ones. Numerals in Fig. 1a mark the following volcanoes: 1 Klyuchevskoi, 2 Kamen', 3 Bezymyannyi, 4 Srednii, 5 Krestovskii, 6 Ushkovskii, 7 Ostryi Tolbachik, 8 Bol'shaya Zimina, 9 Malaya Zimina, 10 Bol'shaya Udina, 11 Malaya Udina. (b) map-view space image of the KGV, numerals mark the same volcanoes.

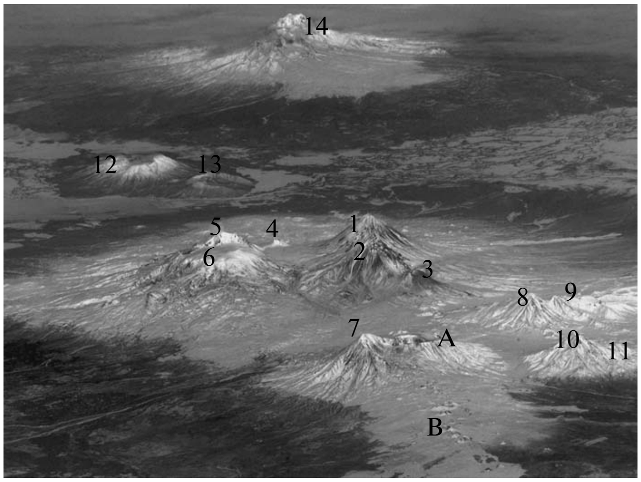


Fig. 2. Northern group of Kamchatka volcanoes: (1) Klyuchevskoi (active), (2) Kamen' (extinct), (3) Bezymyannyi (active), (4) Srednii (extinct), (5) Krestovskii (extinct), (6) Ushkovskii (active), (7) Ostryi Tolbachik (extinct), (8) Bol'shaya Zimina (extinct), (9) Malaya Zimina (extinct), (10) Bol'shaya Udina (extinct), (11) Malaya Udina (extinct), (A) Ploskii Tolbachik (active), B cinder cones around the North vent of the 1975–1976 Great Tolbachik Fissure Eruption (GTFE), (12) Kharchinskii, (13) Zarechnyi, (*14)* Shiveluch (active).

trated in the middle. This important property of KGV volcanism can be seen in the map of the KGV basaltic and basaltic–andesite cinder cones made by A.N. Sirin [42] and in the map of the KGV extrusive domes made by K.M. Timerbaeva [43], (see Figs. 3a and 3b). The band of extrusions is about 45 km long and 10 km wide [30].

Considerable changes in rock composition have been occurring during the entire life of the individual volcanoes, as well as during eruptions. It is a noteworthy fact that andesite extrusions appeared on the summits of Krestovskii and Kamen' volcanoes toward the end of their respective activities (see [42, 43]). B.I. Piip came to the conclusion that there must be a single deep-seated basaltic chamber beneath the entire KGV, while each KGV volcano has its own, long-lived source of magma supply [33]. These concepts were corroborated in [42, 43] and other works of the 1960s.

Further comprehensive petrologic and geochemical studies of the KGV have continued during all of the more recent years. The main results obtained by 1991 can be found in [19]. The concluding section of the present paper incorporates information from recent publications concerning the generation, differentiation, and shaping of the magmas, conduits, and magma chambers in the KGV.

Very important results were achieved during the initial stage of this research from seismological data. A.N. Zavaritskii in 1946 (see his well-known study [25]) called attention to the fact that the volcanic activity in the Kuril–Kamchatka arc region is related to geodynamics, earthquakes and deep-seated processes that are occurring beneath the arc at depths of 100–200 km. Subsequently, this relationship was investigated by P.I. Tokarev, S.A. Fedotov and others [45, 50, 52, etc.].

The first evidence for the magma chamber of Klyuchevskoi Volcano was reported by G.S. Gorshkov in 1956 [16]. He studied how shear waves from Japanese earthquakes were attenuated and found that the chamber in question is in the upper mantle beneath the volcano at a depth of about 60 km and is as large as 30 km across. He followed this finding by proposing a successful international program for the study of volcanic roots.

Extensive seismological observations and research into the KGV earthquakes were continued by P.I. Tokarev, V.I. Gorel'chik and many others [44, 45, etc.].

During the 1960s and in later decades the deep structure and magma chambers of the KGV were investigated using deep seismic sounding (DSS), seismic probing, gravity surveys, electromagnetic and other geophysical techniques [2–5, 11–13, 47, 48, etc.]. A review of the significant results of this research is beyond the scope of the present paper. We wish to remark on one result among them.

An anomalous, nearly vertical, column-like zone 2 km in diameter extending from 50 km depth was identified by seismic probing beneath Klyuchevskoi Volcano. This is thought to be the main magma conduit of the KGV. An andesite magma chamber is at a depth of 10–20 km beneath Bezymyannyi Volcano; this chamber is connected to the magma conduit of the basaltic Klyuchevskoi Volcano [2, 3, etc.]. The Earth's crust is being accreted from below by the magma that is coming from the mantle [5, 26, 49].

Since the early 1960s the main lines of research included studies on the relationships of the volcanism to seismicity, geodynamics and upper mantle properties; the mechanism of volcanic activity, properties of the plumbing system of volcanoes and volcanic centers [11, 36, 56, etc.]. When the Institute of Volcanology, SB USSR Acad. Sci. was set up in 1962 [9] and detailed seismological investigations began in Kamchatka in 1961 [55, 57, etc.], the work was intensified on the multidisciplinary study of eruptions, research on seismicity and deformation of volcanoes and volcanic centers, and the theory of the mechanisms of volcanic activity. The chapters of [56] report on and summarize the results of 124 of S.A. Fedotov's studies from 1961 to 2004 concerned with the relationships of volcanism to seismicity and upper mantle properties, the ascent of magma in the asthenosphere and lithosphere, the structure and mechanism of volcanic plumbing systems, calculation of the properties of magma chambers and conduits, and clarifying the mechanisms of significant eruptions. The chapter dealing with the mechanism of volcanic activity in Kamchatka, the Kuril–Kamchatka arc and similar geologic features [52] in [19], and the conclusions on the origin and mechanism of volcanic activity contained in [56], provide a model of magmatic plumbing systems for central-type volcanoes and volcanic centers in the Kuril–Kamchatka arc and similar geologic features.

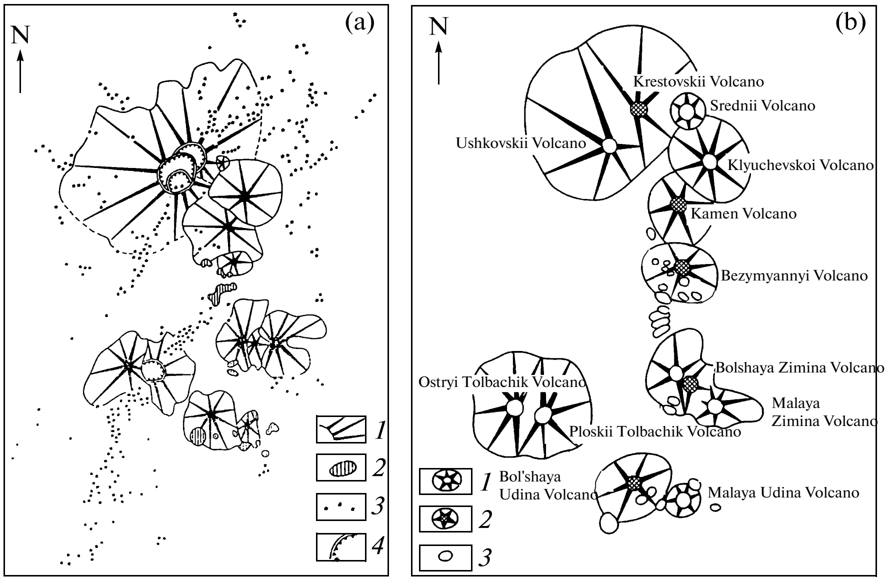


Fig. 3. Positions of cinder cones (a) and extrusive domes (b) in the Klyuchevskoi Dol [42, 43]. Map (a) shows (*1*) central-type volcanoes, (*2*) larger extrusions, (*3*) cinder cones, (*4*) calderas; map (b) shows (*1*) stratovolcanoes, (*2*) stratovolcanoes with summit domes, (*3*) flank domes.

One important and interesting task facing this line of research is the multidisciplinary study of eruptions, earthquakes, and deformation, and the model of the activity and possible evolution of the Klyuchevskoi giant volcano, the main volcano in the KGV, the most powerful in the Kuril–Kamchatka arc. This work has progressed steadily. Dozens of studies on this topic were conducted and published in 1987–2008, among these are [1, 20, 21, 53, 60, 62, 63, 65, 66, 68, 71, etc.]. A model of the Klyuchevskoi Volcano plumbing system was put forth and discussed in [53, 60–62, etc.]. The last reference mentioned here used seismic tomography data.

The present publication considers the mechanisms of volcanic activity, the properties of the plumbing system and its model for the entire Klyuchevskaya group of volcanoes. We are using the available and new data. The principles of this study were set forth in [56]. This paper consists of four parts.

Section 1. Seismological data are considered relating to the following phenomena: the sources of material and energy, the beginning of magma generation in the KGV in the upper part of the Benioff zone; the sources of two basaltic magmas for the 1975–1976 Great Tolbachik Fissure Eruption (GTFE), the ascent and mixing of magmas and their movement along the KGV, the relationships among the KGV magma chambers during that eruption; the ascent of earthquakes through the crust from the intermediate magma chamber of Klyuchevskoi Volcano toward the volcanic edifice before and during its summit eruptions.

Section 2. We consider data relating to the condition and eruptions of Klyuchevskoi Volcano and the results of an analysis of vertical deformation in its cone and basement as determined from multiple geodetic measurements in the period from 1978 to 2009. We report results relating to the supply of magma along the KGV main magma conduit from the mantle to the Klyuchevskoi intermediate chamber at a depth of about 25 km and subsequent flow of magmas from it to the chamber at a depth of about 3 km beneath the volcanic edifice during its summit and adventive eruptions. The scale of intrusive activity is estimated.

Section 3. We consider seismic tomography data on the deep magma sources for the KGV and on relationships among the crustal chambers of the KGV volcanoes.

Section 4. Based on the information supplied in the preceding sections, and other data on the mechanism of volcanic activity and deep structure, as well as the information on the history of evolution of the KGV, rock petrology, and the generation and differentiation of KGV magmas, we develop a geophysical model of the KGV plumbing system. In doing this we use and refine similar models available for the volcanic centers at the Kuril–Kamchatka arc and on Klyuchevskoi Volcano.

1. SEISMOLOGICAL EVIDENCE FOR A DEEP-SEATED SOURCE OF MATERIAL AND ENERGY AND FOR MAGMA MOVEMENT DURING THE GREAT TOLBACHIK FISSURE ERUPTION AND BENEATH THE KLYUCHEVSKOI VOLCANO

It was said in the Introduction that continuous seismological observations of the KGV have been conducted and expanded since 1946. Large amounts of data have been accumulated and hundreds of studies completed. The

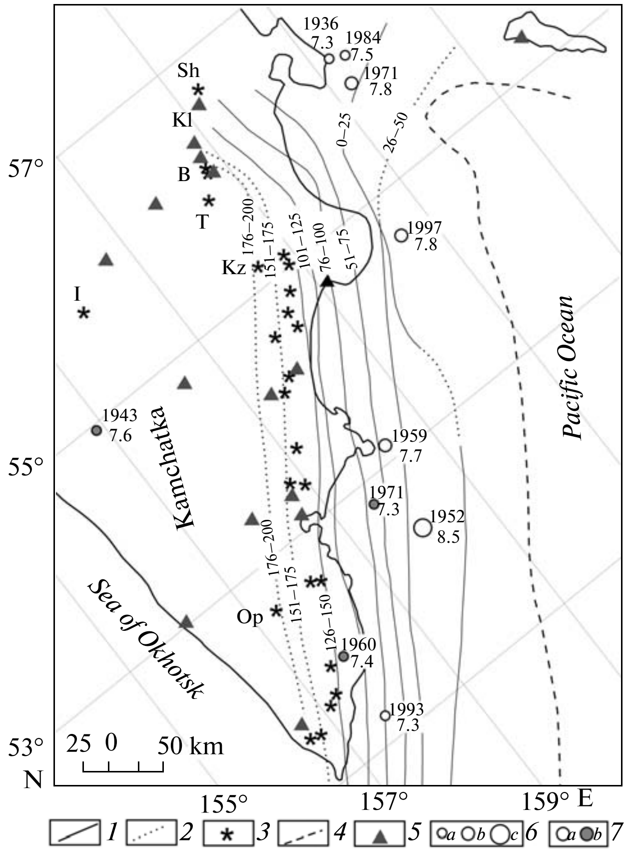


Fig. 4. Maps showing lines of equal focal depth for the 1962–1982 Kamchatka earthquakes [52] and the $M \geq 7.3$ earthquake epicenters for 1930–2008: (*1*) average lines for the depths, (*2*) less accurate segments, (*3*) active volcanoes: Sh Shiveluch, Kl Klyuchevskoi, B Bezymyannyi, T Tolbachik, I Ichinskii, Kz Kizimen, Op Opala, and other (for abbreviations see Fig. 5a); (*4*) deep-sea trench, (*5*) seismic stations, (*6*) epicenters of $M = 7.3$–7.5 earthquakes (*a*), $M = 7.6$–8.0 (*b*), and $M > 8.0$ (*c*), (*7*) epicenters of earthquakes with focal depths shallower than 100 km (*a*), epicenters of $M \geq 7.3$ earthquakes with focal depths greater than 100 km (*b*).

present section provides information on several basic properties of the KGV's volcanic activity and plumbing system derived by seismological methods.

1.1. The relationships between seismicity and volcanism in the Kuril–Kamchatka arc region. The source of material and energy for the volcanoes at depths of 100–220 km. The detailed seismological investigations that have been conducted in the Kuril Islands and Kamchatka since 1957 [55, 57] yielded accurate data on the location of earthquake hypocenters beneath the Kuril–Kamchatka volcanic belt. Relationships were identified between volcanic activity on the one hand and seismicity, upper mantle properties, and the processes occurring at depths of 100–220 km on the other. Below we provide relevant data from [52, 56, 59].

Figure 4 shows lines of equal depth for the average locations of earthquake hypocenters in the Kuril–Kamchatka seismic dipping (Benioff) zone in Kamchatka for different depth ranges between 0 and 200 km based on the results of detailed seismological investigations in Kamchatka during the period from 1962 to 1982; also plotted are active volcanoes and $M \geq 7.3$ earthquake epicenters for the period from 1930 to 2008. Remarkably enough, the KGV, which is the most powerful volcanic center in the Kuril–Kamchatka arc, is situated near the location where the Benioff zone of the Kuril–Kamchatka arc takes a turn and abuts the Aleutian arc.

