THE GEOTHERMAL GRADIENT ANALYSIS FROM THE MOESIAN PLATFORM

ANALIZA GRADIENTULUI GEOTERMAL DIN PLATFORMA MOESICA

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Abstract: In this article are presented and simulated series of dates regarding the geothermal gradient distribution in the Moesian Platform, using the temperature measurements done in oil exploration and production wells. Knowing the thermal conductivity and the geothermal gradient of rocks it is possible to estimate the heat flow, one of the main parameters for the thermal state of geological formation characterization. They are presented the main problems of geothermal conductivity of rocks measurements in the laboratory conditions.

Keywords: geothermal gradient, thermal conductivity, geothermal flow, rock, simulation, pressure, temperature

Rezumat: În acest articol sunt prezentate și simulate o serie de date cu privire la distribuția gradientului geothermal din Platforma Moesică, utilizând măsurători de temperatură efectuate în sondele de exploatare. Cunoscând conductivitatea termică și gradientul geotermal este posibilă estimarea fluxului de temperatură, unul dintre principali parametri utilizați la carcatizarea formațiunilor geologice. Sunt prezentate principalele probleme ale conductivității geotermale, a măsurătorilor rocilor în condiții de laborator.

Cuvinte cheie: gradientul geotermal, conductivitatea termală, fluxul geotermal, rocă, simulare, presiune, temperatura

1. Introduction

An important objective regarding the advances characterization of a reservoir is the identification of the areas with above average saturation in crude oil which represents an economic interest. Obtaining a mobile oil in large quantities that allows the development of the exploitation is controlled on the one hand by the large pressure differences in the reservoir, and the other hand by the contrast of density and viscosity.

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Thus, from the works in wells and the thickening of gauge point of view, the most important heterogeneities are faults, boundaries of genetic units, high permeability contrast and flow barriers such as mars intercalations. One of the defining elements of a reservoir is the temperature gradient.

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When using temperatures to make corrections for interpreting geophysical investigations in wells, it is preferable to take into account the temperature measured during the recording of geophysical diagram wells, although this is usually a few degrees lower than the actual temperature of the formation due to the cooling induced by the drilling fluid.

For the evaluation of the reservoirs and the technological processes applied to the reservoirs, the temperature measurements stabilized from the production wells or the correction of the values from the drilling with the effect of the time and the drilling fluid.

During the evolution of the Moesian Platform, the interruptions in the sedimentation rate delimited four sedimentation cycles (Mutihac 2010; Figure 3): Cambrian medium – Westphalian Cycle; Permian superior – Triassic Cycle; Jurassic medium – Cretacic Cycle; Badenian – Pleistocene Cycle [1].

Notable for our area is the end of the third cycle of sedimentation, because of the outpost formed at the end of the Upper Cretaceous the southern Carpathian. The last deposits, belonging to the Moesian Platform, below the Getic Depression would be of Senonian – Paleocene age, because at the end of the Cretaceous, following the laramic movements, the Moesic Platform behaved as a large continental area formed by basins, where the Paleogene deposits would have been deposited.

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For a better evaluation of the temperatures / temperature gradients of the geological formations in Romania, in Figure 1 are presented the values of the thermal flow and the temperatures at a depth of 3000 m.
The geographical researches of the last years have taken on a great extent due to the multiple implications of knowing the influence and distribution of the temperature in rocks, as well as the thermal flux in both scientific and practical problems.

The research aims to present data on the distribution of the geothermal gradient in the Moesian Platform Figure 2 [5], based on the temperature measurements performed in the hydrocarbon exploration and exploitation wells and the main elements of thermal conductivity measurement of rocks under laboratory conditions. Given the fact that the geothermal gradient and the thermal conductivity of the rocks are known, can be determined the geothermal flow, the main characterization of the thermal regime of the geological formations.

The areas marked in Figure 2 represent the areas with a high geothermal gradient from the Moesian Platform.

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The Moesian Platform behaved like a rigid "corner", imposing a dextral twist in the Southern Carpathians, in the Upper Cretaceous - Paleogene causing an E – W contraction and subsidence in its northern part (Rabagia & Mațenco, 1999). The latter would be responsible for the large amount of sediment from the Upper Cretaceous - Paleogene deposited in this area. The northern limit of the Moesian Platform is represented by the Pericarpatic Fault, a fault that highlights the breach of the deposits of the Getic Depression over those of the platform, during the Upper Miocene.

Based on the production data from the Moesian Platform available, an overview was made regarding the geothermal potential of the platform. Such as the areas marked with red are possible future exploitation fields, from the geothermal point of view.

