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# The Structure of the Discharge Site of Steam Hydrothermal Fluids in the Area of the Upper Pauzhetka Thermal Field (Southern Kamchatka)

**S.O. Feofilaktov, S.N. Rychagov✉, Yu.Yu. Bukatov, I.A. Nuzhdaev, D.K. Denisov**

*Institute of Volcanology and Seismology, Far Eastern Branch of the Russian Academy of Sciences,*
*bul'v. Piipa 9, Petropavlovsk-Kamchatsky, 683006, Russia*

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**Abstract**—Comprehensive geological and geophysical investigations were conducted to obtain new data on the structure and physical nature of the discharge site of steam hydrothermal fluids by the example of the Pauzhetka geothermal deposit (southern Kamchatka). An isometric concentric zonal structure has been identified within the temperature, geoelectric, magnetic, and gravimetric fields. It spatially correlates with an elevated tectonic block previously detected in the area of the Upper Pauzhetka thermal field. The central part of this structure includes a consolidated rock block composed presumably of quartz–adularia metasomatites formed at the pre-Holocene stage of evolution of the Pauzhetka hydrothermal system. The rocks form a physical heterogeneity within the structure of the aquifer, which greatly contributes to the distribution of flows of ascending thermal, mixed, and meteoric waters beneath the Upper Pauzhetka thermal field. The central area of the isometric concentric zonal structure is outlined by a zone consisting of local anomalies of positive magnetic-field values. The wide occurrence of subintrusive bodies (sills, dikes, and extrusion roots) of intermediate to rhyolite composition suggests the magmatic nature of the identified anomalies. The peripheral areas correlate with large discharge sites of high-temperature fluids. Thus, it is demonstrated that the structure of the circulation zones of waters of various types in the area of the Upper Pauzhetka thermal field is governed by the concentric zonal structure of the elevated tectonic block and the distribution of physical heterogeneities, both primary (of magmatic or volcanosedimentary nature) and resulted from the hydrothermal metasomatic alteration of the source rocks.

*Keywords:* geothermal deposit; elevated tectonic block; thermal field; geophysical anomalies; aquifer; physical heterogeneities; steam hydrothermal fluids

## INTRODUCTION

We addressed a fundamental scientific problem of great practical importance in the field of geothermy and recent mineralization by the example of the Pauzhetka geothermal deposit: delineation of the blocks of rocks that control ascending hydrothermal fluids; definition of the physical (geological) nature of heat supply zones and of discharge sites of steam hydrothermal and metal-bearing solutions. This problem is relevant practically for all the World's geothermal deposits and for the Kuril-Kamchatka region in particular (Sugrobov, 1985; Rychagov, 1993; Uchida et al., 1996; Stimac et al., 2010). The Earth's crust of the regions of modern and Quaternary volcanism is highly heterogeneous at all hierarchical levels (Tuyezov, 1975; Lonshakov, 1979; Krasnyi, 1984; Sadovskii et al., 1984).

The hydrothermal systems of volcanic regions are confined to geodynamically active geological structures: regional tectonic joints, zones of discontinuous tectonic dislocations and deep faults (Ivanov, 1956, 1961; Kononov, 1983; Rychagov, 2005). Metamorphism of rocks, infiltration of thermal and meteoric waters, boiling of vapour-gas fluid, leaching and mechanical reprecipitation of mineral components, and other processes result in the further change of the geological environment. Secondary heterogeneities are actively formed, such as strata, layers and horizons of metamorphic and metasomatic facies, blocks of rocks with contrasting petrophysical properties, zones of thermodynamic and geochemical barriers with certain typical physico-chemical parameters, areas of increased fracturing and brecciation (permeability) in primary and newly formed rocks. These processes are especially strong in the areas of ascending fluxes of hydrothermal fluids and at the site of discharge of steam hydrothermal fluids. Therefore, reliability of geological and geophysical models of geothermal deposits directly depends on the level of knowledge about the physical nature of the structural heterogeneities that compose the hydrothermal systems.

The Pauzhetka geothermal deposit is one of the best studied sites of this kind in Kamchatka (Piip, 1965; Belousov et al., 1976; Sugrobov, 1979; Rychagov et al., 1993). About fifty 400–1200-meter-deep boreholes were drilled here in the area of 2.5 × 3 km; large-scale geophysical surveys were conducted; drilling was performed combined with logging;

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✉Corresponding author.
*E-mail address:* rychsn@kscnet.ru (S.N. Rychagov)

hydrogeochemical regime observations were made at the initial stage of the exploration and production. Despite the large scope of the study, 30 years after starting the field development, the first (Northern) area was abandoned due to a temperature and pressure drop of the steam-water mixture in the boreholes; nowadays, degradation of the heat-carrying fluid supplied from the deeper horizons of the new (Southern) area is observed. These trends were already noted in (Rychagov et al., 1993) and, in our opinion, they can be explained by a rather low level of knowledge of the structure and physical nature of the heat supply zones and discharge sites of steam hydrothermal fluids. Earlier, we obtained original data on the structure of a large thermal anomaly located on the eastern flank of the Pauzhetka geothermal deposit (Feofilaktov et al., 2017). An integrated geological and geophysical model was developed to depict the formation patterns of thermal anomalies and the flow conditions of an alkaline metal-bearing fluid.

Based upon the results of detailed geophysical studies, we tried to explain the physical (geological) nature of the structural heterogeneities at the discharge site of the steam hydrothermal fluids in the central part of the Pauzhetka geothermal deposit.

## THE CURRENT STATE OF RESEARCH OF GEOTHERMAL AREAS, SYSTEMS AND DEPOSITS USING GEOPHYSICAL METHODS

Geophysical research methods in geothermy are widely addressed both in Russia and abroad to solve primarily structural problems. The structure of the crystalline basement of geothermal artesian basins was studied, a system of regional tectonic blocks and deep faults that control convective heat fluxes was identified; the position of magmatic and fluid feeding systems was located by means of seismograph investigations (correlation of refraction shooting and the earthquake converted-wave method), the magnetotelluric sounding method and gravimetry by the example of the largest geothermal regions of the World (Geysers, USA, Larderello-Travale, Italy, Kuril-Kamchatka province, Russia, etc.), (Aprelkov et al., 1979; Masurenkov, 1980; Gianelli et al., 1997; Stimac et al., 2001). The traditional and new approaches and methods of geophysical research have made significant progress in studying the structure of modern hydrothermal systems and geothermal deposits in many regions of the World: North and Central America, Northern Africa, Western Europe, Southeast Asia, the Russian Far East (Sugrobov, 1985; Benz et al., 1992; Bernabini et al., 1995; Moroz et al., 2013). Development of geophysical research is largely caused by attention that the World community pays to geothermal resources as renewable sources of thermal and electric energy (Lund and Boyd, 2015). In this regard, the main body of information on the modern hydrothermal systems and geothermal deposits has been obtained recently.

In order to understand the problems of fundamental and practical geothermy, as well as the opportunities and possibilities of studying modern hydrothermal systems with geophysical methods in more detail, we will review the recent global research experience in this field.

Magnetotelluric sounding (MTS) and its variations are among the most commonly used geophysical methods of geothermy research, because they are based on the study of the natural variability of the Earth's electromagnetic field within a wide range of depths: from tens of meters to first kilometres (AMTS), to tens (MTS) and hundreds kilometres (DMTS) (Berdichevskii and Dmitriev, 2009; Spichak and Manzella, 2009). MTS helped in identifying anomalous regions within the structure of the Earth's crust that includes geothermal regions most often interpreted as hydrothermally altered highly porous fluid-saturated rocks. Negative anomalies (zones of reduced electrical resistivity of rocks) form localized regions in hydrothermal systems confined to volcanic calderas and rift structures (Moroz et al., 2013; Lichoro, 2015; Omiti, 2015). Reduced resistance zones mainly correlate with heavily hydrothermally altered (argillized) rocks and modern tectonic faults permeable to mineralized saline solutions; they indirectly reflect temperature changes of the geological environment (Los Bafios et al., 2010; Bertrand et al., 2013; Karlsdottir et al., 2015). Magnetotelluric data allow identification of the structural elements of paleohydrothermal systems: the anomalies of relatively high electrical resistances in the central Philippine Fault Zone are confined to unaltered intrusive bodies, whereas the anomalies of low resistances are confined to sedimentary rocks and heavily illitized and smectitized diorite masses with gold-copper mineralization (Africa et al., 2015). At the same time, the magnetotelluric sounding methods do not yield unambiguous results in investigating the regions with dissected topography and high heterogeneity of the geological environment, which is more typical of recent volcanism areas (Arnason et al., 2010). Besides, magnetotelluric studies mainly solve regional problems.

The modern methods and equipment for seismological investigations first determine location and physical parameters (sizes, boundaries) of geothermal reservoirs in vapour-dominated systems. Liquid-vapour transition zones (Zhatnuev et al., 1996) are differentiated by high microseismicity due to boiling of superheated fluid (Tosha et al., 1998; Dangel et al., 2003), which allows studying the volumetric structure of these regions by means of seismic tomography (Husen et al., 2004; Delliansyah et al., 2015). Over the recent years, methods that use the effect of absorption of low-frequency waves in fluid-saturated zones have been developed for identifying vapour-dominated geothermal reservoirs and deep reservoirs of superheated water (Gorbatikov et al., 2008; Buness et al., 2010; Casini et al., 2010). The authors of this paper have demonstrated the structure of the boiling section of hydrothermal fluids of the Nizhne (Lower) Koshelevsky geothermal deposit (Southern Kamchatka): the dry vapour zone is not located in a single space structure, as noted in (Pisareva, 1987), but hosted in subvertical channels 150–200 m thick that are dipped in the apical part of the multiphase intrusion of diorites–diorite porphyrites (Rychagov et al., 2018). More traditional are microseismic studies, which address the geometry of discontinuous tectonic faults that control infiltration water flows in geothermal deposits (Wolfe, 2007; Mujihardi et al., 2015). The geothermal reservoirs are highly dynamic systems: medium $P$–$T$ parameters are variable both under the influence of deep fluid fluctuations and seasonal changes in the water mass balance. This trait of modern hydrothermal systems of various hydrodynamic types (vapour- and water-dominated ones) is actively used in seismic monitoring of the physical parameters of geothermal environment (Clarke et al., 2009; Bannister et al., 2010; Moya and Taylor, 2010). Thus, seismological investigations contribute significantly to the study of the structure of geothermal systems and deposits.

