Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

The Geological Structure Features of Hydrothermal Discharge Zones at Pauzhetsky Geothermal Deposit According to Geophysical Data (South Kamchatka, Russia)

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Keywords: geothermal deposit, thermal field, gravity field, electric resistivity, anomalous magnetic field, permeable zone, hydrothermal solution.

ABSTRACT

The paper is devoted to the resolution of a fundamental scientific problem – understanding the setting and physical nature of hydrothermal discharge zones by an example of the Pauzhetsky hydrothermal system and the geothermal deposit of the same name. Two large thermal fields, Verkhne- (Upper-) Pauzhetsky and Vostochno- (East-) Pauzhetsky, were studied. It was earlier established that these thermal fields were confined to elevated tectonic or tectonic-magmatic blocks, within which active circulation of hydrothermal solutions and the mixing of waters of the lower and upper aquifers occurred (Structure ..., 1993). However, despite a large scope of activities and the long-term operation of the deposit, many fundamental problems have remained unresolved: the structure of the geothermal heat-carrier circulation zones, the physical nature of the sources of tectonic deformations, the location and type of heat source. To solve these problems, the staff of the Institute of Volcanology and Seismology of the Far East Branch of the Russian Academy of Sciences together with colleagues from Moscow, Irkutsk and other scientific centres of Russia conduct joint geological, geophysical, hydrogeochemical, mineralogical, and other studies of the discharge zones of the steam hydrothermal solutions at the Pauzhetsky geothermal deposit. The geophysical methods included the following: high-precision gravimetry, magnetometry, electric prospecting, and temperature measurement of soils. The interpretation of geological and geophysical data on East-Pauzhetsky thermal field established the presence of a medium or basic composition subintrusive body at a small depth (first tens of meters) (Feofilaktov et al., 2017). Discharge of deep-seated alkaline hydrothermal solutions is confined to the apical parts of this body. A block of compacted rocks in the centre of the geological structure and zone of increased fracture-pore permeability along the periphery of the block was also identified under the Verkhne-Pauzhetsky thermal field. In general, new data on the structure of the upper water-confining layer and the upper aquifer of the Pauzhetsky hydrothermal system were obtained; steam and water-saturated areas and sections of the fracture-pore circulation of the ascending hydrothermal solutions were identified.

1. INTRODUCTION

Geothermal fields have been in focus of researchers around the world. As a rule, they are confined to crust-penetrating geological structures: deep faults, junction zones of regional tectonic blocks, multiphase intrusive complexes associated with magmatic chambers, etc. New geological and geophysical data that are obtained keep the interest unabated. However, even in well-studied geothermal fields, the structure of hydrothermal discharge zones is not adequately addressed not only at depth, but also near the surface. The paper is devoted to the resolution of a fundamental scientific problem – studying the setting and physical nature of discharge zones of hydrothermal solutions by an example of the Pauzhetsky hydrothermal system and the geothermal deposit of the same name. The early studies of the Pauzhetsky geothermal area and the hydrothermal system of the same name considered the thermal springs to be linked to linear discontinuous tectonic disturbances (Pauzhetsky ..., 1965). Later on, a dense network of variously oriented faults that control the thermal regime was plotted on the geological map of the exploration site of the Pauzhetsky geothermal deposit (Belousov et al., 1976). It was then assumed that the flow of high-temperature hydrothermal solutions from the lower aquifer and their mixing with the waters of the upper horizon occurs within linear open fractures. However, based on a detailed study of the core of new deep drill holes and an all-inclusive study of the Pauzhetsky hydrothermal system, elevated tectonic blocks (possibly of a tectonic-magmatic origin) were identified (Structure ..., 1993). It was demonstrated that hydrothermal solutions rose from the lower horizons of the deposit to the upper aquifer and deep-seated fluids mixed with meteoric waters along the boundaries and inside these blocks (Pampura, Sandimirova, 1991).

In recent years, all-inclusive geological and structural-geophysical studies have yielded original data on the structure of a large thermal anomaly located on the eastern flank of the Pauzhetsky geothermal deposit (Feofilaktov et al., 2017). This article summarizes the results of geophysical works in the central part of the deposit in order to explain the mechanisms of discharge of hydrothermal solutions in the producing zones.

2. GEOLOGICAL DESCRIPTION OF PAUZHETKA GEOTHERMAL FIELD

The Pauzhetsky hydrothermal system is confined to the central part of a volcano-tectonic depression of the same name (Long-lived ..., 1980) (a caldera according to other sources) and manifests the modern (Holocene) stage of development of the long-lived Pauzhetsky hydrothermal-magmatic system, detailed information about which is described in the book (Structure ..., 1993). Therefore, we will briefly discuss the setting of the modern hydrothermal system **(Fig.1)**.

