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The Streams of Alkaline Fluids, Controllable by Giant Gas-Rich Hydrothermal Systems (South Kamchatka)

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ABSTRACT

The studies were conducted at Kamchatka's largest Pauzhetsky-Kambalny-Koshelevsky geothermal (ore) region. The region is a long-lived (from the Oligocene to the Holocene) volcanic-ore centre confined to the system of horsts and grabens of the north-east strike. Large geothermal structures were formed within junctions of the raised and down-dropped regional tectonic blocks. We previously demonstrated that the Koshelevsky volcanic massif currently contained a giant gas-rich vapour-dominated hydrothermal system. Heat is supplied with an ascending hydrocarbon fluid; the system is comparable with the world's largest vapour-dominated geothermal fields (Geysers, Larderello, Matsukawa, Kamojang, etc.). The structure of the study area also covers the Kambalny volcanic ridge. The eruption of the Kambalny volcano in 2017 showed that modern gas-hydrothermal processes occured in the depths of this geological and hydrogeological structure at depths of 5–6 km or deeper; the processes control the discharge of heat on the surface and sometimes cause explosive eruptions. The Pauzhetsky hydrothermal system is situated in the junction zone of the tectonic-magmatic uplift of the Kambalny ridge and the volcanic caldera, and probably has its own thermal power supply. Heat is discharged under the influence of deep alkaline fluids. The composition of the fluids includes compounds of rare and other metals. Complex mineral associations are formed in the zone of thermal water discharge under hydrothermal clays that include phosphates, carbonates, zeolites, sulphides, titanium and zirconium silicates, intermetallic compounds and other mineral phases, which reflect changes in the acid-base regime and salt composition of solutions.

This paper describes compilation of geological, structural-geophysical, hydrogeothermal and other data related to the setting of the geothermal area, large modern hydrothermal systems and thermal anomalies.

1. GEOLOGICAL SETTING OF THE STUDY AREA

The Pauzhetsky-Kambalny-Koshelevsky geothermal (ore) region is part of the South Kamchatka geothermal province (Averyev, 1966) and is situated within the inner zone of the Kuril-Kamchatka island arc at the junction of the three main volcanic belts of Kamchatka (Aprelkov, 1971), **Figure 1**. The region occupies the central position in a subcircular tectonic-magmatic structure, which is a slightly sloping accumulative tectonic anticline 35x50 km in size, complicated by a Quaternary age volcano-tectonic depression of 20x25 km in plan size (Long-lived ..., 1980). Thus, the Pauzhetsky-Kambalny-Koshelevsky geothermal (ore) region is associated with the South Kamchatka long-lived volcanogenic-ore centre (Forecast ..., 1977). The development of the region is manifested in three structural stages: the lower one is represented by Oligocene-Middle Miocene volcanogenic-sedimentary rocks containing multiphase intrusive bodies from gabbro to plagiogranites; the middle one is formed by volcanogenic-sedimentary strata of the Middle Miocene – Pliocene; the upper stage is represents the Quaternary stage of development of the island arc and is composed of lavas, tuffs, and Pleistocene-Holocene intrusive rocks of medium and acidic composition (Geological and Geophysical ..., 1987). The area includes three main geological and hydrogeological structures that determine its structure and control the position of geothermal fields: Pauzhetsky hydrothermal system, Kambalny volcanic ridge and Koshelevsky volcanic massif (Structure .., 1993). These structures had been formed at the Quaternary stage of the development of the Kuril-Kamchatka island arc. The base of the structures is composed of middle stage rocks including ore manifestations of the epithermal gold-sulphide type.

2. PAUZHETSKY HYDROTHERMAL SYSTEM

The Pauzhetsky hydrothermal system is confined to the central part of the same-name volcano-tectonic depression (Long-lived ..., 1980). The system is formed at the present stage (Holocene) of development of the long-lived Pauzhetsky hydrothermal-magmatic system that is described in detail in the book (Structure ..., 1993). Therefore, we will briefly discuss the setting of the modern hydrothermal system. According to the hydrodynamic classification, the Pauzhetsky hydrothermal system belongs to the water-dominated type (Pauzhetsky ..., 1965). Two aquifers can be identified within its structure: the upper one is associated with psephytic and coarse tuffs of the Middle and Lower Pauzhetsky subsuites, whereas the lower one is confined to the agglomerate tuffs of the Alneyan suite. The aquifers are separated by two impermeable strata: the upper water-confining stratum is represented by tuffites of the Upper Pauzhetsky subsuite, and the lower one is represented by the Golygin ignimbrites. Apparently, Anavgai sandstones that underlie the cross-section, also act as a water-confining layer. It is supposed that the aquifers are interconnected by separate sub-vertical faults, along which the thermal waters are mixed at depth and waters ascend to the surface (Belousov, 1978). The deep-seated thermal waters are neutral to slightly alkaline hydrocarbonate and chloride-hydrocarbonate. The cation composition is dominated by calcium; ammonium and boron are present. The temperature of solutions in the lower aquifer reaches 220°C. It was established that the structures that control the intensive mixing of thermal and meteoric waters, as well as discharge of the ascending vapour hydrothermal solutions within thermal fields are elevated tectonic and (or) tectonic-magmatic blocks

