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The Deep Structure of the Pauzhetka Hydrothermal System Area, Southern Kamchatka

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Abstract—Multidisciplinary geophysical surveys have been carried out in the Pauzhetka hydrothermal system area and around in order to identify 10–15-km deep geological structures that exercise thermal control of the system. The results of vertical electrical and electromagnetic sounding, magnetometric and gravity surveys have been integrated, and geological–geophysical data have been generalized, to develop a model of layered block structure for the Pauzhetka hydrothermal system area. We provide an explanation of fragmentation (permeability) in upper crustal horizons in the structure of the present-day hydrothermal system and the geothermal field. A horizon of less dense rocks has been identified at depths of 3–4 to 8–9 km; this horizon can be the source of thermal supply for known and hidden temperature anomalies in the Pauzhetka–Kambalnyi–Koshelev geothermal area in southern Kamchatka.

Keywords: geothermal area, hydrothermal system, geothermal field, block structure, aqueous gas fluid, thermal recharge

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INTRODUCTION

The present-day hydrothermal systems at volcanic island arcs are of great interest, because they are confined to deep-seated faults and zones where regional tectonic structures are adjacent (Rychagov, 2003, 2014; Benz et al., 1992; Clarke et al., 2009; Gianelli et al., 1997; Stimac et al., 2001). Many countries worldwide possess and operate geothermal fields whose geothermal power capacity reaches 100 MW or greater. The power of geothermal power stations can occasionally be as high as 1500 MW (the Geysers, US) (Lund et al., 2005). The probable reserves of thermal and electrical energy contained in present-day hydrothermal systems are assessed to be many orders of magnitude greater (Lund and Boyd, 2015).

Over twenty high- and low-temperature hydrothermal systems and hydrothermal fields have been identified and studied in Kamchatka using a variety of techniques, including structural geophysical ones (*Geotermalnye ...,* 2005; *Kompleksnye ...,* 1985; *Strategiya ...,* 2001). The Paratunka, Mutnovsky, Esso, and Pauzhetka geothermal fields are operated at present. The Bolshe-Bannye, Karymshina, Asacha, Opala, Pushchino springs of thermal water, as well as many others, are being used as tourist and balneological attractions. The history of study of hydrothermal systems and geothermal fields in Kamchatka is fairly well described in several publications (*Gidrotermalnye ...,* 1976; Rychagov, 2017; Feofilaktov et al., 2017).

In spite of extensive surveys that have been carried out in the Mutnovsky–Zhirovaya, Paratunka, Banno-Karymchino, and Pauzhetka–Kambalnyi–Koshelev geothermal areas of southern Kamchatka, the key geothermal issue remains unresolved, namely, what is the deep geological structure of these hydrothermal systems. When the issue has been dealt with, one could hope to reconstruct the source of geothermal heat carrier.

The goal of the present team of researchers was to identify those geological structures which control heat transport in the Pauzhetka hydrothermal system at depths upwards of 10–15 km.

THE GEOLOGICAL STRUCTURE OF THE PAUZHETKA HYDROTHERMAL SYSTEM AREA

Descriptions of the geological structure of the Pauzhetka–Kambalnyi–Koshelev geothermal (mineralization) area in southern Kamchatka (Fig. 1), of the long-lived hydrothermal–magmatic, and present-day Pauzhetka hydrothermal system, as well as of the

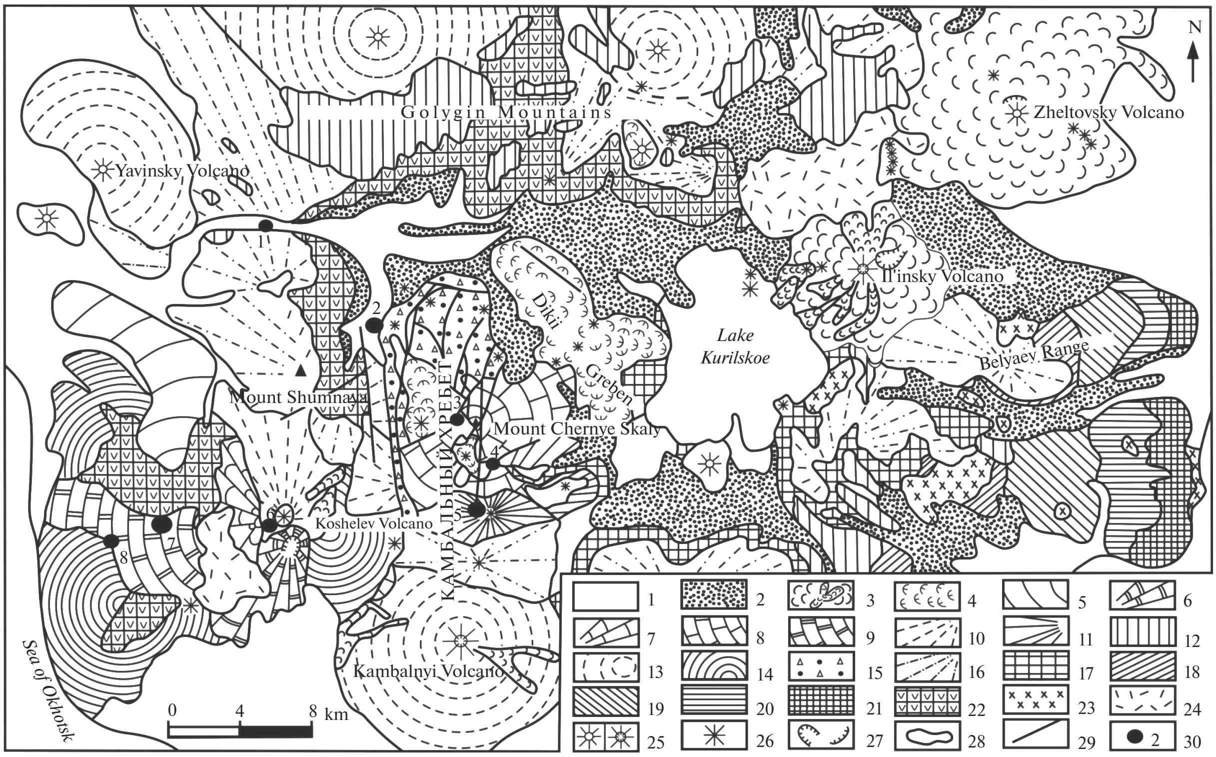

Fig. 1. A schematic geological map of the Pauzhetka–Kambalnyi–Koshelev geothermal (mineralization) area (Belousov, 1978) with modifications. (1–3) Holocene deposits: (1) alluvial, proluvial, and glacial, (2) pyroclastic pumice deposits, (3) basalts and basaltic andesites of active volcanoes and individual lava flows; (4–6) Upper Pleistocene to Holocene deposits: (4) dacite and rhyolite extrusive domes and their lava flows, (5) andesites of Vostochno-Koshelev Volcano, (6) basaltic andesites of Vostochno-Koshelev Volcano; (7, 8) Upper Pleistocene deposits: (7) andesites of Valentin Volcano, (8) basaltic andesites of Chernye Skaly Volcano; (9–12) Middle Pleistocene deposits: (9) andesites of Zapadno-Koshelev Volcano, (10) basalts of older Koshelev Volcano, (11) basaltic andesites of Kambalnyi Mountain Range, (12) ignimbrites and baked tuffs of rhyodacites and rhyolites in the Golygin Range; (13) Lower to Middle Pleistocene volcanoes of basaltic and basaltic-andesite compositions; (14) Lower Pleistocene lavas and tuffs of basalts and basaltic andesites; (15, 16) Upper Pliocene to Middle to Lower Pleistocene deposits: (15) volcanogenic-sedimentary rocks of the Pauzhetka suite, (16) lavas and tuffs of older volcanoes; (17–21) Upper Miocene to Lower Pliocene sedimentary-volcanogenic deposits: (17) conglomerates and sandstones, less frequently tuffs and basalt lavas, (18) basalt tuffs and lavas, tuff conglomerates, (19) tuff breccias and tuff conglomerates, (20) rudaceous tuffs and lavas of basalts, (21) sandstones and conglomerates, less frequently tuffs; (22) Miocene, dominantly volcanogenic unstratified deposits; (23) Upper Miocene to Pliocene subvolcanic intrusions of diorites and diorite porphyrites; (24) unconsolidated deposits of various genesis and age; (25–27) volcanic morphostructures: (25) volcanic cones (*a* simple, *b* with a summit crater), (26) cinder cones, small monogenic volcanoes and extrusions, (27) caldera and remains of caldera walls; (28) lithologic boundaries; (29) tectonic discontinuities; (30) major thermal occurrences (1 Pervye Goryachie Springs; 2 Pauzhetka geothermal field; 3–5 groups of thermal fields at the Kambalnyi Range: 3 Severo-Kambalnyi, 4 Tsentralno-Kambalnyi, 5 Yuzhno-Kambalnyi; 6, 7 thermal anomalies in the Koshelev volcanic massif: 6 Verkhne-Koshelev, 7 Nizhne-Koshelev; 8 Sivuchinskie thermal springs).

eponymous geothermal field, can be found in (Belousov, 1978; *Gidtotermalnye ...*, 1976; *Dolgozhivushchii ...*, 1980; *Pauzhetskie ...*, 1965; Rychagov, 2014; Rychagov et al., 2009; *Struktura ...*, 1993). However, many studies were regional in character or else were concerned with a detailed investigation of individual blocks in a geothermal field. This paper seeks to deal with the main problem outlined above by presenting generalized data on the structure of the hydrothermal system and the zone where it is adjacent to other geological structures of the area.