Precision gravimetric studies of geothermal deposits have a great scientific and practical value. In addition to solving traditional problems, such as isolating intrusive bodies and tectonic blocks of rocks with increased density (Kusumah et al., 2010; Martakusumah et al., 2015), the gravimetric studies are considered effective for monitoring changes in the physical parameters of a medium when operating geothermal deposits (Allis and Hunt, 1986; Nordquist et al., 2004; Cabezas, 2010). In this manner, Nishijima and colleagues detected a change in the gravity field in the production zones of the Takigami geothermal field (Japan) by an average of 50–75 μGal for the period from 1990 to 2004 (Nishijima et al., 2010). The $\Delta g$ of production zones of the Wairakei geothermal field (New Zealand) decreased by 1000 μGal over 30 years of operation (Allis and Hunt, 1986). Besides, seasonal fluctuations of the gravity field were detected as a result of gravimetric monitoring, which reflects a change in the mass balance of the hydrothermal system due to additional influx of meteoric waters (Sofyan et al., 2010; Nishijima et al., 2015). Thus, changes in the gravity field within the structure of hydrothermal systems are associated with the dynamics of hydrothermal flows and meteoric waters. To support this thesis, we can consider the experiment conducted on the Cerro Prieto (Mexico) geothermal field, which involved electromagnetic observations: the electrical conductivity of a medium changes after earthquakes, while the general structure of fluid-saturated zones is maintained. Since the geothermal field is located in the region of influence of the deep active fault, the authors of the study explain this phenomenon by the influx of large masses of mineralized solutions into the fault zone as a response to a change in the deformation field of the Earth (Cortes-Arroyo et al., 2015).

Magnetometric and aeromagnetic ground investigations are traditionally conducted mainly in poorly studied geothermal areas to identify fault zones and fields of hydrothermally altered rocks (Ebbing et al., 2009; Aboud et al., 2011; Soengkono, 2015). However, these data combined with other data carry additional information about the structure and physical properties of the geothermal medium.

In general, there is a consistent trend in the latest geophysical research in geothermy: comprehensive geophysical work is conducted, and data from synthesis of detailed geological, hydrogeological and mineralogical-geochemical investigations are interpreted (Idral, 2010; Idral and Mansoer, 2015; Mwakirani, 2015). This methodology ensures maximum integrity of the results, and thus it is used in this article.

## THE HISTORY OF THE PAUZHETKA DEPOSIT

The first knowledge about the Pauzhetka district geothermal springs dates to the 18th century. S.P. Krasheninnikov, a famous Russian explorer, described “hot springs, fountains, lakes” located in the valley of the Paudzha River in enough detail (Krasheninnikov, 1755). These unusual and rich features of the modern geological processes were in the focus of attention of many scientists and naturalists of the 19–20 centuries (Komarov, 1912; Novograblenov, 1932; Semenov, 1988; Steller, 1999; Ditmar, 2009). In the USSR, systematic geological, geophysical, and hydrogeological studies were conducted in the Pauzhetka district and, in particular, at the discharge area of thermal springs to obtain data on the conditions of their formation, to map hydrogeological structures that control thermal regimes, to study the balneological properties of solutions, etc. (Piip, 1937; Ivanov, 1956, 1961; Aver’ev, 1961). In implementation of the Decree of the Presidium of the USSR Academy of Sciences of March 15, 1954 and as a follow-up of the hydrogeothermal surveys conducted in 1955–1957, A.S. Nekhoroshev and V.V. Ivanov inferred the presence of superheated thermal waters in the depths of the Pauzhetka hydrothermal system. It was then that the first boreholes were drilled, geothermal resources were estimated, and the geothermal deposit was delineated (Piip, 1965). The Pauzhetka GeoPP, the USSR’s first geothermal plant with the electric capacity of 11 MW, was built. The GeoPP has been sustainably operated since 1967. The history of the Pauzhetka geothermal deposit is described in more detail in (Rychagov, 2017). Ongoing drilling (until the 1980s), the observations of the hydrogeochemical regime and the case studies helped the structure of the geothermal deposit to be clarified. Review of the data on the geological structure of the deposit is provided below.

## GEOLOGICAL DESCRIPTION OF THE AREA, HYDROTHERMAL SYSTEM AND GEOTHERMAL DEPOSIT

The Pauzhetka-Kambalny-Koshelevka geothermal (ore) region (the more precise name of the Pauzhetka region (Rychagov, 2003, Rychagov et al., 2009)) is a part of the Southern Kamchatka geothermal province (Aver’ev, 1966; Sugrobov, 1979) and is situated within the inner zone of the Kuril-Kamchatka island arc at the junction of the three main volcanic belts of Kamchatka (Aprelkov, 1971). The region occupies the central position in a subcircular tectonic-magmatic structure, which is a slightly sloping accumulative tectonic anticline 35×50 km in size, complicated by a Quaternary volcano-tectonic depression (a caldera?) (Masurenkov, 1980). Thus, the Pauzhetka-Kambalny-Koshelevska geothermal (ore) region is associated with the long-lived Rychagov Southern Kamchatka volcanogenic-ore centre (Sugrobov, 1976; Vasilevskii, 1977). The development of the region is manifested by three structural stages: the lower one is composed of Oligocene-middle Miocene volcanogenic-sedimentary rocks containing multiphase intrusive bodies from gabbro to plagiogranites; the middle one is formed by volcanogenic-sedimentary strata of the middle Miocene–Pliocene; the upper stage corresponds to the Quaternary stage of development of the island arc and is composed of lavas, tuffs, and Pleistocene–Holocene intrusive rocks of intermediate and acidic composition (Sergeev and Krasnyi, 1987). The area includes three main geological and hydrogeological structures that determine its structure and control the position of geothermal fields: Pauzhetka hydrothermal system, Kambalny volcanic ridge and Koshelevsky volcanic massif (Rychagov et al., 1993). The structures were formed at the Quaternary stage of development of the Kuril-Kamchatka island arc, with their base composed of middle stage rocks containing inclusions of gold-sulphide ores.

The Pauzhetka hydrothermal system is confined to the central part of a volcano-tectonic depression of the same name (Masurenkov, 1980) (a caldera according to other sources) and manifests the modern (Holocene) stage of development of the long-lived Pauzhetka hydrothermal-magmatic system, the detailed information about which is described in the book (Rychagov et al., 1993). Therefore, we will briefly discuss the setting of the modern hydrothermal system (Fig. 1). According to the hydrodynamic classification, the Pauzhetka hydrothermal system is a water-dominated one. Two aquifers are identified within its structure: the upper one is associated with coarse-grained and macrofragmental tuffs of the Srednepauzhetka and Nizhnepauzhetka subformations, whereas the lower one is confined to the agglomerate tuffs of the Alneyan Group (Fig. 2). The aquifers are separated by two water-confining strata: the upper water-confining stratum is composed of tuffites of the

