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To cite this article: O B Selyangin 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **367** 012020

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Structure, substance and near-surface magmatic chambers of Mutnovsky and Gorely volcanoes (Mutnovsky geothermal region, Kamchatka). II. Mutnovsky volcano

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Abstract. Rocks structure and composition and the history of Mutnovsky volcano development which is one of the most favorable objects of geotechnical exploration according to the situation in the infrastructure of Kamchatka and high energy of modern gas-hydrothermal activity are described. Its latest volcanic activity, eruption mechanisms are discussed, the forecast of activity and morphostructural evolution of the volcano is given.

Keywords: stratocone, apical caldera, lava, pumice, eruption, forecast, high temperature fluid.

1. Mutnovsky volcano

The structure of Mutnovsky volcano is a complex ridged edifice (volcanic massive) consisting of four closely contiguous stratocones (which formed one after another) with summit calderas and polygenic daughter intracaldera structures (Figure 1 in [16]).

1.1. Mutnovsky-1 volcano

The structure of Mutnovsky volcano-1 (complex M_1^1 , Figure 1 in [16]) is the oldest northern part of the massive. It is deeply eroded layered cone without any relicts of the initial slopes. Its uncovered northern part is divided by trough valleys modified by erosion into the system of horseshoe ridges Otkhodyashchy and Kleshnya with spurs. To the south the fragments of near-neck zone of Mutnovsky-1 volcano are exposed by one of the young volcano calderas and the canyon of the Vulkannaya river.

The absolute height of Mutnovsky-1 volcano remnant is about 1800 m, the highest relative height is 1400 m in the north-eastern side above the bottom of the Falshivaya river valley. In its right side at the level of 500-550 m Mutnovsky-1 volcano is underlain by early-middle-quaternary ignimbrites. From the north-west its exceeding is only 650-700 m above the surface of late Quaternary ignimbrites of the Gorely volcano caldera overlying here the foot of the remnant.

The explosive coefficient of Mutnovsky-1 volcano is about 70%, the number of pyroclastic material is less in the feet area, but it significantly increases to a near-vent zone. Basalts and basaltic andesites are dominant in the composition of the structure, the proportion of acid-intermediate rocks does not exceed 10-15%.

Great erosional feature and enough exposure of the exposed rock masses of the northern sector of Mutnovsky-1 and its summit caldera zone allowed us to make more detailed (1:10000 – 1:25000 of scale) survey of this part of the volcano together with the neighbor summit caldera-crater complexes of



Mutnovsky-3 and -4 volcanoes in the south (Figure 1). Mapping of deeply exposed volcano of such scale supposes its further clarification relating to the diversity and products abundance of gas-hydrothermal metamorphism of rocks, as well as classification and division of glacial, fluvio-glacial and heterogeneous fluvial deposits of late Quaternary.

In general, volcanites sections of Mutnovsky-1 manifest cyclic variations of their composition during its development, but without expressed total direction. So, in the section of the Otkhodyashchy ridge (north-western sector of the former structure) there is the following alternation: basalts and basaltic andesites – about 180 m of a visual thickness, a flow of two-pyroxene andesites – 30 m; a band of basites again – about 120 m and a flow of mixed olivine-bearing quartz-biotite dacites with porous homoeogene inclusions of dolerite hornblende basaltoids (the products of mixing and mingling) giving rocks a form of rough lavabreccia up to 35 m; basites cinders and lavas crowning the section of spur of 1325,8 m – 80 m. Composite section of a greatly low Otkhodyashchy ridge extending to the Eastern group of the North-Mutnovsky therms includes about 140 m of oxidized tuffs (predominate) and basites lavas, a flow of quartz-biotite dacites with inclusions up to 40 m, and basalts again – 8 m. In a 300-metre section of the upper parts of eastern slope of the Kleshnya ridge there is the only flow of sub-aphyric andesites (10 m) in the middle part and a horizon of red andesite agglutinates (8-10 m) at the crest; dacites with inclusions in the sector of structure already pinch out. Finally, a thick up to 40-50 m output of pseudoclastic two-pyroxene andesites with curve-plate-spheroidal divisional crowns the section of greatly altered rocks of Mutnovsky-1 volcano in the right side of the canyon of the Volcannaya river directly under the complex paleocaldera filling overlain it.

Dacitic bodies with inclusions noted in the sections description as the flows are unique in the history of the volcano development according to the features of mineral composition (see below). Occupying a close position in Mutnovsky-1 periclinal they are, apparently, the parts of the single thick cover of hybrid lavas overlapping the entire north-western sector (possibly the entire western part) of the oldest cone. For this part of it they are horizon marker (M_1^{1n}) dividing its rocks mass in three formations (including themselves) (Figure1).

There are many dikes outputs of basaltic composition predominantly and radial orientation to the former vent on the whole area of eroded old structure. A swarm of steeply dipping, parallel and awry-intersectional dikes of west-north-western extension is exposed in the rock mass of greatly altered pyroclastites of Mutnovsky-1 volcano in the right side of the Volcannaya river (Figure 1 in [16], 1). A number of dikes outputs greatly increases with the increasing of erosional truncation depth. Some of them were blind; others fed terminal eruptions, some – side breakthroughs. A few greatly ruined edifices of the lateral eruptions are preserved at the northern foot of Mutnovsky-1 volcano (Figure 1 in [16]). Their cinders and lavas are represented by olivine-plagioclase and aphyric basalts at the western cones group, hybrid olivine-two-pyroxene basaltic andesites at the eastern cone.

The height of Mutnovsky-1 volcano exceeded 2400 m and the volume was about 58 km³ to the end of its formation and before the formation of summit caldera on it.

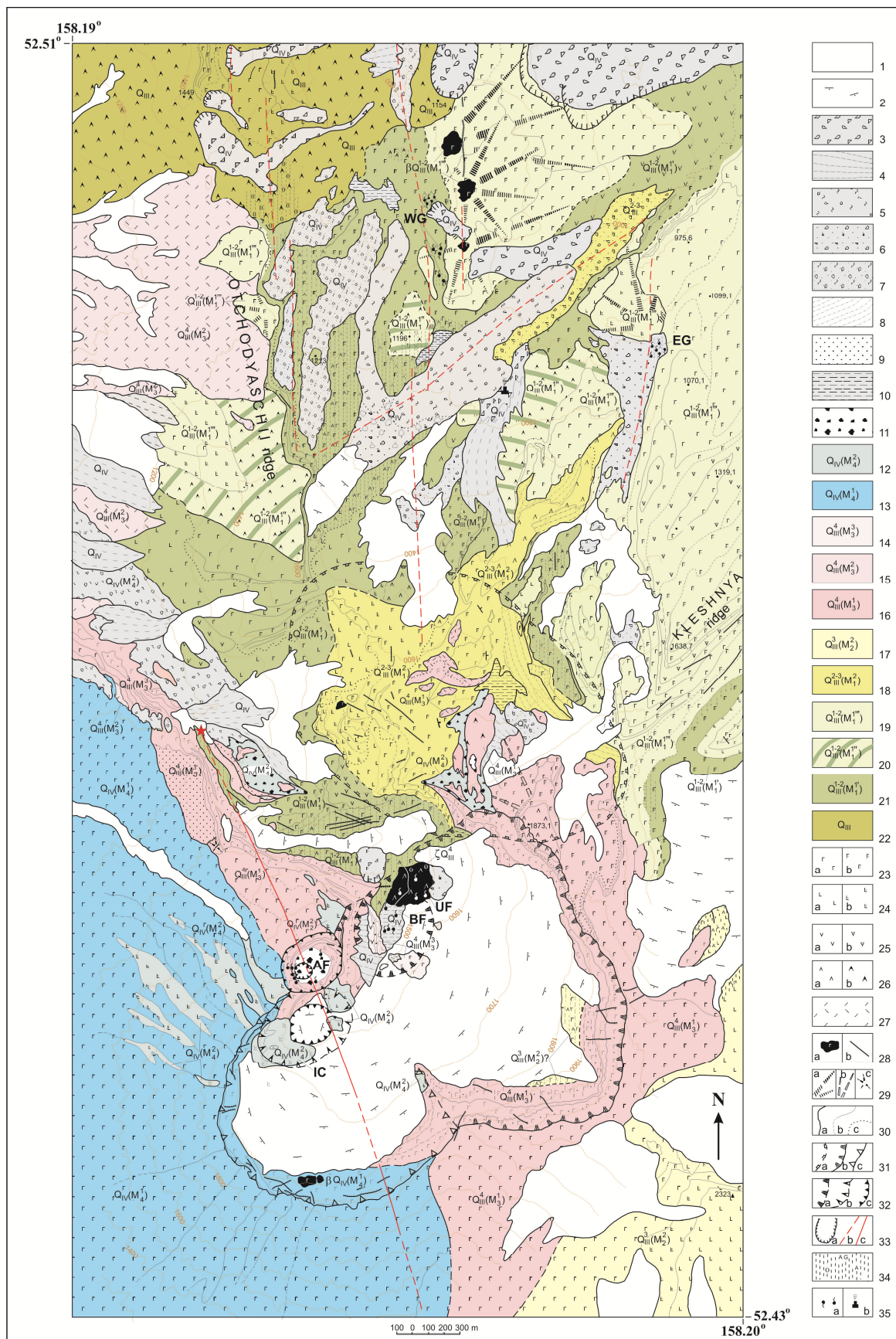


Figure 1. Geologic map of the summit zone and northern sector of Mutnovsky-1 volcano, caldera-crater complexes of Mutnovsky-3 and -4 volcanoes. Made by O.B. Selyangin. Graphic processing is made by Ye M Gazzaeva

