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The study of geothermal resources of Avacha volcanoes group and its flanks

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Abstract: The article is based on the results of the geologic-geophysical researches carried out during different years around the Avacha volcanoes group and its flanks. More attention was paid to the results of electric exploration by the method of magnetotelluric sounding and gravimeter survey of 1:50 000 scale. Works results in the context of heat and power territory potential utilization were given. The complex of geophysical methods to study morphology of the peripheral chamber under Avacha volcano and search of potentially possible zones of chamber interaction with meteoric waters was recommended.

1. Introduction

Volcanologists, geophysicists and other researchers pay much attention to the Avacha group of volcanoes and its flanks as a potential source of heat energy. Indeed, active "domestic" volcanoes Koryaksky and Avacha are located in close proximity to the most habitable and industrially developed agglomeration of South-Eastern Kamchatka.

The territory of Kamchatka south was studied rather well. The entire area is covered by gravimetric and aero magnetic surveys of 1:200 000 scale. Structural and formational map [1] was made according to the material of gravimetric and geological surveys, a number of articles about geological region structure, including its south-eastern part was published [2, 3].

There is a gravimetric minimum of gravity field of the north-western extension which is explained by the existence of a linear negative structure – the latest Avacha graben (Fig. 1) to the south-west from Avacha volcanoes. This structure is included into the Krutogorovsky-Petropavlovsky zone of cross dislocations (ZCD) [4] of the same extension. In the southern part the graben is complicated by volcano-tectonic structure (VTS) where volcanoes of Avacha group are included. Volcanogenic-and-sedimentary and volcanogenic-and-terrigeneous Cainozoic deposits fill the depression.

The most ancient deposits of a studied territory are intensively dislocated deposits of upper Jurassic-Cretaceous relating to graywacke-slate, basalt-andesite-tuff-siliceous formations. The considerable part of the area is occupied by Oligocene-Miocene and Neocene deposits relating to basalt-andesite, andesite-dacite, basalt-andesite-liparite formations. Tectonically the graben is restricted by Kitkhoisky VTS and Nalychevsky uplift in the north-east, by Petropavlovsky horst – in the south-west (Fig. 1).

In terms of the hydrogeological mode the glaciers formed within the Avacha group of volcanoes are the regions of water nutrition for adjacent thermomineral springs, including Ketkinsky thermal water field (TWF) and Bystrinsky fresh water aquifer (FWA). According to the results of hydrodynamic modeling [5] and data of drilled wells the level of ground waters (absolute marks) changes within 100-400 m lowering in the central parts of VTS up to 500-800 m. It is necessary to add that buried channel of the Avacha River, apparently, plays a significant role for water mode formation. The river has left the ancient valley [6] probably due to the accumulation of volcano discharges at the volcanoes foot. The explosive eruption of Avacha volcano directed to the south-west has caused the dam of the Pra-Avacha river and change of its bed to a current state. Possibly, it was the prime cause of the formation of Bystrinsky FWA which was formed at a dam – the western boundary of a cone of volcanic material discharge which is fed by glacial waters now.



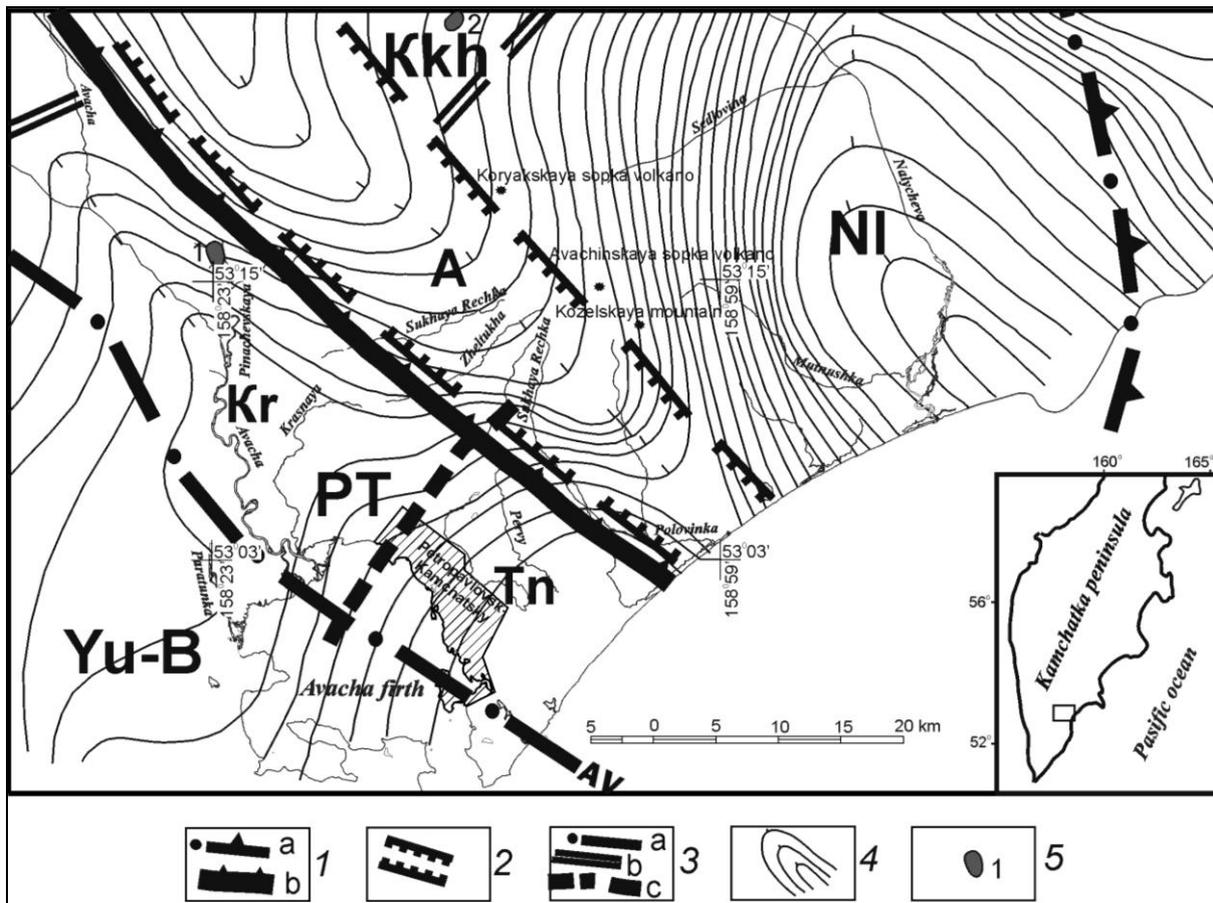


Fig. 1 General tectonic map (according to S.Ye. Aprelkov and O.N. Olshanskaya [1]). Legend: 1 – boundaries of anticlinoriums and horst uplifts: normal (*a*) and tectonic (*b*); 2 – boundaries of the latest graben; 3 – fractures: regional - Avacha (*a*) dividing large blocks (*b*), dividing Petropavlovsky horst into Krasnorechensky depression and Tundrovyy uplift; 4 – isolines of gravity field; 5 – geothermal water fields: 1 – Ketkinsky, 2 – Verkhne-Nalychevsky. Structures legend: Yu-B – Yuzhno-Bystrinsky block, NI – Nalychevsky uplift, PT – Petropavlovsky horst, A – Avacha graben, Kkh – Kitkhoisky volcano-tectonic structure, Kr – Krasnorechensky depression, Tn – Tundrovyy uplift.

2. Brief overview and analysis of the work carried out earlier

Scientists have been paying much attention to Avacha volcano over several decades. In 1960-62 within volcano area the complex of geophysical works [7], including land magnetic and gravimetric surveys were carried out. The results of model simulations along the profile crossing Avacha volcano have shown that there is a magma chamber feeding it in the depths range of 2,5-5 km. The chamber roof is located at the depth ~ 1,5 km below sea-level (b.s.l.). According to some assessments the chamber is presented by andesite-basalts – gabbro-diorites [8].

In 1982-84 the continuous seismic profile of refraction correlation method (RCM) crossing Avacha volcano from the south-west to the north-east was made for the first time. The results of the obtained data showed [9] that Avacha volcano is located in a graben-like depression restricted by fractures on both sides. Under the volcano in the depths range of 1,5-5,0 km below sea-level there is the zone of relative velocity reduction of a seismic wave. In the upper part of the zone there is the region of increased absorption of high-frequency components of transmitted P-waves. These data are coherent with earlier suggested guess [7, 8] about the existence of peripheral magma chamber under Avacha volcano. There is the zone of velocity inversion which authors interpret as the crust magmatic chamber beneath through the section vertically in the depths range of 9-17 km.

Later on basis of the method of tomographic section reconstruction [10] the model of seismogeological section under Avacha volcano was suggested. According to this model the graben basement represented by the rocks of Cretaceous basement is located on the depths of 6 km below sea-level. The authors consider the area of volcano feeding is located in the depression basement and its roof is at the depth about 3 km. Higher through the section, under the volcano, in the depths range of 1-3 km the absorption zone of high-frequency component of seismic waves was determined. The zone indicates "... a considerable heating of crust substance".

In 1979-1983 within the Avacha group of volcanoes the gravimetric survey was carried out. As a result of interpretation the volume model of anomalous bodies under Avacha volcano was obtained and geodensity modeling along the profile RCM was carried out. As the authors of the work [11] note the maximum average density in the block containing the supposed chamber of Avacha volcano is $2,88 \text{ g/cm}^3$.

Later the geodensity model calculated along the line crossing Vilyuchinsky and Avacha volcanoes has been offered [12]. Density modeling was made according to gravimetric survey of 1:200 000 scale. Under Avacha volcano in the depths range of ~ 1-4 km below sea-level there is the object of the increased density ($2,75 \text{ g/cm}^3$) probably reflecting magma chamber existence. From up north a small allotment of deconsolidation $2,57 \text{ g/cm}^3$ adjoins it. This allotment coincides with the zone of "a considerable heating of crust substance" chosen earlier [10].

