Tolmachevsky active magmatic center (South Kamchatka) and its heat-power capacity as estimated by deep geophysical surveys

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Abstract. The structure of the Earth’s crust and upper mantle has been estimated by using geologic-geophysical cross-sections developed along two orthogonal geophysical profiles in the area of the Tolmachevsky active magmatic center. Comprehensive geophysical data have revealed the existence of an intrusive massif of predominantly intermediate-medium-felsic composition whose formation is accounted for by the presence of powerful heat flows and local melting sites. A swarm of small earthquakes reported in 1987-1988 was triggered by the advance of magma in the zone of the assumed eruptive fissure. Meteoric waters interact with the high-temperature media through the infiltration zone, which results in intense hydrothermal activity including the formation of steam-hydrothermal occurrences. The area of the proposed intrusive body is a promising zone for a high-temperature geothermal reservoir.

1. Introduction
Kamchatka hosts a number of well-known hot springs and thermal aquifers developed quite long ago and used to supply heat to small settlements and greenhouse facilities. Some of the steam-hydrothermal occurrences have been involved in the power industry of the peninsula. Thus, in 1966, the Russia’s first geothermal power plant (Pauzhetskaya GeoPP) yielding 12 MW was built in the southwest of the Kamchatka peninsula, in the Pauzhetka River valley. Mutnovskaya GeoPP with capacity of 50 MW was set in operation in 2000 at the northern slopes of the Mutnovsky volcano. Somewhat earlier, the Verkhne-Mutnovskaya GeoPP was developed, which is still effective yielding 12 MW.

Some other possible reservoirs are of certain interest to be used to improve the power balance of the region. Particularly interesting in this respect are the high-temperature Bannye springs located 60 km west of Petropavlovsk-Kamchatsky (Figure 1). This area include the local groups of Malye Banny and Bol’she-Bannye springs. Further south, Karymchinskie thermal springs occur in the valley of the Pravaya Karymchina River. Thirty km west of the mentioned sites, Apachinskie springs discharging thermal waters are located. All the above occurrences are distributed within the area of the Tolmachevsky Active Magmatic Center (TAMC) [1, 2], virtually outlined in Figure 1. Researchers are particularly attracted by the Bol’she-Bannoye deposit springs of steam-water mixture (SWM) where
Figure 1. Tectonic chart for Koryaksko-Kamchatskaya folded area [1, 2]. 1 – Koryaksko-Zapadno-Kamchatskaya folded zone; 2 – Vostochno-Kamchatskaya subzone of Olyutorsko-Vostochno-Kamchatskaya folded zone; 3 – (a) Kuril-South-Kamchatka island-arc volcanic zone, (b) South-Kamchatka volcanic belt; 4 – Structures of folded zones and their designations: BL – Bol’sheretetsk uplift, SK – Sredinno-Kamchatsky horst-anticlinorium; horsts: UN – Unkanovichsky, GP – Gan’isko-Petropavlovsky, PR – Pribrezhnaya; 5 – Pre-Late Cretaceous metamorphic units; 6 – Intrusive bodies of predominantly intermediate and felsic composition; 7 – Margins of the Nachikinskaya (Krutogorovsko-Petropavlovskaya) transverse dislocations zone; 8 – Tsental’nokamchatskaya deep suture zone; 9 – Major faults: (a) outcropping and (b) buried by overlying rocks; 10 – (a) Volcanic-tectonic structures: Kr – Karymskinskaya, Pt – Plotnikovskaya, Kt – Khotyskyaya, Ah – Ahomtenskaya, (b) contours of the Goryachaya Hill paleovolcano; 11 – Boundaries (a: observed, b: assumed) of crustal and mantle-crust anomalously low-resistivity zones, allocated according to MTS, and their numbers: 1 – zone of melting and circulation of hydrothermal solutions – Tolmachevskoye active magmatic center, 2 – zone of melting in the area of Gorely, Mutnovskaya Sopka, Vilyuchinskaya Sopka volcanoes; 3 – zone of intense fluid saturation in the area of Avachinskaya-Koryakskaya group of volcanoes; 12 – Volcanoes: (a) Extinct, (b) Active; 13 – Hydrothermal springs and deposits: 1 – Malye Banny, 2 – Bol’she-Banny, 3 – Karymschinskie, 4 – Apachinskaya, 5 – Verkhne-Zhirovoye, 6 – Skalistye, 7 – Karymschinskaya, 8 – Verkhne-Paratunskaya, 9 – Sredne-Paratunskaya, 10 – Nachikinskaya; 14 – Observation points and their numbers on the Apacha-Mutnaya profile: (a) ECWM, (b), MTS, (c) Combined points of ECWM-MTS; (e) geo-density modelling line; (d) points of ECWM on the Opala-Vahil’ profile.