1 – perennial snowfields and firn fields; 2 – glaciers; 3 – failure deposits; 4 – deluvial trails; 5 – deposits of lahars and debris flows; 6 – main moraine; 7 – lateral moraine and marginal channels deposits (?); 8 – fluvioglacial deposits; 9 – lateral eruption cinders re-deposited by temporary streams; 10 – lake deposits; 11 – explosive deposits; 12 – cinders of inner cone of Mutnovsky-4 volcano and the Active Crater; 13 – Mutnovsky-4 volcano; 14 – volcanites of intercaldera complex of Mutnovsky-3 volcano; 15 – deposits of caldera-forming eruption of Mutnovsky-3 volcano; 16 – Mutnovsky-3 volcano; 17 – rocks of intercaldera complex of Mutnovsky-2 volcano; 18 – intercaldera complex of Mutnovsky-1 volcano; 19 -21 – thickness of eruptive rocks of Mutnovsky-1 volcano: upper, middle, lower; 22 – rocks of Dvugorby volcano; 23 – lavas (a) and pyroclastic deposits of (b) basaltic composition; 24 – lavas (a) and pyroclastic deposits of (b) andesibasalt composition (the mixing of 23 and 24 in some fields of the map marks the allotments of a bad exposure of interbedded members of the rocks of appropriate compositions); 25 – lavas (a) and pyroclastics of (b) andesites; 26 – dacites lavas: homogeneous (a) and with basaltoids inclusions (b); 27 – pumices of dacite composition; 28 – extrusions and nekks (a), dikes of basalts-andesites (b); 29 – cinder cones of lateral eruptions of various degree of preservation: ancient - with morphological structure expressed fragmentarily (a) and supposed (b), younger, partially broken (c); 30 – boundaries of different age complexes and rock masses of Mutnovsky volcano (a), boundaries of individual geological bodies (b) and allotments of insufficient exposure for their allocation (c); 31 – boundaries of summit calderas of the volcano (according to benches brows) – from the most ancient reconstructed (a) to young (b, c); 32 - craters from earlier to modern; 33 – failure cirques (a); faults: buried and supposed (b), eruption fissure of 2000 (c); fields of gas-hydrothermal rocks alterations: opalization (O), argillization (A), argillization and gypsuming (AG); 35 – hot springs and gas-vapor streams of thermal fields (a); non-killed prospecting well ejecting steam and water mixture.

EG and WG are eastern and western groups of the North-Mutnovsky hot springs respectively, UF and BF are Upper and Bottom fumarolic field of the volcano, IC is an inner cone of the Mutnovsky-4 volcano, AB is the Active Crater. Red star is the place of forecast effusive eruption of the volcano (see text).

In review end of the structure and composition of Mutnovsky-1 volcano rocks let's return to the discussed lavas of mixed quartz-biotite dacites with porous dolerite-like inclusions of hornblende basaltoids. They represent a characteristic feature of its petrography and magma-dynamics. This feature is common to neighboring Dvugorby and Skalisty volcanoes which are close in age and destruction degree to Mutnovsky-1 volcano. During all history of multicones Mutnovsky volcano activity these hybrid lavas flew with such great scale only once. They are magmas mixing of contrast, acidic and basaltoid compositions; acidic magmas are predominant. Gas-saturated basic magma dispersed in a colder acidic magma into separate portions, which expressly crystallized and becoming porous inclusions ("drops", "pillows", etc., with the sizes from fractions of mm to 30 – 40 cm) [2, 10] caused a significant heating and mobilization of acidic melt with a corresponding viscosity decrease at the same time. The traces of heated acidic ingredient of the mixture are expressed by its resorption of disseminated ore and significantly glassy composition which is poor of microlites of its basic mass. The degree of viscosity decrease of taxitic, brecciated lavas provided their slow flow under unusually high flows thickness depending on the slope of the underlying surface. Lavas volume of this eruption reached 0.6 – 0.8 km³ was sufficient to form summit caldera of Mutnovsky-1. However, its effusive character and basaltoid inclusions presence in lava show that the eruption developed as the displacement (replacement volume for volume) of the acidic melt by basaltoid magma not forming a cavity for caldera failure. Similar dacite lavas with the inclusions, but with more, up to 100 m, thickness overlain basaltoid structure of neighboring Dvugorby volcano in the north completely. The

same lavas are at the south-eastern foot of Skalisty volcano; here basin-shaped depression of famous Dacha springs of Mutnovsky steam-hydrothermae deposit was made by leaching and erosion. To characterize flow behavior of such lavas with basaltoid inclusions and dacite-rhyodacite matrix it is necessary to mention the same flows of middle Pleistocene Massivny volcano in Malosemyachic volcanic center (these flows have kept initial morphology) [9] flowing on the slope to 10 – 12°. They have the thickness of about 200 meters, flat surfaces with traces of deformation embankments and steep lateral and frontal benches. The length of the largest of bench is 7 km.

It's necessary to specify the age of these lavas in the Mutnovsky region, but their uniformity for some volcanoes close in space and time indicates that at the end of middle – at the first part of late Pleistocene their magma-feeding systems had the same development stages: chambers formation of acidic differentiates with their further filling by basaltic magma. This filling, probably, caused a partial mixing of its initial portions with acidic melting and then almost complete displacement of the formed mixture.

After these great effusive eruptions of acid magmas the activity of Mutnovsky-1 volcano continued with a new cycle of significantly basaltoid volcanism, with sporadic eruptions of "dry", two-pyroxene andesites and dacites of incommensurably smaller volume (up to the stage of caldera-forming on the top). The activity of Dvugorby volcano has finished by small breakthroughs of olivine basalts one of which was exposed by erosion from under the cover of ignimbrites of Gorelovsky centre at its north-western slope (Figure 1 in [16]).

It's curious that soon after the stage of large chambers formation of acid magmas and described effusive eruptions of their mixtures with basaltoids the volcanoes activity of the whole submeridional system (North-Mutnovsky zone) located to the north of Mutnovsky-1 – Dvugorby, Skalisty and Kamenny finishes. The continuation of Mutnovsky-1 activity coincided, apparently, with reorientation of magma-conductive structure of the region from former submeridional direction to the west-north-western. This reorientation was responsible for the orientation of ridged structures of Mutnovsky and Gorely volcanoes forming further.

Acid magma chambers are periodically refilled by smaller portions of hot basaltic magma and emptied by eruptions only partially or not drained by them at all can be heat sources of continuously existing hydrothermal systems in suitable hydrogeological situations.

1.1.1. Caldera of Mutnovsky-1 volcano and intracaldera structure (complex M_1^2 , Figure 1 in [16], figure 1).

Caldera appeared on the ancient volcano stratocone has become the place to form daughter polygenic volcanic structure filled it. Only a fragment of flat-lying mass of lavas and pyroclastics on the crest of the southern part of the Otkhodyashchy ridge has remained. It is possible to reconstruct the structure according to it approximately (Figure 1 in [16], 1). It was slightly shifted relative to the center of mother structure to the north-west, it had an elongated in the same direction shape and sizes of the axes about 2×2.5 km. Mutnovsky-1 became lower up to the level of 1800-1900 m. The character of caldera-forming eruption and the type of appeared structure is unrecoverable now and they can be only supposed by analogy with similar shape of one of the younger parts of the volcano. It is described below.

There is only one distinct area of the caldera side in the crest saddle of the Otkhodyashchy ridge of 1545,8 m. Here a band of fluvioglacial (?) sand-and-gravel deposits with blocks interlayers is exposed. This band occupied a part of atrio around intercaldera cone. The section fragment of the cone exposed in the south-western slope begins below from the level of ~ 1450 m. Its thickness is about 270 m. Lower 150-170 m are for the band of rather evenly interlaid lavas and basalts pyroclastics, and about 100 m at the top section are represented by a band of coarsely-stratified tuffs of plagiobasalts including coarse-porphry anorthite. They are greatly injected by dikes and interlaid by thin flows and sills of similar composition.

The activity of intracaldera structure of Mutnovsky-1 volcano has finished by volcanites eruptions of intermediate acid composition. In its near-summit part there is a long andesites dike of north-

western extension, and in paleovalley of the northern volcano slope (which cut caldera side at one time and now reserved as elevated area of inverted relief) there is a flow of two-pyroxene dacites overlapped by cemented sand-block and fluvioglacial deposits on the sides (Figure 1).

Mutnovsky-1 volcano outlooks in scale and depth of gas-hydrothermal metamorphism of its rocks among other parts of the massive. In general it is a normal for volcanic edifices acid leaching with transformation of basic rocks in argillizites, acidic rocks in opalites with their impregnation by sulphur, gypsum, chalcedony, sometimes sulfides. These changes are preceded by volcanites oxidation and chloritization of their dark-colored minerals. Relative to the main elements of the paleovolcano structure express zonality of metamorphism shows the connection of the main part of the changes with its former activity: their intensity increases with the approach to the vent zone and at lower stratigraphic levels.

