Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

FORMATION OF COMPOSITION AND PETROPHYSICAL PROPERTIES OF HYDROTHERMALLY ALTERED ROCKS IN GEOTHERMAL RESERVOIR

Vladimir Ladygin[1], Julia Frolova[1] and Sergey Rychagov[2]
[1] Moscow State University, Moscow, Russia
[2] Institute of Volcanology, Far East Division, Russian Academy od Sciences, Petropavlovsk-Kamchatsky, Russia

Key Words: hydrothermal zoning, petrophysical properties, Kuril-Kamchatsky region.

ABSTRACT

Since the 60-th years there have been prospecting, explorating and exploiting of geothermal resources in Iceland, Italy, New Zealand, the USA, the Philippines, Japan, Russia (Far East). The present-day geothermal systems attract geologists' professional attention for some reasons: firstly, as an environmentally-friendly, safe and permanently-supplied source of heat and power; secondly, as natural laboratories where various secondary minerals are formed and volcanites are transformed into metasomatic rocks; thirdly, as potential ore and non-metal deposits. Nowadays there have been stored a lot of information about geothermal systems in the field of mineralogy, geochemistry, ore formation, geothermy. But the petrophysical properties of hydrothermally alterated volcanic rocks have been studied incidentally so far, only in connection with treatment of geophysical, enginering-geological and some other problems. At the same time pertophysical analysis allows to obtain some additional information about formation, evolution and structure of geothermal systems. The petrophysical studies we performed on three geothermal systems of Kuril-Kamchatsky region - Pauzhetskaya, Paratunskaya (Southern Kamchatka) and Okeanskaya (Iturup Isl., the Southern Kurils) allowed to elicit some basic laws of formation of rock's composition and properties under hydrothermally-metasomatical processing influence; to determine the zonal character of alteration of rock's properties cross the geothermal reservoir's section. In addition our investigation to show that complex analysis of petrophysical characteristics along with structural-mineralogical peculiarities of rocks allows to make more precise the structure of geothermal system.

1. INTRODUCTION

The present-day geothermal systems are the favourable object for study of formation of new rocks and their properties - from initial volcanic rock to complite altered hydrotremal metasomatites. It is know that volcanic rocks are destroyed under the volcanic gases and agressive therms' influence. The new mineral associations and structures are formed, more stable under conditions of new temperature, pressure and composition of termal water. The pertophysical properties of new rocks distinguish from initial rocks and change widely: from dense and strong secondary quarzites untill loose, high-porous hydrothermal argillites.

The stadied geothermal systems are located in the volcano-tectonic depressions, composed of volcanogenic-sedimentary deposits of Neogen-Quaternary age. Well-permeable tufogenic deposits accomodate a great amount of underground water heated by extremaly high heat flow, generazed by diorite body. The heated stratum causes the convective motion of waters, induced by differences of their densities. Heated chloride-natrium waters, distributed in the Kuril-Kamchatkan region, while rising to the surface turn into solutions of various compositions, acidity-alkalinity and temperature. In a result, volcanites composing the geothermal systems undergo significant secondary changes along with formation of certain types of new rocks - secondary quartzites, propylites, hydrothermal argillites and others. According to the geological data the stadied geothermal systems belong to the different stages of development: the Okeanskaya system belongs to progressive haloid-sulphurous- carbon acid gas, whereas the Pauzhetskaya belongs to regressive sulphurous-carbon acid gas. Intensive drilling during of exploiting of Pauzhetskaya system and explorating of Okeanskaya system allowed to collect a lot of the facts. Detail sampling of 12 drill-holls of Okeanskaya system (untill the depth 1200 m) and 6 drill-holls of Pauzhetskaya system (untill thr depth 600 m) has been carried out. The following petrophysical parameters have been determined: density of rock (ρ), density of mineral particles (ρ_m), porosity (n), hygroscopic moisture (W_g), water absorption (W_w), velocity of longitudinal waves in dry (V_l) and water-saturated condition (V_{lw}), strength (R_s), magnetic susceptibility (k). The petrophysical parameters have been analyzed along with structural and mineral characteristics of rock, studied by means of microscopic, X-ray structural, thermogravimetric analyses and electronic microscope. More that 1000 samples were investigated.

