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A Conceptual Model of the Structure of the Central Part of the Nizhne-Koshelevsky Geothermal Field (South Kamchatka)

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ABSTRACT

Low-frequency seismic sounding method (LFS) was used to study the central part of the Nizhne-Koshelevsky vapour-dominated geothermal field, which is the largest in the Russian Far East. Based on these studies and interpretation of geological and hydrogeological data, the following anomalies were identified immediately below the thermal anomaly: 1) a low-speed bowl-shaped anomaly that extends to a depth of 250–300 m and matches the hypergenesis zone of the modern hydrothermal system; 2) isolated anomalies that spread deeper than 3-5 km and confined to zones of discontinuous tectonic dislocations; 3) deep level subvertical channels, along which a geothermal fluid rises to the surface. The identified seismic anomalies are rock areas with an increased interstice permeability for the vapour-gas fluid; they are routed along the deep fault zone. Based on synthesis of geological, geophysical and hydrogeological data, a conceptual model of the structure of the Nizhne-Koshelevsky vapour-dominated geothermal field is suggested.

1. INTRODUCTION

In the wake of the development of geothermal power industry in Russia's Kamchatka, the geothermal resources of the Koshelevsky volcanic massif (South Kamchatka) were assessed in the 1970s and 80s. Based on all-inclusive hydrogeothermal and geochemical studies, two large thermal anomalies (t/a) were identified: Verkhne- (Upper-) and Nizhne- (Lower-) Koshelevsky with a total heat eflux of 75,000 KW/s (Vakin et al., 1976). A zone of superheated (dry) steam extending to a depth of more than 1.5 km was delineated by wells drilled in the area of Nizhne-Koshelevsky t/a. A vapour-dominated geothermal field with an electrical capacity of ≥ 90 MW was established (Pisareva, 1987). The forecast geothermal resources of the entire Koshelevsky volcanic massif exceed 300 MW (Strategy ..., 2001), which is the reason why this field is in the focus of the socio-economic development of Kamchatka Krai. The unfailing research interest is associated with the particular geodynamic position of the massif and the crust-penetrating nature of the gas-hydrothermal (fluid) system (The Long-Lived ..., 1980; Rychagov, 2014). The authors of the report obtained principally new data on the structure of the Nizhne-Koshelevsky geothermal field and the physical nature of the geological structures that control the dry vapour zone, flows of ascending fluids and the areas where metal-bearing solutions discharge in the upper horizons of the modern hydrothermal system. Based on integration of geological and geophysical data and additional microseismic soundings, a conceptual model of the structure of the Nizhne-Koshelevsky vapour-dominated geothermal field is suggested.

The Nizhne-Koshelevsky thermal anomaly is located on the south western slope of the active Koshelevsky volcano at an absolute altitude of 750-800 m. The geothermal area is an oval-circular negative geomorphological structure with characteristic forms of thermal manifestations: boiling water and mud-water pots, pulsating springs, vapour-gas jets. The thermal anomaly is extended 500 m along a deep ravine cut by the Gremuchy creek with the most active part of the anomaly concentrated on a 150×250 m area. The total heat eflux is estimated at 25 Gcal/s (Vakin et al., 1976). In 2008-2009, Nizhne-Koshelevsky New Thermal Field suddenly formed near the t/a, and the temperature on its surface reached 100°C. Our studies demonstrated that this thermal field formed due to intrusion of a vapour-gas fluid from the main heat source. Structure-wise, the Nizhne-Koshelevsky t/a is confined to the deep fault zone of the wrench-fault type of a sublatitudinal strike (that is radial within the structure of the Koshelevsky volcanic massif). In general, rocks of this zone are characterised by increased fracturing and, consequently, higher permeability for surface and ground waters and gases. The structure of the fault zone, both in the t/a area and along the Gremuchy Creek, has not been studied. This gap did not allow to plot a geological-geophysical model to explain the mechanisms of circulation of high-temperature steam-hydrotherms in the central part of the geothermal field. In this regard, we carried out seismological studies using the microseismic sounding method (MSM). The following zones are identified immediately below the thermal anomaly: 1) a low-speed bowl-shaped anomaly that extends to a depth of 250–300 m and matches the hypergenesis zone of the modern hydrothermal system; 2) isolated anomalies that spread deeper than 3-5 km and confined to zones of discontinuous tectonic dislocations (Abkadyrov et al., 2015). These data encouraged additional studies to detail the geological structure of the thermal anomaly and the deep fault zone in the central part of the geothermal field.