The present-day Pauzhetka hydrothermal system is situated in the eponymous volcano-tectonic depression (*Dolgozhivushchii ...*, 1980). The geological block that is host to the system is adjacent to the west to the Klyuchevskoi igneous complex (Fig. 2). The complex is probably Lower or Middle Quaternary (*Dolgozhivushchii ...*, 1980). The structure of the hydrothermal system is largely controlled by the resurgent tectonomagmatic uplift of the Middle to Upper Quaternary Kambalnyi volcanic mountain range (*Struktura ...*, 1993). The geological section divides into nearly vertical tectonic blocks that rise successively toward the axial zone of the mountain range (Fig. 3). The total uplift amplitude is at least 1000–1200 m. The Pauzhetka and Ozernovsky grabens, which are the western and northern boundaries of the Kambalnyi Range, seem to have originated during the same time, Middle to Upper Quaternary.

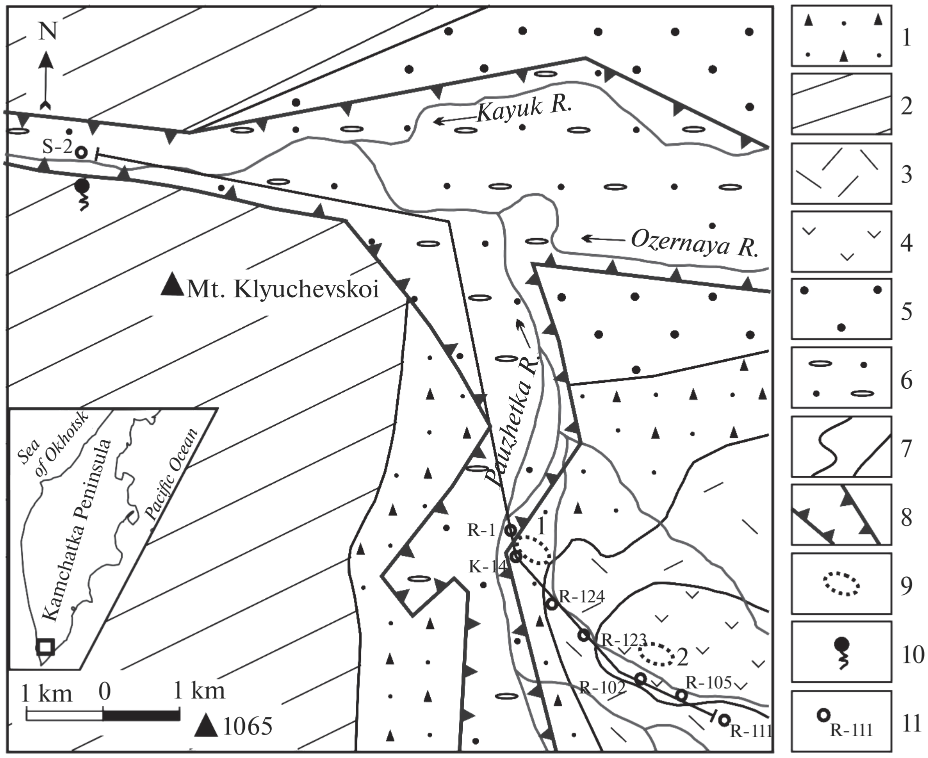

Fig. 2. A schematic geological map of the Pauzhetka hydrothermal system area as developed by S.N. Rychagov on the basis of prospecting surveys and topical research. (1) Pauzhetka suite; (2) magmatic complex of Mt. Klyuchevskoi; (3, 4) lava and extrusive complexes of the Kambalnyi volcanic mountain range: (3) dacites and rhyolites, (4) andesites and basaltic andesites; (5) Upper Quaternary pumice deposits; (6) alluvial boulder and pebble deposits; (7) lithologic boundaries; (8) boundaries of Ozernovsky and Pauzhetka grabens; (9) major thermal fields: (1) Verkhne-Pauzhetka, (2) Vostochno-Pauzhetka; (10) Pervye Goryachie Springs (Pionerlager); (11) deep geothermal wells and their identification numbers.

The Pauzhetka hydrothermal system belongs to the water-dominated hydrodynamic type (*Pauzhetskie ...,* 1965; *Struktura ...,* 1993). The structure includes two water-bearing complexes, with the lower complex being confined to Alnean agglomerate tuffs and the upper complex occurring in two lithologic horizons (the lower and middle Pauzhetka suites), see Fig. 3. The subvertical tectonic discontinuities transport thermal headwater from the lower water-bearing complex to the upper. We showed previously that the bulk of ascending flows of overheated (up to 220–230ºC in the lower complex) hydrothermal fluids is localized in the structure of nearly circular uplifted rock blocks (*Struktura ...,* 1993; Feofilaktov et al., 2017). These blocks are most likely of tectono-magmatic origin. However, much remains unknown, viz., the depth of the features that control heat transport and their structure at the bottom of the geological section.

THE METHOD OF STUDY

Our multidisciplinary geophysical surveys included vertical electrical, magnetotelluric, and audio-magnetotelluric soundings; magnetometric and gravity surveys.

<u>Vertical electrical sounding (VES)</u> used a symmetric four-electrode arrangement (AMNB configuration). The maximum spacing along the current-electrode line (AB/2) varied within the range 250–500 m. Soundings were performed at 43 sites with an irregular spacing along the traverse from northwest to southeast (Fig. 4). A total of 15 to 17 measurements were made at each site, yielding detailed sounding curves. The measurements were carried out at 5 VES sites with the maximum spacing AB/2 = 1500 m. The current-electrode lines were aligned along the traverse. We used advanced electrical prospecting instrumentation, viz., a MERI-24 multifunctional meter (OOO *Severo-Zapad*, Russia) and a VP-1000 electrical prospecting generator (OOO *Elgeo*, Russia). The data were processed using a specialized program package, IPI2win (OOO *Geotekh*, Russia). The uncertainty was ≤3% at a sounding site. The residual between the VES theoretical and observed curves was ≤ 5%.

<u>Electromagnetic surveying</u> was performed using audio-magnetotelluric (AMTS) and magnetotelluric sounding (MTS) methods. The instrumentation included two MTU-5A five-channel stations (Phoenix Geophysics, Canada), which can record electrical (Ex, Ey) and magnetic (Hx, Hy, Hz) components of

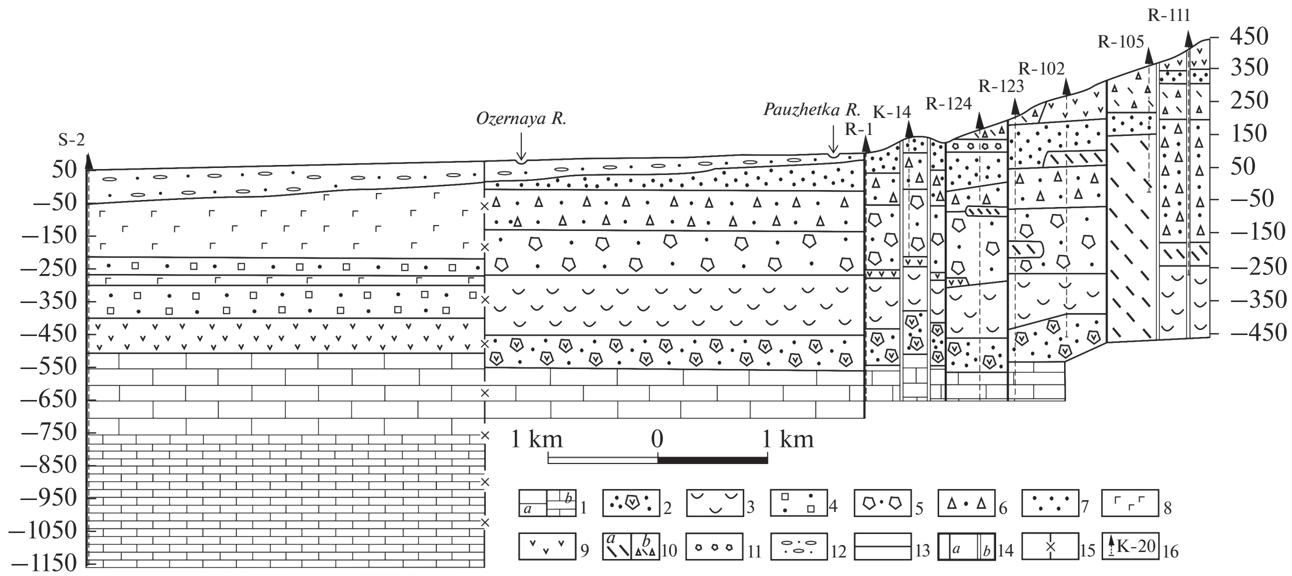

Fig. 3. A geological section of the Pauzhetka hydrothermal system area as developed by S.N. Rychagov on the basis of prospecting surveys and topical research. (1) volcanomictic sandstones and tuff sandstones of the Anavgai Series (*a* with interbeds of gravelite size, *b* fine and small-size deposits at the bottom of the section); (2) basaltic andesite agglomerate tuffs(tuff breccias), Alnean Series; (3) rhyolite crystal-litho-vitroclastic psephite tuffs, Golygin suite; (4) unstratified tuffs and tuffites of the Pauzhetka suite; (5) rudaceous andesitic lithovitroclastic tuffs, lower Pauzhetka suite; (6) dacitic andesite psephite tuffs, middle Pauzhetka subsuite; (7) tuffogenous sedimentary deposits of dacite and dacitic andesite compositions, upper Pauzhetka subsuite; (8) basalts of the Mt. Klyuchevskoi igneous complex, probably of Middle Quaternary age; (9) basaltic andesites, probably of the Alnean series; (10) Middle to Upper Quaternary dacite extrusions (*a*) and lavas (*b*); (11) lava breccias at the foot of lava flows and marginal parts of extrusive bodies; (12) alluvial boulder–pebble deposits; (13) lithologic and intrusive boundaries; (14) tectonic discontinuities (*a* faults, *b* zones of higher cracking in rocks); (15) assumed boundary of the Klyuchevskoi igneous complex (left part of section) and of the lithologic complex of the Pauzhetka volcano-tectonic depression; (16) exploration wells and prospecting wells.