Figure 2. Geological map with geothermal potential [5]
Moesian Platform (processed with the autocad program)

Figure 3. The general stratigraphic column from Moesian Platform (after Tari et. al., 2011)
Pl – Pliocene, Sl – Silurian, C/CO – Cambrian/Ordovician, Pre C – Pre Cambrian
3. Definition and concepts

Regarding the geothermal gradient, theoretically, the following concepts can be defined:

- **Thermal conductivity** ($\lambda$) is the property of the environment to transmit thermal energy. From a quantitative point of view, thermal conductivity expresses the amount of heat $dQ$ that flows at a time $d\tau$ through a parallelepiped of cross section $S$ and length $l$, whose opposite sides are at temperatures $t_1$ and respectively $t_2$ [2]:

$$\lambda = \frac{dQ}{(t_2-t_1)S} \left(\frac{Kcal}{m.^{°}C.orad}\right)$$

The inverse of thermal conductivity is called thermal resistivity:

$$\xi = \frac{1}{\lambda}$$

The two sizes depend on the density, temperature and structure of the rock. Usually, the thermal conductivity increases with density, humidity and permeability of rocks.

- The **thermal diffusion coefficient** ($a$) represents the rate of change of temperature of the unit of volume of the environment in the unit of time. It is expressed quantitatively as follows:

$$\lambda = \frac{\lambda}{c\delta} = \frac{1}{\xi c\delta} \left(\frac{m^2}{°C.orad}\right)$$

where: $\delta$ – density of the environment.

From equation (3) it follows that the thermal diffusion is a function that depends on the same factors as the thermal conductivity. This parameter is important when assessing the attainment of the stabilized thermal regime, after drilling a well for conducting temperature measurements under favorable conditions.

- **Thermal flow** is defined as a vector like that:

$$\vec{f} = -\lambda \text{grad } t = -\lambda \Delta t$$

with components:

$$f_x = -\lambda \frac{\partial t}{\partial x}; f_y = -\lambda \frac{\partial t}{\partial y}; f_z = -\lambda \frac{\partial t}{\partial z}$$

- **Geothermal flow** represents the heat flow that propagates from the inside to the Earth’s surface. It is defined by the following relationship:

$$g = -\lambda \frac{\partial t}{\partial z}$$
- **The Geothermal gradient** represents the variation of temperature with depth:

\[ G_t = \frac{dt}{dz} \]  \hspace{1cm} (7)

The geothermal gradient is determined by the heat flow and thermal conductivity of the rocks:

\[ G_t = -\frac{q}{\lambda} \] \hspace{1cm} (8)

Assuming the constant thermal flux, the high thermal conductivities of the rocks determine small geothermal gradients, and the small thermal conductivities of the rocks determine large geothermal gradients. Generally speaking, the geothermal gradient is expressed by temperature variation (°C)/100 m [1]:

\[ G_t = 100 \frac{t_2 - t_1}{H_2 - H_1} \] \hspace{1cm} (9)

where: \( t_2, t_1 \) – represents the values of the temperature measured at the depths \( H_2, H_1 \).

- **Geothermal step** (the inverse of the geothermal gradient) and represents the distance in meters vertically (in depth) for which a temperature variation of 1 °C.

\[ T = \frac{H_2 - H_1}{t_2 - t_1} \] \hspace{1cm} (10)

### 4. Results and discussions

#### 4.1. The geothermal gradient

The temperatures measurement of wells, can have multiple uses: establishing the lithological nature of the geological formations in the exploitation of useful mineral substances, evaluation of formations according to geophysical logs data, solving problems related to the use of heat resources. The temperatures distribution is a consequence of thermal flux vertical convection and vertical and lateral diffusion. The relation according with this distribution may be computed is:

\[ T = f [\Phi cf + (1 - \Phi)cma] \] \hspace{1cm} (11)

*where:*

- \( T \) – rock fluid system temperature;
- \( \Phi \) – porosity;
- \( cf \) – fluid specific heat;
- \( cma \) – mineral matrix specific heat.
Thus, the temperature variation model is linked with fluids and mineral matrix specific heat. Thermal flux from the inner layers will easily increase the temperature of the deeper formations because they have a smaller porosity and a smaller fluid content so they need a smaller energy consumption in order to achieve a greater temperature. Reaching more porous upper layers the necessary amount for energy to heat same of rock is higher so the temperature will decrease quicker in the shallower formations. That explains why on different depth intervals we may have different temperature variation models. Usually temperature gradient is calculated as a function of temperature variation with depth but the real process is from depth to surface not from surface to deeper layers.

![Temperature variation with depth](image)

**Figure 4.** Temperature variation with depth (Diapire Hold Zone)

In the case of the formations evaluation and the calculation of the geothermal flow, the geothermal gradient is of particular importance. This is determined based on the maximum temperatures recorded in the wells during the investigation or testing of the formations.