The superficial temperature exceeds 100°C. In 1960s it was intended build a geothermal power plant here, which failed however for a number of reasons [1]. The area also hosts many other occurrences and pounds of thermal waters. The development of the Bol’she-Banny area of SWM and the other
high-temperature springs for the power industry of the region would favor the use of its natural resources and economic advance in the region.

Two orthogonal regional geophysical profiles cross the central area of TAMC. One of them is oriented north-east and runs from the Opala Mountain to the Vahil’ River (Opala-Vahil’ profile), while the second one is set from the Apacha Village to the Mutnaya Bay (Apacha-Mutnaya profile) and oriented north-west. In 1987-1993 the area along the two profiles was studied by the Elizovskaya geophysical expedition (EGPE PGC “Kamchatgeология”) whose members carried out deep geophysical surveys using the methods of earthquake converted-waves (ECWM) and magnetotelluric sounding (MTS). The works were conducted under the long-term research program aimed at studying the structural features of the Earth’s crust and upper mantle in the area of recent volcanic activity and intense seismicity. Details of the researches and results were published in scientific reports and papers [3-5]. Later on, data acquired by ECWM were re-interpreted [6], which was followed by depth geologic density modelling carried out along the Opala-Vahil’ profile using the most advanced software. Updated results were used to develop a geologic-geophysical model for the structure of the Earth’s crust and upper mantle [2].

This paper presents the results of interpretation of ECWM, gravimetric surveys and MTS obtained along the Apacha-Mutnaya profile, as well as those of the comprehensive analysis of geologic-geophysical data available for the area of TAMC and its periphery.

2. Geologic-geophysical review and geological setting of the study area
A detailed review of the geologic-geophysical researches conducted in the region has been presented in [1, 2], while the results of the geophysical surveys carried out along the Opala-Vahil’ profile are available in [2]. Here we mention that the Apacha-Mutnaya profile cuts the area studied by gravimetric and aeromagnetic surveys at a scale of 1:200 000, most its part being also covered by 1:50 000 aeromagnetic survey. A 1:200 000 geologic survey was conducted all over the study area. Tectonic zoning of South Kamchatka according to geological and geophysical data was given in [7]. Further on, a tectonic chart was developed for the whole area of the Koryaksko-Kamchatskaya folded area including products of the deep Earth’s crust structure at a scale of 1:1 000 000 [8]. A part of this chart is presented in Figure 1.

Geologically, the profile passes through two folded zones from north-west to south-east: the Koryaksko-Zapadno-Kamchatskaya folded zone, and the Vostochno-Kamchatskaya subzone of the Olyutorsko-Vostochno-Kamchatskaya folded zone. The western area hosts a sector of the Tsentral’no-Kamchatskaya deep suture zone where the island-arc units (paleo-arcs) were attached to Paleo-Kamchatka in Eocene [9, 10]. Northeast of the area is covered by the Nachikinskaya zone of transverse dislocations (ZTD) featuring fractures of NW-strike. The area also hosts a vast zone of areal volcanism extending from the latitude of the Paratunka and Karymchina River valleys in the north (Figure 1) to the Lopatka Cape in the south. Note that one of the rare sites showing maximum concentration of cinder cones is located in the Tolmachev Dale area where the Apacha-Mutnaya geophysical profile has a peculiar curving [11].

