The Structure of the Kamchatka's Largest Nizhne (Lower)-Koshelevsky Vapour-Dominated Geothermal Deposit: New Geology and Geophysics Data

Ilyas F. Abkadyrov, Sergey N. Rychagov, Yury Yu. Bukatov, Sergey O. Feofilaktov, Ivan A. Nuzhdayev

Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences, 9 Piipa Avenue, Petropavlovsk-Kamchatskii, 683006 Russia

E-mail: rychsn@kscnet.ru, aifgf@mail.ru

Keywords: Volcanic massif, vapour-dominated geothermal deposit, thermal anomaly, subvolcanic intrusion, deep-seated fault, boiling region, water-confining stratum, ascending fluid, geophysical methods

ABSTRACT

The development of geothermal power industry in Russia's Kamchatka in the 70-80's induced the assessment of geothermal resources of the Koshelevsky volcanic massif (South Kamchatka). The massif consists of five adjoining quaternary stratovolcanoes and has a complex geodynamic position: It is confined to junction of the volcanic belts and located at the interface of the Kamchatkan and Kurile geological structures. In the central part of the massif, in the volcano crater, the Verkhne (Upper)-Koshelevsky steam jets are located and the Nizhne (Lower)-Koshelevsky thermal anomaly is located on the western slope in the deep-cut ravine of the Gremutchiy (Rattling) Stream. The total heat efflux is 75 GW/s (Vakin et al., 1976). Exploration drilling in the area of the Nizhne-Koshelevsky thermal anomaly revealed a more than 1.5-km-deep zone of superheated (dry) steam. A subintrusive body of diorites – diorite porphyrites surrounded by a brecciated mantle and overlaid by a stratum of volcanogenic-sedimentary rocks has been penetrated at the base of the geological cross-section. Dimensionally, the steam zone is inclined to the apical part of the multi-phase subintrusion. It is hypothesized that a lava-extrusive complex of andesidacites in the near-surface part of the cross-section is the upper water-confining stratum for the modern hydrothermal system. The electric power capacity of the Nizhne-Koshelevsky vapour-dominated geothermal deposit is estimated at 90 MW (Pisareva, 1987), while forecast resources of the whole massif are 300 MW.

In recent years, the South-Kamchatka-Kuril surveying company of Institute of Volcanology and Seismology FED RAS has additionally conducted integrated exploration in order to specify the deep-seated structure of the Nizhne-Koshelevsky geothermal deposit and for understanding of the nature of the geological structures that govern the steam zone. New data on structure of the geothermal deposit have been acquired by means of modern geophysical techniques (high precision gravimetry, magnetometry, resistivity prospecting, microseismic sensing). Based on microseismic sensing, low-velocity regions corresponding to decompressed rocks have been identified: a cup-shaped 250-300-meter-deep zone located directly under the thermal anomaly; a 100-meter-thick 5-km-deep subvertical zone related there of. The first zone corresponds to the hypergenesis zone of the geothermal system and composed of argillaceous rocks saturated with a gas-vapour mixture. Most likely, the second zone is a fracture-breccia structure in the form of a subvertical conduit through which a heat-carrying medium ascends to the surface. This conduit is confined to the previously identified deep-seated fault and dips in the interior of the subintrusive body. High-precision gravimetry identified not only the thermal anomaly but also another zone of reduced density rocks linked to it. We interpret this zone as an oreforming paleo-hydrothermal system composed of argillized rocks and secondary quartzites. A magnetometer survey helped to define more precise boundaries of the Nizhne-Koshelevsky thermal anomaly, thickness and stretch of the lava-extrusive rock unit (the upper water-confining stratum). Resistivity prospecting helped to define the position of local conduits through which a gas-hydrothermal heat-carrying medium is discharged in the upper part of the geothermal deposit.

