AGH DRILLING, OIL, GAS • Vol. 32 • No. 3 • 2015

http://dx.doi.org/10.7494/drill.2015.32.3.551

**Rafał Wiśniowski*, Przemysław Toczek****

# THE METHODS OF PRESSURES PREDICTION BASED ON GEOPHYSICAL DATA

## 1. INTRODUCTION

The gradient of pore pressure, directions of natural rock compaction and geologic conditions plays a very important role for the designing of wells. The optimization of the drilling process imposes definite values of coefficients and parameters of rock layers (source and reservoir rocks) at the stage preceding actual drilling. Known and reliable data on, e.g. pressures in a given area are very useful while designing a new well. The pre-selected data can be used for optimizing physical and rheological properties of drilling fluid for particular wellbore sections at the stage of designing. For the sake of preventing the eruption of drilling fluid to the surface the pressure of the drilled layers should be counteracted by the hydrostatic pressure of the mud column in the well.

Prior to drilling a well, one should possess an engineer's knowledge qualifying him/her to answer the following questions:

- At what depth the overpressure can be expected?
- At what depth and how fast we should increase the specific weight of drilling fluid with the drilling progress?
- What minimum specific weight of drilling mud will be needed for generating extra hydrostatic pressure over the pore pressure of rocks?
- Will the pressure of rock formations drop from abnormal to normal values? If so, at what depth?
- At what depth the casing should be disposed and cemented?

Methods of predicting pressure in rock mass were broadly described in the 1950–60s. In 1965 Hottman and Johnson introduced a dependence between well logs of some rock parameters and abnormal pressure in shales. It was revealed that compact rock formation with

* AGH University of Science and Technology, Faculty of Drilling, Oil and Gas, Krakow, Poland
** Exalo Drilling S.A., Piła, Poland

lower water content, and so lower porosity, have higher resistivity than normally compacted shales [3]. Rocks successively underlying one another were observed to potentially increase the resistivity of shales. Hence a conclusion that each drop of resistivity or its change from the existing and pre-set trend will be indicative of zones of abnormal pressure. Values of wave velocity used by Hottman and Johnson from Sonic Logging Time (SLT) can be used for predicting pore pressure values. This prediction is based on the assumption that a change of seismic wave propagation in the ground will be a result of porosity changes (pore pressure) and pressure of overlying rocks [1, 5, 6].

## 2. EMPIRICAL PREDICTING ROCK MASS PRESSURE

It was already in the 1940s when Terzaghi observed that the change of seismic wave propagation is a result of porosity changes in the ground [7]. He claimed that the stress of overlying strata is a sum of stresses of rock skeleton and of pore pressure. In other words, the sum of pore pressure and effective pressure of the rock skeleton brings about the overburden pressure. This can be written in the following way.

$$S = \sigma + p \tag{1}$$

where:

$S$ – pressure of overburden [MPa],
$\sigma$ – pressure of rock skeleton [MPa],
$p$ – pore pressure [MPa].

The overburden pressure is a function of weight of rock mass skeleton, overlying rock mass and fluids in the pore space of the overlying rocks. Accordingly we have:

$$S(y) = 10^{-6} g \int_0^H \rho(y)dy \tag{2}$$

where:

$\rho(y)$ – density at analyzed depth [kg/m³],
$g$ – gravity acceleration [m/s²],
$H$ – depth of wellbore [m].

Terzaghi simulated a compaction of water-containing silts and clays with the use of a water container and springs. The pressure of the overburden was obtained with a piston, i.e. it was produced by fluid elasticity pressure $P$, as in equation (1). Taking into account the correlation of geophysical data and measured pressure we can find a relation between them. Equations describing these relations are presented below.

$$\frac{p}{h} = f\left(\frac{Rn_{sh}}{Ro_{sh}}\right) \tag{3}$$

$$\frac{p}{h} = f\left(\Delta to_{sh} - \Delta tn_{sh}\right) \tag{4}$$

where:

$p$ – pressure of rock formation [MPa],
$Rn_{sh}$ – natural resistivity of rock layers [Ωm],
$Ro_{sh}$ – recorded resistivity of rock layers [Ωm],
$\Delta tn_{sh}$ – normal interval time of rock layers [μs/m],
$\Delta to_{sh}$ – recorded interval time of rock layers [μs/m],
$h$ – depth at which we analyze pressure [m],
$\left[\frac{Ro_{sh}}{Rn_{sh}}\right]$ – resistivity coefficient [–].