Figure 5a shows the variation of seismicity with depth in Kamchatka based on the detailed seismological investigations made from 1962 to 1982 [52]. The intensity of seismic activity exhibits the highest level existing on Earth at this location. The middle plane of the Benioff zone is at depths of 100–210 km beneath the Kamchatka active volcanoes. The most rapidly decreasing earthquake rate as a function of depth occurs in the Benioff zone beneath the volcanic belt. One notes a minimum in the rate of comparatively large earthquakes (energy class $K_S \geq 10.5$, $K = 1.5\,\mathrm{M} + 4.6$, where M is earthquake magnitude) at depths of 170–190 km. This minimum shows that the earth strength is decreasing at the highest rate in that part of the Benioff zone where the middle plane of the zone is at

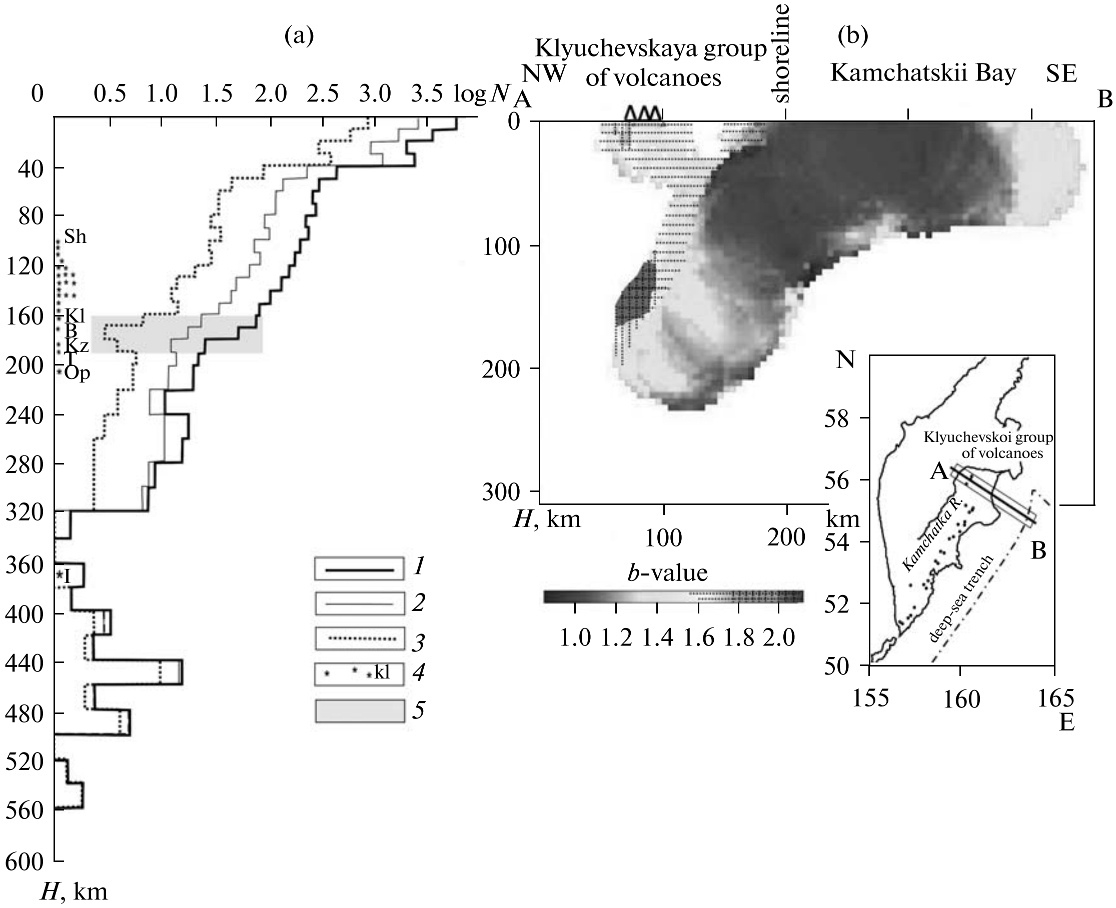


Fig. 5. Distribution of the numbers of Kamchatka earthquakes *N* over depth *H* (a) [52] and variation in the *b*-value ($\log N = a - bM$) along the AB line passing across Kamchatka through the Klyuchevskaya group of volcanoes (b) [62]. Panel a: (*1*) plot of *N*(*H*) for earthquakes with $K_S \geq 8.5$, (*2*) same, with $K_S \geq 9.5$, (*3*) same, with $K_S \geq 10.5$, (*4*) projections of volcanoes (Fig. 4) onto the middle plane of the Benioff zone, (*5*) most probable depth range where initial melting occurs in the Benioff zone.

depths of 170–190 km beneath active volcanoes of Kamchatka.

More evidence to corroborate that inference was derived in recent years by studies of the *b*-value variations beneath Kamchatka. The *b*-value gives the slope of the magnitude–frequency relationship: the rate of earthquakes as a function of their magnitudes is written as $\log N = a - bM$, where *N* is earthquake rate, *M* the respective magnitude, and *a* a constant. A greater *b*-value means a relative increase in the frequency of smaller earthquakes, which takes place with decreasing earth strength. Figure 5b shows changes in *b* in the vertical cross section passing through the KGV across the Kuril–Kamchatka arc based on the data taken from 1971 to 2003 [62]. The greatest *b*-values are observed in the top of the Benioff zone at depths of 120–160 km beneath the KGV.

The rate at which the lithospheric plate is plunging under the Kuril–Kamchatka arc must be identical at different depths in the upper part of the subduction region. However, the seismic activity parameter (normalized number of earthquakes) at depths of about 150 km is smaller than that in the depth range 0–40 km by a factor of 100. The most rapid decline in earthquake rate occurs in the depth range between 40 and 220 km, see Fig. 5a. The same depth range must show as a rapid increase with depth for the fraction of inelastic strain and the associated heat release [52, 56]. The average annual volume of juvenile erupted products at the Kuril–Kamchatka arc is approximately equal to 1% of the annual rock volume that goes down with the descending plate. All the active volcanoes of the Kuril–Kamchatka arc discharge an annual average of 120×10^6 tons of juvenile products; the associated outward heat transport is about 2×10^{17} J/yr. At the same time, the earthquakes occurring at the Kuril–Kamchatka arc release an annual average seismic energy equal to the seismic energy of an earthquake with $M = 7.8$, or 1.8×10^{16} J/yr. The seismic energy is less than one tenth of the total energy liberated by earthquakes. These estimates demonstrate that the thermal energy released by earthquakes and inelastic strain in the descending plate is sufficient to start magma generation at the top of the plate [52, 56].

The above data show that the initial source of energy and material of the KGV magmas may well be situated near the top of the Benioff zone at a depth of 160 km.

1.2. The sources, movement, and mixing of magmas, as well as the relationships among the KGV magma chambers during the Great Tolbachik Fissure Eruption. The Great Tolbachik Fissure Eruption (GTFE) occurred between July 6, 1975 and December 10, 1976 in the Tolbachik zone of the cinder cones south of Ploskii Tolbachik Volcano ([6] (Fig. 1). This is the largest basaltic eruption to have occurred in Kamchatka during historical time. The center of activity from July 6 to September 15, 1975 was at the North vent (NV) of the GTFE, 18 km from the summit caldera of Ploskii Tolbachik (PT) Volcano (Fig. 1). The result was to generate a chain of new cones as high as 330 m (Novye Tolbachinskie volcanoes), smaller cones and lava flows in an area of 9 km^2. Their total volume is 1.2 km^3. Deep, viscous, high magnesian basalts were discharged [6].

The activity of the North vent gave rise in August 1975 to a collapse up to 1600 m in diameter, 400 m deep, and having a volume of 0.35 km^3 in the Ploskii Tolbachik summit caldera (Fig. 1). Previously this caldera contained a crater lava lake filled with high alumina megaplagiophyre basalts. Such basalts were discharged in small portions in the summit caldera a few days before the GTFE, on June 28, 1975 [6]. Five days before the North vent ceased erupting, the basalts that were being discharged began to change in composition from high magnesian to high alumina ones. Magma mixing and the transition to the discharge of high alumina basalts were subsequently occurring for a period of a month at the GTFE South vent [6].

The eruption ceased at the North vent on September 15, 1975, and was resumed on September 17, 1975 in the Tolbachik zone of cones at the South vent (SV) 10 km from the North vent and 28 km from the Ploskii Tolbachik summit caldera, see Fig. 1. Liquid megaplagiophyre basalts were quietly discharged there until December 10, 1976, building a cinder cone as high as 160 m and a lava blanket with an area of 36 km^2 and a total volume of 1 km^3 [6]. The stoppage of eruption at the South vent in December 1976 was at once followed by earthquake swarms, which propagated for 20 km southward from the vent along the Tolbachik zone of cones at depths of 3–6 km. However, magmas no longer came to the ground surface [58].

Seismological observations provided unique and important information on the mechanism and evolution of this complex major eruption, on the sources and movement of magmas, on the plumbing system, and on relationships among the KGV magma chambers [6]. The authors of [58] describe the results of detailed studies in the KGV and GTFE seismicity for 4.5 years before the eruption (from 1971 through June 26, 1975), during the preceding earthquake swarm (June 27 through July 5, 1975), during the activity at the North and South vents (July 6, 1975 through December 10, 1976), and during the 2 years after the eruption (December 11, 1976 through 1978). Below we briefly summarize some of this information, see Figs. 6–10.

The only seismicity increase in the KGV that took place during the period from 1971 to June 26, 1975 was around Klyuchevskoi Volcano, which erupted adventively for 3 months from August 28, 1974 [19], as well as in the zone of areal volcanism near the northeast foot of Klyuchevskoi, where high magnesian lavas are usually discharged, with the most basic composition throughout the KGV. The GTFE area was quiet.

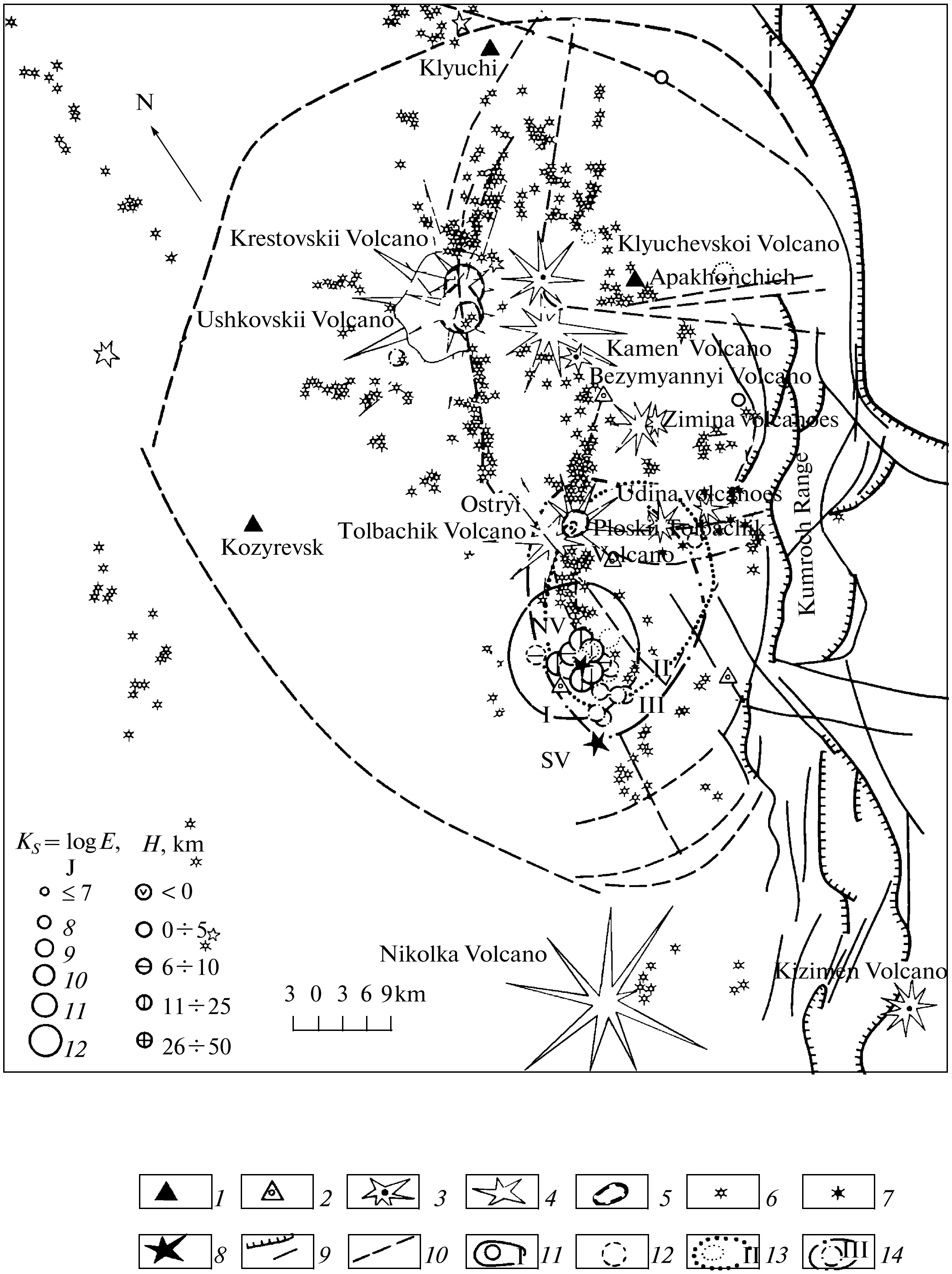
Figure 6 shows a map of earthquake epicenters for the KGV with focal depths $H \leq 40$ km during the preceding swarm (June 27 to July 5, 1975) and during the North vent eruption (July 6 through September 17, 1975). An unusually violent swarm of earthquakes preceding the GTFE occurred around the North vent between June 27 and July 5, 1975. This swarm was used to deliver an accurate forecast of eruption [46]. The two largest earthquakes, with magnitudes of MLH = 5, were recorded beneath the North vent on July 2, 1975 at depths of 10–20 km. It is a noteworthy fact that the seismicity in the rest of the KGV area was lower during the eruption at the vent and discharge of basic magnesian basalts.

Figures 7–9 show maps of the earthquake epicenters for the eruption area and the distribution of hypocenters in the vertical plane passing from Ploskii Tolbachik Volcano to the North and South vents and farther along the southern termination of the Tolbachik zone of cones for the three time intervals that contained the largest changes in the eruption behavior.

Figures 7a and 7b show similar data for the earthquakes that preceded the eruption of June 27 to July 5, 1975 and accompanied the eruption of the Pervyi I cone during the period from July 7 to August 1, 1975. They indicate that the source of the first GTFE high magnesian basalts was located at a depth of 15–18 km or deeper beneath the Tolbachik zone of cinder cones, from which the basalts ascended vertically to the ground surface during the period of one week.

The first GTFE cone I reached a height of 330 m in 34 days and stopped erupting on August 9, 1975. After this, the new Vtoroi II and Tretii III cones formed on August 9 and 17, 1975. These cones continued discharging high magnesian basalts. The fissures on which these formed moved along the Tolbachik zone of cones from the North vent to the Ploskii Tolbachik summit caldera [6, 58].

Other KGV magmas evidently began moving in the last days of July and in the first half of August 1975. A sag appeared and began to grow in size in the Hawaiian-type summit caldera on Ploskii Tolbachik Volcano; the sag must have a shallow magma chamber beneath it containing high alumina megaplagiophyre basalts. By August 25,



June 27 to September 17, 1975

Fig. 6. Map of epicenters of earthquakes with focal depths $H \leq 40$ km in the Klyuchevskaya group of volcanoes area for the period June 27 to September 17, 1975, North vent of the GTFE [58].Notation in the map: (*1*–*2*) seismic stations (*1* permanent, *2* temporary), (*3*) active volcanoes, (*4*) extinct volcanoes, (*5*) calderas, (*6*) cinder cones, (*7*) Upper Pleistocene and Holocene extrusive domes (after I.V. Melekestsev), (*8*) centers of the 1975–1976 Great Tolbachik Fissure Eruption: NV North vent, SV South vent, (*9*–*10*) tectonic faults (after I.V. Melekestsev, *9* certain, *10* inferred), (*11*) outline of the area of the first earthquake swarm (June 27 to July 5, 1975), circles within the outline mark $K_S \geq 11$earthquakes, circles outside the outline stand for $K_S \geq 7.5$ events, (*12*) earthquake epicenters for the period July 6–31, 1975: $K_S \geq 10$ within the outline of the first swarm area and $K_S \geq 7.5$ outside the outline, (*13*) outline of the second earthquake swarm (August 2–17, 1975), circles within the outline mark earthquakes with $K_S \geq 10$, those outside it, with $K_S \geq 7.5$, (*14*) outline of the third earthquake swarm (September 1–17, 1975), circles within the outline mark earthquakes with $K_S \geq 10$ within the outline and with $K_S \geq 7.5$ outside it.

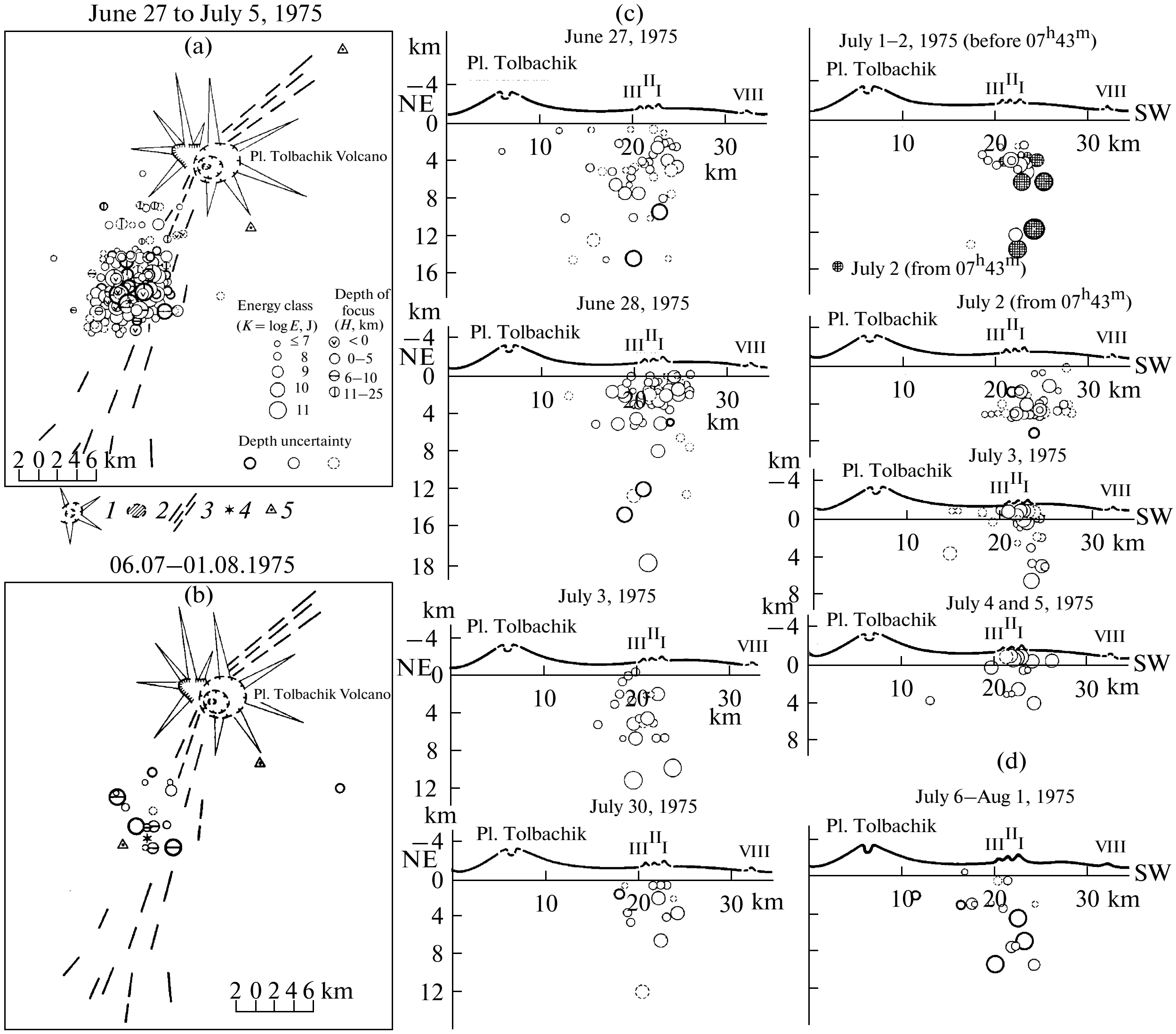


Fig. 7. Maps of earthquakes that preceded the eruption between June 27 and July 5, 1975 (the first swarm) (a) and those which accompanied the eruption of Pervyi cone I between July 6 and August 1, 1975 (b); distribution of earthquakes in the vertical plane passing through Ploskii Tolbachik Volcano and the GTFE North vent a week before the beginning of the GTFE (between June 27 and July 5, 1975) (c), and during the eruption of Pervyi cone between July 6 to August 1, 1975 (d). The cross sections show earthquakes in a band ± 5 km wide.