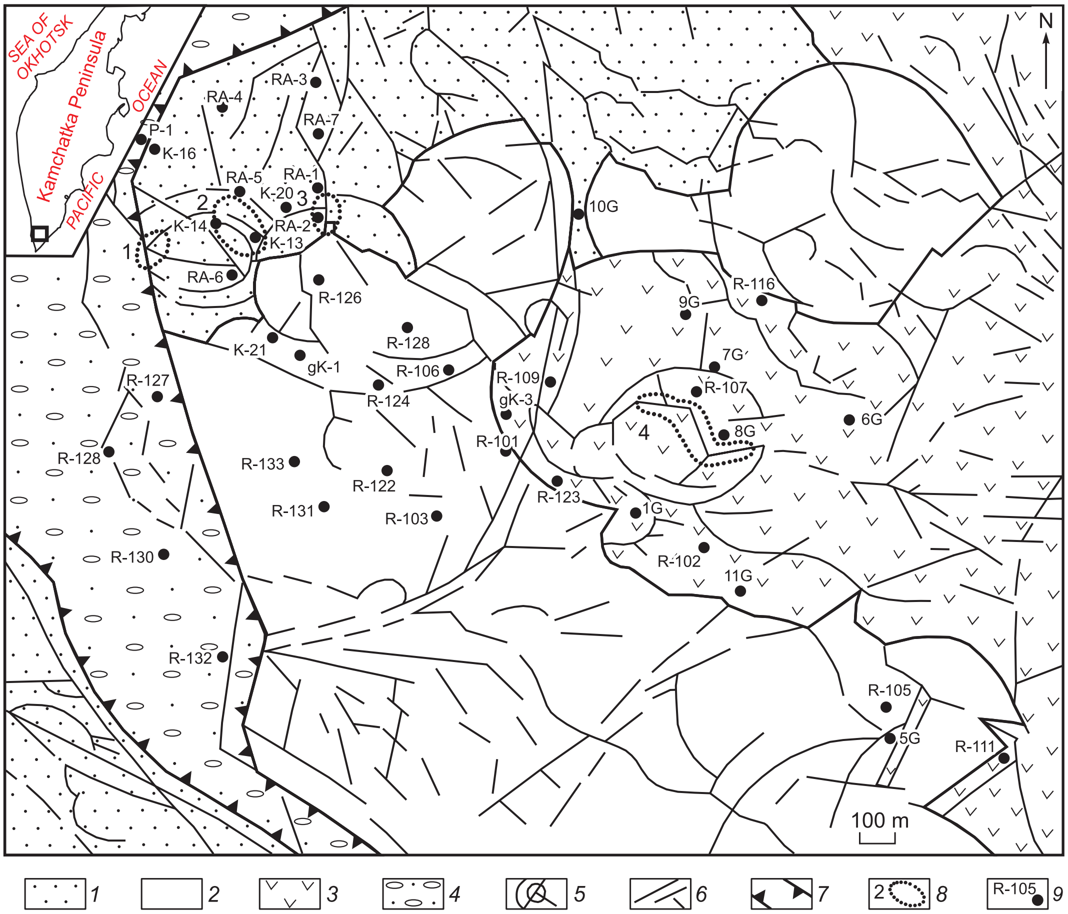

**Fig. 1.** Schematic geological map of the Pauzhetsky hydrothermal system (from Rychagov et al. (1993)). *1*, tuffites and tuffs of the Verkhnepauzhet Formation of upper Neogene-lower-Quaternary Age; *2,* lava-extrusive complex of acid rocks of Middle Quaternary Age; *3*, andesites and andesibasalts of Middle Quaternary Age; *4*, alluvial boulder-pebble deposits; *5*, ring tectonic faults that delineate elevated blocks of rocks and control the position of thermal fields; *6*, linear tectonic faults; *7*, Pauzhetka graben of upper Quaternary Age; *8*, thermal fields: 1, South Pauzhetka, 2, Upper Pauzhetka, 3, Lower Pauzhetka, 4, East Pauzhetka; *9*, drill holes.

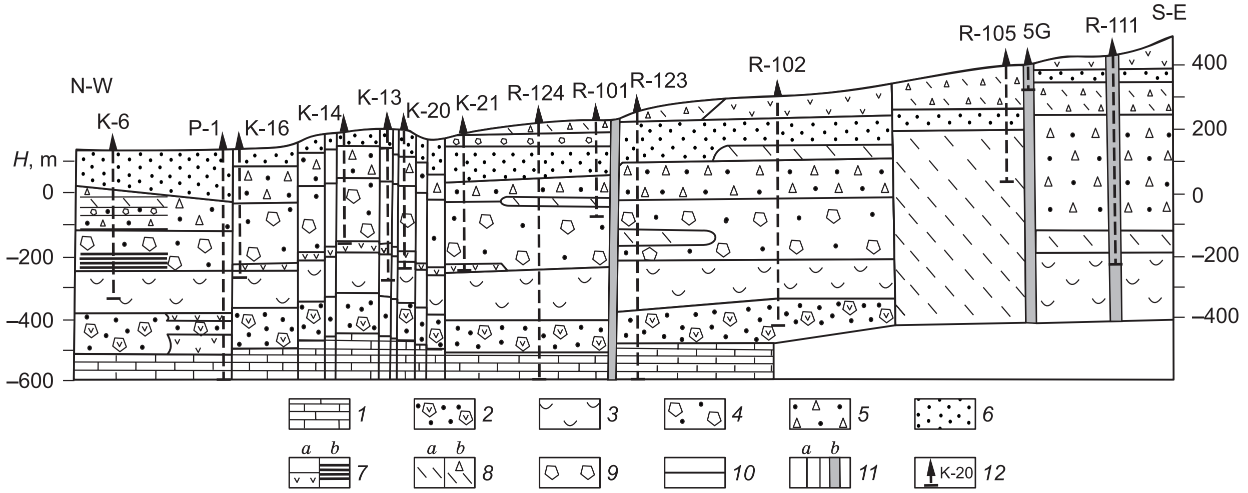

**Fig. 2.** Geological cross-section of the Pauzhetka hydrothermal system (according to Rychagov et al. (1993). *1*, volcanomictic sandstones at the foot of the section, Anavgai Group; *2*, agglomerate tuffs (tuff breccias) of andesibasaltic composition, Alneyan Group; *3,* rhyolite crystallolitho-vitroclastic coarse-grained tuffs, Golygin Formation; *4*, coarse-grained litho-vitroclastic tuffs of andesite composition, Nizhnepauzhet subformation; *5*, coarse-grained tuffs of andesidacites, Srednepauzhet subformation; *6*, tuffaceous-sedimentary deposits of acidic and intermediate composition, Verhnepauzhet subformation; *7*, andesites and andesibasalts of presumably Pliocene-lower Quaternary Age: *a*, large bodies of lavas and subintrusive microdiorites, *b*, dikes; *8*, middle-upper Quaternary extrusions (*a*) and lavas (*b*) of dacites; *9*, lava breccias of bottom of lava flows and edge parts of extrusive bodies; *10*, lithological and intrusive boundaries; *11,* tectonic dislocations: *a*, faults, *b*, zones of elevated fracturing of rocks; *12*, prospecting and exploration wells.

Verhnepauzhet subformation, and the lower one is composed of Golygin ignimbrites. Apparently, the Anavgai sandstones that underlie the cross-section also act as a water-confining layer (Piip, 1965; Belousov, 1978; Rychagov et al., 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 the solutions in the lower aquifer reaches 220 °C (Piip, 1965). Based on detailed petrophysical, petrographic and 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 fluids within thermal fields were elevated tectonic and (or) tectonic-magmatic blocks (Pampura, 1985; Pampura and Sandimirova, 1991; Rychagov et al., 1993). One of such blocks, to which the Upper Pauzhetka thermal field (t/f) is confined, is in the central part of the Pauzhetka geothermal deposit (Figs. 1, 2). A thick long-lived liquid-vapour transition zone (boiling of hydrothermal fluids) was identified within its structure (Zhatnuev et al., 1991). Breccias of tectonic or hydrothermal (hydrothermal-metasomatic?) origin are formed in the near-surface horizons of the block; the breccia matrix contains quartz-adular metasomatites. A complex ore geochemical barrier (Au–Ag–As–B–K–Li–Rb) is confined to these recent 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 the other blocks of the deposit (Rychagov et al., 1993). Despite the high cavern porosity of quartz-adular metasomatites, they have higher density and lower permeability for hydrothermal fluids, as compared to the surrounding pyroclastic rocks of the Pauzhetka Formation.

Upper Pauzhetsky t/f is located at absolute elevations of 150–180 m on a nearly isometrically shaped hill. The field is 150 by 200 m in plan (the border of the t/f is marked along a 20-degree isotherm at the depth of 0.6–0.8 m) and extended in the northwestern direction along the flat-dipping surface. Thermal outcrops are manifested as mud-water boiling pots, gas-vapour jets and steaming soils (hereinafter, grounds are clastic, mainly deluvial sediments that form a cover of argillised dispersed rocks on the surface of thermal fields (Vakin et al., 1976; Trofimov et al., 2005). A large 8–10 m wide boiling mud pot is notable in the centre of the field. Separate small elevations (thermal mounds) with the most heated soils (98–105 °C) are also confined to the central part. The temperature of the aqueous phase does not exceed 98 °C, whereas the vapour-gas temperature reaches 103.5–108.5 °C. The waters that are discharged on the surface are slightly acid (pH = 3.5–5.5) sulphate and hydrocarbonate-sulphate of complex cationic composition (Ca–Na–Mg–K–$NH_4$–Fe–Al–...) with general mineralization of ≤0.8–1.0 g/L. The free and dissolved dry gas mainly contains carbon dioxide. Hydrothermal clays form a continuous stratum near the surface (Rychagov et al., 2009), the boundaries of which have not been defined (they are beyond the 20-degree isotherm).

Geophysical investigations at the Pauzhetka geothermal deposit were conducted in the 1960s. Areal thermometric, magnetic prospecting, electrical prospecting and gravity prospecting works on a scale of 1:10,000 were performed under the leadership of I.M. Zaytsev (unpublished data). The results of those studies were discussed in detail in (Feofilaktov et al., 2017). The area of the Upper Pauzhetka thermal field is identified by increased temperatures of soils and the local negative magnetic field anomaly $\Delta Z_a$. The area of low $\Delta Z_a$ values and high temperatures is traced along the valley of the Bystryi Stream from East to Upper Pauzhetka t/f. A horizon of low electrical resistance of rocks (3–10 Ohm·m) comprised of watered coarse-grained tuffs is identified.

At the initial stage of deposit operation, geothermal regime observations were held under the leadership of V.M. Sugrobov (unpublished data). Vapour-water jets were experimentally released from boreholes located near or directly at the Upper Pauzhetka thermal field, and as a result, the level of thermal waters sharply dropped and then completely restored within a few days after the releases. Such hydrodynamics indicates the existence of a system of vertical and subhorizontal zones with high fracture-pore permeability for fluid at the boundary of the thermal field or under it. However, the location of these zones and their origin were not determined.

Geophysical studies at the Pauzhetka geothermal field were resumed in recent years by the authors of this article (Bukatov et al., 2011; Nuzhdaev and Feofilaktov, 2014; Feofilaktov et al., 2017).

## INSTRUMENTATION AND METHODS OF SURVEY

Comprehensive geophysical studies were conducted in the area of the Upper Pauzhetka t/f: temperature surveys of soils, electrical prospectings by vertical electrical sounding (VES) and self-potential (SP) methods, magnetic and gravity prospecting.