After transforming equation (1) and accounting for the depth at which we analyze the pressure, we have:

$$\frac{p}{h} = \frac{S}{h} - \frac{\sigma}{h} \tag{5}$$

or:

$$\frac{p}{h} = f\left(\frac{S}{h}, \frac{\sigma}{h}\right) \tag{6}$$

Using the trial and error method Eaton derived a relation with which we can quite safely predict abnormal pressure following the Hottman and Johnson method.

$$\frac{p}{h} = \frac{S}{h} - 0.0121 \cdot \left[\frac{Ro_{sh}}{Rn_{sh}}\right]^{1.5} \tag{7}$$

In his method Eaton assumed the following pressure gradient of overburden $\frac{S}{h} = 0.0226$ MPa/m, resistivity coefficient $\left[\frac{Ro_{sh}}{Rn_{sh}}\right] = 1$ [–]. In line with dependence described with equation (7) he obtained the gradient of pore pressure (Fig. 1):

$$\frac{p}{h} = 0.0105 \ \text{[MPa/m]} \tag{8}$$

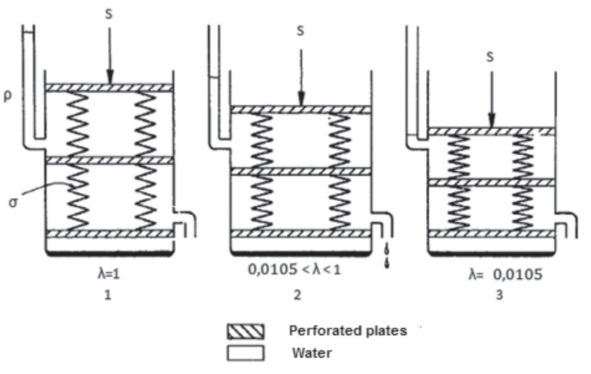


**Fig. 1.** Schematic of silts, clays and shales compaction [7] (values modified according to the SI system)

Gradient of pressure of source rocks in a given point, which underwent natural compaction in the course of orogenic processes will result from a difference between the gradients of overburden pressure and normal pore pressure. The parameters obtained from seismic well logs will depend on the main variables, i.e. the gradient of pressure of overburden and gradient of pore pressure. Depending on the region of the World, the gradient of pressure of overburden will distribute unevenly. It will not make any difference if it stays the same for a given region. In the zones where the compaction and pressure of the rock mass are a result of weight of the overlying rocks, this statement does not hold true.

## 3. PRESSURE CURVES AND SEISMIC WELL LOGS AS METHODS FOR AVERAGING PRESSURES

The effect of generating abnormal pressures in the rock mass is a result of various geomechanical, mechanical, physical, and before all, geological processes taking place inside the rock mass. However, it is hard to point to the process which most importantly affects the formation of zones of abnormal pressure. The following ones are responsible for the formation of anomalous pressure zones, therefore should be taken into account [3]:

- tectonic pressure,
- uneven compaction of the rock mass (dips, faults, tectonic traps),
- expansion of thermal waters,
- processes of mineral formation and alteration,
- age of hydrocarbons in source rocks,
- thermodynamic effects,
- osmosis.

Depending on the way in which we analyze the prediction of rock mass pressure and the data used for predicting pressures, one can distinguish these phenomena. However, we can largely speak about the uneven compaction of sediments and lack of compaction equilibrium as one of the major elements responsible for the formation of zones of anomalous pressure in the rock mass.

The pressure in the overburden is directly connected with the bulk density, which can be easily determined by density logging. By using the cumulative averaging system we can transform the possessed density logs into curves of overburden pressure gradient in a function of wellbore density. However a number of log data are necessary, i.e.

- resistivity logging,
- measured pore pressure,
- density logging.