2. REGIONAL LAWS OF FORMATION OF ROCKS' COMPOSITION AND PROPERTIES

To elucidate the basic laws of alterations of tuffs' properties the section of regional (basic) drill-holl have been investigated. This drill-holl is out of the zone of hydrotherm influence. There is determined that the upper part of geological section (untill the depth nearly 600 m) is composed of loose and slightly cemented volcanogenic-sedimentary deposits of fine- and couse-fragmented (andesite-dacite and andesite-basaltic composition). This deposites are underlied by the stratum which experienced the initial phase of regional epigenetic changes. As a result of cementation with opal and montmorillonite the fragmentary material was transformed into rocks - tuffs. It is necessary to note there aren't some changes of clastic materials untill the depth nearly 1500 m. Only gradually filling of inter-fragmentary space with opal and montmorillonite and changes of clay minerals' microstructure from large-meshed to foliaceous-fine-meshed are observed. The type of cement changes from filmy to pore-basal. Density and strength of tuffs consistently increase with the depth in process of filling of inter-fragmentary space with secondary minerals along with changes of cement type - filmy, pore, pore-basal. Thus porosity decreases from 45 to 20 %, strength increases from 20 to 50-60 MPa (Table 1). It can be assumed it is this rocks composed the geological section of Okeanskaya system before the hydrothermal activity beginning. And subsequently just this rocks were influenced by hydrothermal alteration.

3. FORMATION OF ROCKS' COMPOSITION AND PROPERTIES IN PRESENT-DAY GEOTHERMAL SYSTEMS

The essential diffrent character of rock properties' formation is observed in present-day geothermal systems. The stadied geothermal systems belong to extremely diffrent stages of evolution, characterized by the diffrent termodynamic and physic-chemical conditions and as a result - by various hydrothermal zoning.

3.1 Okeanskaya system (progressive stage of evolution)

Okeanskaya system is younger and higher-temperatured than Pauzhetskaya system. According to the mineralogical data the Okeanskaya system has zonal structure, manifested by distribution of secondary mineral associations. Thus, the section of the system shows the following zones (going upwards): high-medium temperature secondary quartzites (T 350-450^{0}C), medium temperature quartz-albite-chlorite propylites (T 260-350^{0}C), low-temperature zeolites and calcite-hydromica propylites (T 180-260^{0}C), argillized propylites (T 150-200^{0}C), hydrothermal argillites (T 100-150^{0}C), opalites (T nearly 100^{0}C). But the zones are distinguished on the qualitative basis without the consederation of amount of secondary minerals and qualitative estimation of the primary volcanogenic material re-crystallization degree. We have performed X-ray structural, termogravimetric and microscopic stadies which result in the quantitative estimation of hydrothermal alteration's degree. The degree of re-crystallization may range from 10 to 100 % even within the same zone. A complex of petrophysical parameters can also characterize an intensiveness of hydrothermal processing. Below the brife petrophysical characteristic of each zone is given.

The zone of secondary quartzites (depth 1100-1200 m) is a homogeneous stratum composed of completely processed rocks, dense (2.4-2.5 g/cm^3), acoustically "rigid" (V_l 4-5 km/s) with strength of > 100 MPa and porosity of 10-15 %. The high parameters are caused by the development of cryptocrystallic quartz aggregate by cement and debris of tuffs. The dispersion of values of petrophysical parameters within the zone isn't high. This fact proves homogeneity and indicates the high intensiveness of hydrothermal alterations.

The zone of mediume temperature propylites is characterized by a large variety of secondary minerals, such as chloride, quartz, wairakite, albite, epidote, etc. Tuffs are re-crystallized by 60-80 %. In comparison with the preciding zone the values of the petrophysical parameters get lower: ρ - to 2.3 g/cm^3, V_l - by 1 km/sec, R_s - to 50 MPa, porosity gets higher by 15-20%.