2. GEOLOGICAL SUMMARY OF GEOTHERMAL FIELD

The Nizhne-Koshelevsky vapour-dominated geothermal field is within the Pauzhetsky-Kambalny-Koshelevsky geothermal (ore) region of South Kamchatka and is situated on the western slope of the Koshelevsky volcanic massif. The Koshelevsky volcanic massif is built up of five adjoining stratovolcanoes from the Lower Quaternary to the Holocene age **(Figure 1).** The massif is located in the connection zone of the three main volcanic belts of Kamchatka, at the junction of regional tectonic blocks of the Kuril and Kamchatka island arc segments. Magnetotelluric depth sounding, regional gravimetric and isotope-geochemical studies confirmed the deep-seated volcano-tectonic structures of this earth's crust area and marked the impact of the mantle source on the

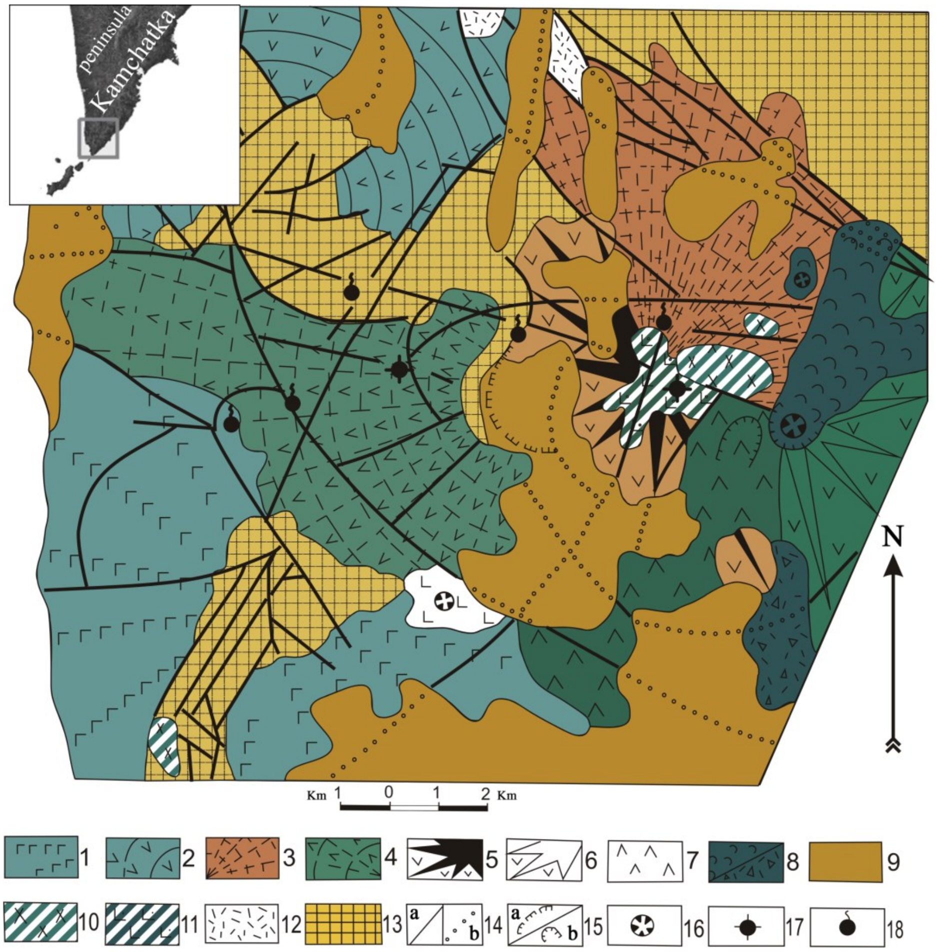

Figure 1: A schematic geological map of the Koshelevsky volcanic massif (Vakin et al., 1976, with modifications). (1-2) effusive and pyroclastic deposits of Lower Quaternary volcanoes: (1) Ded-i-Baba Volcano ($\alpha\beta Q_{I}$), (2) Tret'ya Rechka Volcano ($\alpha\beta Q_{II}$), (3-8) – effusive and pyroclastic deposits in the Koshelevsky volcanic massif: (3) Drevnii Volcano (αQ_{II}), (4) Zapadnyi Volcano (αQ^{1}_{III}), (5) Valentin Volcano (αQ^{2}_{III}), (6) Vostochnyi Volcano ($\beta Q_{III–IV}$), (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 ($\beta Q_{III–IV}$); (12) inferred acidic tuffs of the Verkhne-Pauzhetka Formation; (13) preQuaternary effusive rocks (αN_{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.

composition of the ascending reduced (hydrocarbon) fluid (Pozdeev, Nazhalova, 2008; Polyak et al., 1979). The Upper Koshelevsky thermal anomaly is situated in the central part of the massif within the erosion crater of the Valentin volcano, apparently in the area of influence of the cooling subintrusive diorite – gabbrodiorite body (Vakin et al., 1976; Rychagov, 2014). Nizhne-Koshelevsky thermal anomaly is situated on the western slope of the massif in the deep-cut valley of the Gremuchy Creek and traces the outline of regional tectonic fault (Pozdeev, Nazhalova, 2008). A subvolcanic intrusion of a complex zonal structure has been penetrated at the base of the geological section: diorites change to diorite porphyrites, which in turn are covered by a megabreccia zone with an average thickness of 100-250 m (see Figure 1). Megabreccias are the most