With these data we can make the following plots (Figs 2, 3). These plots can be used only experimentally. It should be also noted that although the curves were drawn on the basis of experimental data, they have two set points. One of them is represented by the gradient of normal pressure from equation (8). The other one is a special case, when the gradient of pore pressure stems from the gradient of overburden pressure. In the latter case we can speak of a situation when the reservoir pressure tends to zero. The above statement, especially dependence (8) which results from the preceding ones, holds true for normal pressure gradients. Then the gradient of source rock pressure is given with the following equation (9).

$$\left(\frac{\sigma}{h}\right)_n = \frac{S}{h} - \left(\frac{p}{h}\right)_n \quad (9)$$

where:

$\left(\frac{\sigma}{h}\right)_n$ – gradient of source rock pressure in normal conditions [MPa/m],

$\left(\frac{p}{h}\right)_n$ – gradient of pore pressure in normal conditions [MPa/m].

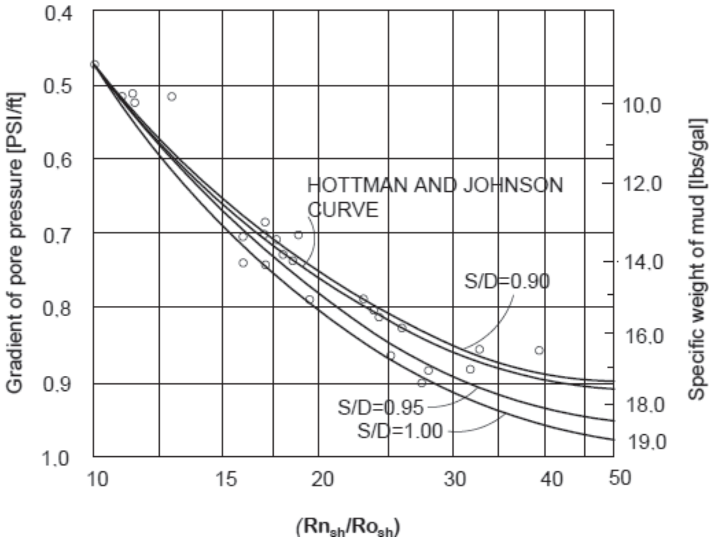


**Fig. 2.** Shale resistivity parameter vs reservoir fluid pressure gradient [2]

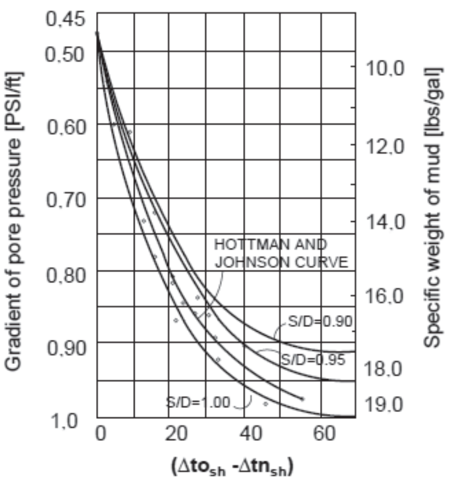


**Fig. 3.** Shale acoustic parameter vs reservoir fluid pressure gradient

In anomalous conditions the gradient of source rock pressure will be approximated with equation (10):

$$\left(\frac{\sigma}{h}\right)_{an}=0,0121\left[\frac{Ro_{sh}}{Rn_{sh}}\right]^{1.5} \tag{10}$$

where $\left(\frac{\sigma}{h}\right)_{an}$ – gradient of source rock pressure in abnormal conditions [MPa/m].

In reality the constant in equation (10) is a gradient of pressure of source rock skeleton if the overburden pressure gradient $\frac{s}{h}=0.0226$ MPa/m, and pore pressure gradient $\frac{p}{h}=0.0105$ MPa/m. If the right side of equation (9) is substituted to equation (10), thus substituting the constant 0.0121, then we obtain an equation for the gradient of pore pressure for a given area. Pore pressure can be estimated with the use of equations (5) and (11). By transforming equation (5) in view of the gradient of source rocks pressure, σ/h and substituting it to equation (11), we have equation (12).

$$\left(\frac{\sigma}{h}\right)_{an}=\left[\frac{S}{h}-\left(\frac{p}{h}\right)_{n}\right]\cdot\left(\frac{Ro_{sh}}{Rn_{sh}}\right)^{1.5} \tag{11}$$

$$\left(\frac{p}{h}\right)=\frac{S}{h}-\left[\frac{S}{h}-\left(\frac{p}{h}\right)_{n}\right]\cdot\left(\frac{Ro_{sh}}{Rn_{sh}}\right)^{1.5} \tag{12}$$

The source rock pressure will be ignored in the case of abnormal pressure conditions. This can be proved by the Ro/Rn ratio. If its value is lower than unity, we have to do with abnormal pressure conditions. If $\left(\frac{Ro_{sh}}{Rn_{sh}}\right)^{1.5}$ is multiplied by normal pressure $\left[\frac{S}{h}-\left(\frac{p}{h}\right)_{n}\right]$, we will obtain abnormal pressure of the source rock, which will be lower than the normal pressure.

