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To cite this article: A.G. Nurmukhamedov and M.D. Sidorov 2019 IOP Conf. Ser.: Earth Environ. Sci. 249 012041

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Deep structure and geothermal potential along the regional profile set from Opala Mountain to Vakhil’ River (Southern Kamchatka)

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Abstract. Here we present results of geologic-geophysical studies of the Earth’s crust and upper mantle carried out along a regional profile set from Opala Mountain to Vakhil’ River. Complex data interpretation allowed developing a geologic-geophysical depth model. High potential capacity of geothermal resources has been reported in the area of the Avacha group of volcanoes and Tolmachevsky active magmatic center hosting several springs discharging thermal-mineral waters and Bol’she-Bannoe field of steam-water mixture.

Keywords: Mokho boundary, Avacha Volcano, intrusive massif, thermal-mineral waters.

1. Introduction
In 1989-1992 Elizovskaya geophysical expedition (EGPE PGC Kamchatgeologiya) carried out geophysical researches using the earthquake converted-wave method (ECWM) and magnetotelluric sounding (MTS) along the regional profile from the Opala Mountain to the Vakhil’ River (Opala-Vakhil’ profile) (Fig. 1). Researches were conducted within the framework of the long-term 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. The profile length is 230 km.

Upon data processing and interpretation, a depth seismic cross-section was developed [1], two-dimensional geoelectric [1, 2] and density [1] models were calculated. Complex interpretation results allowed developing a geologic-geophysical model for the structure of the Earth’s crust and upper mantle [1].

Further analysis of the results has revealed notable thickening of the Earth’s crust at certain sectors of the deep ECWM cross-sections acquired for the Koryak-Kamchatka folded zone [3], which is most commonly observed in the western sectors of the profiles cutting the Kamchatka Peninsula. We therefore performed re-interpretation of ECWM results for certain profiles including the Opala-Vakhil one [3]. Results of interpretation as well as those of density modeling are presented below.

Opala-Vakhil’ profile runs from south-west to north-east across the south-eastern area of the Kamchatka Peninsula (Fig. 1) that hosts numerous active volcanoes and occurrences of thermal-mineral waters. Of specific interest are thermal water resources that can be potentially developed to meet the power supply demands of the region. Thus, the south-western part of the profile cuts the Tolmachevsky active magmatic center (TAMC) [4] where Apachinskie, Bannye and Karymchinskie thermal-mineral springs are located. Notable is the Bol’she-Bannoe field of overheated waters (steam-water mixture, SWM) which temperatures locally reach the values above 100°C even in the shallow levels.

Research results on TAMC, as well as those on the Bannye and Karymchinskie springs were reported in [4]. The above areas belong to the zone of areal volcanism showing abundant hydrothermally altered rocks. In late 1960s, hydrothermal metamorphism and structural localization of thermal water fields were studied by members of the Institute of Volcanology Yu.P. Trukhin, E.N. Erlikh, V.V. Petrov. Hydrothermal processes may account for a number of promising ore manifestations of the gold-silver formation commonly named as “Karymshinskiy ore cluster”.
Development of the Bol’she-Bannoe SWM occurrence and other thermal-mineral waters is quite urgent for the industry of the region.

North-eastern sector of the profile cuts the Avacha group of volcanoes (AGV) that appears
quite attractive as a promising heat source for the south-eastern Kamchatka industry. This issue was challenging for many researchers [5, 6]; detailed geologic-geophysical survey of the AGV area was reported by Nurmuhammedov [7].

2. **Brief review of regional geophysical researches and geological setting of the study area**

The area covered by the Opala-Vakhil’ profile was studied by regional gravimetric and aeromagnetic surveys at a scale of 1:200000, most its part being also covered by 1:50000 aeromagnetic survey. Structure-formation map was compiled [9], papers on the tectonics of Central and Southern Kamchatka were published [10, 11]. MTS-based depth chart was constructed including the Mohorovicic boundary, Conrad discontinuity and roof of the consolidated crust [3]. Figure 2 shows a depth-chart fragment reaching the Mokho boundary.

