Geothermal Reservoir Study Through Petrophysical Data

J. V. Frolova¹, V. M. Ladygin¹, and S. N. Rychagov²

¹Moscow State University, Geology Department
²Institute of Volcanology, Far East Division Russian Academy of Science, Petropavlovsk-Kamchatka

Key Words
Petrophysical properties, hydrothermal reservoir, correlation, zonation

ABSTRACT

This paper considers the application of petrophysical properties to geothermal reservoir studies. Petrophysical properties help to define the character of geothermal reservoirs enabling the determination of aquifers, water confining stratum, hydrothermal zones, lithological horizons, and faults and fracture zones, as well as some other structural units. Petrophysical properties that are easily determined and informative are described and used for geothermal reservoir investigation. The paper describes as well the relationship between some petrophysical properties and their usefulness for studying geothermal systems.

Introduction

One of the main tasks for rational exploitation of a geothermal reservoir is the determination of its geological structure - aquifers, water confining stratum, hydrothermal zones, lithological horizons, faults and fracture zones as well as some other structural units. Traditionally a complex of geochemical, hydrogeological and geophysical methods is used to determine the structure. The studies we performed on several geothermal systems of the Kuril-Kamchatky region (Far East, Russia) - Okeanskaya (Iturup Island), Pauzhetskaya and Paratunskaya (Southern Kamchatka) and the system of Ebecko volcano (Paramushir Island) – have shown that the petrophysical data set helps to obtain some additional information about geothermal reservoir structure. Moreover, petrophysical characteristics of rocks are necessary for geothermal system modeling. Petrophysical measurements of core, together with petrographical studies, help to interpret geophysical logs.

The studied geothermal systems are located in a region of modern volcanic and hydrothermal activity. The intensive drilling and coring conducted during the exploration and exploitation of geothermal systems has allowed study of a large collection of hydrothermal rocks. The resulting database includes petrophysical properties of 470 core samples from 28 boreholes. The data set includes: density of rock (ρ), mineral density (ρm), total (N) and open (N0) porosity, hygroscopic moisture (Ww), velocities of longitudinal (for dry Vl and water-saturated Vw samples) and transversal waves (Vs), acoustic anisotropic parameter, strength (S) (for dry and water-saturated samples) and magnetic susceptibility (k). The rock type and degree of hydrothermal alteration were determined by using thin section examination, XRD analysis and scanning microscopy.

Geothermal Systems Formation and Structure

The investigation of a borehole that is located near the Okeanskaya geothermal system but is not in the area influenced by hydrothermal activity has shown that initially the geothermal systems were composed of loose or slightly cemented (porosity is about 30-45%, density ~1.6-2.0 g/cm³) quite permeable tuffs of Neogene-Quaternary age. Cement type changes from filmy to pore-basal with depth. As a result density, strength, and Vl gradually increase and porosity decreases with depth (Figure 1). A high correlation between the depth and petrophysical parameters is observed (Q=0.9).

Highly porous tuffs contain a great amount of water. In some places, underground-water has been heated by high heat flow from intrusions or dikes and transformed into solutions of various composition, acidity-alkalinity and temperature mineral-
Table 1. Petrophysical properties of the main types of hydrothermal rocks.

<table>
<thead>
<tr>
<th>Hydrothermal rock</th>
<th>Density, g/cm³</th>
<th>Porosity, %</th>
<th>Hydroscopic Moisture, %</th>
<th>Vₙ, Km/sec</th>
<th>Strength, Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary quartzite</td>
<td>2.4-2.6</td>
<td>10-15</td>
<td>0.3-0.5</td>
<td>4.0-5.0</td>
<td>100-170</td>
</tr>
<tr>
<td>Prophylite Quartz-chloride-albite with wairakite, and epidote</td>
<td>2.3-2.4</td>
<td>15-20</td>
<td>0.5-0.7</td>
<td>3.4-3.8</td>
<td>50-60</td>
</tr>
<tr>
<td>Calcite-sericite with hydromica and mixed-layered clays</td>
<td>2.0-2.3</td>
<td>15-20</td>
<td>1.0-3.0</td>
<td>3.0-3.6</td>
<td>30-45</td>
</tr>
<tr>
<td>Argilized</td>
<td>1.8-1.9</td>
<td>35-40</td>
<td>3.0-4.0</td>
<td>2.1-2.5</td>
<td>10-15</td>
</tr>
<tr>
<td>Zeolite, chloride</td>
<td>1.4-1.7</td>
<td>38-45</td>
<td>0.7-1.0</td>
<td>0.8-1.0</td>
<td>3-7</td>
</tr>
<tr>
<td>Hydrothermal argillite with High-silicon content zeolites</td>
<td>1.5-1.8</td>
<td>30-50</td>
<td>3.0-5.0</td>
<td>1.5-2.1</td>
<td>7-10</td>
</tr>
<tr>
<td>Opalite</td>
<td>1.5-1.7</td>
<td>35-40</td>
<td>1.0-1.5</td>
<td>3.0-3.3</td>
<td>30-50</td>
</tr>
<tr>
<td>Primary tuffs</td>
<td>1.25-2.01</td>
<td>30-50</td>
<td>1.5-6.5</td>
<td>1.5-1.8</td>
<td>15-40</td>
</tr>
</tbody>
</table>

Petrophysical Properties Application for Geothermal Reservoir Study

Some petrophysical properties that are easily determined on the one hand and informative on the other have been described and used for geothermal reservoir investigation.