The prediction of rock mass pressures in the place of the planned drilling jobs makes the work of designers of particular drilling operation so much easier. Knowing the pressure (even if it is predicted) at an early stage of designing we can considerably lower the cost of realization of the entire project by accelerating works, early designing of the casing, selecting rheological parameters of muds and designing the downhole part of the string. Below we have a distribution of resistivity coefficient $\left(\frac{Ro_{sh}}{Rn_{sh}}\right)^{1.5}$ with depth. It greatly depends on the type of rocks to be drilled at the analyzed depth of the wellbore. Data used for illustrating this dependence are scarce. It was not possible to use the well logs to determine the dependence for the entire wellbore profile. Nonetheless, with high quality seismic data it can be basically used for predicting the distribution of pore pressures at great depths in the analyzed well (Fig. 4).

For the sake of comparison the prediction method based on well log results was juxtaposed with the analysis of the rocks compaction trends in the Gulf of Mexico area. The analysis was performed on the basis of well logs conducted in boreholes located on an oilfield (Lankahuasa field). Resistivity plots estimated on gamma–gamma logs are presented in Figure 5. The lines of resistivity trend are indicative of abnormal pressure zones under a depth of 2000 m.

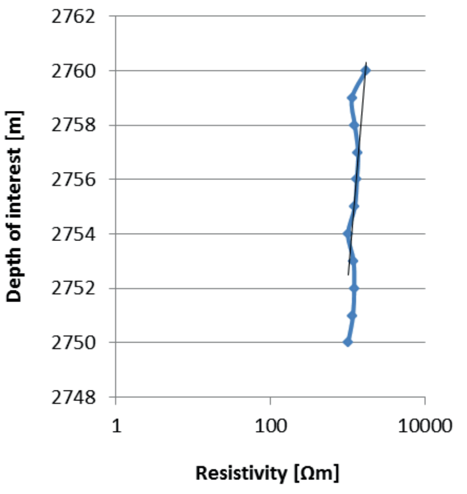


**Fig. 4.** Exemplary averaging of resistivity well measurements

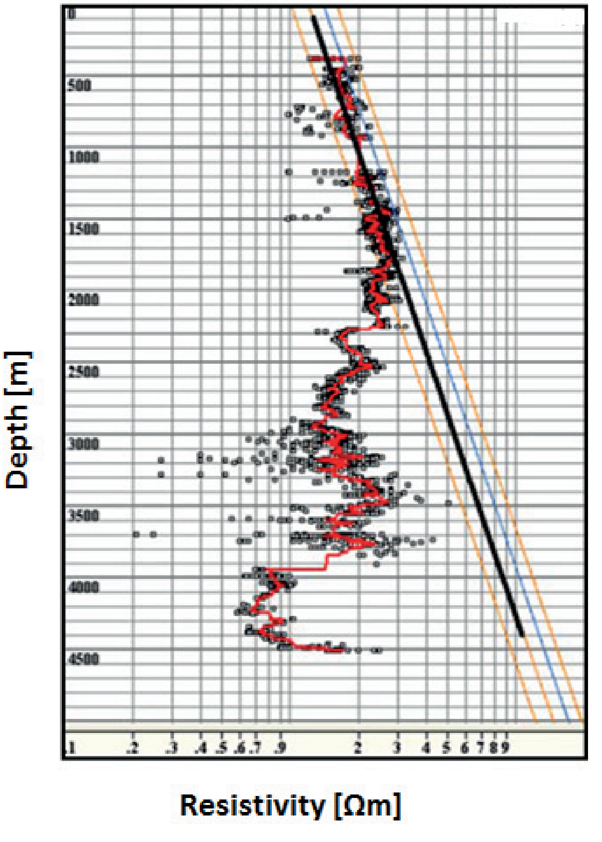