Several volcanic-tectonic structures (VTS) are distinguished in the study area. Thus, the Apacha-Mutnaya profile runs close to the western boundaries of the Karymshinskaya VTS, and cuts the Akhomsentenskaya VTS in the south. Central part of the Karymshinskaya VTS hosts a Pliocene paleovolcano whose midpoint is featured by the Goryachaya Hill (Figure 1). Some thermal occurrences including the Bol’she-Bannoe area of steam-water mixture (SWM) are distributed along the periphery of the paleovolcano.

Results of ECWM surveys conducted over the entire Koryaksko-Kamchatskaya folded area were used to develop the depth charts reaching the Mohorovicic (Moho) and Conrad boundaries and the roof of the consolidated crust [6]. In a previous paper [2] we included a portion of a depth chart extending down to the Moho boundary and depicting the profiles’ intersection area that includes an isometric localized sector sized ~60 × 70 km showing the thickening of the Earth’s crust up to 40-45 km against background values of 32-35 km. Sharp local crust thickening is accounted for by the
enlargement of the interlayer between the crust and the upper mantle in areas hosting active volcanoes and zones of ash-fall volcanism [12]. According to some estimates [1, 2, 13], this area is characterized by a high degree of permeability between the mentioned lithosphere layers, as well as by the presence of a high heat flow. Reaching the upper layers of the crust, the heat flow becomes localized and its density increases, which results in the formation of a local melting zone. This concept quite agrees with the conventional notions of the spatial-temporal geodynamic correspondence [14] of extent, depth and age of the melting sites within the crust and upper mantle beneath the areas of active volcanism.

Active modern geodynamic processes occur in South Kamchatka. In 1987-1988, a swarm of small ($M \leq 5$) earthquakes was reported in TAMC [15] (Figure 2), which was later named the Tolmachevskaya epicentral zone (TEZ) [1]. Spatially, the TEZ matches the sector of maximum concentration of cinder cones and the zone of high permeability. The depth of hypocenters is about 8 km. Earthquakes were likely triggered by magma movements along the weakened zone [2], which is indirectly evidenced by the fact that the TEZ is confined to the assumed melting zone. In general, the area considered is located in the north of the long-lived magma center of South Kamchatka [11, 16].

![Figure 2](image-url)  
**Figure 2.** A swarm of earthquakes in the Tolmachevskaya epicentral zone (TEZ) (based on [1, 2]). 1 – Boundaries (a - Observed, b - Assumed) of the Tolmachevsky active magmatic center; 2 – epicenters of local earthquakes (data for 1987-1988); 3 – Volcanoes: (a) Extinct, (b) Active; 4 – Observation points and their numbers on the Apache-Mutnaya profile: (a) ECWM, (b) MTS, (c) Combined points of ECWM-MTS), (d) Points of ECWM on the Opala-Vahil profile.

Miocene intrusions of intermediate and felsic composition (Figure 1) are likely to have common roots with a large intrusive massif formed in the weakened zone. Based upon the geodynamic correspondence concept [14], we can assume that the intrusive was formed at latest in Early Miocene or even in Late Oligocene.

It should be noted that MTS carried out along the Opala-Vahil’ profile (depth range of 10-35 km) revealed a remarkable conductivity anomaly in the area of TAMC of 5 ohm·m against the background of 500-1000 ohm·m. The authors [3, 4, 13] associate this anomaly with the circulation of hydrothermal solutions in the Earth’s crust, and with the occurrence of melting zones. According to the geologic-geophysical model developed for the structure of the Earth’s crust and upper mantle along the Opala-Vahil’ profile [2], an Earth’s crust unit bearing intrusive bodies of mafic and ultra-mafic composition has been distinguished in the central part of TAMC. In the east, at a depth range of 8-27 km, this unit
is joined by an intrusive massif of predominantly intermediate-medium-felsic composition whose branches stretch towards the upper layers through the weakened zones. Some of these branches reach the surface and have been weathered (Figure 1).