The change of mineral composition in the zone of low-temperature propylites (chloride, corrensite, lomontite, hydromica, calcite) results in the futher decrease of parameters: ρ - to 2.1-2.2 g/cm^3, V_l - to 2.5-3 km/sec, R_s - to 30 MPa, porosity increases to 25 %. The quantity of secondary minerals varies from 50 to 90%.

As chlorites, hydromicas are replaced by mixed-layered clay minerals with montmorillonite component, the zone of argillized propylites is formed. The zone is composed from highly porous (30-40 %) rocks which are slightly cemented (R_s=10-15MPa), hygroscopic (W_g=3-4 %), softened when saturated with water (K_r=0.15-0.3). The degree of hydrothermal alteration is high, reaching 100 %. As regarde to properties the zone is homogeneous enough. The homogeneity is broken by the horizones of high strength and dense (Rs=50-60MPa, ρ=2.2 g/cm^3) with high content of calcite (up to 30%).

The zone of hydrothermal argillites contains the following typomorphic minerals: opal, tridymite and montmorillonite. The zone has a high degree of inhomogeneity becouse of the complex geological structure of cross-section.This is manifested by the non-uniformity of processed rocks and by frequent change of secondary mineral composition. There can be distinuished both low-processed (10-20 %) levels with relaitively high values of properties (ρ=2.1-2.2 g/cm^3, p=20-25 %, V_l=3.5-4 km/sec, R_s=30-60 MPa) and intensively-processed (80-90 %) highly porous (40-45 %), hygroscopic (W_g=3-4 %) strata, having strength < 10 MPa.

There are opal-kaolinite and monoopal subzones in the uppermost zone. Like the preceding zone the first subzone has an extreme irregularity of the values of petrophysical parametrs: ρ=1.6-2.15 g/cm^3, p=20-40 %, V_l=2,4-4 km/sec, R_s=10-60 MPa. The monoopal subzone despite of high porosity (35 %) have significant strength (30-50 MPa) and velocity of longitudinal waves 3.0-3.2 km/sec. It is necessary to remark that the bondaries between all zones are rather distinct.

Each zone has its intrinsic set of petrophysical parameters. The following regularity of properties alternations has been observed upwards the section: tendency towards spasmodic decreasing of density (from 2.6 to 1.6 g/cm^3) and strength (from more than 100 MPa to 10-15 MPa); increasing of porosity (from 10-15 to 30-40 %) and hygroscopic moisture (from 0.5 to 3-4 %). The boundaries between the zones are rather distinct. It is necessary to note that the basic regularity of properties alternations is broken by "hydrotherm boiling" zones. These zones are disposed on fractured areas with a particular hydrodinamic regime and cross, as a rule, the main vertical zoning. Despite their position in the section, quartz-adular rocks, typical of these zones, are dense (2.4-2.5 g/cm^3), acoustically “rigid” (V_l 4-5 km/s) and strong (R_s about 100 MPa).

3.2 Pauzhetskaya system (regressive stage of evolution)

The Pauzhetskaya system is older, lower-temperatured and belows to the regressive stage of evolution. As a result it has somewhat diffrent hydrothermal zoning. There can be distinguished only two zones: the zone of low-temperature propylites (with two subzones - transilvanian and zeolite) and the zone of hydrothermal argillites with high-silicon zeolites (Korobov, 1993). Zeolite propilites are the most accured. They form the zone nearly 500 m thickness. The process of zeolitisation is more intensive and more prolonged than within the Okeanskaya system. As a result tuffs are often transformed into loose (ρ=1.5-1.8 g/cm^3), highly-porous (p = 40 %), heterogeneous chloride-lomontite rock with anomalistically low values Vl < 1 km/sec and strength R_s = 2-5 MPa. The characteristics of the zone of zeolites prorylites is its low hygroscopic moisture (W_g < 1%). Transilvanian propylites are less spreaded as comparison with zeolites propylites and mainly developed in low-permiable tuffs. The main secondary minerals are illite, chlorite, calcite, quartz. The degree of hydrothermal alteration is around 50 %, that specifies rather high values of petrophysical properties: ρ=2.1-2.5 g/cm^3, p=8-22 %, W_g=0.7-3.9 %, V_l > 3 km/sec, R_s = 20-80 MPa. The large despersion of values W_g is caused by the presence of various generations of hydromica, both hydromica and mixed-layered montmorillonite-hydromica. In last case the petrophysical parameters decrease: r - to 2.02 g/cm3, V_l - to 1.2 km/sec, R_s - to 13 MPa.