(Structure ..., 1993). In general, the Pauzhetsky hydrothermal system is currently at a regressive stage of development. The geothermal field of the same name was explored in the central part of the Pauzhetsky hydrothermal system in the 1960s – 1970s. The installed capacity of the first USSR's and Russia's Pauzhetsky GeoPP is 11 MW, the forecast capacity is ≥ 60 MW for 100 years of operation (Strategy ..., 2001).

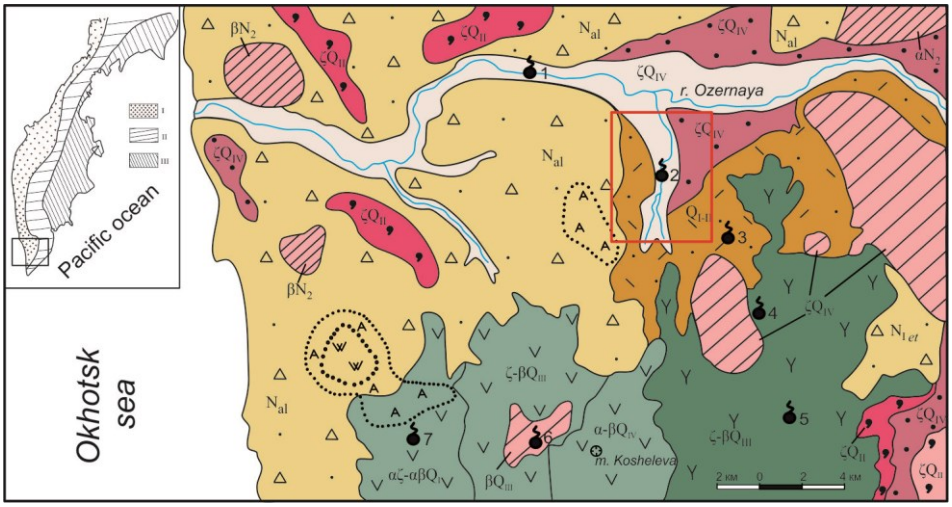

Figure 1: Pauzhetka-Kambalny-Koshelevsky geothermal (ore) region of South Kamchatka. The red square outlines the Pauzhetka hydrothermal system. Numbers on the map – locations of main geothermal anomalies: 1 – Perviye Goriachiye Kluchy, 2 – Vtoriye Goriachiye Kluchy (Pauzhetka system), 3 – Severo-Kambalny, 4 – Tsentralno-Kambalny, 5 – Yuzhno-Kambalny, 6 – Verkhne-Koshelevsky, 7 – Nizhne-Koshelevsky.

3. KOSHELEVSKY VOLCANIC MASSIF. NIZHNE- (LOWER-) KOSHELEVSKY VAPOUR-DOMINATED GEOTHERMAL DEPOSIT

The Koshelevsky volcanic massif was formed at the intersection of the South Kamchatka's fault zones (Vakin et al., 1976). The massif is composed of five volcano edifices (Drevniy, Zapadny, Valentin, Tsentralny and Vostochny), **Figure 2**, as well as extrusive and subvolcanic bodies. In general, it is a typical, but composite andesitic volcano, localized at the junction of the South Kamchatka and North Kuril segments of the Kuril-Kamchatka island arc; the segments are divided by crust-penetrating faults into large regional tectonic blocks. Geophysical data, results of isotopic-geochemical studies, information about ascending hydrocarbon flows including heavy hydrocarbons indicate the crust-penetrating nature of the faults in this area of the South Kamchatka structure: C_6H_{14}, C_7H_{12} and others (Pozdeyev, Nazhalova, 2008). The geological and structural position and evolution of magmatic and post magmatic processes determined the formation of a long-lived ore-forming hydrothermal-magmatic system in the depths of the massif; a giant gas-rich hydrothermal system is identified at the present stage of its development (Rychagov, 2014). Nizhne-Koshelevsky vapour-dominated geothermal field was explored on the western slope of the Koshelevsky volcanic massif in 1975-1984. Its forecast resources are estimated at 210 kg/s of dry steam, which is sufficient for building a 94 MW GeoPP (Pisareva, 1987). Based on drilling of exploration holes up to 1500 m in depth and hydrodynamic testing of wells, a boiling zone of hydrothermal solutions was found. The inverted cone shaped zone extends to a depth of more than 1500 m and wedges out at the surface along the ravine of the Gremuchy Creek. The Gremuchy Creek follows the deep fault zone. The presence of a thick vapour zone and, in general, large forecast thermal energy resources of the entire Koshelevsky volcanic massif totalling to more than 300 MW of electric power (Strategy ..., 2001), ranks this site among the largest vapour dominated geothermal fields in the world, such as Geysers (USA), Larderello-Travale (Italy), Matsukawa (Japan), and Kamojang (Indonesia) (Lund et al., 2005; Lachenbruch, Sass, 1980; Rychagov, 2005; Stimac et al., 2001).