Geodensity modeling was carried out along the axial region of the Avacha graben which has shown stepped basement structure - a number of local depression structures is divided by narrow zones of uplift [13]. But it should be noted that gravity field (GF) modeling along the stretched-out structures restricted by lateral heterogeneities of different density can lead to essential errors in a total density model. Compensating regional background of GF the authors of the model "have lifted" Mokho's boundary in the Avacha graben to the level of 20-22 km. But according to DSS the crustal thickness is about 42-45 km in the analyzed area [14, 15]. It is necessary to note that according to the ECWM (earthquake converted-wave method) obtained along the regional profile crossing the Avacha graben [16] there is a crust-mantle zone of mis-picks of seismic boundaries under the Avacha group of volcanoes. Probably, the reduced zone reflects under the volcanoes in such way.

According to the obtained density model in a narrow reduced zone – in a graben of 15-25 km width there is an uplift of mantle substance with local brow amplitude of more than 20 km (!). It gives the possibility to classify the structure as the latest rift (?). But the existence of such "mantle brow" isn't confirmed by seismoprospecting operations [9]. In any case there is not such "mantle brow" in a section along the RCM profile. Even if the transitional area crust-mantle under the volcanoes can reach 20 km [17] the upper mantle under the Avacha group of volcanoes is much deeper than it was shown in the article [13].

It is obvious that Mokho boundary "restoration", according to DSS data at the depth of 40-45 km, or at least its lowering (lower than it is offered in the article [13]) will lead to density model mismatch. Therefore, three-dimensional numerical simulation of GF taking into account lateral density heterogeneities with use of the modern software is required to study the geological structure of a junction zone of the Avacha graben with VTS and, in particular, specify its density model.

In 1979-1981 Yelizovo geophysical expedition (YeGFE PGO "Kamchatgeologia") carried out regional magnetotelluric soundings in a combination with geomagnetic-variation profiling along the sublatitudinal profile of Ust-Bolsheretsk village – Shipunsky Cape. The work was implemented using quinary analog stations MTL-71. The range of detected periods of MT-field was 10-2000 s, a step along the observation line was 15-20 km with a concentration in the region of Avacha volcano [18]. As a result of the work deep geoelectric sections showing the distribution of electrical conductivity in the earth's crust and upper mantle to the depth of 100 km or more were obtained. Under Avacha volcano the electrical conductivity anomaly was pointed. Its origin was explained [19] by the existence of the peripheral magma chamber at the depth of the first kilometers.

Subsurface exotic heterogeneity represented by a horizontal conductive channel has attracted the attention as well. It was discovered by detailed magnetovariational measurements [20] carried out to

the south-east from Avacha volcano. Currents Канализируемые by this heterogeneity cause significant anomalous effect fixed in the intense diurnal variations of the geomagnetic field. People, made this work, consider that this anomaly is unique, comparing it with the closest analogue – Alertskaya anomaly in the Canadian Arctic.

Analysis of the materials shows that the contours of the "Avacha anomaly" [21] almost completely coincide with the linear structure of the north-western extension – Avacha Graben (Fig. 1). According to geomagnetic-variation profiling [19] a local heterogeneity is reflected in unusual orientation of the induction vector in the MTS point closest to the Graben – parallel to the coast line, while they have orthogonal orientation oceanward in other coastal points.

Except studying of the Avacha group of volcanoes there is a wide complex of geologic-geophysical researches directed to search thermal waters in the region. In particular, Ketkinsky TWF was opened in summer of 1984 as a result of electric exploration by transient electromagnetic method (TEM) [22] made by Elizovo geophysical expedition of production geological association "Kamchatgeologiya". Later, in 1987-1990 the whole territory from the Avacha River head to the lower course of the Nalychevo river (Fig. 1) was studied by the method of magnetotelluric sounding (MTS) and gravimetric surveys of 1:50 000 [23, 24] scale. North-eastern boundaries of the geophysical works area closely adjoin to the feet of volcanoes of the Avacha group. That time the works of MTS were carried out in the region of Verkhne-Nalychevsky TWF. Field contours were specified, the model of its structure was offered⁵.

The results of MTS works in the region located between the Avacha group of volcanoes and city agglomeration of Petropavlovsk-Kamchatsky will be considered.

From the south-west to the north-east the explored area is crossed by a regional profile along which the complex of geophysical methods such as MTS and ECWM [16, 25 and 26] was carried out. In its central part it completely coincides with the profile of MTS crossing the Avacha graben to the north of Avacha volcano (Fig. 2). The works were carried out to study Earth crust and upper mantle in the area of seismic activity and recent volcanism. The station interval along a profile is 2-3 km, the maximum period of the registered variations of MT-field is 1000 s, but in some points it reached 3000 s.

Deep geoelectric model [25] was obtained as a result of two-dimensional numerical simulation made along a profile using the program [27]. According to it in the region of the Avacha group of volcanoes, in the range of depths of 1-6 km there is the zone with anomalously low value of specific resistance – 10 Ω m against 200-1000 Ω m. It was suggested that in this place the Earth crust is penetrated by deep fractures along which magmatic melt comes to its near-surface areas.

Areal survey of MTS on a studied territory was carried out at $\sim 2 \times 2$ km survey grid (Fig. 2). In the Avacha graben, to the east from Radygina settlement the works of MTS were made along four parallel profiles, and in the region of a saddle between Avacha and Koryak volcanoes the MTS separate profile crossing the graben in the north-eastern direction was carried out. The station interval of the profiles is $\sim 0,5$ km. The range of the registered MT-field variations was generally 0,1-100 s, but in some points the maximum period reached 800-1000 s.

The detailed analysis of MTS curves obtained during different years is presented in the articles [25, 28]. According to the carried-out systematization, the curves are divided in strike directions and across the strike of the main structures of Kamchatka. It was noted that so-called longitudinal curves of MTS should be used to study electric conductivity of a deep component of the Earth crust and upper mantle [29, 30 and 31].

Later on two-dimensional modeling along a regional profile was repeated, but using the materials of MTS obtained according to the program of hydro-therms search and prospect [23, 24]. Thus, information density according to the data of MTS in the region of the Avacha volcanoes group was significantly increased. This time, the modeling was carried out using the program of F. Wannamaker [32]. As a result more detailed picture of conductivity distribution along a profile has been obtained [30]. So, low-resistivity object – 20 Ω m against 500 Ω m was chosen to the west from Petropavlovsk horst in depth interval of 24-40 km. Approaching to the Avacha group of volcanoes it rises, and the conductor roof is determined (10 Ω m) at the depths of 10 km within a graben region. Higher in a

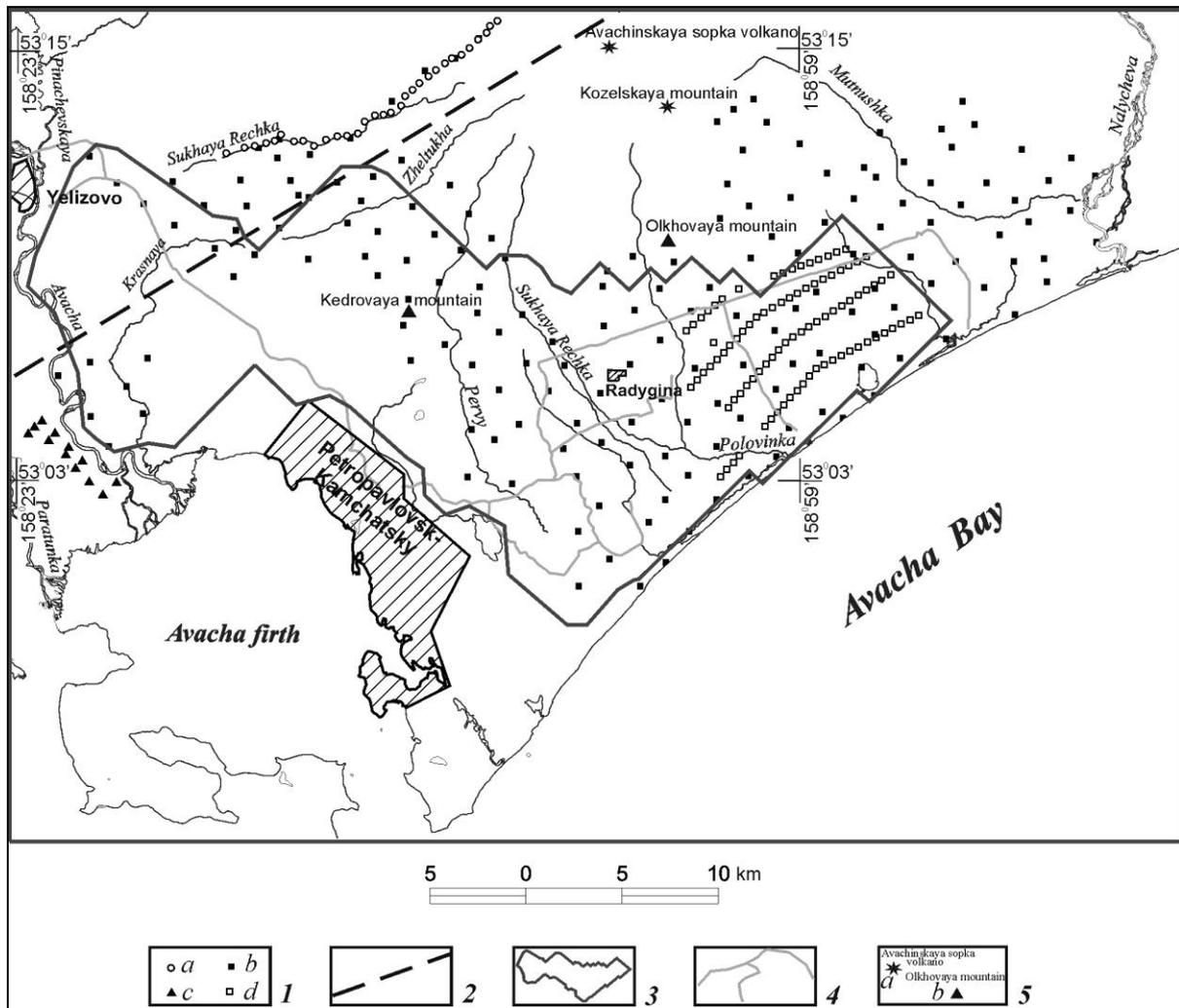


Fig. 2 Physical and geological map of geophysical works. Legend: 1 – MTS points abandoned: along south-western profile part of the Sukhaya rechka river – Sedlovina river (*a*), at a survey grid $\sim 2 \times 2$ km (*b*), at the allotments Nickolaevsky (*c*) and Rudygino (*d*); 2 – the line of seismic profile of RCM-DSS [9]; 3 – contours of gravimetric survey allotment of 1:50 000 scale; 4 – roads; 5 – volcanoes (*a*), peaks (*b*)

section, in the range of 1-5 km, the conductor ($8 \Omega \text{ m}$ against $100 \Omega \text{ m}$) reflecting low-resistivity volcanogenic-and-sedimentary rocks complex filling the Avacha graben was chosen.