3. Methodology

Field surveys along the Apache-Mutnaya profile were conducted using the standard ECWM [17]. Three-component seismic-wave recording was performed at 43 points spaced 2.5–5 km from each other. Recording of seismic events was made in the ‘upon detection’ mode. Each recording period lasted about 30 days, which allowed acquiring sufficient dataset necessary for distinguishing the wave conversion boundary. Field equipment were the ‘Tcherepakha’ (‘Turtle’) complexes composed of sensors ASS-6/12 and seismic-recorders SK-1P. Details on the methods of field surveys as well as on the techniques for interpretation and re-interpretation of ECWM data are available in [6]. The up-to-date variant of the ECWM cross-section along the Apache-Mutnaya profile combined with the deep density model is presented in Figure 3.

Two-dimensional density modelling was performed using the results of gravimetric survey conducted at a scale of 1:200 000 (Figure 3). It was aimed at studying the patterns of rock density distribution in the Earth’s crust and upper mantle in the area of TAMC and its periphery. Similar modelling was performed earlier for the Opala-Vahil’ profile [2]. In both cases, a specific skeleton for the model was constructed using the interlayer boundaries and fractures inferred from the ECWM data [6]. When modelling, input values of the upper-layer density were set as those of the outcropping geologic bodies. Density values of the deeper layers were taken from the available literature [18]. The Geosoft software package (GMSYS, Oasis Montaj, Grav/Mag Interpretation, 3D Euler, MAGMAP filtering) was used for the modelling. Details on the modelling technique are discussed in [19, 20].

Field MTS surveys were performed by the standard technique [3] using a digital electro-prospecting station DES-2. There were 56 sounds in total. At half of those sounds four components (E_x, E_y, H_x, H_y) of magnetotelluric field (MT-field) within the period range of 0.1-100 s were recorded. Additionally, a fifth component (H_z) was recorded at every second site matching the ECWM datapoint. For the matched datapoints, the range of MT-field variations was extended to 1000 s. Initial interpretation of the MTS data was carried out at EGPE PGC “Kamchatgeologiya”.

Inversion was solved using the software developed by M.N. Yudin [21] at the Geophysical Fields Laboratory of the Institute of Volcanic Geology and Geochemistry (IVGG FEB RAS) headed by Dr. Yu. F. Moroz. For the modelling we used the regional-longitudinal curves because they are almost free of the induction effect occurring in the basins of the Sea of Okhotsk and Pacific Ocean [22]. Results of MTS were summarized in [3].

Prior to the modelling, six zones were singled out along the Apache-Mutnaya profile. These zones are characterized by the MTS curves similar in their forms (conformal) but differing by the resistivity levels. Resistivity variations of the curves are associated with lateral inhomogeneity of the upper layers of the cross-section, which results in the occurrence of galvanic effects. To suppress the latter, average curves were calculated for each zone, that were further used for two-dimensional modelling. To develop the initial model for the Apache-Mutnaya profile, the earlier normal depth model of Southern Kamchatka was used [3]. The process of iterative fitting of the model elements resulted in satisfactory agreement between the average experimental and calculated MTS curves developed for each zone (Figure 4). The model (Figure 5) reasonably correlates with the results of geoelectrical modelling carried out at the Opala-Vahil’ profile [3, 4] in the profiles’ intersection area.

By the results of complex interpretation of the acquired data, a depth geologic-geophysical model has been developed (Figure 6) defining the following: the Mohorovicic boundary (M index), distinguishing the Earth’s crust from the upper mantle; an interface separating the upper and lower mantle – Conrad boundary (K_2); roof of the consolidated crust – crystalline basement (K_3), and roof of the Upper Cretaceous rock unit (F). Besides, some other boundaries have been distinguished in the Earth’s crust (K_1, K_3).