1975 the sag became as large as 1200 m across, its depth was 400 m and its volume was 0.27 km^3 [6]. It appears from Figs. 8a and 8b that earthquakes continued occurring at depths of 6 km and shallower beneath the North vent, earthquakes began to occur at depths of up to 4 km between the North vent and Ploskii Tolbachik, in addition to an intensive swarm of earthquakes at depths of up to 2 km beneath Ploskii Tolbachik. Judging from these data, magnesian and alumina basalts were moving at that time between the North vent and Ploskii Tolbachik at depths shallower than 5 km.

During the generation of such a large collapse in the summit caldera of Ploskii Tolbachik the magma pressure was decreasing in its shallow chamber. The earthquake swarm beneath Ploskii Tolbachik may have been caused by cracking in the top of that chamber and the emplacement of sheet and other intrusions of liquid megaplagiophyre magmas of that volcano. Judging from Fig. 8d, the top of the peripheral megaplagiophyre chamber beneath Ploskii Tolbachik may be at a depth of about 2 km, and the chamber may be as large as 6 km across, see Fig. 8b.

Figure 9a shows the distribution of earthquakes for the last 15 days in the activity of the GTFE North vent, September 1–15, 1975 and for the 2 days before the GTFE South vent was generated 10 km from it on September 17,

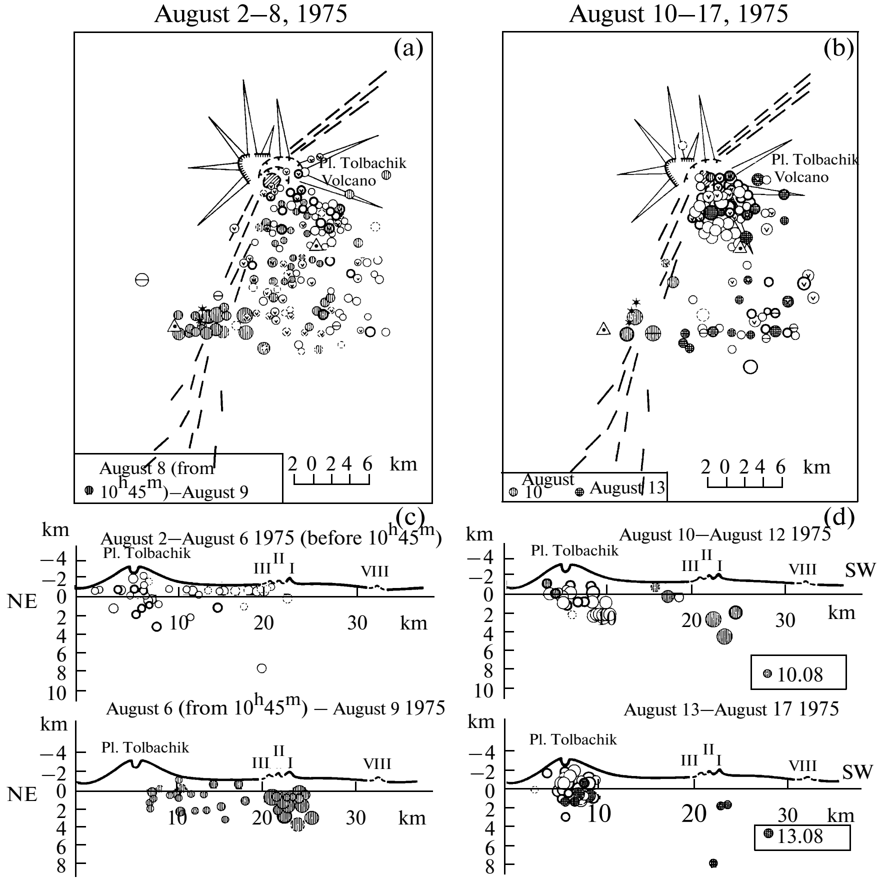


Fig. 8. Epicenters of earthquakes that preceded (August 2–9, 1975) the generation of Vtoroi cone II (a), then (August 10–17, 1975) the generation of Tretii III cone in the GTFE North vent and the collapse of the Ploskii Tolbachik summit caldera (b); the distribution of earthquake hypocenters in the vertical plane passing through Ploskii Tolbachik Volcano and the North vent on the days indicated in panels (c) and (d). The cross sections contain earthquakes in a band ±5 km wide. For depth uncertainty notation see Fig. 7.

1975. The GTFE Vos'moi VIII cone began to grow around the South vent.

Earthquakes were occurring beneath Ploskii Tolbachik at shallower depths than 4 km from September 1 to 10 of 1975. Earthquakes continued to occur in the band between the North vent and Ploskii Tolbachik from September 11–15, 1975. As well, during the 2 days before the South vent was generated (September 16–17, 1975), an earthquake swarm occurred with epicenters moving from the North vent to the South vent at depths shallower than 4 km, see Fig. 9a. It therefore appears that the generation of the South vent was caused by GTFE magmas being emplaced at shallow depths farther for 10 km along the Tolbachik zone of cinder cones, which is similar to the rifts of Hawaiian volcanoes.

It is noteworthy that by that time the bottom of the collapse in the summit caldera of Ploskii Tolbachik subsided by approximately 150 m since the beginning of the eruption to reach an altitude of about 2700 m above sea level. Alumina-high basalts were outflowing from that location. The eruption of magnesian basalts from the North vent began before that time on July 6, 1975 at a height of 880 m at a distance of 18 km from the Ploskii Tolbachik caldera, and the high-alumina basalts began to be discharged from the South vent on September 17, 1975 at a height of 380 m and at a distance of 28 km from the summit caldera after the collapse appeared in it [6].

During the 2 weeks before the North vent eruption ceased, the magnesian basalts of the North vent began mixing with megaplagiophyre basalts, the mixing process continuing for about 2 weeks at the South vent. Later, from the beginning of October 1975 until the GTFE ceased on December 10, 1976, megaplagiophyre basalts were discharged by the South vent. The important fact is that the lavas of these basalts had viscosities two orders of magnitude below that of the magnesian basaltic lavas discharged by the North vent. The lower viscosity values obtained by measurements near the vents of these lavas were equal to 3×10^6 poises at the North vent and $(1–2) \times 10^4$ poises at the South vent [6].

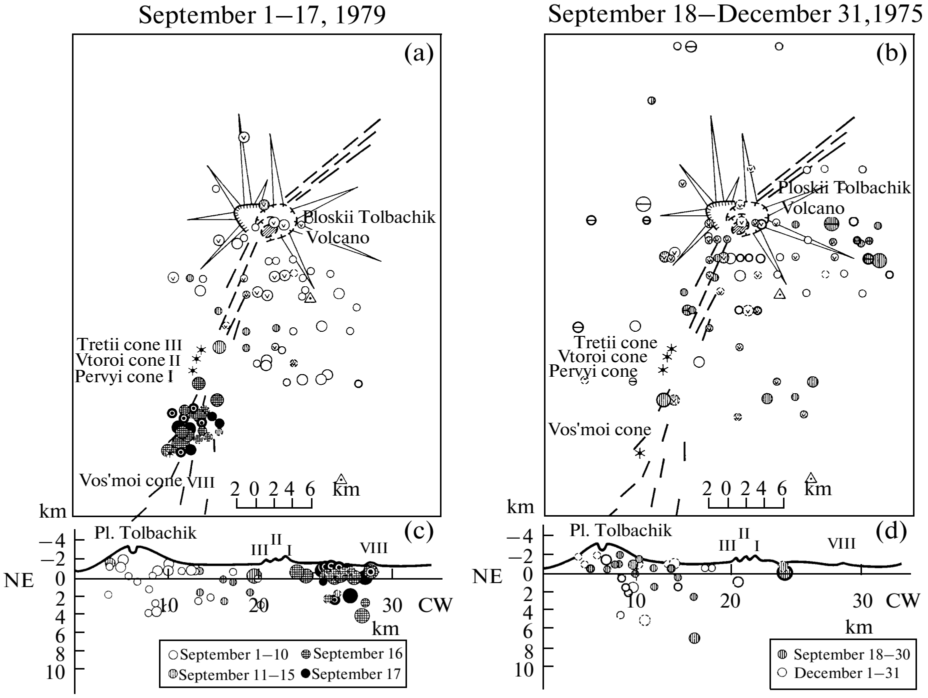


Fig. 9. Maps of epicenters and vertical cross sections of the GTFE earthquake hypocenters before the generation of the South vent (September 1–17, 1975) and during the beginning of its activity (September 18 to December 31, 1975): (a) earthquakes that preceded the eruption, (b) earthquakes that accompanied the beginning of the eruption, (c, d) vertical cross sections along the line from Ploskii Tolbachik Volcano to the South vent; (days, indicated in the figure). The cross sections show earthquakes in a band ±5 km wide. For notation see Fig. 7.

Flows of liquid megaplagiophyre aluminabasalt were discharged from the cone of the South vent at an average rate of 4.83×10^6 t/day and the numerous lava bocche and vents throughout the South vent eruption, from September 17, 1975 to December 10, 1976.

It is noteworthy that the earthquakes in the South vent area ceased after the eruption at that vent began for the time the eruption lasted. It can be seen from Fig. 9b that the small earthquakes in the GTFE area that occurred during the period from September 18 to December 31, 1975 had their hypocenters mostly beneath the Ploskii Tolbachik edifice. Maps of earthquake epicenters for the entire KGV during the South vent eruption (September 17, 1975 to December 10, 1976) can be found in [58]. The maps show that seismicity was lower in the entire KGV during the continuous discharge of basalts at the South vent.

The seismicity of the GTFE area and the entire KGV showed a dramatic change after the South vent eruption ceased. Between December 11, 1976 and the end of 1977 there were several remarkable earthquake swarms, see Fig. 10; an earthquake swarm occurred at once when the South vent eruption ceased (December 11–31, 1976) in a band extending for 20 km farther south as far as the termination of the Tolbachik zone of cinder cones, see Fig. 10. Most probably, a new emplacement of megaplagiophyre basalts occurred here, which could not reach the surface because the magmas had a lower pressure by the end of the eruption [51]. Judgung by the seismological data, magma emplacement during the GTFE was occurring for 50 km along the Tolbachik zone of cones.

In 1978 vigorous seismicity activity began in the area of Klyuchevskoi Volcano and in the area of areal eruptions of magnesian basalts around its northeastern foot, where almost no earthquakes occurred during the GTFE period [58].

The above unique data on the evolution and variation of the KGV seismicity occurring before, during, and after the GTFE show that a relationship emerges between magma chambers and conduits and magma sources in most of the KGV during the GTFE, as 2.2 km^3 of juvenile rock was erupted and the maximum observed outflow of basalts took place from the KGV plumbing system [51].

The discharge of basalt was equal to 1763×10^6 t/yr, or 25 m^3/s, during the 15 months the South vent was erupting; this is 30 times the average discharge (60×10^6 t/yr) of Klyuchevskoi Volcano, the most productive volcano in the KGV. Under these conditions the seismic quiescence obtaining over all of the KGV during the vigorous monotonic eruption at the South vent may have been caused by a pressure decrease due to magma outflow taking place in the greater part of the KGV plumbing system.

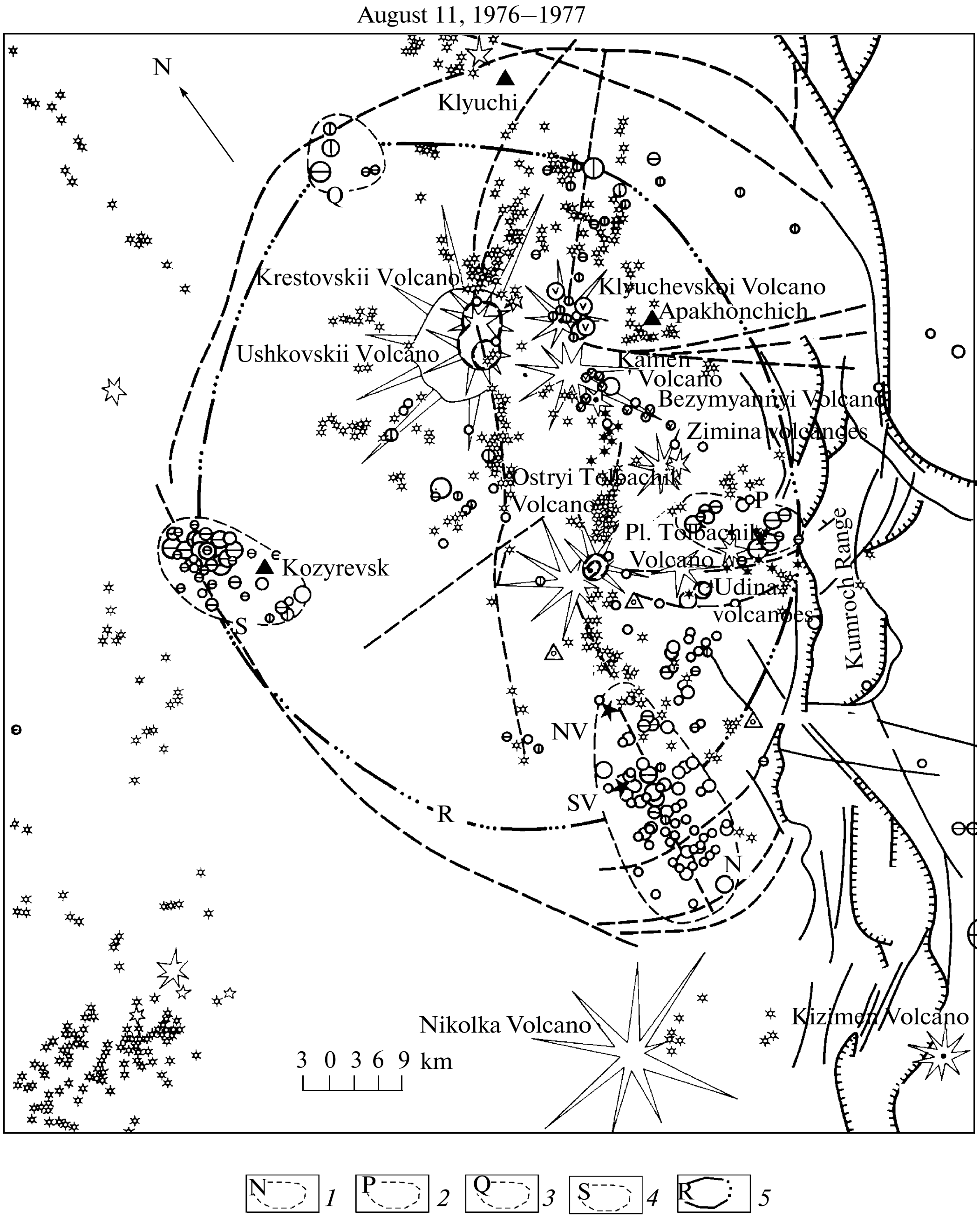


Fig. 10. Map of earthquakes in the Klyuchevskaya group of volcanoes area after the GTFE for the period December 11, 1976 to 1977 [58]: (*1–4*) earthquake swarms, (*1* the December 11–31, 1976 swarm in the eruption area, *2* the April 1977 swam, *3* the May 1977 swarm, *4* the June–August 1977 swarm), (*5*) outline the area involved in intensive movements after the eruption had ended. For the other notations, see Fig. 6.

