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Giant Gas-Hydrothermal Systems of the World: A Role for Formation of Vapour-Dominated Geothermal Deposits and Ore Mineralization

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ABSTRACT

Based on synthesis of literature data and study of the geothermal (ore) regions of Kamchatka and the Kuril islands, the Earth's unique geological structures – giant gas-hydrothermal systems, whose depths in modern times generate the world's largest vapour-dominated geothermal deposits, are characterized. The systems form in the deep-seated faults at the junction of oceanic and continental plates, in the structures of volcanic island arcs, in the areas of tectonic-magmatic activation of the Earth's crust and, probably, in the collision areas at the boundaries of ancient platforms. Such systems are crust-penetrating (mantle-fed?) and have huge geothermal and ore potentials. In these systems, an ascending high-temperature gas-water fluid and all types of mixed waters and new mineral formations in the hypergenesis zone of geothermal anomalies participate in the processes of transportation, accumulation and redistribution of complex metal compounds (Fe, Al, Ti, Au, Ag, Hg, Cu, Zn, and other). It is hypothesized that the giant gas-hydrothermal systems and vapour-dominated geothermal deposits being formed inside them reflect the conditions for inception of meso- and epithermal gold polymetallic and (probably) Au-Ag-Cu-Mo-…porphyry deposits.

1. INTRODUCTION

Areas of recent and Quaternary volcanism were found to contain large axisymmetric geologic structures in which the host rocks are saturated with solutions in pores and fissures and with an overheated (dry) steam-gas fluid. These structures are situated in zones where regional tectonic blocks are in contact in faults that go throughout the crust and generally occur in the central parts of volcanogenic mineralization centers. They control present day gas-rich hydrothermal systems and major vapor-dominated geothermal fields with an energy potential of ≥100 MW (Bertani et al., 2005; Norton and Hulen, 2001; Rychagov, 2005). The better known systems of this kind include the Geysers region, USA; Larderello Travale, Italy; Kakkonda and Matsukawa, Japan; Kamojang and Darajat, Indonesia; the Koshelevskii and possibly the Paramushir system, Russian Far East (Belousov et al., 2002; Bellani et al., 2004; Hanano and Sakagawa, 1990; Rejeki et al., 2010; Stimac et al., 2001). These systems are usually considered as sources of geothermal reserves. However, it was recently shown that such structures have conditions that are suitable for the generation of gold and rare metal epithermal and mesothermal deposits and for Au–Ag–Cu–Mo–… porphyric mineralization (Hedenquist et al., 1996; Rychagov et al., 2002); there can be discoveries of oil and gas occurrences, as well as various nonmetal mineral deposits (Pozdeev and Nazhalova, 2008). They were previously defined as long lived, throughcrustal, mineralizing, hydrothermal magmatic systems that possess a high geothermal potential (Rychagov, 2003). However, our more careful studies revealed a definite type of hydrothermal-magmatic systems - the gas-rich hydrothermal systems, in connection with the special role of gases of varying composition in the transport of heat carrier and chemical compounds. This paper reviews gas-rich hydrothermal systems with major vapor-dominated geothermal deposits that are generated during their recent phase of evolution. The goal of this study was thus to investigate the structure and to derive the main characteristics of these unique geological structures for estimating their role in the generation and transport of thermal energy and deep seated ore forming fluids.

2. CHARACTERIZATION OF GIANT GAS-RICH HYDROTHERMAL SYSTEMS AND VAPOR-DOMINATED FIELDS

2.1 The Geysers gas-rich hydrothermal system (USA)

The Geysers gas-rich hydrothermal system and the eponymous vapor-dominated geothermal field are situated in California. The northwestern USA possess most of the geothermal reserves of the country owing to high conductive and convective heat flows and the presence of numerous present day high temperature hydrothermal systems. California has the highest intensity of heat flow in the region and the largest temperature gradients (Lachenbruch and Sass, 1980), which resulted from the convective zone being superimposed on a high temperature conductive thermal anomaly. The higher convective heat flow is thought to be controlled by near surface cooling acidic intrusions. The tops of these intrusions lie at depths of 3–4 km, the roots are immersed in hot (>700°C) intrusive rocks of a basic composition situated at depths greater than 8 km (Walters and Combs, 1989).

The volcanism of this geothermal region has been evolving since the Pleistocene (caldera generation and the origination of the Clear Lake volcanic fields) until the Holocene (lava and explosive activity in the north of the region). The region contains several present day hydrothermal systems. The Holocene volcanic rocks in the north of the region are host to a system of mostly the aqueous type (the solutions have temperatures of 210–220°C at depths of 1.0–1.5 km) and the Sulphur Bank Mine. The northeastern volcanic field contains a low temperature (<140°C) water-dominated Wilbur Springs system. The famous gas-rich hydrothermal Geysers system and the world largest vapor-dominated geothermal field lie in a field of Middle Quaternary volcanic rocks of mostly acidic composition. Chemical, petrologic, and isotope–geochemical data were examined to find that most mafic lavas are variously contaminated crustal melts that include clasts of crystal line rocks (Futa et al., 1981). The P–T conditions of xenolith generation (780–900°C and 4–6 kbars) provide evidence that part of the mafic magmatic system lies in the middle crust (12–18 km). Two levels are recognized in this magmatic system **(**Figure 1**)**. The deeper part is composed of mafic intrusions, metamorphites of the granulite facies, and local melts of metasedimentary protoliths that gradually give way to contaminated and hybridized magmas of intermediate and acidic compositions, which make a large, inhomogeneous, magma chamber at depths of between 4–5 and 11–12 km (Stimac et al., 2001).