the natural electromagnetic field. The recordable periods are in the range between 0.0001 and 1000 s. Electrical field was recorded by a four-electrode cross array with low-polarization grounding electrodes. The measuring lines were 50 m long for AMTS and 90 m for MTS. The receiving lines were set at azimuths of 0° and 90°. Measurements were carried out at 18 sites (18 for AMTS and 5 for MTS), with the distance between these being 200–700 m (see Fig. 3). We sought to reduce the impact of man-induced and wind noise by using synchronous recording with a remote base station. The data were processed using a special program package (Rodi and Mackie, 2001). The resulting data included impedance tensors, impedance curves, and impedance phases (Berdichevsky and Dmitriev, 2009). The impedance tensor was determined to within a few percent, while the accuracy of impedance phase determination was a few degrees. The components of the impedance tensor were used to find polar diagrams of the main and complementary impedances, as well as the inhomogeneity parameter, which are interpreted to infer the geoelectrical inhomogeneity of the medium. The polar diagrams for main impedance have a nearly circular shape in the range of frequencies between 0.0001 and 15 Hz, the values of the complementary impedance are not large. At higher periods the main-impedance diagram becomes an oval with a neck, the whole resembling a figure eight. The complementary-impedance diagram has the shape of a four-petal rose. The inhomogeneity parameter has values between 0.05 and 0.15 at high frequencies, telling us that the medium is quasi-homogeneous, and increases toward lower frequencies. This is due to the effects of geological structures. The shortest axes of the complementary impedance at low frequencies coincide with the axes of the diagram for main impedance. This tells us that the geoelectrical medium can be approximated as an inhomogeneous one in two dimensions.

Magnetic prospecting has been carried out multiple times in the Pauzhetka hydrothermal system area (Nuzhdaev and Feofilaktov, 2014; Feofilaktov et al., 2017). However, the present study included additional measurements along the main traverse (see Fig. 4) in order to integrate the magnetic characteristics along with gravity and geoelectrical data. The spacing of measurements was 4–5 m. We used GSM-19W (Overhauser) magnetometers (GEM Systems, Canada): one instrument was used as a magnetovariational station and the other for routine measurements, which increased the rate of surveying and enhanced the accuracy. The inter-instrument discrepancy was ≤0.1 nT.

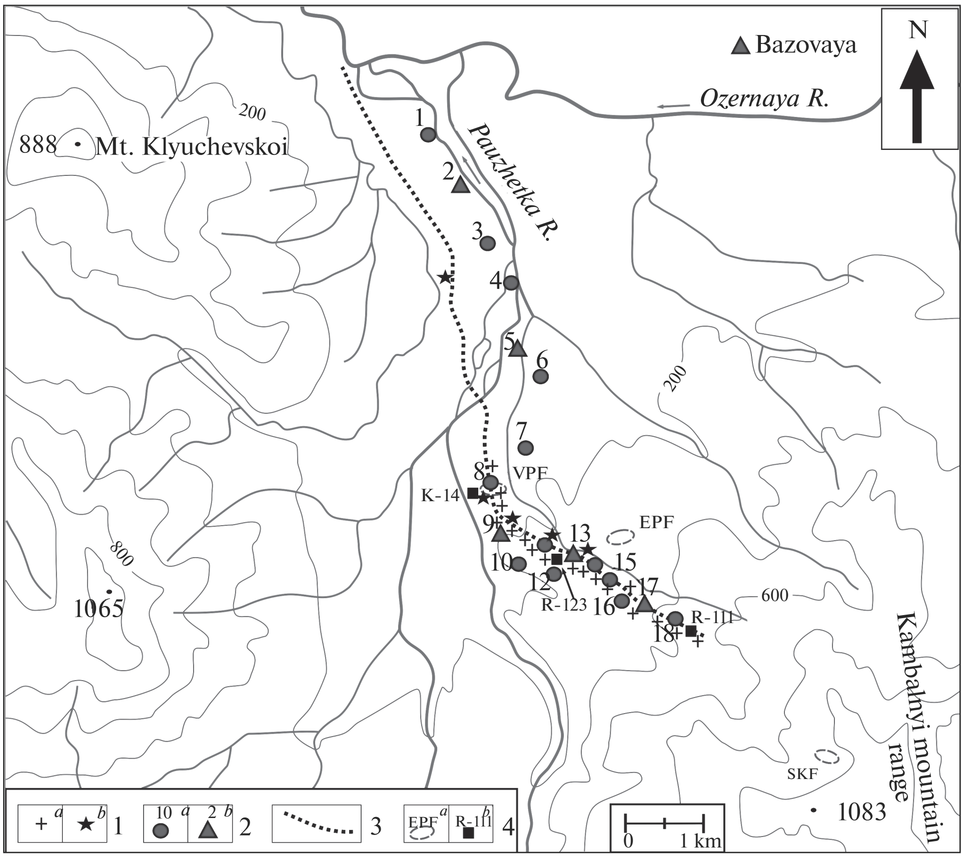

Fig. 4. A schematic map showing the locations of geophysical surveying sites. (1) sites of vertical electrical sounding with current electrodes are separated by a distance of 1 km (*a*) and 3 km (*b*); (2) electrical exploration using AMTS (*a*) and MTS (*b*) with indication of site identification numbers; (3) gravity surveying sites where magnetometric surveys were conducted at shorter intervals; (4) main thermal fields (*a*): VPF stands for Verkhne-Pauzhetka field, EPF for East Pauzhetka field, and NK for Severo-Kambalnyi field; wells and their identification numbers (*b*).

The gravity survey was carried out using a CG-5 Autograv automatic microprocessor gravimeter (Scintrex, Canada). The measuring range is >7000 mGals, the resolution in direct measurement reading is 0.001 mGals. The observations were along a line at a spacing of 100 m (see Fig. 3). The control measurements were 15% of the total number, the rms error was 0.03 mGals. The necessary geodetic data were supplied by GPS Leica GR 10 stations with AR 10 aerials. One station was set apart as the base, while the other was moved along the line. The recording time at each point was ≥15 min. The heights were determined to within ≤7 cm.

To allow for baseline drift, as well as for GPS uncertainties, the measurements were made at base points, with one of these points being on a concrete basement of well K-14 (the Pauzhetka thermal field area). The position of that point has not been changed for gravity surveys which we have conducted since 2011, so that new data could be matched to those obtained previously (Bukatov et al., 2011; Feofilaktov et al., 2017).

THE SURVEY RESULTS

Vertical electrical sounding was performed in order to study conductivity structure in the upper section of the Pauzhetka hydrothermal system and of the zone where it is adjacent to regional geological features. The resulting apparent resistivity (ρ_{ap}) are of the HKH–KHK type (Fig. 5). The near-surface horizons of the geologic section are characterized by high values of ρ_{ap}, with resistivity rapidly decreasing with increasing depth. The lowest values of ρ_{ap} are attained at spacings AB/2 = 150–300 m. The curves develop an inflexion in the spacing range AB/2 = 20–100 m, indicating an intermediate horizon with higher resistivity whose thickness and depth vary along the section. The sounding curves for the Verkhne-Pauzhetka thermal field area (the central discharge of steam-charged hydrothermal fluids in the hydrothermal system structure) have low values of ρ_{ap} in the upper section (downward nearly from the ground surface) which gradually increase downward.

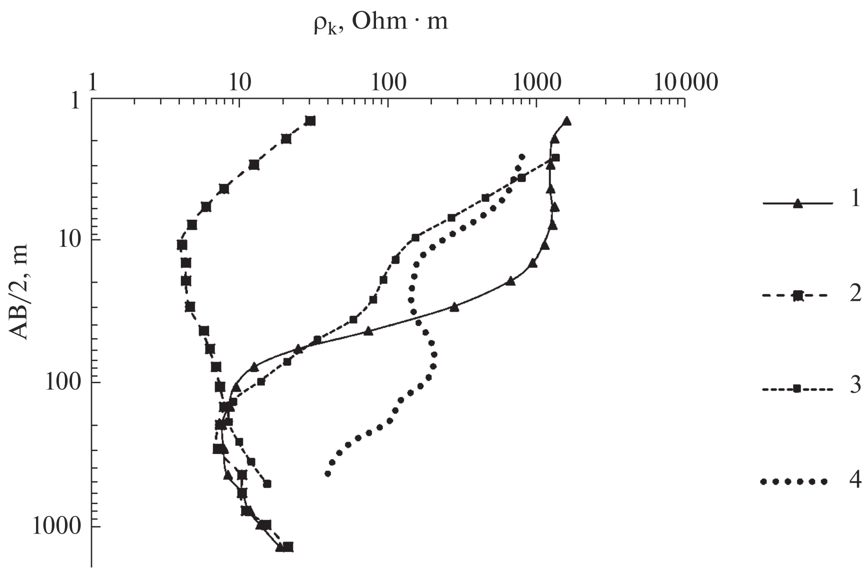

Fig. 5. Curves of vertical electrical sounding that are typical of various segments of the traverse. (*1*) curve corresponding to the NW part of the traverse (left terrace of the Pauzhetka River); (*2*) area of natural discharge for steam–hydrothermal fluids (VPF); (*3*) curve typical of the entire area of the geothermal field (central part of the traverse); (*4*) curve that is characteristic for the SE part of the traverse.