Another factor of rocks metamorphism of Mutnovsky-1 volcano are vapor-hydrothermae of Mutnovsky geothermal deposit southern part of which is located on the northern slope of former volcano, and general linear structure extends far beyond it to north-north-eastern direction (Figure 2 in [16]). There is a question of the involvement of Mutnovsky-1 structure in the system of regional disjunctive tectonics. The question is actual due to the possible role of this factor in the initial volcano localization, the following complication of its structure and the nature of volcanism and hydrothermal activity relations.

At the northern foot of Mutnovsky-1 volcano remnant there are two groups (Western and Eastern) of natural outflows of vapor-hydrothermae called North-Mutnovsky by T Yu Marenina [4]. To the west of them and higher on the slope there are also a lot of spots and linear plots of intense rock alteration earlier marking dead areas of thermal fluid discharge (Figure 1). The placement of these outflows does not depend on the mentioned "volcanic" zonality of metamorphism and has discordance character. They are predominantly of submeridional (as over-mentioned side cones) and north-eastern ($40 - 45^\circ$) orientation and they concentrate in a wide meridional depression between the Otkhodyashchy ridge and western spurs of the Kleshnya ridge. It is supposed that this depression is a graben modified by erosion-exaration processes. According to the shift of the lavas surface of quartz-biotite dacites with inclusions on the Otkhodychshy ridge and on its north-eastern spur belonging, most likely, to one stratigraphic level in a volcano periclinal the immersion depth in this part of the structure is approximately 100 – 120 m.

According to the fracture analysis [3] on the continuation of this zone there is a system of faults of north-north-eastern extension which control the localization and discharge of whole Mutnovsky geothermal deposit. Drilling data given in the paper show that these fractures are little or amplitude-zero. Discordance of their orientation of Mutnovsky volcano with a general north-western extension shows certain differences in the forms and mechanisms of tectonic control of volcanism and hydrothermal activity of a modern time. Their partial convergence takes place only at the upper structural level manifesting in a formation of structures such as sector graben on the volcano and fractures controlled the cones placement of its side eruptions.

However, the combined analysis of morphology and magma-conductive structures of Mutnovsky and Gorely volcanoes shows that the described fractures zone is a part of the volcanic rifts system in a single (for south-Kamchatka volcanoes) stretching zone and the zone of magmatic permeability with general north-eastern extension. On the line Gorely volcano – Mutnovsky volcano it is influenced by double Z-shaped turn with a shift to the south-east of its North-Mutnovsky (or Mutnovsky-Vilyuchinsky) part (Figure 2 in [16]). Differently oriented segments of the zone are characterized by diversification of their long-period magmatic activation. At the end of middle – beginning of late Pleistocene its North-Mutnovsky branch controlled, as noted, the localization of Dvugorby, Skalisty volcanoes and Kamenny volcano further to the north, in the direction of Vilyuchinsky volcano. During late Pleistocene-Holocene the part ("displacer") of north-western direction was the most permeable for magma. It is reflected in the ridged morphology and spatial orientation of Mutnovsky and Gorely volcanoes. It is significant that outside of their near-vent plots gas-hydrothermal activity didn't develop. In contrast, after volcanoes extinction of the North-

Mutnovsky branch its renovated breaks and rocks fracture systems became the conductor of long-lived vapor-hydrothermae that are possibly fed by the heat of residual volcanic chambers. The life of some of them can be prolonged by their filling with hot basaltic magma.

1.2. *Mutnovsky-2 volcano*

The second cone vent in the massive of Mutnovsky volcano (complex M_2^1 , Figure 1 in [16]) was shifted 3 km to the south-east from the axis of the previous cone. It is much better preserved structure like Somma-Vesuvius. Only its northern slope was destroyed by two large troughs, cirques in the heads "have eaten" the northern part of the structure top. Eastern and southern slopes are close to the initial, only near the summit part they are broken by rather deep barrancos and outflow hollows.

According to the study of the available outcrops in the sides of the trough valleys and bench of summit caldera Mutnovsky-2 is a basaltoid (basalts – basaltic andesites) cone similar to the previous one by index of explosivity and proportion of medium-acid derivatives. It has not also features of a one-way evolution of magmatic material. Among dominant basaltoids there is a flow of rhyodacites on interstream area of marked troughs, the flows of two-pyroxene andesites in the "windows" on the north-eastern and southern slopes, a flow of aphyric ferroandesites on the eastern slope. Most of them are overlapped by basalt lavas of the last stage of Mutnovsky-2 volcano formation. Basalt-andesite-basalt flows and cinder cones of side breakthroughs which are available only at its south-western slope refer to the final stage of its activity. Formed cone of Mutnovsky-2 volcano was 2400 m of height and volume of 24 km³.

Volcanic rocks correlations of the complex M_2^1 with glacial forms of the surrounding mountain-valley relief give the possibility to determine the approximate dating of the main volcano structures. Especially impressive is the evolution of the Akhomten river valley. Its lower south-eastern part is a young glacial trough which correlates with the second phase of the late Pleistocene glaciation. Upper submeridional part of the valley is a relic of the ancient trough preserved from the oldest modeling, apparently, due to the upper part of the valley was captured by the Falshivaya river and it was the reason of a sharp erosion weakening. Volcanic accumulation promoted it too: in this part of the valley its right side and bottom are filled by lavas of Mutnovsky-2 volcano. It determines its age that corresponds to the interglacial period generally (Q_3^3). The flows almost of the same lava field but running down to the valley of the Falshivaya river (later transformed into a young trough) are "cut" by it and there is not clothing slope similar to the observed in the Akhomten river head (see sections, Figure 1 in [16]).

1.2.1. *Summit caldera and intracaldera cone of Mutnovsky-2 volcano* (complex M_2^2 , Figure 1 in [16]). Caldera had the diameter of 2,5 km and subhorizontal selvage of ring bench at the level of 2000–2050 m.

Any explosive or pyroclastic deposits were not preserved and there are not large once erupted lava masses with which the origin of this structure could be connected. However, the explosive-failure mechanism of caldera forming during the eruption of acid pyroclastics is the most possible, and it is directed mainly to the north slope structure destroyed now. Taking into account the concept of syneruptive degassing of acid magmas [1] it is not excluded that original trace of the demolished pumices of caldera-forming eruption is elongated and foamed on the periphery the pieces of rhyodacite obsidian of 3-8 cm sizes scattered on remnants of initial surfaces of the eastern and southern feet of the volcano.

Intracaldera cone of Mutnovsky-2 volcano is located with a small shift to the west from the caldera center, and it completely compensated its western part, and a part of its lavas has flown onto steeper slopes of mother structure filled a number of its side cones (Figure 1 in [16]). Small empty atrio plot was preserved only at the south-eastern foot of intracaldera cone. The height of the cone

reached 2350 m, current height of the remnant is 2323 m which is the maximum for the whole volcano.

According to the available part of the section the cone is formed by basalts and basaltic andesites. A thick up to 60-70 m layer of basaltic andesite agglutinates armored by lava of similar composition forms upper parts of the section completely preserved in the south-eastern sector of intracaldera structure. There is a remnant of 130-meter horizontally layered band of argillized and gypsumed volcanoclastic deposits and lavas accumulated at the basement of intercaldera cone on its destroyed and inaccessible northern side, on the ridge separating glacial cirques. In plan and height, however, the boundary of this band is beyond the caldera contour interpolating here; it indicates a probable fault-landslide dislocation of this volcano sector to the Falchshivaya river valley cut its basement.

1.3. *Mutnovsky-3 volcano*

The next third edifice (the complex M_3^1 , Figure 1 in [16]) is on a ready high basement between the peaks of two previous edifices with some shift to the south-west from the saddle separating them. Therefore, with the height ~ 2200 m close to the cones-predecessors height Mutnovsky-3 volcano didn't reach their volume and it got only about 5 km^3 .

The development of Mutnovsky-3 volcano has coincided with the beginning of the second phase of late Pleistocene glaciation of Kamchatka. According to all indications on Mutnovsky volcano the glaciers of its initial stage were mainly occupied by troughs and depressions on the slopes of the volcanic massive significantly eroded, and valleys around its feet. So, on the northern slope of the volcano in the outcrop of the trough heads of the Kuropatka river there is the overlap of the part of the basalt flow of Mutnovsky-3 volcano on a fundamental basis (on trough shoulder), and near in the cirques wall finished trough – the separation surface of the other part, once flowing on the glacier and, obviously, removed by it. To the west in the valley heads between the Kleshnya and Otkhodyashchy ridges the basaltic tuffs margin cirques gap like bench on the place of the former glacier descended together with the part of the tuff band overlain it. Straightness, "cutting" of the western edge of lava fields of Mutnovsky-3 volcano at the side of trough valley of the Osvistannata and Mutnaya rivers are typical. Such boundary character, obviously, could only be obtained by removal of front parts of lava flows flown over glacier.

The structure of Mutnovsky-3 volcano is seen well in a ring bench of its caldera as well as in the left canyon side (Figure 1). The section of the highest and steep-side part of the edifice exposed here is normal interbedding of lavas and pyroclastics with a sharp predominance of the latter. Lavas interlayered by deposits of the lahars in some places are dominant in the section of flat-lying foot of Mutnovsky-3 volcano. In general the index of its explosivity is not below 65 %.