The layers of the Earth’s crust that lie between the boundaries correspond to (top-down): Cenozoic
\textbf{Figure 3}. Deep density model along the Apache-Mutnaya profile. 1 – Seismic boundaries according to ECWM data: (a) Moho boundary; (b) and (c) Other seismic boundaries identified in the Earth’s crust; 2 – ECWM points and their numbers; 3 – Boundaries of the blocks and the average density values for them (g/cm$^3$).

volcanogenic-sedimentary cover, Mesozoic rock unit, granite-metamorphic ("granitic") layer, and granulite-basitic ("basaltic") layer. Upper-mantle layer is depicted at the bottom of the model. The whole series is intersected by crustal and mantle-crustal faults dividing the Earth’s crust and upper mantle into isolated blocks.

Major geological structures intersected by the profile are referenced above the model, as well as their boundaries and names. Detailed legend of the model is given in the figure caption.

It should be noted that geologic-geophysical models developed for the Apache-Mutnaya and Opala-Vahil’ [2] profiles have shown general similarities when both profiles intersects each other (Figure 7).

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Figure 4. Comparison of experimental (1) and calculated (2) MTS curves for the geoelectric model in Figure 5.

Figure 5. Two-dimensional geoelectric model of the Earth’s crust and upper mantle along the Apacha-Mutnaya profile. 1 – Blocks, characterized by different levels of resistivity in ohm-m; 2 – Location of the MT sounds and their numbers; 3 – Modelling line and its length in kilometers; 4 – Boundaries of the modelling zones (a) and their numbers (b).
Figure 6. Geologic-geophysical model along the Apacha-Mutnaya profile. 1 – Layer interfaces inferred by ECWM data: (a) distinct, (b) assumed, matching: roof of the Upper Cretaceous rock unit (F), roof of consolidated crust (K₀), interface between upper and lower crust (K₂) (Conrad boundary?), Mohorovicic boundary (M), other seismic boundaries within the Earth’s crust and upper mantle (K₁, K₃, M₁); 2 – Roof of the Upper Cretaceous rock unit by MTS data; 3 – Fractures: (a) according to the ECWM data, and (b) according to geological data; 4 – Vertical area defined according to the results of density modelling – associated with the axial part of the Tsentral’no-Kamchatksaya deep-seated suture zone; 5 – Zone of no-correlation of exchange boundaries; 6 – Cenozoic volcanogenic-sedimentary rocks; 7 – Mesozoic rocks; 8 – Hydrothermally altered Mesozoic-Cenozoic rocks; 9 – Top layer of metamorphic rocks predominantly occurring in greenschist and epidote-amphibolite facies; 10 – Granite-metamorphic (“granitic”) layer of the upper crust; 11 – Granulite-basitic (“basaltic”) layer of the lower crust; 12 – Upper mantle; 13 – Estimated position of the transition layer between the crust and upper mantle; 14 – Earth’s crust unit bearing numerous intrusive bodies of mafic and ultramafic composition; 15 – (a) Intrusive massif, and (b) its branches of predominantly intermediate, medium-felsic composition; 16 – Intrusion of mafic composition; 17 – Less-density zone (3.22 g/cm³ against the background of 3.33 g/cm³) in the upper mantle, matching the anomalous low-resistivity area (5 ohm·m against the background of 500-1000 ohm·m); 18 – High-density zone (3.4 g/cm³) of presumably peridotite-eclogite composition in the upper mantle; 19 – Crustal and mantle-crust conductivity anomalies (2-20 and 5 ohm·m, respectively, against the background of 500-1000 ohm·m); 20 – Orientation of (a) the presumable heat flows and (b) magmatic melts; 21 – ECWM stations and their numbers.
4. Interpretation of the geologic-geophysical model

If compared to the other regional profiles developed within the Koryaksko-Kamchatskaya folded area, extension of the Apache-Mutnaya profile is quite limited making it impossible to distinguish any systematic variations in this sector of the Earth’s crust and upper mantle. However, deep structure
pattern inferred from the ECWM data was complemented by the results of density modelling (Figure 3). Thus, the boundaries interpreted by ECWM that could not be tracked for long distances, were further extended as boundaries separating layers and blocks of different density. In general, the analysis of the acquired data has shown that the results of the density modelling are quite consistent with the conventional knowledge of the density features of the lithosphere strata.