The structure model of the Earth crust constructed according to MTS and RCM [30] is presented in Fig. 3. According to the model the reduced velocity zones coincide with conductivity anomalies. Most hypocentres of volcanic earthquakes is concentrated above the supposed peripheral chamber.

Later, due to data generalization the geologic-geophysical model of the Earth crust under Avacha volcano was offered [33]. Its parameters are close to the model shown in Fig. 3, but here the considerable attention is paid to a crust anomaly of conductivity which (according to the authors [33]) reflects a permeable zone existence in the Earth crust – the zone of a deep fracture where hydrothermal solutions circulate. The discharge zone of hydrotherms and their accumulation are possible in the Avacha graben. The existence of contrast anomaly of conductivity indicates it in the upper part of the section (1-5 km). This factor attracts intense interest as the analyzed object (the graben complicated by VTS) is located in close proximity to the most developed agglomeration of Southern Kamchatka where supposed hydrothermae can be used for settlements heating.

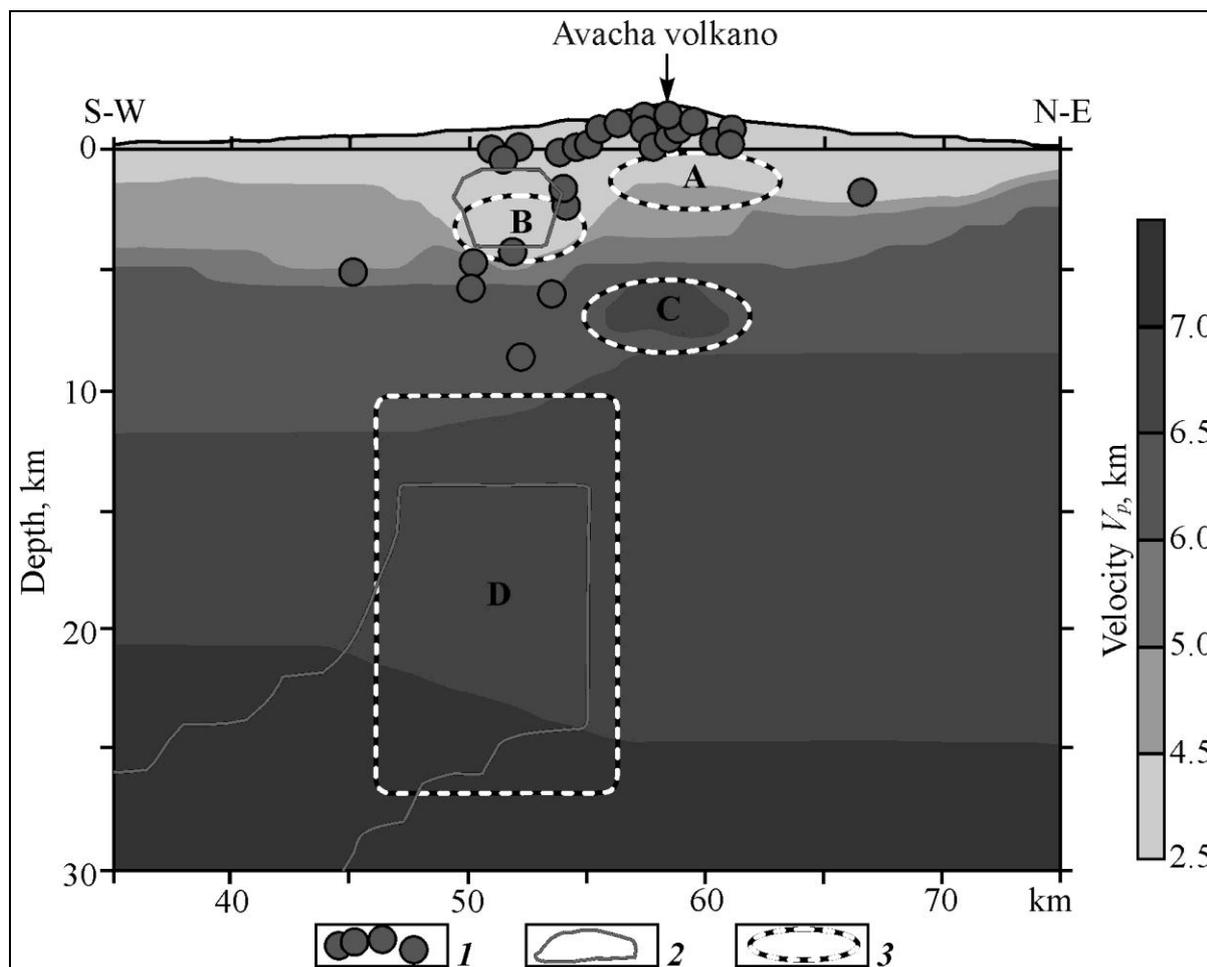


Fig. 3 Seismic model of the Earth crust in the region of Avacha volcano in comparison to conductivity data [30]. Legend: 1 – hypocentres of volcanic earthquakes; 2 – zones of the increased conductivity; 3 – anomalous zones in seismic waves: A – the zone of absorption of a high-frequency component of seismic waves spectrum, B and D – the zone of the reduced velocity, C – the zone of the increased velocity (intrusion)

Works results which were earlier given only in the production reports generate the interest in the contest of both structural geophysics and hydrothermal resources search. So, according to electrical survey of MTS made at 2×2 km survey grid the map of summary lateral conductivity (S) to the surface of high-resistivity basement was constructed (Fig. 4) [24]. Upper-cretaceous rocks complex (UCRC) characterized by a specific resistance of 100-300 Ω m and more is considered to be "high-resistance basement". S value was determined in each point of MTS using a double-layer crossplot (palette) [34] on the ascending branch of an amplitude curve ρ_r , calculated according to effective parameters [35]. S value reflects surface relief of a high-resistivity basement and it is in a direct dependence on thickness of a volcanogenic-and-sedimentary complex of rocks and its conductivity degree.

On the map S the Avacha graben is as an anomalous conductor of the north-western extension. Its boundaries are reflected in gradient zones dividing the allotments with low (10-50 mhos) and high (120-330 mhos) values of S. The allotments with maximum S values reaching 380 mhos and more are determined in the graben complicated by a volcano-tectonic depression. Conductivity level in such places can depend on saturation degree of Cainozoic deposits by thermal waters according to the concept given in the article [33]. Thus, the analyzed map can give the information on availability (existence) of conductive zones (allotments, structures) perspective to detect hydrothermae with

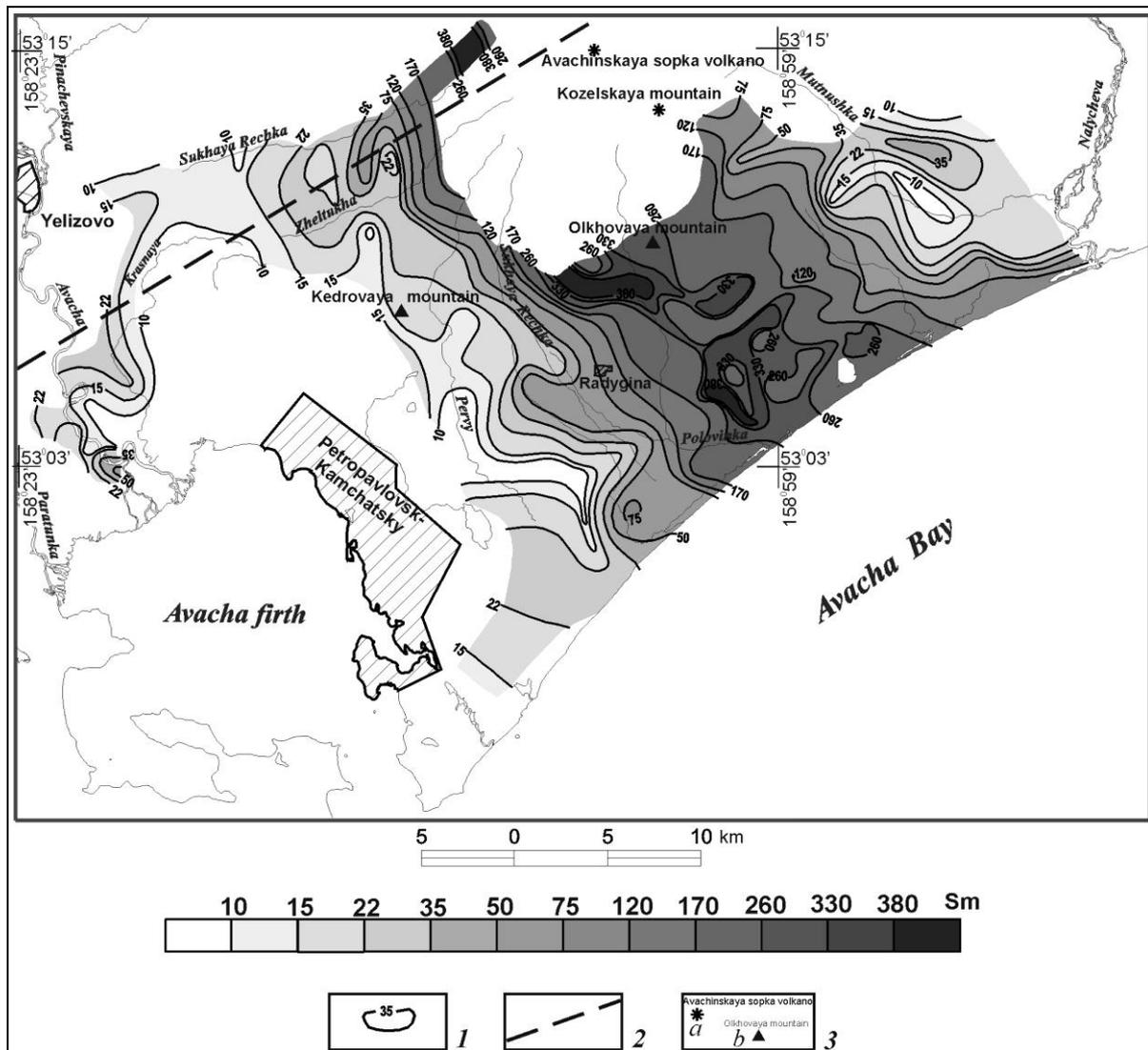


Fig. 4 The map of summary lateral conductivity (S) to the surface of a high-resistivity basement. Legend: 1 – S isolines and conductivity values in siemenses (mhos); 2 – seismic profile line of RCM-DSS [9]; 3 - volcanoes (a), peaks (b)

a latent form of discharge.

