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THE GEOLOGIC STRUCTURE OF STRATOVOLCANOES

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This article emphasizes the complexity of the interior structure of volcanoes, using deeply dissected volcanoes of Kamchatka as examples.

The traditional view of the structure of stratovolcanoes [1] and other central-type volcanoes still prevails: They are conical bodies in which effusive and pyroclastic sheets, or mantles, are disposed symmetrically about a tubular throat and conformably to the surface of the volcano [3]. Such a structural scheme may be found in any textbook on vulcanism and even in recent specialized publications on volcanology [4]. But this scheme, which necessarily envisages a fixed feeder canal throughout the development of the volcanic apparatus, does not reflect the discontinuous character of its activity and the evolution of the volcanic throat during the life of the volcano. Moreover, the formation of a stratovolcano occupies a definite segment of geologic time—some tens of thousands of years [7], and its eruptions occur with a periodicity ranging from a few years to a few thousand years. The traditional idea of the structure of a stratovolcano is thus only a very rough approximation, and is contradicted both by the data obtained from studies of eroded structures above the surrounding land surface that still retain remnants of their primary surfaces, and by observations of the activity of young, Upper Pleistocene to Holocene volcanoes.

The standard Soviet *Geological Dictionary* [1] defines a volcanic throat as follows: "a vertical or almost vertical canal joining the magma chamber of the volcano to the Earth's surface, where the throat ends in a crater." It has been stressed elsewhere [6] that the throat has a nearly cylindrical form with a diameter of some hundreds of meters. Theoretical calculations of the movement of magmatic material [5] are founded on such ideas of the structure of the feeder system. But study of sections through paleovolcanoes fails to confirm the existence of such long cylindrical bodies within their structures

The most informative are paleovolcanoes of Pliocene and Early Pleistocene age sufficiently exposed by erosional or tectonic processes for their internal structure and composition to be studied. Some of them at the same time retain elements of their primary volcanic surfaces, enabling the form and volume of the old structure to be reliably reconstructed. The basal diameters and reconstructed heights of Pliocene and Lower Quaternary stratovolcanoes are on the same order as those of similar Recent structures [13]. This, along with their identical compositions, justifies the supposition that the internal structure of such old volcanoes is like that of their present-day analogs. The latter reveal their structure when deep negative relief forms, chiefly of explosive origin (deep craters and explosive calderas), are present.

Study of sections through paleovolcanoes has shown that, in spite of their complex combinations, the materials making up the above-surface structure can be divided into two main groups of facies: 1) effusive-pyroclastic facies together with the rocks at the volcano's foot, and 2) those forming the feeder of the volcanic system. The combination of these facies groups is what produces the unique and non-recurrent distinguishing characteristics of each particular volcanic structure. Their combination in turn depends on the duration of the volcano's activity and the composition of its eruptive products. A common feature of these facies groups is that they are genetically related and have a prolonged and pulsational history. Each new impulse contributing to the volcano's formation is associated with its growth and destruction, with changes in volume of the volcanic structure, and with the movements of its separate elements in space. In each case, the volcano is the result of a multiphase accumulation of effusive and pyroclastic material (as well as its erosion in intervals of volcanic quiescence), and of numerous injections of magmatic melt into the body of the structure as progressively newer volcanic vents are formed. If there have been effusive outpourings, a "dike-lava flow" system linked by gradual transitions is often developed. The sources of the pyroclastic eruptions are, of course, separated spatially from the pyroclastic deposits. Thus the links between the various pyroclastic formations and their subvolcanic analogs are often hard to determine.

In a number of earlier publications [14, 15, 17] the present author has dwelt on the distinctive features of the structures feeding the volcanic systems. Two main types of these feeders have been distinguished: intrusive-dike and intrusive-extrusive, along with ther combinations.

The present article will consider some examples of the structure of both young and old stratovolcanoes, which were studied chiefly by mapping the Cenozoic volcanic belts of Kamchatka.

Mt. Bakening Volcano

This volcano has been the subject of several publications [9, 12], which have described the distinctive features of its relief and that of the surrounding region. Mt. Bakening is a typical Upper Pleistocene to Holocene stratovolcano, located at the sources of the Avacha River. It has the form of a slightly truncated cone whose relative elevation is 1450 m, with a basal diameter of 8–10 km. Its slopes are dissected by ravines and show no signs of glacial erosion.

The volcano was formed by andesite eruptions, which were accompanied by extrusions of complex composition (ranging from rhyolites to andesites) at its eastern and northern foot. Its slopes are sheathed by a mantle of lava flows.

One noteworthy feature of this volcano is the deep (to 0.5 km) and wide (to 1.0 km) ravine descending the southeast slope of the volcano from its summit to its foot. The steep exposed slopes and scarps of this negative relief form make it possible to "peek" into the young volcano and study its structure and composition. The ravine does not cut into the central part of the volcano where, according to the traditional view, its throat should be located. It penetrates horizontally into the cone for only a few hundred meters: that is, it should expose only the effusive-pyroclastic slope facies. But andesite flows with a total thickness of 100–150 m make up only the uppermost parts of the scarps. Within them can be discerned vertical and steeply inclined dikes, which increase sharply in number in the apical part. Exposed beneath the flows forming the slopes (Fig. 1, I) and apical part of the volcanic structure is a complex combination of bodies belonging chiefly to the volcanic feeder system, along with explosive formations.