In the northern caldera wall and in the mentioned canyon side it can be seen the overlap of less altered volcanic rocks of the complex M_3^1 on deeply altered rocks of Mutnovsky-1 volcano. The rocks of the complex M_2^2 are exposed, apparently, in the south-east in the "window" at the basement of the highest part of caldera bench. There are three volcanic rocks bands with the thickness of up to 40-50 m each in near-vent thickness of Mutnovsky-3 volcano according to the degree of alteration: lower, argillized with the predominant white-yellow-brown color; medium – red, and the upper dark gray, practically unchanged. Bands, obviously, correspond to the great cycles of volcano activity divided by long periods of rest. And the degree of their alteration is the result of consequent overlapping of discrete cycles of gas-hydrothermal metamorphism.

Greater degree of the rocks alteration manifests the eastern part of Mutnovsky-3 structure, where all modern gas-hydrothermal volcano activity is focused. Its description is given in some papers [4, 8, 11, 13]. Here is one example of a large superimposed fluid-conducting structure – the "root" of the former fumarole field on the north-western slope of Mutnovsky-3 volcano. It is exposed in the left canyon side of the Vulkannaya river in the form of V-shaped fracture zone expanding upward and

rocks alteration. This zone cuts the stratification of the complex M_3^1 and still feeds solfataras chain at the brow of rock cliff.

The structure of Mutnovsky-3 volcano is composed by rocks of the differentiated series from basalts to rhyodacites, and we can see a certain direction of the magmatic substance evolution: repeated eruptions of acid volcanic rocks have been dated to the final stage of its development. In general, basalts are dominant in it, the intermediate rocks of basaltic andesite– andesite composition were found in a few places: at the base of the southern part of the saddle between the caldera and the Active Funnel, in one of the flows of the western foot (at Tarbaganiya mountain), and in the section of the eastern the highest part of the caldera bench.

Acid volcanites lie at the upper parts of the section of the volcano north-eastern sector (Figure 1). The flow of small-block rhyodacites of 2.5-meter thickness is exposed under the brow of the northern wall of its caldera. Hypsometrically and through the section from the cirque in the Kuropatka river head a 2-3-meter layer of dacite pumice from the below ash to lapilli (including accretion) at the upper part covers the slope. Pumice is overlapped by 0.5–0.8 meter layer of basalt cinder with bombs of mixed large-porphyry olivine-augite-anortite andesibasalts containing bands(ribbons), lenses and pumice inclusions similar to the underlying ones. The eruption was probably a result of refill of acid melting chamber by basaltic magma. Below along the slope of Mutnovsky-3 volcano and on Mutnovsky-1 parts over the glaciers (around the elev. of 1626 m on the map of 1:25000 scale) there are fragments of this pumices cover (which earlier correlated with pumice cover of later caldera-forming eruption). They are more macrofragmental, mixed with marked basic cinders and bombs (redeposition due to falling on snow ?) and reached the thickness of 12-15 m. Described sediments indicate that rather large masses of acid pyroclastic material connect with Mutnovsky volcano.

There is a remnant of the frontal part of a thick, up to 80 m dacites flow at the north-eastern side of the caldera of Mutnovsky-3 volcano (elev. of 1880,4 m) on the described pumices and cinders, and there is an elongated block tail of dacites with basaltic homoeogene inclusions in slope degradation to the west. Summit extrusion could be their source. In the composition of the explosive material similar dacites are spread at the foot of Mutnovsky-3 volcano on the right bank of the Vulkannaya river.

The next stage of the acid volcanism of Mutnovsky-3 volcano was caldera-forming eruption described below.

Mutnovsky-3 is rich in lateral cones, although some of them located at the south-western edge of its lava field are referred to complex M_3^1 according to the terms of exposure conditionality. Most of them, however, are directly flown over and partially overlapped by lavas of the Mutnovsky-4 volcano. Cinders and lavas of this group of lateral breakthroughs occupying the lowest hypsometric position are represented by basalts enriched by olivine and clinopyroxene.

Three lateral cones erupted ordinary olivine-plagioclase basalts were exposed by the Vulkannaya river valley. The earliest cone washed out and overlapped by lavas of mother structure is exposed in the upper parts of the Opasny ravine; its gray layered cinders compose the largest part of the bench of famous beautiful waterfall. There is one of its latest cone – Krasny Obryv on the lava overlapping cinders, practically on the place of breakthrough. It is formed by oxidized red-brown basaltic cinders and bombs, and now it is divided by the Opasny ravine in two parts: the largest part of its fragment is located on the right side, smaller part – on the left side of the ravine. At the western edge of the right-bank remnant the front bench of a short flow of block lava is exposed from under the cinders.

Another remnant of a small lateral cone (on its own lava flow) is exposed on the left side of the Vulkannaya river valley 2 km higher of the Krasny Obryv cone. Cinders of this (it seems like in winter) eruption re-settled by water flows overlap relicts of initial volcano slopes on both sides of the river valley with a wide tail. Perhaps, this valley hasn't appeared yet by the time of these events.

1.3.1. The caldera of Mutnovsky-3 volcano, deposits connected with it (complex M_3^2) and complex of its filling (M_3^3). The caldera in this case is one (north-eastern) of two large communicating destructive forms on the tops of young parts of the volcano (Figure 1 in [16], figure 1). This caldera was called its "northern crater" or north-eastern part of "eight-shaped crater of Mutnovsky volcano". However, but the most sufficient definition for this morphological structure is "summit caldera": there are correlate pyroclastic deposits connected with it. All other similar forms of the volcano (older and younger) haven't got such deposits.

The caldera of Mutnovsky-3 volcano is an oval shape elongated to the north-west and axes sizes of 1.5×2.0 km in plan. Caldera is shifted to the north-western slope according to mother structure and it is characterized by an asymmetric longitudinal profile with the height of the south-eastern edge of the bench equaled 2185,1 m; the relicts height of the north-western one is about 1700 m and supposed initial height of the bottom of about 1400-1450 m. Cavity volume is about 0.45 km³.

Sediments correlating with the caldera are presented by pumice cover (tephra and pyroclastic flows) at the north-western foot of Mutnovsky-3 volcano. Cover thickness reaches 80-100 m in a distal zone in the section of Pemzovaya and Tarbaganiya mountains and Pumiceous Tarragona behind which it sharply pitches out. It is supposed that the part of the cover continuing it was deposited on the surface of late Pleistocene glacier extended from the caldera of Gorely volcano along the valley of the Osvistannaya and Mutnaya rivers. And this part of the cover was deleted by the glacier.

The connection of pumice cover with structure-forming on a top of the young part of Mutnovsky volcano was earlier supposed by T Yu Marenina [4], however, in this case it was meant the connection with both communicating forms as elements of a single morphological structure. The reasons for connection of pumice cover only with the caldera of Mutnovsky-3 volcano are: 1) stratigraphic cover position corresponding to caldera age and overlying mother structure lava, and in turn, overlain by lavas of Mutnovsky-4 volcano; these ratios can be observed on the left side of the Opasny ravine in the area of the waterfall; 2) structural and spatial arrangement of the caldera and pyroclastic cover erupted and deposited in the direction of the lowest height of caldera bench edge; 3) pumices interbedding with large-block explosive and lahar deposits which excludes their connection with another nearest Gorely volcano.

Control check of the latest popular idea was made on basis of mineral composition studying of the discussed pumices of both volcanoes [7]. It was carried out in comparison with pumices mineralogy of caldera-forming stage in the Gorelovsky center (38 thou. years ago) from the column of oceanic sediments near Kamchatka and it showed the similarity of their associations with each other, but according to our materials it showed the similarity with the minerals of dacite-rhyolite lavas and Mutnovsky-3 extrusions. Mutnovsky-3 differs in some increased potassium alkalinity of its rocks from other cones. The comparison of discussed pumice with Gorely caldera ones according to the ratio of silica and alkali in them [12] has shown the opposite to volcanoes trend of increased potassium-bearing of pumices of Mutnovsky with a much smaller silica-bearing (at the level of andesites), but determined without the conversion of intensely hydrated (up to 6 – 8% H₂O) material for anhydrous. Carrying out this condition the ratio of SiO₂ – K₂O in dacite pumices of the discussed cover are similar to the same in the acidic lavas and extrusions of Mutnovsky-3. In our opinion it proves they belong to the latter.

Pumice cover "has separated" from the caldera bench for 2.5-3.0 km, obviously because it could hold only on the flattened surface of the volcano foot. Caldera-forming eruption began with explosive activity in a summit crater occupied by glacier and lahars sliding which deposits are exposed at the upper parts of the section along valley of the Vulkannaya river (Opasny ravine). In its right side near the waterfall they are covered by: pumice pyroclastic flow with visible thickness of 1.5 – 2.0 m with the traces of rewashing in the upper part; a layer of pumice tephra – 0.5 m as well as partially redeposited; a 2-3-meter layer of cemented mud-stone deposits (another one interpumice lahar); a 4-6-meter band of deposits of the main, apparently, pumice pyroclastic flow. At the north-

western edge of the pumice field M_3^2 the deposits of pyroclastic flow composing Tarbaganiya and Pemzovaya mountains are represented by tuff with typical mural jointing.

