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Structure, substance and near-surface magmatic chambers of Mutnovsky and Gorely volcanoes (Mutnovsky geothermal region, Kamchatka). I. Geological position of the volcanoes

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Abstract. Geological position of two close active volcanoes in Southern Kamchatka – Mutnovsky and Gorely perspective for geotechnological development as sources of energy and raw materials is presented. Multicone ridged volcanoes edifices of a general linear range are localized respectively in front and near rear zones of the Kuril-Kamchatka island arc system in the zone of crust decompression with different depth of their basement. The characteristics of the volcanoes positions are considered as the reasons for the differences of compositions and evolution features of magma feeding them.
Key words: volcanoes, geotechnology, geological structure, tectonic position, gravitational anomaly.

1. Introduction

Mutnovsky and Gorely are two neighboring south-Kamchatka volcanoes located 75 and 70 km to the south-west from Petropavlovsk-Kamchatsky and 25-35 km from the shore of the Pacific Ocean, in the immediate vicinity (from the south and west, correspondingly) to Mutnovsky geothermal deposit. Possible connection its steam-hydrothermae with hydrogeological and maybe magma-conductive volcanoes structures, as well as the potential role of the latter as independent sources of energy and raw material resources allow considering them as the components of a great Mutnovsky geothermal region.

The study of both volcanoes has a long history (beginning from the century before last one): from early observations and descriptions of phenomenological and geographic character to modern geological, volcanological and specialized thematic studies [4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 19, 25, 27, 29, 31, 32]. In 70-s the geological survey of 1:50 000 scale [38] was carried out on the territory of the volcanoes. It gave detailed information about its basement structure.

This work presents main results of a new geological-and-petrological study of Mutnovsky and Gorely volcanoes made on basis of their detailed (1 : 25 000 – 1 : 50 000) geological mapping using tephrochronological method [22, 23] and taking into account new data of other researchers. The work was carried out as a part of geotechnological project for the development of energy and raw materials of magmatic systems of modern volcanoes. The aim of the work is to obtain more detailed information about the structure, prehistory, regularities and prospects of volcanoes development, as well as possible data about the structure and evolution trends of their magma-feeding systems.

2. Tectonic position and volcanoes basement structure

2.1 Geological data

Mutnovsky and Gorely volcanoes belong to Kamchatka segment of the Kuril-Kamchatka island arc system (IAS), (strictly speaking – volcanic island arc system transforming in active continental margin). They are located in front part of the transition region continent-ocean: Mutnovsky volcano is in a near-ocean frontal zon; Gorely volcano is 12 km to the west in its nearest rear part. Ridged structures of both volcanoes with close west-north-western extension are in-line across the general north-eastern direction of IAS. Consequently they are convenient objects to study its cross petrogeochemical zonality expressed by the change of tholeitic series of the frontal zones volcanoes by calc-alkaline and alkaline ones in the rear part, with the increase of general and especially potassium alkalinity of volcanites and their corresponding changing of geochemical characteristics. The reasons of these differences have been mainly studied by geochemical methods recently. They refer to the conditions of initial magma generation for each volcano of different depth areas above subduction zones, with different degree of mantle substratum melting [3, 24]. However, mentioned features of morphostructures and interposition of discussing volcanoes, differences of their basements structures and mineralogical-and-petrographic properties of the rocks allow (even based only on the macrocomponent features of a serial belonging of the latter) checking and refining the conclusions made using kick geochemical methods but without a sufficient consideration of these geological and petrological data. Except for general confinedness to a lineament cross to IAS with the length of over 15 km Mutnovsky and Gorely volcanoes are multiple-cone ridged structures with the length of 3 km each. It allows matching regularities of general-arc zonality with its manifestations at the scale of structures sizes.

Tectonic position of Mutnovsky and Gorely volcanoes is determined by their localization at the northern tip of the South-Kamchatka link of the East-Kamchatka volcanic belt overlain here on Miocene folded structure of the South-Kamchatka depression. From south-east the depression is restricted by a folded-block zone (asymmetrical horst-anticlinorium) of the Coast range formed by dislocated sedimentary and volcanogenic deposits of Paleogene-Neogene intruded by Miocene granitoids. According to the lithofacies features of the rocks, on the one hand, and abnormal characteristics of geophysical fields on the other hand, this structure has been interpreted recently either as "the body of Eocene-Oligocene island arc" or the southern fragment of Miocene "terrain of the Eastern Kamchatka peninsulas" [15]. Mutnovsky volcano is located in the north-western wing of the anticlinorium, and Gorely volcano – 15 km further to the north-west, closer to the depression axis (Figure 1).