In the bottom of the ravine, directly above the volcano's foot and above a proluvial trail, bedrock formations are exposed for a height of 200 m; these are cut by fracture planes resulting in the production of pyramidal forms. The rocks of which they are composed are heterogeneous in structure and texture. Closer examination shows them to be a complex body formed by a system of subparallel steeply dipping and vertical dikes five to seven meters thick with easterly strikes. These dikes are located in a shell of psephitic breccias, which have a brownish hue. The transition from the clastic facies to the massive porphyritic dike rocks is gradual. The spaces between dikes are also filled with clastic facies of the same andesites. This dike system has been traced in the slopes for 400–500 m along the strike from

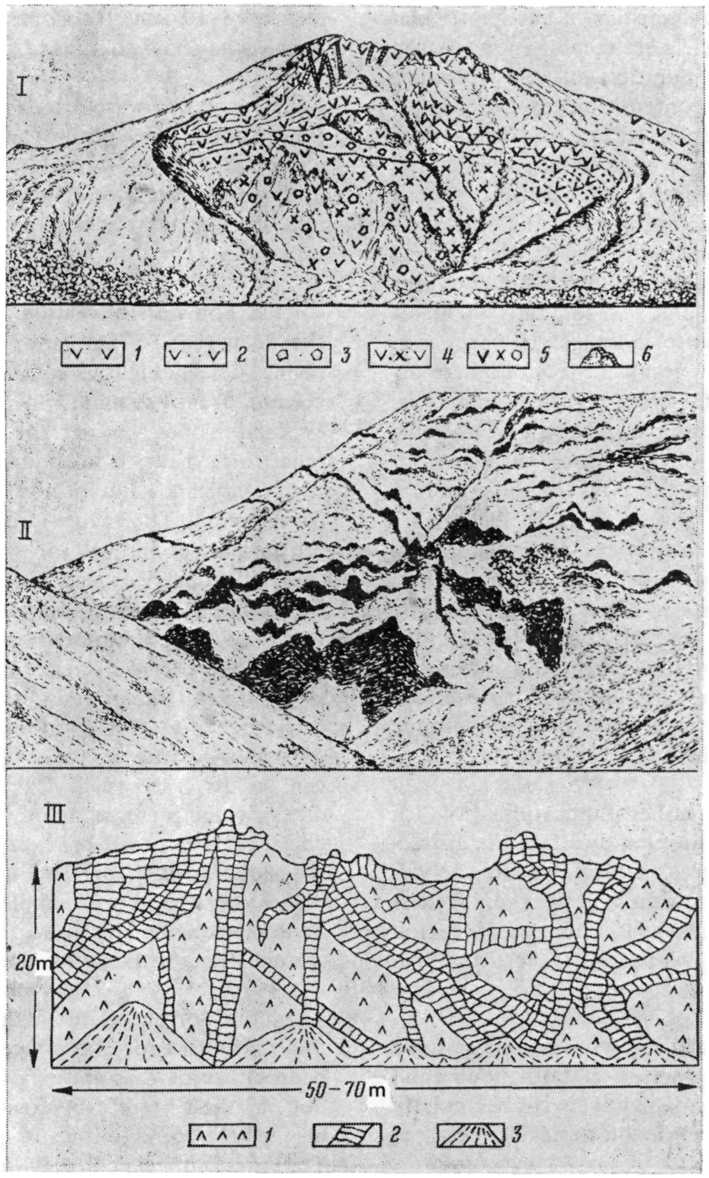

FIGURE 1. Examples of structure of Pleistocene-Holocene volcanoes. I) Mt. Bakening volcano (at the head of the Avacha R.), southeast slopes: 1) andesite lava flows, 2) andesitic tuffs, 3) agglomeratic tuffs, 4) intrusive andesites, 5) intrusive andesitic clastites, 6) andesite dikes. II) Part of Mt. Mutnovskiy crater (southeastern Kamchatka), showing dikes (black) in fumarole-altered rocks. III) Mt. Zheltovskiy volcano (southern Kamchatka), showing basalt dikes in north wall of crater: 1) dacites and andesite-dacites of apical extrusive, 2) dikes, 3) talus.

south to north and across the whole width of the ravine, for a distance of 1000 m.

The outcrops of these bodies are replaced upward by massive greenish hornblende andesites with numerous xenoliths of holocrystalline and more rarely sedimentary rocks. These xenoliths range in size from fractions of a centimeter up to 2–3 cm. It can be seen in the outcrops that the rocks of this body make up a complex of interlinked dikes. The thickness of these dikes (parts of the body) is about five meters and their strike northerly. The relative height of the outcrops of these andesites is about 200 m, and they have been traced along their strike (visually) from south to north for 400–500 m. In the upper part of the body of hornblende andesites are extended exposures of black cataclastic agglomeratic tuffs, up to 20 m in thickness. The contact of the tuffs with the andesites is undulating and uneven, and they show signs of having been baked. Thus they are probably remnants of the rocks overlying the andesite intrusive.