In the structural plan, the profile passes through thee folded zones (Fig. 1) from west to east: Koryak-West-Kamchatka zone, East-Kamchatka subzone of the Olyutorsko-East-Kamchatka zone, and Near-ocean zone. Western sector of the area hosts the Central-Kamchatka deep suture zone represented by a line-elongated structure stretching out for more than 1300 km along the peninsula. Quite extensive is the Krutogorovsko-Petrovlovsk zone of transverse dislocations (ZTD) featuring fractures of NW strike. The area is mostly composed by the ejecta of Cainozoic volcanism that form several volcanic-tectonic structures (VTS). Central part of the Karymshinskaya VTS (Fig. 1) hosts a...
Pliocene [12] paleovolcano which midpoint is featured by the Goryachaya Hill. Malye Bannyte, Bol’she-Bannyte and Karymchinski thermal-mineral springs are distributed along the periphery of the paleovolcano (Fig. 1).

South Kamchatka shows active modern geodynamic processes. Study area is located in the northern part of the long-lived center of current endogenous activity [12] recently evidenced by an earthquake swarm reported in 1987-1988 in the south-east of TAMC. This swarm was named the Tolmachevskaya epicentral zone (TEZ) [4].

MTS results revealed a contrast conductivity anomaly (5 Ohm·m against the background of 500-1000 Ohm·m) within the depth range of 10-35 km beneath TAMC. This anomaly is associated with hydrothermal solutions circulating in the Earth’s crust, as well as with the occurrence of melting zones [1, 2, 13]. Depth of hypocenters is about 8 km. Earthquakes are triggered by magma movements along the weakened zones, which is indirectly evidenced by the fact that TEZ is confined to the assumed melting zone. For this area, a long-lived magma center (LMC) is assumed [13] whose bottom reaches the depth where a permeable zone is located between the Earth’s crust and upper mantle [4]. In Figure 2, this area is featured by notable lowering of the Mokho boundary (40-45 km against the background of 32-35 km). Local crust thickening is accounted for by the enlargement of the interlayer between the crust and mantle in areas hosting active volcanoes and in areal volcanism zones. Thickness of this interlayer may reach 20 km [14]. For LMC, the Mokho boundary is denoted by the horizon separating the upper mantle from the bottom of the interlayer [3] where a permeable zone was formed thus allowing the dense “power flow” [13] to create the melting sites. Outcropping Miocene intrusions of granodiorites (Fig. 1) are likely to have common roots with a large intrusive massif formed in the weakened zone [4]. Based upon the geodynamic correspondence concept [15], huge geological objects occurring at great depths should be older than those found above them and genetically linked to them. Following this concept, we can infer that the above intrusive massif was formed at latest in early Miocene.

Further north-east the profile intersects an anomalously low-resistivity zone [2] in the area of the Avacha group of volcanoes and the namesake graben. Here, ECWM data [3] revealed a zone of lacking correlation of seismic boundaries (ZLCSB) (Fig. 2). Recent MTS surveys conducted at the slopes of Avacha Volcano have revealed that certain fragments of the low-resistance zone show extremely low levels of specific resistivity (SR) ranging from a few hundredths to a few Ohm·m. A number of hypotheses have been put forward on the origin of the above anomalies [16]. For instance, high conductivity of the Avacha graben can be accounted for by the circulation of thermal waters within the mass of volcanogenic-terrigenous rocks [17], whereas the low-Ohm anomalies reported in particular sites at the volcano neck basement can be attributed to the temperature effect of the peripheral magmatic chamber [6].

It is quite possible that the extension of the graben into the Avacha Bay basin is favorable for seawater (~0.3 Ohm·m) penetration into the depression zone, which contributes to the formation of the high-conductivity anomaly. This is evidenced by the strong induction effect generated by the current channeling in the Avacha graben and parametrically exceeding the “coast effect” produced in the deep-see trench [13, 19, 20]. The above pattern was supported by the fact that the R-3 well drilled 7 km offshore from the Avacha Bay intersected a cold aquifer which composition was quite similar to that of the seawater.