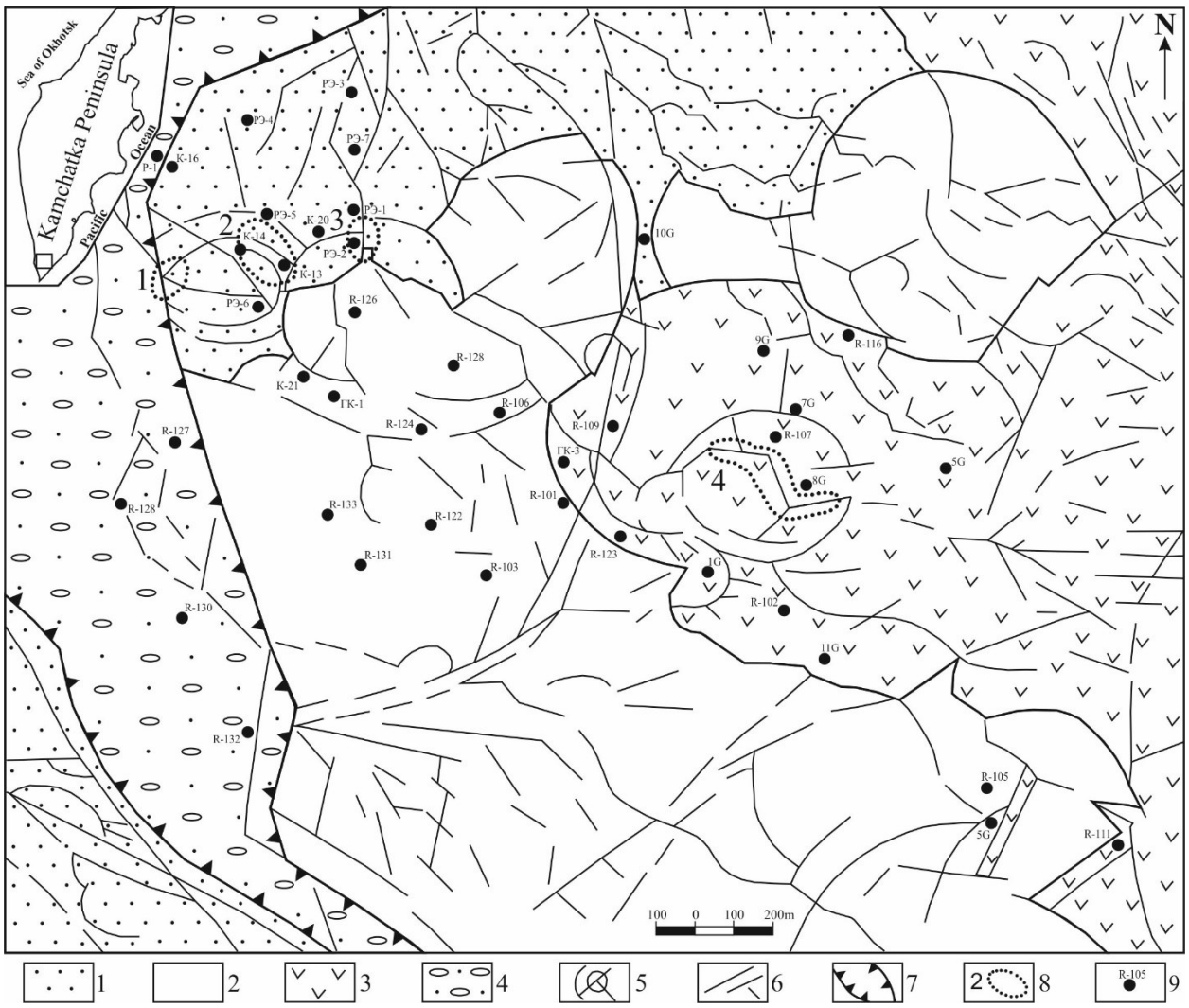

Figure 1: Schematic geological map of the Pauzhetsky hydrothermal system (according to (Structure ..., 1993)). 1 – tuffites and tuffs of the Upper Pauzhetsky subsuite of Upper Neogene – Lower Quaternary age; 2 – lavas and extrusive acid rocks of Middle Quaternary age; 3 – andesites and andesibasalts of Middle Quaternary age; 4 – alluvial boulder-pebble deposits; 5 – ring fractures, contouring raised blocks of rocks and controlling the position of thermal fields; 6 – system of linear tectonic disturbances; 7 – Upper Quaternary Pauzhetsky graben; 8 – thermal fields: 1 –Yuzhno (South)-Pauzhetsky, 2 – Verkhne (Upper)-Pauzhetsky, 3 – Nizhne (Lower)-Pauzhetsky, 4 – Vostochno (East)-Pauzhetsky; 9 – wells.

According to the hydrodynamic classification, the Pauzhetsky hydrothermal system is a water-dominated one. Two aquifers are identified within its structure: the upper one is associated with psephytic and coarse tuffs of the Middle and Lower Pauzhetsky subsuites, whereas the lower one is confined to the agglomerate tuffs of the Alneyan sequence **(Fig 2).** The aquifers are separated by two impermeable strata: the upper water-confining stratum is represented by tuffites of the Upper Pauzhetsky subsuite, and the lower one is represented by the Golygin ignimbrites. Apparently, Anavgai sandstones that underlie the cross-section, also act as a water-confining layer (Pauzhetsky ..., 1965; Belousov, 1978; Structure ..., 1993). It is thought that the aquifers are interconnected by separate sub-vertical faults, along which the thermal waters are mixed at depth and waters ascend to the surface (Belousov, 1976). The deep-seated thermal waters are neutral to slightly alkaline hydrocarbonate and chloride-hydrocarbonate. The cation composition is dominated by calcium; ammonium and boron are present. Elevated concentrations of gold, rare alkali and other elements are identified (Koroleva et al., 1993). The temperature of solutions in the lower aquifer reaches 220°C. (Pauzhetsky ..., 1965). Based on detailed petrophysical, petrographic, mineralogical and geochemical studies it was established that the structures that controlled the intensive mixing of thermal and meteoric waters, as well as discharge of the ascending vapour-hydrothermal solutions within thermal fields were elevated tectonic and (or) tectonic-magmatic blocks (Pampura, Sandimirova, 1991; Structure ..., 1993). One of such blocks, to which the Verkhne-Pauzhetsky thermal field (t/f) is confined, is located in the central part of the Pauzhetsky geothermal deposit (see. Fig. 1, 2). A thick long-lived liquid-vapour transition zone (boiling of hydrothermal solutions) was identified within its structure (Zhatnuev et al., 1996). Breccias of tectonic or hydrothermal (hydrothermal-metasomatic?) origin are formed in the near-surface horizons of the block; the breccia cement contains quartz-adular metasomatites. A complex ore geochemical barrier (Au-Ag-As-B-K-Li-Rb) is confined to these newly formed rocks (Zhatnuev et al., 1996). Probably, these metasomatites were formed at an earlier stage of development of the hydrothermal system, they were also identified in other blocks of the deposit (Structure ..., 1993). Despite a high cavern porosity of quartz-adular metasomatites, they have a higher density and lower permeability for hydrothermal solutions as compared to the surrounding pyroclastic rocks of the Pauzhetsky suite.