Figure 6 shows the variations of the Earth’s crust thickness along the profile from 30-33 km at the periphery of the model up to 44-46 km in its central sector. Following the conventional definitions, authors keep using the term Conrad boundary to denote the K2 boundary separating the upper and lower layers of the Earth’s crust. Besides, we put the layers named “granitic” and “basaltic” within quotation marks, implying their conventionality. Morphology of the Conrad boundary is commonly similar to that of the Moho discontinuity. “Granitic” layer thickness exceeds that of the “basaltic” one. According to the classification by Kosminskaya [23], this type of crust is referred to as the continental one. As it has been already mentioned in Section 1, a drop of the Moho boundary in the center of the model can be accounted for by an interlayer between the Earth’s crust and the upper mantle. The thickness of this interlayer has not been exactly determined, but if we assume its roof to be the K3 boundary, it would be about 10 km. The layer is gradually thinning out south-east, while its northwestern stretch is constrained by the Tsentral’no-Kamchatskaya deep suture zone. Rock densities in the interlayer zone are almost similar to those of the “basaltic” layer bottom.

However, a lower-density zone (2.95 g/cm\(^3\) against the background 3.0 g/cm\(^3\)) appears to the northwest of the interlayer’s center. Further northwest appears a zone of anomalously low specific resistivity (SR) (5 ohm-m against the background 500-1000 ohm-m) at depths of 30-40 km, matching the local low-density zone (3.22 g/cm\(^3\) against the background 3.33 g/cm\(^3\)). This anomalous body was likely formed as a result of the lithospheric units’ interaction during the attachment of island-arc units to Paleo-Kamchatka.

The bottom of the model shows isolated sectors (Figure 3) whose density varies from 3.27 g/cm\(^3\) to 3.33 g/cm\(^3\), which correlates with the density of the upper mantle rocks – peridotites [24]. But in the area of the maximum depth of the Moho boundary (ECWM datapoints 27-36), appears a high density site with value of 3.4 g/cm\(^3\). Ringwood [24] considers such value close to the boundary density between peridotites and “unaltered eclogites” (3.4-3.65 g/cm\(^3\)). This site is assumed to belong to a zone of eclogization of the upper-mantle rocks, formed as a result of ocean lithosphere subduction beneath the continent [2, 13]. Subduction processes preceded the Eocene attachment of the relatively light island-arc blocks to the folded zone of Paleo-Kamchatka.

The top of the cross-section shows the roof of the consolidated crust (K0) – crystalline basement tending to gradually dip from 4-5 km at the model periphery down to ~ 10 km and even deeper in its central area. Structurally, this sector matches TAMC. K0 morphology is generally similar to that of the Conrad and Moho boundaries. However, at point numbers 30-33 of the ECWM and at about 4 km depth, there seems to be another boundary showing features quite similar to those of K0. So far we believe that given the general trend of K0 lowering in the center of the model, the TAMC area hosts a branch of the Earth’s crust unit bearing intrusions of mafic and ultramafic composition (Figure 6), whose roof is depicted as the K0 boundary. Here, above the K0 boundary, within the depth range of 4-5 km (Figure 5), a low-resistivity body has been defined (30 ohm-m against the background 100-1000 ohm-m) whose occurrence can be accounted for by the presence of a heated intrusion and/or a zone of hot water circulation. The massif of the crystalline basement is intersected by a boundary of uncertain nature marked as “K0”?

