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KIZIMEN VOLCANO, KAMCHATKA: A FUTURE MOUNT ST. HELENS?

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The structural position, morphology, geologic structure, eruptive history, and magma evolution of Kizimen, Kamchatka, are considered from the birth of the volcano (12—11 thousand years ago) to the present time, Pour cycles of eruptive activity have been distinguished, each lasting 2 to 3.5 thousand years. The largest eruptions have been dated, and their parameters determined. The volumes and weights of erupted products, the rate of material discharge, and the productivity of the volcano have been estimated for different periods of its activity. It is demonstrated that the Kizimen rocks evolved from dacite to basaltic andesite as a result of dacitic and basaltic magma mixing. It is supposed that eruptions similar to the 1888 eruption of Bandai or the 1980 eruption of Mount St. Helens are likely to occur at Kizimen in the future,

INTRODUCTION

Kizimen (55°08 N, 160° 19,3 E, height 2376[a] m) is the southernmost active volcano in the Central Kamchatka Depression (Figures 1, 2). At the present time it is in the state of fumarolic activity, which has been recorded approximately since 1825 [3]. The only historical eruption was documented in December 1928 to January 1929, when red glare was seen at the summit at nights, and black "smoke" issued from the place where the present-day fumaroles are situated. The eruption was accompanied by frequent earthquakes [15].

Kizimen is still a least known active volcano of Kamchatka. Only two papers are available: one was written in 1946 by Piip [15], where he reported his reconnaissance of the Kizimen activity, the other in the early seventies by Shantser *et al* [19], who described in outline the structure and eruptive history of the volcano. In the present paper we summarize the results of our geological and tephrochronological study of the volcano, which included the interpretation of large-scale air photographs and carbon-14 dating of the rocks. The

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[a] This height was measured during the 1972-1979 topographical survey, earlier maps give 2485 m.

results of this study add to and in many respects modify the existing views on the origin, structure, and the geologic history of the volcano and on the evolution of its magmatic material. New evidence enabled us to elucidate the present-day stage of its activity and assess the type and size of future eruptions.

The history of the Kizimen formation was studied using a technique that had been developed by a group of workers, that were engaged in tephrochronology at the Institute of Volcanology in 1970-1980 [2], [12]. A composite section of the soil-pyroclastic cover at the Kizimen foot (Figure 3) was compiled from 23 local sections from different sectors. The basic markers used in the differentiation of the Kizimen volcanics were ash layers that had been identified and dated by Braitseva *et al.* [20]. These are the Shiveluch ashes (Sh_2, 900 ^{14}C years; Sh_3, 1300-1400 ^{14}C years; Sh_5, 2500-2600 ^{14}C years); the Ksudach ash, 1700-1800 ^{14}C years; the Avacha ash, 3500-3800 ^{14}C years, and the Khangar ash, 6900-7000 ^{14}C years. In describing the Kizimen eruptive history we use the ^{14}C ages for the events that took place in the time interval of 10 000 to 8000 years ago and the ^{14}C ages corrected for changes in the ^{14}C concentrations in the atmosphere [29] for the events that occurred from 8000 years ago to the present time.

STRUCTURAL SETTING, MORPHOLOGY AND GEOLOGIC STRUCTURE

Kizimen Volcano stands on the southeastern side of the Shchapina graben where this graben borders the Tumrok Range horst along a system of large magnitude normal faults of the NE strike. The foundation of the volcano is composed of the volcanic and volcanogenic sedimentary strata of the late Miocene Shchapina Formation and the volcanic rocks of the Tumrok and Iult complexes of late Pliocene to Pleistocene age [18]. All investigators, beginning with Piip [15], considered the age of Kizimen to be late Pleistocene to Holocene on the basis that its rocks fill the troughs of the late Pleistocene glaciation.

As regards its size, Kizimen is a typical example of the active Kamchatkan volcanoes. It is 120 km^2 across at the base, together with the foot flats, and rises to a height of 1950 or 2000 m above the Levaya Shchapina River bed. The slope of the cone in its middle and upper parts is 30° to 40°. The total volume of the cone is about 25 km^3 including the foot flats.

Kizimen is a rather unique formation in terms of morphology (see Figures 1 and 2); it has no exact analogues in the Kurile-Kamchatka region. Although its summit resembles outwardly the cones of ordinary stratovolcanoes, it has an intricate structure. It is a combination of a few closely spaced extrusive domes, differing in size, degree of preservation, and age, each having its own thick agglomerate mantle and lava flows, which differ from the flows of the other domes in morphology length, age, and composition, on the one hand, and

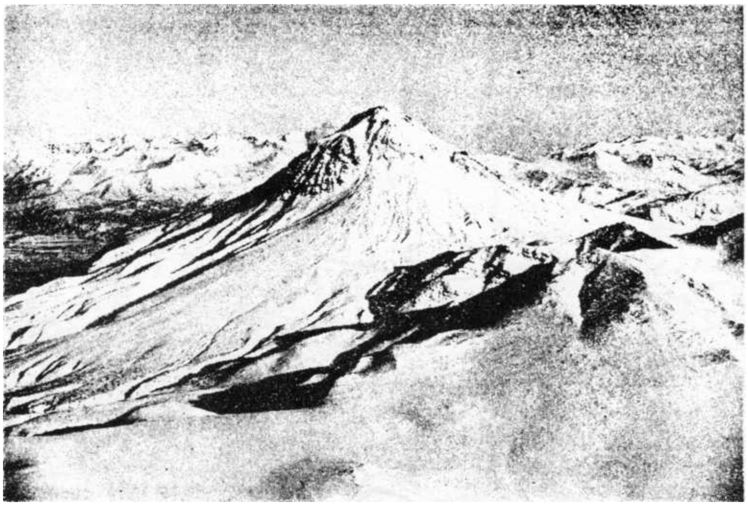


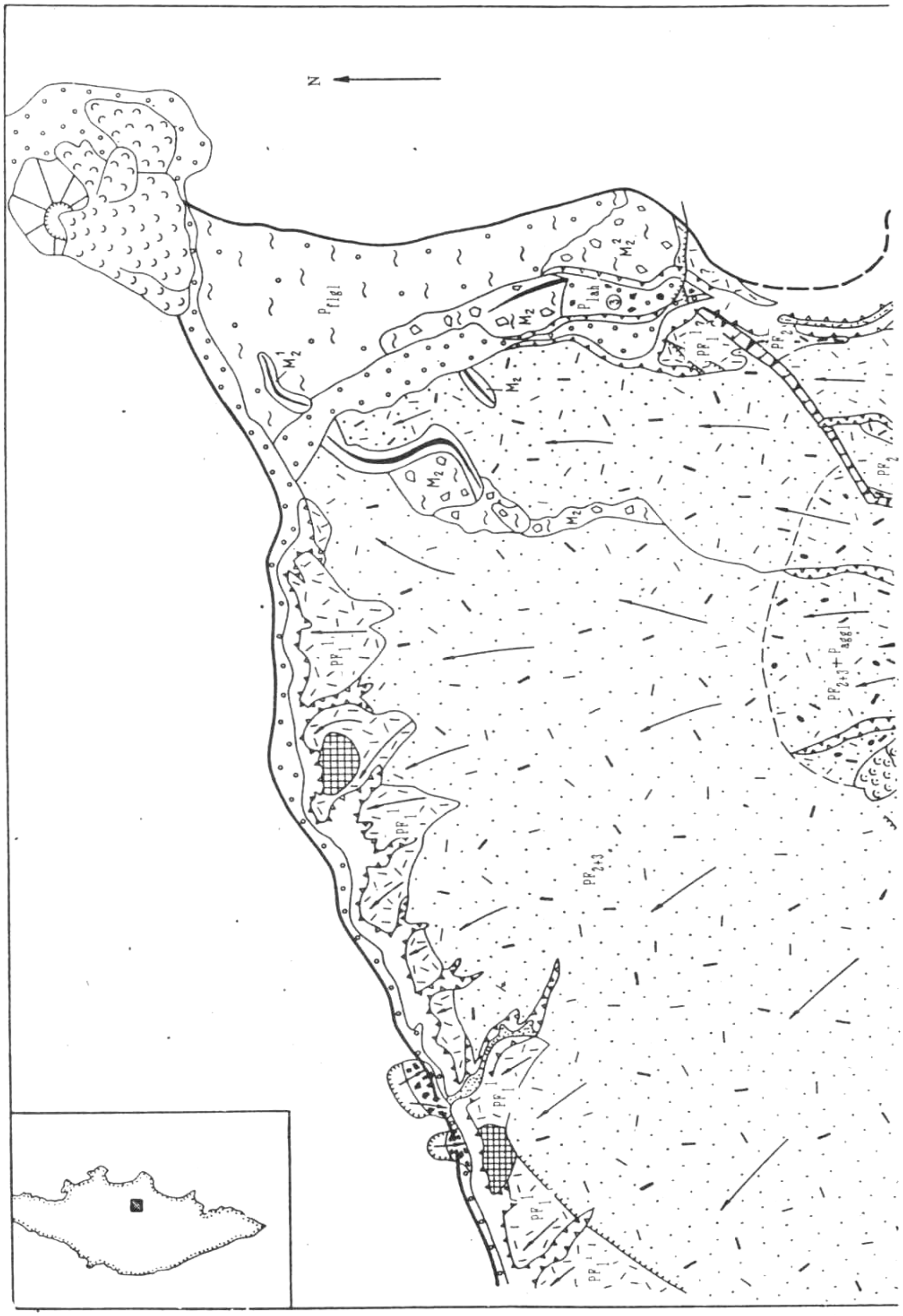
Figure 1 Kizimen Volcano. View from the southwest. Photo by V. N. Dvigalo.