Due to interpretation of MTS data the scheme of depths (from a daylight surface) to a roof of high-resistivity basement (Fig. 5) was made. Depths determination in each point of MTS was carried out on basis of dependence (Fig. 6) of the minimum shift of an amplitude curve ρ_T on the axis \sqrt{T} on the thickness of Cainozoic deposits - depth up to UCRC. To determine this dependence the information on the wells GK-1 (depth is up to UCRC of 470 m), GK-2 (683 m), GK-2A (670 m), R-2 (1290 m), R-3 (1,5 km were passed – UCRC wasn't opened(uncovered)), as well as data of seismic works of RCM on which UCRC roof in the graben around Avacha volcano is at the depth ~ 5 km were used [9]. It is necessary to add that the obtained results (Fig. 5) are well coherent with geoelectric model of the Earth crust [30] where there is a high-resistivity basement (500 Ω m) in the region of the Avacha graben at the depth of 5 km.

The scheme (Fig. 5) shows the maximum depth of UCRC (≥ 5 km) is in the area complicated by VTS. But in the south-eastern part of the graben there is a high-amplitude uplift of its basement. Here the depth to UCRC decreases up to 1,5-2,5 km. Thus, the contrast depths drop in the graben reaches

2,5-3,5 km.

The south-western boundary of the graben is presented as a sudden depths drop up to a high-resistivity basement. So, the depth up to UCRC increases from 1,4 to 3,5 km on 1,5 km of a horizontal distance. This gradient zone is identified with fractures system separating the Avacha graben from Petropavlovsk horst. At the same time, it should be noted that isolines (to the south-west from the volcanoes) have the tendency to turn from the generalized north-western to the north-eastern direction. The same picture is observed in isolines morphology of summary lateral conductivity on the map S (Fig. 4).

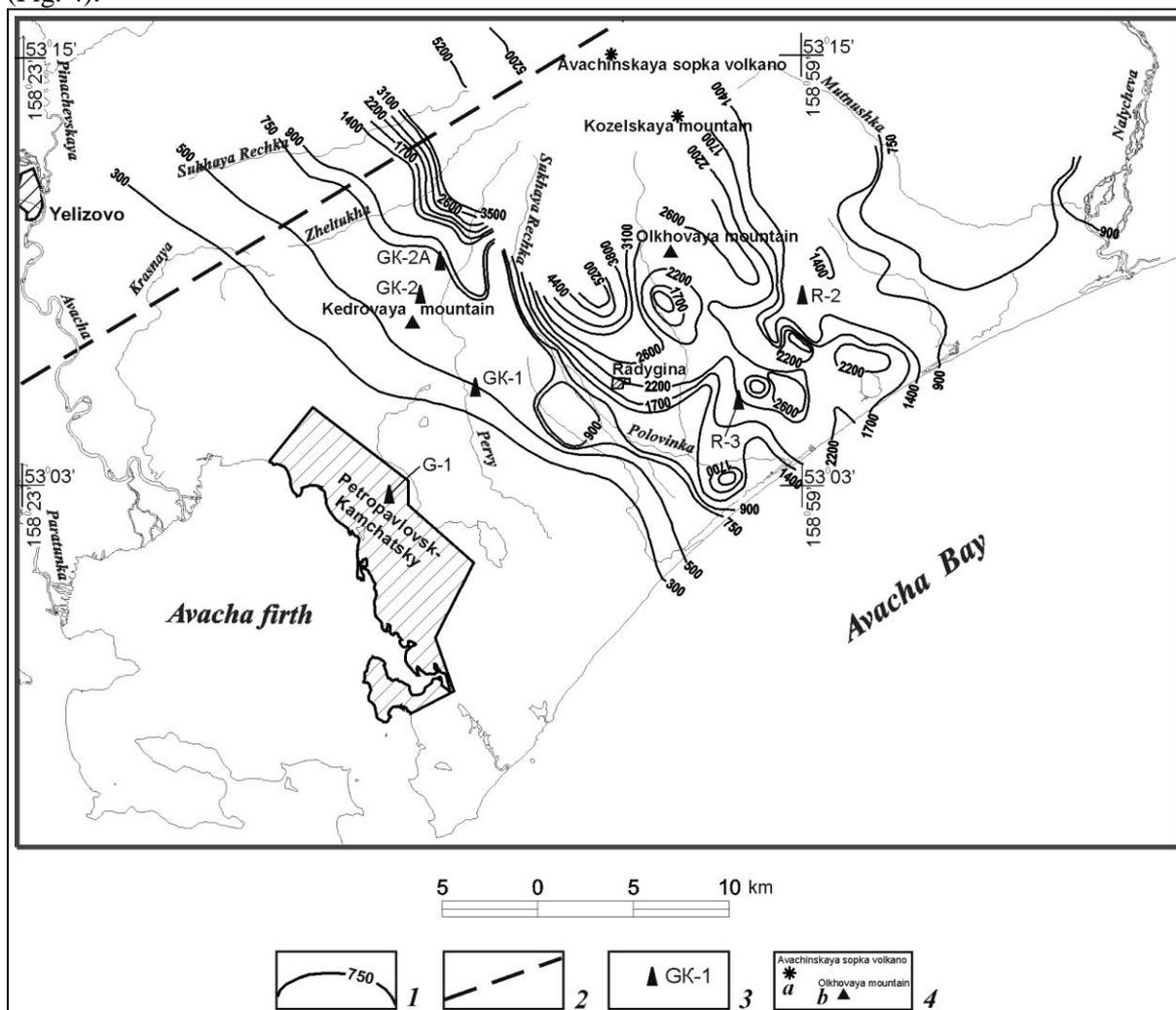


Fig. 5 The map of depths up to high-resistance basis (upper Cretaceous rocks complex). Legend: 1 – isolines and depths values in meters (m); 2 – seismic profile line of RCM-DSS [9]; 3 – drilled wells and their numbers; 4 – volcanoes (a), peaks (b)

One of the important assessments using in electrometry is the geoelectric anisotropy characterizing the degree of medium heterogeneity. Additional information of this parameter can be obtained using Eggers method. The determination of principal values and main directions of an impedance tensor [35] is in the method basis. Heterogeneity parameter is calculated by principal values of an impedance (Z_{max} and Z_{min}):

$$N = |Z_{max} - Z_{min}| / |Z_{max} + Z_{min}|.$$

Method justification and calculation formulas are presented in the article [36]. Parameter N means the following: N = 0 if medium is horizontally homogeneous. Departure of N from 0 is a measure of

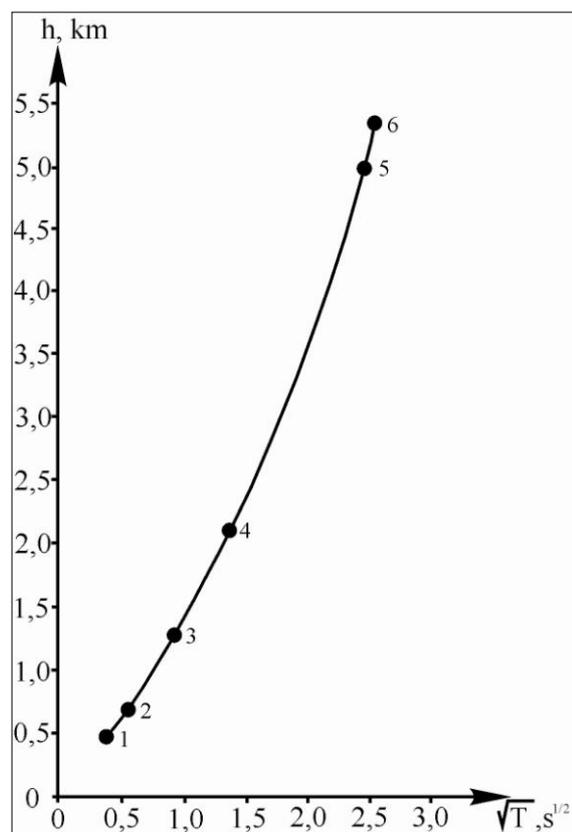


Fig. 6 Dependence diagram of minimum position (\sqrt{T} , s) of the curve MTS on the depth (h, km) to UCRC roof. Points on the diagram are depths values (known according to different data) up to UCRC in comparison to a minimum on the curves of MTS in near points of sights: 1 – 470 m (well GK-1); 2 – 683 m (well GK-2), 670 m (well GK-2A); 3 – 1290 m (well R-2); 4 – 2100 m (according to MTS [23]); 5 – 5000 m (according to MTS [30]); 6 - 5400 m (according to RCM [9])

horizontal geoelectric medium heterogeneity. The calculation of Eggers vectors and N parameters was realized for MT-field variations of 25 s period.