Later in the north-western part of the appeared caldera the volcanic activity was resumed: the formation of intracaldera basalt-andesite cone, and then the growth of the extrusion of two-pyroxene rhyodacites (complex M_3^3 , Figure 1 in [16], figure1) which lasted, probably, during the operation of the next Mutnovsky-4 volcano. The fragments of lava-pyroclastic structure of intracaldera cone which is partially hidden by the glacier and divided by the valley of the Vulkannaya river are exposed on the sides of the valley in the area of the Donny fumarole field. Above it on the right side of the valley in the glacier, probably, the early part of the section of the complex M_3^3 is exposed: up to 30 m ochelized basalt tuff and ~25-meter thickness of complex flow of olivine-plagioclase basalt. It consists of 5-6 monolithic plates-portions of identical composition separated by cinder-block material. A band is gently (15-20°) inclined under the glacier to the south-east. Relating to the surrounding valley area (supposed location of the eccentric crater) it forms the periclinal fragment of a small volcanic structure that filled the caldera up to the level of 1650 m.

In the left side of the valley there is, apparently, the latest part of the complex M_3^3 – the remnant of cup-shaped body of -basaltic andesite interbedded by block material clothing here indigenous caldera slope and supposed crater. Probably it is the trace of lava lake. On the bench of this remnant the fragment of a block flow of black andesites was preserved.

The preserved part of the rhyodacites extrusion is located on the northern edge of the crater of intercaldera structure of Mutnovsky-3 volcano at the exit of the Vulkannaya river canyon outside the caldera. The right-bank part of the extrusion composes the base of the Verkhny fumarolic field, left-bank – northern part of the Donny field. Intensive gas-hydrothermal activity occurred during the extrusion growth: in some places its rocks are crushed and replaced by opal. The fragment of its initial north-western slope (the rising place to the Donny field) is covered by a coat of cemented as breccia block deposits. These block deposits are the remains of agglomerative mantle of forming extrusive dome (material which has run from its slopes and soldered by agglomeration or secondary mineralization by opal and ferrum oxides). Representative indication of gas-hydrothermal activity synchronous to the extrusion process is a wide degree variation of the material alteration of the mantle breccia where the blocks of absolutely fresh glassy rhyodacites can be soldered and the same ones completely transformed into opal.

By the time of the described events the north-western caldera side has not been exposed by the canyon of the Vulkannaya river yet. With extrusion it was the dam(jetty) supporting intracaldera glacier and, apparently, lake near the extrusion. Its development has finished with a large explosive eruption that destroyed its significant part and had catastrophic running (lowering) of water-ice lake mass. The event is dated about 4 000 years ago by the tephrochronologists [5].

The corresponding deposits are represented by 0.2 and 1.5-meter layer of crushed, sometimes secondarily cemented opalites in a narrow band discordant to a modern bed of the Vulkannaya river (fumarole field explosion?) and by a wide up to 3 km fan-shaped tail of block material overlain them (Figure 2).

Extrusion rhyodacites and blocks of breccia especially visible on the surface giant up to 3-4 m in diameter are dominant in the latter. Breccia is similar to the material extrusive mantle described above. The flow was divided into two branches by the top of the Tarbaganiya river. Together with the absent of a visible sorting of debris and blocks according to the size depending on the distance to the source it indicates that the mechanism of their transport was not so much the explosion itself as the transport by gushing water-snow-ice mass. Traced length of the deposits tail of this flow-lahar reaches 6 km up to the Osvistannaya river.

It is not excluded that the reason of explosive activation of the extrusion was the introduction of basalts dike connected with Mutnovsky-4 volcano in its root zone.

In conclusion of Mutnovsky-3 volcano review it can be noted that the existence of pyroclastic deposits connected with its caldera defines it as the structure of compensation, explosion-depression origin as a result of failure of the magma chamber roof desolated by the eruption. Summit calderas of the former cones of Mutnovsky volcano which have not kept the material of pyroclastic deposits connected with them are similar to the caldera of Mutnovsky-3 volcano according to the size and location. It gives the possibility to assume the same formation mechanism for them. Therefore, the development of the third cone of Mutnovsky volcano is fully reflected in the corresponding volcanic forms and deposits (M_3^{1-3}). And it gives the value of a definite standard. Two-term structure of deposits complexes of early volcano cones (M_1^{1-2} , M_2^{1-2}) shown on the map (Figure 1 in [16]) doesn't, obviously, present all phases of their development, but only preserved geological realities.

1.4. *Mutnovsky-4 volcano*

The fourth youngest cone of the volcano (complex M_4^1 , Figure 1 in [16]) is on the south-western slope of Mutnovsky-3 volcano. It alters the common ridged shape of the massive. Its activity time was at the beginning of Holocene.

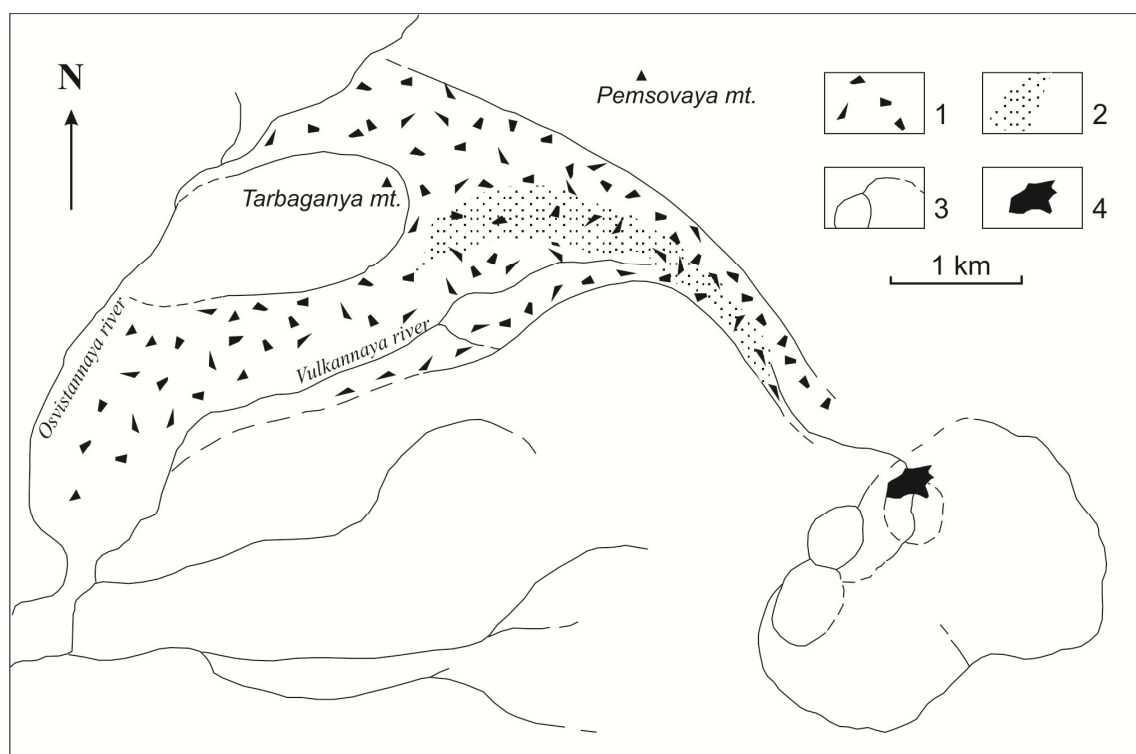


Figure 2. Distribution of lahar deposits connected with the explosion of extrusive dome in the caldera of Mutnovsky-3 volcano ~ 4000 years ago. 1 – gravel-block deposits; 2 – re-deposited opalites; 3 – contours of caldera and craters; 4 – remnant of the extrusive dome.

The current height of the cone is 1941,0 m, its volume is 3.8 km³. It is crowned by a rounded crater (caldera?) with a diameter of 1.3 km partially filled by volcanic rocks of intracrater cone and glacier later. In the north-east it is widely connected with the caldera of Mutnovsky-3 volcano (Figure 1 in [16], figure1). The crater in general is coaxial to the cone and in contrast to caldera it has a near-horizontal edge. The cone surface is divided by numerous shallow barrancos, any structures of lateral eruptions are absent.

Mutnovsky-4 is only composed by olivine-plagioclase ($\pm$ augite) basalts weakly varying in the ratio of these minerals inclusions and, consequently, alumina and magnesia. According to the differences in the degree of rocks variation and a small angular disagreement in the section of the crater wall there are two bands of lavas and pyroclastics with thickness of 120-150 m. Earlier considerably oxidized band composes the lower parts of the section and preserved eastern part of the crater ridge. The second part is almost unchanged and it composes the upper part of the section and western part of the ridge.

1.4.1. The origin of the crater-caldera of Mutnovsky-4 volcano is unclear: there are no any authentic correlate deposits (explosive, pyroclastic, effusive) for it as well as for summit calderas of ancient volcano cones. Owing to apparent youth form this circumstance cannot be attributed to the denudation or glacial drift. Taking into account undifferentiated, purely basaltic composition of new cone volcanic rocks the terminal eruption with next underground outflow (lateral intrusion) of magma and failure of the structure tops can be the mechanism of its crater formation. Maybe just so the process of another reconstruction of magma-feeding system of the volcano started. It was expressed in a linear shift of the edifices of its later eruptions.

Hypothetical character of crater genesis of a young cone makes to match new data and earlier information more detailed. Due to crater connectivity with the caldera of Mutnovsky-3 volcano and similar preservation of their forms the previous researchers considered them in some unity as a dual morphological structure, which was reflected in the application of such terms-names like "double", "eight-shape crater". But, however, there is various genetic sense in them: either practically monogenic, one-act formation of the whole morphological structure in connection with pumices eruption [4], either polygenic origin out of touch with pumices, as the sum of many small destructive forms such craters, explosive craters, landslide cirques, etc. [5]. Note that twoness, "eight-shape" of the final structure are not necessary for both these concepts. So they are considered to be accidental.