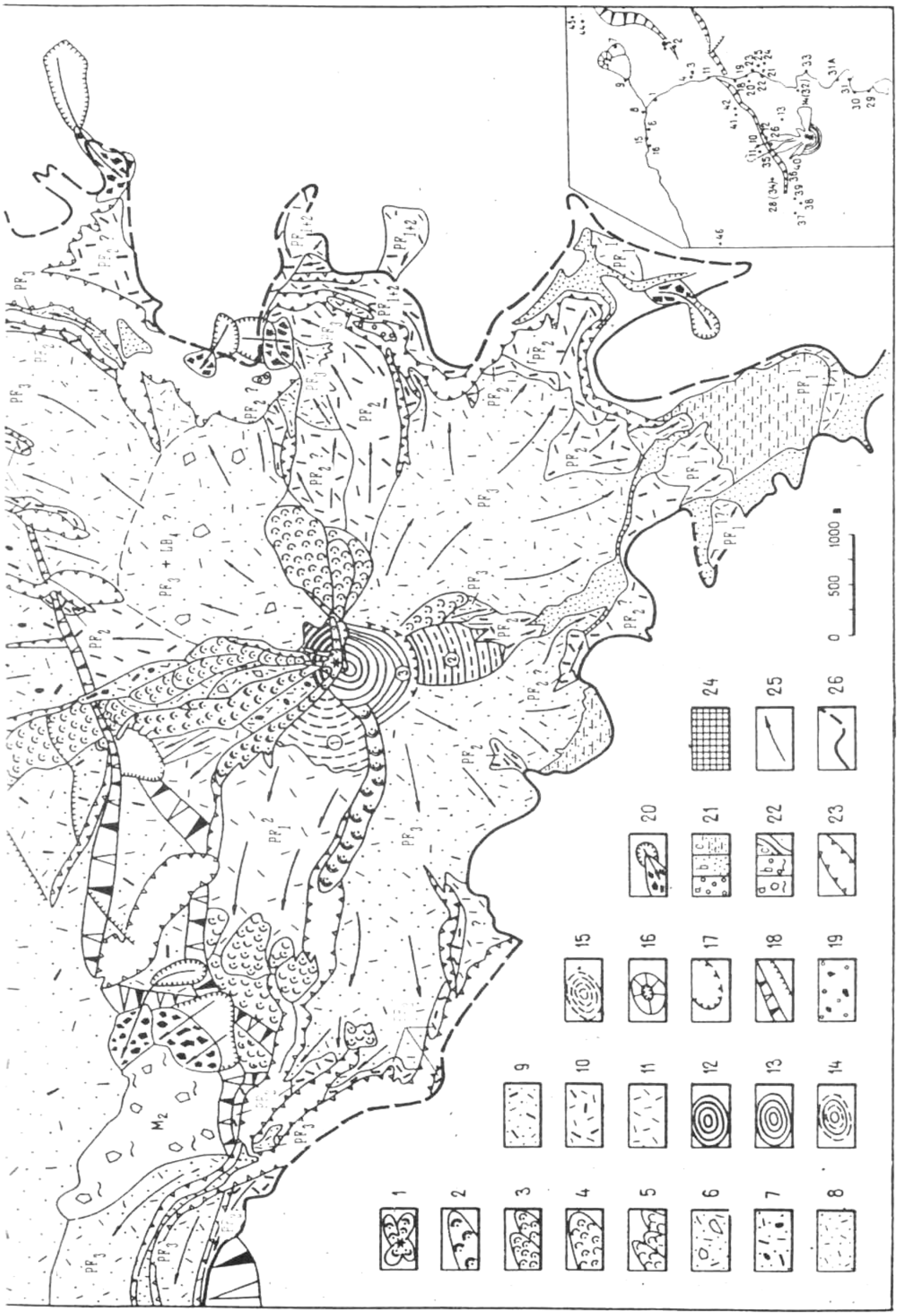
steeply inclined (8° to 10°) level grounds composed of explosion-rockslide deposits and pyroclastic flows, on the other hand. The typical forms at the foot of the cone are extensive, slightly inclined (2° to 5°) pyroclastic flow plains with a network of radial valleys incised to depths of 40 to 170 m.

The Shchapina graben area, where Kizimen is situated, is fragmented by faults [8] which broke into numerous blocks not only the pre Kizimen rocks but also the volcanic cone itself. Of the most distinct and intricate pattern is a system of the NE-trending normal faults (see Figure 2) which deformed the Kizimen cone in the northwest. The magnitudes of displacement vary from 50-60 m in the NE end of the fault zone to 170-200 m in the NW end.

Volcanic activity within the Tumrok morphostructure terminated in the early half of Pleistocene time, 200 or 300 thousand years ago [8]. Yet, in the late Pleistocene the magma sources of the volcanoes that had existed there were activated as a result of active faulting during the formation of the Shchapina graben and the Tumrok Range horst. Apparently, a kind of "galvanization" of these differentiated magma chambers by a high-temperature basalt magma caused the birth of Kizimen Volcano and also of the Tamara cinder cone (named by the writers, see Figure 2) and a few other smaller centers of basalt and andesite volcanism, which preceded the Kizimen birth, and whose lavas and tuff breccias outcrop in a deeply entrenched valley of a creek in the NW sector of the Kizimen foot (see Figure 2, inset, site 28).

According to Kirsanova *et al.* [9], these differentiated magma chambers are the sources of the Verkhneshchapina hot springs situated 10 km to the northeast from Kizimen.


N
$P_{f(gl)}$
M_2^1
M_2
M_2^2
P_{lah}
PP_1
PP_2
PP_{2+3}
$PP_{2+3}+P_{aggl}$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500
1000 m
PP_3
PP_2
PP_1
PP_{1+2}
PP_1^2
$PP_3 + LB_4$?
M_2
①
②
③

ERUPTIVE HISTORY

The earliest traces of the Kizimen eruptive activity are the layers of clastic explosive deposits found at sites 14 and 28 (see Figure 2). They are overlain by tephra which in turn in overlain by compact pyroclastic flow PF_1^0 deposits with columnar jointing. This suggests that the Kizimen activity began with a powerful explosion which was followed by the ejection of a large amount of juvenile pyroclastics. No tephras of the initial phase have been found in the Holocene soil-pyroclastic cover of the study area. On this basis and considering the relations between the volcanic material of this phase and the accumulation forms of phase II of the late Pleistocene glaciation, we may conclude that Kizimen was born in the late Pleistocene, at the close of the glacial, obviously 12 or 11 thousand years ago.

We distinguish four cycles in the Kizimen eruptive history, KZ I, KZ II, KZ III and KZ IV, each consisting of active and repose periods (Figure 4). As a rule, the active period of each cycle began with the growth of an extrusive dome and lava effusion. The cycles differed in the volume and composition of the erupted products, in the character and productivity of eruptions, and in the proportion of the juvenile and resurgent material (see Figures 3 and 4).

Cycle KZ I (12-11 to 8400 years ago). The cycle began with explosions, but their products and the deposits of the first pyroclastic flows, PF_1^0, could not be reconstructed because they are wholly buried under the later deposits and have no topographic expression.

The explosive phase was followed by extrusive activity. The dome itself is not expressed in the geomorphology, for it was obviously almost wholly removed during the subsequent eruptive periods; yet,

Figure 2 Schematic geological and geomorphological map of Kizimen Volcano and a location map of observation sites, 1 thru 5 – lava flows: 1, 2, 3 – cycle KZ IV; 4 – cycle KZ I, 5 – Tamara Cone; 6 – undifferentiated pyroclastic flow and explosion deposits of cycle KZ IV; 7 – undifferentiated deposits of pyroclastic and agglomeration flows of cycle KZ IV and KZ II; 8 thru 11 – pyroclastic flow deposits: 8 – cycle KZ IV, 9 – cycle KZ II and IV, 10 – cycle KZ I and II, 11 – cycle KZ I; 12 thru 15 – extrusive domes: 12 – latter half of KZ IV, 13 – former half of cycle KZ IV, 14 – cycle KZ II, 15 – cycle KZ I; 16 – Tamara cinder cone; 17 – craters; 18 – faults; 19 – lahar deposits of cycle KZ IV; 20 – rockslide avalanche cirques and deposits; 21 – aggradational plains: *a* – alluvial, *b* – proluvial, *c* – lacustrine; 22 – glacial landforms, phase II, late Pleistocene glacial: *a,b* – hummocks and hollows, *c* – morainic ridges; 23 – erosion scarps; 24 – lava plateau fragments; 25 – direction of movement; 26 – extent of dispersal of Kizimen eruption products (excluding far dispersed tephra). PF – pyroclastic flow; LB – lateral blast deposits (rockslide debris ?); P_{aggl} – agglomeration plain; P_{lah} – lahar plain; M_2 – moraine of phase II, late Pleistocene glacial; P_{glfl} – glaciofluvial plain. Top inset shows location of study area, bottom inset, observation sites. Figures in circles are dome numbers.

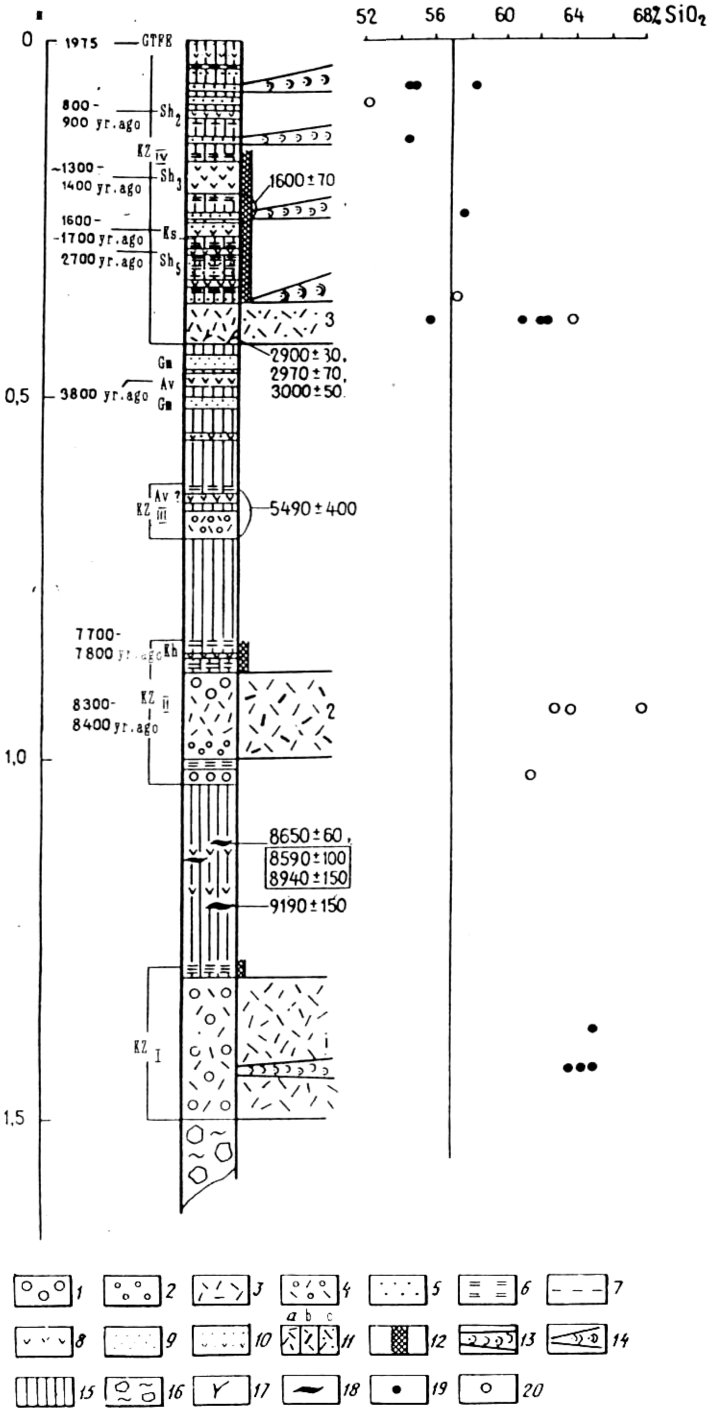
its traces remained at sites 14 and 28 as relics of a thick coarse-clastic mantle covering the PF_1^0 deposits. A distinct stratification of the mantle testifies to a multistage growth of the dome. Its growth was accompanied by the effusion of very viscous lava flows not more than 2.5 or 3 km long. The lavas are of an Amf–Pl dacite and dacitic andesite composition (see Figures 2 and 3). Lava flowed largely in the NW sector of the volcano. Earlier [15], the lavas were thought to be of extrusive origin because of their large thickness (up to 200 m) and the fan-shaped pattern of the lava flow fronts. Their total area was estimated to be 9-10 km^2 and the volume 0.8-1 km^3.