Geodetic measurements taken during the GTFE yielded the result that the magma pressure in the dikes that supplied magma for the eruption as these penetrated onto the ground surface was equal to 100–250 bars. Given this pressure decrease, a mass of the discharged basalts equal to 3.8×10^9 t, and a modulus of compression for the magma equal to $K = 3 \times 10^5$ bars, it was shown that the volume of the part of the KGV plumbing system that provided the GTFE magmas may have been 1600–4000 km^3 [51].

In addition to the seismological evidence just quoted, we note that geodetic data suggest a major source of pressure at a depth of 16.1–22.4 km beneath the area of the North and South vents and a smaller center of deformation at a depth of 5–9 km [67].

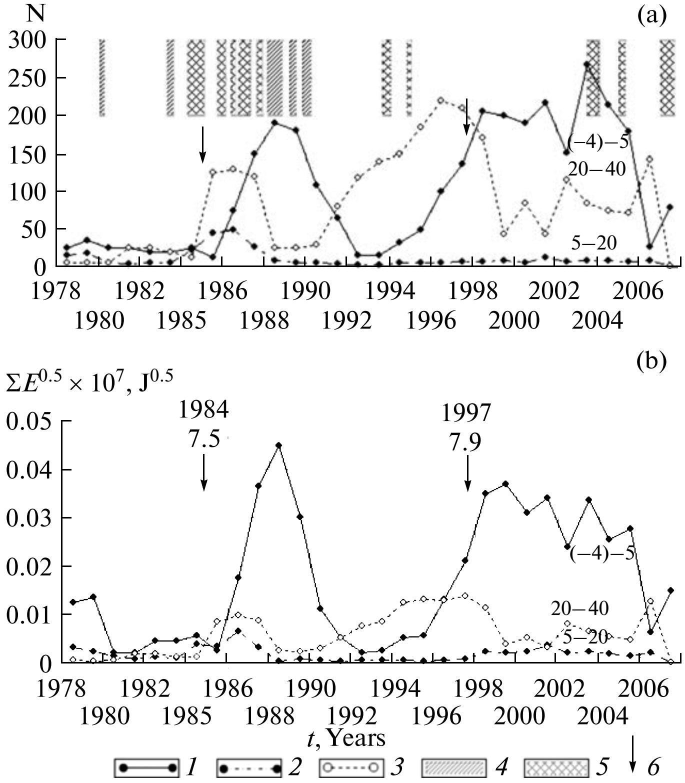


Fig. 11. Variation in the mean annual numbers N of earthquakes for the Klyuchevskoi Volcano area (with the coordinates 56.00°–56.155° N, 160.55°–160.755 E) with energy class $K_S \geq 5.5$ (a) and conventional deformation for these earthquakes $\Sigma E^{0.5}$ (b). Focal depths: (*1*) (+4)–5, (*2*) 5–20, (*3*) 20–40 km, (*4*) time intervals of adventive eruptions, (*5*) time intervals of summit eruptions, (*6*) dates of the two largest earthquakes with $M = 7.5$, December 28, 1984 and $M = 7.9$, December 5, 1997 (Fig. 4).

1.3. Seismological evidence for magma storage in the intermediate chamber of Klyuchevskoi Volcano and magma ascent toward the volcanic edifice during its eruptions. The most complete seismological data on the KGV plumbing systems are available for Klyuchevskoi. Extensive research on Klyuchevskoi seismicity has been conducted from the 1940s until today [16, 40, 44, 63]. The results of studies on Klyuchevskoi earthquakes and their interrelationships were reported by V.I. Gorel'chik in [63, 68, 71]. These studies show that many more earthquakes occur beneath Klyuchevskoi Volcano compared with the other KGV volcanoes, and that the main seismicity concentrations are beneath the volcano in the lower crust or in the crust–mantle layer at depths of 20–35 km, as well as in the volcanic edifice itself and in the underlying rocks above 5 km depth. It is exactly these depths that must host the magma storage regions, and the intermediate and the shallow magma chambers of Klyuchevskoi Volcano.

Figures 11 and 12 present several results for 1978–2008 on earthquakes in the KGV and around Klyuchevskoi Volcano.

Figures 11a and 11b show the annual numbers of earthquakes N (with energy class $K_S \geq 5.5$ (or alternatively $K_S = 1.5M + 4.6$, where M is magnitude) for the Klyuchevskoi area and total earthquake-derived deformation $\Sigma E^{0.5}$, where E is the earthquake energy, for focal depth ranges (–4)–5, 5–20, and 20–40 km. The periods of adventive and summit eruptions on Klyuchevskoi are indicated in this figure, as well as the times of the two great earthquakes, the nearest to the KGV for the period 1978–2008; these are the events in the Kamchatskii Bay in the northern part of the Kuril–Kamchatka Benioff zone (December 28, 1984, $M = 7.5$ and December 5, 1997, $M = 7.9$, see Fig. 4).

One notes a relationship between seismic and volcanic processes that was observed twice in 1978–2008 (Fig. 11a.) The times of great $M \geq 7.5$ earthquakes in the Benioff zone and the maxima in the annual numbers of small earthquakes occurring at depths of 20–40 km were close in time; the latter were certain to be observed as the mantle magma influx into the Klyuchevskoi intermediate chamber increased. Later, over several years the seismicity maximum moved upwards to depths shallower than 5 km and was followed by eruptions discharging large amounts of magma.

More detailed information on the relationships between seismicity and eruptions for Klyuchevskoi was derived from the 2001–2008 data, shown in Fig. 12. This figure contains the following data sets: A map of KGV epi-

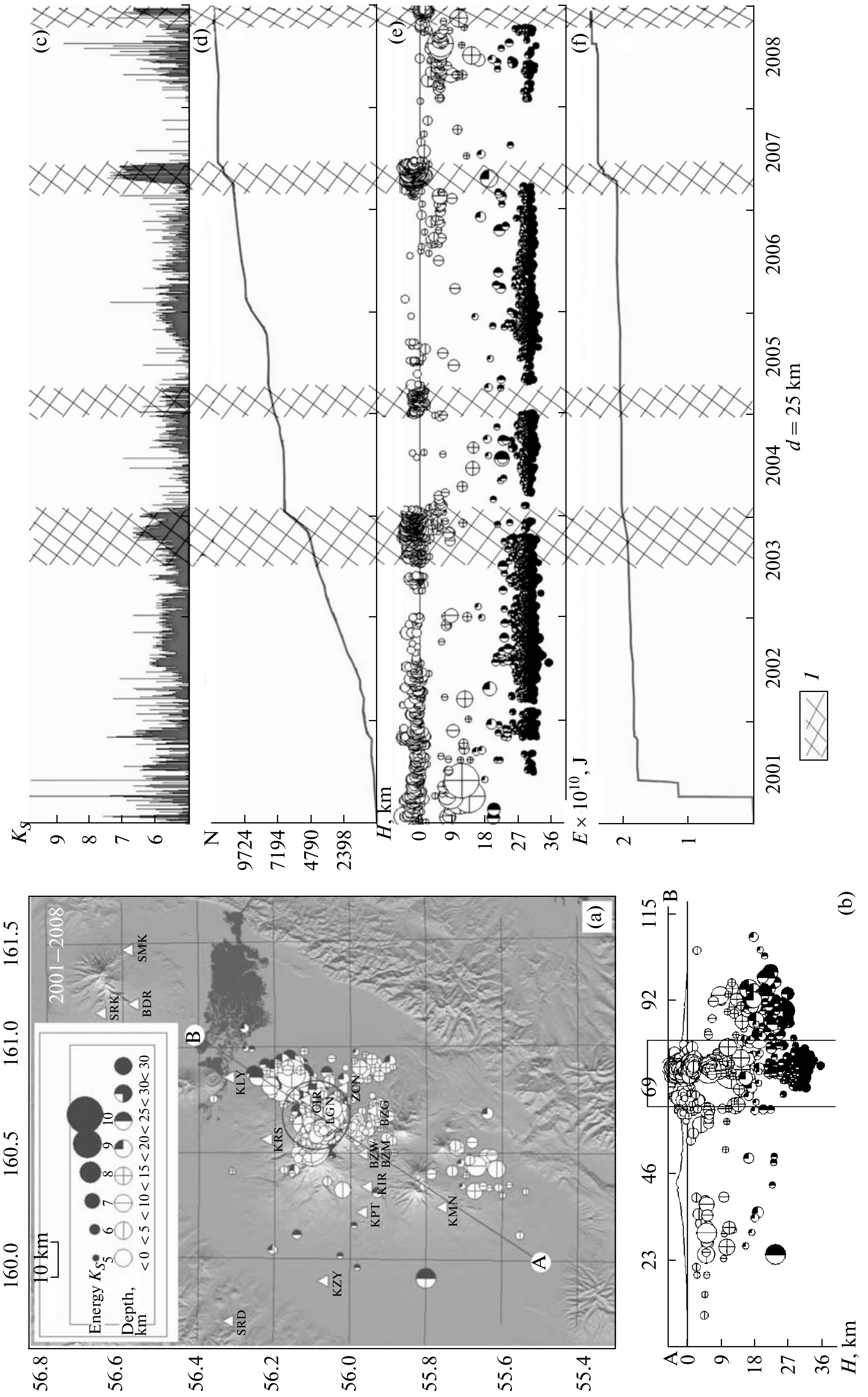


Fig. 12. Map showing the distribution of earthquakes over depth and time for the epicenter zone of Klyuchevskoi Volcano (the zone is 25 km across) for 2001–2008: (a) epicenter map and the identified epicenter zone, (b) cross section along AB, (b–f) variation over time in the epicenter zone for energy class, number of events, depth, and total energy of earthquakes; map (a) shows the locations of telemetry seismic stations (triangles), the circle marks the central epicenter zone around Klyuchevskoi Volcano (the zone is 25 km across); the notation shows energy class K_S and depth of focus. The vertical rectangle shows the cross section of the volcano's central epicenter zone indicated in panel (a). The data are catalogs of the KB GS RAS. 1 cross-hatching shows periods of summit eruptions.

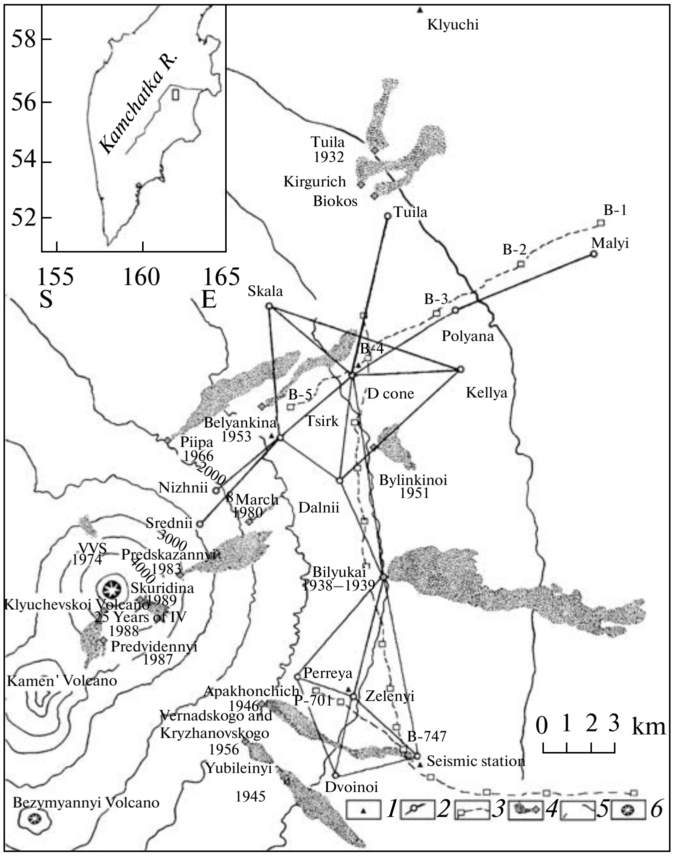


Fig. 13. Map of the study area, locations of adventive eruptions on Klyuchevskoi Volcano for the period 1932–1989, the locations of leveling lines, geodetic networks and seismic stations: (*1*) seismic stations, (*2*) sites of distance measurements, (*3*) benchmarks of leveling lines, (*4*) lava flows from adventive eruptions with indication of name and year of occurrence, (*5*) lines of equal altitude, (*6*) crater of active volcano.

centers for depths shallower than 40 km (Fig. 12a); a vertical cross section across the regions of earthquake occurrence which passes along the KGV axis through the summits of Klyuchevskoi and Ploskii Tolbachik volcanoes (Fig. 12b); earthquake energy class K_S (Fig. 12c); cumulative number of earthquakes N and total earthquake energy over time, (Figs. 12d and 12f), and changes in earthquake distribution over depth for the period 2001–2008 (Fig. 12e). These plots are based on the catalogs of the Kamchatka Branch of the Geophysical Service (KB GS) of the Russian Academy of Sciences (RAS). Figure 12 shows the time intervals of four major summit eruptions on Klyuchevskoi for the period from 2001 to 2008. Figures 12c–12f are for an earthquake source zone 25 km in diameter around Klyuchevskoi Volcano.

The increasing seismicity rate and earthquake swarms beneath the volcanoes indicate magma storage regions, locations of increased pressure, deformation, and emplacement of magmas into the host rock.

The data shown in Fig. 11 and 12, similar inferences drawn in previous years [63, 68, 71], as well as information contained in other publications [56], show the following properties and features of the Klyuchevskoi plumbing system.

The supply of deep magma from the mantle showed two periods of considerable increase several years after large earthquakes that occurred in the Benioff zone at epicentral distances of 150–250 km from the KGV.

The storage region for deep mantle magmas beneath Klyuchevskoi Volcano is an intermediate magma chamber at depths of 20–35 km. Deep magma does not come into this chamber continuously and at a uniform rate. Judging from the duration of earthquake swarms occurring in the chamber, intensive supply of magma took place during the period from 1983 to 1987 for 25% of that time, and during 75% of the period from 2001 to 2008, when four major summit eruptions occurred.

The seven summit eruptions on Klyuchevskoi Volcano, which occurred in the periods from 1983 to 1987 and 2001 to 2008, were preceded by earthquake hypocenters rising from the intermediate chamber toward the volcanic edifice over a period of several months; later, large earthquake swarms occurred in the edifice during the summit eruptions. One notes that swarms stopped occurring in the intermediate chamber during the summit eruptions (see Fig. 12 and the data in [63]). This means that magma outflow from the intermediate chamber occurred during summit eruptions. Judging by the duration of earthquake swarms at depths of about 30 km and by the duration of interswarm intervals (Fig. 12), the time taken by the intensive magma influx into the intermediate chamber in 2001–2008 prior to summit eruptions was about four times the time interval required by the magma to flow away from that chamber during eruptions.

The data concerning the basic properties of volcanic activity and the plumbing system of the KGV given in sections 1.1, 1.2, and 1.3 are summarized in Section 4, where the geophysical model for that system is described.

2. THE PLUMBING SYSTEM OF KLYUCHEVSKOI VOLCANO AS INFERRED FROM GEODETIC MEASUREMENT OF DEFORMATION FROM 1978 TO 2009

Magma may begin to move from a storage area to the surface a few months, and occasionally a few years, before the beginning of an eruption. These magma movements can be deduced from the uplifting of the volcano's slopes before an eruption. The direct evidence for magma movement beneath a volcano consists in changes in benchmark elevations along a radial line running to the volcano. Systematic geodetic measurements on the northeastern slope of Klyuchevskoi have been conducted since 1978 [23]. The geodetic network is shown in Fig. 13. Representative results were obtained from measurements of vertical ground deformations along a radial leveling line running

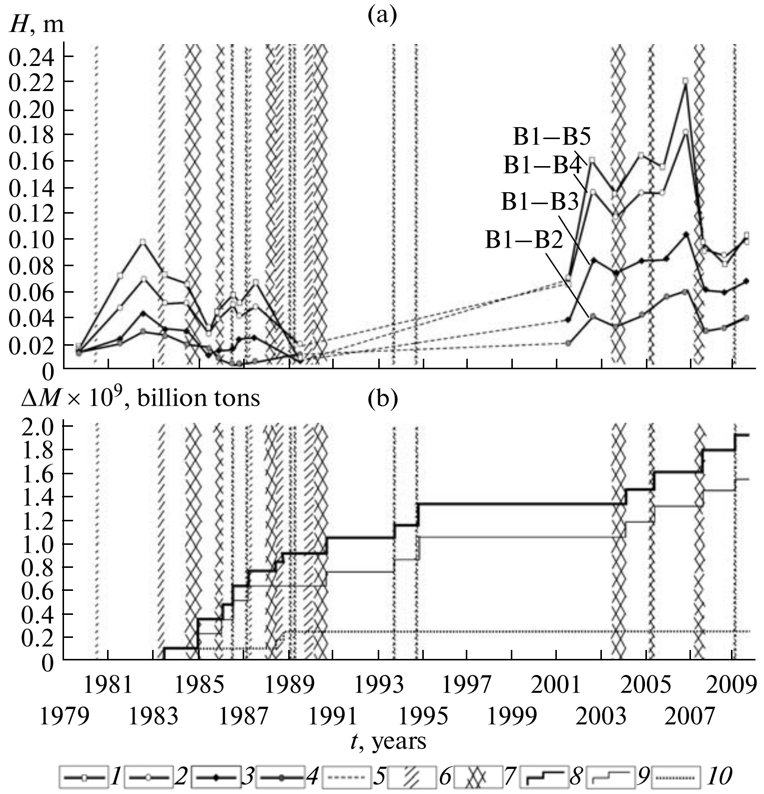


Fig. 14. Vertical displacements along the Kirgurich line for 1979–2009 on the northeastern slope of Klyuchevskoi Volcano: (*1–4*) time variations in vertical displacements between the reference benchmark B1 and the benchmarks B2, B3, B4, and B5 (Fig. 13); (*5*) intermissions in observation, (*6*) periods of adventive eruptions, (*7*) periods of summit eruptions, (*8*) plot showing cumulative amount of eruption products discharged by Klyuchevskoi Volcano during 1979–2009 for summit and adventive eruptions, (*9*) same, for summit eruptions, (*10*) same, for adventive eruptions.

along the Kirgurich River [60, etc.] (Fig. 14.) The highest vertical displacement measured over the 30-year period reached 23 cm at the site nearest to the volcano. The error involved in vertical displacements is equal to ±1 mm $L^{1/2}$ (L is the length of the leveling line in km). At first a line 28 km long was used, but subsequently it was shortened to measure only 15 km, considering that the displacements far from the volcano were small. The reference benchmark is at site B1, which is 26 km from the center of the volcano's crater, the benchmark nearest to the volcano is at site B5 11 km from the crater center.