Based on the measurements made in the wells, a linear relationship between temperature and depth is determined in Figure 4. After the cross right temperature variation as a function of depth, the average geothermal gradient for an area is calculated. The temperature measurements are obtained in a stabilized thermal regime, so that after the drilling fluid circulation has stopped, the well should remain at rest for the fluid to take up the actual temperature of the surrounding rocks.

It is estimated that the rest time required to restore the thermal balance is approximately three times the drilling time of the well (Bullard, 1947).

In this research, the geothermal gradients were determined based on the temperature measurements performed in both stabilized and unstabilized thermal regime. However, the average geothermal gradients determined under such
conditions do not differ by more than 15 – 20% from the values calculated based on the temperature data recorded under stabilized thermal regime.

Also the values of the average geothermal gradients, calculated for the main oil structures in the Moesian Platform [4], are graphically represented in Figure 5 and Figure 6. In the two graphs, the temperature corresponding to the depth of 2000 m considered as landmark, respectively the depths at which intercepts of isogeothermal well of 60 respectively 80 °C.

**Figure 5.** Depth variation at 60 °C depending on the depth of 2000 m

**Figure 6.** Depth variation at 80 °C depending on the depth of 2000 m

According to the history of the drilled wells and exploited in our country, the geothermal gradient is 3 °C/100 m (0.03 °C/m).

At the north of Pericarpatic Fault, the values of the geothermal gradient are between 2 and 3 °C/100 m. These are in agreement with the characteristic values of the depressed areas, with thick neohene deposits, predominantly terigenic with a lower thermal conductivity than that of the formations in the platform areas. Also, in the platform area there are two sectors with different thermal regime:
- the western sector (between Jiu Valley and Dâmbovița Valley) characterized by geothermal gradients and high temperature. In this sector we distinguish area with the largest geothermal gradients determined on the structures: Ciurești (3.73), Glavacioc (3.75), Cartojani (4.8), Videle (4.6), Hărlești (3.42 °C/100 m);

- the east sector (east of Dâmbovița Valley), characterized by geothermal gradients and low temperatures: Periș (1.05), Tinosu (1.23), Urziceni (1.28 °C/100).

Generally, on the platforms the geothermal gradients increase with the increase in profile of sandy – clay rocks and decrease under the conditions of the predominance of the carbonate formations and the hydrochemical deposits.

On the other hand, the net different thermal regime of the two sectors is simulated by the position of the 60 and 80 °C isogeotherms, depending on the variation of the gradient and the temperature corresponding to the depth of 2000 m on an SV – NE profile between Craiova and Ghergheasa Figure 7. Figure 7 shows a sinking area (Tinosu) of the 60 respectively 80 °C isogeotherms, an area on the structural alignment of the Fierbinți Fault (important fracture line that marks the boundary between the two sectors of the platform).

![Figure 7. Simulation of 60 and 80 °C isogeotherms, the variation of the geothermal gradient and the temperature at the depth of 2000 m (Craiova – Ghergheasa Zone)](image)

Based on the available data, a new NE – SV profile was simulated, between Câmpina and Videle, Figure 8 which shows the sinking of the 60 and 80 °C towards depression, an image that suggests a parallel of the evolution of the crystalline basement.

It can be concluded that there are a number of factors that condition the geothermal gradient at depth: the lithological nature of the formations, tectonic factors, hydrogeological regime, local thermal fields.
Figure 8. Simulation of 60 and 80 °C isogeotherms, geothermal gradient variation on a NE – SV profile

4.2. The thermal conductivity of the rocks

In general, the thermal conductivity of rocks is determined by relative methods under stabilized regime. One of the first methods of determining the conductivity is Divided bar method described by Birch (1950). The method principle is represented by a divided bar consisting of two quartz used as reference material with known conductivity, the rock and a series of copper discs Figure 9.

The ends of the bar are kept at constant temperature $t$ și $t'$ controlled by thermostatic baths at a difference temperature of 10 – 15 °C.

Figure 9. Determination of the thermal conductivity (Divided bar method)
After sufficient time to reach the thermal equilibrium, assuming that the heat flux is axial and there is no radial loss, the heat fluxes through the quartz disks and the rock may exist:

\[ Q_2 = Q_1 ; \quad Q_2 = Q_3 \]  
\[ Q_2 = \frac{Q_1 + Q_3}{2} \]  

(12) 

(13)

Given equation (1), equation (14) gets:

\[ \lambda_r \frac{\Delta t_2}{S_2} Z_2 = \lambda_q \frac{\Delta t_1}{S_1} Z_1 + \lambda_q \frac{\Delta t_3}{S_3} Z_3 \]  

(15)

where:

\( \lambda_r \) – thermal conductivity of rock with cross section \( S_2 \) and thickness \( Z_2 \);

\( \lambda_q \) – thermal conductivity of quartz disks with cross sections \( S_1 \) and \( S_3 \) and thickness \( Z_1 \) and \( Z_3 \);

It is simple to make quartz disks, so that:

\[ S_1 = S_3 = S \quad \text{si} \quad Z_1 = Z_3 = Z \]  

(16)

As standard or reference disks, can be used crystalline quartz or molten quartz.