By the time the dome ceased to grow the volume of the volcanic structure was 7 to 10 km^3 according to our reconstruction, and the total volume of the juvenile and resurgent material, including the far dispersed tephra (0.5 to 1 km^3 by analogy with the tephra of similar recent eruptions), might be 7.5 to 11 km^3; the weight of the total erupted material was of the order of 20×10^9 tons.

The climax of cycle KZ I occurred in the early Holocene, ~10 thousand years ago. A series of climactic eruptions was preceded by a great intensification of tectonic and volcano-tectonic movements and by the formation of a dome-shaped volcano-tectonic uplift. Part of this uplift, fragmented by faults with up to 200-250 m displacement into huge steps, is still present in the NW sector of the Kizimen foot (see Figure 2). The faults affected the ends of the previous lava flows. It is quite likely that the major normal fault of the northern foot originated at that time.

A later powerful explosion destroyed part of this uplift and the previously formed extrusive dome. Blocks of the dome material, up to 5-6 m in size, were found during our survey at the base of the pyroclastic flow PF_1^1 on the left-hand bank of the Levaya Shchapina River 9 to 10 km from the eruptive vent. This pyroclastic flow was produced by a voluminous ejection of dacite and dacitic andesite pyroclastics immediately after a climactic explosion and was the largest in the explosive history of the volcano (area 80 to 90 km^2, volume 2.4-3.6 km^3). In the north, its deposits buried a >15 km stretch of the Levaya Shchapina valley. At a distance of 10 to 15 km from the volcano the soil-pyroclastic cover includes light gray stratified sands with pumiceous lapilli, synchronous with the pyroclastic flow PF_1^1, which lie on a moraine (see Figure 2, sites 1, 44, 45); they were interpreted as pyroclastic surge deposits [1]. Although we have not found tephra of the climatic eruption, its volume can be estimated at 1 km^3 by analogy with similar recent eruptions of other volcanoes.

After the pyroclastic eruption, a new extrusive dome (dome 1 in Figure 2) began to grow in the eruptive vent, which is at present the oldest of the domes having a topographic expression. Deposits related to its growth, such as small pyroclastic flows (PF_1^2 in Figure 2), pyroclastic surges, and rockslide debris composing its thick (>100 m) agglomeration mantle, occur near the foot of the volcano. According to our reconstruction, the total volume of the extrusive body with its


0
0,5
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1975
GTFE
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Sh2
KZ IV
~1300-
1400 yr.ago
Sh3
1600-
-1700 yr.ago
Ks
2700 yr.ago
Sh5
Gm
Av
3800 yr.ago
Gm
Av ?
KZ III
7700-
7800 yr.ago
Kh
KZ II
8300-
8400 yr.ago
KZ I
1600±70
3
2900±30,
2970±70,
3000±50
5490±400
2
8650±60,
8590±100
8940±150
9190±150
1
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68% SiO2
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agglomeration mantle was 3.5-4 km, the height of the summit was 2100-2200 m, and the total Kizimen volume of that time was 22 km^3.

The upper age limit (~9500 years) of cycle KZ I is to a first approximation defined by the ^{14}C age (8550±100 to 9190±150 years) of a unit of buried humic sandy loam with rare layers of transit fine ash, which lies on the KZ I deposits.

The juvenile and resurgent material, including the far dispersed tephra, that was erupted during the first 2000 or 2500 years of the volcano's life totals 23.5-24 km^3 in volume and ~50x10^9 tons in weight (Table 1). So the rate of dischage[a] during the first cycle can be estimated at 22x10^6 tons per year. The bulk of the erupted products was a juvenile material: the percentage of the basement rocks in the pyroclastic deposits was 10 to 20 percent of the rock volume in the initial phase, and decreased progressively. The eruptive period of cycle KZ I was succeeded by a repose period of ~ 1100 years.

Eruptive cycle KZ II (8400 to 6400 years ago) began with a series of moderate eruptions which are represented in the soil-pyroclastic sequence by 2 or 3 layers of pumiceous tephra totaling 0.001 to 0.01 km^3 in volume. Later, about 8300 years ago, a climactic eruption took place; it was one of the largest eruptions in Kamchatka at that time. Tephra covered an area of several hundreds of thousand square kilometers [20]. Their layers have been found in Bering Island 360 km to the east-northeast and near Bolshoi Semyachik Volcano 95 km to the south-southwest from Kizimen. At the foot of Kizimen the tephra range between 15 and 30 cm and consist of pumiceous bombs, lapilli, coarse sand, and fine ash. The tephra composition is dacitic andesite and dacite, the volume 2.5 to 3 km^3. The voluminous pyroclastic

Figure 3 Coaposite section of lavas and pyroclastic deposits at the Kizimen foot. *Kizimen tephra:* 1 – pumiceous lapilli; 2 – pumiceous gravel; 3 – light (pale yellow or yellow) fine ash; 4 – light (pale yellow or light gray) fine ash with volcanic sand and gravel and pumiceous lapilli; 5 – black volcanic sand; 6 – sandy loam with admixture, lenses, or indistinct layers of light gray fine ash; 7 – orange fine ash. *Tephra from other volcanoes:* 8 – pale yellow, yellow and light gray ash; 9 – black volcanic sand; 10 – yellow and light gray fine ash with volcanic sand of the same colors; 11 – pyroclastic flows (symbols and numbers correspond to Figure 2); 12 – extrusive domes; 13 – thick viscous lava flows of cycle KZ I; 14 – other lava flows (symbols correspond to Figure 2); 15 – sandy loam; 16 – moraine; 17 – coals; 18 – humic lenses; 19, 20 – composition data points in percent of insolubles: 19 – lavas and pyroclastic flows; 20 – tephras. KZ I, II, III, IV – material deposited during eruptive periods of respective cycles. Indices of transit ashes: Sh2, Sh$_3$, Sh$_5$ – Shiveluch; Ks$_1$ – Ksudach; Av – Avacha; Gm – Gamchenskiy; Kh – Khangar; GTFE – Great Tolbachik fissure eruption, 1975–1976. Transit ash ages are given after [20]. Dates to the right of the column are the ages of the deposits at the foot. The composite section corresponds in thickness to the soil-pyroclastic cover at a distance of 8–9 km from Kizimen.

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[a] We estimated the rate of dischage by dividing the mass of the erupted juvenile material by the length of the eruptive period.

eruption resulted in the formation of extensive (70-80 km^2) pyroclastic flow PF_2 deposits ranging between 10 and 60 m in thickness. Taking the average thickness to be 20-30 m, we estimated the volume to be 1.5-2 km^3. The juvenile material in the deposits is dacitic andesite.

During the closing phase of the eruptive period of cycle KZ II a new large dome grew (dome 2 in Figure 2). Its growth time can be estimated to be 700 years proceeding from thin light gray ash layers associated with it, which lie below and immediately above the tephra of Khangar Volcano whose age is 7700-7800 years (see Figure 3). The volume of the dome, its agglomeration mantle, and the tephra ejected during its growth is 0.3-0.4 km^3. Since dome 2 grew somewhat away from the summit, the height of the volcano did not change.

The cycle KZ II productivity[a] was estimated to be ~3.6xl0^6 per year (see Table 1). The 800-year duration of the eruptive period gives the average rate of dischage to be (7.8-9.4)xl0^6 tons per year. The active period was followed by a relative repose period which lasted ~1200 years. The time of the cycle KZ II eruptive period and the catastrophic character of its climactic eruption do not seem to be incidental: that time interval is known to be an early Holocene climax of explosive activity in Kamchatka and in the Kuril Islands [11].

Eruptive cycle KZ III (6400 to 3000 years ago) was different from the two previous cycles by a lower-scale volcanic activity: merely weak and mild explosive eruptions took place during the eruptive period (6400 to 6000 years ago). The largest explosions occurred at the beginning of this period and ejected ~0.1 km^3 of resurgent and juvenile material. Coarse ejecta fell to the north from the vent. The eruptions that followed produced thin layers of pumiceous tephra which ranged from small lapilli to fine ash. Their total volume is 0.005 to 0.01 km^3. The chemical composition is dacitic andesite. The productivity of the volcano was < 0.1xl0^6 tons per year. The rate of discharge was presumably not larger than 0.5xl0^6 tons per year, i.e., it was an order of magnitude smaller than during cycle KZ II.

Cycle KZ IV (300 years ago to the present time). A powerful eruption at the beginning of this cycle was a turning point in the Kizimen history. It initiated a new series of eruptions after a long period (~3000 years) of relative quiescence which terminated eruptive cycle KZ III. That eruption was similar in character to large eruptions of the opening phases of cycle KZ I and KZ II. The common features were the ejection of voluminous juvenile pyroclastics, the formation of pyroclastic flows, and the growth of a large extrusive dome with lava flows. Yet, there were considerable differences. The juvenile material became more basic and more contrasted: for the first time basaltic andesite was erupted. The total volume (0.7 to 1 km^3) and weight (1.5 to 2xl0^9 tons) of the juvenile material were smaller than in the eruptions of the previous cycles.

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[a] Productivity was estimated by dividing the mass of the erupted material by the duration of the eruptive period together with the preceding repose period,

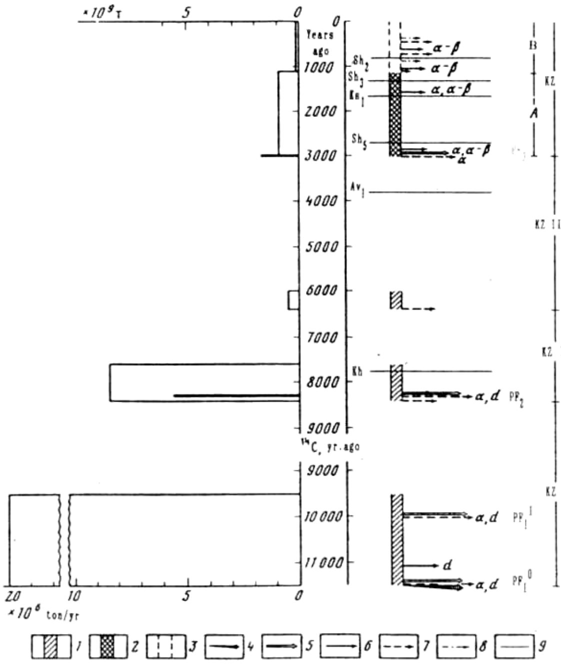

Figure 4 Dynamics of Kizimen eruptive activity. To the right of the time scale: 1 – periods if extrusive and explosive activity: growth of dome accompanied by mild or weak light gray tephra ejections and small pyroclastic flows; 2 – same, with occasional mild eruptions of black basaltic andesite sand; 3 – periods of weak explosive activity; minor ejections of black basaltic andesite sand and mild phreatic eruptions; 4 – lateral blast; 5 – large pyroclastic flows; 6 – lava flows; 7 – single tephra ejections; 8 – phreatic eruptions; 9 – transit ash. Lengths of arrows are proportional to amounts of erupted material. Indicated to the left of the time scale are: the rates of juvenile material discharge during the eruptive periods of cycles KZ I to KZ IV (x10^6 ton/yr), the times of the largest eruptions, and the weight of their juvenile products (x10^9 tons).