As a result the map of heterogeneity parameter N was made where in most points of MTS Eggers (Fig. 7) vectors were represented. The map shows the Avacha graben attracts is notable for the structure characterized by high N (0,6-0,8) values. The allotments with maximum values ($\geq 0,9$) were recorded in the zone adjoining the north-eastern boundary of the graben. In general, graben boundaries are reflected as isolines extended mainly to the north-west. But in that place where depths isolines up to UCRC (Fig. 5) turn the isolines of N

parameter also change their direction from the north-western to the north-eastern. Obviously, in this place in geoelectric parameters the structure which directs cross-strike to the basic structures of a studied territory reflects. Indeed, as a result of gravimetric survey of 1:50 000 scale in the analyzed allotment the tectonic dislocation (fracture) of the north-eastern strike which divides Petropavlovsk horst into Tundra uplift and Krasnorechensky depression (Fig. 1) was determined. The fracture attracts attention due to several transformants of gravity field including its second vertical derivative - V_{zz} (Fig. 8). Perhaps, this tectonic dislocation is a fragment of the Avacha-and-Vilyuchinsky lineament which was earlier determined by Yu.P. Masurenkov [37]. But it should be noted that S.Ye. Aprelkov and A.Ye. Svyatlovsky deny lineament existence. In their article [3] they note that "... this fracture can't be found on standard geological maps, there are not its features in geophysical fields either". But just latest works made in 1990-1992 show that tectonic dislocation of a considerable scale is manifested according to the geophysics data in the region of Petropavlovsky horst (Fig. 7, 8).

Avacha volcano with its crust and peripheral magma chambers is located in a zone of fracture and graben crossing. Possibly, the fracture zone is a multistage fault plane along which a high-amplitude roof uplift of UCRC in the south-eastern part of the graben was formed.

The geologic-geophysical section along the Avacha graben (Fig. 9) was made on basis of data complex. Here the supposed contours of magma chamber and zones of its high-temperature influence were taken out based on estimated simulated data [38]. It is necessary to add that as a result of AMT sounding the works carried out on the southern volcano slopes at the depth of 200-400 m the zones with anomalously low level of specific resistance were determined. Anomalies nature was not studied completely, and according to the authors opinion [39] requires the further studying.

As a result of carried out hydrogeological [40, 41] and geophysical works [24] a number of allotments perspective for hydrothermae opening was determined. According to elaborated recommendations it is necessary to study these areas additionally. It will increase the possibility to obtain geothermal resources as possible sources of thermal energy. In the present article it isn't possible to give detailed information on each perspective objects due to a publication limit size. But,

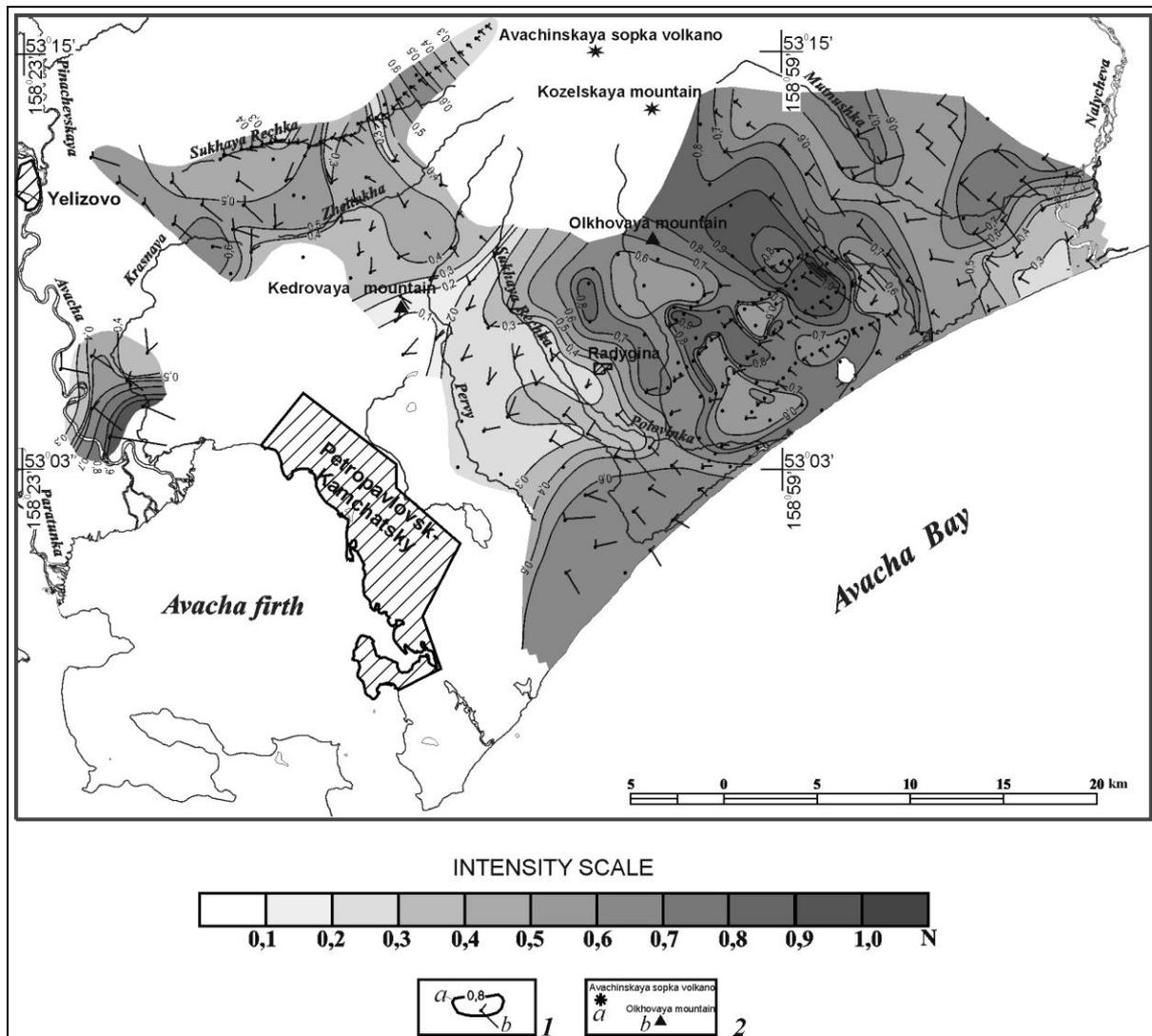


Fig. 7 The map of heterogeneity parameter of N. Legend: 1 – N isolines and their values in conventional units (a); Eggers vectors (b); 2 – volcanoes (a), peaks (b)

nevertheless, it should be noted that their main part adjoins the south-western boundary of the Avacha graben.

Finally the following main conclusions can be made:

- The Avacha graben is an anomalously low-resistivity dominant of a studied territory. Its structure is complicated by a volcano-tectonic depression formed by several volcanoes.

- In a crossing zone of graben and fracture of the north-eastern extension the edifice of Avacha volcano with its crust and shallow lying as peripheral high-temperature chamber was formed. According to the different estimates [10, 30 and 33] the roof of the peripheral chamber is at the depth about 2 km from a daylight surface.

- The allotments adjoining the south-eastern boundary of the Avacha graben have the greatest perspective to detect hydrothermae.

- The peripheral chamber can be the object of study to operate its thermal energy.

3. Opportunities for geophysical surveying

Thermal waters fields, known on the peninsula, are actively used for heat supply of small settlements such as Termalny and Paratunka in South-Eastern Kamchatka or Esso and Anavgay in Central

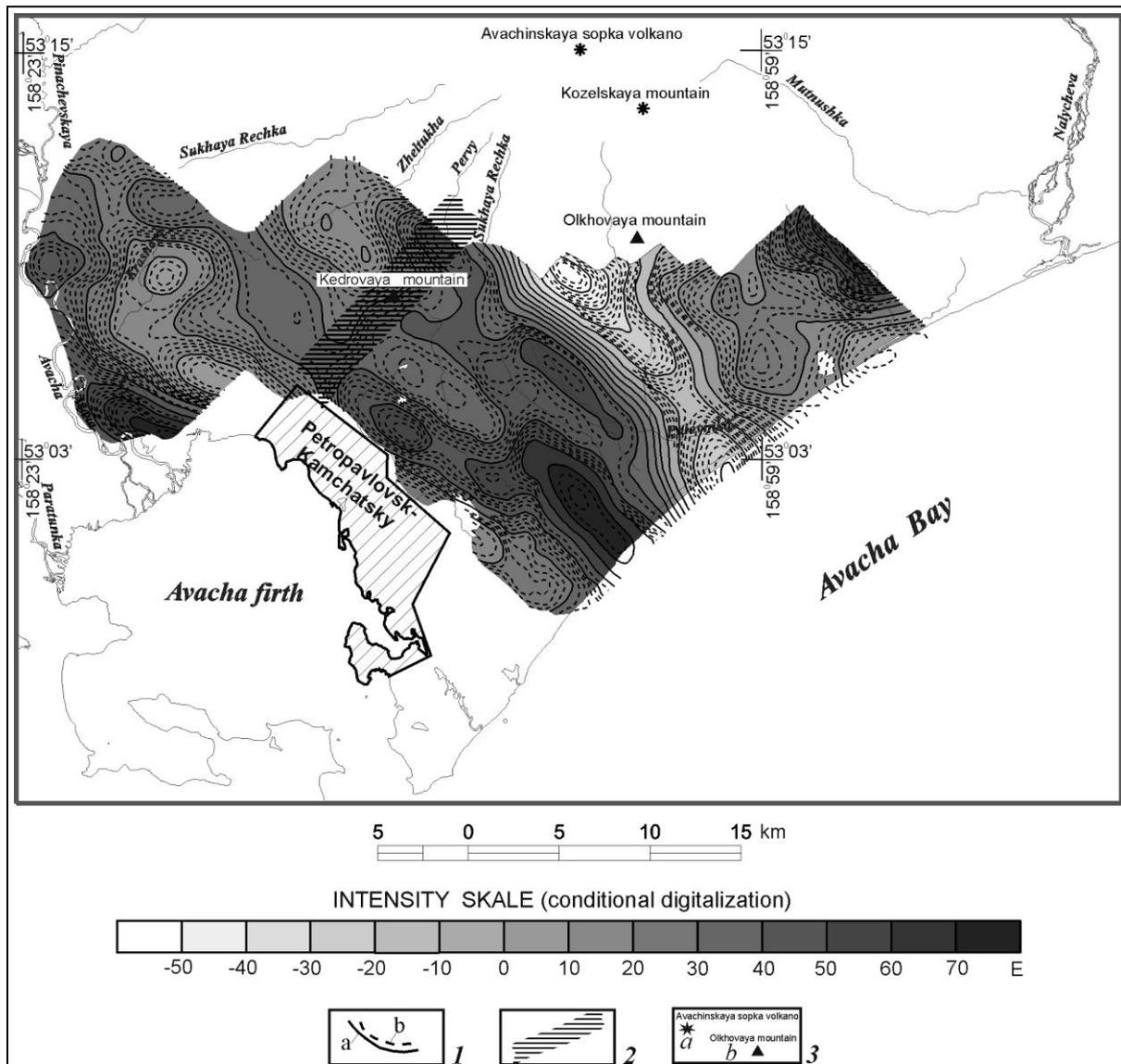


Fig. 8 The map of transformed gravity field. The second vertical derivative - 10 harmonics (conditional level). Legend: 1 – V_{zz} isolines and their values in Eotvos (E): in 10 E (a), in 2 E (b); 2 – the zone of a deep fracture of north-eastern extension; 3 - volcanoes (a), peaks (b)

Kamchatka for a long time. There are also other quite numerous examples of hydrothermae operation in the national economy of Kamchatka Krai. But heat sources of a larger scale and reserves are necessary for heat supply of big cities, such as Petropavlovsk-Kamchatsky, Yelizovo, Vilyuchinsk. Thermal waters of geopower plants on the Mutnovsky field of vapor-hydrothermae (FVHT) which passed a process cycle can be such sources, for example. But hot water delivery for long distances is connected with great technical difficulties and thermal heat losses in the pipeline. Obviously, it is possible to say the same about the perspectives of operation of Verkhne-Paratunka TWD where considerable reserves of hydrothermae aren't used yet.