Figure 2: Koshelevsky volcanic massif, view from the north. Photo by S.N. Rychagov.

4. CAMBALNY VOLCANIC RIDGE AND ASSOCIATED MODERN HYDROTHERMAL SYSTEMS

The Kambalny volcanic ridge extends 18 km from south to north, from the Kambalny volcano to the Ozernaya river valley. The ridge is characterized as a resurgent tectonic-magmatic uplift of the Mid-Upper Quaternary age in the Pauzhetsky volcano-tectonic depression (Long-lived ..., 1980) and is a system of successively elevated blocks of rocks with increasing lifting amplitude toward the axis of the ridge. The total amplitude of the uplift is 1000-1500 m (Structure ..., 1993). The volcanic ridge is composed of lavas, extrusions and intermediate and acid subvolcanic bodies. The rocks are significantly altered by hydrothermal-metasomatic processes to secondary quartzites and opalites due to the development of large hydrothermal systems along the axial zone of the ridge. Probably, three such systems (North, Central and South Kambalny) controlling the corresponding groups of thermal fields can be distinguished within the structure of the Kambalny volcanic ridge. Thermal fields were studied by hydrogeochemical methods without drilling. The hydrothermally altered rocks are covered by lavas and extrusive formations of andesibasalts, which complete the magmatic stage of the geological structure development. The modern Kambalny volcano encloses the volcanic ridge from the south. According to petrological studies, it is a stratovolcano composed of alternating streams of lavas and basalt composition slags (Structure ..., 1993). There is no reliable information about the activity of the volcano in historical time. According to tephrochronological studies, the volcano began to form in the early Holocene with the latest pyroclastics being about 600 years old (Ponomareva et al., 2006). However, in the period from March 25 2017 to April 09 2017, an explosive eruption of the volcano occurred with constant emission of ash **(Figure 3)**. A detailed study of ash composition, geoacoustic and seismic events made it possible to determine the volcano eruption as that of the hydrothermal type (Rychagov et al., 2017; Firstov, Lobacheva, 2018). We believe that a giant modern gas-rich hydrothermal system can exist in the depths of the Kambalny volcanic ridge.

Figure 3: The eruption of the Kambalny volcano, March-April 2017. The South-Kambalny Far thermal field in the foreground, view from the north. Photo by A.S. Gabov.

5. EAST-PAUZHETSKY THERMAL FIELD: DISCHARGE OF AN ALKALINE FLUID AND FORMATION OF RARE-METAL MINERALIZATION

The East Pauzhetsky thermal field is prominent for anomalous geophysical, petrological, and geochemical characteristics (Feofilaktov et al., 2017; Rychagov et al., 2017). Presumably, this is due to the fact that the tectonic-magmatic block containing the thermal field is it confined to the junction zone of the two largest regional structures of South Kamchatka: Unkanovichsky horst and South Kamchatka trough **(Figure 4)**. The zone is a long-lived crust-penetrating mantle-rooted fault that crosses the Pauzhetsky volcano-tectonic depression (Aprelkov et al., 1979; Long-Lived ..., 1980; Geological-Geophysical ..., 1978). The high permeability of this earth's crust area in the Quaternary time predetermined the formation of the Kambalny volcanic ridge – a resurgent tectonic-magmatic uplift in the Pauzhetsky depression (Long-Lived ..., 1980), as well as the formation of the following large modern hydrothermal systems: North, Central and South Kambalny. The East Pauzhetsky thermal field is confined to the western slope of the Kambalny volcanic ridge. Thus, the East Pauzhetsky thermal field and, on the whole, the Pauzhetsky hydrothermal system are in the zone influenced by the through-crustal fracture and, respectively, by deep fluid flows.

