# New Data on Structure of Pauzhetsky Geothermal Deposit (South Kamchatka, Russia)

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## ABSTRACT

The study of the Pauzhetsky hydrothermal system in the 1959-60s triggered the development of geothermal power industry in Kamchatka. In 1966-67s, Pauzhetsky experimental-industrial geothermal power plant that was the first both in USSR and Russia was commissioned and it has been working in a sustainable way up to now providing electric power to a number of settlements and fish factories of Kamchatka Krai's Ust-Bolsheretsk district. However, increased power consumption from population and industrial entities of the district has recently experienced a lack of power supply from Pauzhetsky GeoPP which is also caused by reduction of performance values of production areas at the deposit. In our opinion, the latter reason can be explained by an insufficient level of study of the hydrothermal system in terms of geology. Exploitation of the deposit is based on the use of the geologicalhydrogeological model built at the early stage of study of the hydrothermal system (Pauzhetskiye, 1965). According to this model, high temperature hydrothermal waters flow via two acuifers flat-dipping from the side of the resurgent block of the Kambalny volcanic ridge in the interior of which cooling magma chambers are located. Thus, it is assumed that a heat source for the hydrothermal system is an induced one, and the hydrothermal waters are discharged through subvertical faults and in the valley of the Pauzhetka River (an upper-Quaternary fault trough of the same name). Additional topical research and detailed studies of separate sections of the deposit helped to identify uplifted tectonic-magmatic blocks within which hydrothermal waters actively circulate and the waters of lower and upper aquifers mix (Structure, 1993). The acquired data suggest there is a complex geological block structure of the Pauzhetsky geothermal deposit which governs the ascent and discharge of hydrothermal vapours. In this respect, the resolution of the heat source issue for the hydrothermal system is especially relevant. In recent years, the South-Kamchatka-Kuril surveying company of Institute of Volcanology and Seismology FED RAS has been conducting integrated geological-geophysical research at Pauzhetsky geothermal deposit. New data on structure of the upper water-confining stratum and upper aquifer have been acquired by means of modern geophysical techniques (high precision gravimetry, magnetometry, resistivity prospecting, microseismic sensing), the structure of uplifted "hot" tectonic blocks in the area of Verkhne (Upper)-Pauzhetsky and Vostochno (East)-Pauzhetsky thermal fields has been updated. A large subvertical section of decompressed rocks has been identified in the central part of the deposit which can be interpreted as a zone of an ascending deep gas-hydrothermal fluid and, consequently, it is assumed that this zone is connected with the source of a geothermal heat-carrying medium located within the structure of Pauzhetsky hydrothermal system.

# 1. INTRODUCTION

The Pauzhetsky hydrothermal system and a geothermal deposit of the same name are located at the south of Kamchatka peninsula, Russia (Figure 1). In 1966-67s, Pauzhetsky experimental-industrial geothermal power plant that was the first both in USSR and



Figure 1: The scheme of Pauzhetsky geothermal deposit location.

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Russia was commissioned and it has been supplying electric power up to now to a number of settlements and fish factories of Kamchatka Krai's Ust-Bolsheretsk district. Starting from the 1950-60s, this area has been in focus of state-run geological surveys, topical geophysical, hydrogeological and other studies. Based on these works, Pauzhetsky water-dominated geothermal deposit has been outlined, its reserves have been assessed to be enough for heat and power supply to communities and industries of Ust-Bolsheretsk district. Power demand has gone up in the district in the recent years and the required capacity exceeds the capacity of Pauzhetsky GeoPP. At the same time, the parameters of the production areas of the Pauzhetsky deposit (temperature, amount of produced dry steam) have been observed to have decreased. The latter fact, apart from possible technical reasons, is related to an insufficient level of geological study of the deposit. Namely, a significant correction of the geological-hydrogeological model formulated by V.V. Averyev with colleagues (Pauzhetskiye, 1965) which until now has been the basis for the field development is needed. A need to carry out additional all-inclusive geological-geophysical and hydrogeological studies, prospecting activities, to drill exploration and production wells at the Pauzhetsky deposit is evident.