It should be noted that discovering the conductivity anomalies related to the high-temperature energy carriers and occurring against the background of low-Ohm environments is quite a complicated challenge that requires complex interpretation of geologic-geophysical data accumulated for years of researches carried out on the Avacha group of volcanoes including those of 2016-2017 [16, 21].

3. Methods
Standard ECWM and MTS were applied when carrying out field surveys. ECWM [22] was performed by three-component seismic-wave recording with the station interval of 3-5 km. Techniques of field observations, interpretation and re-interpretation of ECWM data are described in paper [3]. Figure 3
shows the present variant of interpreting the ECWM cross-section along the Opala-Vakhil' profile combined with the density model.

MTS was performed with the station interval of 2-3 km. Four components of the magnetotelluric (MT) field in the period range of 0.1-100 s were recorded. In sites where MTS datapoints coincided to those of ECWM, the range of recorded periods was extended to 3000 s. Methods of field surveys, interpretation of MT-data, as well as the resulting two-dimensional geoelectric section were earlier described in publications [1, 2].

To study the patterns of rock density distribution in the Earth’s crust and upper mantle, two-dimensional density modeling was performed using the results of gravimetric survey conducted at a scale of 1:200 000 (Fig. 3). Boundaries and faults inferred by the results of ECWM data reinterpretation were chosen to serve as specific frame for the model. Input values of the upper-layer density were determined by those of the outcropping geologic bodies. Density values of the deep layers were obtained from the available literature [23]. So, the following density values were taken: Upper Cretaceous sediments - 2.67 g/cm³, granite-metamorphic (“granitic”) layer – 2.6-2.8 g/cm³, lower crust (“basaltic”) layer – 2.80-3.07 g/cm³, and the upper mantle ~3.30 g/cm³. These values were used as input data for initial iterations. Modelling details are described in [24, 25]. In contrast to the previous modeling procedure [1] carried out using the Isaaev Software [26], the present model was calculated by the Geosoft package (GMSYS, Oasis Montaj, Grav/Mag Interpretation, 3D Euler, MAGMAP filtering). Basic difference between the two was the option that allowed us to input local relief and approximate the geologic body shapes by irregular contours.

By the results of complex interpretation, a depth geologic-geophysical model was developed (Fig. 4) distinguishing the Mokho boundary (M index), an interface separating upper and lower mantle – Conrad boundary (K2), roof of the consolidated crust – crystalline basement (K0), and roof of the Upper Cretaceous rock unit (F). Besides, some other boundaries were distinguished in the Earth’s crust (K1, K3) and in the upper mantle (M2).

The following layers of the Earth’s crust lie between the boundaries (top-down: Cainozoic volcanogenic-sedimentary cover, Mesozoic rock unit, granite-metamorphic (“granitic”) layer, and granulite-basitic (“basaltic”) layer. Upper-mantle layer is displayed at the bottom of the model. The whole series is intercepted by crustal and crust-mantle faults dividing the Earth’s crust and upper mantle into isolated units.

4. Results and discussion
It should be noted that similar to Shapiro M.N. and Soloviov A.V. [28] authors of the present paper consider most of the Koryak-Kamchatka folded zone to be formed at the active continental margin by two major processes: subduction of oceanic lithosphere beneath the continental plate and collision. These processes account for the deformation of the attached island-arc units, as well as for the so-called jump-shift of the subduction zone eastward towards the ocean. The attached units consequently become an integral part of continental lithosphere. To the east of the peninsula there lies a Kamchatka deep trench from which the seismic focal zone (SFZ) is subducting beneath the continent. Depth to the SFZ ranges from 120 km in the northeast of the profile to 230-250 km in the southwest [18].