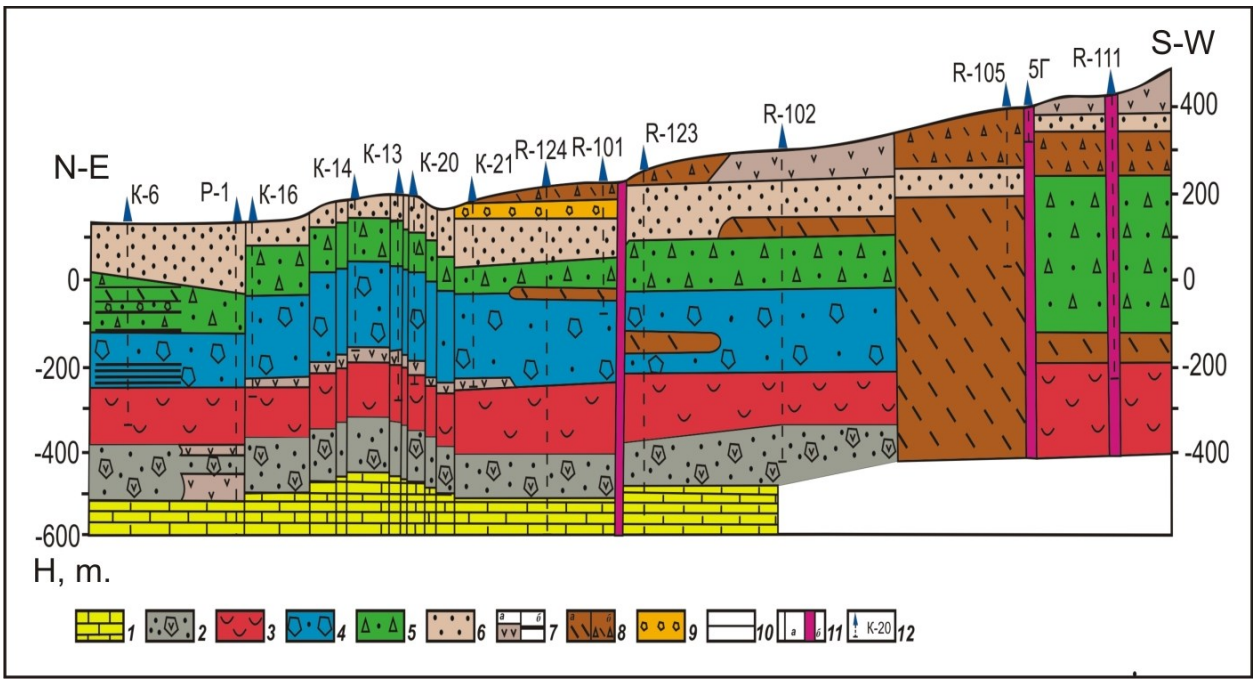

Figure 2: Geological profile of the Pauzhetsky geothermal deposit and the structure of the elevated block in the Verkhne-Pauzhetsky thermal field (Structure ..., 1993). 1 – volcanomictic sandstones of the base of the section, Anavgai sequence; 2 – agglomerate tuffs (tuff-breccias) of andesibasalt composition, Alneyan sequence; 3 – rhyolite crystal-lithic vitroclastic psephytic tuffs, Golygin suite; 4 – coarse-grained litho-vitroclastic tuffs of andesites, Lower Pauzhetsky subsuite; 5 – psephitic tuffs of andesidacites, Middle Pauzhetsky subsuit; 6 – tuffaceous-sedimentary deposits of acidic and intermediate composition, Upper Pauzhetsky subsuit; 7 – andesites and andesibasalts of the Kambalny Range: a – large bodies of lavas and subintrusive formations (microdiorites), b – dikes; 8 – extrusions (a) and lavas (b) of dacites; 9 – lava breccias of foots of lave streams and edge parts of extrusive bodies; 10 – lithological and intrusive boundaries; 11 – tectonic disturbances: a – faults; b – fault zones; 12 – prospecting and exploration wells.

3. RESEARCH TECHNIQUE

Complex geophysical studies were conducted on the largest thermal fields of the Pauzhetsky geothermal deposit: temperature survey of soils, electric prospecting through Vertical Electrical Sounding and Natural Field methods, magnetic and gravity prospecting. The surveys were carried out both for area and profiles that cross several thermal manifestations. All measurements were performed with state-of-the-art equipment with a detailed measurement interval. A detailed description of research technique used on thermal fields was provided in previously published papers (Feofilaktov et al., 2015; Feofilaktov et al. 2017, 2018).