Immediately above the outcrop of dark tuffs overlying the intrusive of "green" andesites in the scarp of the ravine's slope can be seen a nodular bedrock outcrop 60 X 25 m in size. This is made up of pinkish-gray andesites with large light-colored homogeneous xenoliths up to 15 cm in diameter. On its southern flank is the clearly visible intrusive contact of the andesites piercing the terminal flows, which at the contact are deformed into a steep flexural bend. As a result, the younger flows lie with a visible unconformity on the flows penetrated by this body.

No distinct boundaries of major subvolcanic formations have been observed higher up. The form and attitudes of the rocks exposed beneath the lava flows of the volcano's apical part are not clear. Quite a large number of dikes can be seen here visually. The most extended 150–200-meter dike remnant is visible in the northern part of the summit: it has a prismatic form and is about 50 m high.

Thus much of the volume of the exposed part of a typical central volcano's structure is occupied by injected bodies making up a system of subvolcanic intrusives. In the lower part of the cone they form complexes of parallel dikes, but above only individual dike bodies. These pierce the andesitic lava flows and tuffs and are in turn covered by them. Effusive-pyroclastic formations at the same time form both the substrate and the roof of the volcano, and part also of the overlying rocks. On the whole, the part of Mt. Bakening's structure that has been characterized is comparable to a conical container whose thin walls consist of effusive-pyroclastic sheets, while its interior is occupied by injected dikes cutting through relatively older ruptures and dislocating the deposits of the volcano.

Mt. Mutnovskiy Volcano

The Mt. Mutnovskiy volcano is a large rock mass with a relative height of about 2 km and a diameter of 20 km; it developed throughout part of the Pleistocene and in the Holocene. Holocene rocks make up the western part of the volcano, and its northern slopes are cut by troughs up to 600 m deep formed by the Late Pleistocene glaciation (the Kleshnya and Kuropatka ridges). The relationships of the volcano's different facies can be seen on the sides and floors of these glacial valleys; the geologic section is repeated in its general features within each trough. Its upper part consists of series of basalt flows with a total thickness of up to 400 m, whereas basalt stocks and dike systems up to 1 km^2 in area are exposed in the trough bottoms and at the base of the volcano's slopes. The direct substrate of the volcano's north slope consists of Pleistocene ignimbrites, which are overlain by coarse clastic deposits of pyroclastic, proluvial, and glacial origin, with a total thickness of 200 m. These are pierced (according to observations along the Kuropatka River) by a complicated body of basalts consisting of a thick packet of dikes; in its upper part this splits up into solitary dikes enclosed in coarse pyroclastic deposits. Here dikes with distinct rectilinear contacts are accompanied by dikes with agglomeratic endocontact zones. Higher up in the section along the trough slopes is a series of thin (up to 5 m thick) basalt flows, penetrated by rare dikes with rectilinear outlines and thicknesses of 1.5–2.0 m. The thickness of the Mt.

Mutnovskiy volcano's effusive-pyroclastic rocks increases from 200 m near the summit to 500 m at the foot. These envelop a "core" consisting of the branching feeder system, whose bodies were injected into the older rocks of the volcano.

Holocene Volcanoes

The Holocene volcanoes are almost entirely sheathed by an effusive-pyroclastic mantle, so that information on their internal structure must be obtained by studying the walls of craters and ravines. The observations of I. T. Kirsanov [2] on the Mt. Klyuchevskiy volcano, a classic example of a stratovolcano, are of interest. Its crater has a diameter of 650–700 m and is 550–600 m deep. The upper parts of its walls, made up of interlayered lavas and pyroclastic rocks, are pierced by vertical dikes and stock-like bodies. At elevations of 2500 to 4850 m the volcano's slopes are dissected by ravines, which radiate out from the crater. Shatter zones and numerous dikes can be seen in their floors and sides. They are frequently sites of eruptions, so that cinder cones with laval flows often "sit" in them, and explosion funnels can be seen. All this indicates that the formation of the ravines was determined by volcanotectonic processes. Of the recent eruptions associated with ravines here, the injection of a dike and effusion of a lava flow in 1926, and the formation of the Radist cone in 1937 may be mentioned. Numerous subordinate vents of the Mt. Klyuchevskiy volcano lie on the continuations of the ravines in the lower parts of the slopes. Their formation, I. T. Kirsanov notes, was related to the development of dike-filled fissures "which on the surface are marked by chains of explosive funnels."

In view of the fact that many tens of craters and cinder cones lie on the slopes of this volcano, we can state with confidence on the basis of observations in the central crater and the ravines that this entire young volcanic structure is penetrated throughout by a branching system of dikes—the tracers of volcanic vents. The presence of dikes within the crater and their association with the most recent subordinate eruptions indicate that a feeder vent of fissure form is most typical of stratovolcanoes.