The use of peripheral chamber deep heat under Avacha volcano which is located in a close proximity to city agglomeration of Kamchatka capital is very attractive.

As early as in 70-s of previous century the possibility of use of magma chamber heat of Avacha volcano was considered [8]. And in 2006 the academician of RAS A.S. Fedotov with coauthors offered the detailed analysis of the geological and geophysical surveys results given an idea of the

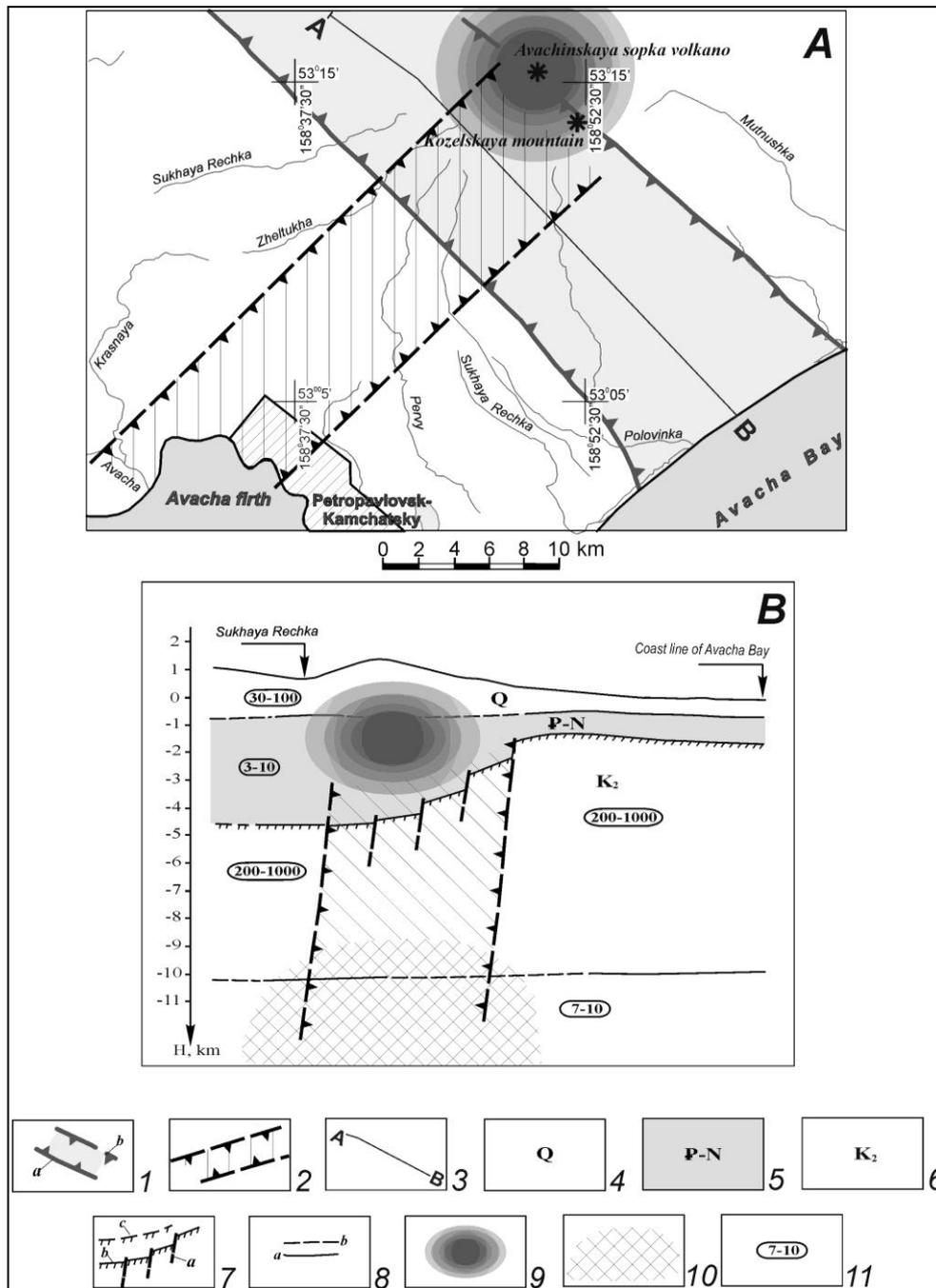


Fig. 9 Supposed position of peripheral magma chamber in plan (A) and section (B). Legend: 1 – boundaries of the Avacha graben according to MTS: proved (a), supposed (b); 2 – the zone of a deep fracture according to MTS and gravimetric survey of 1:50 000 scale; 3 – the line of a geologic-geophysical section; 4 – complex of quaternary (Q) fragmental, coarse, volcanogenic proluvial and cover formations; 5 – Paleogene-Neogene (P-N) volcanogenic-and-sedimentary and volcanogenic formations; 6 – Upper Cretaceous (K₂) intensively dislocated, metamorphosed terrigenous and volcanogenic-and-siliceous formations; 7 – tectonic dislocations (a), roof of upper Cretaceous formations: proved (b), supposed (c); 8 – geoelectric boundaries: proved (a), supposed (b); 9 – peripheral magma chamber and the zone of its temperature influence according to model simulation (according to S.A. Fedotov et al. [38]); 10 – upper crust chamber [9]; 11 – value of specific resistance of the layers in Ω m

existence of unconsolidated magma chamber under Avacha volcano and estimated the depth of its bedding and approximate sizes. Main calculations and ideas are given in a collective work [38] where heat reserves of the rocks heated by volcano magma chamber from the moment of its origin up to the present time is estimated. Geologic-geophysical opportunities for using heat energy of heated rocks hosting magma chamber for heat- and power supply of Petropavlovsk-Kamchatsky city were analyzed.

In the publication the development of underground geothermal circulating system (the fracture heat exchanger) by means of inclined wells drilling about 3,5 km in depth is presented in the work. To extract rocks heat it is supposed to develop an artificial circulating system (heat boiler) in a near-chamber zone. Deep wells and fracture heat exchangers are a part of it. Water is injected into one well (wells system), and then water heated during heat exchange process arrives on a surface through another well or wells system. In the work the authors offer the allotment to drill the wells of the first stage. Its location is planned to be in the south-western part of the volcano foot. The experiment of deep Earth heat extraction according to the specified (above-noted) scheme was realized in France [42].

Theoretical calculations show that except the peripheral chamber with "a wall temperature" of 900°C there is also a near-chamber region of its high-temperature influence [38]. It is expected that at the depth of 3-3,5 km the bottom-hole temperature in a zone of a thermal boiler(chamber) (in a zone of hot dry rocks) will be about 200-350°C. These data were obtained due to theoretical calculations. But, it is supposed that for the expensive deep well (wells) which sinking (development) is planned to be in a high-temperature aggressive medium the experimental data are required. Therefore, the complex of geophysical works (geoelectric prospecting of MTS and gravimetric prospecting) is recommended to specify the model of Avacha volcano structure, in particular, to specify the location of the peripheral chamber and morphology of its roof, to search potentially possible zones of interaction of the mentioned chamber and meteoric waters. It is supposed that these works results will allow choosing the optimum place to sink the first well, defining its inclination, sinking azimuth, and drilling depth reducing if possible.

Positive experience of such works (MTS, gravimetric prospecting) made in 2004-2010 in the region of Mutnovsky FVHT shows high complex effectiveness. It is enough to note that as a result of studies the allotment to drill deep wells was localized (the temperature on a bottom hole is 200-300°C and more) to open a high-temperature energy carrier – superheated steam-and-water mix (SWM). The first Geo-1 well has opened great inflow of SWM [43]. Further drilled four wells were rather productive, too.

There is a positive experience of electric prospecting works of MTS near the Koshelevsky field of vapour-hydrothermae and in other places which are characterized by a high-temperature energy carrier.

4. Suggestion on geophysical works sinking

Offered geophysical methods are planned to be realized at the southern-south-western flanks of Avacha volcano and its slopes. Taking into account the available experience of works the scheme of field observation realization is shown in Fig. 10. Geophysical methods recommended for realization will be considered.

Areal survey of MTS:

The works of MTS at 0,5×0,5 km survey grid is provided to study a junction zone of volcano-tectonic depression with the Avacha graben. Allotment square will be ~ 35 km². Its north-western part coincides with the place offered by the academician S.A. Fedotov and his coauthors [38] for a deep wells drilling. Periods range of registered variations of MT-field is planned to be chosen taking into account the guaranteed section studying at the depth of 10-15 km with registration of four field components (E_x , E_y , H_x , H_y). V5 SYSTEM-2000 "Phoenix Geophysics" technology using the hardware-software complex *MTU-5A* (*MTU-5*; *MTU-2E*) of Canadian is supposed to be used during the work.