disintegrated rocks of the geological section and can be permeable to superheated hydrotherms. The dry vapour zone identified by hydrodynamic testing of wells (Pisareva, 1987) is confined to the apical parts of the subvolcanic intrusion and is probably paragenetically related to it: the intrusive rocks are formed in the lower-mid-Quaternary period, they are currently "cold" and are not a source of heat. It is assumed that heat is transferred by a hydrocarbon fluid from the deeper horizons of the earth's crust. The upper part of the section consists of alternating tuffs and lavas of medium composition, altered to propylites and secondary quartzites. The subsurface lava-extrusive andesidacite complex with an average thickness of 100–150 m is an upper water-confining layer in the modern hydrothermal system (Nuzhdaev, Feofilaktov, 2013). Deep sodium chloride ammonium hydrotherms rise and mixed sulphate waters of complex cationic composition circulate in the vertical loosened rock areas, which does not exclude the presence of sub-horizontal zones of increased fracturing and open porosity of rocks. Despite the spatial separateness and isolation of thermal anomalies in certain volcanic-tectonic structures, it is assumed that they are hydrodynamically related (Kalacheva et al., 2016). It can thus be concluded that a single large hydrothermal (hydrothermal-magmatic) system may exist in the depths of the Koshelevsky volcanic massif (Rychagov, 2014).

3. RESEARCH TECHNIQUE

MSM is based on the registration and spectral analysis of the fundamental mode of the Rayleigh waves as part of natural microseisms. An informative parameter is the distortion of the amplitude field when interacting with the velocity heterogeneities of the Earth's crust. The shape and depth of the heterogeneity is estimated by the distribution of distortion on the surface and the frequency at which this distortion shows. The spectral amplitudes decrease in a certain frequency range on the Earth's surface over high-velocity heterogeneities, and increase over low-velocity ones (Gorbatikov et al., 2008). The MSM is applied to study the cross-section of the earth's crust and to establish the spatial position of anomalous zones even under difficult seismic and geological conditions, while the field work is relatively simple and not costly. That is why the method has been widely used including in Kamchatka (Gorbatikov et al., 2008; Kugayenko et al., 2010).