Like in the previous cycles, most of the juvenile material was erupted in the form of pyroclastic flows (PF_3 in Figure 2), but their total area, 30-35 km^2, was two times as small as that of the KZ I or KZ II flows. The KZ IV flows were the last pyroclastic flows in the Kizimen eruptive history. The other deposits synchronous with the PF_3 flows, are a pyroclastic surge material and a small amount of tephra.

An andesite dome (dome 3 in Figure 2), 1 km by 1.2 km in size, was slowly growing in the exposive crater during a long period of time (up to ~1100 years ago) that followed the climax. The growth of the dome was a multistage process accompanied by explosive and effusive activity. Lava flows varied in size, form, and composition. The older flows, 1 to 2 km long, consisted of ellipsoidal lava, were very thick at the fronts (>100 m), and had an andesite composition, similar to the dome. The younger flows were thinner, amounted to 4 km in

Table 1 Amounts of erupted material, rates of discharge and productivity of Kizimen Volcano.

Cycle and its time interval, thousand years	*Eruptive period, thousand years*	*Amount of erupted material*				*Rate of dischage of juvenile material,* $\times 10^9$ *ton/yr*	*Productivity,* $\times 10^6$ *ton/yr*
		Volume, *кm*^{3}		*Weight,* $\times 10^9$ *tons*			
		Σ	*Juvenile*	Σ	*Juvenile*		
KZ IV B, 0 to 1.1	1.1	0.09 – 0.10	~ 0.03	0.17 – 0.20	~ 0.07	~ 0.06	–
KZ IV A, 1,1 to 3	1.9	1.0 – 1.3	0.7 – 1.0	1.9 – 2.5	1.5 – 2.0	0.8 – 1.1	0.3 – 0.4
KZ IV (A + B)	3.0	1.09 – 1.40	0.73 – 1.03	2.07 – 2.70	1.57 – 2.07	0.5 – 0.7	~ 0.3
KZ III, 3 to 6,4	0.4	0.1	< 0.1	0.2	< 0.2	< 0.5	< 0.1
KZ II, 6.4 to 8.4	0.8	4.4 – 5.4	3.9 – 4.7	7.2 – 8.9	6.2 – 7.5	7.8 – 9.4	3.3 – 3.9
KZ I, 9.5 to 11-12	2.0 – 2.5	23.5 – 24.0	~ 21	~ 50	~ 45	~ 20	–
KZ I to IV	6.2 – 6.7		~26		~ 54	8.1 – 8.7	~ 4.7

Note. Σ denotes total volume or weight of juvenile and resurgent material; A - first phase of cycle KZ IV, B – second phase of cycle KZ IV.

length and consisted of block lava of more basic composition. The total volume of lava was 0.15 or 0.16 km^3. Numerous explosions and gravitational sliding produced a thick agglomeration mantle at the foot of the dome. According to our reconstruction, the dome attained, together with the mantle, a volume of 0.25-0.3 km^3 at the end of its growth and was the major summit form of the volcano. It is not unlikely that Kizimen was higher at that time than it is now.

Judging from the succession of the events, the character of eruptions, and the volcanic forms produced, a rather close analogue of the Kizimen activity of that time is a series of eruptions at Bezymyannyi, which began in 1955 and continue at the present time. The Kizimen dome resembles, in many respects, the dome, called Novyi, which is growing at Bezymyannyi.

The time of the dome 3 growth can be estimated from thin layers of light gray fine tephra in the soil-pyroclastic cover: the first layers lie immediately above the deposits of the cycle KZ IV climactic eruptions, others occur in the sequence that follows, and the last layer rests on the Sh$_3$ marker ash 1200-1300 years of age (see Figure 3). Hence, the duration of the initial phase of cycle KZ IV can be estimated at ~ 1900 years, and its productivity at (0.3-0.4) x10^6 tons per year. It is important to note that at least four layers of black volcanic sand, obviously of more basic composition (see Figure 3), were deposited at that time along with the light gray (andesitic ?) tephra; two of them were apparently produced by eruptions that discharged lava.

The volcanic activity of the initial phase of cycle KZ IV was accompanied by vigorous tectonic movements. A considerable displacement took place along a fault in the N and NE sectors of the Kizimen foot. The displacement of at least 10 m occurred in the area of the Verkhneshchapina hot springs and where the fault intersects one of the KZ IV lava flows. New normal faults originated on both sides of the middle course of the Poperechnyi Creek.

Among the other events associated with the climax, worthy of mention is a large lahar which obviously reached the valley of the Levaya Shchapina River and covered the area where the Verkhneshchapina hot spings are situated.

The second phase of cycle KZ IV (1100 years ago to the present time) exhibited an even more pronounced specific character. First, the initial explosion was not followed, as it was in the first phase, by a voluminous ejection of juvenile pyroclastics. The explosion removed the upper part of dome 3 and produced a 1 km by 0.7 km crater open to the northeast. The resulting coarse debris, 0.05-0.06 km^3 in volume, covered the 60°-70° NE sector of the foot to a distance of 3-3.5 km from the vent. A new, relatively small dome grew in the crater (0.015 km^3 together with the agglomeration mantle) (dome 4 in Figure 2). Secondly, the lava that flowed during the growth of the dome, and the juvenile tephra, were of the most basic composition in the Kizimen history. Moreover, the lava was of the lowest viscosity, and the flows were small in size (total ~ 0.012 km^3).

The soil-pyroclastic cover recorded six eruptions, each represented by a thin ash layer (0.5 to 3 cm at 3 to 5 km from the vent). The layers contain both juvenile and resurgent material. In fact, the last 1100 years seem to witness a larger number of eruptions, many of which might be as mild as the explosive eruption of 1928-1929 which did not produce its own tephra layer.

An important point is that the historical renewals of the Kizimen activity exhibit a distinct correlation with local earthquakes. For instance, the eruption of 1928-1929 was accompanied by frequent earthquakes that came from the side of Tolbachik Volcano [15]. A sudden intensification of fumarolic activity in 1963 [14] took place immediately after local shallow earthquakes of magnitude 6.2 and 5.8, whose epicenter was approximately 25 km to the northwest from Kizimen [16]. Their intensity in the Kizimen area might be 7 or 8 on the 12 - point scale.

During the latter half of cycle KZ IV, the erupted material totaled 0.09-0.1 km^3, less than 40 percent of which were juvenile products: 0,03 km^3 weighing $0.07x10^9$ tons (see Table 1). Productivity was estimated to be < $0.06x10^6$ ton/yr, which is an order of magnitude less than in the former half of the cycle.

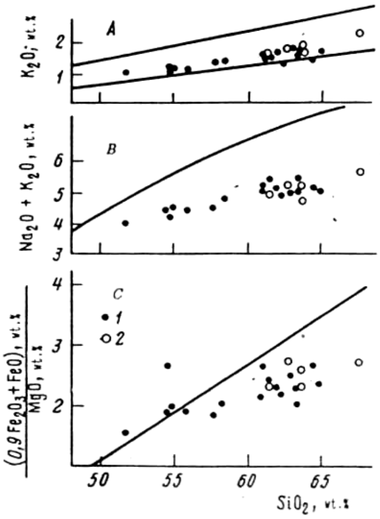

Figure 5 Classification diagrams for Kizimen rocks, *A* – region of mildly potassic rocks after [21], *B* – lower limit of subalkalic rocks after [10], *C* – boundary between calc-alkalic and tholeiitic rocks after [21]. 1 – lava and juvenile pyroclastics; 2 – tephra. In addition to the writers' material, data from [19] were used.

The productivity as low as that (2.5 to 3 thousand kilowatts of thermal power with 400 cal/g of basalt) is at great variance with the thermal power generated by fumarolic activity [9] (46 565 kcal/s, 200 thousand kilowatts). The vents of a recent and an older fumarole occur at the base of dome 3 along its perimeter, where the rocks are extensively altered [14], which suggests the existence of a long-lived source of heat. A great heat discharge and continued activity of the fumaroles seems to be maintained by a large amount of magma (0.5 to 1 km^3) intruded into or immediately below the base of the Kizimen cone. Apparently, a small quantity of this magma has been erupted to the surface, whereas the bulk of it is still present at depth in the form of slowly cooling subvolcanic bodies. Magma intrusion began presumably as far back as the preparation period of the climactic eruption of cycle KZ IV. Supportive of this supposition is the occurrence in the pyroclastic flow deposits of basaltic andesite fragments of varying size, including large blocks. The annual amount of heat given off by the fumaroles equals to the heat loss of (3-4)x10^6 tons of basalt magma as it cools. The weight of magma that cooled during a period of 1825-1990 must be (500-700)x10^6 tons and the volume 0.2 km^3 (with density 2.8 g/cm^3). It is unlikely that there can be any other source of heat capable to produce the great amount of heat that is discharged by the fumaroles.

In terms of the contribution into the cone formation, the character of eruptions, and the composition of the rocks, the first three cycles of the Kizimen activity can be combined into a higher-rank unit - a group of cycles or a volcanic episode. In spite of some differences between them, the cycles consistently continued one another and produced a single volcanic structure. The progressive decrease of the productivity and the rate of discharge, the invariability of the juvenile material, and the unusually long repose period and mild eruptive activity of cycle KZ III infer that cycle KZ III terminated the early episode of the Kizimen volcanic activity. We suggest that the volcanic structure formed during the first three cycles should be called Staryi Kizimen (Old Kizimen), the total time of its existence being 5 to 6 thousand years.

The commencement of a new eruptive cycle, KZ IV, about 3000 years ago was apparently the birth of a new volcano. As has been demonstrated above, it differs from Old Kizimen by the character of eruptive activity, the composition of juvenile material, productivity, and other parameters. We suggest to call it Molodoi Kizimen (Young Kizimen).

An important point is the approximately identical duration of all eruptive cycles: KZ I ~3000 years, KZ II ~2000 years, KZ III ~3400 years, KZ IV ~3000 years. The last cycles seems to be approaching termination.

COMPOSITION, ORIGIN AND EVOLUTION OF ERUPTED MATERIAL

As a result of our study, we found the rocks composing the volcano to be of a basaltic andesite-andesite-dacite series with a progressive increase of basicity from the early to the late phases of its evolution (see Figure 3). All rocks belong to a moderately potassic series, the andesites and dacites lying in the region of the calc-alkalic series, and the more basic varieties at the boundary between tholeiites and calc-alkalic rocks or, less frequently, in the region of tholeiites (Figure 5).

It is important to note that in addition to the dominant andesite-dacite material (Table 2: analysis 9, fragments; an. 8, filling material), the pyroclastic flow PF_3 contains juvenile fragments of basaltic andesite (Table 2, an. 4). This may be indicative of the simultaneous occurrence of dacitic andesite and basaltic andesite melts in the magma source and of their mixing during the course of eruption.