Kola superdeep borehole (1970-1991) drilled in the Fennoscandian Shield proved invalid the Earth’s crust geophysical model dividing the crust into upper (granitic) and lower (basaltic) layers [29, 30]. Drilling results have shown that major seismic boundaries occurring in the upper strata of the crystalline crust are attributed to the changes of the elastic properties of the environment caused either by the rock composition differences or variations of their physical state such as loosening and disruption.

Taking into account the data available on the superdeep borehole, authors of the present paper conventionally denote the K2 boundary as Conrad boundary dividing the Earth’s crust into the upper and lower parts. However, we use the terms “granitic” and “basaltic” layers enclosing them within quotation marks because we believe them to bear certain conventionality.

According to the model developed, thickness of the Earth’s crust varies along the Opala-
Fig. 3. Density model along Opala - Vakhil' profile. 1 – ECWM seismic boundaries (a – Mokho boundary; b – boundary in the upper mantle; c, d – other seismic interfaces distinguished in the Earth’s crust); 2 – ECWM points; 3 – unit frames and average density values (g/cm³).
Fig. 4. Geologic-geophysical model along Opala-Vakhi' profile. Names and frames of structures above the model are given according to Fig. 1 and papers [10, 11] (marked by *).
Symbols for figure 4: $l$ – ECWM observation sites and their numbers; 2 – layer interfaces inferred by ECWM data: distinct (a), assumed (b), matching: the top of the Upper Cretaceous rock unit (F), roof of consolidated crust ($K_0$), interface between upper and lower crust ($K_2$) (Conrad boundary?); Mokho boundary (M), other seismic boundaries within the Earth’s crust and upper mantle ($K_1$, $K_5$, $M_1$); 3 – roof of the Upper Cretaceous rock unit by MTS data; 4 – ruptures inferred by ECWM data; 5 – ZZCSB; 6 – Cainozoic volcanogenic-sedimentary rocks; 7 – Mesozoic rocks; 8 – polymict melange; 9 – hydrothermally altered Meso-Cainozoic rocks; 10 – top layer of metamorphic rocks predominantly occurring in greenschist and epidote-amphibolite facies; 11 – granite-metamorphic (“granitic”) layer of the upper crust; 12 – granulite-basitic (“basaltic”) layer of the lower crust; 13 – upper mantle; 14 – Earth’s crust units: Nalychevsky (a), Shipunsky (b); 15 – Earth’s crust unit bearing numerous intrusive bodies of mafic and ultramafic composition; 16 – intrusive massif (a) and its offshoots (b) of predominantly medium-felsic composition; 17-19 – intrusions in the upper crust and volcanogenic-sedimentary layer: mafic (17), intermediate (18), medium-felsic (19); 20 – yet unfading chamber beneath the Goryachaya Hill paleovolcano; 21 – CMRW-detected objects beneath Avacha Volcano: a – upper-crust magma chamber, b – lateral chamber, c – assumed cooled intrusive body; 22 – loosening zones (a = 2.84 g/cm$^3$, b = 2.78 g/cm$^3$ against background 2.9-3.0 g/cm$^3$) in the lower crust matching the low-conductivity zone (60 Ohm-m against background 500-1000 Ohm-m); 23 – high-density zones (3.4 g/cm$^3$) in the upper mantle, bearing presumably peridotite-eclogite composition; 24 – crustal conductivity anomalies (5-15 Ohm-m against background 500-1000 Ohm-m) – areas of hydrothermal solution circulation, and zones of melting and partial melting; 25 – orientation of the presumable heat fluxes; 26 – interlayer between the Earth’s crust and upper mantle; 27 – ascent of magmatic melts and fluids, 28 – Bol’she-Bannoe field of SWM

Vakhil’ profile ranging from 22 km in the northeast to 34-40 km in the southwest. Moho boundary shows quite stable morphology with a maximum dip down to 43-44 km (Fig. 2-4) in the western sector of the profile (points 7-14). Upper crust also shows a thickening pattern from the northeast (12 km) to the southwest (20 km), reaching maximum values of 27-28 km in the area of the Karymshinskaya VTS (points 12-23). Morphology of the Conrad boundary is generally similar to that of the Mokho discontinuity.