In recent years, the South-Kamchatka-Kuril Surveying Company of IViS FED RAS has been conducting topical studies at the area of the Pauzhetsky hydrothermal system: geological, geochemical and hydrogeological sampling; study of properties of hydrothermal clays and other mineral neoformations; monitoring of changes in temperature and geochemical regimes of thermal fields; study of structure of thermal outflows by geophysical methods (Rychagov, 2008). The package of geophysical works discussed in this report includes high-precision gravimetry, microseismic sensing, magnetometry and electrical exploration (Abkadyrov and Bukatov, 2010; Denisov et al., 2013). The studies are aimed at clarification of the geological structure of the Pauzhetsky hydrothermal system (geothermal deposit) and reproduction of the structure of feeding, mixing and discharging zones of hydrothermal solutions.

## 2. GEOLOGICAL SUMMARY OF PAUZHETSKY GEOTHERMAL DEPOSIT

The Pauzhetsky geothermal deposit is located in a middle-quaternary-aged caldera which is 20-25 km in diameter (Dolgozhivishii tsentr, 1980). The deposit is composed with participation of volcanogenic-sedimentary, volcanic and intrusive rocks of base, medium and acid composition from Miocene to Pleistocene age (Structure, 1993). The most studied upper part is composed of lava flows of andesidacites and andesibasalts formed at the stage of formation of the tectonic-magmatic uplift of the Kambalny ridge and tuffites of the Upper-Pauzhetsky sub-suite and upper-quaternary sediments of Pauzhetsky trough (Figure 2).



Figure 2: The geological scheme of Pauzhetsky geothermal deposit (Structure, 1993). (1) Upper Pauzhetsky depositions (tuffites); (2) dacite lavas; (3) andesite-basaltic lavas; (4) depositions of Pauzhetsky Upper Quaternary graben; (5) system of ring fractures; (6) other faults; (7) boundary of Pauzhetsky Upper Guaternary graben; (8) thermal fields: (1) Yuzhno ('South')-, (II) Verkhne ('Upper')-, and (III) Vostochno ('East')- Pauzhetsky; (9) wells.

Heat outflows on the surface occur at several thermal fields: Vostochno ('East')-, Verkhne ('Upper')-, Yuzhno ('South')- and Nizhne ('Lower')-Pauzhetsky ones as well as on "warm soils" in the valley of the Pauzhetka river (Figure 1). The thermal fields are confined to uplifted tectonic (tectonic-magmatic ?) blocks through which high temperature (220 °C at a depth of 600-800 m) hydrothermal waters ascend to the surface; in fracture-breccia zones inside the blocks and at their boundaries thermal waters mix with precipitation meteoric waters (Figure 3). Probably, such structures in the interior of the Pauzhetsky deposit govern geothermal processes and, moreover, they can be connected to heat sources feeding the Pauzhetsky hydrothermal system. The question about a heat source for the system has remained unanswered. It is traditionally considered that a heat source for the Pauzhetsky hydrothermal system can be induced: it is located in the interior of the Kambalny ridge (Pauzhetskiye, 1965) or in the structure of the Koshelevsky volcanic massif (Voronkov, 1983). In view of recently acquired new data these concepts may be re-considered.



Figure 3: The main cross-section of Pauzhetsky hydrothermal system (Structure..., 1993). (1) Anavgaisky sandstounes, (2) Alneisky tuffs, (3) Golyginsky ignimbrites, (4) Low Pauzhetsky depositions, (5) Middle Pauzhetsky depositions, (6) Upper Pauzhetsky depositions, (7) dykes and silles, (8) extrusives and lavas of dacite, (9) lavas and extrusives breccia, (10) lithological and intrusives boundaries, (11) tectonic faults, (12) wells.

## **3. RESEARCH METHOD**

The interior structure of the Pauzhetsky geothermal deposit has been studied by way of the following methods: magnetometer surveys, vertical electrical sounding (VES), low-frequency microseismic sensing, high-frequency gravimetric surveys (Figure 4).