**Fig. 5.** Change of resistivity with depth for wells drilled in the Gulf of Mexico – Lankahuasa field [3]

## 4. ANALYSIS OF SEISMIC WELL LOGS AND WELL DATA FROM TWO WELLS IN POLAND

Numerous data referred to in the previous sections can be used for making detailed analyses. In our case they will be used for predicting pore pressure and other reservoir parameters in the analyzed area. Our data came from two wells: P1 and P2. This section is devoted to the procedure of predicting pore pressure on the basis of well data in one of the wells, and seismic well logs in the other. Both wells are located in the same geological unit, therefore any error or mistake can be excluded, and proofs of the statements already presented in this paper provided. The dependence of bulk density on the effective porosity of rocks in P2 well is presented in Figure 6. It should be noted that the increase of porosity results in a drop of bulk density and its decrease causes higher bulk density. Bulk density was determined on the basis of gamma–gamma density well log. This method lied in measuring changes of natural or artificial radioactivity, generated along the wellbore profile. Natural radioactivity of the medium changes, depending on its type. Such rocks as limestones, anhydrites, coals, dolomites or sandstones have lower radioactivity than shales. The gamma–gamma density logs are used for assessing the porosity of the rock medium. Based on the dependence between the bulk density and depth of the well on a logarithmic scale, we can infer about the porosity at a given depth. Porosity in a well can be also predicted from sonic logging or conductivity logging.

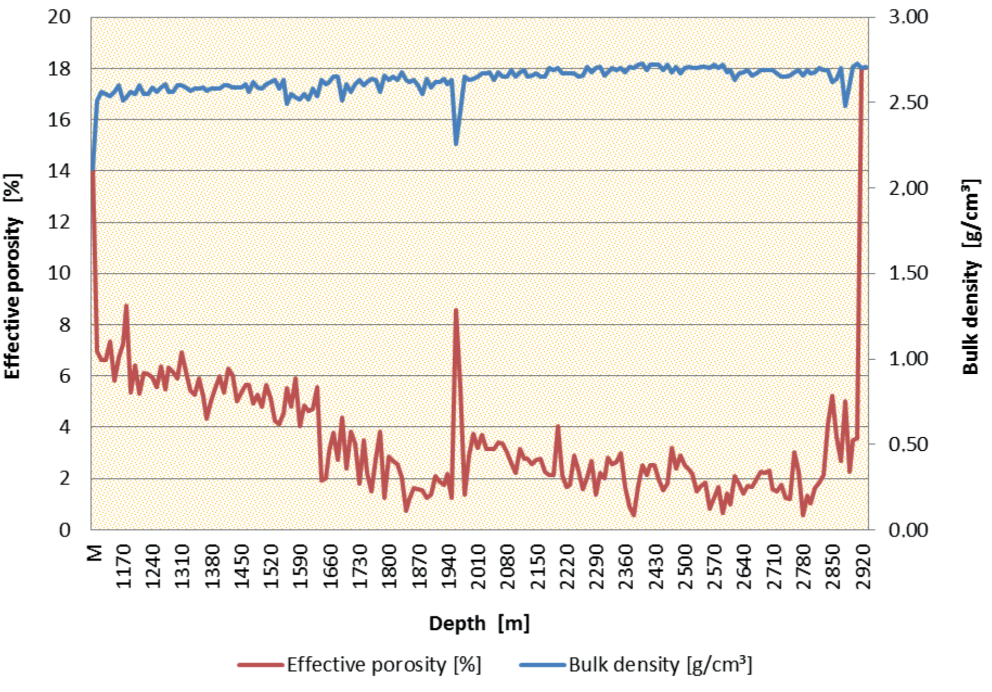


**Fig. 6.** Bulk density vs effective porosity of rocks for P2 well

The increasing resistivity of rocks should be inferred on the basis of their lower effective porosity (Figs 7–9).