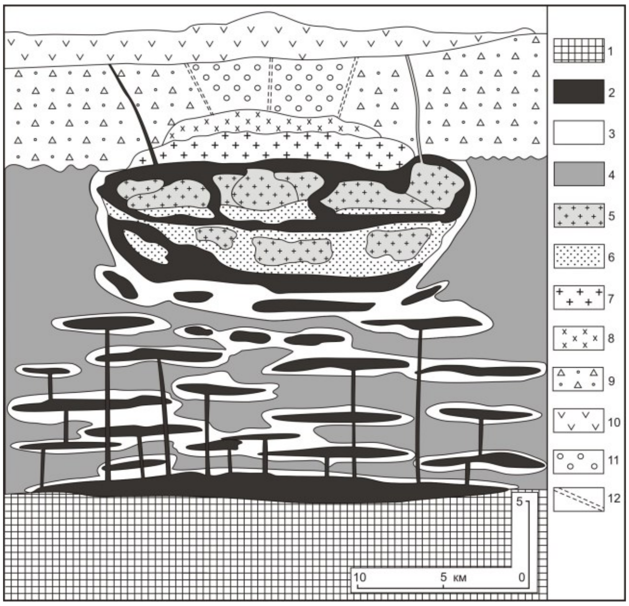

Figure 1: A conceptual cross section of the Geysers hydrothermal–magmatic system (Stimac et al., 2001) with modifications and additions. (1) crystalline rocks; (2) gabbro cumulates; (3) acidic melts; (4) host volcanogenic–sedimentary sequence; (5–6) shallow, dominantly acidic magmatic system: (5) acidic differentiates, (6) melts of higher basicity; (7) graniteporphyries; (8) felsites; (9) Pliocene to Quaternary volcanogenic–sedimentary sequence that is host to the hydrothermal system; (10) andesite and dacite lavas and tuffs with ages between 2.1 Ma and the Holocene; (11) Geysers vapor-dominated system; (12) hypothetical zones of tectonic faults in the hydrothermal system structure.

The Geysers is a very large gas-rich hydrothermal system and is also one of the best studied areas of the crust. The wells have penetrated a long lived hydrothermal system that is confined to the apical parts of the granite porphyric and felsitic plutonic complex. The system consists of three depth levels. The lower paleohydrothermal, mostly liquid, system is 0.7–0.25 Ma old, according to K/Ar and Ar/Ar datings of quartz-adularian veins (McLaughlin et al., 1983) and is situated, not only at the top of the felsite body, but also around the granite porphyries. It is remarkable for a wide occurrence of secondary quartzites and quartz-adularian veins. A study of gas and liquid inclusions gave the temperature of the solutions to be 450°C near the pluton boundary and 330°C at a distance of 1.4 km from the intrusion (Moore and Gunderson, 1995). The fluid inclusions contain concentrated brine (up to 44 wt % NaCl equivalent). Younger fluid inclusions are thought to be poorly mineralized and to be composed of a condensate of steam or hydrothermal water mixed with meteoric water (Moore et al., 2000). The present day system of the water-dominated type occurs in permeable fragmented brittle metamorphic rocks (metagrauwacke, argillite, metabasalts etc.) in a region that mimics the configuration of the felsitic endo-exocontact zone. The solutions have temperatures of 320–230°C. This phase of evolution characteristically involves the generation of calcite veins with sulfide minerals, as well as sulfide mineralization in the form of fine size dispersed impregnation in host metamorphosed rocks. This part of the system underlies the vapor-dominated region, which in turn has a two level structure. The upper ("normal") reservoir, which occupies the greater part of the system, has a temperature of about 240°C and a pressure of 35 bars. It is underlain by a high temperature reservoir (300–340°C) with a vapor pressure that corresponds to the regime of the overlying boiling zone (Walters et al., 1992). The "normal" reservoir is visualized in the shape of a thermal pipe where energy is transported upward by a steam–water mixture; the liquid phase is compactly compressed due to adsorption and capillary forces in microcracks, while the vapor condensate is infiltrated in the form of hydrothermal liquids to deeper horizons of the hydrothermal system (Pruess, 1985). The Geysers geothermal region and the Pleistocene to Holocene Clear Lake volcanic rocks contain numerous springs, fumaroles, and gas jets, which release enormous amounts of CO_2 and CH_4 into the atmosphere (Bergfeld et al., 1997). Isotope geochemical studies showed that the carbon contained in carbon dioxide and methane can come from several sources.

The Geysers gas-rich hydrothermal system thus reflects the neotectonic phase of the long lived (at least since the Upper Miocene to Holocene), throughcrustal, hydrothermal-magmatic system, which is within the Clear Lake volcanic center at the area of contact between oceanic plates (Pacific and Gorda) and a continental plate (North American). Using the Geysers gas-rich hydrothermal system as an example, researchers found a direct connection between a convective hydrothermal cell and a magmatic source of heat and fluid supply (by granitoid intrusions). The evolution of the system during 700 ka consisted in a high temperature (450–330°C) water-dominated regime giving way to one of lower temperature (320–230°C), which is also substantially water-dominated, and subsequently to a vapor-dominated regime during recent times. Carbon dioxide and methane which are generated at greater depths play an important role in the transport of heat and hydrothermal fluids. The phases of evolution of the system with a prevailing water-dominated regime are characterized by the generation of sulfide mineralization that associates with quartz-adularian and calcite veins; phases with a prevailing vapor-dominated regime have a more complex and less known ore mineralization in the form of dispersed fine size impregnation of pyrite and other sulfides (and also, possibly of native metals and intermetallic compounds) in acidic propylitized Quaternary volcanic rocks. We showed previously that large zones of boiling hydrothermal occurrences have distinctive complex mineral zonality and generate native metals and intermetallic compounds that fill in the pores and microcracks in silicified rocks (Rychagov et al., 2002).

2.2. The Larderello-Travale gas-rich hydrothermal system (Italy)

The Larderello-Travale gas-rich hydrothermal system is situated in the collision zone at the boundary of the Adriatic and European plates and is confined to the northern sector of the Tyrrhenian–Apennines tectonic structure (Verdoya et al., 2005). One can distinguish three short phases in the tectono-magmatic evolution of this structure: the older (East Corsican) 14 Ma, the middle (Capraia–Elba) 7 Ma, and the younger phase (eastern Elba) 3 Ma. The last young rifting zone has produced extensive fields of Neogene–Quaternary volcanic rocks coming from upper crustal differentiated magma chambers, as well as some individual centers of Neogene–Quaternary volcanic rocks that overlie the upper crustal chambers of hybridized magma.