4. RESULTS OF RESEARCH

4.1. Verkhne-Pauzhetsky thermal field

All-inclusive large-scale geological and geophysical studies yielded new data on the structure and physical nature of the discharge zones of the steam hydrothermal solutions in the central part of the Pauzhetsky geothermal deposit. Verkhne-Pauzhetsky t/f is located here. An isometric concentric-zonal structure **(Fig. 3)** which spatially correlates with the previously identified elevated tectonic block (Structure ..., 1993) was identified in the temperature, geoelectric, magnetic, and gravimetric fields. The central area of this structure is characterized by discharge of steam hydrothermal solutions on the surface and by high-gradient geophysical anomalies. Based on the results of the magnetometric survey, it is apparent that the central area of the isometric concentric-zonal structure is outlined by a zone consisting of local anomalies of positive ΔT_a values. The wide occurrence of subintrusive bodies (sills, dikes, extrusion roots) from intermediate to rhyolite composition suggests the magmatic nature of the anomalies identified. The peripheral area, which is also most distinctly manifested in the magnetic field, has negative ΔT_a anomalies, which, according to hydrogeological, thermometric and gravimetric data, correlate with discharge zones of steam hydrothermal solutions in the Pauzhetka river valley, along the Bystryi Creek and on the site adjacent to GeoPP.

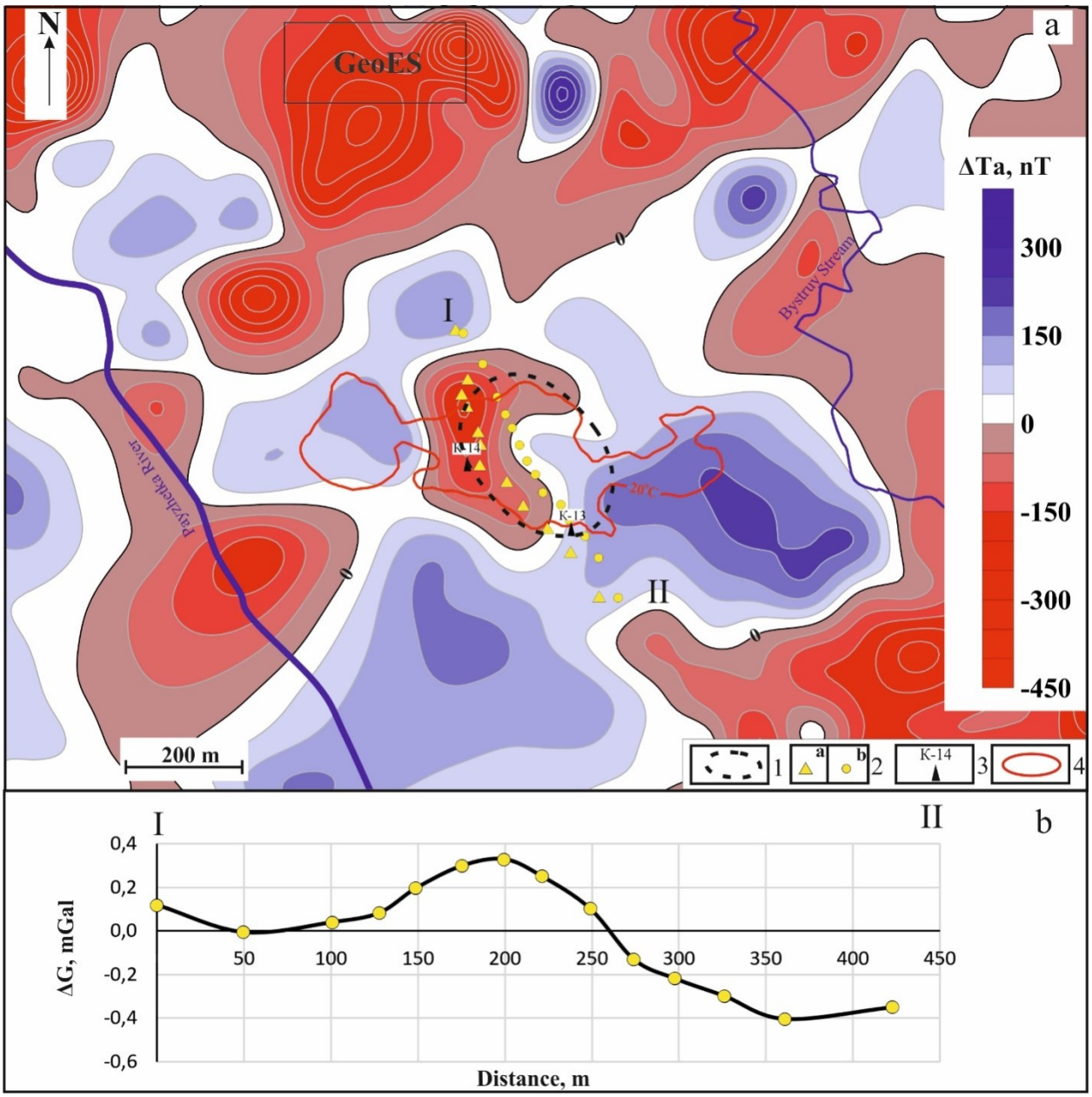

Figure 3: The map of the distribution of the values of the anomalous magnetic field (ΔT) in the central part of the Pauzhetsky geothermal deposit and the distribution diagram of the anomalous gravitational field in the Bouguer reduction (ΔG). 1 – the most active part of the Verkhne-Pauzhetsky thermal field; 2 – measurement points by profiles for Vertical Electrical Sounding method (a) and gravimetry (b); 3 – geothermal wells; 4 – thermal field boundary along the 20°C isotherm.