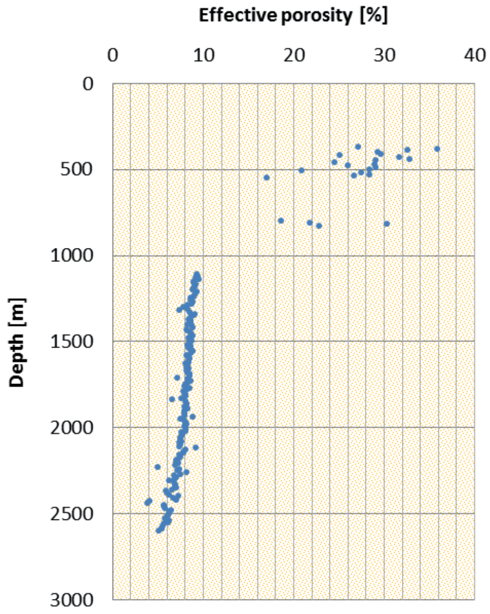


**Fig. 7.** Decreasing effective porosity in rocks with depth in P1 well

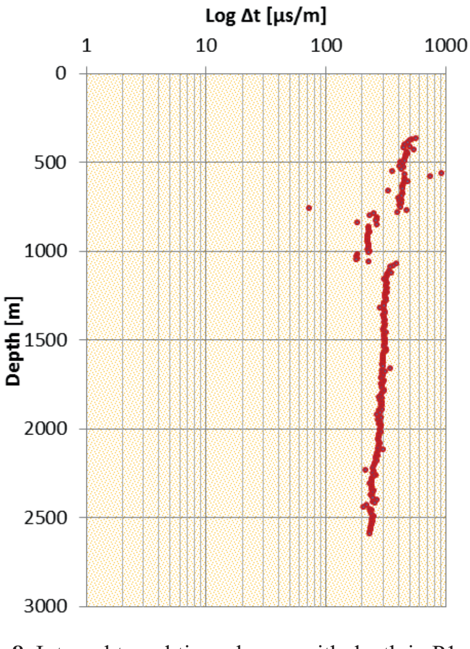


**Fig. 8.** Interval travel time change with depth in P1 well

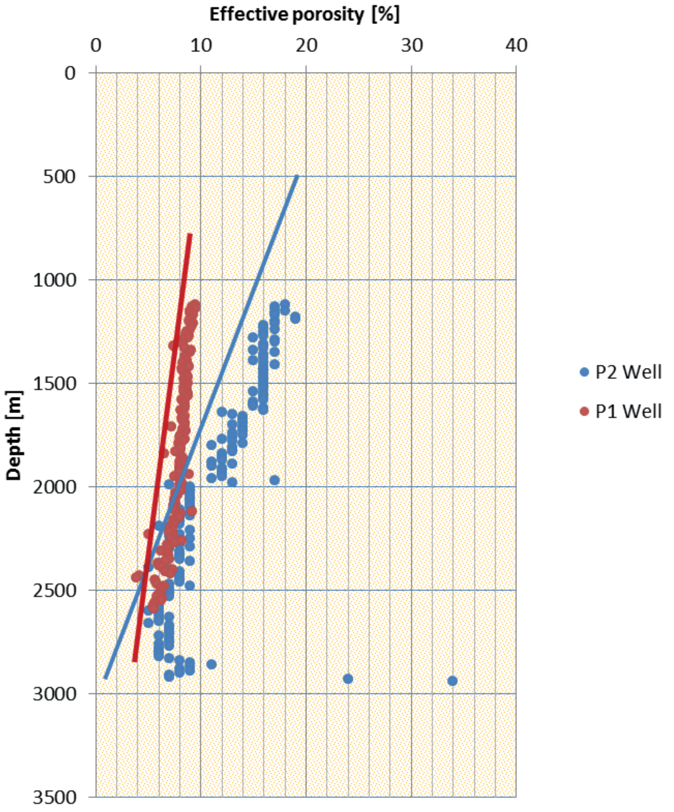


**Fig. 9.** Comparison of effective porosity of rocks in P1 and P2 wells

The interval time trend obtained in the course of sonic well logging (Fig. 8) should be obviously connected with the porosity changes in the wellbore. With the decreasing interval time and the growing depth of the well the porosity of the analyzed well also decreases.

In the following section the authors discuss a method in which the pressure gradient for a given depth can be determined on the basis of geophysical well logs and well data. Initially the dependence between the resistivity of the medium and the depth of the well has to be plotted, as in Figure 10. The data come from long- and medium-distance sonic logging time (LLD and LLS). The rock resistivity trend lines are marked in the figure. Based on the gathered experience, the pressure zones well were determined for P1.