An irregular survey grid (Fig. 3*a*) was employed for temperature surveys of soils. The temperature of the soils was measured at the depth of 60–80 cm according to the generally accepted technique (Vakin et al., 1976), which excludes the impact of daily temperature fluctuations and weather conditions on the regime of the thermal field. A portable multimeter and a set of commercial calibrated thermocouples were used. The measurement accuracy was 0.5 °C. A Garmin 62s GPS navigator was used to set up the survey stakes; the accuracy of coordinates was 3–5 m.

**Vertical electric soundings (VES)** were conducted by symmetric quadripole AMNB electrode arrays. The maximum half-spacing of the power supply line (AB/2) varied within 250–500 m. The soundings were done at 12 points with irregular spacing along the profile from the northwest to the southeast (Fig. 3*b*). Each point was measured from 15 to 17 times to obtain detailed sounding curves. One VES point was completed with maximum spacing of AB/2 = 1500 m. The power supply lines were laid along the profile. The obtained curves are of H type at the periphery of the field and of KH type in the centre. The instruments that were used for the measurements were a MERI multifunction electrical prospecting gauge (manufactured by OOO Severo-Zapad, Russia), an VP-1000 electric survey generator (manufactured by OOO Elgeo, Russia) and a Yamaha EF2000iS inverter generator. The data obtained were processed in office by using the special IPI2win software package (OOO Geotekh, Russia). The measurement accuracy was ≤3% for one sounding location. Discrepancy between the theoretical and practical VES curves was ≤5%.

**Self-potential method (SP) measurements** were made using potential difference between the electrodes on a regular survey grid with a spacing of 20 m (Fig. 3*b*). The potential difference was measured between two non-polarisable electrodes: one was fixed, whereas the other one was moved along the survey points. The time of one measurement was governed by stability of the potential difference values on a digital multimeter and was ≥2 min. The electrodes were shorted prior to work to equalize the potentials. The measurement results were recorded in a field logbook. Check surveys amounted to 25% of points. The standard error of the measurements was ≤3 mV. The resulting data array was used for graphical plotting.

We performed **areal magnetic investigations** repeatedly and at various scales. Two GSM-19W Overhauser effect magnetometers (GEM Systems, Canada) were used for taking measurements. One instrument was used as a magnetovariational station, and the second one was used for ordinary measurements, which increased both the speed and the quality of the survey. The error of readings between the instruments was ≤ 0.1 nT (Nuzhdaev et al., 2014).

The **gravimetric survey** was done with a CG-5 Autograv automatic microprocessor-based gravity meter (Scintrex, Canada). The measuring range of the instrument was >7000 mGal, the resolution of the readings was 0.001 mGal. Areal measurements of the gravity field were taken over the whole grid of 50×50 m and with bridging in the central part to 10×20 m (Fig. 3*c*) (Bukatov et al., 2011). Repeated surveys were conducted along the profile that crosses the t/f from the northwest to the southeast. Check measurements were taken for 15% of the points with a standard measurement error of 0.03 mGal. One reference point was located on a concrete base near the borehole K-14 to consider the instrument drift. The location of this point did not change for surveys in different years, whereas the observation areas overlapped each other, which enabled inclusion of all the results into a single data array.

Geodetic support included Trimble or Leica GR 10 GPS stations with Topcon or AR 10 antennas. Various sets of instrumentation were used in different years. One station served as the base, while the other was moved along the profiles. The point recording time was ≥15 min. The coordinates and heights were measured at reference points to consider the error of instrumentation. One of the reference

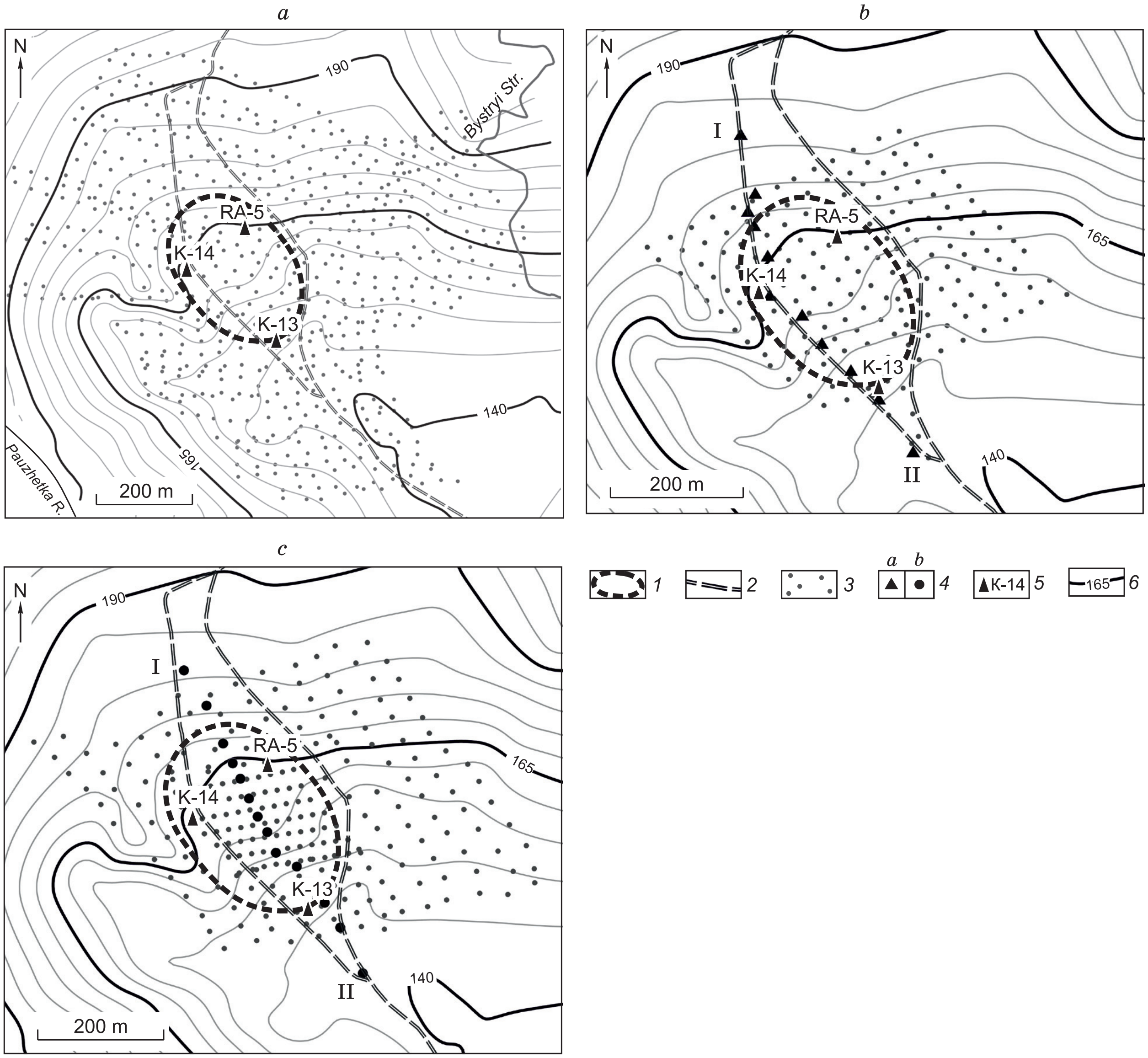

**Fig. 3.** Mapping of information derived from geophysical observations in the area of the Upper Pauzhetka t/f: *a*, temperature survey, *b*, electrical prospecting, *c*, gravity prospecting. We used the magnetic surveys as a topographic base. *1*, averaged contour of the thermal field drawn along the 20-degree isotherm; *2,* roads; *3*, points of geophysical observations in the research area; *4,* VES (*a*) and gravimetry (*b*) method measurement points for profiles; *5*, geothermal wells.

points was located on a pedestal near the borehole K-14. This enabled linking the altitude maps of different years of surveys. Catalogues of coordinates and heights were obtained for all the profiles. The height measurement accuracy was ≤7 cm.

## FACTUAL INFORMATION AND ITS INTERPRETATION

Based on the temperature survey, a large heated region of a complex shape was identified (Fig. 4). The central anomaly forms an oval that is elongated to the northeast and matches the contour of the Upper Pauzhetka t/f that was demonstrated earlier (Fig. 1). The most heated (up to 50–107 °C) area is oriented sublatitudinally and probably traces the zone of upward heat flux elongated radially in the circular structure of the elevated tectonic block. The area is where thermal waters and steam discharge on the surface. It is described above. The general thermal anomaly, the boundaries of which are drawn along the isotherm of 20 °C, is also elongated sublatitudinally and includes separate local heated spots. The western concentric anomaly is actually adjacent to the South Pauzhetka thermal field, which goes beyond the temperature survey due to the swampiness of the site and the rugged topography. The oval-shaped eastern area extends towards the Lower Pauzhetka t/f towards the previously