The evolution of magma chambers of both types controlled the history of the northern Apennines geothermal areas: Larderello-Travale and Mt. Amiata. Larderello-Travale is a major geothermal area and a gas-rich hydrothermal system in the northern Apennines. Deep (occasionally reaching 4.5 km) wells have penetrated igneous, sedimentary, and metamorphic rocks. Two shallow productive reservoirs were reached in carbonate evaporite rocks. Later deep drilling proven the existence of productive horizons in the metamorphic basement that underlies the carbonate evaporite rocks (Bertani et al., 2005). The lower reservoir at Larderello-Travale has a temperature of 300– 350°C and a pressure of 4–7 MPa; it is a vast deep seated (2.5–4.5 km) geothermal system more than 400 km2 in area. Drilling and microseismic sounding helped to identify three thick zones of higher cracking and rock comminution: at the top of a tectonic wedge (at the base of a sequence of phyllites and sheet-like blocks of carbonate rocks), at the top of the metamorphic basement at the exocontact zones of older large granite batholites (the "H" horizon), and at the boundary between younger and older granites (the "K" horizon) **(**Figure 2**)**. The "H" horizon consists of skarns, hornfels, and other silicified metamorphic rocks; the productive zone related to this horizon has temperatures between 300 and 350°C and pressures of 5–5.5 MPa. The "K" horizon as inferred from seismic data probably corresponds to a geothermal reservoir with supercritical P–T fluid parameters. Overall, the Larderello-Travale gas-rich hydrothermal system has a complicated, multilevel structure: each level is underlain by overheated thermal water (probably brine), while the overlying cracked and porous rocks are saturated with a gas–steam phase. The mechanism responsible for the generation of major boiling hydrothermal zones can be visualized as follows. The ascent of young granites ruptured the metamorphic basement and older granites to make uplifted blocks at whose tops this process generated an inhomogeneous breccia block zone that is permeable for gas-rich hydrothermal fluids. That zone is at present the most accessible and the most productive vapor–gas reservoir with high P–T heat carrier parameters (≥350°C and 5–7 MPa). The base of these blocks can probably be regarded as a region where deep seated high temperature (overheated) fluids are generated. The extractable geothermal fields at Larderello-Travale and Lagoni Rossi and the shallow and deep seated geothermal reservoirs, as reached by drilled wells, are situated above these blocks. We demonstrated a similar geological and structural setting of zones of ascending high temperature hydrothermal flows and the location of such zones in horst features or in local uplifted tectono-magmatic blocks using hydrothermal-magmatic systems in the Kuril–Kamchatka island arc as an example (Rychagov, 1993). The

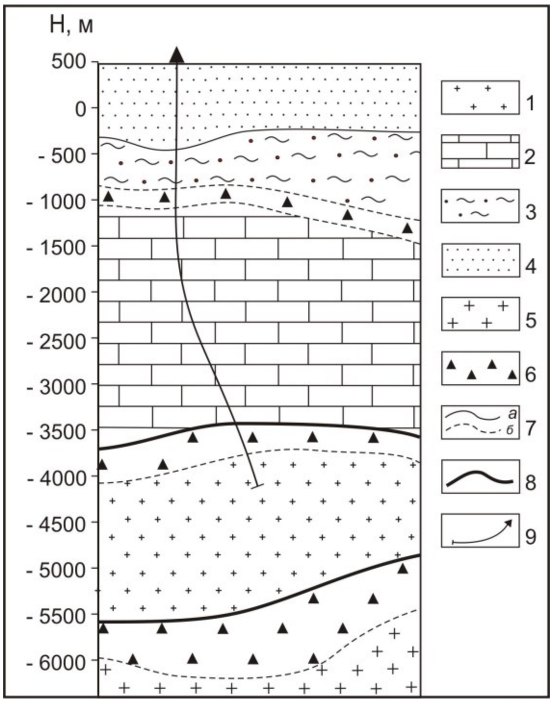

Figure 2: The geological section of a well-known area in the Larderello–Travale gas-rich geothermal system (Bertani et al., 2005). (1) metamorphic basement and older granites; (2) carbonate evaporite deposits; (3) phyllites; (4) volcanogenic–sedimentary deposits; (5) young granites; (6) zones of higher fissuring and rock fragmentation (tectonic markers): the lower is horizon "K," the middle is horizon "H," and the upper is nameless; (7) lithologic (*a*) and tectonic (*b*) boundaries; (8) top of horizons "H" and "K"; (9) drilled well.

Larderello-Travale gas-rich hydrothermal system thus has a magmatic source of heat and deep fluids. It was formed by emplacement of granitoid intrusions into metamorphic host rocks and by the generation of an aureole of cracked breccia zones above and around uplifted tectono-magmatic blocks. The gases, which play a key role in the ascent of fluids and in heat transport, are dominated by carbon dioxide (the Mt. Amiata system gas contains large amounts of Hg, H_2S, HCl and other volatiles, apart from CO_2). Larderello-Travale is a major gas-rich hydrothermal system with a giant vapor-dominated field identified beneath it. Little is known about the ore mineralization in the system. It is nevertheless known that the Mt. Amiata gas-rich hydrothermal system situated in the same area, which may be connected into a single system with Larderello-Travale at depths greater than 5–7 km, is characterized by a high concentration of mercury in the gas composition. Mercury forms sulfide mineral forms (cinnabar and metacinnabar) associating with quartz-carbonate veins and veinlets in the host rocks. Ore mineralization seems to be characteristic, not only for paleo, but also for the recent phase in the evolution of the Mt. Amiata gas-rich hydrothermal system.

2.3. The Kakkonda gas-rich hydrothermal system (Japan)

The Kakkonda gas-rich hydrothermal system and eponymous vapor-dominated geothermal field of Japan are situated in northern Honshu. Geologically, it is a major long lived volcanogenic mineralization center. The present day and neotectonic geological features inherit the Mesozoic ones. Paleogene to Neogene tectono-magmatic activity produced en echelon tectonic features and double island arcs, thick sequence of volcanogenic–sedimentary rocks that have been subjected to greenstone alteration and to later granitization of upper crustal horizons in northern Honshu. This period saw the generation of mineral deposits that today are important for the Japanese economy: epithermal gold–silver, copper–lead–zinc deposits, deposits of the Kuroko type, copper–chlorite, mercury and other deposits (Geological …, 1960). Geological features were formed that control oil and gas occurrences, coal basins, and larger geothermal anomalies. The Quaternary and recent volcanic activity is confined to inner tectonic belts at the Japanese island arc and is genetically related to long lived (from the Cretaceous to Holocene) centers of acidic magmatism. A complicated magmatic complex was reached by deep wells in the Kakkonda volcanic field (Figure 3). The emplacement of a large Early Quaternary batholite in the pre-Tertiary basement rocks produced an uplift and fragmentation of the rocks concerned and of older granites into tectonic blocks at the top of the intrusion. The intrusion has a complex structure and is composed of rocks that were formed during at least two phases of evolution: Early Quaternary granite porphyries and Late Quaternary (young) granites. It is thought that the young granites are not older than 0.6 Ma (Tamanyu, 1991). Most of the section is composed of a Cretaceous lava–pyroclastic rock complex (the Kunimitoge Formation), while the upper part consists of Paleogene to Neogene volcanogenic–sedimentary deposits (the Takinoue–Onsen Formation) and of Miocene "green tuffs" (the Yamatsuda Formation) (Shigeno, 2000; Uchida et al., 1996). The rock mass has been broken through by Holocene acidic magmas that form extrusions and active volcanoes. The heat source for the present day gas-rich hydrothermal system is thought to be heated dry rocks in the Kakkonda granite massif. The present day deep seated geothermal reservoir seems to have a two-level structure. The lower zone consists of an overheated (above 400°C) dominantly liquid fluid that circulates in the zone of contact between the granites of the earlier and later phases and the pre-Tertiary sedimentary rocks. The zone of the dry steam–gas fluid is situated in the megabreccia margin of the granite intrusion in disintegrated rocks; its top is confined within the 350°C isotherm. The other region of liquid–steam transition is situated in the middle and upper tuff sequences of the Kunimitoge Formation and is confined within the 260°C isotherm at the base of the reservoir and 220°C at its top.