A distinctive petrographic feature of the Kizimen rocks is the presence of nonequilibrium mineral associations: the simultaneous occurrence of the phenocrysts of quartz and relatively magnesian olivine in the andesite and dacite, the presence of compositionally contrasted plagioclase phenocrysts, the orthopyroxene reaction rims developed around the olinines, the high Mg content of the orthopyroxene microlites as compared to its phenocrysts, and so on. An important observation is the ubiquitous presence of amphibole phenocrysts in all rock types from the dacite to the basaltic andesite.

Table 2 Representative chemical analyses of Kizimen rocks.

Oxide	1	2	3	4	5	6
	7K	35K/2	26Ka	22K/2	11K	40K
SiO_2	51.70	54.44	54.52	55.90	57.66	57.96
TiO_2	1.00	0.93	1.11	1.01	0.81	0.89
Al_2O_3	16.95	18.79	17.63	17.40	17.94	16.80
Fe_2O_3	3.19	2.79	3.62	5.00	2.05	8.20
FeO	7.26	5.50	6.19	3.62	4.86	—
MnO	0.15	0.18	0.12	0.15	0.13	0.14
MgO	6.68	4.13	3.58	4.20	3.61	3.60
CaO	8.32	7.91	8.20	8.00	7.37	6.80
Na_2O	2.92	3.31	3.17	3.32	3.26	3.43
K_2O	1.00	1.20	1.25	1.13	1.35	1.37
H_2O^-	0.10	—	0.02	—	—	—
H_2O^+	0.54	—	0.28	—	0.43	—
P_2O_5	0.26	0.12	0.09	0.34	0.16	0.09
LOI	—	—	—	0.53	—	0.32
Sum	100.07	99.70	99.78	100.60	99.63	99.60

Oxide	7	8	9	10	11	12
	34K/2	18K/4	22K/1	31K/2	6K	35K/1
SiO_2	59.52	61.14	61.45	61.56	63.38	63.72
TiO_2	0.70	0.72	0.73	0.69	0.62	0.58
Al_2O_3	17.08	16.74	16.40	15.99	15.60	16.94
Fe_2O_3	2.47	2.69	2.70	2.88	1.80	2.24
FeO	3.63	3.51	3.23	3.46	3.60	2.85
MnO	0.11	0.13	0.12	0.12	0.10	0.11
MgO	2.48	2.59	2.60	2.43	2.20	1.84
CaO	5.92	6.07	6.20	5.55	5.10	5.70
Na_2O	3.31	3.46	3.60	3.19	3.24	3.68
K_2O	1.54	1.63	1.32	1.78	1.73	1.49
H_2O^-	0.84	0.28	—	0.54	—	0.26
H_2O^+	0.76	0.87	—	1.60	—	0.12
P_2O_5	0.14	0.04	0.26	0.14	0.17	0.17
LOI	1.36	—	0.91	0.37	2.84	0.14
Sum	99.86	99.87	99.52	100.30	100.28	99.84

Note. 1 – Tamara cinder cone lava. *Kizimen rocks:* 2 thru 6,8,9 – rocks of cycle KZ IV (last 3000 years): 2,3,5,6 – lavas; 4, 8, 9 – PF$_3$ pyroclastic flow (4, 9 – juvenile fragments, 8 – filling material); 7, 10 – rocks of cycle KZ II: 7 – coarse pumiceous tephra, 10 – fragments from PF$_2$ pyroclastic flow; 11, 12 – rocks of cycle KZ I: 11 – pumiceous lapilli from PF$_4$ pyroclastic flow, 12 – lava. Analyses 2, 3, 5, 7, 8, 10 and 12 were made at the Central Laboratory of the Institute of Volcanology, the other at the Institute of Geochemistry, Siberian Division, RAS. Minerals from samples 7K, 26Ka, 11K and 35K/1 were determined with an electron microprobe.

Table 3 Composition of plagioclases from Kizinen rocks.

Oxide, *component*	1 (Pc)	2 (Pm)	3 (M)	4 (Pc)	5 (Pc)	6 (Piz)	7(Pc)	8(M)	9(Pc)	10(Pc)	11(Pm)	12(M)	13(P)
SiO_2	47.99	52.95	53.01	46.63	56.23	48.66	51.85	53.34	46.75	56.23	51.60	54.43	55.81
TiO_2	0.05	0.08	0.09	0.00	0.00	0.00	0.01	0.05	0.00	0.02	0.00	0.08	0.03
Al_2O_3	33.69	29.99	29.71	33.57	28.14	32.24	29.90	29.26	33.97	27.56	30.18	27.93	27.41
FeO	0.71	1.09	1.14	0.65	0.29	0.67	0.80	0.98	0.56	0.29	0.69	1.02	0.29
MnO	0.03	0.03	0.04	0.00	0.00	0.00	0.01	0.03	0.00	0.01	0.00	0.05	0.02
MgO	0.11	0.13	0.10	0.00	0.00	0.00	0.00	0.13	0.00	0.01	0.03	0.13	0.02
CaO	16.23	12.76	12.43	17.15	10.27	15.44	13.20	12.16	17.11	9.65	12.27	10.81	9.79
Na_2O	1.94	3.72	4.00	1.84	5.69	2.73	4.06	4.13	1.82	5.69	4.03	4.63	5.59
K_2O	0.08	0.27	0.28	0.02	0.23	0.10	0.18	0.23	0.00	0.28	0.15	0.41	0.27
Σ	100.83	101.02	100.79	99.87	100.81	99.84	99.99	100.32	100.22	99.74	99.96	99.49	99.23
An	81.8	64.4	62.2	83.7	49.2	75.3	63.5	61.0	83.8	47.6	64.0	54.9	48.4
Ab	17.7	34.0	36.1	16.1	49.7	24.1	35.4	37.6	16.2	50.7	35.2	42.6	50.0
Or	0.5	1.6	1.7	0.1	1.4	0.6	1.1	0.4	0.00	1.7	0.8	2.5	1.6
n	4	4	6	7	10	4	7	5	9	13	8	5	10

Note. 1, 2, 3 — basalt; 4 thru 8 — basaltic andesite; 9 thru 12 — andesite; 13 — dacite. Here and in the tables that follow: *P* — phenocryst (Pc — core, *Pm* — margin, *Piz* — intermediate zone), *M* — microlite, *Pin* — inclusion in phenocryst. Analyses were made with a Camebax microprobe, operators G. P. Ponomarev and V. A. Ananiev.

Based on the data of the mineral compositions presented in Tables 3 thru 6, these features are considered below in more detail. Two groups of plagioclase phenocrysts can be distinguished in the basaltic andesites and the andesites: one group with the cores of bytownite (An_{68-91}), like in basalts, the other with the cores of andesine-

Table 4 Compositions of olivines and amphiboles in Kizimen rocks.

Oxide	1 (Pc)	2 (Pm)	3 (Pc)	4 (Pm)	5 (Pc)	6 (Pc)	7 (P)	8 (M)
SiO_2	39.75	38.16	38.58	37.90	38.13	38.22	45.79	45.79
TiO_2	0.04	0.05	0.00	0.02	0.03	0.04	1.77	1.85
Al_2O_3	0.05	0.04	0.00	0.01	0.04	0.03	9.00	9.24
Fe_2O_3	0.05	0.02	0.01	0.01	0.01	0.01	0.02	0.00
FeO	17.78	26.42	20.73	26.93	22.17	21.27	13.28	14.24
MnO	0.27	0.49	0.29	0.47	0.36	0.55	0.37	0.43
MgO	42.37	34.88	40.18	34.43	37.87	38.63	13.61	13.14
CaO	0.09	0.18	0.09	0.17	0.14	0.04	10.98	10.99
Na_2O	0.00	0.01	0.01	0.05	0.01	0.02	1.58	1.51
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.42
Σ	100.40	100.24	99.83	99.99	98.75	98.81	96.74	97.61
f, at%	19.1	30.4	22.6	31.0	25.0	24.1	36.1	38.5
n	7	7	7	7	7	3	5	1

Note. 1, 2 – basalt; 3, 4 – basaltic andesite; 5 – andesite; 6, 7, 8 – dacite, 1 thru 6 – olivines; 7, 8 – amphiboles, For explanation of abbreviations see Table 3.

labradorite (An_{44-55}), like in dacites. The margins of the plagioclases of both groups are close in composition, An_{47-72} and An_{49-74}, respectively. They are similar to the plagioclase of the microlites (An_{50-66}) and are compositionally intermediate between the cores of the two groups (Figure 6, Table 3). Sometimes, the sodic cores are surrounded by intermediate zones of calcic plagioclase (An_{63-72}) exhibiting a "cribrate" texture due to minute glass inclusions.

The presence of two different groups of plagioclases in the basaltic andesites and andesites is clearly seen in the FeO-An diagram of Figure 7. The sodic plagioclases lie in the field of plagioclases from dacites and are lower in FeO (0.2-0.4 wt.%), whereas the calcic plagioclases occur in the region of plagioclases from basalts and are higher in FeO (0.5-0.9 wt.%). The microlites from the basaltic andesites lie between these regions and show maximum FeO concentrations (0.75-1.35 wt.%). The outer zones on the cores of the calcic plagioclases are shifted toward the field of the microlites, and the compositions of the cribrate zones and the outer rims on the cores of the sodic plagioclases fall first in the field of the calcic cores and are then also shifted into the field of the microlites.

The cores of the olivine phenocrysts from the basaltic andesites, andesites, and dacites are close in composition, Fo_{73-79}, (Table 4, Figure 8). The olivines in the andesites and dacites, and occasionally in the basaltic andesites, are surrounded by orthopyroxene and magnetite rims, which indicates that this mineral was not in equilibrium with the respective melts. This is supported by the results of calculation by Roeder and Emslie's method [28]: the distribution ratios

Table 5 Composition of pyroxenes in Kizimen rocks.

Oxide, component	1(M)	2(M)	3(M)	4(P)	5(P)	6(M)	7(M)
SiO_2	51.17	52.77	53.06	50.86	53.46	50.87	53.69
TiO_2	0.91	0.61	0.44	0.77	0.18	0.90	0.26
Al_2O_3	3.03	1.63	1.18	3.61	2.98	3.65	1.71
Cr_2O_3	0.02	0.02	0.01	0.02	0.01	0.02	0.00
FeO	12.47	17.79	20.26	9.65	17.46	10.64	17.28
MnO	0.43	0.62	0.78	0.30	0.63	0.35	0.67
MgO	14.42	16.81	19.13	14.28	23.43	13.89	23.89
CaO	16.84	10.27	5.18	19.51	1.47	18.54	2.06
Na_2O	0.22	0.11	0.04	0.18	0.10	0.16	0.00
K_2O	0.02	0.02	0.03	0.00	0.08	0.02	0.07
Σ	99.54	100.63	100.11	99.19	99.81	99.04	99.62
Wo	35.8	21.4	10.7	41.5	3.1	40.0	4.2
En	42.7	48.6	55.2	42.2	67.6	41.5	68.1
Fs	21.5	40.0	34.1	16.3	29.3	18.5	27.7
n	8	3	9	10	5	13	5

Oxide, component	8(P)	9(P)	10(Piz)	11(M)	12(M)	13(M)	14(P)	15(M)
SiO_2	50.54	53.64	54.05	50.27	52.40	53.09	52.47	53.20
TiO_2	0.82	0.13	0.30	0.85	0.35	0.29	0.13	0.24
Al_2O_3	3.83	0.80	1.32	3.82	2.52	1.53	0.83	1.50
Cr_2O_3	0.03	0.03	0.00	0.02	0.00	0.00	0.00	0.03
FeO	9.36	21.66	15.62	10.34	16.40	17.52	21.63	20.09
MnO	0.34	1.17	0.52	0.40	0.46	0.56	1.12	0.84
MgO	14.41	21.83	24.74	14.33	22.25	23.84	21.92	22.11
CaO	19.37	0.75	1.87	18.26	3.91	1.84	0.67	1.26
Na_2O	0.19	0.02	0.01	0.11	0.01	0.02	0.01	0.01
K_2O	0.01	0.00	0.00	0.02	0.00	0.02	0.00	0.00
Σ	98.90	100.01	98.42	98.42	98.31	98.71	98.78	99.28
Wo	41.2	1.5	3.8	39.2	8.2	3.8	1.4	2.6
En	42.7	62.1	70.4	42.8	64.9	67.8	62.3	63.6
Fs	16.1	36.4	25.6	18.0	26.9	28.4	36.3	33.8
n	4	8	1	7	1	17	6	2

Note. 1, 2, 3 – basalt; 4, 5, 6, 7 – basaltic andesite; 8 thru 13 – andesite; 14, 15 – dacite; 1, 4, 6, 8, 11 – clinopyroxenes; 2 – subcalcic augite; 3, 12 – pigeonite; 5, 7, 9, 10, 13, 14, 15 – orthopyroxenes. Abbreviations are explained in Table 3.

