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NUCLEAR MAGNETIC RESONANCE (NMR) AND MERCURY POROSIMETRY MEASUREMENTS FOR PERMEABILITY DETERMINATION

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Abstract: Permeability, the most important reservoir property of rock can be directly measured on samples and determined using various statistical relationships between petrophysical parameters. We tested usefulness of Swanson parameter obtained from the mercury porosimetry results and T2 relaxation time from the Nuclear Magnetic Resonance (NMR) to find adequate formulas to improve permeability determination. We used the Devonian carbonates and the Carboniferous mudstones from the Western Carpathians and the Rotliegend sandstones from the Foresudetic Monocline in Poland. New factors as Swanson parameter or T2 relaxation time in NMR are effective in creating empirical relations describing reservoir parameters of rocks. Precision of measurements and features of rock decide about quality of the relations and their effectiveness.

Key words: permeability, nuclear magnetic resonance, NMR, mercury porosimetry

1. Introduction

Permeability belongs to a group of rock properties which are very difficult to determine. It can be directly, precisely measured in labs with permeameters or calculated on the basis of effective porosity or dynamic porosity (FFI) and irreducible water saturation including other parameters like: specific surface, tortuosity of porous channels, radii and shapes of pores, and viscosity of porous media.

Petrophysicists and log analysts can find many positions in the literature dealing with permeability determination. We want to point out papers of Kozeny (1927) and Carman (1937), Timur (1968), Coates & Dumanoir (1974), Coates et al. (1999) and Zawisza (1993) and the last paper from 2008 by Xiao et al. The common element of all these works is searching for adequate quantities and parametrization of them for getting the best correlation between permeability and other properties easy to be measured.

In the presented paper T2 relaxation times recorded at NMR lab measurements were combined with Swanson parameter (Swanson, 1981, Glover et al., 2005) defined on the basis of mercury porosimetry results in shaly sandstones, mudstones and carbonate formations.

2. Methods

Porosimetry results are presented among others like plots of cumulative intrusion of mercury on the horizontal axis in linear scale vs. pressure on the vertical axis in logarithmic scale. Regression line between the mentioned mercury porosimetry data in two-logarithmic scale plot is a hyperbole. At the point of inflexion of the hyperbole Swanson parameter is defined (Xiao et al., 2008) as a ratio of pressure to volume of intruded mercury. It well correlates to factor describing hydraulic ability of rock formation, i.e. square root of ratio of permeability and porosity, named here perm/poro factor. This factor is well related with Fluid Zone Index, FZI, used by various authors as a good tool for dividing rock formation to units of similar hydraulic ability (Amaefule et al., 1993, Prasad, 2000, Bała and Jarzyna, 2004, Jarzyna and Ha Quang Man, 2009). Swanson parameter also well correlates to geometric mean of T2 relaxation time (Xiao et al., 2008). T2 relaxation time belongs to standard results of NMR measurements both in lab and well-logging investigations, so we present the method of scaling permeability measurements with NMR outcomes.

Three methods - mercury porosimetry measurements and FZI calculation and NMR measurement are based on movement of water or hydrocarbons in porous space. Mentioned methods have various physical phenomena as the basis but all of them provide porosity (effective or dynamic – FFI) related to absolute permeability.

3. Data for analyses

In the research rock samples form the Western Carpathians (R3, L7, J2k wells, Poland) and from the Wolsztyn Ridge, Foresudetic Monocline, (CG5 well, Poland) were used (Fig. 1).

Fig. 1. Location map of regions of investigation against the background of map of Poland

The Carpathian samples, numbers 7861-65, from the Ja2k well belong to the Upper Carboniferous profile from the interval 3464-3469 m. Hard mudstones, hard sandstones with silica binder and shaly mudstones and sandstones laminated with mudstones are present in this interval. Carbonates and coal debris happen in the examined samples. The group of 7876-80 samples from the R3 well contains rocks of the Upper and Middle Devonian from the interval 1300-1309 m. They are dolomitic, organogenic reef-type limestones. Near the bottom dolomitic limestones change into limy dolomites. In the upper and middle parts of the examined depth interval numerous cracks and fractures occur. Wide and passable fractures prevail. On the basis of horizontal and vertical cracks and stylolithic sutures caverns are developed. In the L7 well samples come from the interval 2826-2839 m. They belong to the Upper Devonian, the Frasnian. They are hard limestones, locally with clay material encrustations, with singular cracks, usually filled with clay material. No caverns exist in the upper interval. The 7890 and 91 samples represent limestones with clay material.