1. A high value of hygroscopic moisture (Wₕ > 2%) provides evidence of high content of adsorbed water within the rock and also indicates that argillized rocks formed under conditions of relatively low temperature (not exceeding 150°C). Hydrothermal argillites as well as argillized propylites, as a rule, form water confining layers in spite of high porosity (30-40%) and low density (1.5-1.8 g/cm³). The reason is the following: the main minerals of hydrothermal argillites are montmorillonite, corrensite or mixed-layered clay minerals having small pore-size and ability to swell. Hygroscopic moisture is easily determined by heating the rock sample (air-dry powder) for 8 hours at temperatures as high as 150°C. Hygroscopic moisture (Wₕ) is then calculated as:

\[ Wₕ = \left( \frac{m₁ - m₂}{m₂} \right) \times 100 \]

where \( m₁ \) is the mass of air-dry powder and \( m₂ \) is the mass of the powder after heating.

The location of the zones of hydrothermal argillites and argillized propylites is easily determined by Wₕ without using XDR analyses. Figure 3 shows an example of the determination of the argillization zone through Wₕ in borehole 54 (Okeanskaya GTS). The zones of hydrothermal argillites and argillized propylite occur from 70 m downward to 430 m. The location of the argillized zone obtained by Wₕ correlates with the mineralogical data of XDR analyses.

![Figure 2](image1.png)  
*Figure 2. The irregular change of total porosity and velocity of longitudinal waves with the depth (borehole 54, Okeanskaya GTS).*

![Figure 3](image2.png)  
*Figure 3. The change of hygroscopic moisture with the depth in borehole 54 (Okeanskaya GTS).*
2. A low value of velocity of longitudinal waves (V_l < 1000 m/sec) indicates the zone of zeolitization which is characterized by a high degree of alteration, high porosity (35-45%), low density (1.5-1.7 g/cm³) and low strength (1-5 MPa). This loose, fragile 200-500 m thick zone is the main porous aquifer in the Pauzhetskaya system and it is easily recognized by low V_l.

3. High values of density (>2.5 g/cm³), strength (>150 MPa) and V_l (>4000 m/sec) are the evidence of either secondary quartzites or quartz-adularia metasomatites formed within fault zones or magmatic rocks.

4. A low value of magnetic susceptibility (0.01-0.02*10^{-3} SI) is characteristic either of secondary quartzites or "boiling or steam generation" zones within faults composed of quartz-adularia rocks.

5. A strong correlation between total and open porosity has been determined (Q=0.97) and a regression equation has been calculated (Figure 4). The equation is a polynomial:

\[ N = 3.409 + 3.242 N_0 - 0.084 N_0^2 + 0.001 N_0^3 \]

Thus, total porosity can be calculated through open porosity (water absorption) which is calculated as:

\[ N_o = \left( \frac{M_1 - M_2}{M_2} \right) * 100 \]

where M_1 is the mass of the water-saturated sample (after 8 days of saturation), and M_2 is the mass of dry sample (after 105°C heating).

6. Petrophysical properties help to describe the heterogeneity of geothermal reservoirs as well as hydrothermal zones. The older a geothermal system is the more homogeneous are the hydrothermal zones and the greater is the difference between the zones. Thus the zones of Pauzhetskaya system, which are older than those of the Okeanskaya system, are more processed and therefore more homogeneous. Each zone is characterized by its intrinsic set of petrophysical parameters (Figure 6). The Pauzhetskaya system has reached a certain stability in rock property alteration while the Okeanskaya system is characterized by a wide dispersion of petrophysical properties values.

**Conclusion**

Petrophysical parameters can be effectively used for studying geothermal systems:

1. The high correlation between depth and petrophysical parameters is characterized for a geological section that is out of the area of hydrothermal activity. Since the structure of geothermal reservoirs resembles "puff-pastry," no correlation is observed between the depth and petrophysical parameters in the geothermal systems.

2. The location of aquifers as well as the alteration of their productivity can be predicted by petrophysical parameters.

3. Some easily determined petrophysical properties (especially W_n, N_0, V_l, k) are useful for geothermal reservoir investigation. Use of these petrophysical parameters helps to determine hydrothermal zones.

4. The dispersion of petrophysical parameters allows us to describe the heterogeneity of geothermal reservoirs and hydrothermal zones, as well as the degree of hydrothermal alteration.

5. The high correlation (Q=0.97) between open and total porosity allows calculation of the latter from open porosity.

**References**