If structure formation is connected with pumices eruption the given data about their bedding between the complexes M_3^1 and M_4^1 exclude the hypothesis of monogeneity of a dual morphostructure. There is only one right interpretation of its genesis – consequent formation of its elements with time gap during which Mutnovsky-4 formed.

If the indicated relationship with pumices is ignored there is a hypothesis about monogenic and polygenic formation of the summit structure, but only after Mutnovsky-4 volcano formation. Indeed, there are no direct geological data which deny the following assumptions: farness of pumice cover from the edge of the caldera of Mutnovsky-3 volcano admits doubts about their genetic connection; the caldera is not filled by lavas of Mutnovsky-4 volcano, as it could be expected under their closeness; the complexes of caldera (M_3^3) and crater (M_4^2) are separated and they don't have any direct relationships.

However, a distinct individualization of both elements of a dual structure and the relationship of each of them (and in their own way) with its mother structure show their independence and different age. Reconstruction of the top of Mutnovsky-4 volcano (Figure 3) shows that the comb of caldera side was uncovered till the end of its growth between Mutnovsky-4 volcano and caldera of Mutnovsky-3 volcano in the form of a narrow dam. The caldera itself (now it is extended by failures) was earlier filled by glacier preserved it because it was not even uncovered by the Vulkannaya river: river valley (Opasny ravine) was formed exactly on the northern edge of the lava field of Mutnovsky-4 volcano, and therefore, after the completion of its formation. Finally, the morphology of a dual structure doesn't

give any reasons to believe it as a complex of small destructive forms. Two such forms described below complicate the crater of Mutnovsky-4 volcano being substantially younger than it; another one – the crater on the place of Donny fumarolic field in the caldera of Mutnovsky-3 volcano is the complex of its latest filling (M_3^3).

Intracater cone (complex M_4^2) is presented by monogenic nonsymmetrical cinder structure of basaltic andesites composition. Its vent was formed practically on the crest of the northern wall of the crater of Mutnovsky-4 volcano within which almost all mass of erupted material was deposited (Figure 3). In a confined space only sector ($\sim 1/4$) of a normal cone structure (called "the cone" in brief) formed. Its crater (now imposed by the head of the Vulkannaya river) was an oval shape oriented to the north-east and axes size of 300×600 m. The absolute height of its edge was 1750–1770 m, the height above bottom was 210–230 m. According to the geologist V. M. Nikolsky who studied volcano sulfur-bearing, in 1950-s the crater contained a warm (up to 42°C in 1954) lake where sulfur silts deposited. The cone is almost completely overlapped by the glacier, with the exception of a large output of pyroclastic thickness in the southern wall of its crater. Here under a 2–5-metre-thick band of cinders and colluvial crust clothing the slopes of the crater the thickness of cinders of two-pyroxene ibasaltic andesites of 120 m is exposed periclinally. Cinders are altered somewhere and mineralized by gypsum. Lavas are not exposed in the section of the structure.

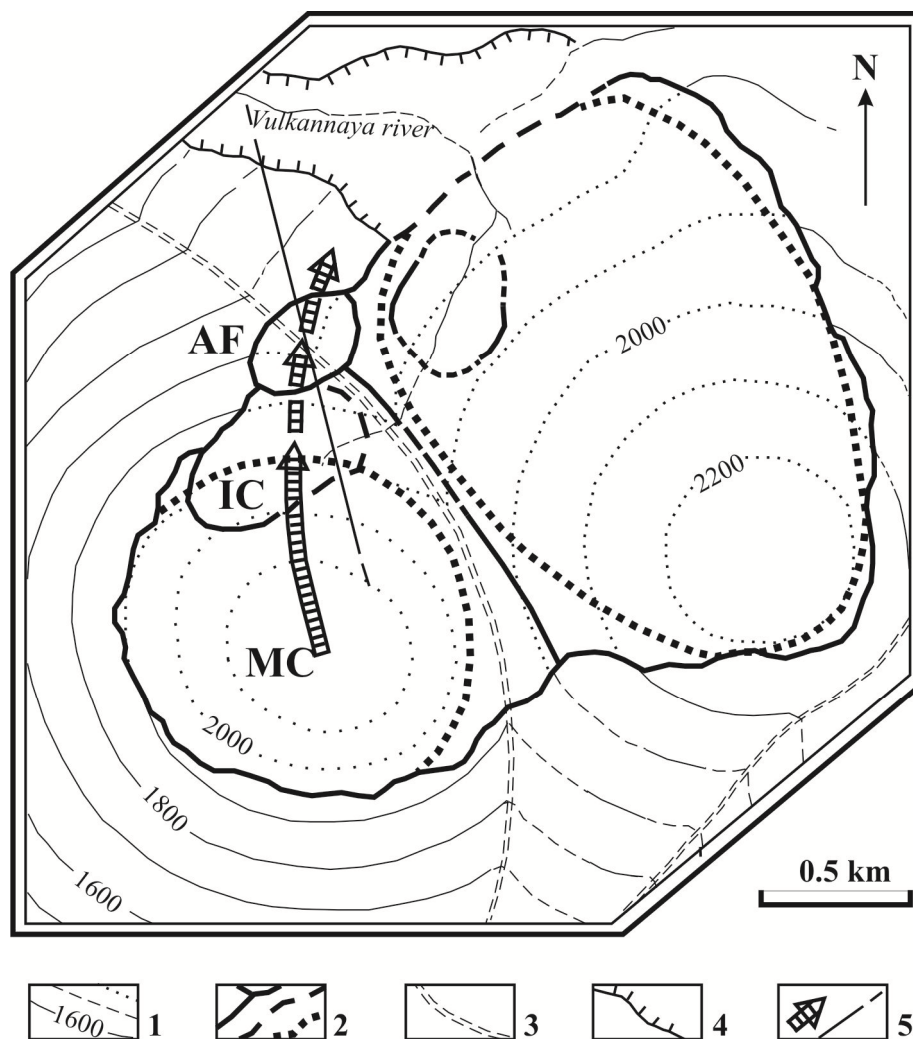


Figure 3. Reconstruction of the tops of Mutnovsky-3 and Mutnovsky-4 volcanoes. 1 – slopes structural contours: close to initial, eroded, and destroyed during caldera and craters formation; 2 – crests and benches brows of caldera and craters: distinct modern, prospective and probable in initial position; 3 – junction boundaries of multiple-aged volcanoes cones; 4 – brows of failure slopes of canyons; 5 – visual trajectory of the shift of the latest eruptive volcano centers and real fissure stretching of eruption of 2000 (MC is the crater of the main cone of Mutnovsky-4 volcano; IC is the crater of its internal cone; AB is the Active Crater).

In March of 2000 the crater of inner cone of Mutnovsky-4 volcano became one of the centers of its activity (another eruption described below).

1.5. *Modern activity of Mutnovsky volcano*

The latest stage of Mutnovsky volcano activity was mainly connected with the Active Funnel – a young explosive crater appeared on the common crest of Mutnovsky-3 caldera and Mutnovsky-4 crater. Its location reflects a new stage of reconstruction of magma-conductive volcano system planned by planned eccentric formation of the crater of the described inner cone: step-by-step linear shift of eruptive edifices beyond the central structure controlled them earlier (crater-caldera of Mutnovsky-4 volcano) (Figure 3).

Strictly speaking, according to this feature the eruption formed the Active Funnel could be considered the beginning of a new fifth cycle of Mutnovsky volcano activity and its deposits could be marked as M_5^1 . However, visible gradual migration in volcanism localization, relatively small scale of the eruption and uncertainty of future sustainability give the possibility to refer the activity and deposits of the Active Funnel to the cycle and complex M_4^2 .

The crater has an oval shape with the axes length of 300 and 450 m, gentle bottom at the level of 1526-1530 m and steep rock walls with the height from 80 to 190 m. It is almost entirely formed in the thickness of rocks of Mutnovsky-3 volcano overlapped only by one basalts flow and cinders layer of Mutnovsky-4 volcano. The most complete section of the eruption deposits formed the Active Funnel can be seen in a rocky bench in the glacier at the foot of the eastern wall of the crater of Mutnovsky-4 cone. In the lower parts of the section a band of black laminated volcanic sands with a capacity of up to 6-7 m is exposed here. An 8-meter layer of explosive block deposits of altered rocks of the walls of the Funnel with few bombs impregnations of black juvenile basaltic andesites lies on it (on this band). The basaltic andesites are a hybrid rock with mixed mineral-impregnations associations, in particular, with large aggregates of plagioclase (anortite), olivine and augite. On a sharp irregular boundary these deposits of phreatomagmatic eruption stage are overlapped by a 6-meter layer of andesite-basalte bombs and cinders (which are the same as marked) – with a minimum admixture of resurgent material and rare gabbro exclusions. This pyroclastic in original bedding (up to 3-4 m) and screes is distributed mainly in the summit part of Mutnovsky-4 volcano to the west, south-west and south from the Active Funnel; thin layers of explosive deposits with rare bombs of basaltic andesites are at the north-western foot and northern edge of Mutnovsky-3 caldera (Figure 1).