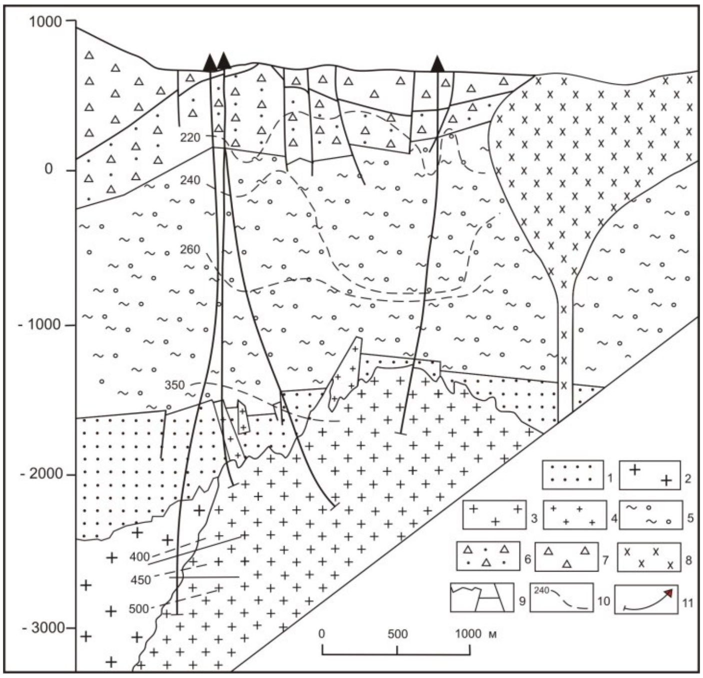

Figure 3: The geological section of the Kakkonda hydrothermal-magmatic system and of the eponymous geothermal field, northern Honshu (Uchida et al., 1996; Tamanya and Fujimoto, 2005). (1) pre-Tertiary sedimentary rocks; (2–3) granites in Kakkonda intrusion: (2) earlier, (3) later; (4) older granites; (5) Miocene to Pliocene volcanogenic–sedimentary complex; (6–7) Quaternary intermediate lavas and tuffs (6) Takinoue–Onsen Formation; (7) Yamatsuda Formation; (8) Holocene extrusive dacite complex; (9) tectonic faults and boundaries; (10) isotherms based on drilling data; (11) wells.

The model of the Kakkonda gas-rich hydrothermal system can thus be visualized as follows. The system includes two geothermal reservoirs. The deeper one is in the contact zone of multiphase Quaternary cooling granites that have been emplaced in the basement sediments and formed a megabreccia permeable region above and around the intrusion. The overheated steam– gas fluid has temperatures between 500–450°C at the bottom and 350°C at the top of the transitional liquid– steam zone. The shallower (500–1700 m from the ground surface) geothermal reservoir is formed by an ascending, dominantly liquid fluid as it penetrated from the Kinimitoge relatively dense but cracked rocks into rocks of the same formation, but which had an increased open porosity (cracked hydrothermally altered tuffs). The zone of boiling fluid has temperatures between 260 and 220°C. The reservoir forms an isometric region about 1.5×1.5 km in the vertical cross section. Similar geothermal reservoirs can probably be found above the apical parts of other uplifted blocks that consist of young granite. Deep drilling data and an analysis of microseismic data suggest a connection between the shallower and the deeper geothermal reservoir by infiltration of meteoric and mixed waters into the megabreccia exocontact intrusion zone and rapidly cooling granites (Tosha et al., 1998). The ore mineralization to be found in the rocks of the Kakkonda hydrothermal-magmatic system is diverse. The Paleogene to Neogene phase of evolution typically exhibits mesothermal and epithermal, gold–silver, complex, and mercury mineralization confined to the contact zones between acidic intrusions and subvolcanic bodies on the one side and the host rocks on the other. The recent phase of mineralization is less known and seems to consist of vein–impregnated sulfide mineralization that associates with quartz–chalcedony veins. This impregnated vein mineralization system is situated in cracked and porous tuffs of the Kinimitoge Formation above the apical parts of granite intrusions.

2.4. The hydrothermal-magmatic system Darajat (Indonesia)

The hydrothermal-magmatic system Darajat are found in the inner zone of the Indonesian island arc and belong to major volcanic center. The magmatic activity that determined the increased convective heat flow in the Darajat area began during Miocene to Pleistocene time with emplacement of alkaline magmas of a basic composition and with the generation of bodies consisting of microdiorites and tholeiitic lavas at the center of this structure (Rejeki et al., 2005). The Pleistocene phase saw the generation of a major basaltic andesite stratovolcano. Melt differentiation in the magma source led to caldera generation and to the deposition of thick pyroclastic and lava sequences ranging from andesites to rhyolites at the periphery of the structure. The Darajat volcanic field is confined within the Kendang semicircular fault and is composed of numerous eruptive centers and individual volcano-plutonic circular dome structures. One notes a system of “dominant” NE and transverse NW zones of tectonic faults that divide the volcanic field into elongate or isometric blocks 1.0–1.5 km across (Pramono and Colombo, 2005). Drilled wells revealed that the cross section of each block is not uniform and differs from that of adjacent blocks in lithologic structure (the composition and thickness of lava and tuff horizons), permeability structure, petrophysical and other properties of the constituent rocks (Hadi et al., 2005). The Darajat volcanic field seems to be dominated by a non-uniform mosaic block structure that is generally typical of andesitic volcanoes and associated hydrothermal-magmatic systems: adjacent blocks differ in contrasting petrophysical rock properties (Ladygin and Rychagov, 1995). This structure controls the dynamics of the ascending convective heat flow and the infiltration of meteoric water to greater depths (Rychagov, 1993).