Four parallel profiles in the SSW-NNE direction propagating orthogonally to the central strike line of the deep fault were plotted on the Nizhne-Koshelevsky thermal anomaly during the field work. The length of the profiles was 400-600 m, the average measurement interval was 50 m, the interval between the profiles was 150 m **(Figure 2).** Three portable broadband digital Guralp CMG-6TD seismometers were used to record the probing signal which provided for the registration of microseisms for three components in the frequency range f = 0.033-50 Hz. Two stations made measurements on the profile and at the same time one station made measurements on the reference point to remove the effect of signal instability. The signal sampling was 100. The sampling synchronization was ensured by integrated GPS receivers. The recording time at each point was at least 150 minutes according to the requirements to achieve statistical stability of the spectrum.

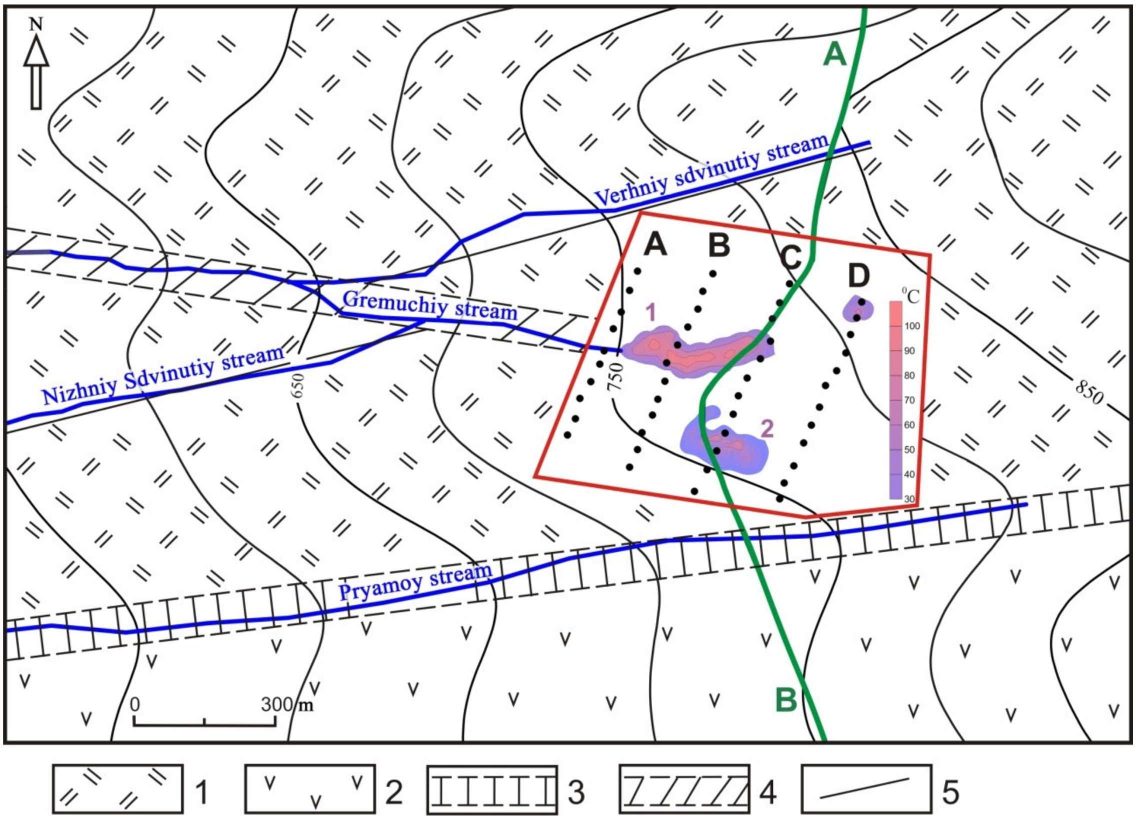

Figure 2: MSM surveys in the area of Nizhne-Koshelevsky thermal anomaly. 1- dacites, andesidacites; 2- andesites, andesibasalts; 3 - the ancient fault of Priamoy Creek (characterized by hydrothermal alterations of rocks at the paleohydrothermal stage); 4 - modern tectonic zone of Gremuchy Creek; 5 - separate tectonic faults. In frame: 1 - Nizhne-Koshelevskya t/a; 2 - Nizhne-Koshelevsky New thermal field. Green line - AB profile; Black dots are sounding locations for profiles A, B, C, D.