1. INTRODUCTION

The Nizhne-Koshelevsky vapour-dominated geothermal deposit located on the South of Kamchatka is the largest deposit of this type in Russia's Far East. The inferred resources of the deposit were estimated at 210 kg/sec of dry steam which was equivalent to an electric capacity of 90 MW (Pisareva, 1987). Exploration drilling and hydrodynamic tests have revealed a more than 1.5-km-deep zone of superheated (dry) steam. The drilling wells have penetrated a multi-phase subvolcanic intrusion of diorites – diorite porphyrites to the apical part of which the steam zone is spatially inclined. But intrusive rocks were formed in the lower-middle-quaternary period and they are "cold" now and, probably, cannot act as a heat source for the geothermal deposit. It is assumed that the deposit is included within the structure of the large Koshelevsky hydrothermal system which is confined to the zone of a deep-seated regional fault; heat comes as part of a hydrocarbon fluid from lower horizons of the Earth's crust or the upper mantle (see reports of S. Rychagov and Ye. Kalacheva with co-authors in the proceedings of WGC2015). Apart from resolution of key issues related to the deposit's heat source and its structural confinedness, the geological setting and hydrogeological structure of this area of the Koshelevsky hydrothermal system remain unclear: extent and thickness of the upper water-confining layer, structure of the hypergenesis zone and feeding conduits for a high-temperature fluid, structure of meteoric waters precipitation zones, availability and internal structure of the Nizhne (Lower)-Koshelevsky vapour-dominated geothermal deposit based on compilation of geological data and all-inclusive geophysical studies.

2. GEOLOGICAL SUMMARY OF THE DEPOSIT

The Nizhne (Lower)-Koshelevsky vapour-dominated geothermal deposit is situated within the limits of the Pauzhetsky-Kambalny-Koshelevsky Geothermal (Ore) region of South Kamchatka and located on the western slope of the Koshelevsky volcanic massif (Figure 1). The region features a complex geodynamic position: It is situated at the conjunction of Kamchatka's three volcanic



Figure 1: A schematic geological map of the Koshelevsky volcanic massif (Vakin et al., 1976) with modifications. (1-2) effusive and pyroclastic deposits of Lower Quaternary volcanoes: (1) Ded-i-Baba Volcano ($\alpha\beta Q_{I}$), (2) Tret'ya Rechka Volcano ($\alpha\beta Q_{II}$), (3-8) – effusive and pyroclastic deposits in the Koshelevsky volcanic massif: (3) Drevnii Volcano (αQ_{II}), (4) Zapadnyi Volcano (αQ_{III}^{1}), (5) Valentin Volcano (αQ_{III}^{2}), (6) Vostochnyi Volcano (βQ_{III-IV}); (7) Tsentral'nyi Volcano ($\alpha\beta Q_{III-IV}$); (8) formations in Aktivnyi Crater (Q_{IV}): (*a*) lava flows, (*b*) deposits due to a directed blast; (9) unconsolidated deposits of diverse origin and ages ($Q_{II} - Q_{IV}$); (10) Holocene extrusions; (11) subvolcanic dolerite intrusions (βQ_{III-IV}); (12) inferred acidic tuffs of the Verkhne-Pauzhetka Formation; (13) preQuaternary effusive rocks ($\alpha N_1 - N_2$); (14) discontinuities: (*a*) certain, (*b*) inferred; (15) negative features: (*a*) calderas, (*b*) erosion craters and explosion craters; (16) effusive and extrusive cones; (17) main thermal anomalies (Verkhne-Koshelevsky and Nizhne-Koshelevsky); (18) local discharges of thermal water.

belts and at the interface of regional tectonic blocks of the Kurile and Kamchatka island arc segments. A lot of papers have been devoted to description of the geological structure of the region (Belousov, 1978; *Dolgozhivishii* ..., 1980; Rychagov et al., 2009). Two thermal anomalies (t/a) – Nizhne (Lower)-Koshelevsky and Verkhne (Upper)-Koshelevsky ones with an estimated capacity of 25 and 50 GW/sec respectively (Vakin et al., 1976) were identified after geological-hydrogeological studies. It is assumed that the thermal anomalies are hydrodynamically connected and, subsequently, a same large hydrothermal system may be available in the interior of the Koshelevsky volcanic massif (Pozdeev, Nazhalova, 2008). In 1970-80th, wells were drilled in the Nizhne-Koshelevsky thermal anomaly area to a depth of 1,500 m. The geological cross-section is manifested by alternating layers of neutral and acid tuffs and lavas hydrothermally altered to propylites and secondary quartzites; the upper layer is composed of weakly-altered lava flows of andesidacites (Figure 2). This layer is considered to play a role of the upper water-confining layer in