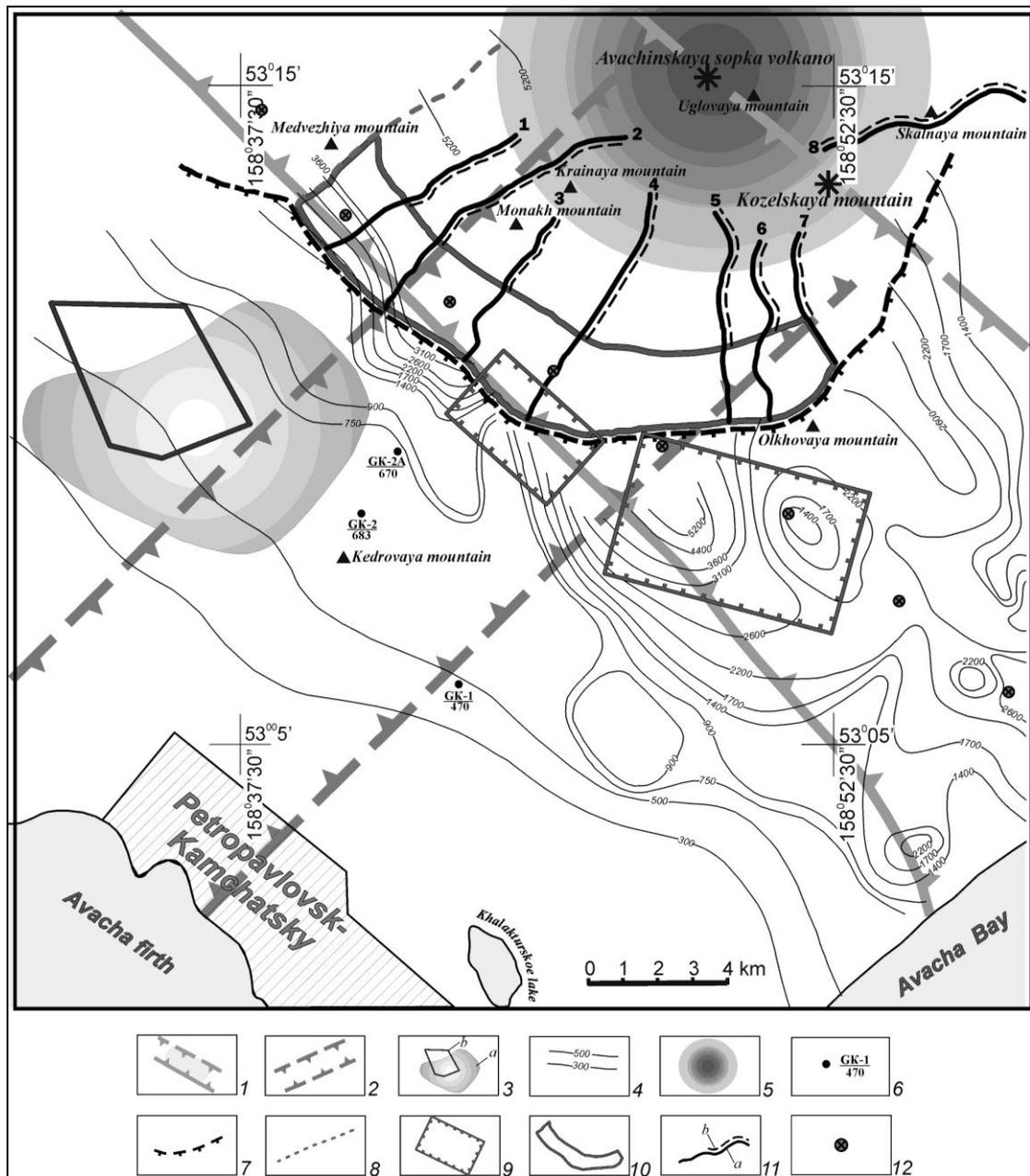


Fig. 10 Review scheme of geophysical work recommended for the implementation. Legend: 1 – boundaries of the Avacha graben according to MTS; 2 - deep fracture zone according to MTS and gravity survey of 1:50 000 scale; 3 - the contours of fresh groundwater field "Bystrinskoye" by a complex of geophysical data (a), allotment with measured water reserves (b); 4 – depths isolines up to UCRC; 5 - supposed position of the peripheral chamber and the zone of its temperature influence (according to S.A. Fedotov et al. [38]); 6 - drilled wells: the numerator is well number, the denominator is the depth in meters up to the UCRC roof; 7 - northern boundaries of MTS work (2×2 km) and gravimetric survey of 1:50 000 scale; 8 - MTS profile developed at a pitch of 0,5 km; 9 – allotments contours of detailed electric survey recommended according to the results of geophysical studies made in 1990-1991. Recommended geophysical works: 10 - works allotment of MTS at ~ 0,5×0,5 km grid; 11 - two-dimensional survey: gravimetric survey in the conventional level at a pitch of observation of 200 m along the profile (in-line) (a), works AMTS-MTS at a pitch of observation of 500 m (b); 12 – points of GMTS

MTS works along some profiles:

These works are planned to be organized in those places on volcano's slopes where the work at 0,5×0,5 km grid is impossible. In total about 8 profiles with a total length about 30 lin km are planned to be developed. Station interval on a profile is 0,5 km. The technology of the work and the equipment are provided to be the same as during the work of MTS at 0,5×0,5 km grid.

According to the obtained data as a result of two-dimensional numerical simulation of MT-field 2D-geolectric models (2D-sections) covering the depths to 10-15 km will be developed. A set of sections obtained on each profile will be the initial material for the first iterations to realize three-dimensional modeling. It is expected that 3D-geolectric model of Avacha volcano will be the final result. Geoelectric heterogeneities characterized by various level of specific resistance, including relatively low-resistivity allotment identified with the peripheral chamber will be determined here.

Deep magnetotelluric sounding – DMS:

It is supposed to fulfill the MTS profile along the Avacha graben, orthogonally to Avacha Bay coastline for quantitative assessment of influence of regional induction effect (coastal effect) [29, 31] on the results of magnetotelluric sounding (Fig. 10). MT-field registration will be carried out as deep magnetotelluric sounding – DMS. Except the analysis of coastal effect the picture of conductivity distribution at great depths covering the lower part of the Earth crust and upper mantle in a zone of a modern volcanism will be corrected. These data [30] will be basic information during 3D-modeling taking into account available results of MTS obtained earlier along the regional profile. Proposed length of the profile is ~ 20 km, station interval is 2-3 km. Five components registration of MT-field - Ex, Ey, Hx, Hy, Hz is to be provided. Periods range of the registered MT-field will be presumably from 0,0025 to 5000-10000 s (400 ÷ 0,0001 Hz).

Gravimetric survey along some profiles:

According to the available data the zone of the peripheral chamber is characterized by the increased density. According to one data it is 2,75 g/cm³ [12], to other - 2,88 g/cm³ [11]. It is close to the density index of rocks of an average-basic composition. Background value of the vicinity is 2,45-2,6 g/cm³ [12]. Such density ratio promotes gravimetric survey to specify the position of the peripheral chamber and its possible apophyses.

Gravimetric survey on several profiles with a general length about 50 lin km (Fig. 10) with a station interval of 200 m is recommended to realize on a studied area.

Density two-dimensional models calculated along each profile will be the basis to make three-dimensional geodensity model (3D model). The materials of gravimetric surveys of 1:50 000 and 1:200 000 scales are planned to be used for background values of GF, for neighbor and remote flanks of a studied allotment. It is expected that 3D-geodensity model of Avacha volcano will be the final result of the gravimetric works where density heterogeneities will be determined, including the specifying of the peripheral chamber position.

5. Complex interpretation of geologic-geophysical data. Expected results

On basis of new data the integrated interpretation of the whole geologic-geophysical data is provided, including predecessors materials given from production reports, scientific publications, monographs. The results of some geophysical methods complement each other, and complexation greatly narrows the ambiguity of geological interpretation typical for each method.

The results of gravimetric survey to study its density heterogeneities is planned to be widely used creating the schemes and models of Avacha volcano structure. Geoelectric data of MTS will be used to choose high-resistivity objects identified with intrusive bodies, and anomalously low-resistivity – with melting zones (partial melting?) and allotments saturated by high-temperature fluids.

It is supposed that the main results of the work will be:

- specified position of the peripheral chamber and its roof morphology;
- determination of potentially possible zones of interaction of the high-temperature chamber periphery with meteoric waters;

- choosing the optimum place to sink the first deep parametric well with the determination of its inclination, azimuth and depth.

Nowadays Research geotechnological center (RGC FEB RAS) has organized a thermometric monitoring in the south-western part of Avacha volcano foot. The monitoring is carried out using the equipment set in 25 shallow wells (20 m) cased by polyethylene pipes. The development of 3D-thermohydrodynamic and 3D-thermofluiddynamic models is planned to be done according to the monitoring results. It is expected that these models will promote geological interpretation of geophysical materials and more accurate estimation of thermal resources of observed system. Besides, the obtained models will be used to develop the generalized three-dimensional geologic-geophysical model of a studied area.

It should be added that analysis results of a complex geologic-geophysical data and results of a conductive thermal flow modeling [44] indicate high degree of prospectivity of thermal resources development of magma chamber. Completed technical and economic assessment of thermal resources development of the Avacha magmatogene geothermal system [44] demonstrates its economic efficiency.

Foreign experience of exploitation of Earth deep heat in a zone of active volcanism in Iceland, Nicaragua, and in some other countries gives promise that similar technologies will be finally applied in Kamchatka.