We constructed pseudo- and geoelectrical sections of apparent resistivity in the medium (abbreviated as a. r.). The pseudo-electrical section (Fig. 6) shows high values of ρ_{ap} in the upper part of the section (AB/2 up to 100 m), as well as a horizontal differentiation of resistivity. The region of low ρ_{ap} is localized in the lower section, approaching the ground surface very close to the discharge zone of steam-charged hydrothermal fluids (VPF, see Fig. 6). The geoelectric section includes five horizons (from top to bottom) that are characterized by rather different ranges of a. r.

The 1st horizon, a. r. = 100–3000 Ohm · m. The thickness is 10 to 38 m in the NW and central parts of the traverse, wedging out toward the ground surface in the VPF area. The thickness increases to reach 60 m in the SE. This horizon has corresponding to it in the geological section alluvial deposits of the Pauzhetka and Ozernovsky grabens (left segment of the line) and the lava–extrusive complex of dacites and andesites in the Kambalnyi mountain range (right segment of the line). It thus appears that the rocks of this horizon seem to act as an aquifuge both for ascending thermal waters and for meteoric waters.

The 2nd horizon, a. r. = 20–100 Ohm · m. The horizon occurs throughout the section, the thickness varies from 7 m at the location of steam-charged hydrothermal fluid discharge to as much as 50 m; it is much greater on the slope of the Kambalnyi mountain range (see Fig. 5). The horizon consists of fine-grained tuffs and tuffites of dacitic andesites in the Verkhne-Pauzhetka subsuite. The rocks are relatively dense. Cracking and open porosity occur in fragmented patches adjacent to tectonic (tectono-magmatic) blocks that control flows of hydrothermal fluids in the Pauzhetka system structure and regions where these flows mix with meteoric water (in particular, in the VPF area).

The 3rd horizon, a. r. = 3–10 Ohm · m. The thickness fluctuates between 50 and 160 m, sharply increasing in the structure of the hydrothermal system. The horizon consists of a sequence of psephite tuffs of the Middle Pauzhetka subsuite. The rocks are porous, cracked, and intensively altered hydrothermally, being argillized and zeolitized.

The 4th horizon, a. r. = 10–40 Ohm · m. The thickness is 160–240 m. The horizon consists of larger-grained (psephitic to agglomerate) tuffs of dacitic andesites in the lower Pauzhetka subsuite. The rocks are also intensively altered hydrothermally: silicified, zeolitized, chlorized, but the argillization is lower compared with the overburden. The cracks are frequently welded with minerals of silica, zeolite, chlorites, and other newly formed minerals, which probably reduces the total water content in these rocks.

Horizons 3 and 4 characterize the upper water-bearing complex in the structure of the Pauzhetka hydrothermal system, as stated in (*Struktura …,* 1993).

The 5th horizon, a. r. = 40–300 Ohm · m, is the basement of the section, the top of the horizon lies at depths of 330–550 m from the ground surface. It would be a problematic procedure to try to identify the horizon based on VES curves alone because of the effect of the overlying thick water-bearing complex of the Pauzhetka suite, which serves as a kind of screen in the geoelectrical medium. The top of the fifth horizon has not been identified from the resulting VES curves

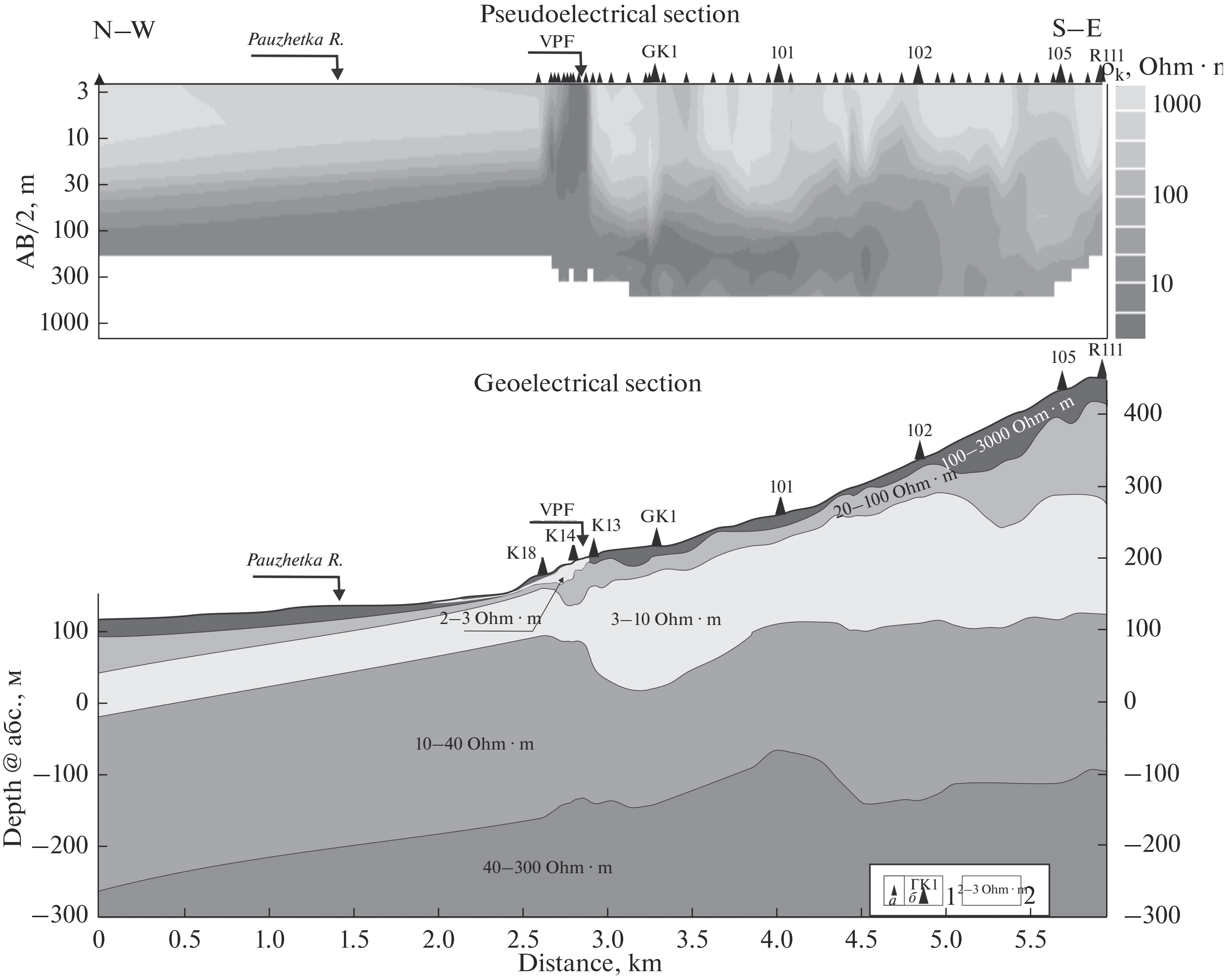

Fig. 6. Pseudo- and geoelectrical sections for the Pauzhetka hydrothermal system area based on vertical electrical sounding data.

in the SE part of the section because the power line AB was too short. We tried to determine the depth to the top of the horizon to greater accuracy by invoking data from prospecting wells. Overall, the horizon consists of Golygin dense massive ignimbrites, which make an intermediate aquifer in the structure of the Pauzhetka hydrothermal system (see Fig. 3).

A small (in length and thickness) region (lens) has been identified in the area of the Verkhne-Pauzhetka thermal field with a. r. = 2–3 Ohm · m (see Fig. 6). The region is composed of intensively argillized porous and cracked tuffs (tuffites) saturated with hydrocarbonaceous sulfate waters that are discharged onto the ground surface. The high contrasts in the structure of the geoelectric section beneath the Verkhne-Pauzhetka thermal field suggests the presence of subvertical tectonic discontinuities which are conducting hydrothermal headwater which are then mixed with meteoric waters; this is in agreement with ideas put forward by other researchers (Pampura and Sandimirova, 1990; *Struktura ...,* 1993).

Electromagnetic surveys furnished data from which to construct longitudinal and transverse sounding curves (Fig. 7). Longitudinal curves largely reflect deep conductive zones, while transverse curves carry the most reliable information on near-surface parts of the section. For this reason we calculated numerical models from longitudinal (in the TE modification) and from transverse (in the TM modification) curves (Berdichevsky and Dmitriev, 2009). The curves were inverted using a program for numerical 2D modeling following the algorithm of Rodi and Mackie (2001). The prior data in this case consisted in a one-dimensional model of the area in question incorporating all known geological and geophysical knowledge (see Figs. 2, 3).