According to the data of the Vertical Electrical Sounding and lithological mappings, the south-eastern boundary of the area is represented by a sub-vertical fracture tectonic disturbance, which is a zone of increased fracture-pore permeability for ascending hydrothermal solutions in tuffs and tuffites of the Pauzhetsky suite (Fig. 4). Ascending neutral (to slightly alkaline) hydrothermal solutions intensively mix with meteoric waters at the north-western border of the central area and ferromagnetic minerals are leached from host rocks by acidic thermal solutions. At a depth of 40-60 m from the surface, the studies identified the roof of a block of compacted rocks most likely composed of quartz-adular metasomatites formed before the Holocene stage of development of the hydrothermal system (Zhatnuev et al., 1996). The analysis of logs of drill holes K-13, K-14, K-20 and K-21 identified that quartz-adular mineralization was distributed in the depth range of 45-60 m to 150-200 m in different parts of the elevated tectonic block structure (Structure ..., 1993) and the area where thermal and meteoric waters are intensively mixed extends to the bottom of the upper aquifer (Pampura, Sandimirova, 1991), the thickness of which, according to our data, is 150-250 m. Thus, a block of compacted rocks presumably composed of quartz-adular metasomatites was identified in the structure of the upper aquifer. The block controls ascending flows of thermal, mixed and meteoric waters under the Verkhne-Pauzhetsky thermal field.

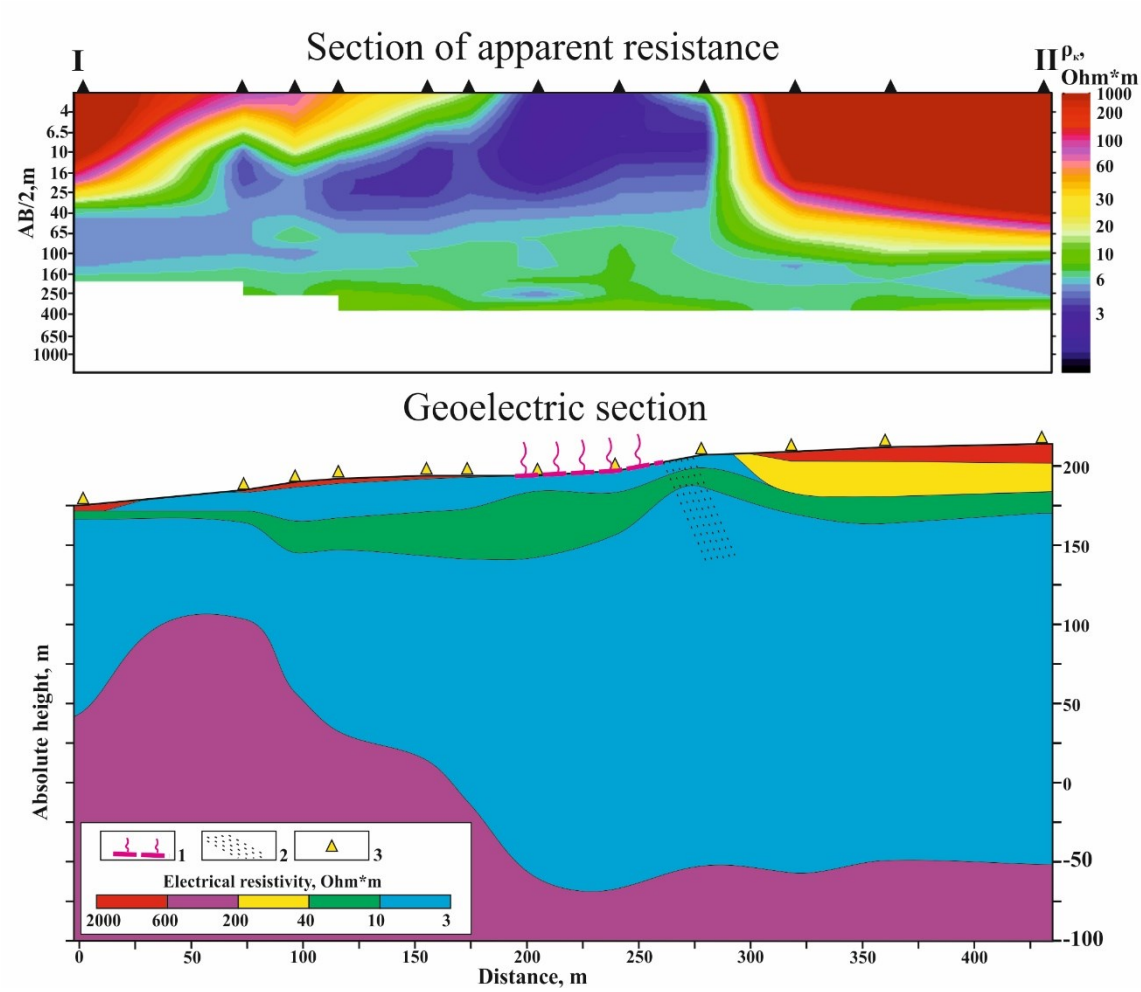

Figure 4: The results of electrical exploration by the method of Vertical Electrical Sounding on profile I-II (see Fig. 3) in the Verkhne-Pauzhetsky thermal field. 1 – the area of discharge of vapour hydrothermal solutions on the surface; 2 – zone of presumed tectonic disturbance; 3 – probing points.

Thus, the structure of the circulation zones of various types of waters in the central part of the Pauzhetsky geothermal deposit is governed by the concentric-zonal structure of the elevated tectonic block and the distribution of physical heterogeneities both primary (of magmatic or volcanogenic-sedimentary origin) and formed by hydrothermal-metasomatic alteration of the source rocks.

4.2. Vostochno-Pauzhetsky thermal field

Data on the structure of the discharge zone of thermal waters in the Vostochno-Pauzhetsky thermal field were obtained from a set of geophysical methods, pits and core holes. The central part of the field is notable for high temperatures of the soils (up to 105°C at a depth of 1.0 m) – this is where the main heat efflux to the surface takes place by means of steam-gas jets. Separate areas heated to 70°C are located on the periphery of the high-temperature anomaly. The temperature field of the Central area, on the whole, correlates with the structure of the natural electric field, the most conspicuous positive anomalies of which reflect the zones of hidden discharge of the vapour-gas mixture or thermal waters gravitating towards the NW part of the thermal field. The magnetic field within the Vostochno-Pauzhetsky thermal filed has a concentric-zonal structure **(Fig. 5)**: the central region is prominent for a positive anomaly ~ 30 × 50 m in plan size; a wide area of negative ΔT_a is extended along the periphery.