When modeling the ground deformation above magma chambers in volcanology it is assumed that the pressure source responsible for this deformation has the shape of a spherical cavity, a horizontal disk, or a cylindrical cavity [78, 81]. One previous study [60] assumed an axisymmetric model for Klyuchevskoi Volcano. The results of geodetic observation were used to estimate the center of the effective excess magma pressure and its magnitude [60]. The result was that the center of the effective pressure source was moving during the volcanic activity from 1981 to 2006 in the depth range 25–3 km from the probable storage region of deep magmas in the intermediate chamber toward the peripheral chamber and the layers that underlie the volcano's edifice. In contrast to previous studies, the interpretation and processing of the data on vertical displacements is performed by two methods in Section 2.

One important property of the Klyuchevskoi plumbing system is that it involves two main sources of excess magma pressure, the intermediate and the peripheral chamber, whose depths are constant and equal 25 and 3 km, respectively, see Section 1.3 (Fig. 12) [60, etc.]. Based on this finding, the second method for interpreting the data on vertical ground displacements of Klyuchevskoi assumes two pressure sources at different depths. The two depths were specified according to an analysis of seismological and geodetic observations that was previously obtained.

According to seismological data, one of the two main clusters of earthquake hypocenters beneath Klyuchevskoi Volcano is situated either in the lower crust or in the crust–mantle layer at depths of 20–35 km. The other maximum is observed in the volcano's edifice and the underlying rocks. The position of the intermediate magma chamber is also found from the depth at which the center of the effective pressure source is situated based on geodetic data. Based on these considerations, the two spherical pressure sources were assumed to lie at depths of 25 and 3 km. When two spherical pressure sources are present at depths H_1 and H_2 ($H_2 > H_1$), the ground displacements U will equal the sum of the displacements due to the two sources:

$$U\text{H} = U\text{H}_1 + U\text{H}_2. \tag{1}$$

The displacements were calculated from relations derived in [20, 78, 81]:

$$\begin{aligned} U\text{H} &= \left\{-2\Delta P_1 \frac{1-\nu^2}{C} R_1^3 \frac{H_1}{(r_i^2 + H_1^2)^{3/2}}\right\} \\ &+ \left\{-2\Delta P_2 \frac{1-\nu^2}{C} R_2^3 \frac{H_2}{(r_i^2 + H_2^2)^{3/2}}\right\}. \end{aligned} \tag{2}$$

We shall use the following notation for some expressions in (2):

$$a_i = \frac{H_1}{(r_i^2 + H_1^2)^{3/2}}, \quad b_i = \frac{H_2}{(r_i^2 + H_2^2)^{3/2}}, \tag{3}$$

$$\begin{aligned} x &= A_{3\text{km}} = -2\Delta P_1 \frac{1-\nu^2}{C} R_1^3, \\ y &= A_{25\text{km}} = -2\Delta P_2 \frac{1-\nu^2}{C} R_2^3. \end{aligned} \tag{4}$$

In the first method of data processing, the first step was to find the depth Z_0 of one of the effective pressure sources, and then to calculate the multiplier A^1, which incorporates the excess pressure ΔP, the geometry of the pressure source, and the elastic properties of the host rocks. The resulting values of Z_0 and A^1 were then used to estimate the relative change in the volume of the effective pressure source V^1 [60].

The second method fixes the depths, while the multipliers $A_{3\text{km}}$ and $A_{25\text{km}}$ are determined by directly solving the equations of condition (5). The following notation is used in (2) through (4): C is Young's modulus, ν is Poisson's ratio, r_i is the distance from the vertical axis passing through the center of the volcano (through the crater) to the observation site (the appropriate leveling site), R_1 and R_2 are the radii of the spherical sources at depths $H_1 =$ 3 km and $H_2 = 25$ km, and ΔP_1 and ΔP_2 are the excess pressures at depths H_1 and H_2. We find the unknowns x and y by setting up equations of condition for each observation year:

$$a_1 x + \text{в}_1 y = U_{1i}, \quad a_2 x + \text{в}_2 y = U_{2i}, \quad a_3 x + \text{в}_3 y = U_{3i}. \tag{5}$$

The quantity U is the elevation change between the reference benchmark P1 and the benchmark in the relevant area P_i for the time period between the beginning of eruption (1979) and the year of repeated measurement. Equations (5) involve U_li, which is elevation change between benchmark P_1 and P_3, $\text{U}_{2\text{i}}$ between P_1 and P_4 and $\text{U}_{3\text{i}}$ between P_1 and P_5. The values of x and y were obtained by solving (5) for each year of observation, and the resulting values of x and y were used to estimate the volumes of the effective pressure sources V_1 and V_2. To a first approximation the quantities ν and $C_{1,2}$ which depend on rock properties, will be assumed to be constant during short intervals of time. The excess pressures ΔP_1 and ΔP_2 vary within the depth range $H_1 - H_2$.

We denote

$$K_1 = -8.38\Delta P_1 \frac{1-\nu^2}{C_1}, \quad K_2 = -8.38\Delta P_2 \frac{1-\nu^2}{C_2}. \tag{6}$$

Since the volume of a sphere of radius R is equal to $V = \frac{4}{3}\pi R^3$, it follows that with (2) and (6) incorporated, the volumes V_1 and V_2 will equal

$$V_1 = x/K_1 \quad \text{and } V_2 = y/K_2, \tag{7}$$

where V_1 is the volume of the pressure source in the peripheral, shallow chamber at 3 km depth and V_2 is that in the intermediate chamber at 25 km depth.

A continuous magma conduit is situated at depths of 25–5 km, where magma is moving from the intermediate chamber to the peripheral chamber and to the Klyuchevskoi crater. The excess magma pressure at a depth of 3 km in the conduit can reach 300–500 bars and can decrease by 100–150 bars when the bottom of the summit crater subsides by 600 m [53, 60]. Our calculation of the volumes of the intermediate and the shallow peripheral chamber is based on the following values of excess magma pressure: $\Delta P_1 = 500$ bars is the excess pressure in the peripheral chamber at 3 km depth, $\Delta P_2 = 300$ and 500 bars is the excess pressure in the intermediate chamber at 25 km depth. To calculate the Young's moduli, C_1 and C_2, for depths of 3 and 25 km, we used the average shear velocities ($V_s = 1.40$ km/s for the upper crustal layers 3 km thick and $V_s = 3.03$ km/s for the crustal layers 25 km thick), as well as average densities of $\rho_1 = 2.20$ g/cm^3 for the layer 3 km thick and $\rho_2 = 2.57$ g/cm^3 for the layer 25 km thick. The following values were obtained: $C_1 = 0.108 \times 10^6$ and $C_2 = 0.590 \times 10^6$.

Figures 15a–15e show the characteristics of the Klyuchevskoi plumbing system derived from geodetic observations using the two methods referred to above where (a) is the change in the depth Z_0 of the effective magma pressure source beneath the volcano, (b) are the values of the multiplier A^1 showing how the deformation due to a single effective magma pressure source depends on excess pressure, host rock properties, and the source the deformation due to a single volume (4), as well as the values of the other analogous multipliers A_3 and A_{25} for two spherical magma pressure sources at fixed depths of $H = 3$ km and $H = 25$ km, (c) are the probable volumes of the effective magma pressure sources V_1 and V_2 for these same depths, (d) is a time-dependent quantity showing

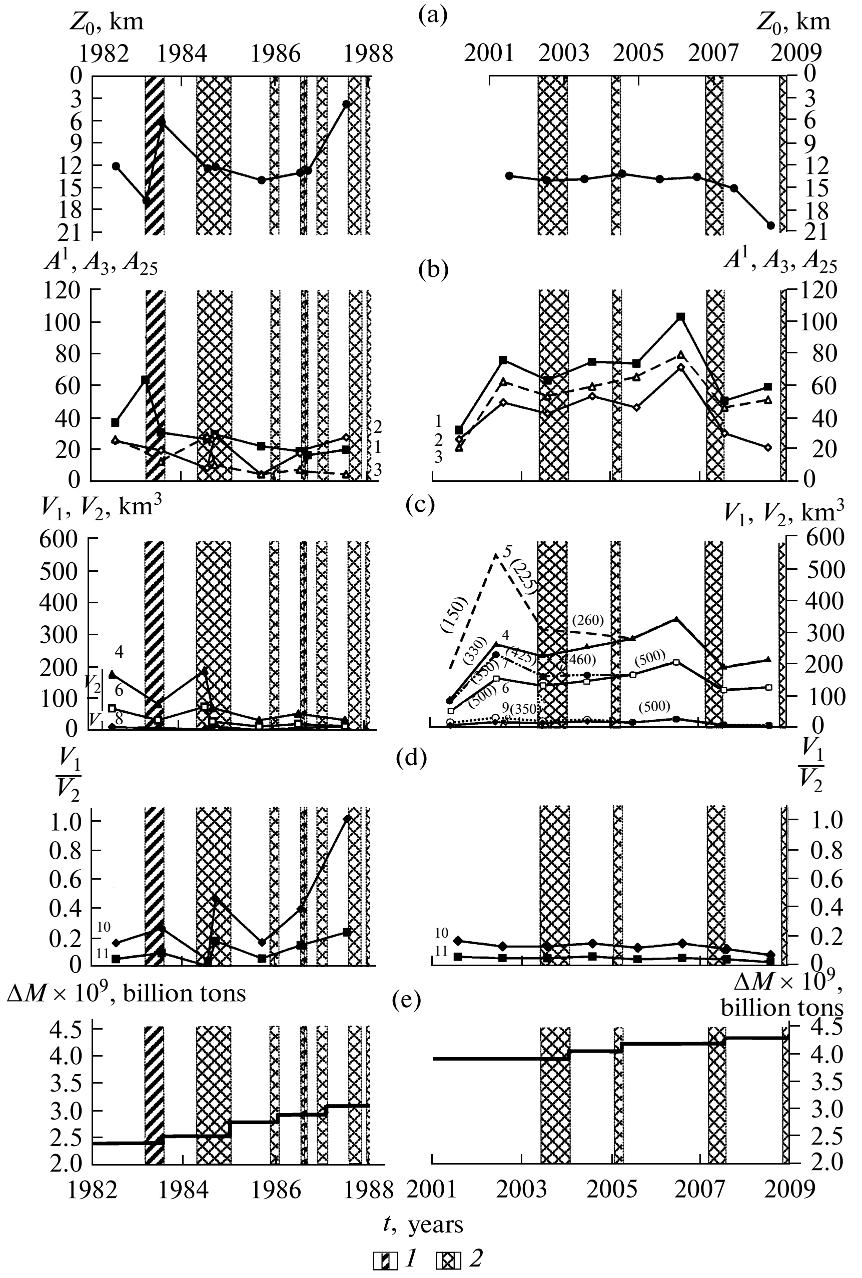


Fig. 15. Characteristics of the plumbing system of Klyuchevskoi Volcano inferred from the 1982–1988 and 2001–2008 geodetic data: (a) depth of the center of effective pressure, z_0 assuming a single pressure center, (b) variations in parameter A which incorporates excess pressure, the dimensions of the pressure source, and elastic earth properties: (1) A^1 for a magma chamber with a variable depth to the pressure center, (2 and 3) A_3 and A_{25} for two centers of magma pressure situated at depths of 3 and 25 km, (the parameter A is in units of volume, its values in Fig. 15b are normalized); (c) possible volumes of pressure sources in the area of the intermediate (V_2) and the peripheral (V_1) chamber, numerals at curves denote various values of excess magma pressure, (4) $\Delta P_2 = 300$ bars, (5) $150 \le \Delta P_2 \le 300$, (6) $\Delta P_2 = 500$, (7) $350 \le \Delta P_2 \le 500$, (8)$\Delta P_1 = 500$, (9) $350 \le \Delta P_1 \le 500$ bars; (d) ratios of pressure source volumes (peripheral to intermediate), the intermediate source of excess pressure has $\Delta P_1 = 500$ bars, the peripheral chamber has $\Delta P_2 = 500$ and $\Delta P_2 = 200$ bars, (10) $V_1(500)/V_2(500)$, (11) $V_1(500)/V_2(200)$; (e) total volume of eruption products for Klyuchevskoi Volcano, the period 1982–2009. The periods of summit and adventive eruptions are denoted *1* and *2*.

what percentage of the magmas available in the system is found in the shallow, peripheral chamber (the volume ratio V_1 to V_2), and (e) is the accumulation of the products discharged by the Klyuchevskaya group of volcanoes during the period from 1982 to 2008.

The volcano's activity in 1978–2008 can be divided into two periods [60, 62].

The first of these periods, 1978 to 1990, saw a gradual ascent of the absolute altitudes of adventive vents toward the volcano's summit; the summit crater was overfilled during adventive and summit eruptions and the lava flowed onto the volcano's slopes for a long period of time. The center of the effective pressure during these events in 1978–1988 was moving in the depth range from 3 to 17 km and was the shallowest in 1988, before the adventive eruptions ceased (Fig. 15a).

The quiescent period (1995–2002) involved uplift on the volcano's slope and magma storage in the intermediate chamber at depths of 25–30 km, (Figs. 14 and 15b). The coefficients A^1, A_3, and A_{25}, which characterize the effective excess pressure at a single pressure source with a variable depth and at two sources with their pressure centers at depths of 3 and 25 km, increased again and in 2001 reached the 1983 level, which was observed before the major eruption series of 1983–1990, shown in Figs. 15b and 15c.

Summit eruptions alone were occurring during the second period of activity, from 2001 to 2009, see Figs. 14 and 15e. The center of effective magma pressure was at a constant depth near 15 km; it was only toward the end of the series of summit eruptions that the center of magma pressure moved deeper to reach 21 km (Fig. 15a). The uncertainties in determining the depth of the effective pressure center lie in the range 1–3 km [60]. During that period considerable magma storage took place and the excess pressure in the volcano's plumbing system may have increased, as shown in Figs. 14 and 15b.

We calculated the volumes of possible pressure sources. The calculated values of pressure source volumes V_1 and V_2 are found from assumed values of excess magma pressure in these sources (4) (Fig. 15c). The spherical effective source of magma pressure is the simplest model. Actually, magma pressure may be caused by a set of interconnected magma chambers, may substantially increase as new magma comes in and new intrusions form, and may decrease as the magma flows out, the intrusions solidify, and individual magma bodies become temporarily isolated. For this reason the calculated volumes V_1, V_3, and V_{25} and relations between these can also serve as indicators of the intensity of intrusive processes in the volume occupied by the intermediate and peripheral chambers.

The volume ratio between the peripheral and intermediate chambers, V_1/V_2, varied between 0.1 and 1.0 at a constant excess pressure in the shallow chamber ($\Delta P_1 =$ 500 bars) and a variable excess pressure in the intermediate chamber (it was assumed that ΔP_2 was increasing from 300 to 500 bars as new magma was coming in during the period from 2001 to 2009) (Fig. 15d).

In the case where the excess pressures in the peripheral and the intermediate chambers were equal, $\Delta P_1 = \Delta P_2 =$ 500 bars, the average source volumes based on 15 measurements in 1982–2009 were equal to $V_1 = (15.2 \pm 8.4)$ km^3 and $V_2 = (95.0 \pm 64.6)$ km^3, and their ratio was 0.16 (Fig. 15). The excess pressure in the peripheral chamber varied within a restricted range, from 500 to 350 bars, as the crater bottom subsided by 600 m. For this reason the calculated changes in V_1 must have been largely controlled by changes in the volume of the pressure source and by the appearance and solidification of new dikes and sills in it.

As Klyuchevskoi Volcano showed the greatest activity during the period of alternating adventive and summit eruptions (1983–1990); the annual discharge of erupted products was equal to 175 million tons and was 2.1 times that during the next period of summit eruptions (2002–2008), (Figs. 14 and 15e). The average Klyuchevskoi discharge is 60×10^6 t/yr.