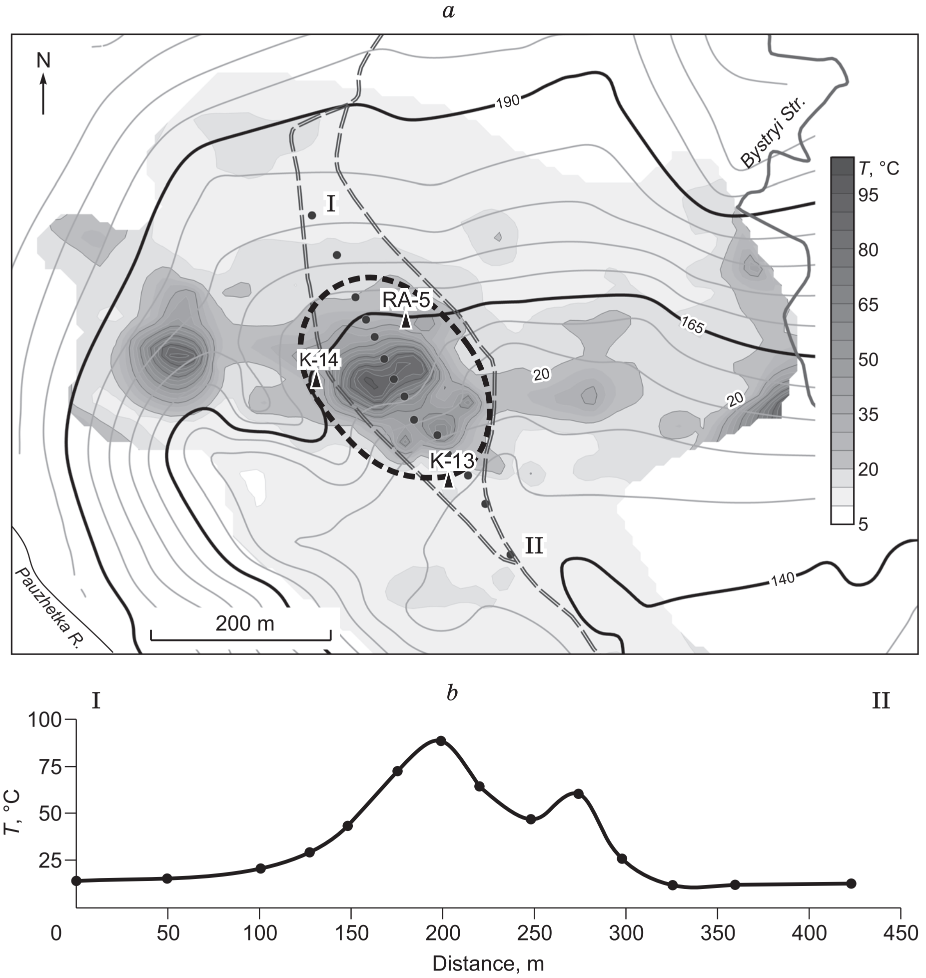

**Fig. 4.** Distribution of soil temperatures across the area (*a*) and the section (*b*). The remaining symbols here and below match those in Fig. 3.

identified hot zone tracing the fault of the Bystryi Stream. Thus, a certain structural pattern is observed in the soil temperature distribution diagram, which, on the one hand, as a whole, correlates with the radial-circular tectonic structure of the elevated block, on the other hand, it can also be caused by the complex nature of the articulation of the two circular blocks shown in Fig. 1.

**Electrical prospecting** was carried out to study the structure of thermal water flows and zones of vapour and gas saturation of rocks in the area of the Upper Pauzhetka t/f.

Based on VES, apparent resistivity and geoelectric sections of the distribution of the electrical resistivity of the medium were plotted. The pseudoelectric section (Fig. 5) features horizontal differentiation of values in the upper part of the section AB/2 – up to 100 m. Low electrical resistivity area is in the central part of the thermal field and confined directly to the discharge site of steam hydrothermal fluids. The area is delineated by rocks with high electrical resistivity from north and south. The northern boundary of the contact has a flat dip, whereas the southern one dips subvertically.

The geoelectric section (Fig. 5) is characterized by the following parameters (from top to bottom):

a) near-surface horizon, electrical resistivity = 200–2000 Ohm·m. Its thickness is 1.5–3 m in the northern part of the section, and it increases up to 10 m in the southern part; the horizon wedges to the day surface in the central part. The rocks are mainly finely clastic diluvial sediments with inclusions of topsoil and hydrothermal clays of kaolinite-montmorillonite composition. In general, the sediments are weakly permeable for surface meteoric waters and condensate hydrothermal fluids circulating in the base of the stratum;

b) horizon with minimum values (2–7 Ohm·m) and extending to the main part of the section. It consists of two layers. It is composed of the Pauzhetka Formation coarse-grained tuffs (the upper layer is composed of finer clastic tuffs and tuffites) that are hydrothermally altered and permeable to a geothermal medium. The thickness of the horizon varies from 80 to 220 m. According to Rychagov et al. (1993), this area corresponds to the upper aquifer of the deposit structure. Apart from the lithological features of the section, the presence of two layers is explained by different composition of the aqueous phase: rocks are mainly saturated with hydrocarbonate solutions coming from the depths and the upper “lens” is saturated with condensate sulphate waters;

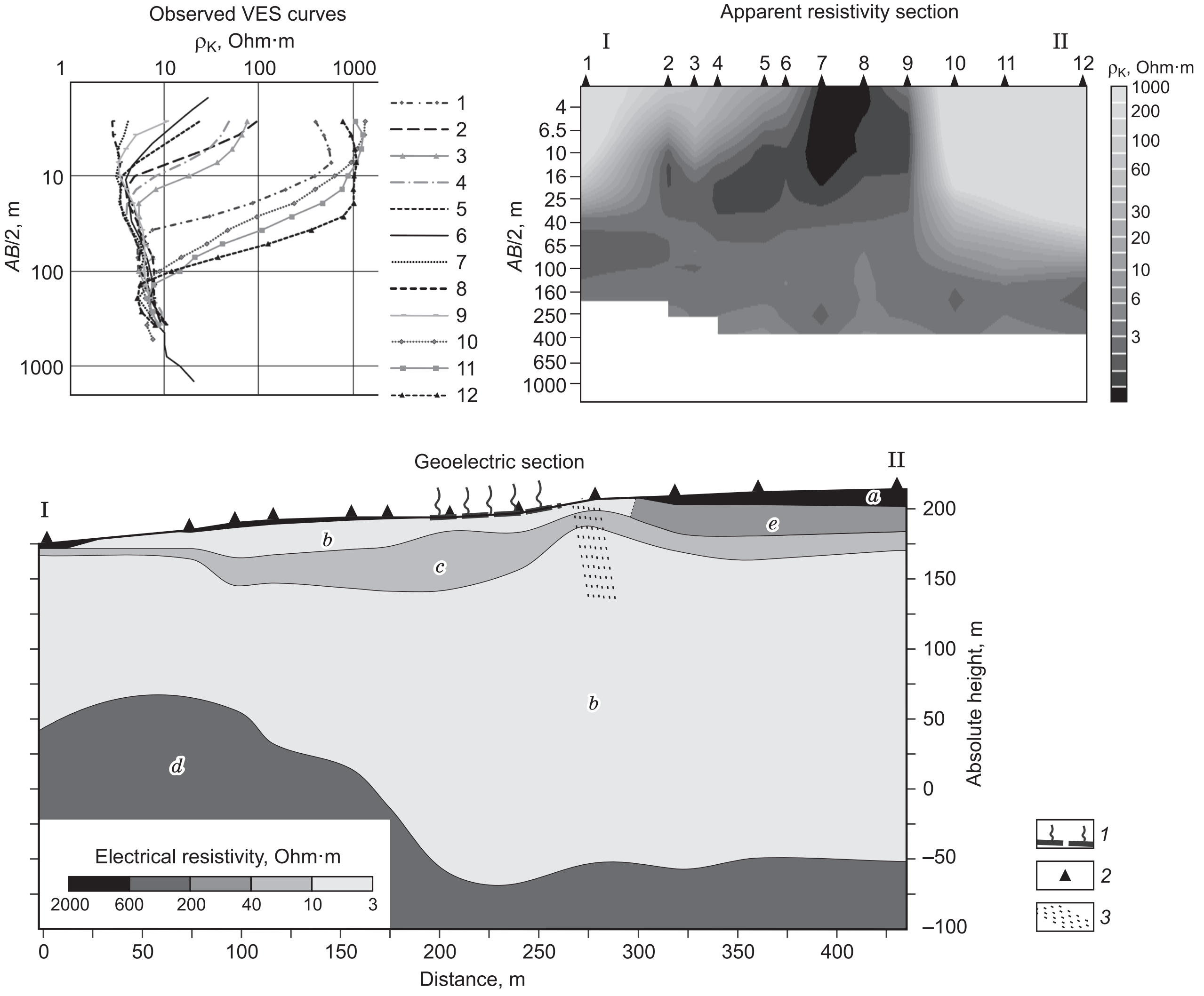

**Fig. 5.** Apparent resistivity and geoelectric sections of the area of the Upper Pauzhetka t/f: *a-d*, layers that have electrical resistivity values that are contrasting with the medium (see the text). *1*, the area of discharge of vapour hydrothermal solutions on the surface; *2*, VES points; *3*, uniformity-loss zone.

c) an intermediate horizon with electrical resistivity equal to 10–25 Ohm·m is identified inside the conductive layer (b). Its thickness varies from 5–10 m at the edges of the section to 40 m in the central part. Based on study of the core from the borehole K-14, the rocks of this horizon are composed of relatively dense but fractured tuffs; pores are filled with zeolites, pyrite, silica minerals; a significant number of cracks are open. Probably, this horizon can be considered an intermediate water-confining stratum in the Upper Pauzhetka aquifer;

d) underlying horizon with electrical resistivity equal to 100–400 Ohm·m. The depth of the upper boundary varies from 65 m in the northwestern part of the profile to 250 m in the southeast one. The lower boundary has not been identified. Judging by properties of the core from the borehole K-14, the rocks of this horizon are composed of fractured but dense andesitic tuff breccias. The geoelectric parameters and composition of the rocks suggest that this horizon refers to the water-confining stratum;

e) area with electric resistivity equal to 40–60 Ohm·m. In terms of the cross-section, this interlayer is a continuation of horizon "b" but has an increased electrical resistivity of the medium. In view of the recent geological data, relatively high values of electrical resistivity in this part of the horizon can be explained by lateral lithological heterogeneity of the cross-section: at the boundary of the thermal field, UPP-5/11 borehole penetrated the upper part of the flow of lavas of dacites that had been completely transformed into opalites.