Figure 4: The scheme of observation points on Pauzhetsky hydrothermal system complex of geophysical methods. (1) profile A-B crosses all Pauzhetsky hydrothermal system, in which gravity observations made, microseismic sensing and VES; (2) irregular network magnetometer observations.

**3.1 Magnetometer surveys** were conducted in summer and winter (March) time. The areal magnetometer survey has been conducted in the area of the largest thermal fields of Verkhne (Upper) -Pauzhetsky and Vostochno(East) -Pauzhetsky. Spacing of the surveys was 20 x 5 m. A denser network with a spacing of 10 x 2.5 m covered the areas where there were outflows of hydrothermal vapours. In March 2014, the areal magnetometer survey with irregular spacing covering a significant part of the area of the Pauzhetsky geothermal deposit was conducted. The survey covered an area of 11 km<sup>2</sup> (Figure 4). Besides, profile A-B which crosses the main geological structures of the deposit from SE to NW was explored. Two modern GSM-19 v 7.0 Overhauser effect

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magnetometers were used. The observational technique imposes consideration of daily variations of the magnetic field therefore one instrument was used as a stationary recording magnetometer whose readings were recorded every 20 seconds. The second instrument was used for conventional measurements in the manual mode. In the summer, measurement spacing was determined in steps, whereas in winter, time intervals between indications (every 6 seconds on the average) were used. Altitude of the instrument both in the summer and winter time was around 2.2 m which ensured a minimal noise level. The depth of snow was 1 to 5 m. The depth of snow was not accounted for during generation of a magnetic anomaly map. Root mean square accuracy of the measurements was  $\pm 18$  nT for 9 % of reference points.

**3.2 Vertical electrical sounding (VES)** was conducted by a multifunctional electric meter MERI 24 manufactured by OOO "Nord-West". The power to the feed line was supplied by an exploration electric generator VP-1000 manufactured by OOO "Elgeo"; the generator provided the maximum amplitude of a stabilized current of up to 2 A. VP-1000 was powered from an AC inverter generator Yamaha EF2000iS. The feed line was fitted with steel electrodes and the receiving line was fitted with brass electrodes. VES was carried out in by way of a symmetrical four-electrode pattern as per the well-known technique (Electrorazvedka, 2005) at 33 points on profile A-B which transects the geothermal deposit. A 100 m spacing between measurements was used and a 50 m spacing was used in the area of the thermal fields. A span of the feed line ranged from 4 to 1040 m. Control measurements in an amount of 6 % were conducted for the quality control of the surveys. Mean relative error of the measurements amounted to 2.5 %. Apparent resistivity values were calculated for each span directly at sounding points and then the values were plotted on a chart in a logarithmic scale. Further on, the curves of the apparent resistivity were inputted to IPI2WIN software developed at the geophysics department of Moscow State University (authors: A.A. Bobachev, I.N. Modin and V.A. Shevnin) and then the cross-sections were modelled.

3.3 Method of low-frequency microseismic sensing was applied on the area of the Pauzhetsky geothermal deposit to study the deep-seated geological structure. This method is based on the property of velocity heterogeneity to distort the spectrum of a lowfrequency microseismic field (Gorbatikov et al., 2008). It is considered that a microseismic field is mainly contributed to by the fundamental Rayleigh modes. The distortion of the amplitude field caused by interaction with velocity heterogeneity is an informative parameter. Phase information is not applied. A form and depth of heterogeneity occurrence is assessed by distortion distribution on the surface and a frequency at which the distortion appears. The paper (Gorbatikov and Tsukanov, 2011) demonstrates that on the Earth's surface the spectrum amplitudes above the high-velocity heterogeneity in a certain frequency range decrease and they increase above the low-velocity ones. There is an f frequency of a Rayleigh wave for which distortions caused by heterogeneity at an H depth of occurrence are largest. This f frequency is related to the depth of occurrence of H heterogeneity and velocity of the fundamental mode of an  $V_R(f)$  Rayleigh wave by the formula  $H \approx 0.4 \cdot V_R(f)/f$ , which was confirmed by studies of various scale and genesis geological features and by model calculations. This formula is applied when assessing occurrence depth of an unknown heterogeneity which forms the amplitude distortions (the ones we can measure) at an f frequency. According to numerical experiments (Gorbatikov and Tsukanov, 2011) the horizontal resolution of the technique is estimated as  $(0.25-0.3)\lambda$ . where  $\lambda$  is an effective sensing wavelength. The vertical resolution is estimated at a value of  $(0.3 - 0.5)\lambda$ , where  $\lambda$  is an effective wavelength for the mean depth between heterogeneities. It was also demonstrated that presence of a small isolated heterogeneity could be detected even if its size was 10 and more times smaller than a wavelength.