Figure 15d shows that the most intensive processes to occur in 1983–1988 included the increase in the relative size of the pressure source in the peripheral chamber and the transport of magma from great depths to the surface from the intermediate to the peripheral chamber.

A significant restructuring of Klyuchevskoi's activity in the period from 1930 to 2009 took place during geodetic measurements (1979–1989, 2001–2008) [60, 62, 68]. The results of these geodetic observations revealed a tendency towards uplifting for the northeastern slope of the volcano due to magma storage in the volcano's plumbing system (Fig. 14a). Significant uplift episodes were alternating with subsidences which accompanied the volcano's eruptions, both adventive ones and at the summit. A technique was used in data processing and interpretation which permitted extracting estimates for the volumes of magma chambers beneath Klyuchevskoi Volcano (the intermediate chamber at a depth of 25 km and the peripheral chamber at a depth of 3 km) from directly measured vertical displacements. Great changes in the plumbing system were detected. Considerable outflow of magma from the intermediate chamber and the movement of the pressure center to the peripheral chamber in 1983–1990 were determined, when a series of 10 adventive and summit eruptions occurred discharging large magma volumes. During the period 2003–2009, when summit eruptions only occurred, inflow and storage of magma in the intermediate chamber were taking place.

The above approximate estimates for the volumes V_1 and V_2 for the effective sources of excess magma pressure show (Fig. 15) that the scale of intrusive activity in the crust–mantle layer and in the lower crustal layers at depths near 25 km during 1982–2009 was on the average 6 times that at a depth of about 3 km. The ratio was approximately 4 during the series of Klyuchevskoi adventive and summit eruptions in 1983–1988, and approximately 7 during the 2003–2009 Klyuchevskoi summit eruptions.

3. DATA FROM SEISMIC TOMOGRAPHY ON THE DEEP STRUCTURE AND MAGMA SOURCES OF THE KLYUCHEVSKAYA GROUP OF VOLCANOES

At present one of the most advanced and fruitful geophysical methods is seismic tomography; it uses certain features in the propagation of earthquake seismic waves to deduce the 3-D velocity structure of the crust and upper mantle, where the rocks are traversed by ray paths [34, 37, etc.]. Basically similar methods have been used in Kamchatka since 1956 to study velocity variations in the crust and upper mantle and for detecting magma chambers [16, 41, 48, 64, etc.]. These methods were further developed in the tomographic investigations of deep structure and geodynamics for the Kamchatka segment of the Kuril–Kamchatka island arc, the region where it intersects the Aleutian arc, and for the Kamchatka volcanic centers, in particular, the Klyuchevskaya group of volcanoes [14, 72, 73, 75, 76, 79, etc.].

Section 3 gives an account of the seismic tomography results obtained by a research team at the Institute of Volcanology and Seismology, FED RAS, the Institute of the Geodynamics of Geospheres, RAS, and the University of Zurich, Switzerland [79, etc.]. The 3-D images were calculated using the same method with station data (arrival times of *P* and *S* waves) as found in various catalogs made by the Kamchatka Branch of the Geophysical Service of the RAS (KB GS RAS). The velocity (regional) model for the crust and upper mantle was developed from the data of regional earthquakes as recorded by the Kamchatka network of stations during the period 1971–2003. Simultaneously with this, a more detailed (local) crustal velocity model was constructed directly for the Klyuchevskaya group of volcanoes area. The input data were digital records of volcanotectonic (VT) earthquakes made by 12 telemetry stations operated by KB GS RAS during 2000–2004.

The interpretation of *P* and *S* arrival times involved several main steps, including calculations of station corrections and the optimal 1-D velocity models, which provide the minimum mean value of the travel-time errors for all earthquakes (1), revision on this basis of hypocentral coordinates for the earthquakes selected from the catalog (2), and estimating the resolution capability and modeling of the 3-D velocity structure (3). Questions involved in the selection of earthquakes that have been reliably located by the available network are set forth in [79]. The regional model is based on 6561 selected events and the local model is based on 11357 events. The calculation of 1-D models for the eastern Kamchatka and the Klyuchevskaya group of volcanoes was carried out using the VELEST program [74]. After this, the coordinates of all the hypocenters were revised according to the new travel times, which were calculated by the SIMULPS14 program currently in wide use. The 3-D images used the following parameterization: the earth properties were averaged by rectangular blocks with sides 30 × 30 × 20 km for the regional model and 10 × 10 × 5 km for the local model. When choosing the size of the blocks, one had to consider the frequencies of the seismic signals excited by regional and volcanotectonic earthquakes (1 and 5 Hz, respectively), the a priori errors in the input data, and the deep structure of the object under study. The P-wave wavelengths are 8 and 1.5 km at these frequencies, and smaller bodies cannot be detected.

The paths of calculated seismic rays encompass the crustal and upper mantle volume under study so as to achieve the best resolution in the depth interval 20–120 km for eastern Kamchatka and 5–40 km beneath the Klyuchevskaya group of volcanoes.

The 3-D images of deep velocity models derived from *P* and *S* wave data as distributions of the parameters V_p, V_s, and V_p/V_s are presented in this paper as their vertical cross sections, onto which the earthquakes are projected from a band ±10 km wide on regional profiles and ±5 km on local ones, respectively, see Figs. 16 and 17.

Figure 16 illustrates a cross section along a line which traverses the Klyuchevskaya group of volcanoes in the northern part of the Central Kamchatka depression from northwest to southeast and the water area of the Kamchatskii Bay, and nearly reaches the Kuril–Kamchatka trench. The geometry of the Benioff zone and the properties of the Pacific plate experience a significant change there [38, 39, 59, etc.]. This is probably related to the close proximity of the underwater Emperor seamounts to the coast of the peninsula in the Kamchatskii Bay area. Several different geodynamic reconstructions have been proposed for this area in order to provide an explanation of the vigorous volcanism of the Northern group of volcanoes in Kamchatka [38, 73, etc.].

It follows from the V_p cross section in Fig. 16a that the mantle lithosphere is not thick in the area, viz., 20–30 km. The asthenosphere layer that is related to the roots of mantle magma supply to the Klyuchevskoi volcanoes can be clearly identified from a low velocity anomaly in the depth range 80–130 km, which begins nearly from the top of the high-velocity Benioff zone. The V_p velocity is abnormally high in the zone, 8.5–8.7 km/s, which may be due to velocity anisotropy.

The V_p velocity cross section (Fig. 16b) exhibits a nearly vertical low velocity anomaly—probably a highly permeable zone where the conduits are situated supplying hot material (magmas, fluids, and melts) to the crust from depths of 120–130 km.

The crustal velocity structure directly beneath the Klyuchevskoi group of volcanoes, as derived from the processing of volcanotectonic earthquakes, is illustrated by a northeast-striking vertical cross section traversing the 3-D V_p and V_s models along the axial line of volcanoes (Figs. 17a and 17b). The crustal structure is clearly reflected in velocity anomalies. The most intensive low velocity anomaly occurs in the lower crust; its center is at a depth of ~25 km, it is 7–10 km thick and the anomaly

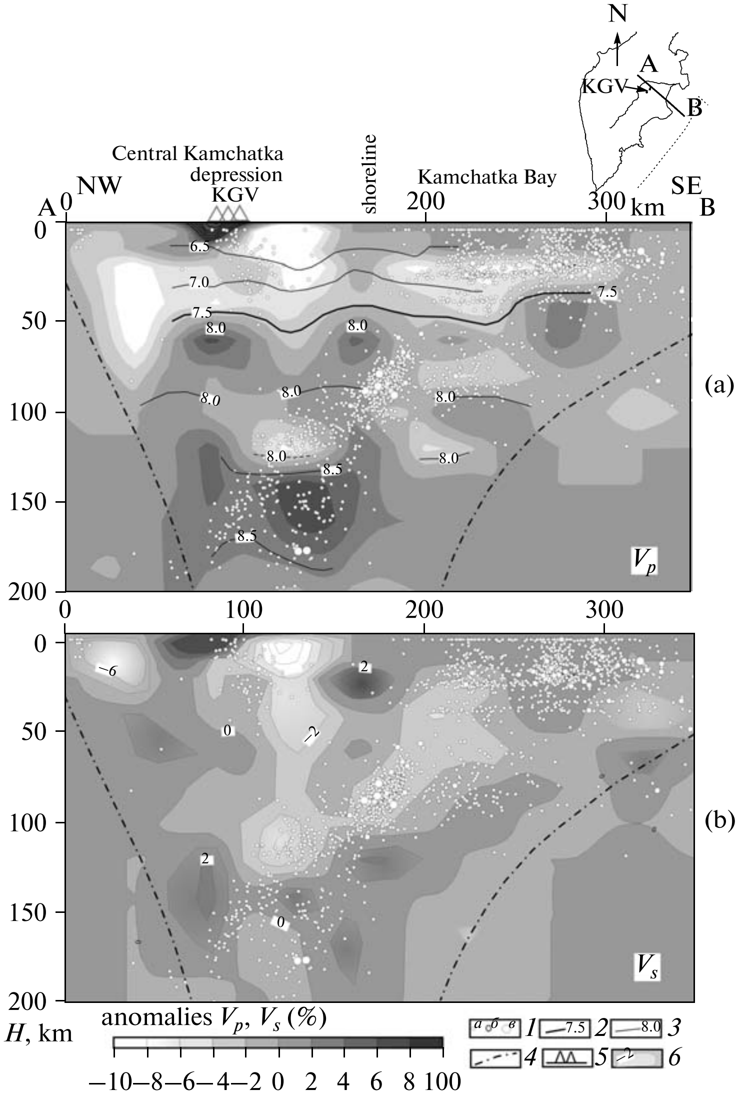


Fig. 16. Vertical cross sections of the 3-D tomographic model of the crust and upper mantle along AB based on arrival times of *P* and *S* waves from regional Kamchatka earthquakes (a and b), respectively: (*1*) hypocenters of earthquakes with energy class $K_s \approx$ 10–11 (a), $K_S \approx$ 11–13 (b), $K_S >$ 13 (c); (*2*) isolines of V_p = 7.5 km/s corresponding to the Moho, (*3*) other isolines of V_p in lithosphere and asthenosphere, (*4*) lines that confine the area of reliable inference in the cross section, (*5*) volcanoes, (*6*) identified V_s anomalies. The inset shows the AB line and the Klyuchevskaya group of volcanoes (KGV). The hypocenters were taken in a band ±10 km wide.

strength in V_p is 8–10% (Fig. 17a), which, in V_s is less pronounced, about 2–4% (Fig. 17b). The region of this anomaly has generated long-period earthquakes with clearly discernible *S* waves in the records [15]. A joint analysis of velocity data and seismicity suggests a relationship between this anomalous zone and the intermediate magma chamber of Klyuchevskoi Volcano. A second intensive low-velocity anomaly (up to 14–16%) was identified in the volcano-sedimentary layer; its center is situated at a depth of about 5 km. The latter anomaly (with due account for petrologic data) is interpreted as the shallow peripheral chamber of Klyuchevskoi Volcano [69].

One variant of the calculated 3-D V_p velocity model is also reported in [75, 76]. These authors relate a conical low velocity anomaly in the lower crust, which was identified in the 35–22 km depth range, to the intermediate magma chamber. The velocity anomaly in the lower crust thus shows sufficient contrast and is clearly identified from a variety of data (both analog and digital) and by different methods of data interpretation.

The zones of low velocity parameters (V_p, V_s, and V_p/V_s) as detected by seismic tomography in combination with previous data from controlled-source seismology (using the correlation method of refracted waves and deep seismic sounding) [2, 4, 14, etc.] give us some idea of the magma chambers beneath the Klyuchevskaya group of volcanoes and the possible channelways for magma ascending from the upper mantle to the intermediate and

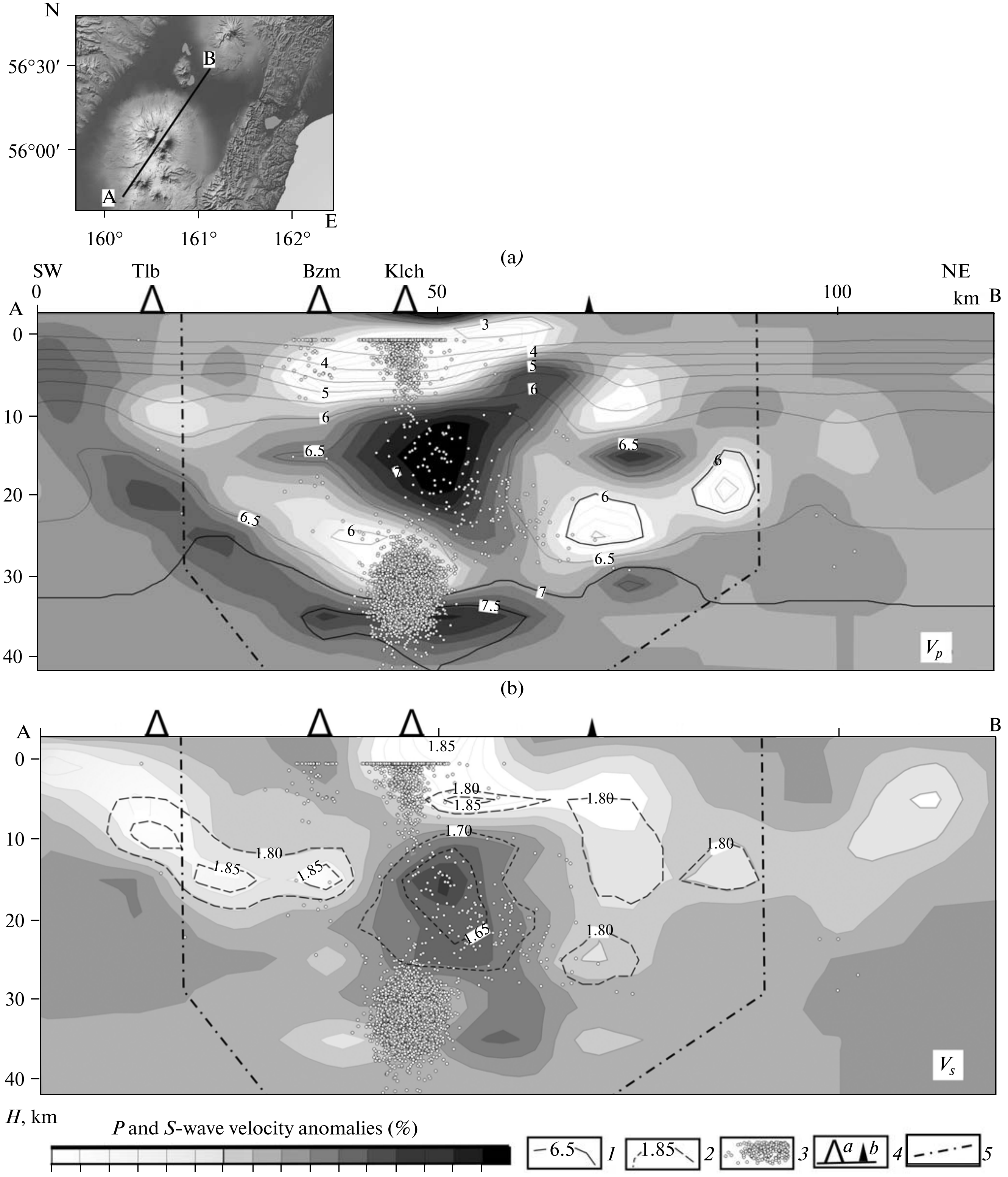


Fig. 17. Vertical cross sections of the 3-D velocity model for the crust based on arrival times of *P* and *S* waves from volcanotectonic earthquakes (a and b), respectively: (*1*) isolines of absolute values of V_p, km/s, (*2*) isolines of the parameter V_p / V_s, (*3*) hypocenters of volcanotectonic earthquakes ($K_S \geq 5.5$), (*4*) volcanoes: (a) Tolbachik (Tlb), Bezymyannyi (Bzm), Klyuchevskoi (Klch); (b) Kirgurich cone, (*5*) lines that confine the area of reliable inference in the cross section. The inset shows the AB line. The hypocenters were taken in a band ±5 km wide. Volcanoes and the areal Kirgurich cone are plotted in Figs. 1 and 13.