Based on the highly contrasting electrical properties of the medium and the differences of the levels of geoelectric horizons, it is assumed that there is a zone of permeable tectonic fault at the southern border of the Upper Pauzhetka t/f, along which thermal waters are filtered to the surface. Iden-

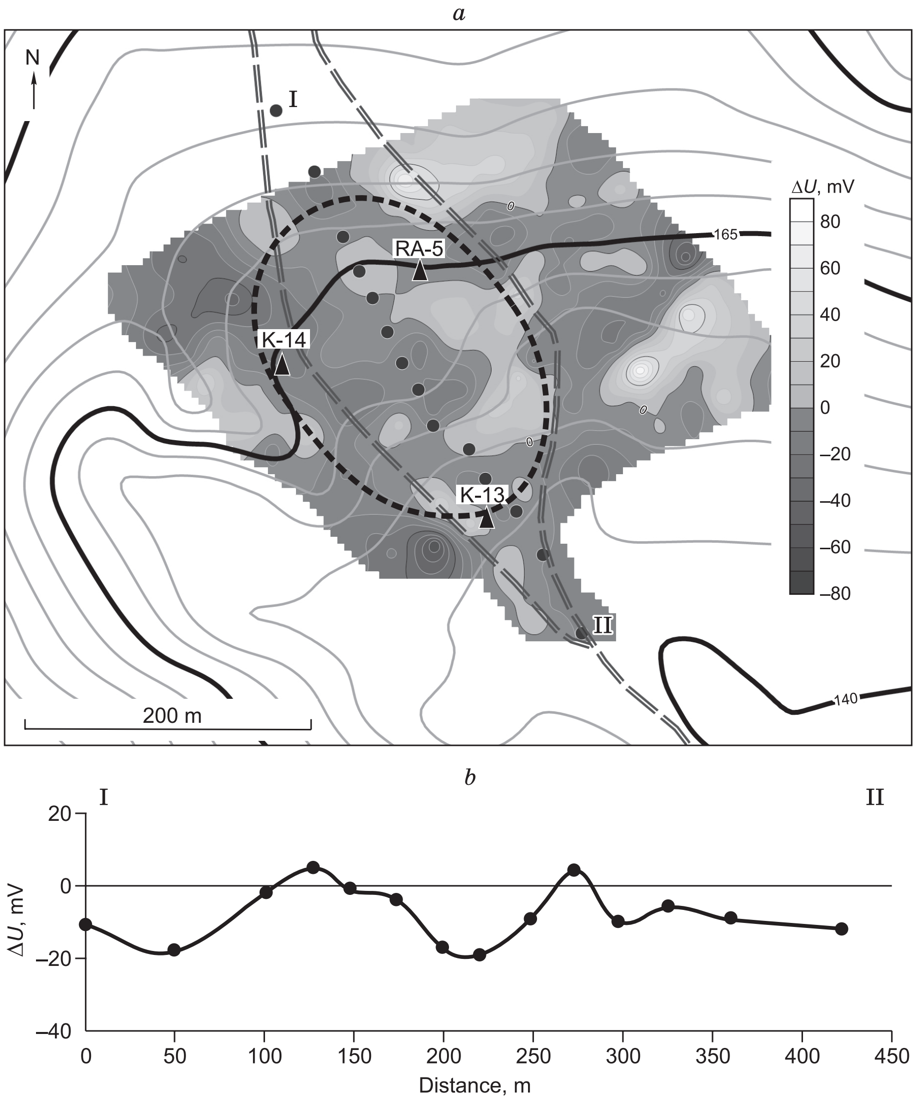

**Fig. 6.** The diagram of distribution of the self-potential field values in the Upper Pauzhetka t/p: *a*, on the area, *b*, along the profile.

tification of this tectonic fault, which is permeable to hydrothermal fluids, confirms the previously formed beliefs about the tectonic structure of the geothermal deposit (Fig. 1).

Geoelectric investigations in the area of the Upper Pauzhetka t/f were also performed using the SP method (Fig. 6). The variation of the potential difference $\Delta U$ is from –80 to +75 mV. A significant part of the survey area is an area with a negative geoelectric field, where there are spots with positive values. The thermal field is in the region of low SP values ($\Delta U$ reaches –25 mV). The redistribution of potentials is due to the heterogeneous nature of the hydrothermal alteration of the rocks occurring near the surface, due to a contrasting change in the acid-base properties of non-uniformly argillised (acidic conditions), zeoliticized (alkaline conditions), or relatively weakly altered (near-neutral conditions) rocks. Therefore, the maxima of the SP values in the magnetic field ($\Delta T_a$) correspond to similarly shaped anomalous areas with a value of up to +200 nT, indicating that the rocks there are weakly altered.

Based on Profile I-II, a $\Delta U$ distribution graph is plotted, where steam hydrothermal fluids are most intensively discharged on the surface in the section of 125–250 m (Fig. 6*b*). Two peak values are in this interval: a maximum of 127 m and a minimum of 221 m. In the geological cross-section penetrated by the borehole K-14, the minimum $\Delta U$ values are confined to the zone of heavy hydrothermal-metasomatic alterations in the tuff stratum; alterations go along with heavy deposition of pyrite and other sulphides. According to preliminary estimates obtained by the maximum-slope method (Khmelevskoy, 1970), the depth of occurrence of an anomaly-forming body is 40 m. Such estimates correlate well with the VES data: a horizon of rocks with electric resistivity equal to 40–60 Ohm·m is distinguished in this depth interval.

The resultant map of distribution of the **anomalous magnetic field** for the Pauzhetka geothermal field demonstrates that the Upper Pauzhetka t/f region is identified by an isometric concentric-zonal structure with a negative anomaly

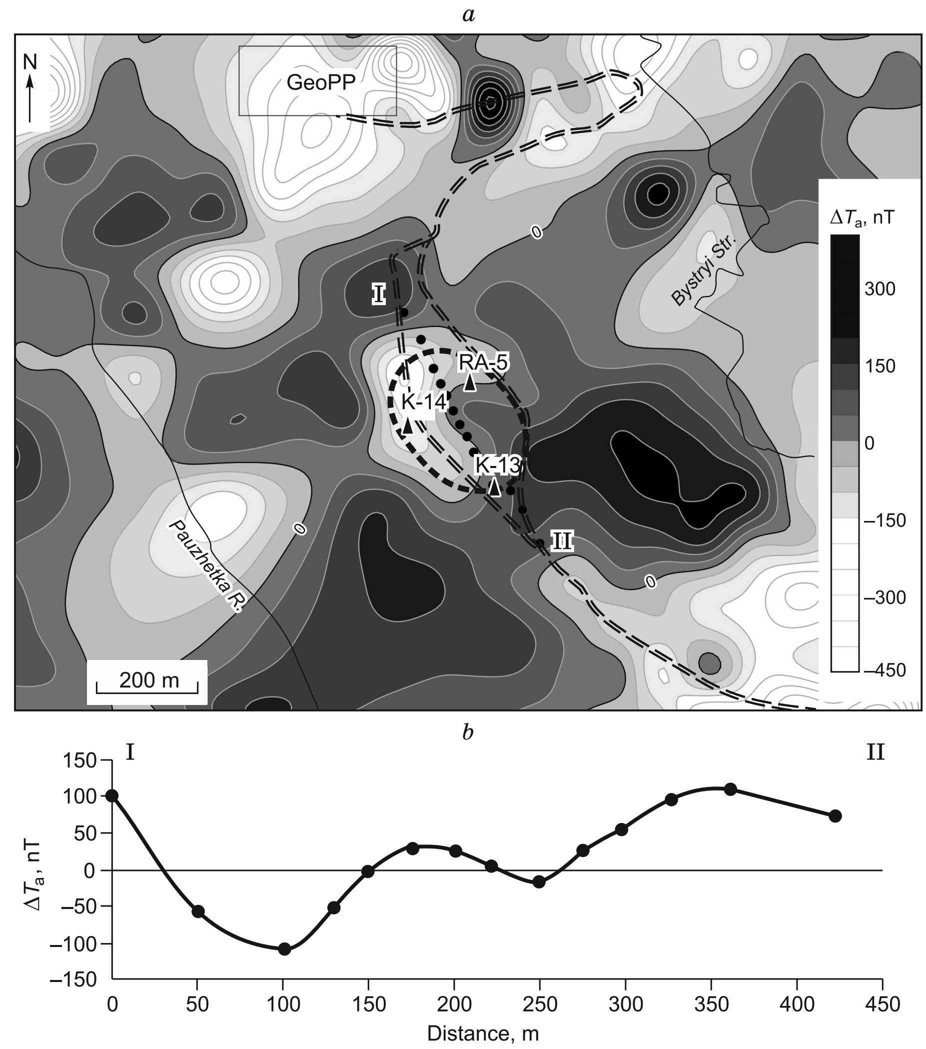

**Fig. 7.** A fragment of the map of the anomalous magnetic field of the Pauzhetka geothermal deposit (from (Nuzhdaev et al., 2014)): distribution of $\Delta T_a$ values on the area (*a*) and along the profile (*b*).

in the centre, positive anomalies around it and negative again near the boundaries (Fig. 7) (Nuzhdaev et al., 2014 ). The thermal field is confined to the negative anomaly $\Delta T_a$, which confirms the physical nature of the heterogeneity formed due to leaching of ferromagnetic minerals in the zone of rock argillization. A certain shift of the negative magnetic anomaly from the t/f contour to the west correlates with the VES data (Fig. 5) and can be explained by the active impact of the lateral flow of acidic thermal waters from the main discharge site on the host rocks. The localization of positive anomalies in a large isometric region that overlaps the area of the previously identified circular tectonic structure (Rychagov et al., 1993) is of great interest: $\Delta T_a$ anomalies with values ≥100–200 nT undoubtedly reflect the position of rocks with increased residual magnetization (weakly altered ones possibly including intrusive bodies). High-gradient negative anomalies near the boundaries of this region are confined to other zones of discharge of thermal waters of the South Pauzhetka t/f, the steaming area in the northwestern end, the hot zone that traces the Bystryi Stream.