Figure 2: A geological cross-section of the Nizhne-Koshelevsky vapor-dominated geothermal deposit (Pisareva, 1987). (1) diorites; (2) diorite porphyries; (3) megabreccia in apical parts of intrusion; (4) andesitic lavas; (5) andesitic and basaltic andesite tuffs and tuffites; (6) andesitic and dacitic-andesite lavas and tuffs; (7) dacitic-andesite and dacite lavas and extrusions; (8) top of intrusive complex; (9) tectonic discontinuities that have been healed with secondary hydrothermal minerals; (10) same, permeable for presentday hydrothermal fluids; (11) boundary of boiling hydrothermal fluids as inferred from hydrodynamic tests at wells; (12) vapor; (13) wells.

the hydrothermal system (Pisareva, 1987). A subvolcanic intrusion of complicated zonal structure was penetrated at the base of the geological section: diorites are gradually (?) replaced with diorite porphyrites which in their turn are invested with a thick (100 to 200 m on the average) zone of megabreccias. Megabreccias are the most disintegrated rocks of the geological section and may be permeable for a deep high-temperature fluid (Rychagov, 2014). In general, circulation of deep thermal waters takes place via the subvertical zones of decompressed rocks, however, presence of subhorizontal highly fractured zones and zones of open porosity of rocks should not be excluded which we will demonstrate below based on factual research data.

3. RESEARCH METHOD

The following types of geophysical works have been carried out on the site of the Nizhne-Koshelevsky vapour-dominated geothermal deposit: magnetometer areal survey, vertical electrical sounding (VES), microseismic sensing and gravity surveys.

3.1 Magnetometer surveys

Magnetometer surveys were conducted during two field seasons in 2010-2011 (**Figure 3**). Two proton magnetometers MMP-203 with an accuracy of ± 1 nT were used. One instrument was used for recording of magnetic field variations whereas the other was used for conventional measurements. In 2010 the surveys were carried out across the system of profiles: spacing between profiles was 100 m with a survey step of 10 m; in 2011, spacing between profiles was 50 m with a survey step of 5 m. Root mean square accuracy was calculated by means of repeated measurements in an amount of 15 % of the total amount and didn't exceed ± 10 nT.



Figure 3: A scheme of research area. (1) microseismic profile A-B, (2) points of VES, (3) magnetometer profiles, (4) points of gravity surveys, (5) outline of Nizhne-Koshelevsky t/a.

3.2 Electrical exploration

Electrical exploration was carried out in 2013 by VES method by way of a symmetrical four-electrode pattern AMNB. The following pieces of hardware were used: a multifunctional electric meter MERI 24 (manufactured by OOO "Nord-West"), an exploration electric generator VP-1000 (manufactured by OOO "Elgeo") powered by an AC inverter generator Yamaha EF2000iS. The feed and receiving lines were grounded by steel and brass electrodes; reliable grounding of the feed line at distant spans was provided by grouping several electrodes (Khmelevskoi, 1970). Vertical electrical sounding was carried out on profile D-C. In total 11 points were surveyed by VES with a step of 200 m; spacing between points in the area of the thermal anomaly was 50 m. The length of the profile was 1.2 km (See Figure 3). The profile crossed Nizhne (Lower)-Koshelevsky New Thermal Field in point NP. Mean relative error of the survey was 2.4 % which was calculated using control measurements in an amount of 8 % of the total number of observations. Then the curves of apparent resistivity were entered to IP12WIN software developed at the geophysics department of Moscow State University (A.A. Bobachev, I.N. Modin and V.A. Shevnin) and then the cross-sections were plotted.