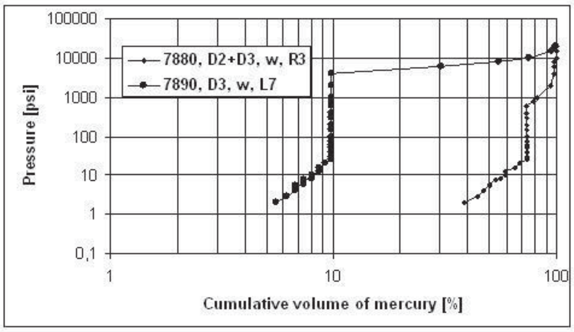
In the CG5 well the Rotliegend (P1) formation in the depth interval 2665.4 – 2797.6 m was analysed. Upper fine and medium grained sandstones with limey or limey-argillaceous cements revealed good and very good porosity. Lower conglomerate-sandstone formation consisted of sandstone, mudstone and claystone clasts and pieces of volcanic rocks. Clasts are disordered in the mudstone-sandstone mass with calcite aggregations. The conglomerate-sandstone formation is hard, of very low porosity.

Lab measurements of bulk density, matrix density, effective porosity, resistivity and permeability on the rock samples were done in Oil and Gas Institute in Cracow, Poland. T2 relaxation times of NMR were measured for all samples using Maran Ultra 23 MHz Spectrometer at AGH UST in Cracow, Poland and Maran Ultra 7 MHz Spectrometer at Oil and Gas Institute. Autopore 9220 equipment was used for porosimetry measurements.

4. Results of measurements and mutual relations between parameters

Mercury porosimetry results were presented in the template enabling Swanson parameter determination (Figs 2, 3). We observed that rocks of various lithology and different type of porous space can be distinguished due to different route of plots, but in all cases the inflection points were distinctly visible. Sample no 7880 is a carbonate (mix of limestone and dolomite) with numerous cracks and fissures. Sample no 7890 is a cracked limestone with clay material. At the same level of pressure only 9.9% of porous space is filled with mercury in sample no 7880 while as many as 73,5% in sample no 7890 (Fig. 2a). Such result shows greater ability to media flow in the sample no 7890. Tight mudstones and hard sandstones with silicon cement and clayely mudstones and sandstones with mudstone laminas in the Ja2k well reveal heterogenity. In pressure up to circa 1000 psi sample no 7861 shows lower ability to penetrate porous space than sample no 7865. Only under high pressure both of them keep similarly (Fig. 2b).

Plots of cumulative intrusion of mercury vs. pressure in the Rotliegend terrigene rocks in the CG5 well are also various (Figs 3a-3b). Each curve has its own curvature related to the type of porous space, especially to that part of pores responsible for the media flow.



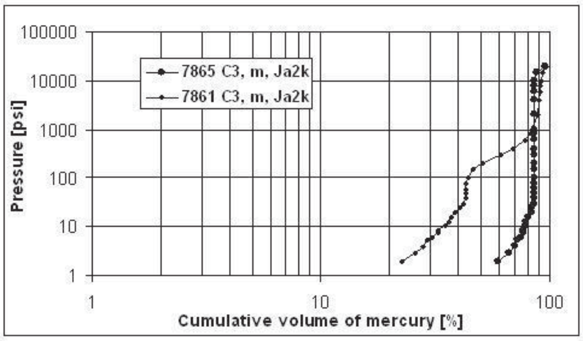
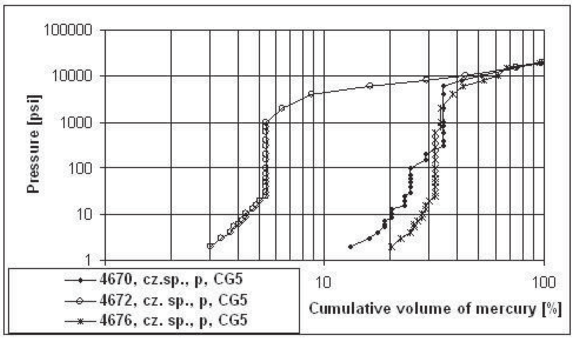