After establishing the trend of rock compaction (in our case it was resistivity-based), the ratio $\left(\frac{Ro_{sh}}{Rn_{sh}}\right)^E$ should be calculated, where *Ro* and *Rn* are observed or recorded resistivity, and normal resistivity for a given type of rocks. The recorded resistivity values come from seismic logs, whereas normal resistivity values for a given type of rocks from the table presented below in Figure 11.

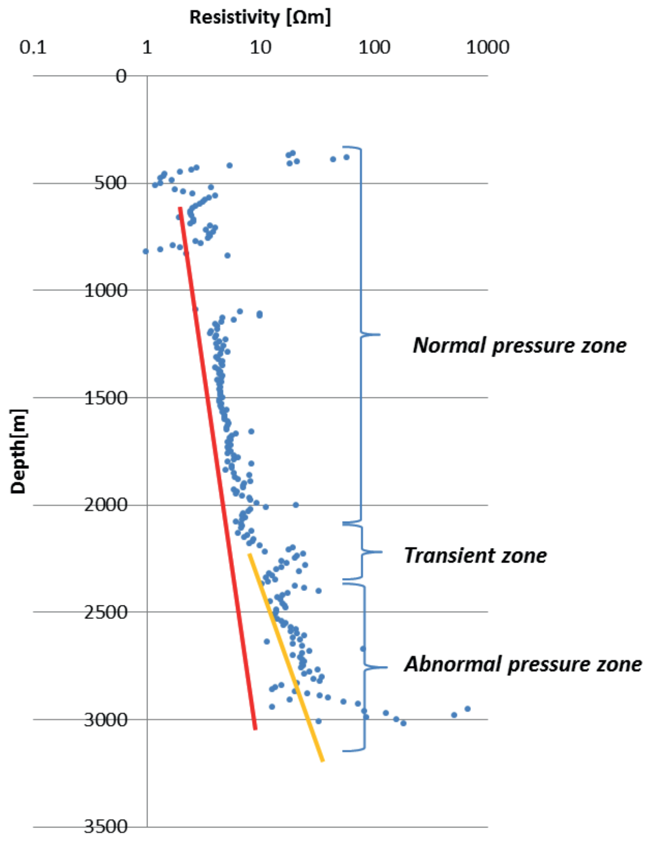


**Fig. 10.** Changes and resistivity trend lines in a function of depth of P1 well

The exponent $E$ is Eaton coefficient. In our analyses it was $E = 1.5$, but obviously it is not a constant value. It can be assumed in a broad range, e.g. Eaton B.A. in his work assumed $E \in (1.2;1.5)$. Rock layers for which normal resistivity is determined along the well profile are strictly defined in the geologic and technical well's project. Such a project preceded drilling jobs on a new well.

Then the gradient of geostatic pressure (pressure of rock overburden) should be determined with rock density logs along the well. Then the gradient of normal pressure should be established for the whole area. The gradient assumed for the analyzed geologic area equaled to 0.013 MPa/m.

With all these data we can use equation (12) to calculate the fracture pressure gradient.

In the analyzed example authors only predicted the gradient of pressure for one depth, i.e. 720 [m]. Eaton coefficient was predefined $E = 1.5$. The value of this coefficient can be assumed in the similar ranges as Eaton B.A., i.e. 1.0 to 1.5.