3.3 Method of low-frequency microseismic sensing (MMS)

Method of low-frequency microseismic sensing (MMS) is a passive seismic method (SPAC - methods, H/V- methods). This method is based on the property of the Earth's crust velocity heterogeneity to distort the spectrum of a low-frequency microseismic field in its vicinity, i.e. spectrum amplitudes of microseisms (at *f* frequency) above the high-velocity heterogeneity decrease and increase above the low-velocity ones (Gorbatikov et al., 2008). The purpose of MMS application at Nizhne-Koshelevsky deposit was to differentiate the main components of the geological structure of the hydrothermal system. Profile A-B was cross-line of the Nizhne-Koshelevsky thermal anomaly and crossed the main, previously known, geological structures (See Figure 3). In this respect, a 4-km long profile with NS general trend consisted of multidirectional interconnected line segments. A microseismic signal was logged gradually from point to point with a step of 100 m, the step was decreased to 20 - 40 m within the limits of the thermal anomaly. The logging time in each point lasted at least 150 minutes to achieve the statistical stability of the spectrum. A portable broadband seismometer consisting of a pack of 5 sets of Guralp CMG-6TD sensors (f=0.033-50 Hz) was used for logging. Two of the sets were used as reference ones for elimination of the unsteady effect of the sensing microseismic signal.

Abkadyrov et al.

3.4 Gravity surveys

Gravity surveys were carried out by a high-precision gravity meter Scintrex CG-5 Autograv. This instrument is an automatic microprocessor gravity meter. Its measurement range exceeds 7,000 mGal with a resolution of 0.001 mGal. Readings in the Autograv system are derived through on-going averaging of measurements taken in the space of one second. Geodetic support was provided by Trimble and Topcon GPS-stations. One station was used in the steady-state, whereas the other was moved along the profiles. Such a system allowed achieving the required accuracy in determining elevations at recording stations. 10 profiles were surveyed in the study area. Each profile was 1 km long, spacing between profiles was 100-150 m, and survey spacing along the profile was 100 m (See Figure 3). Perpendicularly to working profiles, a reference profile was staked at which measurements were taken repeatedly to take into account instrumental drift. Subsurface density in the profile was estimated by Nettleton Graphical Method (*Gravirazvedka...*, 1990).

4. RESEARCH OUTPUTS

The magnetic anomaly of the central part of the Nizhne-Koshelevsky vapour-dominated geothermal deposit was mapped (Figure 4). Three negative anomalies ΔT_a were identified: northern, central and southern. The formation of the southern anomaly is



Figure 4: The map of magnetic field anomalies in the area of Nizhne-Koshelevsky t/a. (1) ancient tectonic fault.

connected to the sublatitudinal tectonic zone which is traced by the valley of the Priamoi (Straight) stream and which was identified earlier as a result of geological surveys and regional geophysical works (Pisareva, 1987). The negative magnetic anomaly adjacent to this tectonic zone can be explained by leaching of ferromagnetic minerals (magnetite, titanomagnetite) out of rocks in process of paleohydrothermal activity: no modern thermal springs were found in the vicinity of the Priamoi stream but based on data obtained during drilling, propyllitized rocks and secondary quartzites were detected at a depth of first tens of meters from the surface (Pozdeev, Nazhalova, 2008). The central anomaly propagates in the area of the modern geothermal structure where many components of rocks including ferromagnetic minerals are leached. Furthermore, the size of the magnetic anomaly exceeds the size of the temperature field restricted by 20 °C isothermal line which indicates in favour of wide occurrence of highly-argillized rocks beyond the visible limits of the Nizhne-Koshelevsky thermal anomaly. The northern area of negative values ΔT_a is spatially inclined to Verkhniy Sdvinutiy ('Upper Shifted') discontinuous tectonic fault zone and, probably, is connected to the geothermal structure at depth (Feofilaktov, Nuzhdayev, 2013). This area may be prospective for exploration of superheated vapour or hydrothermal waters. The areas with positive values ΔT_a are confined to non-altered or weakly hydrothermally-altered highly magnetic rocks of the Koshelevsky volcanic massif.