Fig. 2. (a) Pressure vs. volume of intruded mercury for the Devonian limestone samples from the R3 well and L7 well; arrows show points for readings to calculate Swanson parameter, (b) Pressure vs. volume of intruded mercury for the Upper Carboniferous mudstone and sandstone samples from the Ja2k well; arrows show points for readings to calculate Swanson parameter.

Plots of the cumulative NMR signals for the conglomerate-sandstone formation and sandstone formation completed the information from the CG5 well (Fig.4). Similar courses of the cumulative NMR curves (Fig. 4) and porosimetry plots (Figs 2-3) reveal that media flow is crucial for both methods.

T2 relaxation time distributions (Fig. 5) inform if hydrogen nuclei in the media in porous space are most free and fluids can be exploited (KP3), or they are closed in the capillary type pores (KP2) or they are included in the layered-ribboned structure of clay minerals as inter-packet water or hydroxilic groups, -OH, (KP1) (Coates et al. 1999, Klaja et al. 2008). Maxima in plots enable interpreter to make cut offs and divide the plot into parts related to hydrogen in water or hydrocarbons located in various part of rocks.

Maxima in the plot in figure 4a show that free flow media dominate in the net of cracks and fissures in the rock in the sample no 7880. In sample no 7890 water occurs as irreducible medium in porous-fractured space (maximum is located between 1ms and 10 ms). In the CG5 well for the sandstone sample no 4656 two maxima have almost the same amplitudes pointing out that the similar volume of water is closed in capillary type pores (maximum over 1 ms) and can realize free flow (maximum over 30 ms). In the plot illustrating media flow in the sample no 4652 one can observe several maxima, from which the first (about 0.5 ms) is related to water involved in the layered-ribboned structure of clay mineral (KP1), the second (about 50 ms) – to water closed in the capillary type pores (KP2) and the lasts are related to free flow media (KP3).



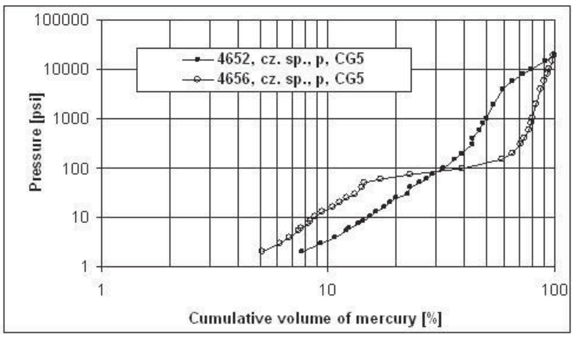


Fig. 3. (a) Pressure vs. volume of intruded mercury for the Rotliegend conglomerate – sandstone formation in the CG5 well, (b) Pressure vs. volume of intruded mercury for the Rotliegend sandstone formation in the CG5 well.

To combine the information from porosimetry and NMR measurements Swanson parameter was correlated to median of T2 relaxation time (Fig. 6). The division of T2 relaxation time distribution into parts corresponding to pore size and status of hydrogen nuclei in process of relaxation was made (Fig. 7). It is worth to point out the variability of the curvature of T2 relaxation time distribution in parts related to irreducible water (KP1), capillary water (KP2) and free water (Fig. 5a).