Thickness of the upper crust exceeds that of the lower crust along the entire profile, showing similar values only in the near-ocean sector. I.P. Kosminskaya [31] classifies the Earth’s crust as the continental type. However, northeastern extremity of the profile shows elevation of the Moho boundary from 24 up to 22 km. Thickness of the upper and lower crust here are almost similar, but given the general thinness of the crust, here we may suggest the occurrence of the sub-continental crust. Geologically, this area hosts the Shipunsky horst (Fig. 1) modelled as a namesake high-density (2.94-3.03 g/cm$^3$) crust unit (Fig. 4) formed in late Miocene by the attachment of an island-arc body (Shipunsky terrain [1]) to the Kamchatka Peninsula [32]. West of the Shipunsky unit, Nalychevsky one is distinguished in the Earth’s crust, showing similar density parameters. Gravity field morphology [33] suggests that the above two units are probably constituents of the single Shipunsky terrain. Units are separated from each other by the loosening zone (2.7-2.9 g/cm$^3$) that is also notable for the lack of correlation of seismic boundaries, and matches the Vakhil’ graben-syncline [11] of the northwestern strike. The loosening zone was likely formed after the attachment of the island-arc unit in Miocene.

Top of the cross-section shows distinct “granitic” layer roof ($K_0$) that is the shallowest in the central sector of the profile (points 24-37) in the area of the Pribruzhny horst (Fig. 1). Here, a layer of metamorphic complexes is recognized occurring mostly within the greenschist and epidote-amphibolite facies. Levels above the “granitic” layer roof almost universally (except for the northeastern extremity) host an Upper Cretaceous rock unit overlapped by Cainozoic sediments. In the northeastern part of the cross-section, the Cainozoic unit is bedded immediately upon the crystalline basement. In the upper portions of the crust the density model shows units that can be identified as intrusive bodies of mafic, intermediate and medium-felsic composition. Density features of the model
bottom (Fig. 3) generally correspond to those of the upper mantle (3.25-3.37 g/cm³) matter, i.e. peridotites [34]. However, at the depth of 40 km and deeper, two high density areas have been revealed (points 9-17 and 48-53) showing values of 3.4 g/cm³. A.E. Ringwood [34] considers such values close to the borderline indices between peridotites and “unaltered eclogites” (3.4-3.65 g/cm³). The above areas are assumed to belong to the zones of eclogization of the upper-mantle rocks formed as a result of ocean lithosphere subduction beneath the continent in the east of the study area, and paleo-subduction in its west. Occurrence of the paleo-subduction zone is supported by the concept on the dipping of the Central-Kamchatka deep suture zone (Fig. 1) at a westward slope [13].

Earth’s crust and upper mantle are ruptured by mostly crust-mantle faults that function as unit margins. In the southwest of the profile (points 9-13), a high-density (2.89-3.00 g/cm³) unit is distinguished featured by an intense peak of the Bouguer anomaly (Fig. 3). By the dataset available, this object is interpreted as an Earth’s crust unit bearing numerous intrusive bodies of mafic and ultramafic composition. West of this anomaly, below the K₀ seismic boundary, at depths of 3-8 km, the model shows an offshoot resembling a sole injection – sill. The considered sector of the profile cuts a dynamically active zone between the Earth’s crust and upper mantle (see Chapter 1). Maximum heat fluxes are confined to the faults framing the unit (Fig. 4). East of the massive unit, ambient density corresponds to that of intermediate and medium-felsic rocks. Here we may assume the occurrence of a large intrusive massif dominated by diorites and granodiorites, with a number of offshoots some of them being affected by erosion (Fig. 1). In the cross-section, the area of this massif is characterized by the lack of seismic boundary correlation and anomalously low SR (5 Ohm·m against background values of 500-1000 Ohm·m). Formation of this massif is thought to be related to an intense heat flux and occurrence of local melting zones [4, 13].