4. FACTUAL EVIDENCE

The result of the MSM-based studies is presented in the form of vertical sections demonstrating the distribution of variations of the amplitudes of microseisms (in dB) to a depth of 2500 m below sea level **(Figure 3)**. All the cross-sections are dominated by high-amplitude anomalies obtained directly below the thermal anomaly and which are characterized by low transverse seismic wave velocities. As a rule, such anomalies within high-temperature geothermal systems are associated with the saturation of pores and cracks with a gas-vapour mixture, which leads to an increase in intra-pore pressure and, consequently, to a decrease in the effective stress and decrease in the velocities of elastic wave (Kisin, 2009). The cup-shaped form of the near-surface anomaly (up to depths of 250-300 m) is typical for all the cross-sections; a similar anomaly was identified earlier (Abkadyrov et al., 2015). Thus, a single near-surface zone is identified in the area of the thermal anomaly, which represents the area of the argilized rocks saturated with a vapour-gas mixture.

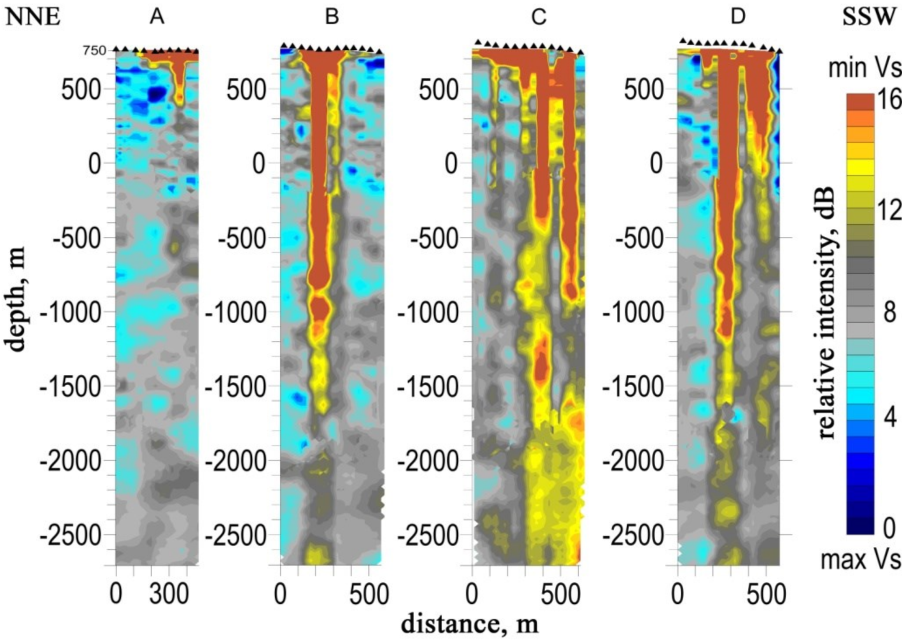

Figure 3: The cross-sections that match the distribution of variations of microseism amplitudes (in dB) associated with the velocity anomalies of transverse seismic waves within Nizhne-Koshelevskya t/a.