This conclusion is clearly supported by the structures of the older volcanoes of the Klyuchevskiy group, whose summits and slopes have been worked over by glaciers in Late Pleistocene and Holocene time. Numerous dikes are found in the troughs dissecting their slopes. Conjugate dike complexes have been mapped in the circumapical parts of the Ploskaya Dal'nyaya and Ploskaya Blizhnyaya mud cones at distances of five to eight kilometers from the peak. The stocks and rows formed by such dikes are hundreds of meters to a few kilometers in size horizontally. The extensive occurrence of dikes on the slopes of the Ploskiye cones was noted some time ago by A. N. Sirin [10]. They are no less typical of the Mt. Kamen' volcano, whose west and southwest slopes are pierced by a system of extended (up to 3 km) dikes of northwest strike, while large bodies of intravolcanic injections several square kilometers in area have been mapped in the lower parts of its slopes. The aforementioned example of the Klyuchevskiy volcanic group shows clearly that the number of dike bodies found depends on the duration of the erosional processes acting on the slopes of the volcanic structure. Moreover it must be kept in mind that the number of such dikes is obviously a function not so much of the duration of the volcanic structure's existence as of the volcano's active life.

In spite of the comparatively meager information yielded by such young volcanoes about their internal structures, observations of them are extremely useful since only they can show persuasively that the conical form of a central-type volcano and the funnel-like shape of its crater are not at all inconsistent with the fissure forms of its volcanic vents or the dike bodies of the volcanic feeder system. In addition to the volcanoes of the Klyuchevskiy group, numerous other volcanoes such as Mts. Avacha, Mutnovskiy, Opala, Ksudach, Khodutka, Zheltovskiy, etc. are likewise indicative in this respect.

In the Mt. Avacha volcano, dikes have been found both in its crater and its somma, where they form the present dike extrusives. The numerous crater dikes of Mt. Mutnovskiy (Fig. 1, II) pierce the rocks of the crater walls, which have been altered by fumarole processes, so that the dikes can be easily distinguished against their light-colored background. The apical necks of the Holocene Mts. Opala and Khodutka volcanoes are represented by dike rows. Transitions of dikes cutting through the relatively earlier volcanic sheets into younger laval flows can be seen on their slopes. The crater of the Mt. Zheltovskiy somma-volcano on Southern Kamchatka has been carved into its apical andesite-dacite extrusive. The walls of this crater are 200–300 m high and its diameter is 400–500 m. The northern part of this crater wall is pierced by a dense network of vertical and inclined branching dikes, each from one to five meters thick (Fig. 1, III). These dikes are the roots of the basalt flows sheathing the volcano's north slope.

Bol'shaya Ipel'ka Volcano

The Bol'shaya Ipel'ka basalt volcano is a typical shield structure with an essentially effusive section through the lower parts of its slopes and an apical effusive-pyroclastic zone. It formed in Early Quaternary time. Its diameter is 35–40 km, its area 1150–1200 km^2, and its volume about 400 km^3; the reconstructed former height of this mass is 2500 m, and its present height 900–1000 m. During the Late Pleistocene this volcano underwent intensive glacial erosion, which largely destroyed the structure, especially its apical part, where vast cirques were formed. But the volcano's slopes between the wide radiating glacial trough valleys remained intact. Their inclination varies from 5° to 10°, reaching 20° near the summit. The visible thickness of the series of basalt flows in the lower parts of the slopes is no more than a few hundred meters, and that of the effusive-pyroclastic rocks forming the summit 300–400 m.

In the very large exposures of the cirque and trough walls can be seen the extremely intensive feeder volcanic system, which is saturated with injected bodies (Fig. 2, I). Its outer boundary has been mapped along the border of the dike field, whose area is about 120 km^2. The