The eastern part of the Upper Pauzhetka t/f is in the field of positive $\Delta T_a$ values. Based on assessments by the maximum-slope method (Nikitinskii, 1980), it can be assumed that the depth of occurrence of the upper edge of the anomaly-forming body is 30 m (Fig. 7*b*). Presumably, this body is a subintrusion of intermediate composition or the roots of dacite extrusions: sills, dikes, intrusions from diorites to rhyolites are widespread within the structure of the Pauzhetka hydrothermal system (Rychagov et al., 1993; Feofilaktov et al., 2017).

Based on the **gravimetric survey**, a map of the distribution of the gravity anomalies in the Bouguer reduction ($\Delta g$) was plotted for an intermediate layer density of 2.1 g/cm$^3$ (Fig. 8). The anomaly values grow from the west to east: from –1.1 mGal in the valley of the Bystryi Stream to +0.45 mGal in the Pauzhetka River valley. The Upper Pau-

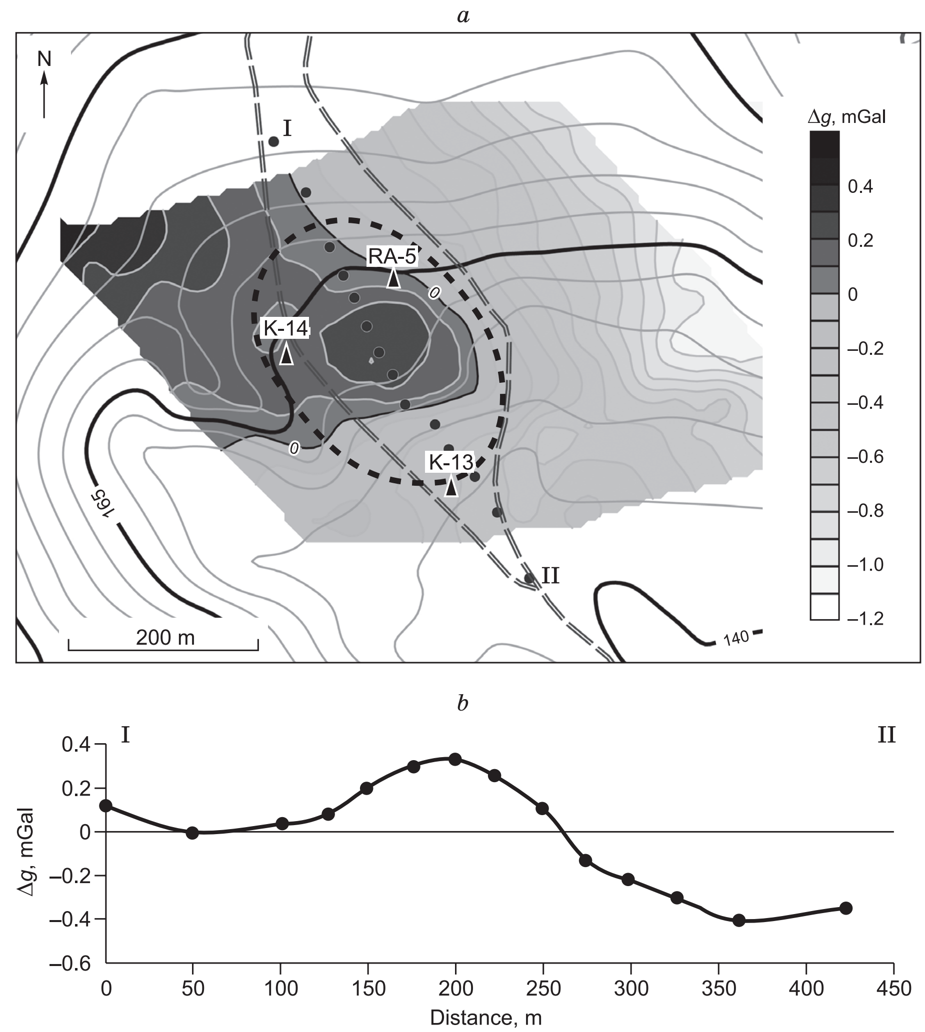

**Fig. 8.** The distribution of the values of the anomalous gravitational field for the Bouguer reduction (Δ*g*) on the area (*a*) and along the profile (*b*).

zhetka t/f is confined to the zone of local positive anomaly (up to +0.3 mGal). The anomaly values vary from –0.45 to +0.33 mGal on the map of the distribution of the gravity anomalies in the Bouguer reduction (Δ*g*) for an intermediate layer density of 2.1 g/cm$^3$. A positive anomaly Δ*g* is identified in the central part. Its peak value spatially correlates with the highest-temperature portion of the thermal field. It was preliminarily estimated by the material infinite slab inflection-tangent-intersection (ITI) method that the occurrence depth of the cylinder axis is 60–70 m and its radius is 104 m (Mudretsova and Veselov, 1990).

**The petrophysical properties of the rocks** on site were studied previously. According to the unpublished data of I.M. Zaitsev, the residual magnetism ($J_n$) of the thermal field's rocks varies from 0 to 6 A/m and the magnetic susceptibility (æ) varies from 0.00002 to 0.0126 SI. Basalts and andesites have the maximum level of residual magnetism and magnetic susceptibility – $J_n$ = 1–5 A/m, æ = 0.0037–0.044 SI and $J_n$ = 1–5 A/m, æ = 0.0125 SI, respectively. Siltstone tuffs have $J_n$ values that are close to zero and low æ values from 0.000025 to 0.0037 SI. Based on the research of Yu.V. Frolova with co-authors, the physical and physico-mechanical properties of tuffs (from slightly altered to zeoliticized and argillized) and hydrothermal clays of the Upper Pauzhetka t/f (Frolova et al., 2016) were determined. The average density of air-seasoned samples of slightly altered tuffs varies widely: 1.17–1.97 g/cm$^3$, which depends on the initial particle size composition of the rocks (from finely clastic to denser). The similar density of altered tuffs has a narrower range of values: 1.84–2.05 g/cm$^3$. Thus, the total density of the rocks slightly increases in the process of alteration of tuffs in the area of the Upper Pauzhetka t/f, but the density of solid particles decreases (from 2.85 to 2.52 g/cm$^3$) due to vigorous replacement of litho- and crystalloclasts with porous zeolites and smectites. Two different processes occur during argillization and zeolitisation: on the one hand, dense volcanic glass is replaced by porous smectites, and on the other hand, voids in tuffs are filled with smectites and zeolites. Source and altered rocks differ in terms of general porosity: 25–63% and 20–29%, respectively. Thus, vigorous hydrothermal-metasomatic processes lead to a general decrease of quantity of open large pores, but they sharply increase micro- and nanoporosity, hence the saturation of the rocks with moisture. This circumstance is very important for interpretation of electrical prospecting data.

The transformations of rocks mostly affect magnetic susceptibility, which decreases by an order of magnitude. Thus, æ of unaltered tuffs varies from $6–21 \cdot 10^{-3}$ SI, while the values of æ = $2.3–3.1 \cdot 10^{-3}$ SI correspond to altered tuffs. This trend reflects alterations of ore minerals: it is associated with decomposition of titanomagnetite. Clay horizons are formed by conversion of tuffs under impact of steam hydrothermal fluids; the density of the clay horizons is 1.4–1.6 g/cm$^3$, æ = $0.95–9 \cdot 10^{-3}$ SI. Thus, slightly altered tuffs and their hydrothermal-metasomatic variances differ mainly in density and magnetic susceptibility, as well as in the origin of porosity.

## THE GRAVITY-MAGNETIC MODEL DESCRIBING THE GEOLOGICAL STRUCTURE OF THE UPPER PAUZHETKA THERMAL FIELD

We compared the gravimetric and magnetometric data to identify a series of rock blocks along the profile I-II (Fig. 9). The model's upper single layer is associated with deluvial near-surface and surface sediments and with heavily argillized rocks (up to hydrothermal clays). The underlying stratum is divided into a series of blocks that have contrasting total density and magnetic susceptibility of the rocks. The central block with elevated density is located directly under the hot section of the Upper Pauzhetka t/f. The edge zones of the block are loose rocks. The identification of a block of loose rocks in the northwestern part of the profile is correlated with geoelectric and hydrodynamic data, since mixed acidic thermal waters spread in this part of the thermal field. It is known that the impact of acid hydrothermal solutions on rocks results in a significant decrease of their total and mineral densities and leaching of magnetic minerals (Ladygin et al., 2014).