Three layers of rocks with contrast resistivity are differentiated on the geoelectric section (Figure 5). The first layer of rocks with a



Figure 5: The geoelectric cross-section of Nizhne-Koshelevsky geothermal deposit central part (profile D-C, See Figure 3).

resistivity of ≥ 2000 Ohm-m, has a thickness of up to 40 m in the western part, decreases to 4 m in the eastern part of section D-C and thins out in the area of the Nizhne-Koshelevsky thermal anomaly. The second layer of rocks with a resistivity of 500-600 Ohmm is differentiated in the eastern part of the profile, it has stable occurrence and a thickness of 16-31 m. The third layer of rocks is characterized by an apparent resistivity of 120-170 Ohm-m, its thickness varies widely: from 3 m in the western part of the profile to ≥ 155 m in the eastern one. Apparently, the three described layers of rocks have properties of the upper water-confining stratum for the hydrothermal system (Figure 6). The lower part of the cross-section is manifested by a low-resistivity rock stratum with a resistivity of 3-30 Ohm-m (the fourth layer). The upper edge of this layer approaches the surface near the Nizhne-Koshelevsky thermal anomaly. Anomalously low values of the apparent resistivity (less than 5 Ohm-m) are observed in the area of Nizhne-Koshelevsky New Thermal Field which indicates in favour of formation of this field due to inflow of a geothermal heat-carrying medium via the subvertical zone of higher fissure-pore permeability of rocks (See report of A. Nuzhdayev with co-authors in the proceedings of WGC2015). Thus, the fourth layer corresponds to the hypergenesis zone of the geothermal system and is a near-surface geothermal pool - a section of argillized rocks saturated with a gas-vapour mixture.



Figure 6: A pseudo-electrical cross-section along profile D-C.

Based on low-frequency microseismic sensing, a cross-section was built which reflected distribution of rock sections (zones) characterized by contrast velocities of crosswise seismic waves in the Earth's crust to a depth of 5 km (Figure 7). The cross-section has a complicated and heterogeneous structure both vertically and horizontally. On the whole, it can be divided into two parts sharply differentiated by physical parameters of the environment. The northern part of the profile intersects the edge of an erosion crater. The anomalies in this part of the cross-section are characterized by low-amplitude values of a seismic signal intensity which points at high velocities of passage of seismic waves through rocks. As a rule, such anomalies match high density rocks. The anomalies propagate to a depth of 700-800 m from the surface. According to geological data, this section is manifested by a lava-extrusive complex of andesidacites of Zapadniy ('West') volcano included within the structure of the Koshelevsky volcanic massif (Nuzhdayev, Feofilaktov, 2013). Probably, the thickness of this complex at the head of Argillizitoviy stream matches the anomaly



Figure 7: The microseismic cross-section of Nizhne-Koshelevsky geothermal deposit central part (profile A-B, See Figure 3). (1,2,4) ancient tectonic faults; (3,5 and NKN) modern tectonic faults.

identified by MMS (See Figure 7). A subvertical low-velocity anomaly with a cross-section of 100 m which intersects this area spatially coincides with the valley of the Argillizitoviy stream tracing the previously identified fault. One more low-velocity subvertical anomaly (in the central part of the profile) propagates to a depth of 1 km and also matches the discontinuous tectonic fault. High-amplitude anomalies characterized by low velocities of seismic waves' passage prevail in the southern part of the crosssection. The nature of such anomalies within the limits of high-temperature geothermal systems is associated with saturation of pores and fissures with a gas-vapor mixture. This leads to a rise of interstitial pressure and, as a sequence, to reduction of actual stress and decrease of velocities of elastic waves (Kissin, 2009). Two low-velocity anomalies are differentiated directly under the Nizhne-Koshelevsky thermal anomaly. One anomaly is cup-shaped and propagates to a depth of 250-300 m. It corresponds to the hypergenesis zone of the geothermal system and composed of argillaceous rocks saturated with a gas-vapour mixture. At a depth of over 300 m, this anomaly changes to a less pronounced and heterogeneous subvertical zone whose thickness slightly increases with depth. Most likely, this zone is a fracture-breccia structure in the form of a subvertical conduit or a system of fractures through which a heat-carrying medium ascends to the surface. This anomaly is confined to the previously identified deep-seated fault which traces the Gremutchiy ('Rattling') stream and dips in the interior of the subintrusive body. One more low-velocity anomaly is differentiated to the south of the Nizhne-Koshelevsky thermal anomaly. It is well pronounced and propagates to a depth of up to 3 km. Spatially, this anomaly is located under the Nizhne-Koshelevsky New Thermal Field. The anomaly is of a great interest for practical geothermics: its position, depth continuity and formation of lens-shaped sections unifying it with the anomaly of the Gremutchiy stream at a depth of 1.5-2.0 km - all this suggests that it can match a zone of an ascending flux of a gas-vapour heatcarrying medium.