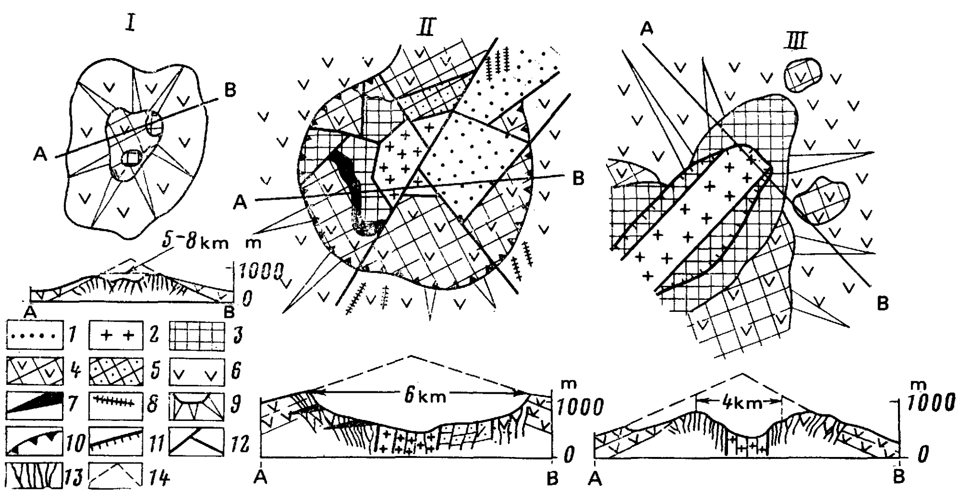

FIGURE 2. Sketch maps and sections showing geologic structure of paleovolcanoes: I) Lower Quaternary Bol'shaya Ipel'ka volcano; II) Pliocene-Quaternary Mt. Zhirovskoy volcano; III) Pliocene Mt. Aga volcano. 1) Terrigenous basement rocks; 2–5) feeder facies of volcanic system: 2) intrusives in deep (lower) zone, 3) intrusives in middle zone (nearby dike, stock, and neck complexes), 4) intravolcanic dike injections in upper zone, 5) dike fields in basement rocks; 6) effusive-pyroclastic mantles sheathing slopes of volcanoes; 7) sills; 8) dikes carved out in relief; 9) slopes of volcanoes; 10) scarps of erosional caldera; 11) trough valley scarps; 12) tectonic ruptures; 13–14) only in sections: 13) injection bodies, 14) profile of reconstructed volcano.

individual dikes are sill-like, inclined and vertical, often branching, and have thicknesses of 1-2 m. They are spaced at intervals of 5-10 m in all directions. Some dikes can be seen grading into flows. Within the dike field are also stock-like bodies up to 4 km^2 in area, made up of tightly clustered, interwoven basalt dikes. The boundaries of such bodies must be drawn somewhat arbitrarily, because of the numerous dike apophyses. Only the small extrusives of light-colored hornblende andesites in the circumapical zone have well-defined boundaries.

Thus no single throat can be found in the well-exposed apical zone of this volcano (at elevations of 800-1100 m). Instead, one sees a densely clustered system of dikes occupying about one-tenth of the volcano's area. In the central part of the dike field the dikes become even more tightly clustered.

The structure of the Bol'shaya Ipel'ka volcano is typical of Lower and Middle Quaternary paleovolcanoes. Such well-known volcanoes as Mts. Kharchinskiy and Ogonsigly [13] have many features in common with the structure characterized above.

The measurements of the concealed subsurface volcanic feeder system are, of course, limited to the zone of active erosion. Where the volcanic apparatus has been more intensively destroyed, the area in which the feeder system has been exposed is fully commensurate with the area of the volcanic apparatus itself. Such a situation can be seen in the structure of the Mt. Ochchamo volcanic massif in the Mid-Kamchatka Range.

Mt. Ochchamo Volcano

This Lower Quaternary volcano has been intensively eroded: of its original basalt shield structure, which was 15-20 km in diameter, only several narrow fragments spreading out radially from the volcano's peak have been preserved. This volcanic complex is represented by an effusive facies and by bodies predominantly of the upper zone of the volcano's feeder system; the two facies are approximately equal in area. The thickness of the effusives reaches 400 m. The bodies of the feeder system are extensively developed laterally: they form a dense dike and sill system developed both in the apical part of the paleovolcano and on its slopes. In the former case they are contained in agglomeratic tuffs, whereas in the slope facies they cut through the basalt flows. Where the effusive and pyroclastic sheets are eroded, the bodies of the feeder system are exposed within the basement rocks. They are concentrated mainly in radial fractures of the basement complex. No tightly clustered dike bodies were observed in the central part of the volcano.

As the erosional downcutting increases, the different natures of the vertical facies making up the volcanic structure are increasingly revealed.

Mt. Zhirovskoy Volcano

This volcano lies in the southeastern part of Kamchatka, near its Pacific shore, where it occupies the watershed between the Zhirovaya and Fal'shivaya rivers. It is a deeply dissected equant mountain massif measuring 14 X 16 km. Its southern and eastern parts have retained the primary inclination of the volcanic slopes. The central part of the mass is deeply eroded. The erosional caldera of oval outline has a diameter of about 6 km at the upper edge of the scarps forming it. The elevation of the top of these cliffs is 1200-1300 m above sea level; the caldera floor lies at elevations below 90 m. In the more than one kilometer section through the caldera, effusive-pyroclastic rocks form the upper part of its walls, some 400-500 m; rock bodies of the complex volcanic feeder system are exposed in the lower parts and on the caldera bottom (Fig. 2, II).

At the base of the effusive-pyroclastic section is a coarse interlayering of agglomeratic tuffs (30-50 m) and andesite-basalt flows (5-10 m), to a total thickness of 150-200 m. Effusive series predominate above.

The feeder system is of the intrusive-dike type. Its rocks are exposed over the whole area of the erosional caldera and can be traced both in the clastic basement rocks and directly within the volcanic structure on land. Deep (lower), middle, and upper zones can be discerned in the vertical section through the feeder system.

The lower zone consists of an intrusive body of complex composition, including gabbronorites, gabbro-dolerites, and dolerites, exposed at elevations from 0 to 500 m over an area of about 4 km^2. This body is made up of parallel vertical prisms some tens of meters thick, and is enclosed in the clastic rocks of the volcano's basement.