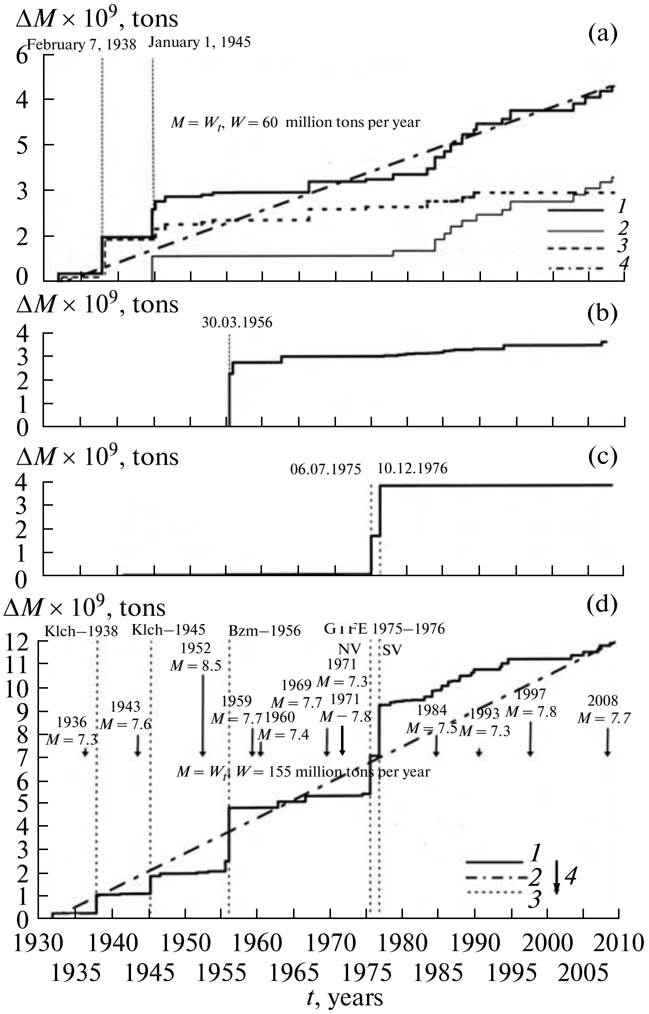


Fig. 18. Increase in total weight of juvenile erupted products for the entire KGV and its principal volcanoes, Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik. (a) plots for Klyuchevskoi Volcano: (*1*) discharge of all eruptions of the volcano, (*2*) discharge of adventive eruptions, (*3*) discharge of summit eruptions, (*4*) average plot for all eruptions; (b) plot for Bezymyannyi Volcano; (c) plot for Ploskii Tolbachik Volcano and the Tolbachik zone of cinder cones; (d) plot for the entire KGV: (*1*) total plot, (*2*) total plot's average line, (*3*) dates of major eruptions, (*4*) years and magnitudes of $M \geq 7.3$ Kamchatka earthquakes for the period 1930–2008 (the map in Fig. 4).

peripheral chambers, as well as the relationships and magma movements between the chambers and the magma sources for the volcanoes of the Klyuchevskaya group.

4. PROPERTIES OF THE KGV PLUMBING SYSTEM

As was noted in the Introduction, the properties of the magmatic plumbing systems for volcanoes of the Kuril–Kamchatka arc and Klyuchevskoi Volcano were considered previously in [52, 53, 56, 60, 61]. Geophysical models for these have been developed. The last description of one such model can be found in [60, 62]. These studies were based on the data on eruptions, seismicity, ground deformation and other geophysical data, with appeal to the theory of the mechanism of volcanic activity. This section contains a similar discussion of the features, properties, and mechanism of activity for the plumbing system of the entire KGV. We use and summarize the results set forth in sections 1 through 3, information from previous publications, additional evidence relating to the properties of the plumbing systems, as well as data on the deep structure and rock petrology of the KGV. In all, five basic parts can be distinguished in the KGV plumbing system, similarly to what was found in previous publications. The present section is concerned with the properties of the two upper parts of that system, those in the crust and in volcanic edifices. The plumbing system has undergone drastic changes in the course of the KGV's long-term evolution. The present-day state of the system is discussed with additional information and estimates.

The upper part of the plunging Pacific plate, at a depth of approximately 160 km beneath the KGV. The source of material and energy. Section 1 contains seismological evidence to show that it is at this depth that the source of energy and volatiles necessary for magma generation is situated (Fig. 4). The heat that is released from deformation in the Benioff zone can be sufficient to start partial melting. One notes that some opinions exist that are different from those given here. For example, [77] contains the conclusion that such heating is not the primary source of melting near the top of the plunging plate. However, the authors did not properly take into account the enormous energy released by earthquakes that occur there.

Figure 18 shows plots of volcanic and magmatic activity beneath the KGV and demonstrates some relationships between these and the processes occurring in the Benioff zone of Kamchatka. Figures 18a–18d contain plots of the cumulative total weight of juvenile volcanic rocks discharged in 1930–2008 by the Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik volcanoes, together with the Tolbachik zone of monogenic cones and by the entire KGV. The total average magma discharge from these volcanoes of the KGV (155 million t/yr) was more than half the total magma discharge from all 70 active volcanoes of the Kuril–Kamchatka arc (250 million t/yr). Most of the output occurred during the following eruptions: 1938, Bilyukai, the largest adventive eruption on Klyuchevskoi; 1945, a paroxysmal eruption of Klyuchevskoi Volcano; 1956, an explosion of the andesitic Bezymyannyi Volcano; 1975–1976, the Great Tolbachik Fissure Eruption [19] (Fig. 18). One notes the remarkable fact that the rare catastrophic eruption of the giant andesitic Shiveluch Volcano, 80 km northeast from Klyuchevskoi, occurred in 1964 [18, 19].

Figure 18d indicates the years and magnitudes of the $M \geq 7.3$ earthquakes which occurred in Kamchatka dur-

The 1930–2008 Kamchatka earthquakes, $M \geq 7.3$

Date: year, month, day	Time: h, min	North lat., deg	East lon., deg	Depth, km	Magnitude M
1936.11.13	12 31	56.2	163.3	10–40	7.3
1943.11.28	17 11	54.9	156.8	350	7.6
1952.11.04	16 58	52.3	161.0	10–40	8.5
1959.05.04	07 15	53.1	160.3	20	7.7
1960.10.28	13 18	51.8	157.8	110	7.4
1969. 11.22	23 09	57.8	163.6	20	7.7
1971.11.24	19 35	52.7	159.5	125	7.3
1971.12.15	08 30	55.9	163.4	30	7.8
1984. 2.28	10 38	56.2	163.4	19	7.5
1993.06.08	13 03	51.2	157.8	40	7.3
1997.12.05	11 35	54.6	162.5	10	7.8
2008.07.05	02 12	54.1	152.2	650	7.7

Note: For epicenter map see Fig. 4.

ing the period from 1930 to 2008. The basic data on these events are given in the table (see p. 28); the epicenters are shown in Fig. 4. All the four major eruptions in the KGV were preceded by $M \geq 7.3$ earthquakes occurring in the Benioff zone of Kamchatka 2–4 years before the eruptions. The $M = 7.7$ earthquake, which occurred on May 4, 1959 (Fig. 4, table) preceded the catastrophic explosion of Shiveluch Volcano, which took place on November 12, 1964 [18, 19]. There was a considerable increase in the summit activity of Klyuchevskoi Volcano (Figs. 11 and 18) after the earthquakes of December 28, 1984, $M = 7.5$ and December 5, 1997, $M = 7.9$, which occurred in the KGV area (Fig. 4 and table). The most conspicuous phenomenon of this kind was observed in Kamchatka in the early 20th century, on March 25, 1904, when two $M = 7.7$ earthquakes occurred off the Pacific coast of southern Kamchatka, while on March 28, 1907, 100 km from that location in the Ksudach caldera, the greatest eruption of the early 20th century in Kamchatka took place, discharging 3 km^3 rocks [18, 31]. These data show that major eruptions took place in the KGV a few years after great earthquakes and increased activity of deep-seated processes in the Benioff zone of Kamchatka.

The segment of the Benioff zone beneath the KGV where magma generation begins extends for about 100 km along the Kuril–Kamchatka arc. Seismological evidence for the thickness of the underthrusting plate gives the figure 50 km [59]. According to geodetic data, the plate moves at a rate of 8–10 cm/yr. Using these data, we deduce that the part of the plate that is annually submerged under the KGV has a volume of approximately 0.5 km^3 and weighs 1.5×10^9 tons. According to Section 2 and Fig. 18, the average annual discharge from the greatest KGV volcano, Klyuchevskoi, is equal to 60×10^6 t/yr, while the figure for the entire KGV was 155×10^6 t/yr during the very active period from 1930 to 2008. The weight of all discharged KGV rocks thus amounts to 4–10% of the weight of the plunging plate. The percentage may be a few times greater for the top of the plate.

The area of the Benioff zone beneath the KGV is 10000 times the crater area of the active KGV volcanoes. The ascent of magmas results in an enormous concentration of material and energy in the asthenosphere and lithosphere. This process can begin from the top of the Benioff zone.

The asthenosphere, the region of magma generation and ascent toward the intermediate magma chambers in the KGV, depths of 160–40 km. According to geophysical and geochemical data, partial melting of mantle material and the generation of deep-seated magmas beneath the KGV are taking place in the lower asthenosphere. Melting is intensified as volatiles come in from the plunging plate and because of decompression as the material that is melting is ascending. The principal force that is responsible for magma ascent is due to decreased density of molten rocks. The ascent of magmas in the asthenosphere can occur by gravitational convection in diapirs, asthenoliths, magmatic asthenosphere columns, and jets. The most rapid ascent can occur in extended magmatic asthenosphere columns. There are calculations of dimensions, velocities and magma discharges for these [56, etc.].

Magma can also rise in solitons along vertical, cylindrical channelways in a viscous host rock [22]. Magma ascent along thin vertical fissures is little likely to occur above the zone of initial melting, because such fissures rapidly solidify.

Seismic tomography shows that there is a region of low shear velocity in the KGV area extending upward from the Benioff zone toward the crust, see Section 3 (Fig. 16b).

The excess magma pressure depends on the difference between the densities of the magma and the host rocks and on the vertical extent of magma conduits. The density difference between crystalline rocks and their melts is near 0.1 g/cm^3 when half of the material has been melted [80, etc.]. With so small a density difference the excess magma pressure ΔP in the upper part of an asthenosphere conduit will be above 300 bars, if its height is greater than 30 km. Such estimates show the minimum values of ΔP under the crustal bottom during the ascent of ultramafic magmas. When the base of a magmatic asthenosphere column is at a depth of 150 km or when basaltic or andesitic magma is rising in it, and the difference in density between magma and host rock $\Delta\rho$ is about 0.5 g/cm^3, we find that the excess pressure of deep-seated magmas at the crustal bottom equals 1000–2000 bars [56]. Basaltic and andesitic magmas must quickly be squeezed from under the crust. The excess pressure of deep-seated magmas at the crustal bottom is frequently in the range 500–1500 bars.

Approximate estimates of the excess magma pressure show that, assuming the average magma density to equal 2.85 g/cm^3, one finds that the base of the continuous magma conduit extending from the asthenosphere as far upward as the Klyuchevskoi crater must be at a depth of about 60 km [62, etc.]. The principal mantle conduit of the KGV is at present beneath Klyuchevskoi Volcano, whose age is about 6000 years. It is along this conduit that more than 75% of all KGV mantle magma is supplied. In Pleistocene time there must have been another magma conduit beneath the giant Ushkovskii Volcano, which is becoming extinct in Holocene time. Another active Hawaiian-type volcano, Ploskii Tolbachik, together with its Tolbachik zone of cinder cones (see Introduction and Section 1.2) is the second only to Klyuchevskoi in output in the KGV during Holocene time. According to [6, 19], these vents have discharged an average of 20 × 10^6 tons of basalt per year in the Holocene. Ploskii Tolbachik might have a conduit of its own, but we possess no definite geophysical evidence for its existence at present.

The crust–mantle layers and the lower crust, the intermediate magma chamber, depths of 40–25 km. According to data on the KGV deep structure [2, 3, etc.], the average depth to the bottom of the crust–mantle layer beneath the KGV is equal to 40 km, the crystalline part of the crust is at depths of 25–7 km, while the sedimentary layers of the crust lie above 7–5 km. The character of the KGV magmatic activity experiences a change above that boundary. Under it, in the upper mantle, the initial melting and ascent of magmas occur. The processes above it include magma storage, the generation of the KGV intermediate magma chamber, conduits, crustal magma chambers beneath their respective volcanoes, and terminal conduits.

Figure 19 presents a diagram of the structure and a geophysical model for the upper parts of the KGV plumbing system above the mantle on a vertical cross section passing along the KGV axial line through the active Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik volcanoes. This figure shows the earth properties beneath the KGV: the average depths of the crust–mantle, "basaltic," "granite," and sedimentary layers, the depth-dependent variation in rock temperature and density, as well as the terrain relief along the cross section. Also shown are the positions and dimensions of magma chambers of volcanoes and their vertical conduits, storage regions of magnesian basalts, conduits of adventive and areal eruptions, observed and hypothetical channelways for magma movement in layers of neutral buoyancy in the KGV. Figure 19 shows how the KGV magma chambers can be connected. We indicate approximate volumes of the magma chambers, the excess magma pressure in these, as well as the content of SiO_2 and MgO (in %) in various places of the KGV plumbing system. Below we discuss several properties of the model.

The rock density in the crust–mantle layer decreases from 3.2–3.3 g/cm^3 in the upper mantle to 2.9–3.1 g/cm^3 in that layer [2, 53]. The excess pressure of ultramafic and basic magmas which are uprising from the mantle becomes the greatest, creating the most favorable conditions for the storage of these magmas and their emplacement in the host rocks along layers of neutral buoyancy. The density of the magma in such layers is equal to that of the host rock [77]. Because the rock temperature is 500–800°C there, only plastic or elastoplastic deformation which can occur [53, 62, etc.].

According to seismological and geodetic data, see Sections 1.3 and 2, the Intermediate magma chamber of Klyuchevskoi Volcano or the magma storage region beneath it is situated at depths of 35–25 km. This location is identified from swarms of small earthquakes with many long-period earthquakes among these, which are characteristic for volcanic roots (Fig. 12). It has long been hypothesized that dehydration can occur in the crust–mantle layer [2, etc.]. This intermediate chamber is the source of basalt for the summit and adventive eruptions on Klyuchevskoi. It is from there that intrusions of ultramafic and basic magmas can be emplaced; these magmas are moving beneath the KGV along layers of neutral buoyancy near the crustal bottom at depths of 20–30 km. The process may give rise to various sheet magma bodies.

The volume of that chamber was estimated from the amount of rocks discharged by Klyuchevskoi major eruptions and from the pressure decrease in the chamber after eruptions [53, etc.]. The adventive Bilyukai eruption of 1938 discharged 310 × 10^6 m^3 of high-magnesian basalts [60, 68, etc.], see Fig. 13. Major summit eruptions of the volcano resulted in the crater bottom subsiding by 600 m, the magma pressure in the chamber being diminished by 150 bars. The pressure decrease after the GTFE was 100–250 bars [6]. Assuming the 1938 eruption to have diminished the magma pressure by $\Delta P = 150$ bars and the bulk

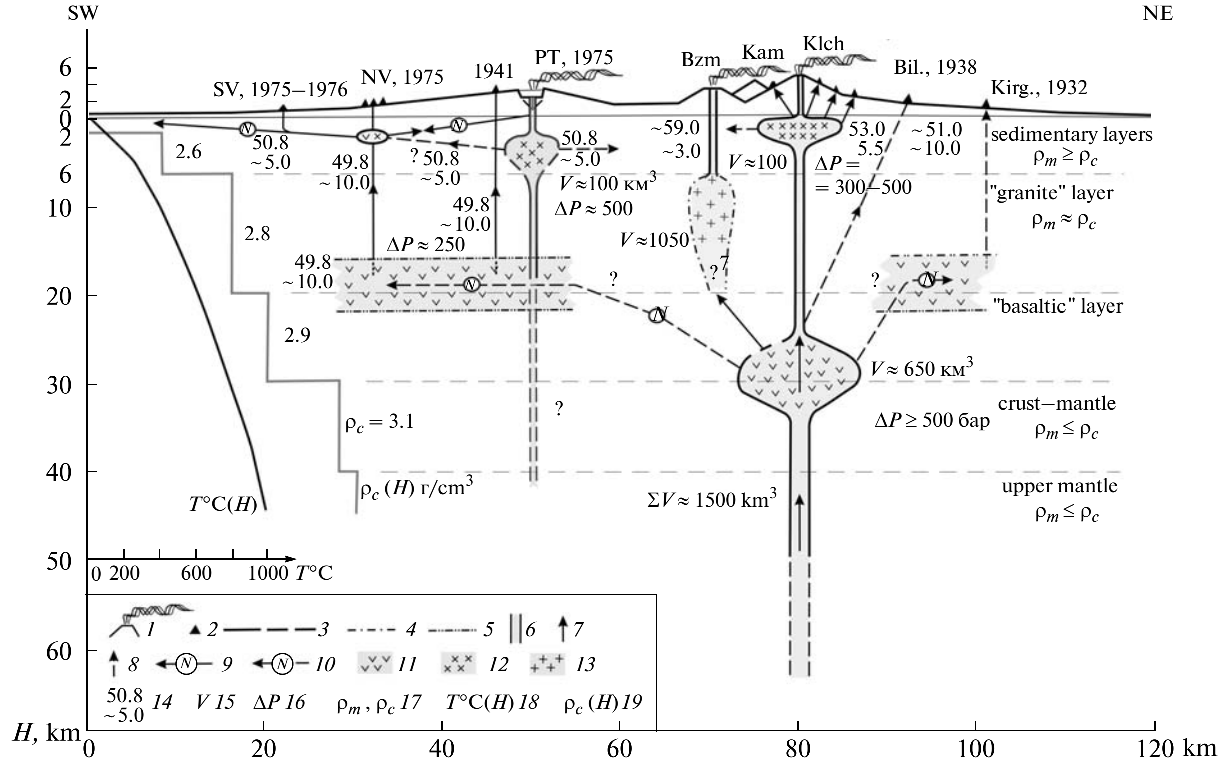


Fig. 19. The KGV plumbing system: present-day structure, movement and storage of magmas. Geophysical model. Vertical cross section along the KGV axial line: (*1*) active volcanoes, (*2*) cones of 1930–2008 monogenic eruptions, (*3*) boundaries of basaltic magma chambers, (*4*) boundary of a possible source of andesite magmas for Bezymyannyi Volcano, (*5*) possible boundaries of storage and movement regions for magnesian basalts, (*6*) vertical conduits, (*7*) observed locations of magma ascent, (*8*) possible lines of magma ascent, (*9*) observed magma movements in layers of neutral buoyancy, (*10*) possible magma movements in layers of neutral buoyancy, (*11*) magnesian basalts, (*12*) alumina basalts, (*13*) andesite, (*14*) concentration of SiO_2 and MgO in magmas, %, (*15*) volumes of magma chambers, km^3, (*16*) excess magma pressure, in bars, (*17*) rock and magma densities, ρ_m and ρ_c, g/cm^3, (*18*) variation in rock temperature with depth, T°C (H) km, (*19*) rock density variation with depth, $\rho_c(H)$, g/cm^3. Locations of active volcanoes in the KGV, the 1932 areal Kirgurich eruption, the 1938 adventive Bilyukai eruption, the North and South vents of the 1975–1976 GTFE as shown in Figs. 1, 2, and 13.

modulus of the magmas to be $K = 3 \times 10^5$ bars, as was the case during the GTFE [51], then the magma volume in the intermediate chamber of Klyuchevskoi Volcano might well be 650 km^3 (380 and 940 km^3 for pressure decreases of 100 and 250 bars). The chamber location is shown in Fig. 19, which displays the locations of the KGV magma chambers at depths shallower than 60 km along the KGV axial line.