The East Pauzhetsky thermal field is composed of lavas of andesites completely altered into hydrothermal clays. The composition and structure of the hydrothermal clays are described in another paper presented at the Geothermal Congress (Rychagov, Kravchenko, WGC-2020). Zones with mineral ore associations are formed in the lower part of the section of the mass in relatively dry clays: siliceous-carbonate-sulphide, phosphate-aluminosilicate-sulphide and more complex composition. The base of the clay mass is represented by argillized andesites and metasomatic breccias over andesites. The rocks are broken down by zones of intensive hydrothermal alterations. The zones consist of Ca-Na-K-zeolites, Ca-Mg-Mn-carbonates, smectites, Fe-Mg-chlorites, potassium feldspar, silica minerals, etc. F-Cl-apatite and hydroxylapatite, as well as rare metal phosphates, titanium and zirconium silicates, and other mineral phases, including rare-earth elements are ubiquitous. Thus, the mineral composition of the altered rocks and hydrothermal zones of the base of the clay mass of the East Pauzhetsky thermal field indicates a profound transformation of the source rocks due to the discharge of alkaline metalliferous solutions and the influence of the deep-seated reduced fluid on the hydrothermal system’s hypergenesis zone.

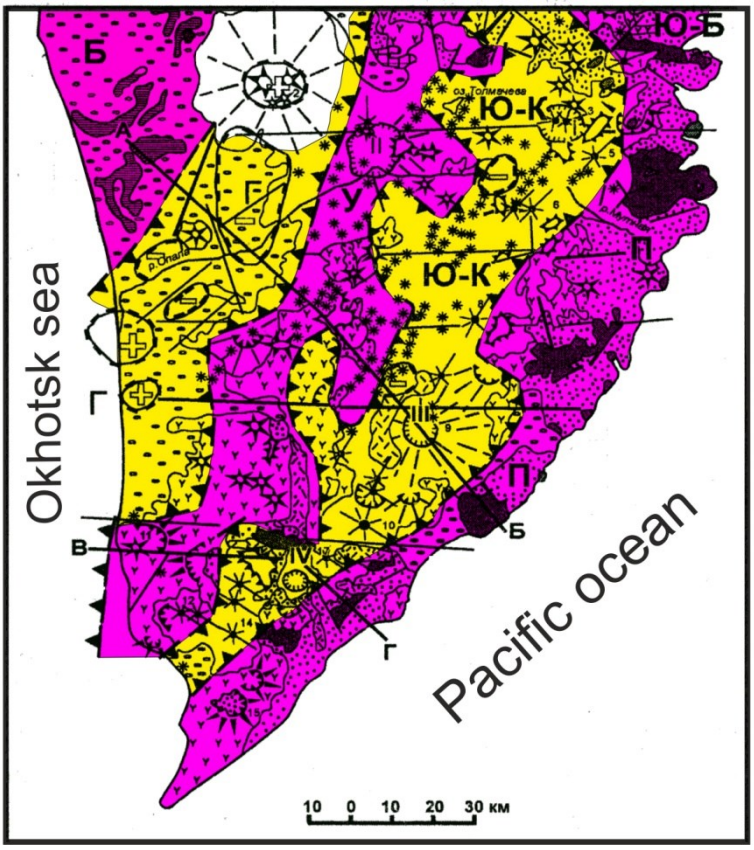

Figure 4: Schematic structure of South Kamchatka (Aprelkov et al., 1979). The red colour depicts horsts: Pribrezhny (eastern) and Unkanovichsky (central); the yellow colour depicts grabens: Yuzhno-Kamchatsky (central) and Golyginsky (western).

6. CONCLUSION

The Pauzhetsky-Kambalny-Koshelevsky region is the largest geothermal area in Kamchatka. Producing (Pauzhetsky) and proved (Nizhne-Koshelevsky, Ozernovsky) geothermal deposits of different hydrodynamic types are located here. The forecast resources of modern hydrothermal systems (Pauzhetsky, Koshelevsky, Kambalny) greatly exceed the demand of the Kamchatka Krai for thermal and electrical power. In addition to the geothermal resources, the region has rich reserves of mineral raw materials including ore; thermal and cold waters have balneological properties; thermal anomalies, active volcanoes and Kurile Lake that is the pearl of South Kamchatka have a huge potential for tourism development. Thus, the region is very important for the socio-economic development of the Kamchatka Krai.

The authors of this paper pay special attention to the unique properties of the modern hydrothermal systems of this region: they may represent prototypes of the initial stages of the formation of rare metal deposits.

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