It is recommended to use crystalline quartz, the disk being cut, so that the thermal flux is normal on the optical axis. Thus, the thermal conductivity of the quartz at different temperatures is determined by the equation:

\[ \lambda_q = \frac{1}{60.7 + 0.242t} \]  

(17)

Also, the variation of the thermal conductivity of the crystalline quartz for the temperature range 0 – 100 °C is shown in Figure 10.

![Figure 10. Variation of the thermal conductivity of the crystalline quartz (range 0 – 100 °C)](image-url)
Given the fact that melted quartz disks are easier and cheaper to make, they can be used as standard, so using crystalline quartz. The obtained values have an error margin of about 2%
.

The thermal conductivity of the molten quartz for the temperature range between $-150 \, ^{\circ}C < t < 50 \, ^{\circ}C$, it is determined by following the relationship:

$$
\lambda_q = 0.00316 + 46 \cdot 10^{-7} t - 0.16 \cdot 10^{-7} t^2
$$  \hspace{1cm} (18)

Variation $\lambda_q$ for the temperature range $0 - 50 \, ^{\circ}C$ is shown in Figure 11.

![Figure 11. Variation of the thermal conductivity of the molten quartz (range 0 – 50 °C)](image)

An important problem is the reduction of the thermal resistance to the contact between the quartz disks. This is achieved by applying a layer of petroleum jelly on the sides of the disks and exerting an axial pressure of $50 – 100 \, \text{atm}$ on the ends of the split bar.

5. Conclusions and proposals

Studying the existing (fields and literature) materials we may depict the next facts and proposals:

- The general geological frame (Moesian Platform) [3] provides an optimistic scenario for the existence of thermal energy in research area.
- These area were evaluated by electrical (SEV) surveys and field mapping.
- Also, an efficient geophysical survey method for deep located water saturated reservoirs is magneto telluric survey which for a proper definition may realized with a density about 3 point on square kilometer.
- For a better approach may by achieved well logs in the existing wells. A relative cheap, efficient and rapid method consists of Radioactive well logging (Gama Ray and Neutronic curves) which may emphasize the existence or different layers (lithology) and also may evaluate rocks porosity.
- Between the existing wells may be accomplished an interference study which can show the existence of a communication between them an improve the existing geological and hydrodynamic models.
- In order to estimate the resources will be important to have porosity data (from cores and/or well logs). Reservoir thickness also may be evaluated from mentioned well logs [6]. Areal dimension of the field are more difficult to be established, mainly from geophysical surface survey.

- Also may be taken into account the possibility that drilling deep wells, which will cross the Moesian Platform wells, the pelitic (clay) intervals may provide efficient seals which will block the heat flow mechanisms and thus the, recorded temperature will be much higher corresponding to thermal flow rate and regional temperature gradient.

The most important applications regarding the knowledge of temperature distribution, geothermal gradients and geothermal flow are:

- studying the dynamic processes in the deposits with geothermal potential as well as the characterization of the mantle – crustal unconformity;
- the ability to explain the earthquakes on account of temperature inhomogeneities (especially those related to volcanic activity);
- defining the basic conditions of hydrocarbon formation, migration and accumulation in fields, by determining the thermal regime of the geological formations;
- the design and construction of modern geophysical equipment for the deep research and the correct interpretation of geophysical well diagram;
- proper design of the drilling and exploitation of the wells involved;
- establishing the necessary characteristics of the drilling fluid and cement used;
- identifying the most suitable procedures for opening the layers under high temperature conditions and using the energy under established technical economic conditions;
- proper selection of drilling fluids for different special operations (hydraulic cracking, acidification);
- the use of the exploitation of the wells by thermal methods, which implies the knowledge of the thermal properties of the rocks (thermal conductivity);
- applying the suitable methods for combating corrosion;
- identification in the profile of the investigated wells of the different useful mineral substances (gases, hydro-chemical deposits, coals, sulphides, aquifer horizons) based on the local thermal fields produced by these substances;
- studies of regional geology and tectonics, which can help identify anticline basins, salt domes and protrusions buried by carbonate rocks (metamorphic and magmatic) with high thermal conductivity;
- research of the hydrodynamic characteristics of the oil and gas fields;
- study of the technical condition of the wells: specifying the places of influx and circulation of water behind the columns, the control of the primary cementation of the columns. Can be made in wells acoustic cementation logs:
- Sectorial Bond Tool (SBT);
- Cement Bond Log (CBL).
  - for measuring flow, temperature and density, they can be executed in wells PLT (Production Loc Tool).

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