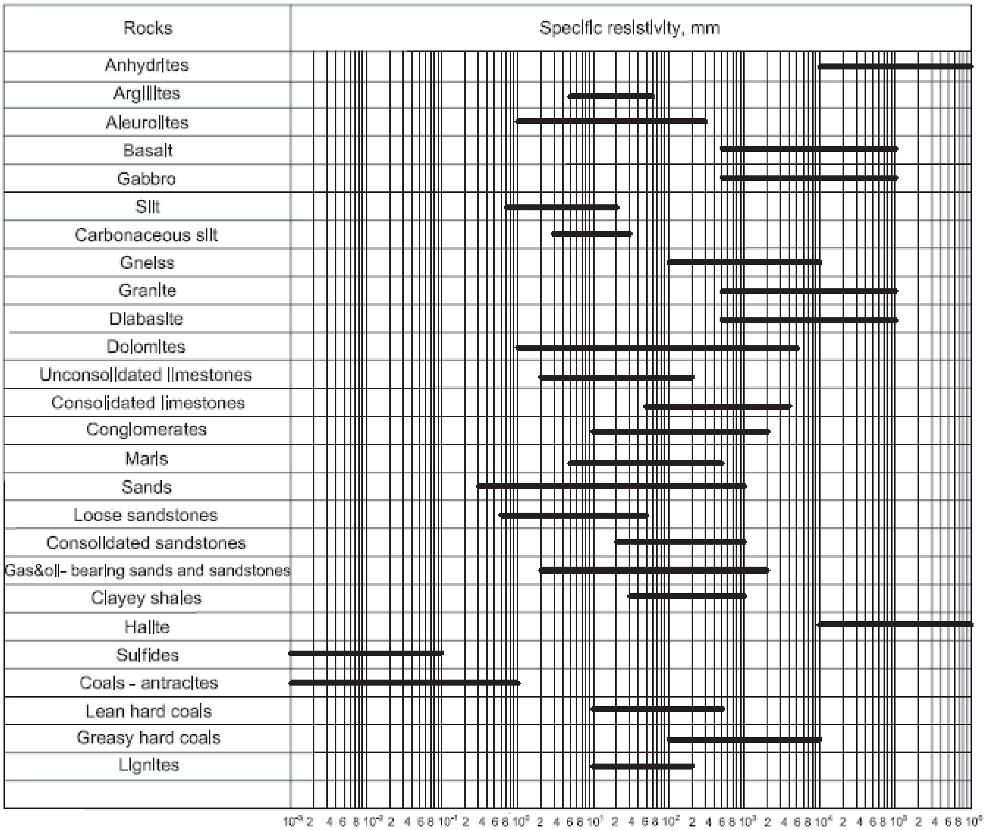


**Fig. 11.** Specific resistivity of rocks [4]

On this basis we can quite safely determine a highly approximated value of the predicted pressure, assuming and applying this value in our calculations:

$$\left(\frac{p}{h}\right) = \frac{S}{h} - \left[\frac{S}{h} - \left(\frac{p}{h}\right)_n\right] \cdot \left(\frac{Ro_{sh}}{Rn_{sh}}\right)^{1.5}$$

$$\left(\frac{p}{h}\right) = 0.023 - [0.023 - 0.013] \cdot 1.015$$

$$\left(\frac{p}{h}\right) = 0.012\ [\text{MPa/m}]$$

By comparing the obtained value of pressure gradient in P1 well with pressure values measured during well tests, while drilling P2 well one can safely conclude that the pressure prediction methods described in this paper are good pressure indicators for new projects and wells performed in similar geologic units.

## 5. CONCLUDING REMARKS

Bearing in mind the growing demand for optimized drilling works, especially the cost of performing particular wells, specialists should search for solutions which can significantly help us reach this aim. Obviously the cost of the entire drilling process should be optimized as well.

The earliest attempts at predicting pressure of the rock mass were undertaken in the 1940–1950s. The described methods are easy and very practicable, provided we have well data and high quality seismic data along the wellbore profile. With the well adapted data all the questions posed in the Introduction can be answered and the obtained information will be very useful while planning deepening operations on the existing well or performing new ones within the same geologic units.

It should be remembered that the accuracy of the predicted pressure with the presented methods largely depends on the available data, therefore it is not a good idea to focus on data from one logging. All data referring to the analyzed geologic unit should undergo a complex analysis. Only after making such an analysis one can infer on the probable correctness of the predicted pressure.

## REFERENCES


[1] Ben E.L.: *Abnormal pressures in hydrocarbon environments*. AAPG Memoir, vol. 70, 1994.

[2] Eaton B.A.: *The equation for geopressure prediction from well logs*. SPE 5544, 1975.

[3] Lopez-Solis V., Velazquez-Cruz D.: *Normal resistivity trends for geopressure analysis in Mexican offshore wells*. Offshore Technology Conferrence, Houston, May 2006.

[4] Plewa S.: *Geofizyka wiertnicza*. Wydawnictwo Śląsk, Katowice 1972.

[5] Ransom R.C.: *A method for calculating pore pressures form well logs*. The Log Analyst, Unocal Corporation, Brea, California, March–April 1986.

[6] Rubey W.W., King Hubbert M.: *Role of fluid pressure in mechanics of overthrust faulting*. Bulletin of the Geological Society of America, February 1959.

[7] Terzaghi K., Peck R.B.: *Soil mechanics in engineering practice*. John Willey & Sons Inc., New York 1948.