The field measurements technique comes down to accumulation of the power spectrum of a microseismic signal during a certain period of time sequentially from point to point along the cross-section by means of several hand-held sensors. At the same time a microseismic signal is registered at a reference point within the limits of a survey loop for elimination of the unsteady effect of the sensing microseismic signal. The microseismic profile A-B was explored during the reconnaissance field works (Figure 4). In total, 39 points with a spacing of 100 m were surveyed on the profile; the length of the profile amounted to 4 km. A portable broadband seismometer comprising a pack of 5 sets of Guralp CMG-6TD sensors was used for logging. The sensors logged microseisms by three components in a frequency range of f = 0.033-50 Hz. Such a wide frequency range is possible thanks to use of the force balance sensor technology with a feedback circuit. Signal sampling was 100 readings/sec. Analogue-digital conversion range was 24 bits. Syncing of readings in time was induced by integrated GPS receivers. The logging time in each point lasted at least 150 minutes to achieve the statistical stability of the spectrum.

**3.4 The gravimetric survey** on the area of the Pauzhetsky geothermal deposit was also carried out for the above-mentioned profile A-B. An CG-5 Autograv high-precision gravity meter by Canadian firm Scintrex was used. The instrument is an automatic microprocessor gravity meter with a measurement range of 7,000 mGal and a resolution of 0.001 mGal. Readings in the Autograv system are derived through on-going averaging of measurements taken in the space of one second. The spacing of measurement points across the section was 100 m and a total of 39 points was metered. Control measurements in an amount of 25 % were conducted for the quality control of the instrument reading accuracy. Root mean square accuracy of the measurements in the section was 0.03 mGal. Two Leica GR 10 GNSS reference stations with AR 10 antennas were used as geodetic support. For a GNSS reference station Leica GR 10, the values of allowable root mean accuracy for measurements in the Static are as follows: In plan -  $5+0.5*10^{-6}*D$ ; in height -  $10+0.5*10^{-6}*D$ ; where D is a measured distance in mm. One station was used in the steady-state, whereas the other was moved along profiles. Also, the data of the stationary network of GPS surveys were used for processing. The logging time at each survey point amounted to at least 15 minutes. As a result of processing of data for profile A-B, a list of coordinates and elevations has been produced. Elevation measurement accuracy by GPS was 3 - 7 cm. Subsurface density in the profile was estimated by Nettleton Graphical Method (Gravirazvedka, 1990). The least correlation with the relief of the Bouguer gravity anomaly variation was observed at a subsurface density of 1.9 g/cm<sup>3</sup>.

#### 4. RESEARCH OUTPUTS

Two large areas with the negative values of residual magnetism of rocks are differentiated on the map of magnetic anomaly  $\Delta T_a$  against a background of positive values  $\Delta T_a$  (Figure 5). The NW sector includes a vast field on the Left terrace of the Pauzhetka River and all main areas of outflows of hydrothermal waters on the surface. These areas include above-mentioned "warm soils",



Figure 5: Anomaly map of the magnetic field  $\Delta T_a$  for the area of Pauzhetsky geothermal field according magnetic survey in 2014. (1) Verkhne-Pauzhetsky thermal field; (2) Vostochno-Pauzhetsky thermal field.