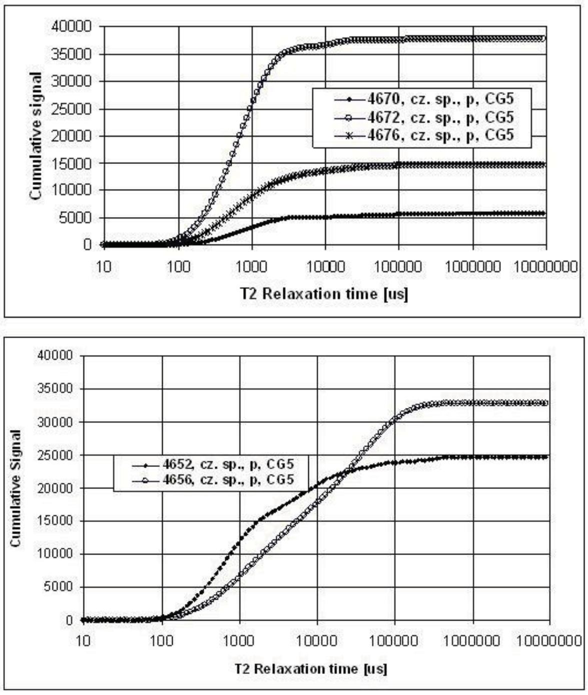


Fig. 4. (a) Cumulative NMR signals of samples from the Rotliegend conglomerate-sandstone formation in the CG5 well, (b) Cumulative NMR signals of samples from the Rotliegend sandstone formation in the CG5 well.

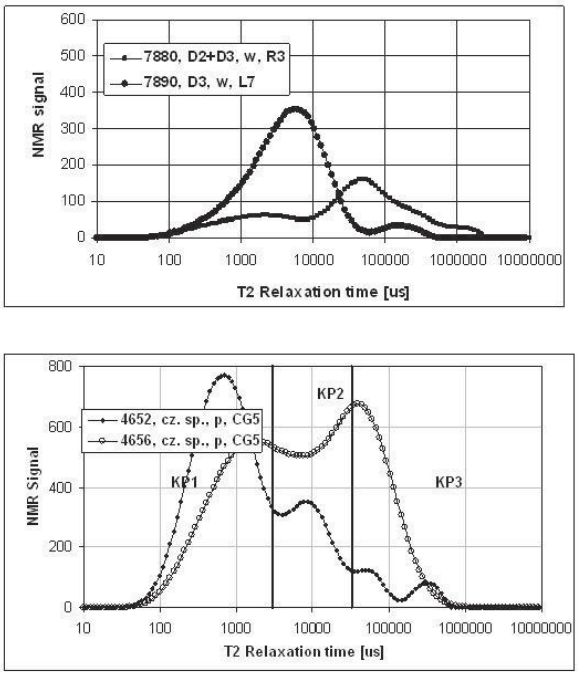


Fig. 5. (a) T2 relaxation time distributions of the Devonian limestone in the R3 well and the Ja2k well, (b) T2 relaxation time distributions of the Rotliegend sandstone formation in the CG5 well.

A special factor characterizing ability of rock for media flow was defined as a square root of permeability [mD] and porosity [%] similarly to definition of Flow Zone Index, FZI. Swanson parameter was correlated to this factor, here named perm/poro and it was a method to scale results of NMR vs. permeability (Figs 8-9). High determination coefficients between the correlated quantities show that the method can be used as routine procedure in industry practice. Both in terrigene and carbonate lithology determination coefficients can be considered as satisfactory (Figs 8-9). Thanks to the proposed methodology the expensive and destructive porosimetry investigations can be limited up the necessary minimum and exchange into non-invasive NMR measurements to provide with exact information on reservoir parameters of terrigene and carbonate rocks. Results of laboratory measurements of other parameters well correlate with reservoir parameters and complete NMR results (Fig. 10).

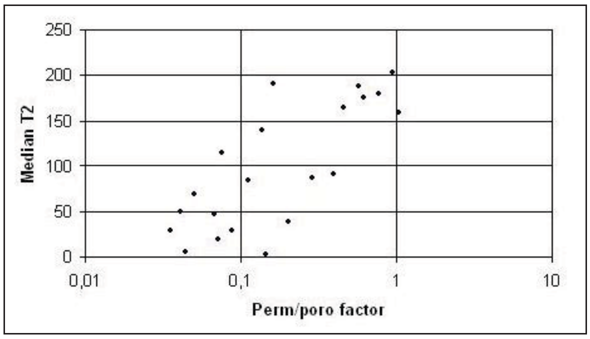


Fig.6. Median of T2 (full signal) vs. perm/poro factor; the Rotliegend sandstone samples.