Highlighting part of the model is an Earth’s crust unit bearing abundant intrusions of mafic and ultramafic composition. In the gravity survey, this place is marked by a peak of the Ag values (Figure 3). We suggest that intrusion of ultramafic melts occurred through a weakened zone formed both, at the boundary between the crust and the mantle and within the crust itself. ECWM depth profile [6] reveals here a zone with no correlation with seismic boundaries, whereas the two-dimensional model shows an area with isolated spots of varied density. A sub-vertical zone cuts the horizontally stratified
portion of the Earth’s crust and then spreads as numerous fractures at depth of about 30 km. The fractures are pathways for the penetration of mantle matter in the form of magma melts, high-temperature fluids, and high heat flows into the upper crust.

South-east of that unit (ECWM datapoints 20-29), the density corresponds to rocks of intermediate and medium-felsic composition. In the Δg diagram, this place is featured by an abrupt drop of the gravity field (Figure 3) complicated by local small-range peaks. From the dataset available we can infer the occurrence of a large intrusive massif composed mostly of diorites and granodiorites, with a number of branches, some of which are exposed at the surface (Figure 1). In the cross-section, the area of this massif is characterized by the lack of seismic boundary correlation and anomalously low resistivity (2-20 ohm-m against the background values of 500-1000 ohm-m). The formation of such massif is presumably related to an intense heat flow and the occurrence of local melting zones [1, 2, 13].

As mentioned above, the rising of magmatic melts to the upper layers of the Earth’s crust is accompanied by a swarm of small earthquakes (Figure 2), the latter being likely triggered by the formation of a local tension systems typical of volcanic earthquakes [25]. However, there is no active volcanoes in the vicinity of the swarms. So, this can be the case of the formation of eruptive fissures or, probably, the reactivation of existing ones [25] in the area of upper Pleistocene-Holocene [11] ash-fall volcanism. It should be noted that the swarm is elongated in sub-latitudinal direction and enters the zone of the co-oriented large Opalinsky-Gorelovsky fault previously identified by gravimetric surveys [7].

The study area presents favorable environments for the accumulation of groundwater [26, 27] or aquifers that interact with the high-temperature melting sites and heated intrusions through the infiltration zones. These factors contribute to the intense hydrothermal activity in the vicinity of the intrusive body, which is evidenced by numerous occurrences of hydrothermally altered rocks in areas of the Bannye, Karymchinskie, Apachinskie hydrotherms, and other zones over TAMC. The most outstanding here is the Bolf’she-Bannoe occurrence of steam-water mixture located at the northern sides of a paleovolcano whose center is featured by the Goryachaya Hill (Figures 1 and 7).

5. Conclusions
- Two-dimensional density modelling has been performed along the Apache-Mutnaya profile for the first time. Interlayer boundaries and fractures inferred from the ECWM data served as a specific skeleton for the density model. Based upon the data acquired by ECWM, gravimetric surveys, MTS and other methods, a geologic-geophysical model has been developed for the structure of the Earth’s crust and upper mantle representing the updated location of major lithosphere boundaries: Mohorovicic and Conrad discontinuities, top of consolidated crust, and others. Earth’s crust along the profile has been referred to the continental type. Geologic-geophysical models developed for the Apache-Mutnaya and Opala-Vahil’ profiles show general similarity in the area of the profiles’ intersection point.
- The model is dominated by a high-density object: an Earth’s crust unit with abundant intrusions of mafic and ultra-mafic composition, and an intrusive massif of predominantly intermediate-medium-felsic composition. Formation of this unit is related to a dynamically active permeable zone existing between the crust and the upper mantle and is accounted for by the presence of powerful heat flows and sites of local melting.
- A swarm of small earthquakes reported in 1987-1988 is related to the area hosting numerous cinder cones. The earthquakes are assumed to have been triggered by magma movements in the area of an eruptive fissure of sub-latitudinal strike.
- The area of the intrusive massif is favorable for the accumulation of groundwater that can be heated and can interact with the rocks through infiltration.
- Analysis of the geologic-geophysical dataset acquired for the TAMC area shows that a high-temperature geothermal resource is possibly located at the subsurface of the study area. The area of the discovered intrusive body should be considered the most promising with regard to its geothermal
potential (Figures 6 and 7).

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