It seems reasonable to distinguish the central block with contrasting physical properties with respect to the host rocks in view of mineralogical and geochemical data. Therefore, N.S. Zhatnuev and colleagues detected quartz-adular metasomatites that formed in fault zones due to boiling of superheated thermal waters (Zhatnuev et al., 1991, 1996). Metasomatites form cavernous but dense bodies in zones of discontinuous tectonic faults (they were detected in the cross-sections of boreholes K-13 and K-14) due to boiling of solutions and filling of cracks and open pores with silica gel, which eventually crystallizes into silica and potassium feldspar minerals. The upper edge of these bodies varies from 40–50 to 80 m. The same interval is marked with a change in the hydrodynamic regime and the presence of zones where hydrothermal and drilling fluids are absorbed in the borehole K-14. The exocontact zones of the bodies of quartz-adular metasomatites have elevated open permeability. It is likely that modern ascending hydrothermal fluids wash such bodies and the identified "dense" block and then discharge as steam-gas jets and steam condensate in the hot area of the Upper Pauzhetka t/f. Thus, the central block with properties contrasting with respect to the host rocks that was delineated within the model is consistent with the concept

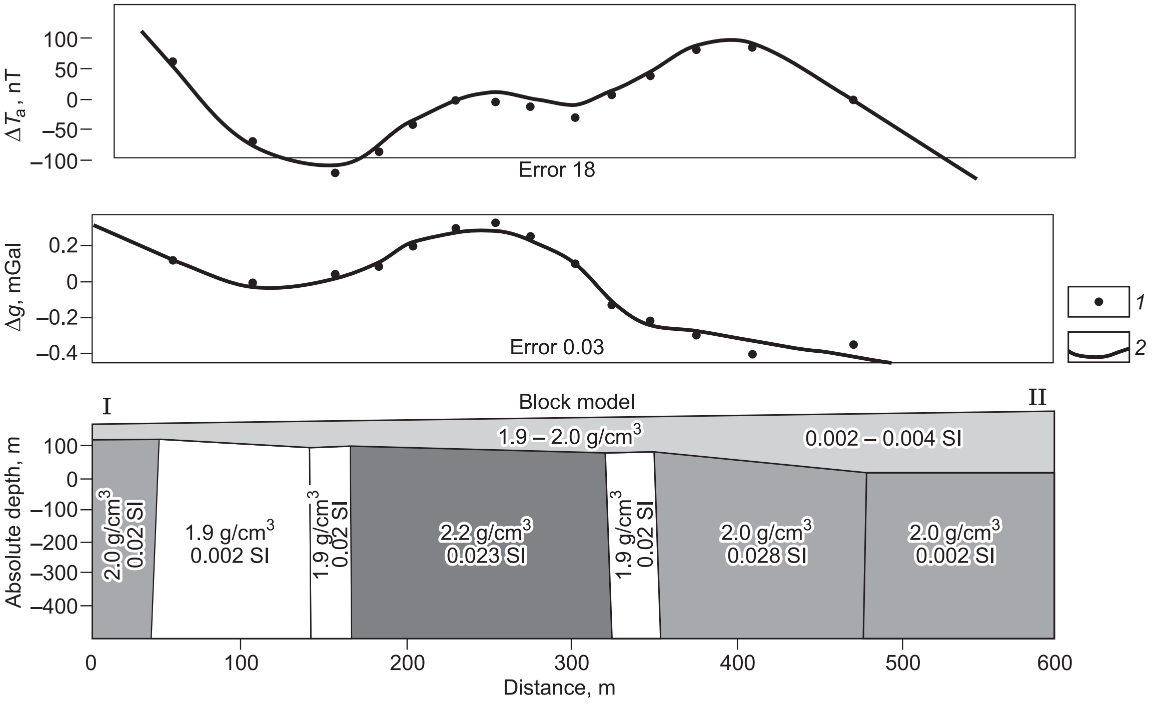

**Fig. 9.** A model for the structure of the Upper Pauzhetka t/f area according to gravimagnetic data.

about evolution of hydrothermal boiling zones and the transformation of rocks in the depths of the thermal field.

## CONCLUSIONS

Comprehensive large-scale geological and geophysical studies yielded new data on the structure and physical nature of the discharge sites of the steam hydrothermal fluids in the area of the Upper Pauzhetka t/f of the Pauzhetka geothermal deposit. An isometric concentric-zonal structure, which spatially correlates with the elevated tectonic block (Rychagov et al., 1993), was identified within the temperature, geoelectric, magnetic, and gravimetric fields. The central area of this structure is characterized by discharge of steam hydrothermal fluids on the surface and by high-gradient geophysical anomalies. According to the VES data and lithological mappings, the southeastern boundary of the area is represented by a sub-vertical fault, which is a zone of increased fracture-pore permeability for ascending hydrothermal fluids in tuffs and tuffites of the Pauzhetka Formation. Ascending neutral (to slightly alkaline) hydrothermal fluids intensively mix with meteoric waters at the northwestern border of the central area, and ferromagnetic minerals are leached from host rocks by acidic thermal solutions. The studies identified the roof of a block of compacted rocks at the depth of 40–60 m from the surface, which are most likely composed of quartz-adular metasomatites formed before the Holocene stage of development of the hydrothermal system (Zhatnuev et al., 1991, 1996). The analysis of logs of boreholes K-13, K-14, K-20 and K-21 identified that quartz-adular mineralization was distributed in different parts of the elevated tectonic block structure (Rychagov et al., 1993) and the area where thermal and meteoric waters are vigorously mixed extends to the foot of the upper aquifer (Pampura and 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 Upper Pauzhetka thermal field.

The central area of the isometric concentric-zonal structure is outlined by a zone consisting of local anomalies of positive $\Delta T_a$ 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 pronounced in the magnetic field (Fig. 7), has negative $\Delta T_a$ anomalies, which, according to hydrogeological, thermometric and gravimetric data, correlate with the discharge sites of steam hydrothermal fluids in the Pauzhetka river valley, along the Bystryi Stream and in the area adjacent to GeoPP.

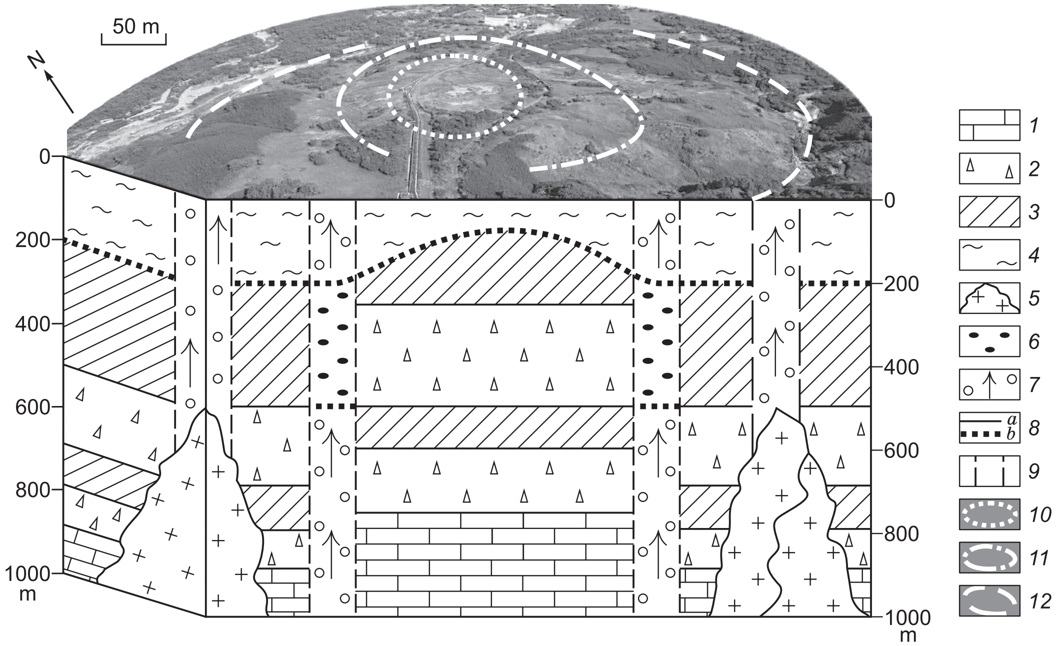

**Fig. 10.** A conceptual model for the structure of the Upper Pauzhetka t/f of the Pauzhetka hydrothermal system (Photo by M.S. Chernov). *1*, the foundation of the structure: volcanomictic sandstones; *2*, water-bearing strata of rocks: lower, agglomerate tuffs, upper, coarse-grained tuffs; *3*, aquifers: lower, ignimbrites, upper, tuffites; *4*, argillised rocks; *5*, subvolcanic intrusions; *6*, quartz-adular metasomatites; *7*, zones of ascension and discharge of gas-water fluids and steam hydrothermal solutions; *8*, lithological (*a*) and metasomatic (*b*) boundaries; *9*, zones of discontinuous faults; *10*, boundaries of the thermal field; *11*, the axial line of the zone of tectonic faults, which delineates the central elevated block; *12*, conventional boundaries of the tectonic-magmatic uplift.

Thus, the structure of the circulation zones of various types of waters in the area of the Upper Pauzhetka thermal field 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. The proposed model reflects the main structural features of the central part of the Pauzhetka geothermal field (Fig. 10). Probably, the elevated tectonic block was formed due to penetration of diorites and gabbro-diorites into the weakened zones of intrusions at the stage of the formation of the multi-stage resurgent uplift of the Kambalny volcanic ridge (Masurenkov, 1980). The subvolcanic facies of these intermediate and acidic intrusions in the form of dikes and interstratal bodies are penetrated by boreholes in various sections and horizons of the geological section of the Pauzhetka geothermal field (Rychagov et al., 1993), and we also assume their presence based on geophysical data and, apparently, they play the role of structural deformographs: zones of increased fracture-pore permeability are formed in the apical parts of subintrusions. Based on the general concepts about the evolution of modern hydrothermal systems and thermal fields (Rychagov, 2005), we believe that formation of the structure of the zones of discharge of steam hydrothermal fluids on the Pauzhetka deposit occurred during the Holocene. Slightly acidic to alkaline thermal waters are discharged in the near-surface horizons of the deposit. The interaction of thermal waters with the host rocks (tuffs and andesites) results in an increase in the thickness of the argillized rocks, an increase in fracture-pore permeability at the base of the upper water-confining layer (as well as at other lithological boundaries) and deposition of ore mineralization in the zones of mixing alkaline and acidic waters (Rychagov et al., 2019). Thus, the structure of the discharge sites of ascending thermal waters at the Pauzhetka geothermal field is forming at the present time.

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