To the north-east of the volcanoes the system of the mentioned elements of the regional structure with total-Kamchatka north-eastern extension is interrupted by horst structure of Malki-Petropavlovsk zone of lateral (north-western extension) dislocations. Thus, both volcanoes are localized in an original "structural corner" formed by specified positive megastructures. This is the territory of a great volcanic accumulation developing since Miocene with breaks.

The main body of horst-anticlinorium of the Coast range is composed by folded mass including a number of suites of facial-changeable volcanogenic-sedimentary rocks and volcanogenic complexes from Oligocene to Late Miocene divided by nonconformities[2]. The thickness of younger of them increases to the depression axis. These formations are combined in a lower layer of a lower structural region level according to the similar degree of rocks deformity. To the east of Mutnovsky volcano this thickness is broken by granitoids of Akhomtensky massive which age corresponds to the boundary of the middle and upper Miocene – 11.4 + 0.3 million years [28].

The mass of greenstone-altered and silicified volcanic and volcanic-sedimentary rocks with the thickness up to 1000 m contorted in gentle folds is exposed in the output of the oldest basement rocks which is the nearest one to Mutnovsky volcano, in interfluve of Akhomten – Perevalny brook (Figure 1). Lower parts of the mass are mainly formed by rudaceous volcanoclastic rocks of basic-intermediate composition: gravelites, conglomerates and conglobreccias, with horizons of plagioporhyrites and numerous basalt dikes and sills. The upper part of the section consists of thin-bedded flushoid band of silicified tuffaceous sandstones and siltstones. The sediments mainly of acidic volcanites of early

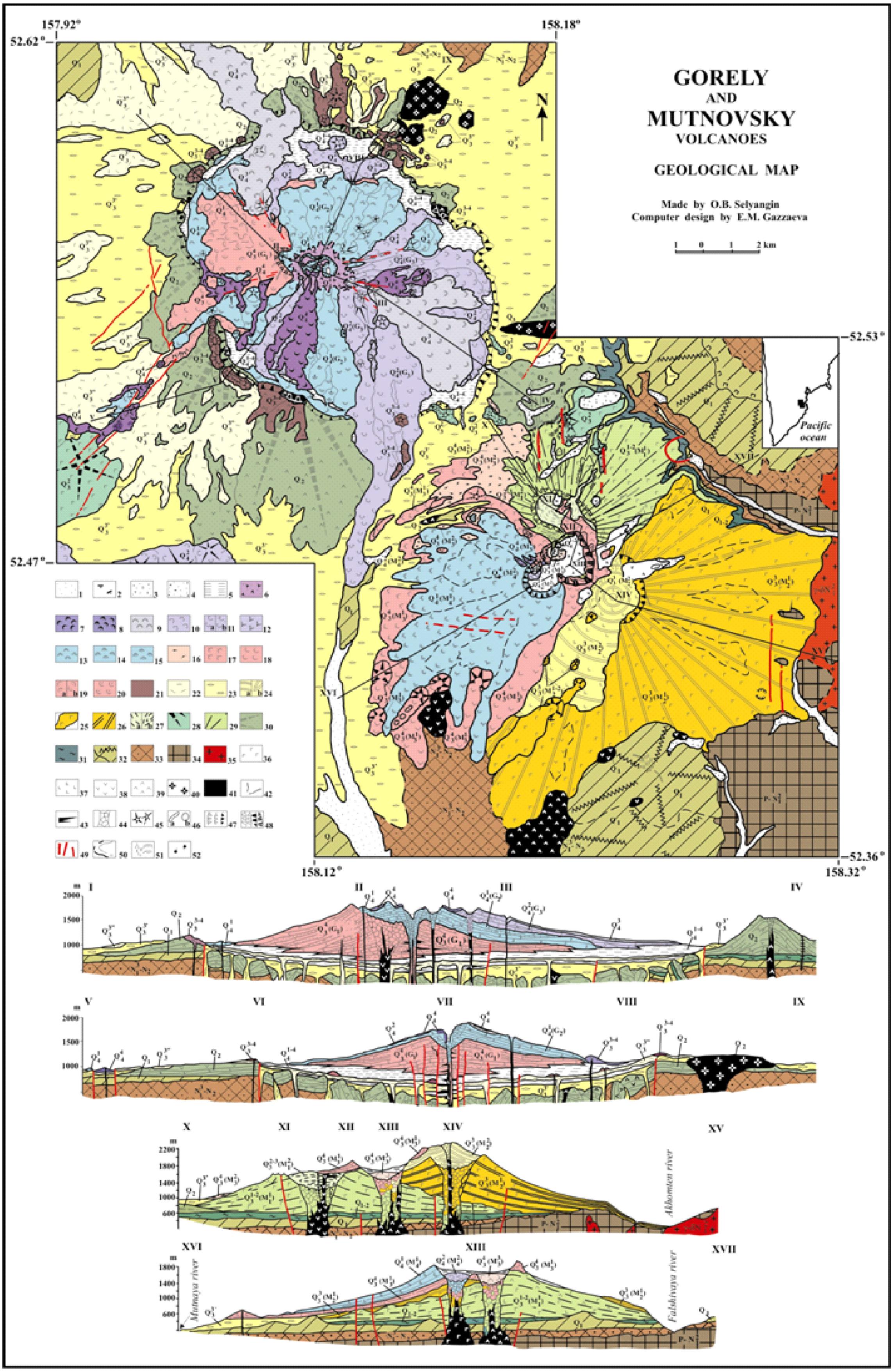
GORELY
AND
MUTNOVSKY
VOLCANOES
GEOLOGICAL MAP
Made by O.B. Selyangin
Computer design by E.M. Gazzaeva
157.92°
158.18°
52.62°
52.53°
52.47°
52.36°
158.12°
158.32°
Pacific ocean
Akhomten river
Mutnaya river
Falshivaya river