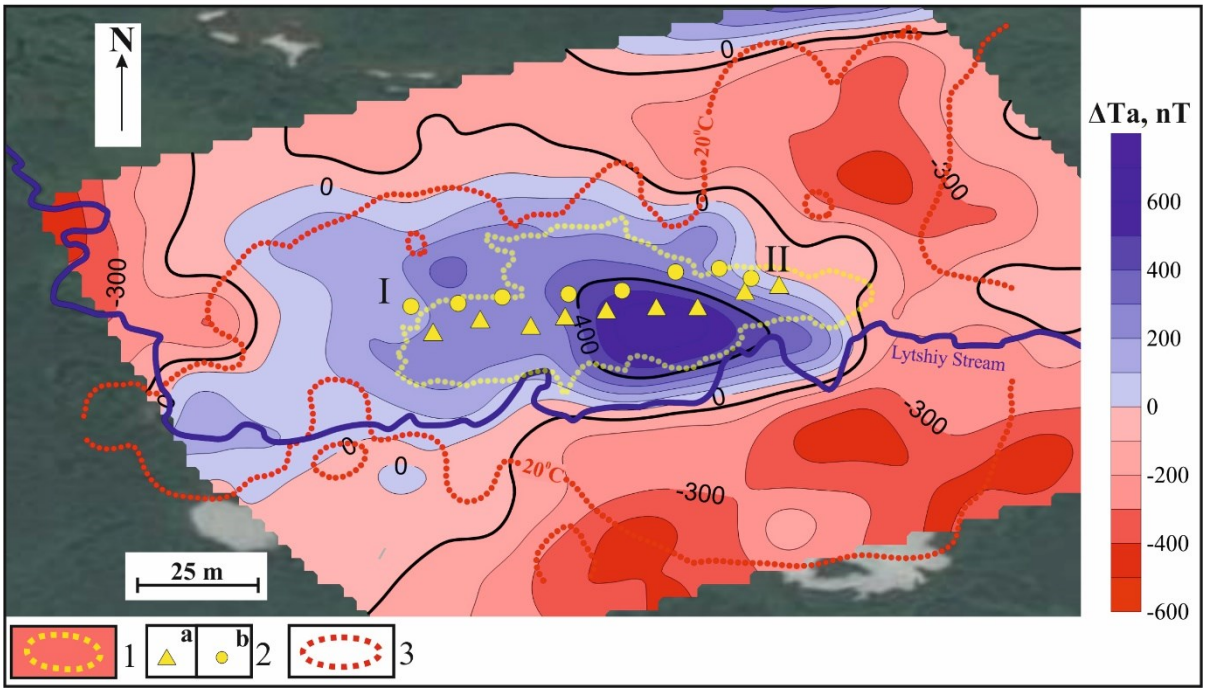

Figure 5: The map of the distribution of the values of the anomalous magnetic field (ΔT) at the territory of the Vostochno-Pauzhetsky thermal field. 1 – the most active part (hot) of the thermal field; 2 – measurement points by profiles for Vertical Electrical Sounding method (a) and gravimetry (b); 3 – thermal field boundary along the 20°C isotherm.

A stratified mass of hydrothermal clays was identified in the cross-section of the thermal field (from top to bottom): relatively dry due to intensive evaporation of moisture kaolinite iron clays of the sulphuric acid leaching zone; kaolinite-montmorillonite clays with a high content of pyrite and silica minerals saturated with pore solutions; relatively dry smectite clays including mineral ore formations in the form of slightly dipping vein zones. The lower horizon, as well as the kaolinite-montmorillonite layer of pyritized moist clays, is notable for increased electrical conductivity due to the high concentration of sulphides and oxides of iron, copper and zinc in clays. The thickness of the layers varies from 0.5–1.0 m in the hottest part of the thermal field to 2-3 m and more at the periphery. The base of the clay mass is represented by fractured, argillized lavas of andesites enriched with sulphides and metal oxides. According to the data of gravimetric and magnetometric surveys an anomalous body differing in density and magnetic properties from the surrounding rocks is identified under the clay mass **(Fig. 6)**.