The middle zone of the feeder system combines the dike fields in the uppermost part of the volcano's basement. These are represented by distinctive dike intrusives made up in turn by subparallel basalt, dolerite, and andesite-basalt dikes, often without any host rock between adjacent dikes. They represent the upward continuation of the intrusive in the lower zone, and occur at elevations from 90 to 700 m above sea level. The individual dikes are 1–5 m and the separate interwoven dike bodies 30–40 m in thickness. In addition, there are thick (up to 200 m) and extended (up to 2 km) basalt sills. The zone of transition from the basement into the volcanic structure above the surface has frequent branchings of the dike "trunks" and mutually intersecting bodies.

The upper zone is one of intravolcanic injections and traces of the lava vents within the structure above the surface. They are marked by basalt and andesite-basalt dikes, which typically have brecciated endocontact facies. The breccias were formed by movements of partly solidified material along the fissures. The rocks in the central parts of the dikes are massive and unbrecciated. Ordinary dikes are also present. Basalt sills up to 250 m thick have been mapped in the base of the above-surface volcanic structure; these sills are up to one kilometer in extent. At the top and base of the sills are agglutinated agglomerates tens of meters thick. The sills are combined with dike rows, each dike being 1–3 m thick. In some individual areas the dikes form tight clusters of volcanic-neck type 200 m in diameter. Clastic-lava endocontacts are characteristic of some of these dikes.

The feeder system of the Mt. Zhirovskoy volcano combines bodies made up both of holocrystalline and of porphyritic rocks. The intrusive bodies typically have a prismatic-dike structure, which can be attributed to the supply of molten material to the upper parts of the Earth's crust and its surface in portions along successively opened fissures. The preserved effusive-pyroclastic (slope) facies were formed in the late stage of the volcano's eruptions.

The area in which the bodies of the feeder system are developed is not limited to the zone of the erosional caldera; they are also exposed on the outer slopes of the volcano (in the Fal'shivaya River valley), wherever these slopes have undergone intensive glacial erosion.

An interesting feature is the presence of thick horizontal bodies—former magmatic bodies—within the structure above the surrounding land surface. These bodies were related to the injection of fairly short dikes tens or a few hundreds of meters long. The Mt. Zhirovskoy volcano is by no means unique in this respect. Magmatic rock bodies several hundred meters thick—sills 3–4 km in extent—combined both with deeper uniformly holocrystalline intrusives and with dikes and diatremes [17] are characteristic of the Pliocene stratovolcanoes in the basin of the Levaya Khodutka and Nalacheva rivers. They have been mapped at its source, the Porozhistaya River, and also in the Levaya Avacha River basin along the Vershinskaya, Poperechnaya, and Pad' Kornevskaya rivers. The Pliocene volcanic structures of the Avacha and Nalacheva rivers form large, deeply eroded centers of paleovolcanoes, within which the individual paleovolcanic apparatus is hard to distinguish.

Mt. Aga Paleovolcano

This paleovolcano forms a mountain massif in the Mid-Kamchatka Range, and is separated from the adjacent mountain ranges and masses by the valleys of large rivers, the Ketachan and Kopyl'ye. The elevation of this mass above sea level is 1400–1800 m, and its relative height 1200–1400 m above the surrounding land surface. Its central part is cut through by the deep trough of the Aga River valley. This valley trough is about 1000 m deep and 3–4 km wide, and its slopes are steep. The outer slopes of the Mt. Aga mass representing the stratovolcano are made up of interlayered effusive-pyroclastic rocks that have retained their primary undisturbed attitude comformable to the slopes, inclined at from 5° to 15° (on the watersheds). Characteristically, in spite of the kilometer-deep downcutting, the volcano's basement is not exposed in the Aga River valley, on whose floor and slopes the interrelationships of the bodies forming the feeder system can be seen; these bodies were injected into the structure and are part of its make-up (Fig. 2, III).

Thus the volcanic feeder system is exposed in only one intravolcanic zone, but the amplitude of its exposure there is so great that three facies can be discerned in vertical section.

The lower facies is a complex intrusive exposed along the floor slopes of the trough and to heights of about 300 m. It includes such holocrystalline rocks as gabbro, gabbro-diorite, diorite, diorite porphyrite, and more rarely granodiorite, but dolerite, andesite, and andesite-basalt predominate. This intrusive is a complex combination of vertical dike bodies each about 2 m thick. Two adjacent dikes can differ sharply in composition and structure. Dikes made up of rocks with clastic structures have been found here.

The boundary between the lower and middle facies of the feeder system is arbitrary. It is drawn on the level at which an agglomerate mesostasis appears between the dike complexes. The middle facies is a combination of basalt and andesite-basalt sills and dikes. A characteristic feature is the presence of bodies of rocks with clastic structure, to which hydrothermal veins and veinlet zones are often confined. The interwoven dikes have been traced along the rise until they crop out at the paleosurface in the form of extrusives with characteristic clastic injection facies.

The upper facies of the feeder system is closely associated with the effusive-pyroclastic rocks. It consists of dike bodies within sheets and extrusives. The latter are actually dike clusters within the agglomeratic tuffs, and the dikes often have agglomeratic endocontacts. Such extrusives are from 300 m to 1000 m in size horizontally.