Eastern part of the TAMC hosts a Pliocene paleovolcano which middle is distinguished by the Goryachaya Hill. Thermal-mineral waters discharge along the margins of the paleovolcano (Fig. 1). Earlier researchers [35] suggested a “hypothetic pattern” for the formation of hydrothermal systems, which claimed the occurrence of a high-temperature source – the so-called “fluid localization chamber” – at the depth of 6-8 km beneath the volcano. Processing of geologic-geophysical data shows that such a chamber is likely to exist, but at much shallower layers. Density model (Fig. 3) depicts a lenticular stratum (2.57 g/cm³) located at depth of 2.5-4 km beneath the paleovolcano. Based upon the experience of carrying out geophysical surveys at the Mutnovskoe occurrence of steam-hydrothermae where the melting zone was reported at depth of 3-3.5 km and deeper [36], we may assume the existence of a high-temperature pocket beneath the Goryachaya Hill within the depth range that covers the abovementioned lenticular stratum.

Area hosting thermal springs, particularly the Bol’she-Bannoe occurrence of SWM, is favorable for the accumulation of meteoric waters [35, 37]. Passing through the infiltration zone, these waters get affected by the high-temperature environment of the pocket. The SWM occurrence itself can be represented as natural chambers accumulating the overheated waters under great depths and high pressure conditions [36].

Central sector of the profile (points 24-37) intersects the Pribrzhny horst where the Plotnikovskaya VTS is located. Here, a layer of metamorphized units occurs in the upper part of the cross-section, mostly within the greenschist and epidote-amphibolite facies. Gradual elevation of the Conrad boundary up to 17-18 km has been reported. Roof of this elevated area, at depths of 18-28 km in the lower crust, shows some loosening zones (2.84 and 2.78 g/cm³ against background values of 2.9-3.0 g/cm³) that match a high-conductivity layer (60 Ohm·m against the background of 500-1000 Ohm·m [2]). This may evidence the existence of the supply area of an ancient volcano in the lower crust, manifesting itself at the surface as the Plotnikovskaya VTS.

ZLCSB has been distinguished in the area of the Avacha Volcano. This zone has been traced from the top horizon of the Earth’s crust till the upper mantle. ECWM surveys have failed to reliably identify and trace seismic boundaries down to the cross-section bottom. Distinct is only the K₀, which is the roof of the consolidated crust “underlying” the basement of the Avacha graben. This place is marked by the relative minimum of the gravity field (Fig. 3), whereas its density model shows notable
density drop in each of the crust and upper mantle layers. The zone has been also reported to gradually enlarge if we move from the Moho boundary towards the top layers of the crust, which is likely attributed to the weakened area where magmatic melts ascend to active volcanoes. Of specific interest is a peculiar fissure cutting the Earth’s crust and upper mantle. This fissure is orthogonal to the major structures of Kamchatka Peninsula (Fig. 2). The described zone hosts active and faded volcanoes as well as the recent Avacha graben [10]. It is possible that the whole weakened zone can be referred to the structures of the recent stretching.

Model developed by the data acquired using the correlation method of refracted waves (CMRW) shows an upper-crust magma chamber occurring at a depth of 12-18 km beneath the Avacha Volcano. Above this chamber there lies the zone of absorption of the high-frequency seismic signal spectrum that features the assumed peripheral magma chamber which bottom occurs 2-3 km below sea level [27]. Between the chambers, a cooled intrusion is assumed to occur at depths of 6-9 km (Fig. 4). The density model has distinguished a small unit (2.8 g/cm³) at depths of 7-9 km (Fig. 3) that matches the above intrusive body observed in the section plane.

General density distribution pattern in the area of the Avacha Volcano is quite irregular. Thus, a sub-vertical unit of 2.72 g/cm³ density and presumably intermediate composition has been reported immediately under the volcanic neck, whereas volcanogenic-terrigenous sediments of the Avacha graben show density drop down to the values of 2.45-2.51 g/cm³. Results of density modeling (Fig. 3) have not revealed any allocated unit that would match the assumed peripheral magma chamber. The upper-crust feeding chamber has been reported in the loosened zone showing density of 2.8 g/cm³ against the background values of 2.85-2.86 g/cm³.