Gravity surveys in the middle of the Darajat volcanic field revealed a large positive gravity anomaly due to a domelike feature that is interpreted to be a dense intrusive diorite body (Rejeki et al., 2010). Microdiorites were reached at depths of 1.5 to 2.5 km at the top of this feature. According to these gravity surveys, one clearly distinguishes volumes of lower density: an extensive chlorite–pyrite–epidote–quartz–illite metasomatic zone as thick as 1000 m above the marginal parts of the intrusion, with the density of these rocks being 2.2 g/cm^3, and a more compact zone of illite–wairakite metasomatites in the abovedome part of the intrusive complex, with the rock density being 2.4 g/cm^3. The intrusive rocks have densities of 2.75 to 2.65 g/cm^3. The overlying illite–smectite deposits, a few tens of meters thick at the center of the feature and reaching 500 m at the flanks, serve as the upper aquifuge and probably form a heat insulating horizon. These argillized, fine-dispersed, poorly permeable (for fissure and fissure–pore circulation of steam–hydrothermal fluids) mineral formations have a density of 2.5 g/cm^3. The illite–wairakite zone that forms a “cap” as thick as 500 m above the intrusive dome marks the region of boiling hydrothermal fluids. The rocks in the productive horizons are generally macrofragmental (from psephite to agglomerate size), xenogenic tuffs and tuff breccia (Stimac et al., 2010).

Thus the following model for the Darajat gas-rich hydrothermal system was proposed based on integrated geological and geophysical results (Figure 4). A liquid–steam transition region with a zonal structure was identified at depths of 1.0–1.5 to 4.0 km below the ground surface. The inner zone is the region of boiling hydrothermal fluids proper where heat is being transported by the fluid in propylitized volcanogenic-sedimentary rocks of lower density. The outer zone has a low open porosity and was formed by the infilling of the fissure–pore space with siliceous minerals (tridymite, cristobalite, chalcedony, and quartz) at the base of and around the boiling region. That zone can be regarded as a kind of screen and a thermal insulator. The supply of heat to the gas-rich hydrothermal system and its connection to the magma chamber are provided by deep seated fluids rising along zones of individual tectonic faults. Microconvective hydrothermal cells probably control the transport of steam–gas mixture along tectonic faults inside the boiling zone. It follows that Darajat is an example of a self-insulated convective hydrothermal system with the generation of a large steam–gas reservoir (≥50 km^3 in volume) and a zone of circulation for high temperature (supercritical ?) fluids at the bottom and marginal parts of the boiling region. Self-insulation seems to be one of the main mechanisms for generating major gas-rich hydrothermal systems with vapor reservoirs (Zhatnuev et al., 1996; Rychagov, 2003). The intrusive diorite–microdiorite complex with spatial and genetic relationships to the gas-rich hydrothermal system is probably a multiphase intrusion whose roots reach into the present day magma chamber.

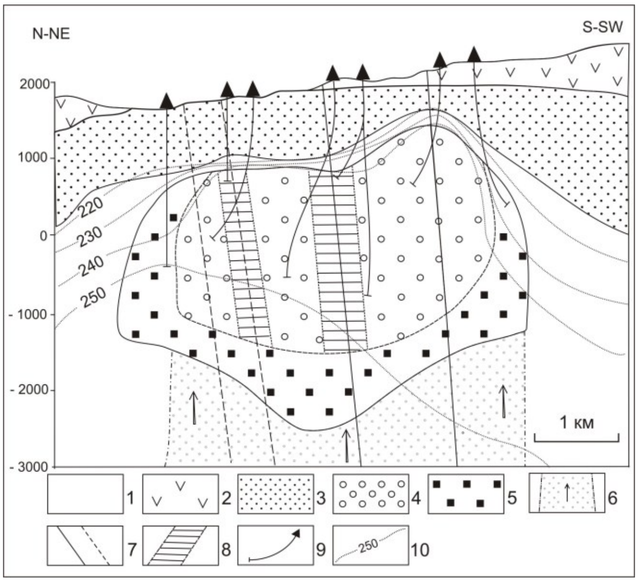

Figure 4: A conceptual model of the Daradjat gas-rich hydrothermal system (Rejeki et al., 2010) with modifications and additions. (1) Miocene to Pliocene volcanogenic–sedimentary rocks that are host to the system; (2) Holocene lavas and tuffs; (3) Quaternary argillized tuffs and tuffites (upper aquifuge for the hydrothermal system); (4) region of boiling hydrothermal fluids; (5) bottom and marginal zones of boiling region where the fissure–pore space has been healed with secondary minerals; (6) zone of ascending gas–water fluids; (7) tectonic faults, certain (solid line) and inferred; (8) zones of higher conductivity (hydrothermal steam fluid circulation) within the region of boiling brine; (9) wells; (10) isotherms.

2.5. The Koshelevskii gas-rich hydrothermal system (Russia)

The Koshelevskii gas-rich hydrothermal system belongs to the Pauzhetka–Kambal'nyi–Koshelevskii geothermal (mineralization) area, South Kamchatka (Rychagov et al., 2006). The area is within the South Kamchatka geothermal province (Sugrobov, 1979) and is situated within the inner zone of the Kuril–Kamchatka island arc at the junction of three main volcanic belts of Kamchatka (Figure 5). The Koshelevskii gas-rich hydrothermal system is directly connected to the eponymous volcanic massif of Oligocene–