The map of the Bouguer variation anomalous gravity field was calculated for a density of 2.1 g/cm³ of subsurface rocks (Figure 8).



Figure 8: The map of the Bouguer variation anomalous gravity field in the area of Nizhne-Koshelevsky t/a.

This density mostly corresponds to the average volume density of hydrothermally-altered rocks composing the area of the Nizhne-Koshelevsky thermal anomaly. A system of adjacent gravity fields is differentiated which indicates the presence of density heterogeneity in the upper part of the cross-section (Figure 9). It is known that gravity inversions have no single-value decisions and there are many variants of density models corresponding to the observed values of the gravity field along profile I-II. When selecting a most probable density model the authors were guided by three criteria: 1) maximum possible simplicity of a model, 2) best match of observed and calculated gravity field charts, 3) actual values of excessive density which do not contradict to geological data. The density model is manifested by 7 blocks in which the density of rocks varies from 1.9 to 2.3 g/cm³. The modelling accuracy is 0.065. Three blocks of rocks are differentiated in the area of the Nizhne-Koshelevsky thermal anomaly with a density of 2.0 g/cm³, 2.1 g/cm³ and 2.2 g/cm³ and a thickness of 200 to 400 m. The gravity anomalies have a near east-west strike corresponding to the direction of the main tectonic fault zone along the valley of the Gremutchiy stream. A block of rocks with a density of 1.9 g/cm³ was differentiated in the central part of the cross-section under the Nizhne-Koshelevsky New Thermal Field. These data correlate well with the results of microseismic sensing thus confirming the presence of a newly-formed thermal field of highly fractured (porous) rocks which may act as a subvertical conduit for an ascending heat flux.



Figure 9: Bidimentional model of Nizhne-Koshelevsky geothermal deposit central part density rocks on profile I-II (See Figure 8). (a) chart of observed gravity field, (b) model of density (g/cm³).

5. CONCLUSION

Based on all-inclusive geological-geophysical and hydrogeological studies, the structure of the largest on Russia's Far East Nizhne-Koshelevsky vapour-dominated geothermal deposit was updated. The hypergenesis zone of the geothermal system was identified directly under the Nizhne-Koshelevsky thermal anomaly: isometric in plan and propagating to a depth of 250-300 m irregular cupshaped section of decompressed highly argillized rocks saturated with a gas-vapour mixture. It has been established that the hypergenesis zone is significantly wider in plan than the size of the Nizhne-Koshelevsky thermal anomaly at the surface (by reference to the geomorphologic boundaries of the thermal anomaly and its delimiting 20 °C isothermal line). The hypergenesis zone communicates with a heat source through a subvertical 100-150 m thick conduit dipping to a depth of over 2 km (the zone of fractured and porous rocks). This conduit is connected with even a more pronounced subvertical more than 5 km deep zone of higher permeability for a gas-vapour fluid. Probably, it is this conduit which participated in the formation of the new thermal anomaly (the Nizhne-Koshelevsky New Thermal Field) on the western slope of the Koshelevsky volcanic massif in 2008-2009. Separate subvertical conduits of highly fractured (porous) rocks through which a gas-vapour mixture and hydrothermal solutions outflow to the surface in the area of the main Nizhne-Koshelevsky thermal anomaly have been identified in the hypergenesis zone of the geothermal system. An example of the Nizhne-Koshelevsky New Thermal Field demonstrates that rather powerful concealed discharges of a heat-carrying medium may occur in near-surface layers of a geothermal deposit. Apart from geothermal structures, components of the paleohydrothermal system have been identified in the interior of the deposit: relatively "cold" blocks of rocks composed of propylites and secondary quartzites with epithermal ore mineralization. The blocks of rocks belonging to the modern and paleohydrothermal systems are divided by steep discontinuous tectonic faults with an average thickness of 100-150 m. The subvolcanic intrusion penetrated by drilling in the interior of the modern hydrothermal system is probably not a heat source but plays a big role as large heterogeneity and a source of tectonic deformations in the enclosing volcanogenic-sedimentary rocks and inside the intrusion composed of separate bodies of various age and composition. A big role in the structure of the hydrothermal system may be also played by the brecciated mantle of the subvolcanic intrusion as a cross-flow zone of ascending hightemperature hydrothermal vapours, infiltration of condensate and mixed waters. Most likely, lower layers of the Earth's crust or the upper mantle in this highly dynamic region of South Kamchatka are the main heat sources what is indicated by regional geophysical data and materials of isotope-geochemical studies. Heat is carried by a crust-penetrating (intratelluric according to D.S. Korzhinsky) hydrocarbon fluid flow. The study area possesses not only large geothermal resources but also stocks of various construction materials, mineral water springs with balneological and other properties, and many other useful resources. The geothermal energy of the Koshelevsky volcanic massif may be sought after for the socio-economic development of South Kamchatka and the whole Kamchatka Krai.