Figure 1. Geological map of Mutnovsky and Gorely volcanoes. Made by O.B. Selyangin. Computer processing is made by Ye M Gazzaeva

Legend

Indices $G_{1\text{-}3}$ and $M_{1\text{-}4}$ mark main stratocones which are the components of Gorely and Mutnovsky volcanoes, with subdivision for Mutnovsky volcano (M_1^{1-2} and etc.) accordingly to the activity stages.

Modern and undivided Holocene deposits:

1 – alluvium; 2 – glaciers; 3 – deposits of landslides, debris flows and lahars; 4 – moraine; 5 – complex of aqueoglacial and alluvial-proluvial and lake deposits with interbeds of volcanic ashes and cinders (Q_4^{1-4}); 6 – resurgent ashes and blocks of the last Gorely volcano eruptions.

Late Holocene (Q_4^4, 2.6 thou. years ago – now):

7 – andesibasalts and andesites of the last effusive eruption of Gorely volcano; 8 – cinders of the Active Crater of Mutnovsky volcano.

Middle Holocene (Q_4^3, 5.75 – 2.6 thou. years ago):

9 – andesibasalts.

Early Holocene (Q_4^2, 8.9 – 5.75 thou. years ago):

10 – basalts; 11 – andesibasalts, lavas (a) and tuffs (б).

Ancient Holocene (Q_4^1, 10.1 – 8.9 thou. years ago):

12 – basalts; 13 – andesibasalts; 14 – andesites; 15 – dacites.

Upper parts of late Pleistocene (Q_3^4):

16 – dacite pumices of caldera-forming eruption of Mutnovsky volcano-3 (M_3^2); 17 – basalts; 18 – andesibasalts; 19 – andesites, lavas (a) and agglomerates-agglutinates (б); 20 – dacites.