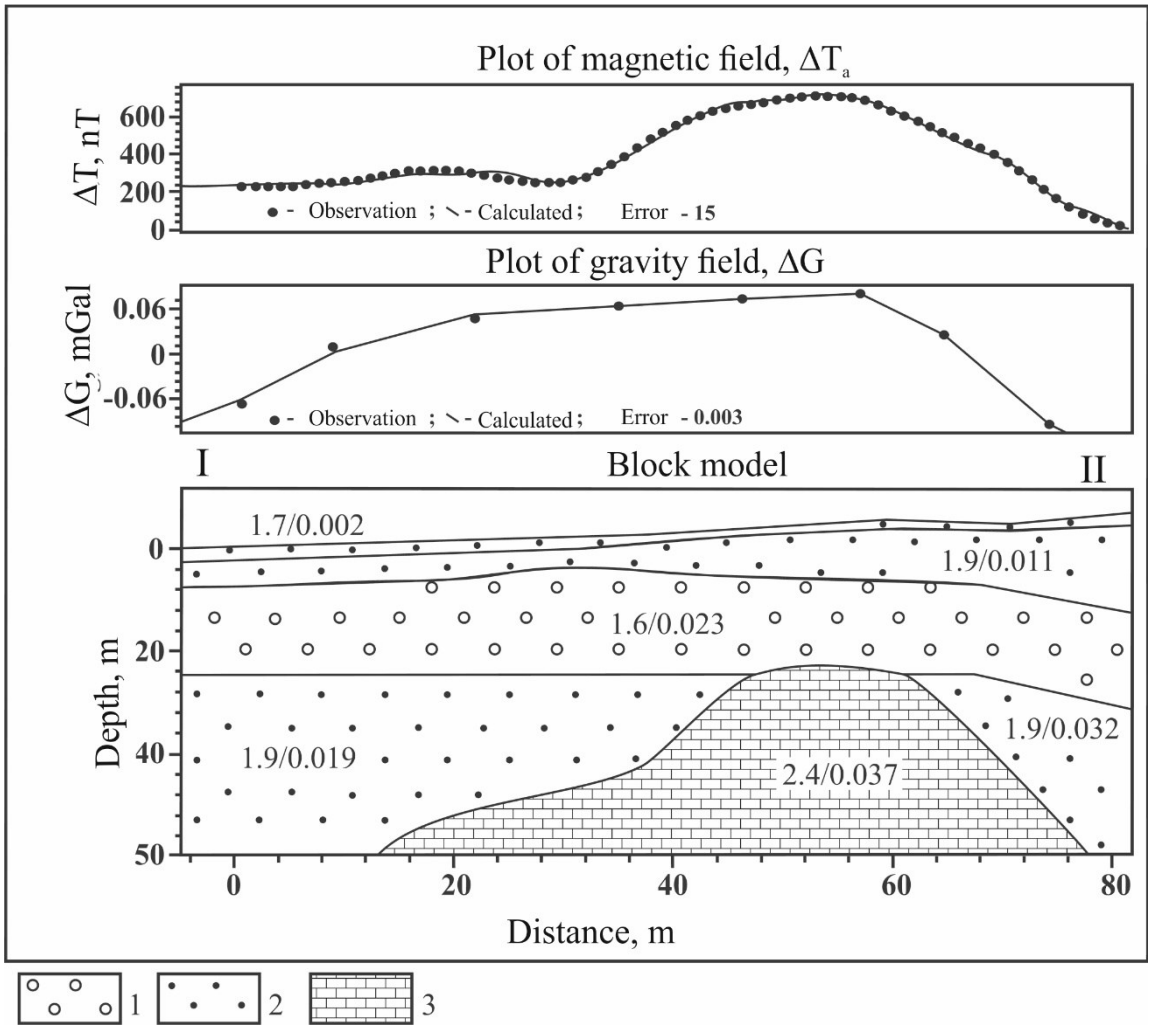

Figure 6: The model of the structure of the Vostochno-Pauzhetsky thermal field developed using gravity, magnetic and lithological data: 1 – a group of blocks with a density of 1.6 g/cm^3, 2 – same, 1.7-2.1 g/cm^3, 3 – same, 2.4 g/cm^3. The numbers on the diagram indicate the average values of density and magnetic susceptibility (denominator) for each block.

Based on the above, a conceptual model of the structure and formation conditions of the discharge zone of the steam hydrothermal solutions in the Vostochno-Pauzhetsky t/f was developed **(Fig. 7)**. The model is based on the location of the subintrusive body of a basic or intermediate composition, the roof of which is at a depth of several tens of meters from the level of the present-day landform. The body breaks through the tuffs of the Verkhne-Pauzhetsky sub-suite into the foot of the lava complex of andesites of the Middle Quaternary age of the Kambalny Range. Such bodies, as demonstrated by state geological surveys at a scale of 1: 200 000 and case studies (Belousov, 1978; Long-Lived Centre ..., 1980; Structure ..., 1993), are typical for all stages of development of the resurgent uplift of the Kambalny Ridge. Due to the intrusion of the subintrusive body into the host rocks into its apical part and into the overlying andesites, a system of blocks with contrasting physical and mechanical properties of the rocks was formed: 1) loosened fractured and 2) massive relatively impermeable to gas-water fluids. The endo-exocontact zones of such bodies, as a rule, are heavily brecciated and act as conductors for ascending hydrothermal solutions or meteoric waters (Structure ..., 1993). It is unlikely that the intrusion of this body occurred at the present stage of development of the hydrothermal system because the magmatism in this area had ended in the Pleistocene and Early Holocene (Belousov, 1978; Long-lived ..., 1980). But the spatial and genetic relation of such bodies in the structure of the Pauzhetsky hydrothermal system with intrusions and magma chambers of the Kambalny Ridge is possible, which had been demonstrated earlier by petrological and geochemical data (Serumkin, 1993). Consequently, the subintrusive body can play a role of a natural deformograph and conductor of deep-seated fluids that influence the hydrothermal system. Prolonged exposure of andesites to high-temperature solutions in the rock crushing zone caused the formation of the thermal field and the mass of hydrothermal clays (as is commonly believed, the present-day hydrothermal systems and, respectively, thermal fields are Holocene-old (Naboko, 1980)). Due to the discharge of alkaline metal-bearing waters, zones with mineral ore associations were formed at the base of the mass under the horizon of soft-firm clay with the properties of a thermodynamic barrier (the mechanism of their formation is described in paper (Rychagov et al., 2017)). Thus, the discharge zone of hydrothermal solutions within the Vostochno-Pauzhetsky thermal field has a layered-block structure and is probably connected with the apical part of the subintrusive body of the basic or intermediate composition. The brecciated rocks of the endo- and exocontact zones of this body have an increased fracture-pore permeability for ascending gas-water fluids, which likely to form at the level of the lower aquifer of the Pauzhetsky hydrothermal system or in the depths of the Kambalny volcanic ridge. A large hidden area where mixed thermal waters are spreading is formed to the north-west from the central section of the thermal field,

which is consistent with the monoclinal dip of volcanogenic-sedimentary rocks of the Pauzhetsky suite and the flows of the lava complex.