An analysis of the sounding curves resulted in geoelectric sections down to depths of 2 and 15 km (Fig. 8). A qualitative analysis of the curves showed that they were subject to the ρ-effect. The effect is seen as displacement of amplitude curves along the axis of ordinates, in contrast to phase curves, which are not subject to this effect. The ρ-effect has a galvanic origin

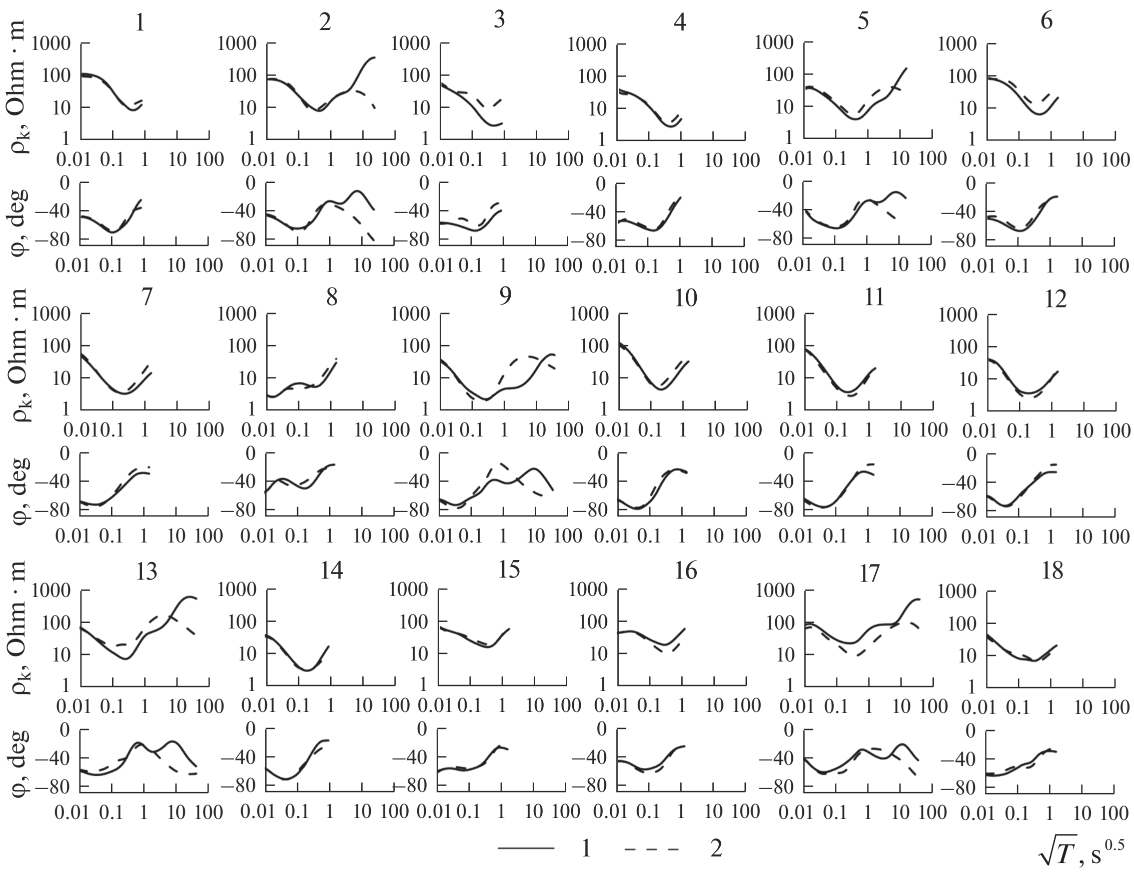

Fig. 7. AMTS and MTS amplitude and phase curves. Numbers mark sounding sites. (*1*) longitudinal; (*2*) transverse.

and is due to the influence of local geoelectric inhomogeneities (Berdichevsky, 2009). One can see a maximum in the left part of longitudinal and transverse amplitude curves ($\sqrt{T}$ between 0.01 and 0.1 $s^{0.5}$), which characterizes alluvial and deluvial deposits with apparent resistivity (ρ_{ap}) reaching 100 Ohm·m. Further at higher frequencies (the range of $\sqrt{T}$ between 0.5 and 0.8 $s^{0.5}$), a minimum is found at longitudinal and transverse curves, which is due to the presence of volcanogenic-sedimentary rocks with ρ_{ap} = 2–20 Ohm·m.

The volcanogenic-sedimentary rock sequence is largely composed of tuffs of the Pauzhetka suite. There is an anomalous section around observation site no. 8: no maximum is found at longitudinal and transverse curves, and the curves have the lowest values of ρ_{ap}. Such values are characteristic for sections in the central part of the Pauzhetka hydrothermal system (the Verkhne-Pauzhetka thermal field area). The anomalous shape of the curves is probably due to the discharge of steam-charged hydrothermal fluids at the location. The MTS longitudinal curves have a maximum in their right parts ($\sqrt{T}$ between 1 and 1.5 $s^{0.5}$), which is caused by a horizon with ρ_{ap} = 20–50 Ohm·m. The horizon consists of Anavgai sandstones. Further on, the ascending branch of the longitudinal curves (with $\sqrt{T}$ between 30 and 40 $s^{0.5}$) points to a zone of 100 to 500 Ohm·m or greater, while a maximum can be identified in the MTS transverse curves ($\sqrt{T}$ between 5 and 15 $s^{0.5}$). This zone most likely reflects the position of the Cretaceous basement in the section: earlier geophysical surveys determined the top of the Cretaceous basement lying at depths of 2 to 3.5 km (Zubin, 1980).

There is a minimum at the MTS longitudinal curves at low frequencies, indicating a zone with lower ρ_{ap} (10–20 Ohm·m) in the range of depth between 3.5–4 km and 8 km or greater. That zone is 4–5 km thick on average. The zone is of great interest, because it is associated with a zone of higher conductivity for geothermal fluids, with the so-called "crustal conductive layer" as identified in many areas over Kamchatka (Moroz, 1991; Moroz and Gontovaya, 2017).

The bottom of the geoelectric section is characterized by values of ρ_{ap} over 150–200 Ohm · m at depths of 8–9 to 15 km. The lower horizon identified here is probably the top of the crystalline basement. Our results are not in disagreement with those in (*Dolgozhivushchii ...,* 1980].

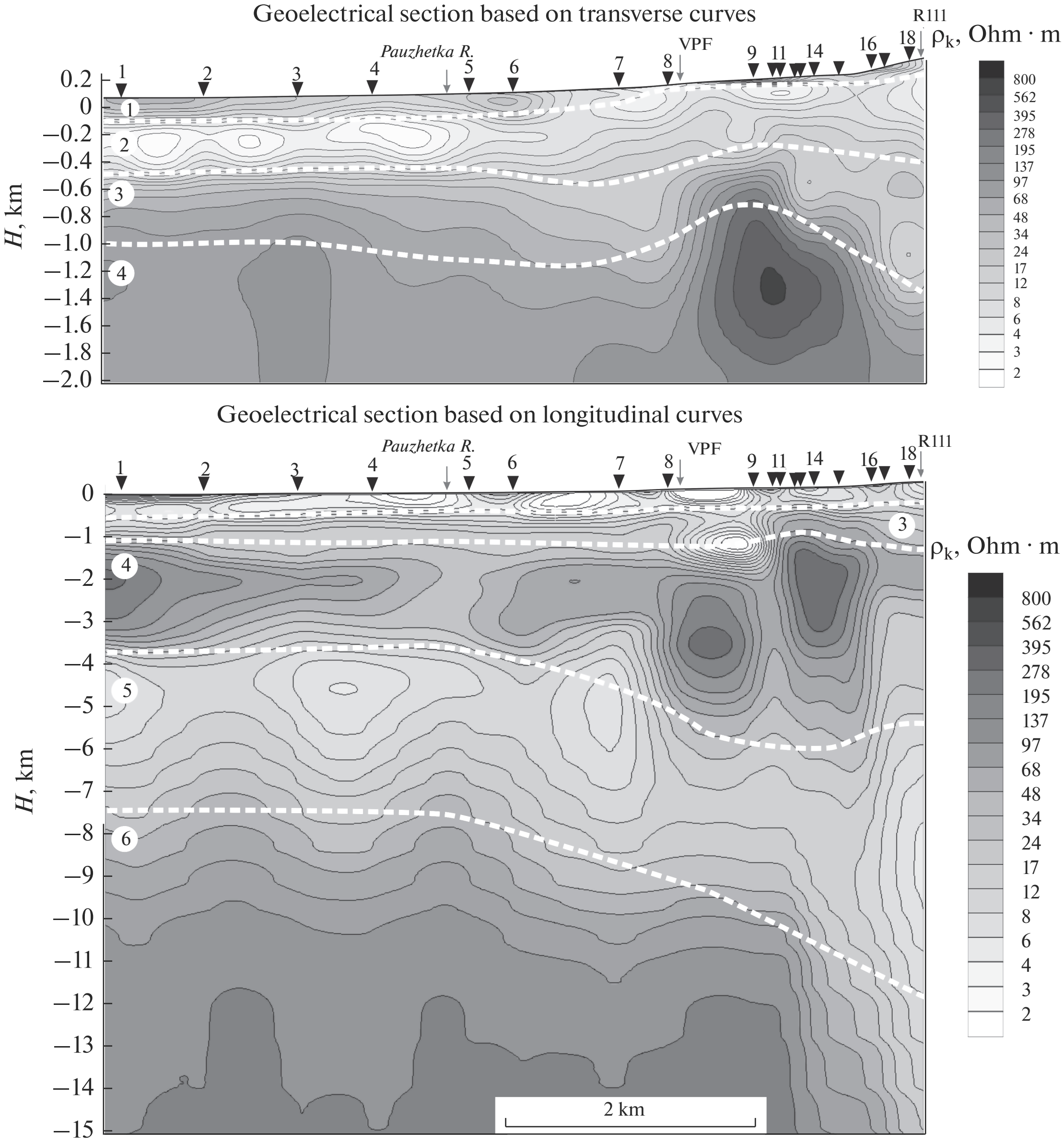

Fig. 8. A geoelectrical section of the Pauzhetka hydrothermal system based on MTS and AMTS data.