$K_d^{Fe\text{-}Mg}$) in the dacites, andesites, and calc-alkalic basaltic andesites ire higher than the equilibrium values (K_d = 0.36, 0.44, and 0.35, respectively), and only in the tholeiitic basaltic andesites does the K_d

Table 6 Compositions of ore minerals in Kizimen rocks.

Oxide	1(Pin)	2(Pin)	3(P)	4(P)	5(P)	6(M)	7(Pin)
SiO_2	–	–	0.12	0.00	0.00	0.17	0.01
TiO_2	1.42	5.07	11.54	12.15	44.00	13.61	7.52
Al_2O_3	24.79	11.37	2.24	1.44	0.00	1.51	3.21
Cr_2O_3	21.92	14.67	0.10	0.00	0.00	0.08	0.09
Fe_2O_3	19.21	33.43	45.39	45.84	19.82	41.29	53.36
FeO	23.10	28.75	38.93	39.66	33.75	40.76	34.80
MnO	0.34	0.44	0.44	0.50	0.55	0.52	0.50
MgO	9.10	5.53	1.92	1.87	2.95	1.61	2.68
CaO	–	–	0.07	0.00	0.00	0.16	0.09
Na_2O	–	–	0.01	0.00	0.00	0.04	0.00
K_2O	–	–	0.00	0.00	0.00	0.00	0.00
Σ	99.83	99.26	100.76	101.47	101.07	99.74	102.26
f	59.2	74.4	92.0	92.3	86.5	93.5	87.9
n	14	14	6	2	2	11	5

Oxide	8(Pin)	9(Pin)	10(Pin)	11(Pin)	12(M)	13(P)	14(P)
SiO_2	0.00	0.00	0.00	0.00	0.05	0.01	0.01
TiO_2	6.29	36.43	12.16	44.44	11.87	5.96	39.73
Al_2O_3	2.00	0.00	1.33	0.00	2.06	2.15	0.50
Cr_2O_3	0.06	0.00	0.00	0.00	0.02	0.06	0.03
Fe_2O_3	57.54	31.85	45.40	17.71	39.85	56.53	24.96
FeO	35.36	28.13	40.12	34.91	44.57	35.17	31.89
MnO	0.45	0.80	0.44	0.57	0.52	0.50	0.66
MgO	1.59	2.26	1.50	2.51	1.40	1.13	1.98
CaO	0.00	0.00	0.00	0.00	0.11	0.01	0.01
Na_2O	0.00	0.00	0.00	0.00	0.00	0.01	0.00
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ	103.29	99.26	100.95	100.14	100.45	101.54	99.77
f	92.6	87.5	93.8	88.6	94.2	94.6	90.2
n	1	1	1	1	2	4	3

Note. 1, 2 – basalt, inclusion in olivine; 3 thru 6 – basaltic andesite (4, 5 – aggregates of crystal grains); 7 thru 12 – andesite (7 – inclusion in clinopyroxene; 8, 9 – inclusion in the core of an orthopyroxene crystal; 10, 11 – aggregate-inclusion in the margin of the same crystal); 13, 14 – dacite.

value corresponds to the equilibrium (0.31).

In addition to single olivine crystals, many basaltic andesites and andesites contain aggregates of olivine and calcic plagioclase (bytownite). Such grains are often surrounded by clasts of the crystallized groundmass which is markedly different from the mesostasis, containing clasts of rocks with colorless or gray glass, by

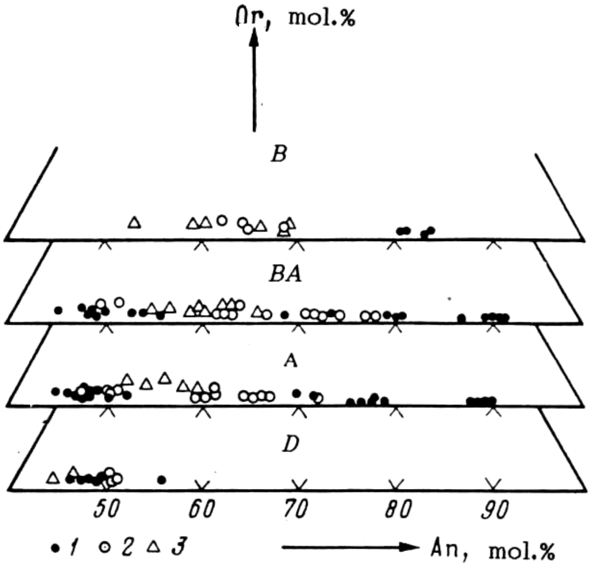

Figure 6 Composition of plagioclases from Kizimen rocks, 1,2 - phenocrysts (1 - core, 2 - margin); 3 - microlites. B - basalt, BA - basaltic andesite, A - andesite, D – dacite.

the brown color of its glass and a greater degree of crystallization. The cores of olivine phenocrysts from the intermediate and acid lavas ire slightly more ferric than their cores in basalts ($Fo_{79.7-81.5}$).

The phenocrysts of amphibole are absolutely fresh in the dacitic andesites and dacites and are wholly dissociated and replaced by an aggregate of subcalcic augite (Fo_{24-27} En_{42-53} Fs_{22-31}), andesine-labradorite (An_{43-62}), and titanomagnetite in the basaltic andesites and basic andesites. This suggests that amphibole was not in equilibrium with the basaltic andesite and andesite liquids.

The compositions of orthopyroxene phenocrysts from the andesites and dacites are identical in the iron and aluminum contents but are markedly different in these parameters from the orthopyroxene phenocrysts of the basaltic andesites, whereas the orthopyroxene microlites from the andesites and basaltic andesites lie in one field (Figure 8 and 9; Table 5). The microlites of orthopyroxene are more magnesian slightly in the dacites and markedly in the andesites, and averagely more aluminous than the phenocrysts, whereas the microlites in the basaltic andesites are similar to the phenocrysts in the iron content but differ in the aluminum content which is notably smaller in the microlites. The orthopyroxene phenocrysts are usually unzoned, though some andesites do contain scarce zoned crystals whose intermediate zones tend to the field of the basaltic andesites,

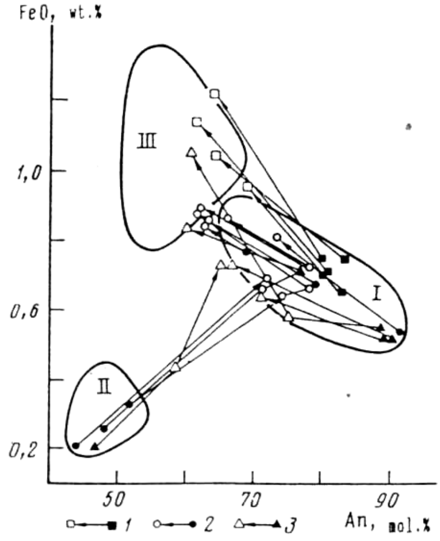

Figure 7 Variation of the FeO content in zoned plagioclase phenocrysts from Kizimen rocks, 1 – basalt; 2 – basaltic andesite; 3 – andesite. Solid symbols are cores, open, intermediate and outer zones. Arrows indicate composition variation from core to margin in some crystals, I – plagioclase phenocrysts from basalts, II – plagioclase phenocrysts from dacites, III – microlites from intermediate to basic rocks.

and the outer zones to the field of the microlites (Figure 9). In some of the andesite samples, the orthopyroxene phenocrysts have rims of clinopyroxene. These facts permit the conclusion that the orthopyroxene crystals were not in equilibrium with the andesite melt and were likely to be in equilibrium with the basaltic andesite melt.

No clinopyroxene phenocrysts were found in the dacites (they contain amphiboles instead); those found in the basaltic andesites and andesites are identical in composition. In both cases the microlites of clinopyroxene are slightly less calcic and more ferric than the phenocrysts, though the basaltic andesites contain microlites of pigeonite, in addition to those of clino- and orthopyroxene, which are very scarce in the andesites (Table 5; Figure 8). Minute clinopyroxene crystals are seen to grow on the pigeonites from the basaltic andesites. No phenocrysts of clinopyroxene or orthopyroxene were found in the basalts; the microlites they contain are of clinopyroxene or pigeonite, in equal amounts, or occasionally of subcalcic augite.

The basalts contain ore mineral protocrysts of Al-Cr-Fe spinel or Cr-magnetite, which are enclosed in the olivine phenocrysts. The pyroxenes from the basaltic andesite, andesite, and dacite enclose crystals of titanomagnetite or, less common, ilmenite (Table 6), the TiO_2 content in the former decreasing slowly from the basaltic andesite to andesite to dacite: 9-14, 6-12, and 5-7 wt.%, respectively.

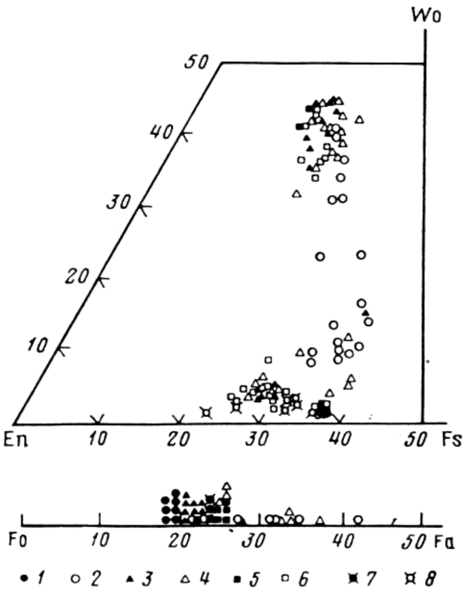

Figure 8 Compositions of pyroxenes and olivines from Kizimen rocks. 1, 2 – basalt; 3, 4 – basaltic andesite; 5, 6 – andesite; 7, 8 – dacite. Solid symbols are cores of phenocrysts, open, microlites.