6. ACKNOWLEDGEMENTS

The authors deeply appreciate the contribution from all the participants from the South-Kamchatka-Kuril surveying company of Institute of Volcanology and Seismology FED RAS who helped with the field research. This work has been carried out with a financial support from the Russian Foundation for Fundamental Research (Project 13-05-00262a) and Far-Eastern Division of the Russian Academy of Science.

REFERENCES

Belousov, V.I. Geologiya geotermalnikh polei (Geology of Thermal Fields). Moscow: Nauka. 1978. 176 p.

- Dolgozhivischii tsentr endogennoy activnosti Yuzhnoy Kamchatki (The Long-Lived Center of Endogenic Activity of the South Kamchatka) Moscow: Nauka, 1980. 172 p.
- Gorbatikov, A.V., Stepanova, M.Yu., Korablev, G.Ye. Zakonomernosti formirovaniya mikroseismicheskogo polia... (The Way a Microseismic Field is Formed under Influence of Local Geological Heterogeneities and Environment Sensing by Microseisms) // Physics of the Earth. 2008. № 7. P. 66-84.

- *Gravirazvedka* (Gravity Survey). Geophysics' Reference Book / Under the editorship of Ye.A. Mudretsova, K.Ye. Veselov. Moscow: Nedra, 1990. 587 p.
- Khmelevskoi, V.K. Basic Course of Resistivity Prospecting // Moscow: Publishing House of Moscow University, 1970, Part 1. 241 p.
- Kissin, I.G. *Fluidi v zemnoi kore*... (Fluids in the Earth's Crust: Geophysical and Tectonic Aspects) // Moscow: Nauka. 2009. 328 p.
- Nuzhdayev, I.A., Feofilaktov, S.O. Sovremennoye sostoyaniye izuchennosti stroyeniya... (Modern State of Exploration of Nizhne-Koshelevsky Geothermal Deposit (South Kamchatka) and Results of Magnetometer Survey) // Bulletin of Kamchatka Regional Association "Scientific Training Center". Earth Sciences. 2013. № 2 (22). P. 231-241.
- Pisareva, M.V., "Zone of Natural Vapor of the Nizhne-Koshelevskoe Geothermal Deposit," J. Volcanol. Seismol. 2, 52-63 (1987).
- Pozdeev, A.I., and Nazhalova, I.N., "The Geology, Hydrodynamics, and the Oil and Gas Potential of the Kosheleva Stream–Water Field in Kamchatka," J. Volcanol. Seismol. 3, 32–45 (2008).
- Rychagov, S.N. "Giant Gas-Rich Hydrothermal Systems and their Role in the Generation of Vapor-Dominated Geothermal Fields and Ore Mineralization", J. Volcanol. Seismol. 2, 3-28 (2014).
- Rychagov, S.N., Davletbaev, R.G., and Kovina, O.V., "Hydrothermal Clays and Pyrite in Geothermal Fields: Their Significance for the Geochemistry of PresentDay Endogenous Processes in Southern Kamchatka," J. Volcanol. Seismol. 3, 105–120 (2009).
- Vakin, E.A., Dekusar, Z.B., Serezhnikov, A.I., and Spichenkova, M.V., "Hydrothermal Vents of the Koshelevskoe Volcanic Massif," in *Hydrothermal Systems and Thermal Fields of Kamchatka* (DVNTs AN SSSR, Vladivostok, 1976), pp. 58–84 [in Russian].