Low-speed sub-vertical anomalies that are confined to zones of discontinuous tectonic faults attract special attention. This anomaly has a small thickness and reaches an absolute mark of ≈ 400 m in the section along profile "A" stretching along the western boundary of the thermal anomaly (isotherm below 30°C). The near-surface low-speed anomaly at a depth of about 300 m enters a sub-vertical anomaly and extends to a depth of more than 2000 m relative to the day surface at the section along profile "B", which intersects the central part of the thermal anomaly. Most likely, this zone is a fissure-breccia structure in the form of a subvertical channel through which a vapour-gas heat carrier rises to the surface. The near-surface low-velocity anomaly propagates across its width at the section along profile "C" stretching along the eastern border of the Nizhne-Koshelevsky thermal anomaly and through the central part of the Nizhne-Koshelevsky New Thermal Field which supports the wide occurrence of argilized vapour-gas-saturated rocks at a certain depth. Also this section has two powerful sub-vertical low-speed anomalies directly below the thermal anomaly in the central part and in the SSW part of the cross-section under the New Thermal Field, reaching depths of 2500 m and 1000 meters with respect to sea level, respectively. Both sub-vertical anomalies have a common junction zone at a depth of about 500 m relative to the day surface: the interrelation of these structures was also demonstrated via electrical survey methods (Feofilaktov, 2017). A similar pattern with a shared near-surface low-speed anomaly that merges with the sub-vertical zones is also observed in the cross-section along profile "D". The central seismic anomaly sinks to a depth of more than 2000 m and spatially matches the Nizhne-Koshelevsky thermal anomaly. Probably, this anomaly that was identified on all profiles matches a deep channel through which the hydrotherms ascend to the surface. The anomaly in the SSW part of the cross-section is confined to the Nizhne-Koshelevsky New Thermal Field.

5. CONCLUSION

Based on integrated geological, geophysical, and hydrogeochemical studies, principally new data on the structure of the Russia's Far East largest vapour-dominated Nizhne-Koshelevsky geothermal field were obtained **(Figure 4)**. The hypergenesis zone of the hydrothermal system was identified directly beneath the Nizhne-Koshelevsky thermal anomaly: isometric in plan, irregularly bowl-shaped and stretching to a depth of 250–300 m to the area of loosened intensively argillized rocks saturated with a vapour-gas mixture. It was established that the hypergenesis zone was much wider than the area of the Nizhne-Koshelevsky thermal anomaly on the surface: it goes out beyond the limits of the geomorphological boundaries of the thermal anomaly and its delineating 20°C isotherm. It is connected with the heat source by a sub-vertical channel linked to an even more pronounced zone of increased permeability for a vapour-gas fluid with a thickness of up to 300-350 m dipping to a depth of > 5 km. Probably, this zone is "responsible" for formation of new thermal anomaly on the western slope of the Koshelevsky volcanic massif - the Nizhne-Koshelevsky New Thermal Field in 2008–2009. In the near-surface horizons of the hydrothermal system, separate sub-vertical channels of increased permeability of rocks were identified, along which the vapour-gas mixture and hydrothermal solutions come out in the area of Nizhne-Koshelevsky thermal anomaly. By the example of the Nizhne-Koshelevsky New Thermal Field, it was demonstrated that the hypergenesis zone of the geothermal field contained concealed areas where the heat carrier discharges. Some components of the paleohydrothermal system were also identified in the depths of the field: 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 partitioned by steeply dipping tectonic faults. Multiphase subvolcanic intrusion is a major physical heterogeneity and a source of tectonic deformations within the structure of hydrothermal systems. The breccia mantle of subintrusions can serve as a cross-flow zone for high-temperature (superheated) sodium chloride hydrotherms. Condensate and mixed acidic sulphate waters seep in volcanogenic-sedimentary rocks under the upper watertight stratum – a lava-extrusive andesidacite complex. The heat source is, probably, of a magmatic nature and is located in the lower horizons of the Earth's crust, which is confirmed by regional geophysical data and materials of isotope-geochemical studies. Heat is transferred by the crust-penetrating flow of recovered hydrocarbon fluid. Geothermal energy of the Koshelevsky volcanic massif can be harnessed for the socio-economic development of the South Kamchatka and the entire Kamchatka Krai.