Summing up, we can state that electromagnetic surveys have helped identify 6 horizons (from to bottom, see Fig. 8) in the geoelectric section of the Pauzhetka hydrothermal system; these are hypothesized to have the following geological content:

(1) a layer of alluvial and deluvial deposits as thick as 100 m in places;

(2) a sequence of tuffs and tuffogenic-sedimentary rocks of the Pauzhetka suite, as well as agglomerate tuffs of the Alnean series, which are water-bearing horizons in the hydrothermal system structure; the second horizon has a thickness varying in the range 200–300 m in the left part of the geologic section and increasing to exceed 1 km in the right part;

(3) a sequence of volcanomictic sandstones–gravelites of the Anavgai series, which are commonly thought to make the lower aquifer in the structure of the Pauzhetka geothermal field (*Struktura …,* 1993); the horizon is about 1 km thick;

(4) deposits of the Cretaceous basement consisting in this area of metamorphosed sandstones and volcanogenic rocks; the horizon has a thickness varying between 1.5 and 5 km; the greater thickness is due to the presence of inhomogeneities with higher ρ_{ap}, which may consist of dense rock blocks (large intrusive bodies?) in the middle of the Pauzhetka hydrothermal system or of the Mt. Klyuchevskoi igneous complex in the western part of the section;

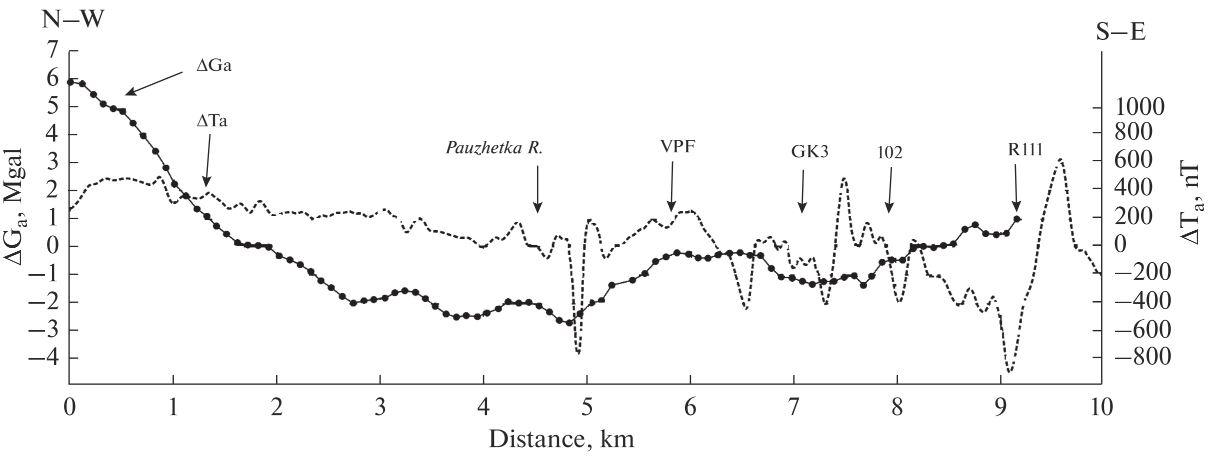

Fig. 9. Plots of anomalous magnetic field (ΔT_a) and of Bouguer gravity field (ΔG_a) with relief along the traverse incorporated.

(5) a horizon of probably less dense rocks, Cretaceous or older, and which is a zone of high conduction for geothermal fluids, a "crustal conductive layer"; the thickness of this horizon is rather constant, varying in the range 4–5 km; in the right part of the section the horizon descends under the structure of the Kambalnyi volcanic range;

(6) rocks of the crystalline basement in the depth range between 8–9 km and 15 km.

The anomalous magnetic field in the area of study shows two types of distribution of ΔT_a (Fig. 9). A quiet slowly varying field with mostly positive values occurs in the Ozernovsky and Pauzhetka grabens (the NW part of the line of traverse as far as the Pauzhetka R.), while a rapidly changing field dominated by negative values of ΔT_a occurs in the structure of the Pauzhetka hydrothermal system and in the junction of this and the subsided block of the Pauzhetka graben. The values of ΔT_a vary along the traverse in the range between −895 and +638 nT. Manmade noise which affects the anomalous magnetic field has been taken into account for these magnetometric surveys (pipelines, wells, separators, "metal waste" buried just under the ground). As well, we sought to achieve the most reliable interpretation by smoothing the plot by averaging over several adjacent values (a moving average of 9). Large sign-varying changes in the field characterize definite geologic features. The boundary of the Pauzhetka graben (a normal-displacement tectonic discontinuity) is seen as a sharp negative anomaly (the area of the Pauzhetka River). Previous data from low frequency seismic sounding (unpublished work of I.F. Abkadyrov, I.A. Nuzhdaev, and others) show that zones of seismic attenuation are confined to the right wall of the Pauzhetka graben. These zones are here interpreted as regions of ascending heat flow. Many of the drilled prospecting–operating wells in the structure of the junction between the graben and the rocks that compose the uplifted blocks of the Pauzhetka geothermal field are producing wells, demonstrating a high permeability of this area in the Pauzhetka hydrothermal system (*Struktura ...,* 1993). The area of the Verkhne-Pauzhetka thermal field is characterized by positive values of ΔT_a (the maximum is +256 nT), but this maximum is complicated with a lowering of the measured values down to +143 nT in the middle of the anomaly. That fact indicates the presence of hydrothermally altered rocks having lower magnetic properties due to leaching of ferromagnetic minerals. Overall, however, the identified major positive anomaly of ΔT_a in this area of the hydrothermal system provides evidence of rocks with sufficiently high remanent magnetization. The rocks in the structure of the system primarily include subvolcanic formations of intermediate composition (*Struktura ...,* 1993; Feofilaktov et al., 2017). A preliminary estimate using the method of tangents (*Magnitorazvedka,* 1980) suggests that the top of the anomaly-generating body lies at a depth of 240 m. We hypothesize that the area of the central uplifted block in the Pauzhetka geothermal field includes a large subvolcanic body of diorites or gabbro diorites, or else several bodies combined to make a subintrusive complex. The top of this complex may lie at a depth between a few hundreds of meters and 1–1.5 km. These data are in agreement with the identification of a positive ΔT_a anomaly in the left part of the traverse (see Fig. 9): the top of the anomaly-generating body was at a depth of 1380 m. The well-pronounced negative anomalies ΔT_a in the section probably reflect the locations of major tectonic discontinuities with higher permeability for the geothermal heat carrier, or else structures with older hydrothermal mineralization in which associations of secondary minerals do not contain ferromagnetic phases.

A gravimetric survey was carried out to derive a plot of Bouguer gravity variation for the intermediate layer with density 1.9 g/cm^3 (see Fig. 9). The values of ΔG_a are +5.95 to −2.7 mGals. High density values characterize the marginal parts of the traverse, which is explained by the presence of dense igneous rock massifs there, viz., basaltic andesites, and probably their subvolcanic analogues in the Mt. Klyuchevskoi complex (in the NW), as well as extrusive lava complexes of dacites and andesites in the Kambalnyi volcanic range (in the SE). The middle of the traverse has lower values of the anomalous gravity field, attaining a minimum in the Pauzhetka R. valley. While the general background is one of negative values, there are three areas with comparatively high values of ΔG_a: the Ozernaya R. valley and the Verkhne-Pauzhetka thermal field area. Preliminary estimates using the method of characteristic points for a horizontal circular cylinder that has an infinite extent along the Y axis (an infinite material rod) gave the depth to the cylinder axis and the radius of the cylinder, assuming the effective density of the material to be 0.3 g/cm^3 (*Gravirazvedka ...*, 1990). The theoretical parameters of the anomaly-generating bodies have the following values: depth to cylinder axis = 1.05 km, radius = 2.2 km in the NW part of the traverse and 900 m in the SE part. Two maxima of ΔG_a in the Ozernaya R. graben (the maximum values are –1.55 mGals and –2 mGals) give the depth to the anomaly-generating body as 200–300 m, the radii are 550 and 630 m. In the central part of the Pauzhetka hydrothermal system (VPF area), superposed upon the general background of negative gravity values, there is a major maximum of ΔG_a with two extremums of -0.18 mGals and lower values reaching –0.39 mGals in the inflexion between the branches of the plot. The depth to the body of higher density in the left branch is 530 m (radius is 283 m) and 250 m in the right (radius 184 m). The resulting theoretical depths to the anomaly-generating bodies (1.05–1.1 km based on gravity data and 1–1.5 km from magnetic data) are consistent among themselves, and provide more accurate information on the positions and depths of the top of high density rock blocks in the structure of the tectono-magmatic uplift of the Verkhne-Pauzhetka thermal field area.