Tephrochronological data available for Mutnovsky volcano [5, 6] is insufficient to date any of its forms or deposits geologically significant. Preserved section of Holocene volcanoclastics is younger than Mutnovsky-4 cone. The resurgent material of the latest explosive, phreatic and phreatomagmatic eruptions is dominant in it. The juvenile fraction is mainly of andesitic composition. Deposits of four largest eruptions dating from the time of 7000, 6000, 4000-4100 and 1200-1300 years ago are determined. The first of them according to the predominant of the juvenile tephra in it can be associated with the activity of intracaldera cone of Mutnovsky-4 volcano. Most probable, the explosive deposits of 1200-1300 years are connected with the formation of the Active Funnel.

Apparently, from the date of origin the Active Funnel is the place of intense fumarolic volcano activity, and sometimes the center of more or less powerful phreatomagmatic and phreatic eruptions.

During the historic period they were noted in 1848, 1852-1854, 1898, 1904, 1916, 1927-1929 and 1938-1939; next to last eruption occurred in 1960. Eruptions mostly took out the resurgent ashes. During the past three decades the volcano is characterized by extremely high and stable level gas-hydrothermal activity.

On the 17th of March, 2000 there was another episode of eruptive activity of Mutnovsky volcano. It was expressed by phreatic eruption in the crater of inner cone of Mutnovsky-4 volcano and by usual "dry" explosion in the Active Funnel.

The eruption in the crater of inner cone has broken a part of glacier occupied its bottom and carried sulfurous lake deposits covered the whole glacier by a layer (up to 0.5 m) of gray viscous mud in a crater-caldera complex and surrounding area. In a renewed steep-slope crater of 230-250 m diameter the part of the glacier melted by fumarole gases and refilled by ice failure from the slopes formed a hot lake during 2-3 months. Water temperature of the Vulkannaya river flowing from it under a coastal glacier exceeded 30° in June, 2000. It has melted, broken by mid-July, the part of glacier hidden the head of the Vulkannaya river was washed out, and the level of the lake significantly decreased.

The explosion of the Active Funnel occurred in the lower part of its high south-western slope at the place of discharge of the most active fumaroles. The funnel with a diameter of ~ 70 m has formed here. Block material thrown out of it has deposited at the foot of the slope, and new fumaroles outputs have concentrated at the foot of its south wall on the edge of a flat inclined bottom.

The lake in the crater of the internal cone of Mutnovsky-4 volcano being cooled was covered by ice again in winter, 2001-2002, and the following summer there was only narrow open water at the eastern bank. So rapid fall of the thermal flow feeding lake indicates the reason of phreatic eruption in 2000 was, apparently, the introduction of relatively thin magmatic body (dike) into watered rocks of a vent volcano area. However, in the spring of 2003 a new water warming-up with rapid ice melting began. Perhaps there was a new magma intrusion or seismogenic modernization of gas-conductive fissures gradually blocked. The lake froze again in the winter of 2003-2004.

Such eruptive activity in the crater of inner cone (which didn't leave long-keeping traces) could occur in the past.

The eruption of 2000 showed that the above-discussed linear shift of the eruptive volcano centers has (while keeping its general direction) a broken, back-and-forth character. Both described centers of explosions of this eruption are confined to the appeared (renewed?) fissure of stretching, clearly visible on the aerial photograph, 2003 (Figure 6), but it was not noted in the operative report about the eruption [14]. It crosses the main crater of Mutnovsky-4 volcano passing through the eastern crater edge of its inner cone, the middle of the Active Funnel and down along the north-western slope of the volcano up to the canyon of the Vulkannaya river. Obviously, it can be a place of a future large effusive eruption of Mutnovsky volcano (Figure4).

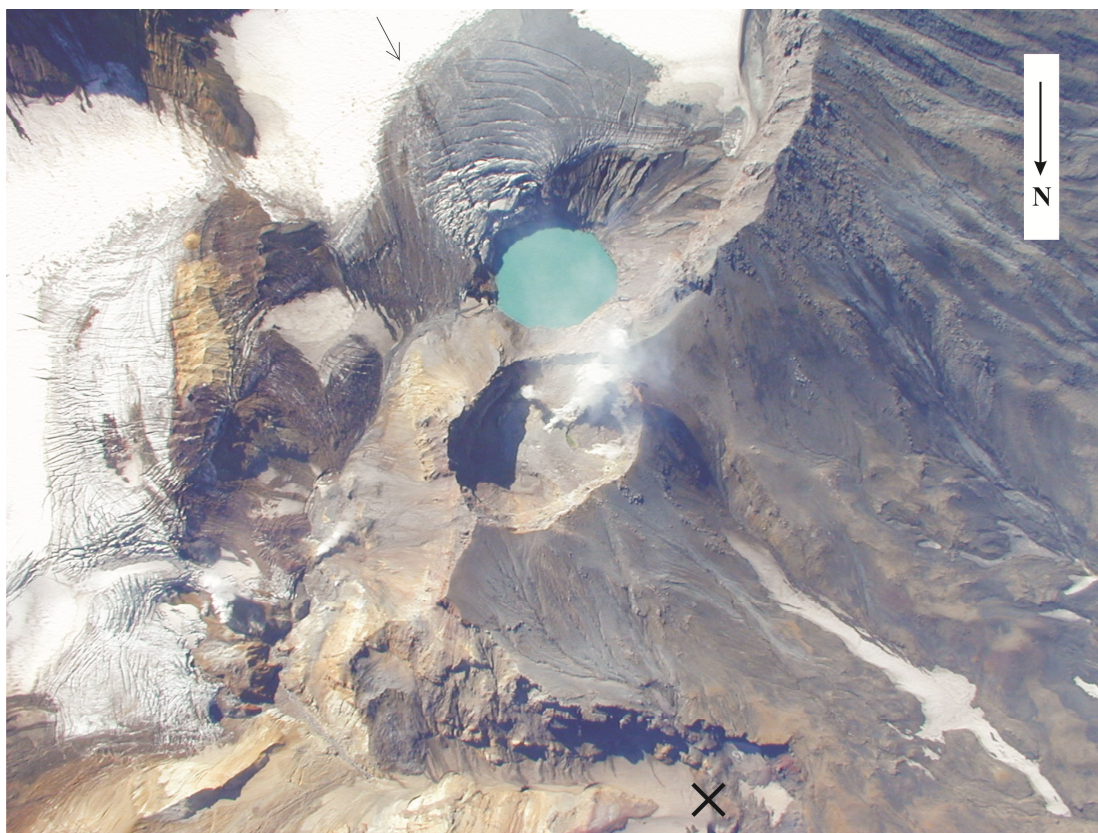


Figure 4. Summit zone of Mutnovsky-3 and Mutnovsky-4 volcanoes and eruption fissure, 2000 (marked by arrow). August, 2003. Aerial picture is made by N I Seliverstov. The place of probable effusive eruption is marked by sidelong cross.

1.6. Assumptions about feeding system development and basis for the prediction of Mutnovsky volcano activity

Mutnovsky volcano consists of four double stratocones developed according to the same scheme: cone growth – summit caldera formation (or a large crater) – growth of intercaldera structure and volcano dying, after which the shift of the output channel took place and the cycle was repeated at a new location.

The reason of such macrocycling of the volcanic process is a periodic achievement of growth certain limits by the volcano cones. It is from the very nature of its morphological evolution reflecting the alternation of two main types of reconstruction of magma-conductive volcano system – the decreasing of channel height by cones cut during caldera-forming or due to its lateral migration. The same their effect is a reduction of hypsometric level of magma discharge to the day surface and, thus, providing the opportunities for further development of the volcanic process.

Compared to the common type of maximum high volcanoes-ridges consisted of elementary cones the structure of Mutnovsky volcano is rather unique by four-time repetition of the same complex structures "volcano in a volcano" (like Somma-Vesuvius in various degrees of completeness). Absolute heights of the cones of Mutnovsky volcano reconstructed up to the levels at which they would have craters of the same diameter of 600 meters reduce progressively but in a relatively narrow range. They are ~2400 m for Mutnovsky-1 and Mutnovsky-2 volcanoes, 2200 m for Mutnovsky-3 volcano and 2100 m for Mutnovsky-4 volcano. The heights of three preserved intracaldera structures manifest sharper but not so persistent alteration: ~2350-1650-1750 m, with a corresponding decrease in the compensation degree of the summit structures. Probably, the main reasons for these alterations are the appropriate variations of the magma composition and gas

saturation which determine its density, explosivity and therefore the ability to rising and break through. In particular, the lowest Mutnovsky-4 cone has the least differentiated, purely basaltic composition of the rocks. An additional factor to limit the growth of daughter structures could be glaciers in calderas and craters.

Rocks associations of three early volcano cones (Figure 5) are characterized by practically the same ranges of differentiation from basalts to rhyodacites (in a shortened series of Mutnovsky-1 volcano mixed amphibole dacites contain quartz-biotite rhyodacites-rhyolites as the acidic ingredient). The repeatability of volcanites series is typical for intracaldera structures with narrower basalt-andesite intervals of differentiation. On macrocomponent and mineralogical levels the most visible feature of a directional change of magma evolution of the volcano is the change of early rocks association with acid amphibole- and biotite-bearing derivatives for fully waterless. It can indicate less deep, in general, location of the peripheral chambers of late cones comparing with early ones.