A few words of explanation are in order to clarify the method we use for approximate estimation of the volumes of magma chambers and magma sources. The method was considered in [51, 54]. The desired volume can be found from the relation

$$\Delta P = -K(\Delta B + D)/B, \qquad (8)$$

where ΔP is the decrease in magma pressure during an eruption, K is the bulk modulus of the magma (its reciprocal is compressibility $1/K = \beta$), ΔB is the volume of erupted magma, D the volume of the intrusions produced by eruption, and B the desired volume of the magma source [51]. The choice of the value of β must consider the fact that the compressibility of magma decreases with increasing chamber depth and rock pressure, but increases by a factor of 5 in the interval of magma melting [27, 80]. Relation (8) does not incorporate the magma storage due to the rocks around the chamber being compressed, and it gives upper bounds on chamber volume. The volume of the magma source is below the value derived from (8) by 0.2 of the value for spherical chambers, by 0.3 for cylindrical chambers, and by 0.4 for lenses, with the ratio of thickness to length being equal to 1/10. Relation (8) cannot be used to estimate the volume of the magmas in dikes [54].

According to seismological data, see Section 1.3, the supply of mantle magma into the intermediate chamber of Klyuchevskoi Volcano does not occur at a uniform rate. Judging by the earthquake swarms in the chamber, the supply lasts from one to three quarters of the time during different periods.

The crust–mantle layer is the principal storage location for mantle magmas in the KGV. Geodetic estimates (Section 2) and calculations of magma volumes in magma sources (the present section), the layer contains more than 80% of all KGV magmas and most intrusive activity may occur there.

Magma chambers and conduits, magma movement in the crust beneath the KGV. Depths of 25–5 km, 5–0 km, and volcanic edifices. The present section considers the properties of these two upper parts of the plumbing systems in conjunction. We preface the discussion by giving some brief information on the crustal magma chambers and conduits of active volcanoes in the KGV.

The properties of these two parts of the Klyuchevskoi plumbing system can be found in [60, 62, etc.]. The depth range from 25 to 5 km contains a continuous, vertical magma conduit along which magma is rising from the intermediate chamber to depths of 5 km or less into the sedimentary layers that underlie the volcano and into its edifice (Fig. 19). This region contains the upper magma storage area, the peripheral chamber, the source of basaltic magmas for the summit and adventive eruptions of Klyuchevskoi Volcano. The excess magma pressure can reach 500 bars and be diminished by 100 bars or more during major eruptions. Many radial dikes are generated to supply adventive eruptions with magma as far as 20 km from the volcano's summit [53].

The upper bound on the volume of the Klyuchevskoi peripheral chamber was obtained from the amount of lavas discharged by the largest adventive eruption of high alumina basalts on the volcano. This was the Piip eruption, which began on October 6, 1966 in the middle of the volcanic cone at an altitude of 2000 m and at a distance of 6 km from the summit. The output of high alumina basalts was 90×10^6 m^3 over 3 months time; the basalts were stored in the top of the Klyuchevskoi plumbing system [32, 60, 68]. The magma compressibility is greater there because confining pressure decreases with depth. When $\Delta P = 150$ bars and $\beta = 6 \times 10^{-6}$ bar^{-1}, we obtain the result that the volume of the peripheral chamber is $B \leq 100$ km^3 (Fig. 19).

According to geodetic and seismological data, Sections 1, 2, etc., magma ascent from the intermediate to the peripheral chamber begins a few months before a summit eruption.

Seismic probing of the KGV [2, 3, etc.] revealed that the crustal magma chamber of the andesitic Bezymyannyi Volcano may be at depths of 5–10 to 20 km beneath the volcano (Fig. 19). This is confirmed by clusters of small earthquakes occurring beneath the volcano down to depths of 15 km (Fig. 12). A catastrophic eruption of Bezymyannyi occurred on March 30, 1956 discharging fresh pyroclastic andesite flows from the crater produced by the explosion, 1 km^3 in volume and with a density 2 g/cm^3 [17]. The new crater was 600–700 m deep, and the pressure at the source was diminished by 150 bars. The magma chamber of Bezymyannyi Volcano is centered 10–15 km higher than the Klyuchevskoi intermediate chamber, and the magma compressibility is greater in it. Assuming $\beta = 5 \times 10^{-6}$ bar^{-1} or $K = 2 \times 10^5$ bars, we obtain the result that the source that supplied magmas for the catastrophic eruption of Bezymyannyi Volcano might be as large as 1050 km^3 in volume (Fig. 19).

A Hawaiian-type caldera 3 km in diameter is situated on top of the basaltic Ploskii Tolbachik Volcano. The top of the magma chamber beneath the caldera is at a depth of 2 km, and the chamber is 4–5 km across, see Figs. 8 and 19. The chamber contains megaplagiophyre alumina basalts, see Section 1.2. A collapse crater 100–200 m deep had been in the volcano's summit caldera prior to the GTFE, with a lava lake appearing and disappearing on the bottom. At that time the plumbing system of the volcano was in a stationary state. The excess magma pressure in the plumbing system was estimated for the crustal density profile beneath the KGV given in [2]. Assuming the magma of megaplagiophyre alumina basalts to have a density of 2.65 g/cm^3, we obtain the result that the source of these magmas beneath Ploskii Tolbachik Volcano is deeper than 23 km, and the excess magma pressure is equal to 300–bars at the bottom of the sedimentary layer at a depth of about 7 km (Fig. 19).

Magnesian basalts are rocks of the most basic composition in the KGV. They were erupted again in 1975 at the North vent of the Great Tolbachik Fissure Eruption in the Tolbachik zone of cinder cones 18 km southwest from the summit caldera of Ploskii Tolbachik [6]. According to seismological and geodetic data, Section 1.2, the source of those basalts was at a depth of 16–22 km beneath the North vent, Figs. 6, 7, and 19. The excess magma pressure near the ground surface was equal to 100–250 bars [67]. The preceding eruption of high-magnesian basalts took place in that zone of cinder cones during May 5–14, 1941 at a distance of 4 km from the summit caldera (Fig. 19). Less than 2000 years ago high-magnesian basalts were erupted in that same zone 27 km from the summit caldera [6, 19]. The source of these eruptions was the segment of the conduit that allows passage for the KGV magnesian basalts; the segment is situated in the lower half of the crust under the southwestern end of the KGV axial line (Fig. 19).

Geophysical data [6] were used to determine the location of a chamber at a depth of 2–4 km beneath the GTFE North vent; the chamber was formed at the beginning of that eruption. The chamber may have been responsible for mixing of magnesian and megaplagiophyre alumina basalts during the GTFE (Fig. 19).

Magmas are supplied to peripheral chambers and to the craters of active central-type volcanoes along extended vertical conduits, i.e., the channelways for magmas coming to the locations of hundreds of monogenic cones, with adventive eruptions and extrusions in the KGV being fissures that solidify after eruptions [56, etc.]. The volume of hundreds of radial dikes as long as 20 km beneath Klyuchevskoi Volcano may equal the volume of the entire edifice [53, etc.]. The dikes of its adventive eruptions are shown diagrammatically in Fig. 19.

Quick emplacement, mixing, and flow of basalts was occurring for one and a half years during the GTFE at depths of a few kilometers for 50 km along the Tolbachik zone of cones, see Section 1.2 (Figs. 8–10 and 19). This magma movement was similar to that of basalts in zones of neutral buoyancy along volcanic rifts in Iceland and other regions [77, etc.].

The magma pressure decrease during the GTFE, 100–250 bars, the mass of erupted basalts, 3.8×10^9 tons, and the magma bulk modulus $K = 10^5$ bars were used to derive an approximate volume of that part of the plumbing system from which magmas were issuing during the GTFE; this figure might well be $(1.6–4.0) \times 10^3$ km^3 [51].

The total volume of the magma chambers of the active Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik volcanoes shown in Fig. 19 is below 1.9×10^3 km^3. Based on these approximate estimates, we infer that comparable magma volumes in the KGV may reside in the magma chamber of the decaying Ushkovskii Volcano, in the large intrusions throughout the KGV, and in the magma channelways beneath the KGV axial line. Mantle magmas are probably for the most part emplaced and stored at the base of the crust.

The above estimates are consistent with determinations of the volume ratios between the pressure sources in the peripheral and intermediate chambers of Klyuchevskoi Volcano obtained from geodetic data. The latter yield the result that the scale of intrusive activity beneath Klyuchevskoi Volcano at depths of 25 km is six times that at a depth of about 3 km, see Section 2.

The interrelationships among magma chambers and sources over the entire KGV area could be seen during the greatest basaltic eruption (GTFE) in 1975–1976 and subsequent eruptions in 1977–1978, see Section 1.2 and [6].

Below we list some information obtained from petrologic studies and construction of petrologic geochemical models for the KGV; this information may furnish some explanation of these relationships.

The eruptions of the most basic rocks in the KGV, magnesian basalts, only occur in the Tolbachik zone of cones, for 30 km from the summit caldera of Ploskii Tolbachik, and in the areal zone of cones 10–20 km northeast from the Klyuchevskoi crater [10, etc.]. These places lie at the ends of the KGV axial line passing through Klyuchevskoi, Bezymyannyi, and Ploskii Tolbachik volcanoes along the trend of the Kamchatka volcanic belt (Fig. 1). The layer of neutral buoyancy for magnesian basalts, which can transport these in the basaltic crustal layer beneath the KGV, must extend along the KGV axial line (Fig. 19).

The basaltic magmas of Klyuchevskoi Volcano and the andesitic magmas of Bezymyannyi Volcano have a common deep-seated source; their channelways branch out at a depth of about 30 km. This is confirmed by the fact that when either of the adjacent Klyuchevskoi and Bezymyannyi volcanoes shows increased activity the other is quiescent [32, etc.].

A genetic relationship between the magmas of Klyuchevskoi, Bezymyannyi, and Kamen' volcanoes is quite probable. The active Klyuchevskoi and Bezymyannyi volcanoes formed in the Holocene at the edges of the extinct Upper Pleistocene Kamen' Volcano. These three volcanoes are arranged in a 10-km row along the KGV axial line (Fig. 1). Ushkovskii Volcano, which shows little present-day activity, has a different mantle source [70]. These conclusions from petrologic research are corroborated by data on the distribution of earthquake hypocenters beneath the KGV (see Section 1.3, etc.) and are consistent with the geophysical model (Fig. 19). The model sheds light on the positions, significance, and relationships among the magma chambers of the three volcanoes referred to above in the entire plumbing system of the KGV.

The high-magnesian and high-alumina magmas of Klyuchevskoi Volcano are generated during the ascent and differentiation of mantle magmas in the channelways and chambers of the KGV plumbing system situated beneath the volcano in the asthenosphere, in the transitional layer, and in the crust [32, 69, etc.]. According to seismological and geodetic data (see sections 1 and 2) the time intervals during the period from 1978 to 2008 when magma was rising from the intermediate chamber of Klyuchevskoi Volcano toward its peripheral chamber lasted less than a third of this time. The longest periods of time were those which favored magma differentiation.

Magmas of magnesian alumina basalts and andesites are generated in the KGV plumbing system (see the Introduction etc.). Eruptions of alumina basalts are occurring throughout the KGV area, but andesites are discharged in its middle only (see the Introduction and Figs. 3 and 19). According to the properties of the geophysical model, the movements of alumina basalts throughout the KGV can take place in intrusions along the layer of neutral buoyancy for these basalts, which is situated in the crustal sedimentary layer. In this case the accumulation of andesites in the middle of the KGV may be due to the thicker volcanogenic–sedimentary layer there. Such a distribution of igneous rocks with differing compositions exists in many volcanic centers. Further examination of this geophysical model for the KGV plumbing system may form the subject of future publications.

The present paper, especially Section 4, have considered and accounted for many properties of the present-day KGV plumbing system. It should be borne in mind that other volcanoes had been active in the KGV area during Upper Pleistocene time, and the KGV plumbing system had a substantially different structure at that time.

It should be noted that we are in a position at present to calculate many properties of the model set forth here: the parameters and properties of dikes, sills, cylindrical conduits, spherical and lens-like magma chambers, and the mechanisms of different eruptions and of plumbing systems [56]. The theory of volcanic activity is used to study various properties of the KGV, its volcanoes and eruptions. Geophysical data are helpful for the formulation and interpretation of results from petrologic, geochemical and other research.

CONCLUSIONS

The study of the roots of volcanoes, their magmatic plumbing systems, and the origins and mechanisms of volcanic activity is one of the main problems facing volcanology. This research is conducted using modern methods of volcanology, geology, geophysics, geochemistry and related sciences. The Klyuchevskaya group of volcanoes (KGV), which is the most powerful volcanic center that exists at any island arc, is a most important object of this research in Russia and worldwide. Research has been conducted there since the early 1930s. The present paper contains a brief summary of the research, examines and explains the properties of the KGV plumbing system, and discusses the KGV geophysical model based on results from the studies of eruptions, seismicity, ground deformation, and the mechanism of volcanic activity. We proceed to summarize a few of the most important conclusions.

(1) By the 1960s a general idea of the KGV magma sources had been obtained from geological and petrographic data. A large basaltic magma chamber was supposed to exist beneath the KGV with the chambers of individual volcanoes above it (see the Introduction).

(2) A great impetus to geophysical and other research was given by G.S. Gorshkov's 1956 discovery of a mantle magma chamber beneath Klyuchevskoi Volcano from seismological data. The half century that followed saw many hundreds of studies on eruptions, earthquakes, ground deformation, deep structure, the mechanism of volcanic activity, petrology, geochemistry, and so on. Among these studies, the multidisciplinary investigation of the 1975–1976 Great Tolbachik Fissure Eruption stands out. Some idea of the progress of knowledge for this half century and the advanced level of relevant research can be gathered from the present account of the results and of the geophysical model for the KGV plumbing system considered in this paper (sections 1–4), as well as from petrologic, geochemical and other models of the KGV.

(3) Further long-term, comprehensive research is envisaged in the future. It is necessary to continue current studies and to start new observations and interpretations. These must include comprehensive studies of eruptions, seismicity, precision measurements of ground deformation on all active KGV volcanoes, detailed studies in the KGV's deep structure and magma chambers, and research on the mechanisms of volcanic activity, petrology, and geochemistry. The long research experience reported in the present paper may be of help in deciding on future problems to tackle.

We express our sincere gratitude to hundreds of workers who have taken part in these 80 years of successful research and wish success for those who continue this research in the 21st century.

This study is dedicated to the famous volcanologist G.S. Gorshkov, to the volcanologists and petrologists A.N. Sirin and K.M. Timerbaeva, to the seismologist P.I. Tokarev, all inspired investigators of the KGV, friends and colleagues of S.A. Fedotov since the 1950s, whose fundamental works on eruptions, seismicity, and petrology of the KGV were published in quick succession in 1965, 1966, 1967, and 1968 [17, 42–44].

The Introduction, sections 1 and 4, and the Conclusions are written by S.A. Fedotov, Section 2 was written by N.A. Zharinov and S.A. Fedotov, and Section 3 by L.I. Gontovaya and S.A. Fedotov.

ACKNOWLEDGEMENTS

This work was supported by Basic Research Program 16 of the RAS Presidium, project 2.7, and by the Russian Foundation for Basic Research no. 08-05-00453a.

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