References

- [1] Aprelkov S Ye and Olshanskaya O N 1986 The Report on the Synthesis of Gravimetric Survey Materials of 1:200 000 Scale to Make Structural-Formational Map of South Kamchatka of 1:500 000 Scale. (Yelizovo: Ielizovo geophysical expedition) 303 p
- [2] Aprelkov S Ye and Olshanskaya O N 1989 Tectonic classification of Central and Southern Kamchatka according to geological and geophysical data *J. Pacific geology* **1** pp 53-65
- [3] Aprelkov S Ye and Svyatlovsky A Ye 1989 Avacha bay origin in Kamchatka *J. Pacific geology* **4** pp 108-11
- [4] Rotman V K 1984 *Metallogene of the USSR. Metallogenic Map of Kamchatka, Sakhalin and the Kuril Islands of 1:1 500 000 Scale* (Leningrad: A P Karpinsky Russian Geological Research Institute) pp 32-55
- [5] Kiryukhin A V, Manukhin Yu F, Fedotov S A, Lavrushin V Yu, Rychkova T V, Ryabinin G V, Polyakov A Yu and Voronin P O 2015 Geofluids of Avacha-Koryak volcanogenic basin, Kamchatka *Russ. J. Geoecol. Engineer. Geol. Hydrogeol. Geocryol.* **5** pp 400-14
- [6] Aprelkov S Ye 1963 Old valley of Kamchatka Avacha river *Geological and Geophysical Surveys in Volcanic Belts* ed K N Rudich (Moskva: Publishing house Academy of Sciences of the USSR) pp 88-92
- [7] Shteinberg G S and Zubin M I 1963 About magma chamber depth under Avacha volcano *Reports of Academy of Sciences of the USSR* **152** (4) pp 968-71
- [8] Fedotov S A, Balesta S T, Droznin V A, Masurenkov Yu P and Sugrobov V P 1977 About the application of magma chamber heat of Avacha volcano *Bulletin of Volcanological Stations* **53** pp 27-37
- [9] Balesta S T, Gontovaya L I, Kargopoltseva A A, Pushkarev V G and Senyukov S L 1988 Seismic model of Avacha volcano (according to RCM-DSS) *J. Volcanology and seismology* **2** pp 43-53
- [10] Gontovaya L I, Efimova Ye A, Kostyukevich S A and Piip V B 1990 Seismic section of Avacha volcano according to RM-DSS *J. Physics of the Earth* **3** pp 73-82
- [11] Zubin M I and Kozyrev A I 1989 Gravitational model of Avacha volcano structure (Kamchatka) *J. Volcanology and seismology* **1** pp 81-94
- [12] Sheimovich V S and Sidorov M D 2000 The structure of the volcanic belt basement *Russ. J. Volcanology and seismology* **5** pp 68-75
- [13] Popruzhenko S V and Aprelkov S Ye 1997 Basement structure of the Avacha depression *Russ. J. Volcanology and seismology* **6** pp 15-24
- [14] Anosov G I, Bikkenina S K, Popov A A, Sergeev K F, Utnasin V K and Fedorchenko V I 1978 *Deep Seismic Sounding of Kamchatka* ed A A Popov and G S Gnibidenko (Moscow:

- Nauka) 130 p
- [15] Popov A A, Anosov G I, Argentov V V, Bikkenina S K, Zlobin T K, Nemchenko G S and Petrov A V 1987 The Earth crust structure according to seismic data *Geologic-Geophysical Atlas of Kuril-Kamchatka Island System* ed K F Sergeev and M L Krasny (Leningrad: A P Karpinsky Russian Geological Research Institute) p 18
- [16] Nurmukhamedov A G, Nedyad'ko V V, Rakitov V A and Lipat'ev M S 2016 Lithosphere boundaries of Kamchatka according to the earthquake converted-wave method *Russ. J. KRAUNTS Bulletin. Sciences about Earth* **1** (iss. 29) pp 35-52
- [17] Balesta S T and Gontovaya L I 1985 Seismic model of the Earth crust of the Asia-Pacific zone of transition in the region of Kamchatka *J. Volcanology and seismology* **4** pp 83-90
- [18] Pak G and Nurmukhamedov A G 1982 *Report of the Special Complex Geological-Geophysical Survey Carried out in the South Kamchatka According to the Program of Earthquakes Forecast in 1980–1982 (Avacha Party to Forecast the Earthquakes)* (Yelizovo: Ielizovo geophysical expedition) 283 p
- [19] Nurmukhamedov A G and Smirnov V S 1985 Results of deep electromagnetic investigations in the South Kamchatka *Geology and Minerals of the Koryak-Kamchatka Folded Region (materials of the 5th Kamchatka geol. conf.)* ed A I Pozdeev et al (Petropavlovsk-Kamchatsky: STS-mountain) pp 69-82
- [20] Rokityansky I I and Kurnosov A L 1983 Geomagnetic-variation profiling on modular measurement in Kamchatka *J. Earth's magnetism and aeronomy* **23** (6) pp 1029-32
- [21] Rokityansky I I, Kilikyan V A, Vardanyants I L, Rokityanskaya D A and Baltazhi P V 1984 Avacha anomaly of electrical conductivity *J. Geophysical journal* **6** (5) pp 65-72
- [22] Nurmukhamedov A G and Netyesov Yu P 1984 *The Report on the Geophysical Work Carried out by the 2nd Ketkinsky Party in 1982-84. Pinachevsky Area* (Yelizovo: Ielizovo geophysical expedition) 86 p
- [23] Nurmukhamedov A G and Popruzenko S V 1989 *The Report on the General Search of Thermal Waters in the North-Western Part of Petropavlovsk Geothermal Region. The 1st Stage - Geophysical Survey of 1987-1989. Yelizovo Party. Book I - the Report Text* (Yelizovo: Ielizovo geophysical expedition) 256 p
- [24] Nurmukhamedov A G and Zheltukhin A S 1992 *The Report on the Preparation of Geophysical Basis to Search Thermal Waters (Forward-Works) in the South-Eastern Part of Petropavlovsk Geothermal Region in 1988-90 and in the North-Eastern Part in 1990-1992. Mokhovskaya Party. Book I - the Report Text.* (Yelizovo: Ielizovo geophysical expedition) 312 p
- [25] Moroz Yu F, Nurmukhamedov A G and Loshchinskaya G A 1995 Magnetotelluric sounding of the Southern Kamchatka crust *Russ. J. Volcanology and seismology* **4-5** pp 127-38
- [26] Mishin V V 1996 Deep structure and Earth crust types of the south Kamchatka *Russ. J. Pacific geology* **1** pp 110-9
- [27] Yudin M N and Kazantsev V V 1977 The program of calculation of magnetotelluric field in two-dimensional layered mediums containing local heterogeneities (E- and H-polarization) *Software Library for Processing of Geophysical Data on the Computer. Electrical Survey* (Moscow: AURIGeophysics) 36 p
- [28] Moroz Yu F and Nurmukhamedov A G 1998 Magnetotelluric sounding of Petropavlovsk geodynamic ground (survey loop) in Kamchatka *Russ. J. Volcanology and seismology* **2** pp 77-84
- [29] Okulesky B A, Porai-Koshits A M, Smirnov V S and Nurmukhamedov A G 1988 Deep geoelectric structure of the Kamchatka south *Asthenosphere According to a Complex of Geophysical Methods* ed L L Van'yan (Kiev: Naukova dumka) pp 72-83
- [30] Moroz Yu F, Nurmukhamedov A G and Moroz T A 2001 Deep geoelectric model of Petropavlovsk geodynamic ground in Kamchatka *Russ. J. Physics of the Earth* **6** pp 58-66
- [31] Moroz Yu F and Moroz T A 2011 Numerical three-dimensional modeling of magnetotelluric field of Kamchatka *Russ. J. Physics of the Earth* **2** pp 64-73
- [32] Wannamaker P E, Stadt J A and Rejol A 1987 A stable finite element solution for two-dimensional magnetotellure modeling *Geophys. J. R. Astr. Soc.* **88** pp 277-96
- [33] Moroz Yu F and Gontovaya L I 2003 Deep structure of the region of the Avacha-Koryak volcanoes group of Kamchatka *Russ. J. Volcanology and seismology* **4** pp 3-10
- [34] Van'yan L L and Butkovskaya A I 1980 *Magnetotelluric Sounding of Layered Grounds* (Moscow: Nedra) 228 p

- [35] Berdichevsky M N 1968 *Electric Prospecting by Magnetotelluric Profiling* (Moscow: Nedra) 256 p
- [36] Ashirov N G, Berdichevsky M N, Dubrovsky V G, Il'amanov K, Kramarenko S A, Nepesov K N and Yakovlev A G 1989 New data on a deep geoelectric section of the East-Turkmen syncline *J. Physics of the Earth* **4** pp 96-101
- [37] Masurenkov Yu P 1985 Thermogenous structures and search criteria of hidden hydrothermal systems in the neighborhood of Petropavlovsk-Kamchatsky *J. Volcanology and seismology* **4** pp 68-82
- [38] Fedotov S F, Sugrobov V M, Utkin I S and Utkina L I 2007 Application of magma chamber heat of Avacha volcano and rocks surrounding it for heat and power supply *Russ. G. Volcanology and seismology* **1** pp 32-46
- [39] Pashkevich R I, Pesotsky D G, Balykov A A and Mamaev D V 2014 Magnetotelluric survey in the southern sector of the Avacha geothermal system *Russ. J. Mining Research and Information Bulletin (Scientific and Technical Journal) Kamchatka* (Moscow: Mining book) **2** (Fascicle) pp 47-53
- [40] Vorozheikina L A 1995 *Experimental-Methodical Work on the Application of Geological-and-Structural, Geophysical and Remote Search Criteria of Thermal Water in Closed Areas. The Report of Avacha Thematic Hydrogeological Party about the Results of Work Carried out Petropavlovsk Area in 1989-1995* (Kamchatgeolkom) 258 p
- [41] Serezhnikov A I and Lazarev V A 2000 *The Report on the Results of Hydrogeological Additional Appraisal with Engineering-Geological and Geo-Ecological Studies and Mapping of 1:200 000 Scale Carried out on the Territory of the Sheet N-57-XXVII in 1991-1996. Books I, II - the Report Text* (DC "Kamchatnedra") 386 p
- [42] Baumgärtner J, Jung R, Gerard A, Baria R and Garnish J 1996 The European HDR project at Soultz-sous-Forêts; stimulation of the second deep well and first circulation experiments *21st Workshop on Geothermal Reservoir Engineering* (Stanford: Stanford University Publishing House) p
- [43] Nurmukhamedov A G, Chernev I I, Alekseev D A and Yakovlev 2010 *Russ. J. Physics of the Earth* **9** pp 15-26
- [44] Pashkevich R I, Trukhin Yu P 2014 Perspectives of commercial development of the resources of near-surface magma chambers of Kamchatka and Kuril Islands *Mining Research and Information Bulletin (Scientific and Technical Journal) Kamchatka* (Moscow: Mining book) **2** (Fascicle) pp 7-21