The typomorphic mineral of the next zone - the zone of hydrothermal argillites - are montmorillonite, opal, high-silicon zeolites. The degree of hygrothermal alteration is significantly higher (60-90 %) than within the analogous zone of the Okeanskaya system. Accordingly, the zone is more homogeneous by properties. Rocks are light (ρ = 1.07-1.7 g/cm^3), high-porous (p=33-57 %), hygroscopic (W_g=1-5 %). Parameter V_l varies within 1.5-2.5 km/sec, R_s changes from 3 to 30 MPa. Some dispersion is caused by variations of quantitative ratio of montmorillonite, opal and zeolites, as well as by the forms of theire effusion.

3.3 Paratunskaya system

The properties of some samples from 6 drill-holes untill the depth 2200 m have been stadied. The zoning of Paratunskaya system has some differences. The following zones are exposed: zeolite, albite-zeolite, albite-calcite with sericite, albite, albite-epidote, albite-actinolite. As distinct from preceding systems the most widely-distributed mineral is albite, presenting practically within all zones. It is one of the reason of high dense (2.35-2.96 g/cm^3) and strength. The rocks from zeolite and albite-zeotite zones have the lowest density (2.35-2.45 g/cm^3). The rocks from albite-epidote and epidote-actinolite zones are the most dense (ρ from 2.75-2.85 to 2.96 g/cm^3). All rocks are acoustically “rigid”, with the exception of zeolite and albite-zeolite zones (V_l = 1.25-2.95 km/sec). The rocks from albite-calcite-sericite zone have V_l = 3.5-4.5 km/sec. Within the albite-epidote zone V_l increases to 4.5-5.5 km/sec, and within epidote-actinolite zone - untill 5.5-6 km/sec. The strength changes from 33 to 325 MPa. The zeolite propilites are the least strong (33 MPa). The strength of albite, albite-zeolite, albite-calcite-sericite propilites varies from 50 to 130 MPa. The strength of albite-epidote propylites increases to 150-200 MPa. The epidote-actinolite propylites are the strongest (Rs > 200 MPa).

4. DISCUSSION

4.1 The estimation of homogenity of hydrothermal zones

Hydrothermal zoning and rocks’ properties of each system have both common and particular features. The zones of Okeanskaya system are more heterogeneous, i.e. characterized by a wide dispersion of petrophysical parameters, caused by the irregularity and the incompleteness of hydrothermal transformations (Fig.1 A). The zones of Pauzhetskaya system (which is older and lower-temperatured than Okeanskaya system) are more processed, therefore more homogeneous. Each zone is characterized by its intrinsic set of petrophysical parameters (Fig.1B). It is evidence of a more prolonged and directed change of rocks’ properties in comparison with Okeanskaya system. It also indicates that the geothermal system has reached a certain stability in properties alterations.

4.2 The alteration of rocks' petrophysical parameters during the hydrothermal processing

During the hydrothermal-metasomatic processing, the values of petrophysical parameters of rocks initially differing in their composition, structure and properties, get gradually equalized within every zone. The properties of cinder, psammite, psefite and even agglomerated tuffs having experienced an intensive influence of thermal solutions, get similar in the zones of zeolite propylites of the Pauzhetskaya system (Table 2), argillized propylites, secondary quartzites and opalites of Okeanskaya system and in both systems’ zones of steam generation. Thus, composition, structure and properties of hydrothermal-metasomatic rocks are independent of their primary particularities but controled only by temperature and composition of thermal solutions. Volcanites’ primary particularities influence the speed of rock’s hydrothermal transformation. Psammite-psephite tuffs which are the most pervious among tuffs, have the highest speed of transformation. The speed of cinder tuffs’ transformation is lower because they are impermeable, but include in their composition a great amount of volcanic glass which is easy destroyed. The speed of geothermal processing is the lowest for the agglomerated tuffs, because of their impermeability.