The genetic unity of all facies and facies zones of the feeder systems with the effusive-pyroclastic rocks of the deeply exposed Mts. Zhirovskoy and Aga is shown by their closely similar petrochemical properties [17], in addition to the geological observations. A generalized section through a paleostratovolcano is shown in Fig. 3.

There are also volcanic structures of the central type not typefied by dike-sill formations. These resemble present-day extrusive structures. These volcanoes as a rule have an andesitic composition, with large extrusive domes developed in their apical parts. Cropping out from beneath the fairly thick interlayering of effusive-pyroclastic rocks is a subvolcanic intrusive, which occupies the main volume of the structure. A. Rittman explains the effusion mechanism of extrusive volcanoes as follows: "If the supply of magma is large, the morphological capacity of the already extruded dome is exceeded, the dome's sides are split, and its contents are poured out in the form of a lava flow" [8, p. 189].

An example of such a volcano is Mt. Skalistaya, located near the head of the Khetik River in southern Kamchatka. It is made up of Pliocene andesite vulcanites. Its basal area is about 200 km^2, its horizontal dimensions are 20 × 14 km, the relative height of the present massif is 800 m, and the depth of the trough valleys in its central part reaches 500 m. The slopes are sheathed with lava flows of plagioclase-hypersthene andesite, forming a periclinal dome with inclinations of as much as 10°. The thickness of the series of flows is usually up to 200 m. Cropping out beneath them are andesite bodies of the same composition showing no indications of being part of the mantle sheathing the slopes. Holocrystalline porphyritic rocks occur in the lowest parts of the sections.

Such a structure characterizes the Pleistocene Mt. Fedotov volcano (height 1012 m), which lies at the head of the Pravaya Khodutka River. This is an extrusive shield volcano. Bodies

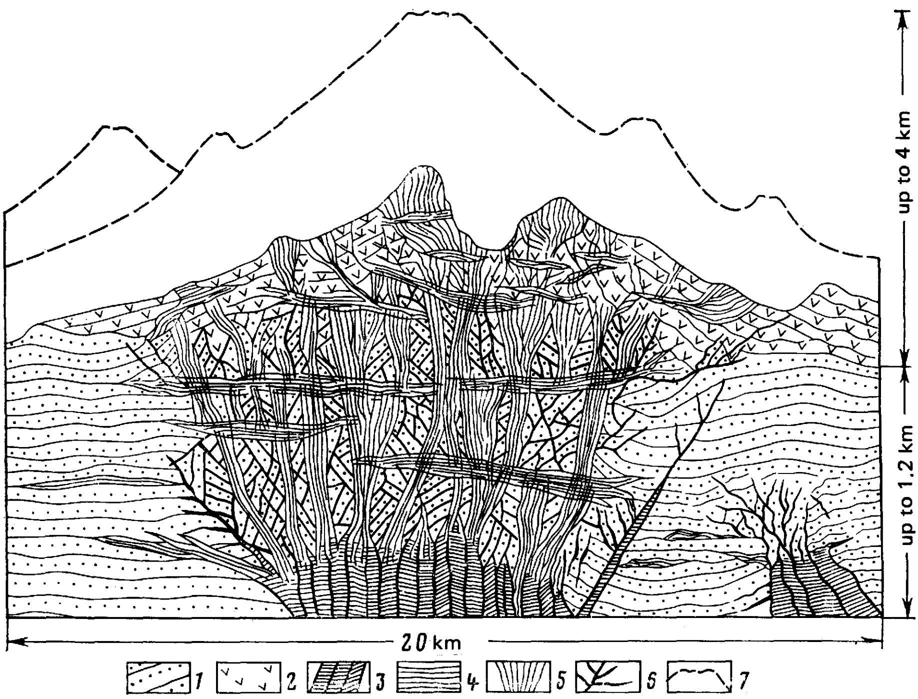

FIGURE 3. Generalized section and profile showing structure of paleovolcano: 1) deposits of basement complex; 2) effusive-pyroclastic sheets; 3) subvolcanic intrusive body consisting of magmatic dikes; 4) sills-magmatic ledges; 5) dike clusters and rows; 6) cavities of tectonic ruptures partly filled with magmatic material; 7) reconstructed profile of paleovolcano.

of andesites are exposed beneath fairly thick sheets of andesites and ignimbrites here.

The structure of such volcanoes demonstrates that the formation of the lava and agglomerate sheets was a result of fissuring of the walls around the intravolcanic cavities and of eruptions from short subordinate fissure vents.