## Yuzhno-Pauzhetsky, Nizhne-Pauzhetsky and Verkhne-Pauzhetsky thermal fields. On the whole, this sector belongs to the zone of lateral spread of hydrothermal solutions of the Pauzhetsky hydrothermal system which, apparently, explains a weakly-differentiated negative magnetic field. Location of the Verkhne-Pauzhetsky thermal field in the isometric negative anomaly surrounded by rocks with high residual magnetism indirectly confirms the previous conclusion that there is an upstanding block of rocks which governs an ascending geothermal flow and near-surface vapour zone. The SE sector differs from the NW sector of negative values $\Delta T_a$ by presence of a great number of local negative anomalies $\Delta T_a$ to one of which the Vostochno-Pauzhetsky thermal field is confined. However, a positive magnetic anomaly with values $\Delta T_a$ up to +505 nT is differentiated in the central part. This output is confirmed by the data of a micromagnetic survey conducted earlier in the summer field season. We assume that the positive magnetic anomaly in the centre of the thermal field may indicate in favour of presence of a subvertical intrusive body of base-medium composition whose top is near the surface and with which the formation of the tectonic-magmatic uplift of the Vostochno-Pauzhetsky thermal field is associated. The large area of negative values $\Delta T_a$ around this positive anomaly $\Delta T_a$ may indicate the presence of concealed discharge of hydrothermal solutions in a geological structure sized 700 x 800 m in plan. A large relatively isometric anomaly of positive $\Delta T_a$ values is differentiated near the Beriozovaya Mountain which, based on indirect data, was described earlier as a dacite composition extrusion (Belousov, 1978). Out data confirm the presence of a large, apparently, extrusive-subvolcanic body but of base or medium composition. In general, the whole SE sector is of a high interest in terms of identification of local geological structures (tectonic or tectonic-magmatic blocks) which may control flows of a geothermal heat-carrying medium.

A geoelectric 100 m deep cross-section was mapped based on results of VES. The length of the profile was 3.4 km (Figure 4). Three layers with different electric resistance of rocks are differentiated on the cross-section (Figure 6). The first layer (red-yellow



Figure 6: Geoelectric cross-section on the results of the VES profile on A-B.

on the diagram) is a near-surface high-resistivity layer with an apparent specific resistance of 800-3500 Ohm/m whose maximum thickness amounts to 20 m (Stake 20). This layer is missing in the area of the Verkhne-Pauzhetsky thermal field (Stakes P 01, 33) (thins away sharply and rises to the surface) which can be clearly observed on pseudo-electric (Figure 7) and geoelectric cross-sections. The second layer (green on the diagram) is characterized by a resistance of 50-100 Ohm/m, the geoelectric cross-section shows that its upper edge is at a depth of 5-15 m, this layer is from 3 to 30 meters in thickness. This layer is also missing in the area of the Verkhne-Pauzhetsky thermal field. The third layer of rocks (blue and black colours on the diagram) with a resistance of 3-50 Ohm/m outcrops on the surface in the area of the Verkhne-Pauzhetsky thermal field whereas on the rest of the territory it occurs at a depth of 30 to  $\geq$  100 m. According to geological data this layer is associated with fractured water-saturated rocks of the Middle-Pauzhetsky sub-suite. In some blocks the upper edge of this layer rises up to level 8-10 m from the surface which can be interpreted as presence of tectonic fault zones saturated by a geothermal heat-carrying medium.



Figure 7: Pseudo-electric cross-section on the results of the VES profile on A-B.

In the microseismic cross-section (Figure 8) high-amplitude anomalies prevail which are characterized by low velocities of elastic waves (Gorbatikov et al., 2008). The upper part of the cross-section is divided into two highly contrast anomalies to a depth of 200 m. A high-velocity anomaly matching consolidated rocks is located in the SW part of the profile. Such rocks are the lava-extrusive complex of andesibasalts formed during resurgent uplifting of the Kambalny Ridge (Structure, 1993). We assume that this complex of rocks acts as an upper water-confining stratum for thermal waters in this part of the Pauzhetsky hydrothermal system. On the contrary, the NE part of the profile is manifested by a strongly pronounced low-velocity near-surface anomaly. In this part of the Pauzhetsky geothermal deposit the upper aquifer (the Middle-Pauzhetsky sub-suite composed of fractured and highly-porous psephitic tuffs) is located near the surface, hydrothermal waters are discharged here on several thermal fields (Verkhne-, Yuzhno-and Nizhne-Pauzhetsky fields and "warm soils"). The deep low-velocity anomalies are apparently also connected to layers of rocks which are permeable for hydrothermal vapours. They are of a high interest for prospecting and exploration activities and drilling of wells to a depth of 1,500 m. A large subvertical low-velocity anomaly propagating to a depth of above 1 km was differentiated in the central part of the cross-section. Spatially, this anomaly coincides with the arc zone of tectonic faults, i.e. the boundary of a large block within the structure of the Pauzhetsky hydrothermal system (Figure 2). Out data confirm the high prospectivity of this zone for finding a geothermal heat-carrying medium.