A BLOCK GRAVITY MODEL FOR THE PAUZHETKA HYDROTHERMAL SYSTEM AREA

<u>The petrophysical properties of the rocks</u> in the Pauzhetka hydrothermal system were studied in detail by I.M. Zaitsev[1] and by the present authors (Ladygin et al., 1993; Molostovsky and Frolov, 1993). We consider the main data on density (ρ) and magnetic susceptibility (æ) of the rocks. The rocks of highest density are basalts and andesites (2.5–2.8 g/cm^3 on average). Dacites and rhyolites have slightly lower densities (2–2.5 g/cm^3). The psammite and psephite tuffs have a wide range of density, 1.4–2.3 g/cm^3. Depending on what is the composition, the tuffs divide into acid (1.6 g/cm^3) and intermediate (2.2 g/cm^3) varieties. The acid ones have been as a rule subjected to greater hydrothermal alteration, and this seems to account for their lower density. The aleuropelite tuffs that lie in the upper section have densities of 1.4–1.5 g/cm^3. The lowest values occur in pumice deposits (below 1 g/cm^3). The sections of the wells have their densest thick horizons in the form of andesitic tuff breccias, 2.3 g/cm^3. The tuffs, tuffites, and tuff breccias have much lower densities in zones of argillization and zeolitization, by 50% or more, while the density is greater in rock volumes of intense silicification and adularization owing to the replacement of original components with massive cryptocrystalline quartz (Ladygin et al., 1993).

The range of magnetic susceptibility is large. The rocks of highest magnetism are basalts (æ = 3.7×10^{-3}–45×10^{-3} SI) and andesites (up to 13×10^{-3} SI). Intermediate tuffs and tuff breccias have nearly the same values of æ as the latter rocks. Lavas and extrusive dacites and rhyolites have moderate magnetic properties (æ = 0.9×10^{-3}–25×10^{-3} SI). Aleuropelite tuffs have small values (0.02×10^{-3}– 4×10^{-3} SI). The pumice is nearly amagnetic. The sections of the wells have low values of æ occurring in various rocks from zones of water recharge (0.25–0.1×10^{-3} SI).

The remanent magnetization (J_n) of the rocks varies between 0 and 6 A/m. The maximum values occur in basalts, andesites, and dacites (1–5 A/m). Intermediate and acid tuffs have J_n = 0.1–0.7 A/m. The aleuropelite tuffs have nearly zero values of J_n. We thus see that the rocks in the Pauzhetka hydrothermal system are clearly differentiated by both density and magnetic properties.

Based on our studies and a generalization of data on the petrophysical properties of rocks in the area, we performed <u>gravimetric modeling</u> (Fig. 10). A layered block model for the upper section was compared with geological evidence (see Fig. 3), and the model deeper than 1 km depth was compared with the results of electromagnetic surveys.

It goes without saying that the high degree of detail and reliability for characteristics of the upper part of the modeled section (down to 1 km depth) is determined, unlike deeper horizons, both by the resolution of the structural geophysical methods used here and by the availability of a detailed geological information

The upper part of the model (horizon *a*) consists of two horizontal layers in the northwestern part and one layer in the southeastern part. The first layer corresponds to alluvial deposits of the Pauzhetka and Ozernovsky grabens, and the second to the sequence of tuffites and tuffs of the Pauzhetka suite. The density

[1] *Зайцев И.М.* Отчет о комплексных геофизических исследованиях в районе Паужетского геотермального месторождения в 1969 г. Территориальный фонд геологической информации по Дальневосточному федеральному округу. Петропавловск-Камчатский, 1970. 116 с.

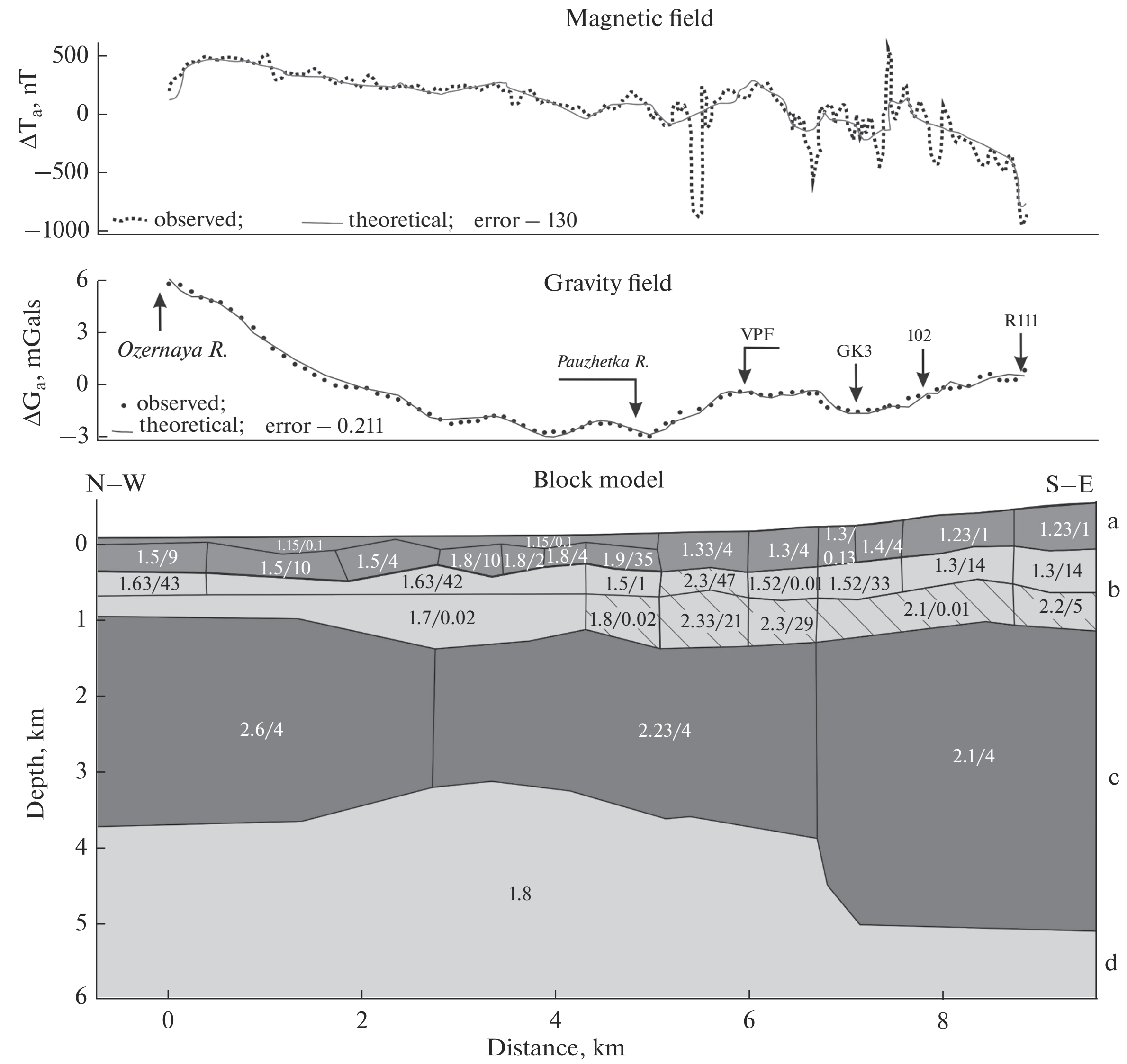

Fig. 10. A gravimagnetic block model for the structure of the Pauzhetka hydrothermal system area. Numerals show average density (in the numerator) and magnetic susceptibility (in the denominator, æ = $n \cdot 10^{-3}$ SI) for each block.

and magnetic susceptibility of the alluvium are 1.15 g/cm^3 and 0.1 × 10^{-3} SI, respectively; those for the tuffs and volcanogenic–sedimentary rocks are 1.23–1.9 g/cm^3 and 1 × 10^{-3}–35 × 10^{-3} SI. The great number of minor blocks in the second layer is probably due to a high original inhomogeneity of volcanic rocks, their tectonic fragmentation, and the effects of steam-charged hydrothermal fluids on their properties.

Horizon *b* in the model also consists of two layers. The upper layer has a lower density (ρ = 1.31–2.31 g/cm^3), but a higher magnetic susceptibility (æ = 1–42 × 10^{-3} SI); the lower is characterized by the values ρ = 1.7–2.33 g/cm^3, æ = 2–29 × 10^{-3} SI. The upper layer is in greater agreement with the tuffs of the Pauzhetka suite and with the underlying rocks (the Anavgai sandstones). The lower layer has a higher density and probably a lower permeability for hydrothermal fluids, it is similar to the Anavgai sandstones in the geological section. Looking at the central part of the Pauzhetka hydrothermal system (in the VPF area), we find that the blocks occurring at the horizon have higher densities and contrasting values of magnetic susceptibilities (highlighted by hatching in Fig. 9). The blocks of rocks with relatively higher density in this part of the geological section may correspond to subvolcanic formations and those of lower density to argillized and zeolitized tuffs, tuff breccias, and sandstones.

Horizon *c* has been identified at a depth between 1 km and 4 km; the horizon consists of three blocks with densities of 2.1 to 2.6 g/cm^3 and magnetic susceptibility 4 × $10^{-3\,\mathrm{SI}}$. The horizon is comparable with horizon no. 4, which we identified from electromagnetic data (see Fig. 8). The horizon corresponds to rocks of the Cretaceous basement, the lower boundary is tentative. However, gravity data revealed a layer with lower density (1.8 g/cm^3) at the bottom of the model corresponding to horizon no. 5 based on MTS data. This allows us to assign the lower horizon in the block model to the zone of higher permeability for deep fluids, namely, the "crustal conductive layer" as deduced in (Moroz et al., 2017; Nurmukhamedov et al., 2010).