Late Pleistocene (Q_3):

21 – Q_3^{3-4}, a complex of early-postcaldera monogene volcanic formations of the Gorelovsky center;

22 – $Q_3^{3''}$, dacite pumices of the final stage of caldera-forming eruptions of the Gorelovsky center;

23 – $Q_3^{3'}$, dacite, andesidacite, andesite pumices and ignimbrites of the main stage of caldera-forming eruptions of the Gorelovsky center; 24 – Q_3^3, complex of summit caldera filling of Mutnovsky-2 volcano: lake deposits and lava-pyroclastic formations of intercaldera cone – on the map (a) and on sections (M_2^2); 25 – Q_3^3, lavas of lateral breakthroughs of Mutnovsky-2 volcano (M_2^{1-2}); 26 – Q_3^3, volcanites of the main cone of Mutnovsky-2 volcano (M_2^1) (solid line – slopes close to initial, dash line – eroded); 27 – Q_3^{2-3}, complex of summit caldera filling of Mutnovsky-1 (M_1^2) – aqueoglacial deposits, basalts – andesites of intercaldera structure: (a) – on the map, (б) – on the sections; 28 – Q_3^2, lateral breakthroughs and monogene volcanoes of precaldera stage; 29 – Q_3^{1-2}, volcanites of the main cone of Mutnovsky-1volcano (M_1^1).

Middle Pleistocene (Q_2):

30 – formations of before caldera structures of Pra-Gorely volcano and neighboring volcanoes.

Early-middle Pleistocene ($Q_{1\text{-}2}$):

31 – dacite pumices and ignimbrites.

Early Pleistocene (Q_1):

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32 – lava covers and remnants of stratovolcanoes, basalts – andesites.

Late Miocene – Pliocene (N_1^3 – N_2):
33 – weak dislocated thickness of contrast, basaltoid and acid volcanites with extrusions and subvolcanic bodies of biotite-amphibole rhyolites (Alney series).

Oligocene – middle Miocene (P – N_1^2):
34 – dislocated thickness of greenstone-metamorphosed and silicified volcanic and volcanogenic-sedimentary deposits – tuffoconglobreccias, flushoid tuff sandstones and siltstones, lavas, dikes and sills of basaltic – andesite porphyrites; 35 – intrusions of granodiorites-granites.
Other legend.
Rocks compositions of not separated in detail formations of the middle – late Pleistocene:
36 – basalts; 37 – andesibasalts; 38 – andesites; 39 – dacites; 40 – rhyodacites – rhyolites;
41 – effusive domes, extrusions, subvolcanic bodies and lava necks (on the sections); rocks composition – the same as 36 – 40; 42 – dikes; 43 – sills (on the sections); 44 – necks breccias – eruptive-failures; 45 – cinder cones – young and ancient partially destroyed; 46 – lava bocca and explosive craters; 47 – craters crests, from ancient to young; 48 – crests and brows of caldera benches, from ancient to young; 49 – faults: with determined shift, zero-amplitude, damping and buried; 50 – geological boundaries: between age complexes and individual bodies (interformational); 51 – altered rocks zones; 52 – hot springs and gas-vapor flows.
Holocene division according to [39].

Miocene Berezovskaya suite correspond to this basement complex to the north of Gorely volcano, in the catchment of the Paratunka river.

The upper layer of the lower structural level is unconformable, weakly dislocated mass of contrast, basaltoid and acidic volcanites – Alney series (late Miocene – Pliocene). At the north-eastern foot of Mutnovsky volcano, in the Falshivaya river valley, its rocks overlap eroded tuff sandstones and siltstones which are the same as in the composition of the lower layer. Mass thickness hollow descending to the west is about 400 m. Its composition contains volcanites of a wide composition spectrum and different facial outlook – from basaltic and andesitic-basaltic lavas with interbeds of tuffs, lenses of tuff sandstones and extrusions of hornblende andesites in the lower parts of the section to pumice tuffs and quartz-hornblende rhyodacitic ignimbrites in the upper part. Rocks are propylitized in varying degrees. To the west the deposits thickness of the series increases to 1000-1100 m.

The upper structural level of the region consists of the volcanic rocks of Quaternary age practically without plicative deformations. The most ancient of them of early Pleistocene form basaltoid complex as plateau-lavas of broken abundance, with thickness from tens to the first hundreds of meters, and several volcanic structures deeply eroded. The largest among them are the basalt-andesite-basaltic volcano Zhirovsky to the north-east from Mutnovsky volcano, as well as double andesite structure Pereval-Tumannaya mountains (Pereval volcano) in the south. Volcanoes of the row closest to the ocean lay on the eroded surface of an ancient Oligocene-early Miocene complex of the region basement. Apparently, deeply eroded basalt structure with extrusion of biotitic dacites (Vskrytyi volcano) at the western foot of Mutnovsky volcano refers to the same age range. Its remnant as "cowstone" pressed by glacier is exposed from under late Quaternary ignimbrites of the Gorelovsky center in the canyon of the Vulkannaya river (Opasny ravine).