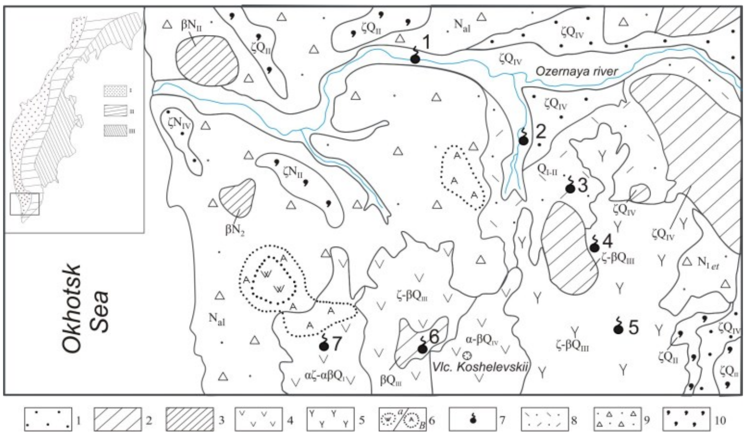

Figure 5: A schematic geological map of the Pauzhetka–Kambal'nyi–Koshelevskii geothermal (mineralization) region in southern Kamchatka. Compiled by S. Rychagov from materials of research and government sponsored geological surveys to a scale of 1 : 200 000. The inset shows main volcanic belts of Kamchatka (Western, Central, and Eastern) and the area of study. (1) basement lava–pyroclastic deposits (N_{al}, Alnei Formation, Neogene); (2) Lower to Middle Quaternary volcanogenic–sedimentary deposits (tuffites) of the Pauzhetka Formation ($Q_{I–II}$); (3) Middle Quaternary ignimbrites (Q_{II}); (4) magmatic complex of Koshelevskii volcanic massif: Lower Quaternary dacitic-andesites and basaltic-andesites in the western part ($\alpha\zeta$ – $\alpha\beta Q_I$), Middle Quaternary dacites and basalts in the central part ($\zeta\beta Q_{III}$), Upper Quaternary basaltic andesites in the eastern part ($\alpha\beta Q_{IV}$); (5) dacite to basalt lava–extrusive complex of Kambal'nyi Range ($\zeta\beta Q_{III}$); (6) Upper Quaternary dacite to rhyolite pumice deposits (ζQ_{IV}); (7) Neogene basic subvolcanic and extrusive bodies; (8) same, with contrasting (from basalts to dacites) Middle to Upper Quaternary composition (βQ_{III}, $\zeta\beta Q_{III}$, ζQ_{IV}); (9) fields of secondary quartzites (a) and argillites (b); (10) main thermal anomalies in the area of study: (1) Pervye Goryachie Klyuchi (Pionerlager'), (2) Vtorye Goryachie Klyuchi (Pauzhetka field), (3) Severo-Kambal'nyi,(4) Tsentral'no-Kambal'nyi, (5) Yuzhno-Kambal'nyi, (6) Verkhne-Koshelevskii, (7) Nizhne-Koshelevskii.

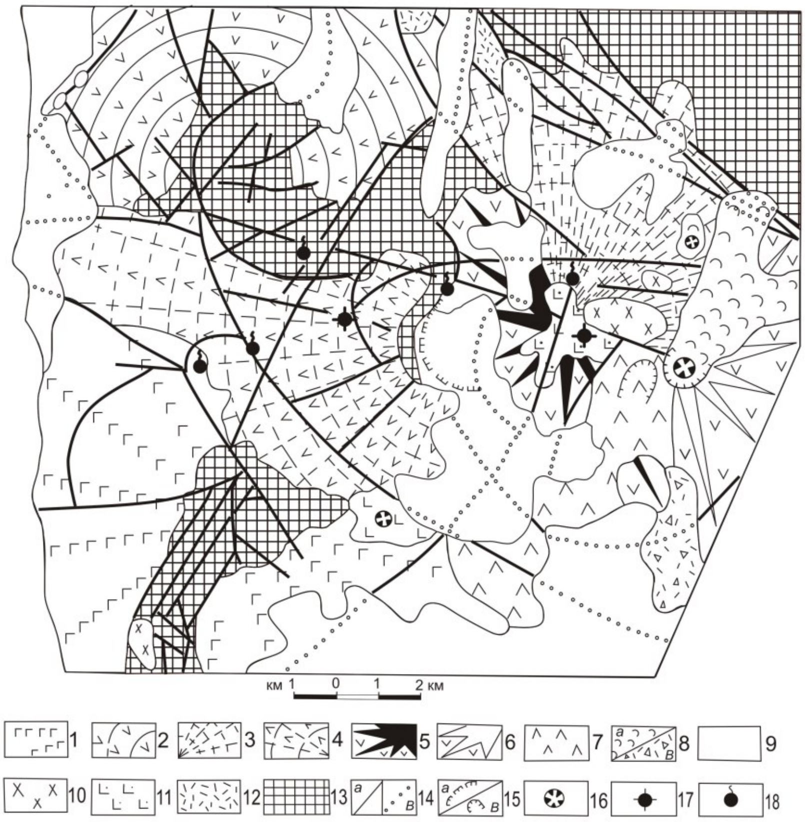

Figure 6: A schematic geological map of the Koshelevskii volcanic massif (Vakin et al., 1976) with modifications. (1-2) effusive and pyroclastic deposits of Lower Quaternary volcanoes: (1) Ded-i-Baba Volcano ($\alpha\beta Q_I$), (2) Tret'ya Rechka Volcano ($\alpha\beta Q_{II}$), (3-8) – effusive and pyroclastic dposits in the Koshelevskii volcanic massif: (3) Drevnii Volcano (αQ_{II}), (4) Zapadnyi Volcano (αQ^1_{III}), (5) Valentin Volcano (αQ^2_{III}), (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 (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-Koshelevskii and Nizhne-Koshelevskii); (18) local discharges of thermal water.

Holocene age (Figure 6) consisting of five coalesced stratovolcanoes and individual monogenic edifices (Vakin et al., 1976). The massif originated at the junction of the South Kamchatka and the North Kuril island arc segment owing to the evolution of a major peripheral magma chamber that is situated in the zone where northeast and northwest trending faults intersect. That the faults extend throughout the entire crustal thickness is indicated by data of magnetotelluric sounding, results of isotope geochemical studies ($^3He/^4He$, $^{87}Sr/^{86}Sr$), and evidence for the presence of ascending flows of deoxidized fluids consisting of carbon dioxide, hydrogen, methane, and heavy hydrocarbons (Lebedev and Dekusar, 1980; Pozdeev and Nazhalova, 2008).