According to the alternation of acidic and basic volcanites in the structures as well as the presence of various contrast products of mixing such chambers were small and inconsistent, they periodically appeared and died during the life of each cone occupying, apparently, a less deep position. In any case, equally shallow location of the chambers during the final stages of the cones activity explains the appearance of small summit calderas on them. Common reason of comparatively high location of magmatic reservoirs in the earth's crust under Mutnovsky volcano is, apparently, its localization in the zone (on the slope) of uplift of dense rocks of the basement and correspondingly high position of the level of neutral buoyancy of magma feeding it.

With the volcano cones dying their chambers, apparently, died out. During the development of intercaldera structures any large near-surface chambers didn't appear. The results of "self-sounding" indicate it: for example, the channel of Mutnovsky-4 cone formed closest to the axis of the earlier structure (1.2 km) carried primitive basaltic magma onto the surface but not differentiated or mixed melting, as it could be expected crossing the shallow reservoir by it.

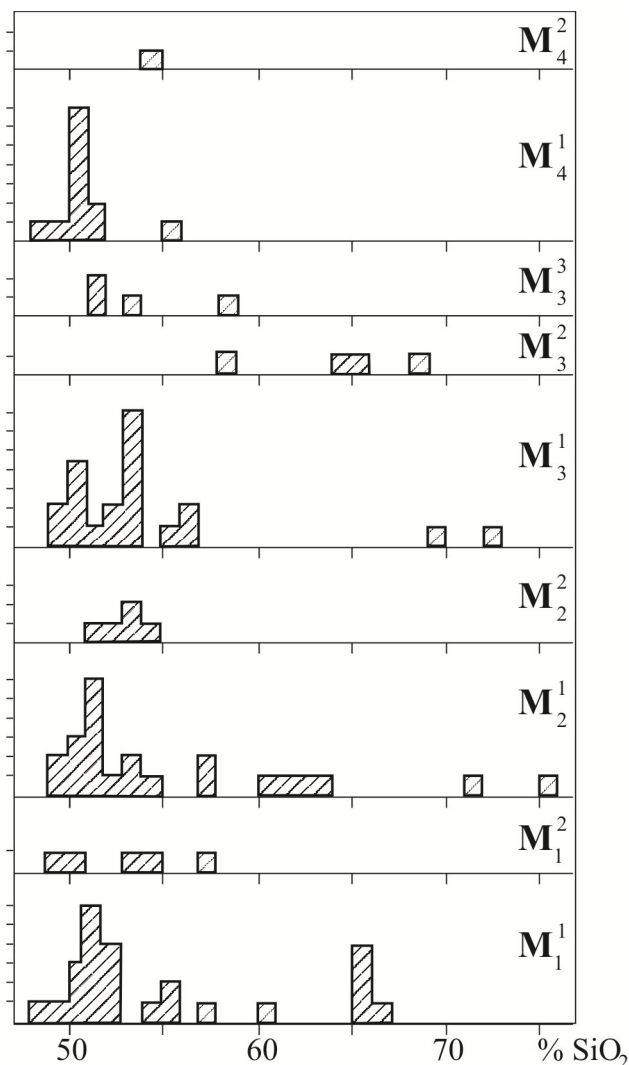


Figure 5. The distribution of rocks compositions of Mutnovsky volcano according to its activity cycles. There is a number of tests on the vertical axis.

Hybridization took place in the case of the Active Funnel, and it gives the possibility to estimate the sizes and conditions of the modern volcano chamber approximately. Apparently, it has kept evolved melting since the activity of intercaldera cone of Mutnovsky-4 volcano and it was refilled by fresh basaltic magma shortly before the Funnel breakthrough. Its center was located 400 m from the vent of intracaldera cone. The presence of gabbroid inclusions in its andesibasalts indicates that the channel passes chamber marginal area the diameter of which was about 1 km in this case.

Probably, after the breakthrough magma localized at a level sufficiently high for its further intense degassing. It takes place under the conditions of dynamic equilibrium of an open system: most of the time the volcanic edifice works as a separator of gas-magma mixture. During last decades the intensity of the heat removal by volcano fumaroles is practically adequate to a continuous eruption. High, more than 580° temperatures of fumarole gases indicate a close location of magma chambers to the surface under the Active Funnel.

Such long and great emanations(emissions) discharging from magma reservoir of a limited volume is supported, obviously, by crystallization and convection of boiling melting – aerated and pulsate translational due to a periodic chamber refilling by deep magma.

Thus, fissure opening (renewal?) during the eruption of 2000 shows that it was initiated by dike introduction. It is unclear whether it intruded mainly laterally in both directions from the chamber under the Active Crater that refilled by deep magma through the tubiform channel or it had an independent, substantially vertical fracture introduction of deep magma partially “caught” by near surface chamber took place. Significant length (>3 km) and independent straight-crosscutting nature of the fissure according to old eruptions edifices confirm the second assumption (see Figure 1, 4) although the same old edifices were sometimes the places of new explosions. The key to this problem can be two types of the eruption in 2000: phreatic one in the crater of inner cone of Mutnovsky-4 volcano and “dry” explosive (volcanic) eruption in the Active Funnel. The first type is obviously related to introduction of one of the summit dike benches into water-bearing rocks under the bottom of crater mentioned. The driving force of the second eruption was, most likely, a sharp increase of gas liberation of dike in a near-surface chamber refilled by magma (Figure 6).

Probably, low gas saturation (may be degassing at an intermediate chamber) of upper portions of deep magma makes it unable for breakthrough up to the surface in the summit volcano zone. In the spreading of fissure wedging by dikes far down-slopes you can see the mechanism of the formation of future magma breakthrough at a low hypsometric level. Lifting of its larger portions can lead to a significantly effusive eruption at the lowest fissure point (existing or parallel to a new one), in the canyon of the Vulcannaya river (Figures 1, 4) – under the simultaneous explosive activity of the summit craters or without it. According to hydraulic features of such magma-conductive system it can be expected the appearance a primitive deep magma in the advanced portions with further inflow and mixing of more differentiated melting from the surface chamber to it.

Described structural features of the eruption of 2000 occurred after the break that was nearly maximum for Mutnovsky volcano, as well as the known series of the eruptive events close in time indicate possible updating of the medium-term (for decades) forecast of its effusive eruption [9].

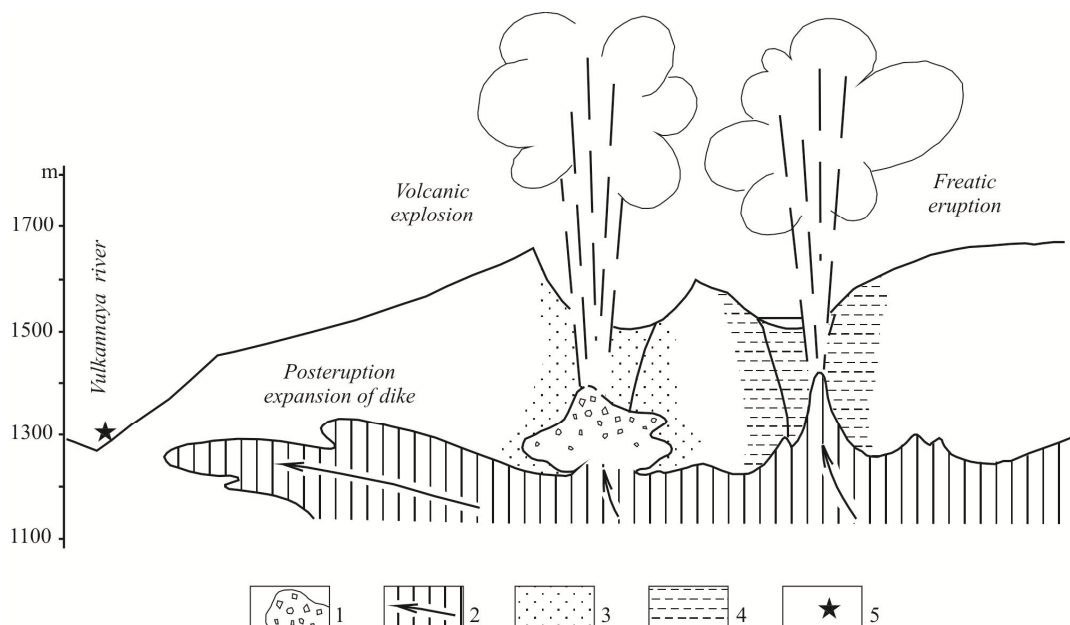


Figure 6. Probable mechanism of Mutnovsky volcano eruption, 17 March, 2000 (section is in the plane of the dike activated it, see the text). 1 – boiling magma chamber; 2 – dike and the direction of magma flow in it; 3 - dry-warmed rocks; 4 – cold water-bearing rocks; 5 – place of forecast effusive eruption of the volcano.

Long-term forecast of the evolution of complex multi-cones Mutnovsky volcano supposes the formation of the next, fifth stratocone in the composition of its structure on its western slope. The tendency of a linear shift of its young eruptive centers confirmed and significantly clarified by the events of 2000 shows the mechanism of a gradual transformation of magma-conductive system of mature volcano that once again reached probably the maximum of its (to lift magma feeding it) height. The mechanism involves in the lateral expansion of dike intrusions in the zone of common (Mutnovsky-Gorelovsky) magma-controlling lineament with further breakthroughs on the low hypsometric level of more gas-saturated deep magma, in stabilization of a new eruptive center, in formation of shallow chambers, etc. – according to the script of cones-predecessors.

Acknowledgements

The author thanks his colleagues Ye M Gazzaeva, I V Maslovskaya and R I Pashkevich for their help for implementation of this work.

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