Remnants of great pre-caldera andesite-dacite structure of the Gorelovsky volcanic center (Pra-Gorely volcano) and dacite-rhyolite extrusions in the north and south of the investigated region are dated by early-middle Quaternary time. Rock mass of more ancient pumice-ignimbrite deposits up to 100 m exposed at the base of Mutnovsky volcano in the valley of the Falshivaya river can be close to this complex. Two rather small destroyed stratovolcanoes of the mountains Dvugorbaya and Skalistaya (hereinafter Dvugorby and Skalisty volcanoes) with high-grade, basalt–dacite-rhyodacite rocks associations are combined in middle-Pleistocene (possible till the middle of late Pleistocene) complex; absolute age of the latest element of the structure of Skalisty volcano (intraglacial extrusion of rhyodacites with flows, apparently) is 61 + 24 thou. years [20].

Rock mass of the four "cold units" of pumice-ignimbrite deposits of andesite-dacite composition associated with caldera formation of Gorely volcano has referred to late Pleistocene. The lowest of them is exposed locally at the water line of the Vulkannaya river. Three upper pumice-ignimbrite covers lying in a single sections form a gentle periclinal around the caldera as an original crater of a giant shield-shaped ignimbrite volcano. Deposits were dated by the time of 38 – 40 thou. years on basis of identical geological position with ignimbrites of the Opala volcano caldera in the west with corresponding radiocarbon dating [14] This age value of caldera-forming eruption in the Gorelovsky center was also confirmed by the same dating of pumice-and-ash interlayer in the bottom sediments of the nearby parts of the Pacific Ocean correlated with it [18].

However, new testing and Ar^{40}/Ar^{39}-dating of ignimbrites in different outlets around the Gorely caldera [21] have shown that only the uppermost ignimbrites band has this age (3 units?). Three units exposed to the south in the Opasny canyon have shown the following values (down cut) ~227, 300, 324 and 332 thou. years, and ignimbrites of one of the outlets to the north from the caldera – 361 thou. years. If all of them are connected with the Gorely caldera its formation is much more multistage and longer, although it is necessary to make direct dating of deposits underlying and overlying ignimbrites, mapping of their abundance, as well as explanations of a very limited development of ignimbrites erosion during very long breaks between their eruptions for "integrity of test". According to geochemical and isotope data it is considered that hydrothermally-altered rocks of the crust took part in magma formation of one part of these ignimbrites, for others it is supposed a large role of assimilation of Miocene granitoids of the Akhomtensky massive located rather close to the Gorely volcano caldera, but almost the whole its diameter further to the south from the location given in the work scheme.

The basement of the intracaldera Gorely volcano is composed probably by megabreccia of the caldera bottom (the ruins of the former arch of magma chamber partially emptied by the eruptions and refilled overlain by pyroclastic, water-glacial and proluvial-lake deposits (Figure 1). Such structure as "broken plates" was supposed during the interpretation of earlier geophysical studies of caldera [32].

Mutnovsky and Gorely volcanoes are dated back to late Pleistocene – Holocene according to their correlations with glacial forms of this time and tephrochronology data [13, 14]. As noted, their ridged structures are focused close to a single line of north-western direction formed a short broken range which is cross to the main north-eastern extension of the volcanic Kamchatka chains. This indicates their connection with a common area of crust magma permeability in which localization there is a quite obvious effect of the mentioned system of cross dislocations. However, on both structures sides this zone does not continue. On its upper levels modern Mutnovsky and Gorely volcanoes are separated by a narrow impermeable, amagmatic zone. The features of the material composition erupted by them argue for the independence of magmatic sources feeding them.

2.2. Geophysical exploration

Geophysical explorations such as gravity, magnetic, seismic, electrical, magnetotelluric and thermal were made at the region of volcanoes in different times. Data was synthesized in the reports of the workers of the Central complex thematic expedition of PGA Kamchatgeologia [36, 37].