CONCLUSIONS

We integrated the results of vertical electrical sounding and electromagnetic sounding, magnetometric and gravimetric surveys, along with a generalization of previous geological and structural geophysical data, to develop a model of layered block structure for the Pauzhetka hydrothermal system. The structure of this crustal block contains 6 main horizons within 15 km depth characterized by contrasting electromagnetic and gravity properties, and an explanation is provided of their geological origin (Fig. 11):

1 alluvial deposits of the Ozernovsky and Pauzhetka grabens, as well as tuffites of the Verkhne-Pauzhetka subsuite and lavas of the Kambalnyi mountain range. These are all comparatively dense rocks with few cracks, they can serve as the upper aquifer for thermal and meteoric waters in the structure of the Pauzhetka volcano-tectonic depression;

2 tuff sequences of the Pauzhetka suite and tuff breccias (tuff conglomerates) of the Alnean series, which constitute the main water-bearing complex in the structure of the Pauzhetka hydrothermal system separated by an intermediate aquifer; the horizon of higher conductivity (lower density) corresponding to these rocks also extends in the subsided blocks of the Pauzhetka and Ozernovsky grabens, which enhances the likelihood of detecting steam-charged hydrothermal fluids outside the Pauzhetka geothermal field;

3 relatively dense and poorly permeable volcanomictic sandstones and gravelites of the Anavgai series; the horizon may be the lower aquifer for the main water-bearing rock sequence that has been well drilled in the field;

4 volcanogenic-sedimentary metamorphic deposits of the Cretaceous basement; the horizon includes major tectonic inhomogeneities that are blocks of dense rocks with high remanent magnetization, which may correspond to intermediate–basic igneous complexes or to highs of the crystalline basement;

5 metamorphosed rocks of Cretaceous or earlier ages; they have low density and are saturated with water; the high crack-and-pore permeability (fluid saturation) of the rocks may be caused by a considerable time gap between the formation of the lower (crystalline) and the intermediate (Cretaceous) structural stages;

6 deposits of the crystalline basement.

Summing up, we can thus state that the upper section extending down to the top of the Cretaceous basement is characterized by an inhomogeneous structure, and contains a present-day water-dominated hydrothermal system. Two water-bearing horizons are identified that occur widely in the structure of the Pauzhetka–Kambalnyi–Koshelev geothermal area. The vertical rock blocks are separated by zones of tectonic discontinuities. A region of ascending heat carrier (geothermal aqueous gas fluid) is confined to the central uplifted block in the structure of the hydrothermal system. Regions such as these probably exist in other parts of the geological system where hidden discharges of thermal water occur.

The top of the crystalline basement (the bottom of the Cretaceous deposits) was found to contain a horizon that is characterized by high electrical conductivity and which is likely to be a zone of ascending heat flow coming from below. The studies of Yu.F. Moroz and his associates have identified a "crustal conductive layer" at depths of 15–30 to 60 km nearly throughout all of Kamchatka (Moroz, 1991; Moroz and Gontovaya, 2017). The top of that layer is shallower, reaching depths of 10 km or less in geothermal areas (Moroz et al., 2017; Nurmukhamedov et al., 2010). The 5th horizon identified in this study seems to be that "crustal conductive layer".

The identification of a thick (4–5 km) horizon of higher permeability for aqueous gas fluid in the Pauzhetka–Kambalnyi–Koshelev geothermal (ore) area at depths of 3–4 to 8–9 km modifies the earlier schematic model of heat supply to the Pauzhetka hydrothermal system which assumed the heat source to reside in the interior of the Kambalnyi volcanic range (Averiev, 1966; Belousov, 1978; *Pauzhetskie ...,* 1965). At the same time, the horizon seems to occur widely in the structure of the Pauzhetka–Kambalnyi–Koshelev area, and can serve as a source of heat both for known geothermal fields (the Pauzhetka and Nizhne-Ozernovsky fields) and for hidden thermal anomalies abundant in the area (near-bottom discharge in the middle of Lake Kurilskoe, hot springs in the Teplaya Bay in Lake Kurilskoe and in the upper reaches of the Levaya Pauzhetka River, and elsewhere).

The high activity of heat flow from depth in the structure of the Pauzhetka hydrothermal system is due to fragmentation separating the western slope of the Kambalnyi Range into small tectonic (tectono-magmatic) blocks and to emplacement of intrusions that form an extensive system of subvolcanic complexes and discrete magmatic bodies. Areas of higher tectono-magmatic activity like the Verkhne- and Vostochno-Pauzhetka thermal fields serve as vertical channelways that conduct heat flow at depth to shallow water-bearing horizons.

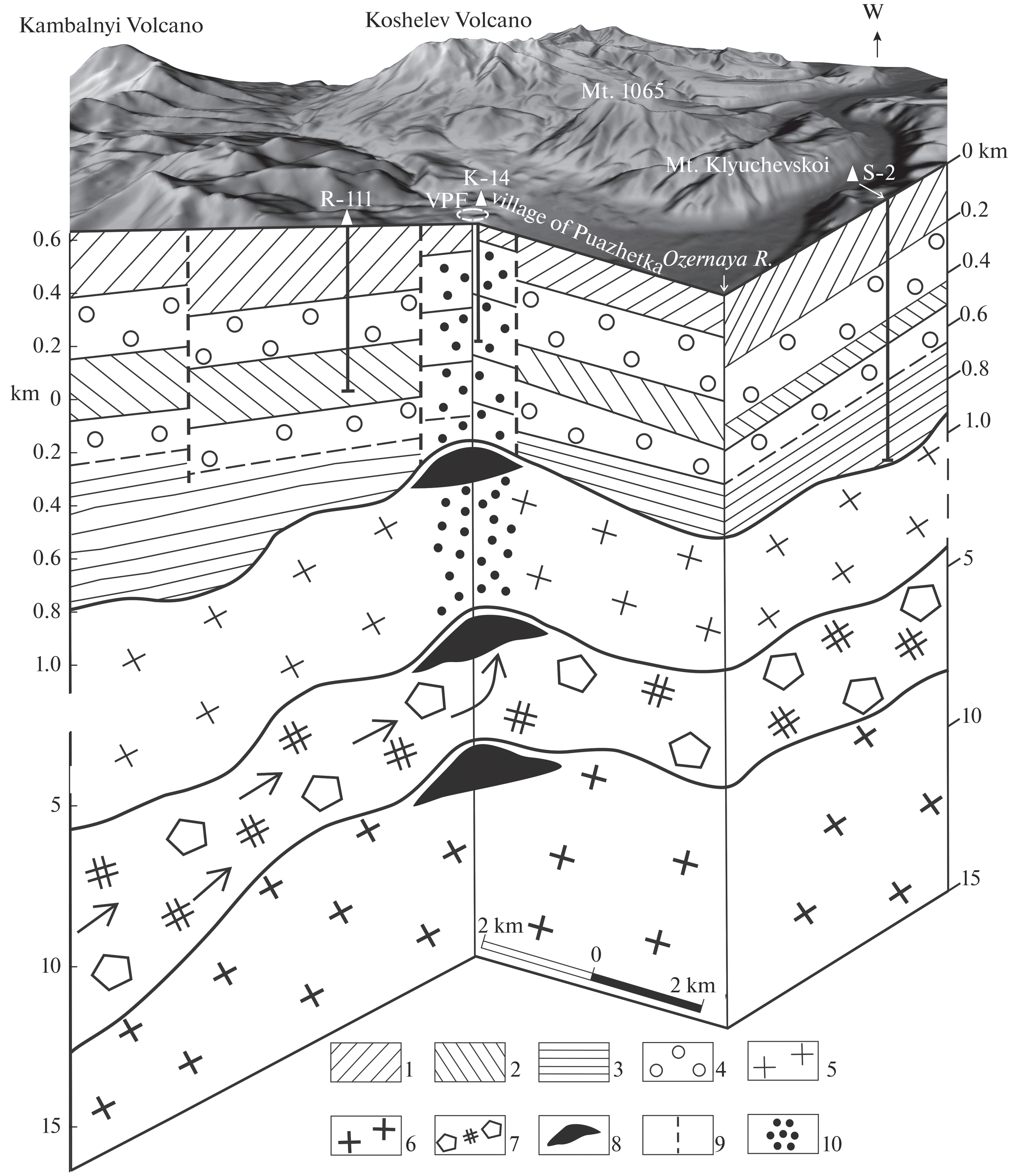

Fig. 11. A conceptual model for the structure of the Pauzhetka hydrothermal system area. (1–3) aquifers in the geological structure of the hydrothermal system: (1) upper aquifer consisting of alluvial boulder–pebble deposits in the Ozernovsky and Pauzhetka grabens (in the right part of the model), as well as of tuffites of the upper Pauzhetka subsuite and of lavas of the Kambalnyi volcanic range, (2) middle aquifer, which includes igneous rocks of the Klyuchevskoi complex and Golygin ignimbrites of the hydrothermal field area, (3) lower aquifer consisting of Anavgai sandstones; (4) water-bearing rock complex consisting of tuffs of the Pauzhetka suite (upper horizon) and of Alnean tuff breccias (lower horizon); (5) Cretaceous basement; (6) crystalline basement; (7) less dense rocks at the top of the crystalline basement (bottom of the Cretaceous basement), which is supposed to be a zone of high conductivity of the geothermal fluid; (8) geothermal fluid flux confined to highs of the Cretaceous and crystalline basements and/or major intrusive complexes. Arrows show the direction in which the deep fluid is moving, from beneath the bottom of the Kambalnyi Range.

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SPELL: OK