Heat, steam–gas mixture, and hydrothermal fluids are discharged at the ground surface within the Nizhne- and Verkhne-Koshelevskii thermal fields, as well as in individual areas of the Koshelevskii volcanic massif. The power produced by the thermal fields is estimated as 25 and 50 Gcal/s, respectively (Vakin et al., 1976). The Nizhne-Koshelevskii thermal field is situated in the deeply incised valley of Gremuchii Brook, which shows the location of a fault that is permeable to present day steam and hydrothermal fluids. The hypergenesis zone produces low acidic to neutral and low alkaline sulfate and hydrocarbonate–sulfate ammonia waters at temperatures of 20 to 98°C. The cation composition is mixed, dominated by ammonium, Ca, Na, K, and Fe with some Al, H, rare alkalis, etc. The dissolved and free gases are dominated by CO_2, H_2S, SO_2, CH_4, nitrogen, and heavy hydrocarbons (Vakin et al., 1976; Rychagov et al., 2008). The Verkhne-Koshelevskii thermal field is in the middle of the Koshelevskii volcanic massif in the erosional crater of Valentin Volcano and is confined to the contact zones of a cooling extrusive subvolcanic dacitic-andesite complex. It has higher P–T parameters of steam–gas jets (up to 150°C and up to 7–10 atm at fumarole mouths), a large area of warmer soil (about 300 by 500 m), and a discharge of acidic and low acidic sulfate waters. The gas composition is dominated by CO_2, H_2S, and SO_2; the total of acidic gases may reach 97% of dry gas volume (Vakin et al., 1976). The Nizhne-Koshelevskii geothermal deposit was explored in 1975–1984. By deep wells wear penetrated a multiphase intrusive body in the interval 300–1200 m from the ground surface (Figure 7). Its central part is composed of diorites that give way gradually (?) to diorite porphyrites. The apical part is a zone of megabreccia composed of blocks of intrusive and host rocks that have been cemented by intrusive (automagmatic) breccia. The host rocks are intermediate tuffs and tuffites, probably of Pliocene age. The lava extrusive dacitic andesite complex is the upper aquifuge in the hydrothermal system. Hydrodynamic testing of prospecting wells revealed a zone of overheated ("dry") vapor that goes down to a depth greater than 1500 m and wedges out at the ground surface in the thermal field area. The probable reserves of this field were estimated as 210 kg/s dry steam, which is equivalent to 90 MW of electrical energy (Pisareva, 1987). The hydrogeological structure of the Nizhne-Koshelevskii field is thought to have a hydrodynamic connection to the Verkhne-Koshelevskii thermal field (Pozdeev and Nazhalova, 2008), so that a single major gas-rich hydrothermal system may exist in the interior of the Koshelevskii volcanic massif. The probable geothermal reserves of this system are estimated as 300 MWe (Strategiya …, 2001), thus ranking with the world's greatest gas-rich hydrothermal systems. A mixed water–vapor-dominated regime seems to have existed during the initial phase of evolution of the hydrogeological structure in the interior of the Nizhne-Koshelevskii geothermal field. The geological section exhibits a zonality that is typical of water-dominated systems (upward): a hypabyssal facies of quartz–epidote–albite propyllites gives way to a subvolcanic facies of quartz–chlorite–zeolite–pyrite propyllites and subsurface carbonitized and argillized rocks. There is evidence to suggest that the exocontact zones of intrusions contain quartz–adularian metasomatites and monoquartzites, which usually result from boiling, acidic, overheated solutions. The megabreccia margin of the intrusive body probably serves as a zone where high temperature (supercritical ?) hydrothermal solutions are in motion, both during the paleo and recent phase of evolution of this system.

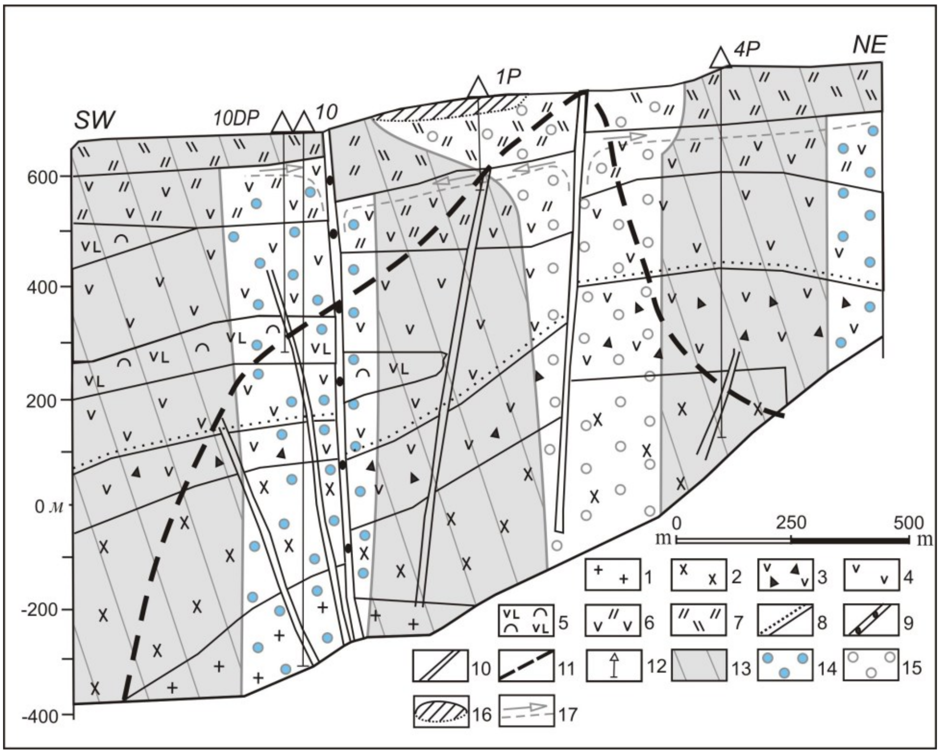

Figure 7: A geological section of the Nizhne-Koshelevskii vapor-dominated geothermal field (Pisareva, 1987) and the structure of the present day and paleohydrothermal systems in the section of the field based on results from the South Kamchatka–Kuril Expedition of the Institute of Volcanology and Seismology. (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 present day hydrothermal fluids; (11) boundary of boiling hydrothermal fluids as inferred from hydrodynamic tests at wells; (12) wells; (13) rock blocks: rigid, highvelocity ones for microseismic waves and poorly permeable for hydrothermal fluids; (14) rock blocks with relatively lower density where fissures and pores have been healed with secondary hydrothermal minerals; (15) rock blocks with lower density—zone of present day steam generation and ascending gas and hydrothermal flow; (16) Nizhne-Koshelevskii Novoe thermal field (projection onto the section); (17) zones of flow (circulation) of condensate waters and/or hydrothermal fluids that rise along subvertical fissures.