In the andesites, the titanomagnetites enclosed in the cores of the pyroxene phenocrysts, contain 6-12% TiO_2 and those in the margins 9-12% TiO_2.

The oxygen fugacity calculated after [27] for a magnetite and ilmenite aggregate from a phenocryst in basaltic andesite is approximately an order of magnitude larger than the f_{o_2} buffer and lies on the curve calculated for the bulk basalt and andesite composition by a technique suggested in [23]. The f_{o_2} value obtained for a magnetite-ilmenite pair from the dacite is one more order of magnitude larger and lies on the curve calculated for the bulk dacite composition. The oxygen fugacity calculation for the magnetite-ilmenite pairs from the core and the margin of an orthopyroxene phenocryst in the andesite yielded different values corresponding to the dacite curve for the former and to the basalt-andesite curve for the latter (Figure 10).

Three mechanisms can be invoked to account for the nonequilibrium mineral associations in the rocks: an abrupt change in the PT conditions, a wall rock assimilation, or magma mixing. The last mechanism seems to be more likely.

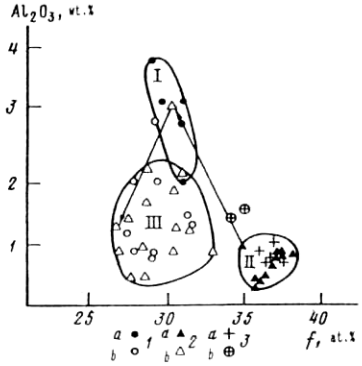

Figure 9 Variation of iron and alumina contents in orthopyroxenes from Kizimen rocks. 1 – basaltic andesite; 2 – andesite; 3 – dacite; *a* – phenocrysts, *b* – microlites and outer zones of zoned phenocrysts, I – phenocrysts from basaltic andesite, II – phenocrysts from andesite and dacite, III – microlites from basaltic andesite and andesite.

Indeed, a relationship between the An and FeO contents in the plagioclases from the basaltic andesite and andesite shows that the sodic and calcic cores of the plagioclase phenocrysts might only crystallize from melts that had different calcium and iron contents, whereas their margins from a homogeneous melt. The ingredients of the mixed melts might be dacite and basalt, since the sodic cores of plagioclases from the basaltic andesite and andesite are similar to plagioclase from dacite and the calcic to plagioclase from basalt. Evidence in support of this supposition is the coexistence of magnesian olivine and quartz in the phenocrysts from the andesite, and also the fact that many olivine phenocrysts are surrounded by the clasts of a material which is different in composition and texture from the mesostasis of the host rocks. Furthermore, most of the dacites themselves contain a minor admixture of basaltic material as evidenced by the presence of olivine grains in them. Supportive of the mixing mechanism is also a larger Mg content of the orthopyroxene microlites, as compared to the phenocrysts in the andesite, and also a reversed zoning that is occasionally observed in the plagioclase crystals. Another point in support is a difference between the oxygen fugacity values for the magnetite-ilmenite pairs from the core and the margin of an orthopyroxene phenocryst in the andesite. Finally, the least squares calculation of the rock compositions showed that the andesites (Table 2, analysis 5) might be derived from a mixed melt consisting of 46% dacite and 53.8% basalt (Table 2, analyses 12 and 1, respectively).

The alternative hypothesis that the Kizimen rocks originated as a result of basaltic magma fractional crystallization has been tested by the least squares method using the MIN program and found to be invalid by A. D. Babanskiy from the Institute of the Geology of Ore

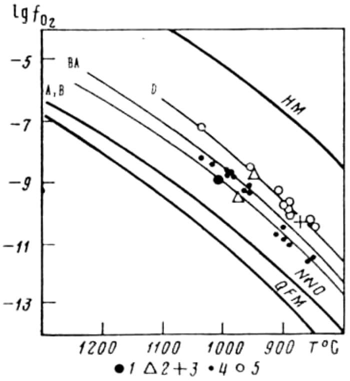

Figure 10 Oxygen fugacity and crystallization temperature of ore mineral oxides in Kizimen rocks. 1 – basaltic andesite; 2 – andesite; 3 – dacite; 4, 5 – lavas of Quaternary volcanoes of Kamchatka and the Kuril Islands: 4 – two-pyroxene lavas, 5 – amphibole- and biotite-containing lavas. B – basalt, BA – basaltic andesite, A – andesite, D – dacite.

Deposits, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences. The sum of the differences squared in the rock-forming oxide contents for the basalt-andesite and basalt-dacite pairs was larger than unity (which was impermissible by the calculation conditions) and, moreover, all calculation variants demanded that the residual liquid should have accumulated spinel (Table 7). The fractionation of basaltic andesite magma might produce andesite on condition that the residual liquid accumulated a small amount of olivine (0.5%) or orthopyroxene (1.1%). It was only for the andesite-dacite pair that the fractionation model yielded satisfactory results Table 7).

Taking the mixed magma to consist of a basalt and a dacite melt, we can attempt to determine some of the physicochemical parameters of the melts proceeding from the assumption that they underwent some crystallization before mixing. According to experimental data [7], the amphibole-pyroxene andesites of the Klyuchevskoi volcanic group in Kamchatka crystallize in the presence of 5-6 wt.% H_2O, and the amphibole andesites at 6-7 wt. % H_2O, which corresponds to P_{H_2O}= 1.5 to 2 kbar and ≥ 2 kbar, respectively. Extending these values to the pyroxene-amphibole dacite of Kizimen Volcano, whose SiO_2 content of ~64% is only slightly larger than that of the andesites, we found the temperature of plagioclase crystallization, using the Kudo-Weill plagioclase geothermometer [24], to be 920°C with P_{H_2O} = 2 kbar and 960°C with P_{H_2O} = 1.5 kbar. These values are close to the temperature at which amphibole is stable in adesite (dacite ?) melt, 925 ± 25°C [7]. In fact, we often found amphibole-plagioclase aggregates in the dacite, which testifies to their simultaneous (or closely spaced) crystallization. The oxygen fugacity values obtained by the magnetite-ilmenite geothermometer [27] and the bulk dacite composition [23] give similar results (Figure 10) and indicate that the dacite melts crystallized at oxygen fugacities two order of magnitude larger than the NNO buffer. It is more difficult to determine these parameters for the basalts. The calculation of the Fe and Mg partition coefficient between olivine and a basalt melt yielded a value larger than the equilibrium [28], $K_d = 0.44$. However, assuming that the degree of iron oxidation was initially close to the value universally accepted for such melts, $Fe_2O_3/FeO = 0.15$, the new value of the partition coefficient becomes consistent with the equilibrium ($K_d = 0.305$), and the oxygen fugacity curve computed for basalt approaches the NNO buffer (Figure 10). Using this assumption and a nomogram from [28], we found the temperature of olivine crystallization from basalt melt to be 1165°C. A value of 1146°C, close to this temperature, was obtained using an olivine-spinel geothermometer [5]. This strengthens the validity of our assumption. The crystallization temperature of the cores of plagioclase phenocrysts, calculated by the Kudo-Weill geothermometer [24] for moderate P_{H2O} values was substantially larger than the olivine equilibrium temperature: 1292° C for $P_{H2O} = 0.5$ kbar and 1257° C for $P_{H2O} = 1$ kbar. This result suggests that the plagioclase crystallized before the olivine. The assumption that these minerals crystallized simultaneously at $T = 1145°$ to 1165 °C, demands that P_{H2O} in the melt must be as high as 2 kbar and hence the H_2O content must be 4.5 wt.% [6]. Regrettably, a thin section study gives no way of forming an opinion concerning the relative crystallization time of these minerals.

The oxygen fugacity during basalt magma crystallization was evidently an order of magnitude larger than the NNO buffer, as follows from the calculation based on the bulk basalt composition.

To sum up, in spite of our assumptions we can conclude that the liquidus temperatures of the basalt and the dacite melt were different by at least 200°C, and the oxygen fugacities by an order of magnitude. The rise of a high temperature basalt magma from a deep-seated source into a shallow chamber containing low temperature acid magma, which had remained there from the previous eruptive phase, caused its heating to the boiling point and, as a consequence, provoked the eruption of the two mixed melts which reacted differently with one another.

Two observations are of particular interest: (1) the presence of nonequilibrium minerals in all rocks under study (except for the basalts of the Tamara Cone), and (2) a progressive increase in the basicity of the erupted products.

Table 7 Results of balance calculation based on fractionation model.

Component	*Pairs of rocks*						
	Basalt – basaltic andesite	Basalt–andesite	*Basalt – andesite*	*Basaltic andesite – andesite*		*Andesite – dacite*	
Percentage of fractionated minerals, wt. %	10.0 Ol 15.5 Pl −2.8 Sp 2.7 MTcr	11.1 Ol 23.0 Pl −9.5 Sp 11.6 MTcr	14.6 Ol 34.5 Pl −13.0 Sp 16.8 MTcr	−0.5 Ol 5.4 Cpx 2.2 Pl_1 7.6 Pl_2 4.5 MTti	−1.1 Opx 5.5 Cpx 1.9 Pl_1 7.3 Pl_2 4.6 MTti	4.5 Ol 3.5 Cpx 11.8 Pl_1 6.2 Pl_2 2.2 MTti	8.6 Opx 3.3 Cpx 11.5 Pl_1 11.7 Pl_2 1.7 MTti
Percentage of residual melt, wt. %	73.3	62.2	45.5	81.1	82.1	71.0	61.8
Deviance	0.54	1.08	1.60	0.05	0.03	0.13	0.26

Note. Analyses of rocks are given in Table 2 (1 – basalt, 3 – basaltic andesite, 5 – andesite, 12 – dacite), For compositions of mineral phases see Table 3 thru 6. Calculation was based on the compositions of phenocrysts. Code: Ol – olivine, Cpx – clinopyroxene, Opx – orthopyroxene, Pl_1 – calcic plagioclase, Pl_2 – sodic plagioclase, Sp – spinal, MTcr – chrome magnetite, MTti – titanomagnetite. The sign minus denotes that this mineral phase must have accumulated in the residual melt.

The first observation indicates that the rocks under study do not represent a "pure trend" but are products of a more or less advanced mixing of magmatic melts. So volcanic eruptions were preceded by magma mixing, and the mixture was homogenized during the time interval between the intrusion of basalt melt into an acid magma chamber and the eruption.

That the volcanics grew more basic with time fits the hypothesis of a progressive displacement of dacite magma from a shallow chamber by basalt melt rising from a deep-seated source and the growth of the basalt magma proportion in the mixed product with time. Whereas the role of basalt magma was evidently small in the generation of the Old Kizimen rocks and can only be conjectured from the findings of olivine phenocrysts in the dacite and acid andesite (along with quartz and acid plagioclase phenocrysts), the rocks of Young Kizimen are obvious hybrids (andesites and basaltic andesites of nonequilibrium minerals composition), the genuine acid rocks with imperceptible indications of mixing being only recorded in the early stage of its eruptive history.