4.3 The influence of tectonic position upon the hydrothermal zoning

The geological-tectonic peculiarities of region cause essential alterations in the general scheme of hydrothermal zoning, as they control prysical-chemical and thermodynamic conditions as well as permeability of rock in the interior parts of hydrothermal system. In this way they influence the character and degree of hydrothermal alterations, thickness of zones and their homogeneity. Thus, the hydrothermal zoning has a number of pecularities in different tectonic blocks. The most active hydrothermal processes take place within horsts (present-day and neotectonic), composed of intensively disturbed, fractured rocks. The horsts are characterized by an inhomogeneous structure of the temperature field. As a result, quartz-adular metasomes are formed within the high-temperatured open tectonic disturbances intersecting and controling the horsts and secondary quartzites are formed within the exocontact zones of subintrusions feeding the geothermal systems. Both types of rocks are dense, strong, and acoustically “rigid”. At some distance from them there are cooled segments (temperature < 200^0 C), where thick strata of loose, not dense, fragile, highly porous zeolites and argillized propylites are formed. All hydrothermal zones of horsts are notable for a high degree of processing of initial rocks (80-100 %) and homogeneity of petrophysical properties.

Tectonically stable structures (relatively subsident blocks) are composed of less disturbed rocks and characterized by temperature growing gradually with depth and, therefore, by a distinct consecutive change of hydrothermal zones along the section. There is a distinct tendency towards decreasing of density by 1 g/cm^3 and strength - 10 times, increasing porosity - 3-4 times, appearing of hygroscopic moisture upwards the section from zone to zone.

Thus, petrophysical data allow to obtain some additional information about the structure of geothermal systems.

4.4 Petrophysical analysis aplication for geothermal systems study

It is well known, that one of the main conditions for a rational exploitation of a geothermal system is the determination of its geological structure. Traditionally, a complex of geological, geochemical and mineralogical methods of drill core study as well as hydrogeological methods (such as thermal water klick) are used to solve this problem. Using of borehole geophysical measurements and logging is very dufficult because of pressurized, high temperatured (T up to 400°C) and aggressive solutions circulating within the geothermal system.

The studies we performed on three geothermal systems of Kuril-Kamchatsky region showed that a complex of petrophysical data helps to obtain some additional information about the systems’ structure. Petrophysical analysis allows to describe physical heterogeneity of the geothermal system; to determine hydrothermal zones, lithological horizons, tectonic blocks, contact zones of subintrusions as well as collectors, upper and lower confining layers, zones of prospective water flow, zones of steam generation, etc.

5. CONCLUSION

Thus, the stady of rocks' petrophysical properties on three hydrothermal systems of Kuril-Kamchatka region allows to draw following conclusions. The formation of rocks' petrophysical properties in geothermal reservoirs has zonal character. The zones are characterized by various values of petrophysical properties, also differ from each other by degree of homogeneity.

The rocks properties' alterations during hydrothermal processing have different directions. In depention from types and quantity of secondary minerals there may be both increase as well as decrease of volues of petrophysical parameters.

The properties of new rocks (hydrothermal metasomatites) independ from their initial peticularities. The last one influense only upon the velosity of hydrothermal re-crystallization.

The hydrothermal zoning within the various tectonic blocks of hydrothermal system have some particularities.

The petrophysical characteristics of rocks from various geothermal systems are differed significantly that is resulte from various structural-mineralogical paticularities of rocks. But common laws of properties’ alterations are also exposed.