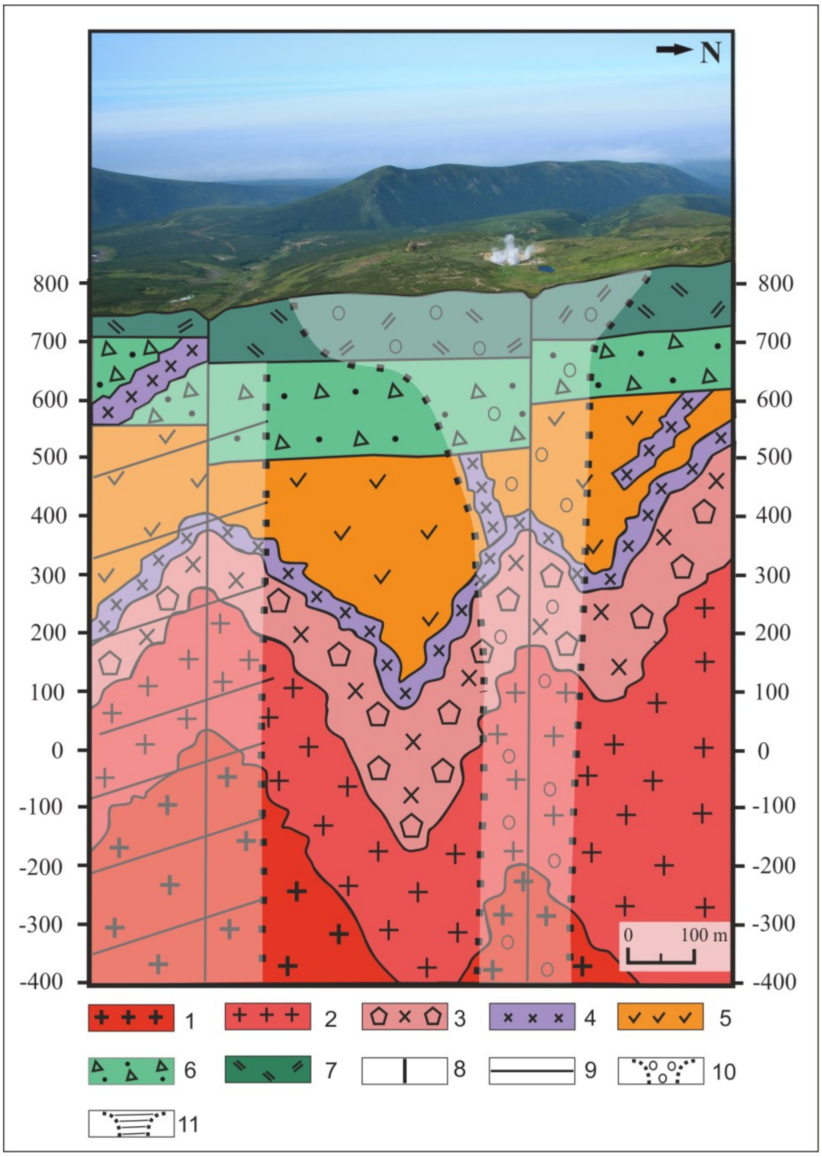

Figure 4: A conceptual model of the structure of the central part of the Nizhne-Koshelevsky geothermal deposit. 1- diorites; 2 - diorite porphyrites; 3 - subintrusive xenobreccias; 4 - dike complex; 5 - andesidacites of lava-extrusive complex; 6 - andesibasalts tuffs; 7 - lavas of andesidacites; 8 - open faults and cracks; 9 - lithological boundaries; 10 - zone of increased fracture-pore permeability for vapour-gas fluid; 11 - increased permeability zone filled by hydrothermal minerals.

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