It is important to note that quartz-olivine andesites and dacitic andesites, similar to the Kizimen lavas in the above mentioned and other features of their mineral composition, are known in a number of other Kamchatkan volcanoes. They have been reported from Dikiy Greben [13], Aag and Arik [17], and also found by O. N. Volynets at Bolshoi and Tolmachev Dol (personal communication). Like the Kizimen rocks, these are obvious products of magma mixing.

Although quartz-olivine volcanics are comparatively rare rocks, many intermediate calc-alkalic lavas of Kamchatkan volcanoes contain compositionally contrasted plagioclase phenocrysts, and their orthopyroxene phenocrysts are more ferric than the microlites, this being another indication of mixing. This fact and a wide development of heterotaxitic lavas and pumices [4] among Quaternary Kamchatkan volcanics suggest that magma mixing is one of the important processes that are responsible for a diversity of igneous rocks.

SUPPOSITIONAL FORECAST OF THE TYPE AND PARAMETERS OF FUTURE ERUPTIONS. HAZARD ASSESSMENT

A long-term prediction of the volcanic hazard, type, and size of future eruptions is offered here on the basis of the principles worked out earlier [26] and used for this purpose at other volcanoes. The approach consists essentially in recognizing the volcano's past eruptive pattern and periodicity, establishing the stage in which the volcano is at the present time, and forecasting the character and number of eruptions that are likely to occur at the present-day stage of its activity.

The imperative and principal condition is a detailed, comprehensive reconstruction of the eruptive activity and the evolution of the erupted material since the birth of the volcano, or for a long period of its eruptive history, as we have done for Kizimen above. We have shown that in spite of a comparatively recent birth, Kizimen is a rather mature volcano. Old Kizimen, which was active during three eruptive cycles, ceased to be active about 6000 years ago, and a new volcano, Young Kizimen was born in its place after a 3000-year quiescence. The forecasting of future eruptions must therefore be based on the evidence obtained for Young Kizimen: the character and frequency of its former eruptions and their variations in time, the compositional evolution of the rocks, and the productivity of the volcano during various time intervals up to the present time. In a large measure, the character and parameters of eruptive activity are controlled by "internal" processes that are directly related to the life of the magma source and the peculiarities of the feeding mechanism.

A forecast must, however, take into account the "external" factors that may influence the process of future eruptions. In our case these are primarily the morphology of the Kizimen structure and the location of the volcano on the side of the seismically active Shchapina graben.

As mentioned above, the birth of Young Kizimen 3000 years ago was marked by a powerful explosion and an ejection of large-tonnage juvenile pyroclastics of contrasted chemical composition, which, being dominated by acid andesite, contained a small amount of basaltic andesite material. For a long period of time that followed (until ~1100 years ago), volcanic activity consisted in the growth of an andesite dome in the crater, which was accompanied by some outpouring of andesite lava and weak or mild explosions.

By the close of the penultimate millenium or at the beginning of the last thousand-year period, a new explosion started a series of eruptions of the closing phase of cycle KZ IV. For the first time in the Kizimen history the explosion was not followed by an ejection of a considerable quantity of juvenile pyroclastics. A small dome grew in the crater, and mild explosive and effusive eruptions took place. The material produced was of the highest basicity in the Kizimen history. During the last centuries the volcano was in the state of fumarolic activity with scarce phreatic explosions (the last occurred in 1928).

During the whole of cycle KZ IV the Young Kizimen activity was characterized by low productivity and a small rate of dischage, especially during the closing phase of the cycle (see Table 1).

It looks as if Young Kizimen Volcano repeated the Old Kizimen history during cycle KZ IV, which was three times as short and was characterized by an abruptly decreased productivity, a low rate of dischage, and a more basic composition of the erupted juvenile material. Proceeding from these facts alone, one may conclude that the Young Kizimen eruptive activity has been completed (or is nearing completion).

In that case, the long-term forecast of future eruptions at Young Kizimen would be rather simple: the volcanic activity in the near decades or even centuries must be as it was in the last 150-200 years. The volcano must be in the state of a more or less intensified fumarolic activity with infrequent mild phreatic explosions similar to those of 1928. Naturally the volcanic hazard must be small - within the volcanic structure and only during explosions (Figure 11). Coarse material produced by explosions will fall in the immediate vicinity of the vent, and ash will be deposited on the cone and at its foot. The ash cover may range within a few centimeters near the vent and fractions of a millimeter at 5-10 km from it. The direction and length of the ash fall zone will be controlled by the direction and force of the wind. The total volume of the transported material must not be larger than 0.001 km^3.

However, considering the "external" factors, a long-term forecast of the character of future eruptions and volcanic hazard may be different. The decisive role may be played either by any factor individual or by a combination of factors along with eruptions themselves.

The fact is that the destruction of the large steep-sided dome in the Kizimen summit crater may be followed by events similar to the events that took place at Bandai Volcano, Japan, in 1888, or at Mount St. Helens in 1980.

An explosion may be caused by a short-lived (a few tens of years)

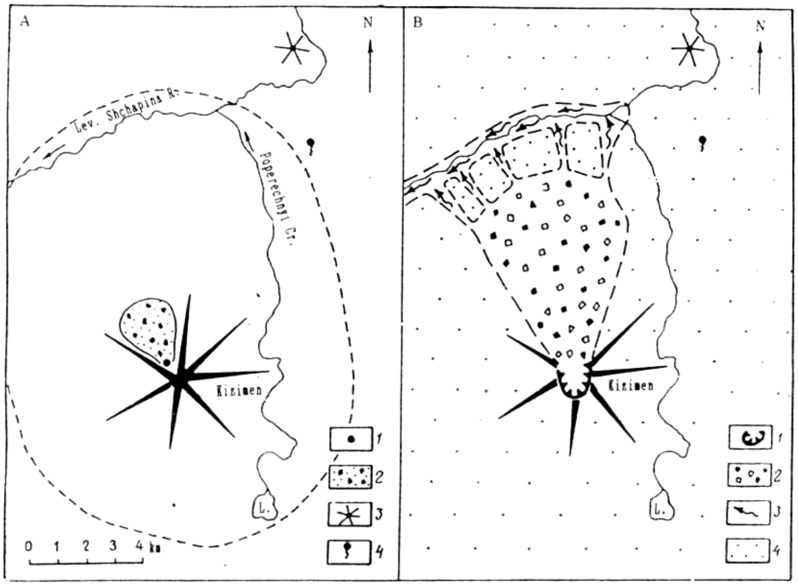

Figure 11 Sketch maps showing the extent of inferred volcanic hazard for the Kizinen area. A – *minimum hazard:* 1 – location of eruptive vent; 2 – area covered by explosive products; 3 – Tamara cinder cone; 4 – Verkhneshchapina hot springs. The broken line contours an ash-fall area with a > 0,1 mm tephra cover. B – *maximum hazard:* 1 – rockslide avalanche and explosion crater; 2 – area covered by rockslide debris and explosion products; 3 – lahars; 4 – ash fall area with a > 1 cm tephra cover.

plugging of fumarole channels (e.g., as a result of an earthquake), considering a great intensity of fumarolic activity. If an explosion takes place from beneath the dome, where the fumaroles are located, and is strong enough, part of the dome will collapse. The dome may likewise collapse as a result of a class 9 or 10 earthquake in the Shchapino graben.

In any case, whatever the cause, a large rockslide avalanche may provoke an eruption that will be many times as large as the phreatic explosion of 1928. It may be as large and have the same geological effect as the Bandai eruption of July 15, 1988, whose rockslide debris totaled 15 km^3, and explosive products 0.011 km^3 [22]. No juvenile material was erupted.

An earthquake-triggered landslide avalanche and a lateral blast may occur at Kizimen as a result of an intrusion of viscous magma under the dome, as it happened during the 1980 catastrophic eruption of Mount St. Helens [25]. This possibility is not unlikely, because the KZ IV cycle is nearing completion, and a new, fifth cycle may begin with an injection of the next portion of fresh magma in the Kizimen feeder system.

This supposition is realistic because Kizimen stands on the system of faults that bounds a large volcano-tectonic depression in which the Northern group of Kamchatkan volcanoes is located [11]. These volcanoes grew increasingly active during the last centuries: the catastrophic events that occurred there and a large number of flank eruptions discharged ~20×10^9 tons of juvenile material. This may be indicative of a regional renewal of magmatic activity within this structure, the Kizimen area included.

Both of the above versions of eruptive activity will pose great hazards not only near but also far from the vent. Explosion and rockslide debris may cover an extensive area at the northern foot of the volcano as far as the valley of the Levaya Shchapina River, and lahars may flow as long as tens of kilometers (see Figure 11). The most hazardous zone is likely to be an area between the Verkhneshchapina and the Nizhneshchapina hot springs. Tephra may cover an area of $n\times10^4$ to $n\times10^5$ km^2 with a thickness of > 1 cm at a distance of 10-15 km from the vent. The volume of transported material may range between 0.1 and 1 km^3.

The present-day knowledge of the Kizimen activity and the Shchapina graben seismicity is not enough to decide between the two versions. A reliable forecast of future Kizimen eruptions requires more investigation to recognize the volcano's eruptive pattern and periodicity in the last thousand years, study in more detail the evolution of the erupted material, and survey the state of the volcano's "roots" by geophysical methods.

CONCLUSIONS

1. Kizimen Volcano was born in a zone of large-magnitude normal faults of the Shchapina graben 12 or 11 thousand years ago, when high-temperature basalt magma was injected into a cooling shallow dacite magma chamber that had remained after the early Pleistocene episode of volcanic activity in the Tumrok Range. This basalt magma injection, synchronous with the late Pleistocene flood basalt volcanism of Kamchatka, stimulated a powerful eruption of dacite magma which gave birth to a new volcano.
2. Some features of the mineral composition of the Kizimen eruptive products (primarily the presence of the "prohibited" quartz-olivine association of phenocrysts in all rock types) provide evidence that the rocks were derived from a magma that had been produced by the mixing of melts contrasted in the silica content. Judging from the evolution of the Kizimen rocks with time, dacitic magma was gradually displaced from the chamber by basaltic magma, which rose from a deep-seated reservoir, and the mixed magma was growing progressively more basaltic.
3. Four cycles of approximately similar duration (2-3.5 thousand years) have been distinguished in the eruptive history of Kizimen Volcano. The early phases of each cycle were eruptive period of high

productivity, the closing phases were poorly productive. This kind of cyclicity is believed to have been caused primarily by the injections of new portions of basalt magma into the feeding system of the volcano. The onsets of cycles KZ I, KZ II and KZ IV coincided with the periods of the regional renewals of magmatic activity. The last cycle, KZ IV (~3000 years), is nearing termination, and a new, fifth cycle is likely to begin in the near hundreds of years.

4. If cycle KZ IV lasts for the forthcoming tens or hundreds of years, the volcano is expected to remain in the present-day state of fumarolic activity with infrequent phreatic explosions. But if an earthquake causes a rockslide avalanche of the summit dome, a large eruption of the Bandai type may take place. A catastrophic eruption, like the 1980 eruption of Mount St. Helens, is likely to occur at the beginning of the next, fifth cycle of the volcano's activity. However, even in that case the eruption of large amounts of acid juvenile material is unlikely because dacitic magma that was stored in the source has been depleted.

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