Our knowledge of the deep structure of the overheated vapor zone and the central part of the Nizhne-Koshelevskii field was refined using information from detailed geological and geophysical studies carried out by the South Kamchatka–Kuril Expedition of the Institute of Volcanology and Seismology, Far East Branch of the Russian Academy of Sciences using high precision gravity surveying, microseismic sounding, and magnetic measurements (Abkadyrov et al., 2010; Feofilaktov and Nuzhdaev, 2011). This zone is composed of subvertical rock blocks with contrasting petrophysical properties: less dense (permeable to steam hydrothermal fluids) and dense (rigid, poorly permeable for gas–water fluids). The central conducting zone goes down to a depth of 2.0 km and is "dissolved" in the interior of the intrusive body; near the ground surface it has the shape of a cup where micropores in rocks that have been argillized as far as to become hydrothermal clay are filled with a steam–gas mixture. The flanks of the section contain blocks with low seismic velocities. These blocks are composed of metasomatites (rocks of lower density) that developed during the paleohydrothermal phase in the evolution of the system. Mineralization in the interior of the system is related to secondary quartzites, monoquartzites, and quartz veins that are exposed by erosion at the base of the Koshelevskii volcanic massif (the Tret'ya Rechka paleohydrothermal system which occurs in Neogene volcanic rocks). Mineral generation and mineralization found during the recent phase of evolution may be related to hydrothermal metasomatic zones identified in the interior of the system (Pozdeev and Nazhalova, 2008) and to (inferred here) quartz–adularian and monoquartz bodies in the exocontact zones of the intrusions. This geological and mineralogic–geochemical setting is generally typical of long lived hydrothermal-magmatic systems that are situated in the volcano-plutonic complexes of the Kuril–Kamchatka island arc (Rychagov, 1993; Rychagov et al., 2002).

The other gas-rich hydrothermal systems at the Kuril–Kamchatka island arc that can probably be classified as giant fields have either not been drilled at all or very little. These are the Uzon caldera and Geysers Valley system, eastern Kamchatka and the North-Paramushir system, North Kuril Islands. Three deep geothermal wells (from 1.1 to 2.5 km deep) reached an aquifer of thermal water (130–160°C) at depths of 700–1300 m within the North-Paramushir system in a tectonic block and penetrated dry hot rocks (210–220°C) at depths of 2–2.5 km in another block (Rychagov et al., 2010). There is a region of active circulation of gas-rich hydrothermal fluids in the crater zone of Ebeko Volcano. However, the information thus acquired is insufficient for classifying this system as belonging to the water-dominated, vapor-dominated or mixed type. For this reason we have restricted ourselves in this paper to a description of the Koshelevskii gas-rich hydrothermal system.

3. CONCLUSION

Giant gas-rich hydrothermal systems are generated in various geodynamic mobile structures on the Earth: in deep fault zones at boundaries of oceanic and continental plates, at volcanic island arcs, or in areas of tectono-magmatic activation. All these structures have high conductive and convective heat flows. The high level of conductive heat flow is due to regional blocks being uplifted by mantle upwelling or by some other mechanisms that is operative in the ascent of magma melts and intratelluric (after D.S. Korzhinskii) fluids in lower crust. High convective heat flow is caused by intermediate to acidic intrusions being emplaced in the upper crust. The differentiation in peripheral magma chambers produces volcanic (volcanogenic–mineralizing) centers with thick sequences of acidic tuffs and ignimbrites being deposited during the terminal (calderagenerating) phase of evolution of these chambers. In this way large axisymmetric volcano-tectonic structures are formed along with hydrothermal-magmatic systems in their interiors. Water is supplied to such systems from large artesian basins that form in the calderas. The water supply to gas-rich hydrothermal systems (up to 90–95% as estimated by most researchers) is by waters of meteoric and marine origin. The heat supply is provided by differentiated magma chambers and multiphase intrusive bodies ranging from gabbrodiorites and diorites to granite porphyries.

The composition of ascending convective heat flow is primarily composed of gases of magmatic and hydrothermal origin: CO_2 > CH_4 > HCl > HF > H_2 and other volatiles. Increased concentrations of carbon dioxide, heavy hydrocarbons, hydrogen, deoxidized nitrogen, mercury, compounds of chlorine and fluorine indicate a deep seated source of heat and fluid supply for hydrothermal-magmatic systems. The geological structure of such systems occupies the entire crustal thickness and thus implies a mantle supply. Some systems or individual blocks of these systems are thought to hold promise for combustible gas. Such throughcrustal geological structures include, in particular, the Nizhne-Koshelevskii geothermal anomaly which was formed in the zone of a deep seated fault at the junction of the South Kamchatka and the North Kuril segment of the island arc. Acid gases characterize shallow hydrothermal systems that are situated above small intrusions and subvolcanic bodies that consist of gabbro diorites, quartz diorites, and granite porphyries. Such a setting is typical of the hydrothermal systems that occur in the crater zones of major volcanic massifs: the Verkhne-Koshelevskii and possibly the North Paramushir system.

Gas-rich hydrothermal systems are associated with world’s largest vapordominated geothermal fields. The energy potential of such fields is ≥100 MWe; indeed, it can reach 1500 MWe. They provide the bulk of geothermal electrical energy in several countries and have high promise for dealing with energy problems in many regions worldwide, including the Russian Far East. The geothermal reservoirs of the vapor-dominated type generally have a three-level structure. The region of overheated (“dry”) vapor is found above the source of magmatic heat (cooling multiphase intrusions) in volcanic rocks having high fissure–pore permeability (tuffs and breccia). A zone of vapor–gas condensation forms above this region, leading to mass healing of open pores and fissures with secondary minerals (more frequently with siliceous minerals and alumosilicates) and to the generation of an additional aquifuge and a heat insulating horizon as thick as 1000 m (Rychagov et al., 2002). The boiling region is underlain by a high temperature vapor-dominated reservoir that is confined to a complex structured megabreccia mantle of multiphase intrusions. The processes that are occurring in the liquid–vapor transition zone include active migration of chemical compounds, the generation of mineral ore zonality, and the transport of complex metal compounds from deeper horizons into the hypergenesis zone of geothermal anomalies. It should be noted as a comment to the above that gas-rich hydrothermal systems are a certain type of long lived hydrothermal-magmatic system, for which the transport of heat and various chemical compounds with deep seated gas-charged fluids is especially important. The giant gas-hydrothermal systems and vapor-dominated geothermal fields that are forming in their interiors are of vast interest for basic science in order to study the mechanism that operates in the transport of thermal energy and ore compounds at various crustal horizons and for predicting the energy and mineral reserves in areas of recent and older volcanism.

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