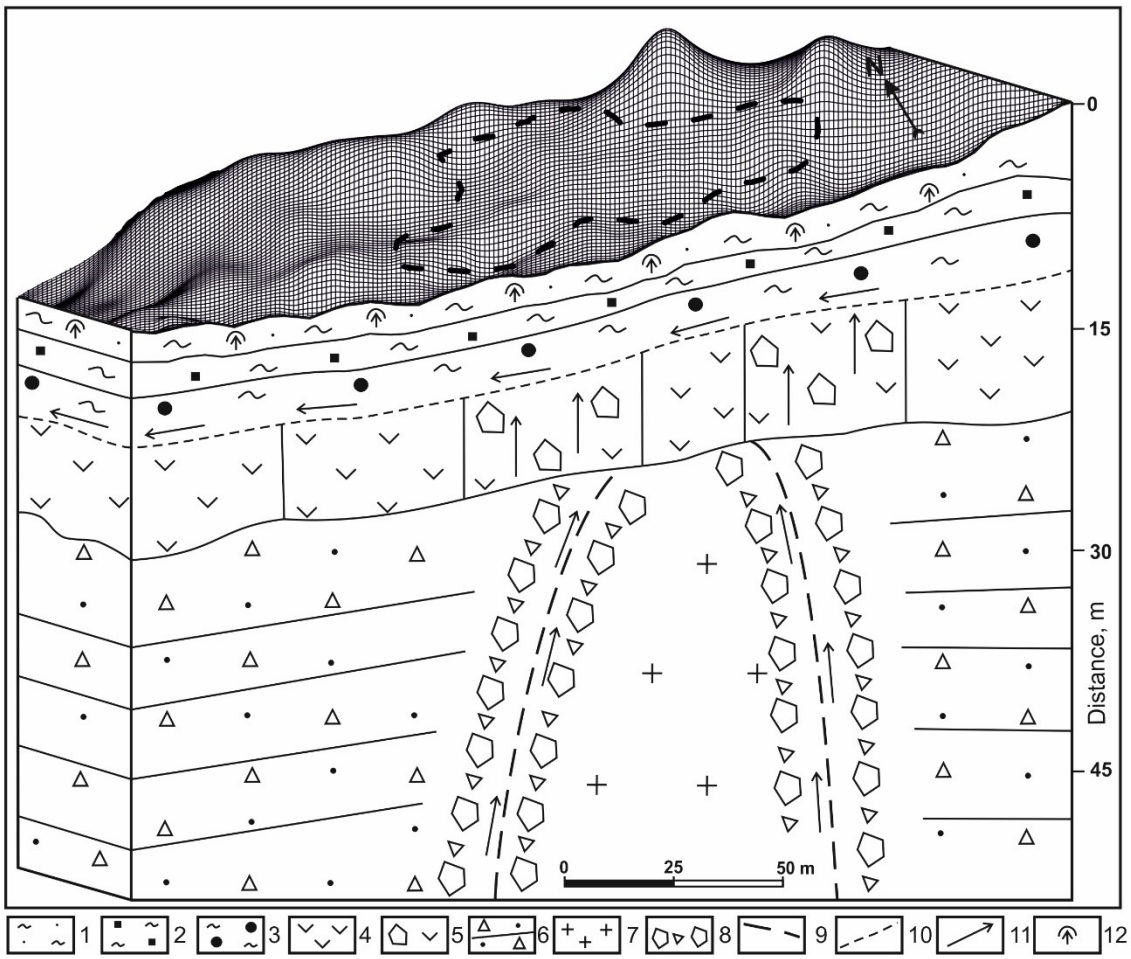

Figure 7: A conceptual model of the structure and formation conditions of the discharge zone of the vapour hydrothermal solutions in the East Pauzhetsky t/f. 1 – horizon of hydrothermal clays of the sulphuric acid leaching zone; 2 – horizon of soft-firm moisture-saturated clays of the carbon dioxide leaching zone; 3 – horizon of "dry" clays including layers with mineral ore associations; 4 – lavas of andesites; 5 – same, intensely fractured and brecciated; 6 – tuffs and tuffites of the Upper Pauzhetsky sub-suite; 7 – subintrusive rocks; 8 – breccias in the endo-exocontact zone of the subintrusive body; 9 – conventional border of the apical part of the subintrusive body; 10 – foot of the hydrothermal clays, the zone where mixed thermal waters are spreading; 11 – ascending gas-water fluids; 12 – intensive moisture evaporation zone.

5. CONCLUSION

All-inclusive structural-geophysical studies yielded new data on the structure of the discharge zones of the steam hydrothermal solutions in the central part of the Pauzhetsky geothermal deposit (South Kamchatka, Russia). The ascending heat flow is confined to the apical parts of subintrusive bodies and blocks of rocks with increased density. Secondary heterogeneities of the geological environment formed during hydrothermal-metasomatic activity play a significant role in the distribution of ascending thermal and infiltration meteoric waters. Geological and geophysical models of geothermal fields were developed to explain the mechanisms of formation of discharge zones of vapour hydrothermal solutions.

6. ACKNOWLEDGEMENTS

The authors deeply appreciate the input from all the colleagues from the South-Kamchatka-Kuril surveying company of Institute of Volcanology and Seismology FED RAS during field studies. This work was supported by the Russian Foundation for Basic Research (Projects No. 18-35-00138 and 19-05-00102) and the Far East Branch of the Russian Academy of Sciences (Project No. 18-2-003).

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