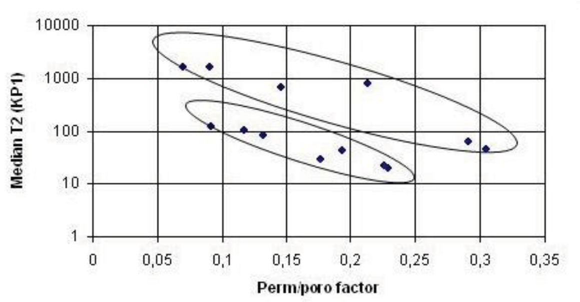


Fig. 7. Median of T2 (low time part of signal-KP1) vs. perm/poro factor; the Carpathian samples; limestone and mudstone with a system of small fissures - smaller ellipse, dolomite – greater ellipse.

5. Conclusions

Investigations of adequate relations between permeability and porosity and other quantities describing geometry and media flow of porous space are still a subject of research since the beginning of 20^{th} century. New factors as Swanson parameter or T2 relaxation time in NMR are effective in creating empirical relations describing reservoir parameters of rocks. Precision of measurements and features of rock decide about quality of the relations and their effectiveness. Further research are necessary to include influence of clay content (shaliness) and specific surface into relations describing permeability and porosity. Considerations should be lead separately for selected parts of porous space occupied by irreducible water, capillary water and free fluid flow.

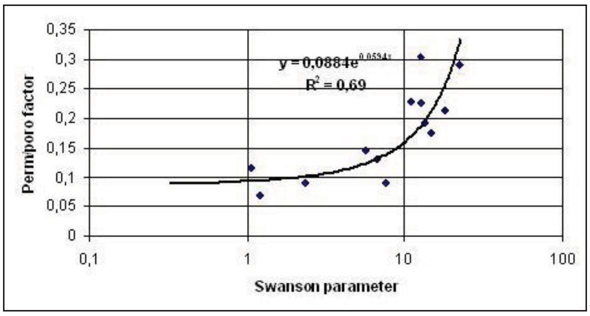


Fig. 8. Perm/poro factor vs. Swanson parameter; the Carpathian samples.

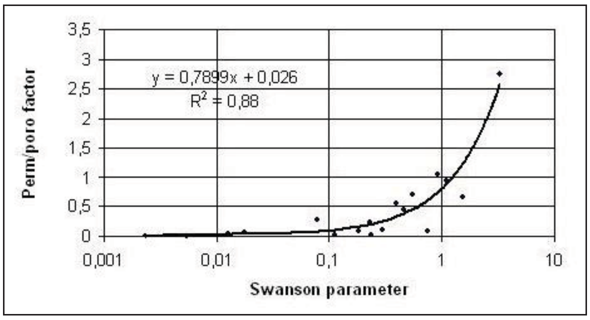


Fig. 9. Perm/poro factor vs. Swanson parameter; the Rotliegend sandstone samples.

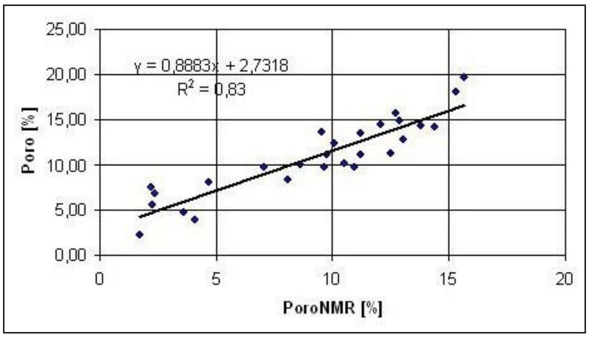


Fig. 10. Total porosity from lab measurements vs. total porosity from NMR; the Rotliegend samples.

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