Probably, at a certain period of geologic history, the now cooled intrusive body used to exist as an upper-crust magma chamber. Nowadays this intrusion serves as a sort of barrier hampering the magma migration from the upper-crust feeding chamber to the peripheral one. The weakened zone featured by a system of northeastern strike fractures beneath the Avacha graben could function as a conduit for magma migration [27]. Ascent of melts and fluids towards the upper-crust chamber might also occur through the above-described zone. The weakened zone itself is detected by a complex of geophysical methods including those defining it as a sub-vertical anomaly of electric conductivity (Fig. 4).

It should be noted that along with the seismic modelling of the Earth’s crust beneath the Avacha Volcano that was based upon the CMRW results, another model was developed by the data acquired by the deep seismic sounding (DSS) [6]. The models differ from each other. DSS results have shown that the crust under the Avacha Volcano is of “anomalous structure”, and its thickness compared to the adjacent areas is quite small making just 22-23 km. Supply area of the volcano is reported at a depth of 19 km and deeper, while the peripheral magma chamber occurs at depth of 1-4 km.

Based upon the results of ECWM, gravimetric surveys, and MTS, authors of the present paper prefer to favor the first variant of the model [27].

5. Conclusion

1. Upon re-interpreting the ECWM data acquired along the Opala-Vakhil’ profile [3] density modeling has been developed using a modified algorithm. Based upon the results of ECWM, gravimetric surveys, MTS and other geologic-geophysical observations [4] a geologic-geophysical model has been developed for the Earth’s crust and upper mantle showing the updated locations of major lithospheric boundaries: Mokho, Conrad, roof of consolidated crust, and others. Unknown elements of the Earth’s crust structure have been defined. The Earth’s crust occurring along the profile can be referred to the continental type, while that in the northeast of the profile – to the sub-continental one.

2. Western sector of the model has shown an Earth’s crust unit bearing intrusive bodies of mafic and ultra-mafic composition, associated with the dynamically active permeable zone located between the Earth’s crust and upper mantle. Eastern part of this structure is adjoined by an intrusive massif of intermediate-medium-felsic composition. It has been assumed that the formation of this
massif could have been associated with the strong heat flux and occurrence of the local melting zones. The intrusive massif is a constituent part of the Tolmachevsky active magmatic center which eastern sector hosts a Pliocene paleovolcano with the Goryachaya Hill in its middle. Springs discharging thermal-mineral waters, including the Bol’she-Bannoe field of SWM, are distributed along the rim of the paleovolcano. High-temperature pocket can be located 2.5-4 km beneath the Goryachaya Hill. The area hosting the hot springs is favorable for the accumulation of huge volumes of meteoric waters. Passing through the infiltration zone, these waters get affected by the high-temperature media of the pocket. The field of SWM can be presented as a number of natural chambers accumulating the overheated waters at great depths and under high pressure.

3. Central part of the model has shown elevation of the Conrad boundary up to 17-18 km. Top of this elevation sector entering the lower crust hosts the loosening zones that match the layer of increased electric conductivity. Such a set of geophysical anomalies may evidence the existence of the supply chamber of an ancient volcano in the lower crust, occurring at the surface as the Plotnikovskaya VTS.

4. ZLCSB has been distinguished in the area of the Avacha Volcano. Only the roof of the consolidated crust (K0 - boundary) matching the Avacha graben basement can be reliably traced. This sector of the model shows density drop in each of the layers constituting the Earth’s crust and upper mantle. Variability of density values has been observed for the area of the Avachinsky Volcano, which might evidence the complex structure of its flanks. ZLCSB has been reported to enlarge as we move from the Moho boundary to the upper layers of the crust. This zone is likely the pathway by which magmatic melts and fluids ascend towards active volcanoes. The extent of this zone is orthogonal to the northeastern structures of the Kamchatka Peninsula, so the zone itself can be referred to as a structure formed as a result of current stretching.

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