Gravimetry data is the most important for the deep structure of the region and possible structure of the root zones of volcanoes. According to them two largest structural elements were determined in the region (Figure 2): the gradient zone (with the amplitude of up to 80 MGal and gradient up to 5 mGal/km) at the western restriction of the South-Kamchatka horst-anticlinorium (the Coast Range) discussing as the system of high-angle faults, and a large negative gravity anomaly called the Tolmachev-Gorely depression or Gorely downdip block adjoining to it in the west.

The amplitude of gravitational stage restricting it reaches 18-20 mGal. Gorely and Mutnovsky volcanoes are located within it, at the same time Mutnovsky volcano is in the gradient zone. The Gorely volcano caldera is only a small part of depression and it has not any similar intensity reflection in a gravitational field. The depression itself is not expressed in near-surface geological structure, except for a part of its south-western boundary coinciding with the corresponding part of caldera bench.

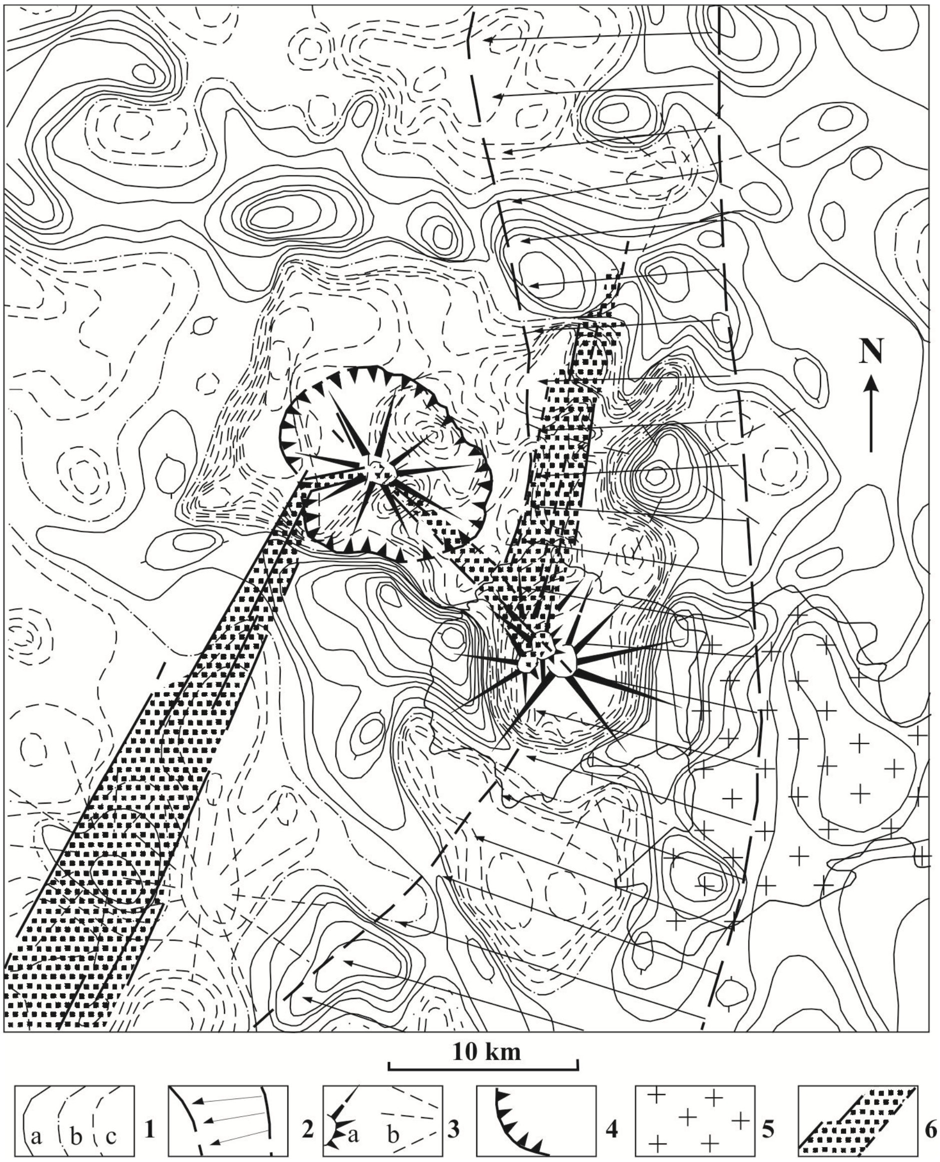

Figure 2. The scheme of local anomalies ΔG and the position of the main structural and magmatic elements of the Mutnovsky-Gorelovsky region. It’s made using V V Ardashev and V A Volkov data. 1 – gravity isolines – positive, zero, negative; 2 – regional gravity step; 3 – the largest volcanoes structures – extinct and active; 4 – bench of Gorely volcano caldera; 5 – Akhomtensky intrusive granitoids; 6 – regional zone of magma-controlling breakthroughs (hereinafter).

In [32] the depth to the upper edge of the gravitating object of Tolmachev-Gorelovsky anomaly is estimated more than 12 km; the anomaly in the Gorely volcano caldera is characterized as a complex one but "generally negative" with the formation depth of the anomalous object equaled ~2 km.

Geological interpretation of gravity anomaly supposes rock fault of Cretaceous region basement from 1.5 km in the east to 3 km in the west. It is assumed that it corresponds to a large buried caldera. However, rock fault does not correspond to the calculated mass defect, so the observed decompaction is interpreted by the introduction of crustal chamber-intrusive of acid composition with which Pliocene-Quaternary volcanic activity, the latest structure-forming, hydrothermae and well-known gold-silver mineralization are connected.

According to magnetotelluric sounding the zone of high conductivity at the depths ranging from 4-5 to 20 km, i.e. within the crust which thickness in the region is 30 km forms under the downdip block. Two discrete regions of "plastic rocks" with the relation of p and s wave velocities k = 1.85 run back to the depth of ~10 km are determined within this zone according to the seismic data. One region corresponds to a indistinct Gorelovsky