REFERENCES

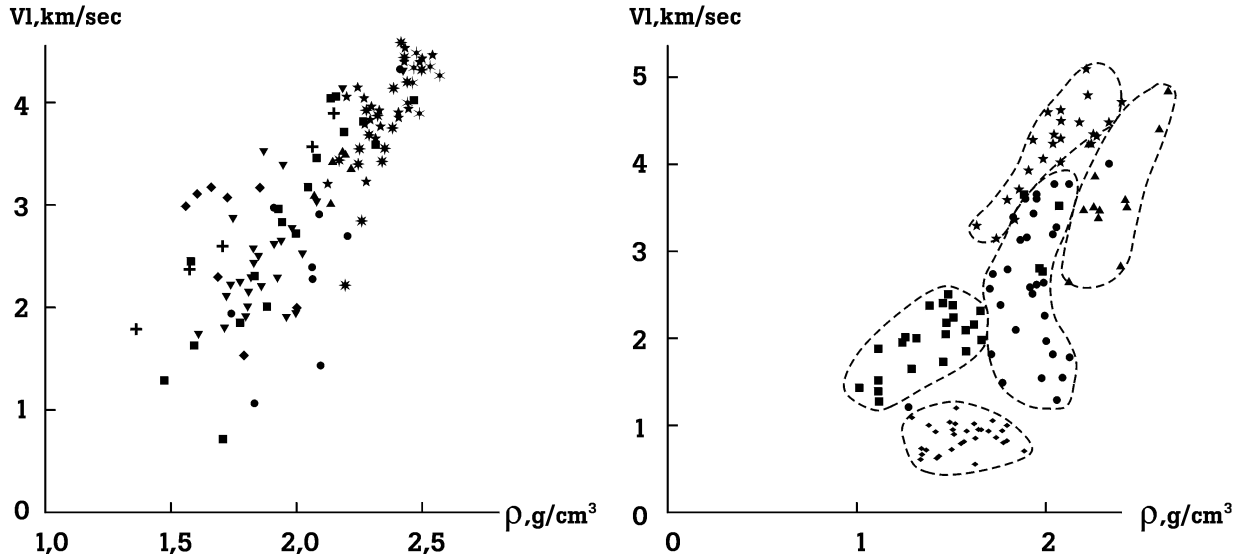
(Chapter in a book)

Korobov A.D., Goncharenko O.P., Glavatskykh S.F., Rikhter Ya.A. and Rychagov S.N. (1993). History of hydrothermal mineral formation in the Pauzhetka hydrothermal field and in the paleohydrothermal systems in the region. In: The structure of hydrothermal system, V.I. Belousov and I.S. Lomonosov (Ed)., Moscow, pp.88-120.

Table 1. The alteration of tufogenic rocks' properties during regional epigenesis

depth, m	type of cement	ρ, g/cm^3	p, %	V_l, km/sec	R_s, MPa
650-700	--------------	1.34	47	1.85	18
700-800	filmy	1.61	44	1.5	26
800-1250	interstitial-filmy	2.02	29	1.65	35
1250-1500	interstitial-basal	2.27	21	2.15	45

A - Okeanskaya system B - Pauzhetskaya system



Legend

- ◆ opalites
- ■ hydrothermal argillites
- zeolites propylites:
- degree of alteration –
- ● 50-80%
- ♦ 80-100%
- ✚ opal-kaolinites
- ▼ argillized propylites
- ▲ calcite-hydromica propylites
- ✷ quartz-albite-chlorite propylites
- ✶ secondary quartzites
- ★ quartz-adular metasomatites

Figure 1. Ratio V_l-ρ for various hydrothemal zones

Table 2. The alteration of tuffs' petrophysical properties during zeolitization.

degree of alteration, %	50-80 %			80-100 %		
type of tuff	cinder	psam.	pseph.	cinder	psam.	pseph.
p, %	44	31	26	37	39	39
V_l, km/s	1.95	2.3	3.8	0.8	0.85	0.85
R_s, MPa	17	22	57	4	3	3
quantity of samples	8	10	4	20	92	20