Study of stratovolcanoes and other volcanoes of the central type, both young and old, shows that the actual structure of their feeder systems is clearly quite different from the traditional scheme. Mature volcanic structures that have undergone prolonged development are conical mountain massifs of often compound form. Sheets of effusive-pyroclastic rocks make up only the slopes of these massifs; their thickness is not great (only a few hundred meters). As a rule, they are products of the latest eruptions. Beneath the effusive-pyroclastic mantle are bodies filling the vents of the volcanic feeder–the dike-sill system. The latter is an extremely complicated branching system, filled with dikes and sills, and bodies of injection into the products of earlier eruptions, which have been deformed, dislocated, disintegrated, and largely driven out from the structure's interior to its surface by explosions and other means [15]. The sills, each a few hundred meters thick and up to 4 km in extent, were the reservoirs from which magmatic material came to the surface through fissure vents. These sill bodies are most often confined to the zone of transition from the volcanic structure above the surrounding land surface to its basement. The dikes associated with the sills are not localized in any one part of the structure's roof, and may be distributed over a large area. The thickness of these dikes, which mark the volcanic vents, is no more than 5 m and their extent only a few hundred meters. The fissure vents, judging by the number of dikes in the feeder systems of central volcanoes, play an extremely large part, no less than that of the vents of linear fissure eruptions. The diameters of the dike systems reach tens of kilometers, and their areas 100 km^2 or more. In eroded paleovolcanic structures it can be seen that the dike-sill system is fully commensuate in area to that of the whole structure, and comparable in plan to the size of the peripheral magma chambers identified geophysically [18]. This suggests that the ascent of magmatic material from the magma chamber took place over the whole area of the volcano's roof, through fissure vents, into large subhorizontal magmatic bodies, which may consist of several layers. The large number of dikes in the feeder system is due to the brief existence of the individual fissure vents and the fact that the site of an old vent could not be inherited by a new one [11]. The number of dikes in a feeder system reflects the duration of the active life of the volcanic apparatus and the intensity of activity during its life.

Thus study of the sections through central-type paleovolcanoes, stratovolcanoes, and shield volcanoes shows that the volcanic throat occupies no single fixed space within their structure. Instead, the majority of volcanoes studied have a system of dike vents over a large area; these vents supplied magmatic melt both to the central crater and to the slopes. The dike vent is the main, but short-lived, supplier of melt to andesite-basalt volcanoes. During the active life of such volcanoes (which on average lasted several tens of thousands of years [7]), dikes little by little probably "closed off" the whole area within which magma could ascend from the magma chamber along lines of least resistance. The result, after a time, was a spatial shift of the volcanic activity, with the formation of parasitic volcanoes and volcanic ridges. If a volcano does not shift its vents in this manner, it becomes extinct or else there is a catastrophic eruption that forms an explosive caldera. If its activity continues, the new feeder system is superimposed on the old destroyed one during the formation of the somma volcano (Fig. 4, I). It is clear that a large volcanic apparatus could not arise without such growth and displacement of the feeder system. Only small cinder cones have a simple throat with few if any branches.

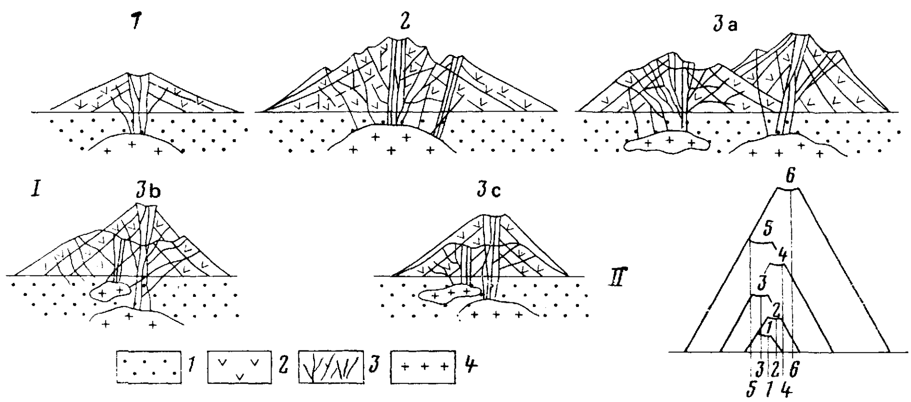

FIGURE 4. Diagrams illustrating development of feeder system of a paleovolcano. I) Schematic geologic sections: 1-3) stages of development: 1) early (simple cone); 2) middle (cone complicated by centers of flank eruptions and embryonic parasitic volcanoes); 3) late stage, in which old volcanic structure no longer develops, but is destroyed, and newly risen young (a) volcano becomes mixed with ("side-stepping" of volcanoes and formation of volcanic ranges) and partly covers central part (b) of disintegrating old volcano (formation of somma volcano), and then completely covers it (c); 1) rocks forming basement of volcanic structure; 2) effusive-pyroclastic sheets; 3) bodies of feeder system; 4) inferred magma chamber. II) diagrammatic illustration of growth of a stratovolcano with shifted feeders and craters; six growth stages shown.

Figure 4, II shows diagrammatically the growth of a cone with a moving volcanic vent. Geologic observations indicate that volcanic vents may form at any point in the volcano's section relative to the vent of the first initial cone. Although they are simplified, these diagrams illustrate the actual displacements of the apical part of a volcano and its crater resulting from the shifting of the volcanic vent. It also explains the considerable volume of rocks making up the feeder system, as well as its growth from the top downward.

Thus the crater of a volcano moves both vertically and horizontally as the volcano grows. Its present position marks the greatest concentration of the most recent volcanic vents. The funnel-shaped form of the crater is not inconsistent with the fissure form of the vents, as is confirmed by the presence of dikes, often very numerous, in the crater walls.

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