chamber under the modern volcano caldera and some north from it. The estimated position of the “pluton roof” at the eastern foot of Gorely volcano is about 2 km. Another region is the Mutnovsky chamber extending to the depths of 7-10 km from the center of the Mutnovsky volcano structure up to 10-12 km to the north with the width of 5-6 km. One more region of a high plasticity of the environment is in the zone between the volcanoes below the first two zone, with some shift to the west from them.

On geoelectric section of the Gorelovsky block there are layers of high conductivity in the upper parts of the section and vertical conductive zones stretching to the depth of 3-5 km and more. They are interpreted as a system of fault-line channels and zones of the flowing of depth heat carrier rising from magma chamber. In thermal field temperature anomalies of Gorely and Mutnovsky volcanoes located in their near-crater zones are discrete for all available depth research.

Given interpretations of the geophysical work results are rather disputable. The indistinct of Tolmachev-Gorelovsky depression in a real geological structure of the region was told above-mentioned. Another example of apparent contradictions to understand the nature of this anomaly as chamber-intrusive one is its eastern part coinciding to the Akhomtensky intrusive: it forms a steep positive step in the gravity field restricting the anomaly from the east with significantly granitoid composition of the intrusion (Figure 1). Perhaps, it indicates a bedded shape and small intrusive thickness underlain by high-density rocks. The allocation of such great Mutnovsky volcano chamber is not convincing: it is difficult to imagine hydrodynamically that its magma that rose up to 1800 m to the active volcano crater did not manifest any young breakthrough at low levels in tectonically active place of its occurrence.

Substantially basaltoid (basalts and basaltic andesites) composition of the modern volcanoes products is the main counter-argument about the existence of acidic magma chambers within the depression. At the same time it gives the problem: how heavy basaltic magma can rise in a structure of low density. The most possible source of gravitational anomaly is considered to be a large probably laminated pluton of granite-diorite composition crystallized to an effectively coarse condition, but perhaps noncompletely cool yet.

On the other hand, mentioned various depth of the roof location of solid Cretaceous basement in the east and west of the depression, i.e. under Mutnovsky and Gorely volcanoes should be considered as one of the reasons for the differences in their structural and material evolution due to a possible its effect on the placement depth and the sizes of their peripheral chambers.

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