Figure 8: The microseismic cross-section along profile A-B, which shows the distribution of velocity contrasts (in dB) of Swaves inside the Earth's crust.

Based on the gravity survey data combined with other geophysical and geological materials, one-dimensional modelling of the Pauzhetsky hydrothermal system cross-section along the profile A-B down to a depth of 500 m (Figure 9) has been done. The acquired density model consists of 9 blocks. The modelling accuracy was 0.288. The rocks of blocks I, IV and VIII have a density of 2.4 g/cm<sup>3</sup>, 2.3 g/cm<sup>3</sup> and 2.3 g/cm<sup>3</sup>; and a thickness of 140 m, 120 m and 200 m, respectively. These blocks correspond to tuffogenic-sedimentary formations of dacite and andesidacite of the Upper-Pauzhetsky sub-suite (Structure, 1993). The rocks of Block II have a density of 1.8 g/cm<sup>3</sup> and a thickness of about 500 m. Block III differs by a higher density of rocks (2.9 g/cm<sup>3</sup>) and its thickness is 500 m. By geological data this block conforms to the tectonic-magmatic uplifting identified earlier in the area of the Verkhne-Pauzhetsky thermal field (Structure, 1993). Probably, the central part of the block is composed of high-density intrusive rocks (diorites ?). The rocks of blocks V and IX have a density of 2.2 g/cm<sup>3</sup> and thickness of the const-section to vulcanomictous sandstones in the footing of the geological cross-section – Figure 3). The relatively low density of rocks and their amalgamation in large blocks is apparently explained by a high degree of hydrothermal-metasomatic alteration of the rocks. Blocks VI and VII have a thickness of 800 m and rocks with a density of 2.1 g/cm<sup>3</sup> and 2.0 g/cm<sup>3</sup>, respectively. The delineation of these two joint blocks with the low-density rocks correlates well with the results of low-frequency microseismic sensing and confirms the

presence of a large tectonic fault in this section of the Pauzhetsky hydrothermal system; the fault, apparently, plays a great role in distribution of flows of a geothermal heat-carrying medium.



#### Figure 9: Model density inhomogeneities along the profile A-B. (a) dates ΔT<sub>a</sub> anomalous magnetic field at observation points, nT; (b) - dates anomalous gravitational field in the Bouguer reduction, mGal: (1) calculated field, (2) outliers field; (c) density model of block structure on the profile depth in meters. Roman numerals designate the numbers of blocks.

#### 5. CONCLUSION

We have acquired new data on the structure of the Pauzhetsky geothermal deposit which is situated in the southern end of Kamchatka peninsula and which has a large influence on the economic life of the district. Large geological blocks and discontinuous tectonic fault zones which apparently govern the main flows of a geothermal heat-carrying medium have been delineated. The structure of tectonic-magmatic upheavals having a zonal structure and responsible for discharge of the local flows of ascending high-temperature fluids in the area of Verkhne-Pauzhetsky and Vostochno-Pauzhetsky thermal fields has been clarified. There is a reason to believe that in future such geological structures may be found in other areas of the Pauzhetsky hydrothermal system. They have deep-seated roots and are promising from a viewpoint of finding heat sources and superheated hydrothermal solutions. It is necessary to continue all-inclusive geological-geophysical and hydrogeological studies for building a new geological-hydrogeological model for the Pauzhetsky hydrothermal system and for correction of the development of the geothermal deposit.

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