Petrophysical Study of Szolnok Formation, Endrod Gas Field, Hungary

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Abstract: Investigation of rock porosity and permeability is highly beneficial for geologists, petro-physicist and petroleum engineers in order to evaluate reservoir pore space geometry through the time and space. Clastic reservoir quality and classification could perform based on the petrophysical data correlations. Study of the Szolnok formation was our target. It is composed mainly of sandstones with clay-marlstone and siltstones. Two hundred thirteen-core samples of Upper and Lower Pliocene and Miocene age were subjected for petrophysical investigations. Pore size distribution using MICP, Mercury and Helium porosity, horizontal and vertical permeability were measured for studied core samples. The Szolnok Formation has two main lithologic facies: a. 141 clean sandstone samples and b. 72 siltstone and clay-marlstone samples. Ultrasonic laboratory measurements were carried out for only 30 selected sandstone core samples. Sonic viewer-120 is used to measure sonic velocities and other mechanical properties such as rigidity, bulk modulus and Young's modulus. Gas permeability and Helium porosity were plotted versus sonic wave velocity indicates that both permeability and porosity could be outlined from either compressional or shear wave velocity. Effective pore radius is outlined from both of them. The highest sample porosity was recorded for the Miocene in age followed by the Lower Pliocene and then for the Upper Pliocene samples respectively. Miocene samples are relatively clayey free followed by Lower Pliocene samples because they have higher sonic velocity (Vp and Vs) than the Upper Pliocene samples. The Miocene and Lower Pliocene samples have relatively lower dynamic mechanical parameters than Upper Pliocene samples which represent good gas reservoirs in the Endrod field. Several regression line equations with high coefficient of correlation have been calculated to predict Szolnok reservoir parameters.

1. Introduction
The Endrod field is situated in the eastern part of the Pannonian Basin System (figure 1). This field consists of several individual deep-water fan-type rock bodies which belong to the Szolnok Formation. The developing of this formation is connected to period of the Lake Pannon existence. The Lake Pannon was the remnant of the Paratethys, which earlier separated from the Tethys Sea gradually from the Oligocene. The Pannon Basin System was formed because of the tensions caused by subduction. In the Early and Middle Miocene it had been connected with the Paleo- Mediterranean Sea and the Indo-Pacific Ocean. In the Sarmatian stage, these connections did not exist anymore and disintegration of Paratethys resulted in creation of several larger brackish lakes. One of them was the Lake Pannon. In such environment the salinity fluctuated extremely, and eventually decreased regionally when it became brackish with 8-15‰ salinity. At the same time, the uplifting of the Alps and Carpathians...
produced a great amount of sediment. According to the mineralogy of the sandstones in the Pannonian Basin System, the sources of the sediment were mainly the metamorphoses of the Western Carpathians and partly the volcanic rocks of Inner Carpathians. The sedimentary environments can be classified by the morphology of the lake. According to seismic stratigraphy view; there were three depositional paleoenvironments active in the Lake Pannon, also highly influenced by paleomorphology. Those were: (a) basin, (b) slope and (c) shelf. The basin was located in the inner parts of the lake where the slow, lacustric pelagic sedimentation was disturbed only occasionally by turbidites. On the slope, coarse grain sediment was eroded far away, and mostly claystones and siltstones were remained and lithified. The shelf and the coastal parts had been filled by lagoonal, swampy and marshy, shallow marine, littoral and river sediments.

The analyzed sediments lithostratigraphically belong to the Upper Miocene aged Szolnok Formation. It was formed >8 million years ago. It contains sediments deposited in turbidity systems which fill in the deepest parts of the basin or pelitic sediments from the calm period. Its deltaic fringe part is mainly consists of siltstones and claystones, while the channel part is made of fine sands. The maximal thickness of the Szolnok Formation is 1000 m. It is underlain by Endrod hemi-plegic marlstone and overlain by Algyő clay-marlstone silt and sandstone sediments.

Figure 1. Location map of Endrod field

The sedimentary sequences of the Pannonian basin in the great Hungarian plain were geologically and geophysically studied by a number of authors such as [1-11]. In the present work, 213 core samples have been selected from seven wells and belonging to the Szolnok Formation in order to perform special and routine core analysis such as pore throat distribution using mercury injection capillary pressure (MICP), Helium porosity, vertical and horizontal permeability, ultrasonic wave velocity and dynamic mechanical properties. The main target of this research work is to distinguish the effect of pore architecture on both acoustic and dynamic mechanical properties characterize the Szolnok reservoir rocks.

2. Methodology
There were cut 213 core samples into standard plugs of 2.5 cm diameter and 5.0 cm length for further petrophysical investigations. Laboratory measurements of both helium and mercury porosity are followed methods introduced by [12]. Horizontal and vertical permeability were conducted using Hassler type core holder and dry Nitrogen gas with pressure of 2.0 MPa. The porosity of a rock is defined as the ratio of the rock void spaces to its bulk volume, multiplied by one hundred to express it in percent. This can be expressed as:

$$\Phi = \left( \frac{V_p}{V_b} \right) \times 100$$  \hspace{1cm} (1)
where:

\( \phi = \) porosity, percent; \( V_p = \) pore volume, cc; \( V_b = \) rock bulk volume, cc

Gas Permeability is calculated using the following equation:

\[
K = c \cdot Q \cdot h_w \cdot L / 200 \cdot V_b
\]  

(2)

where:

\( K = \) gas permeability, \( \mu m^2 \); \( h_w = \) orifice manometer reading, mm; \( L = \) sample length, cm.

The capillary pressure as used in this study refers to the injection pressure necessary to inject non-wetting fluids (mercury) into the rock pore spaces. The capillary pressure was calculated using Wardlaw’s equation:

\[
P_c = 2\gamma \cos \Theta / r
\]  

(3)

where: \( \gamma \) is the surface tension of Hg (845 dynes/cm), \( \Theta \) is contact angle of mercury in air (140°) and \( r \) is radius of pore aperture for a cylindrical pore.

The mercury injection pressure is increased in a stepwise manner and the percentage of rock pore volume at each step is corrected after allowing sufficient time for equilibrium to be reached. The pressure is then plotted against the mercury saturation, while the pore throats are calculated by the equation adopted by [13]:

\[
r = 107.6 / P_c
\]  

(4)

where: \( r \) is pore throat radius, \( \mu m \)

The effective pore radius (\( R_{1.87}\mu \)) introduced by [3] has been calculated from MICP results and plotted against several reservoir parameters. Compressional (P-wave) and shear (S-wave) velocities were measured at room temperature and ambient pressure on the cylindrical samples using two channel Sonic Viewer–170, (petrophysical lab in department of Geophysics of Ain Shams University) performing fast sampling digital recording and single stacking in 16-bit memory improves the S/N ratio and widens its applicability to weak signals. The P-wave and S-wave velocities have been measured at ultrasonic frequencies of 63 and 33 KHz respectively [14]. Dynamic mechanical properties were calculated as,

\[
V_p = \left[ \frac{(k + (4/3).G)}{\rho_b} \right]^{1/2}
\]  

(5)

\[
V_s = \left[ \frac{(G/\rho_b)}{\rho_b} \right]^{1/2} = \left\{ \frac{E/\rho_b}{2(1+\nu)} \right\}^{1/2}
\]  

(6)

where: \( \rho_b = \) bulk density, gm/cc ; \( G = \) rigidity (shear) modulus of the medium, Kgf/cm²

\( K = \) bulk modulus of the medium (incompressibility), Kgf/cm²;

\( E = \) Young’s modulus, kg/cm²; \( \nu = \) Poisson’s ratio

3. Results and Discussions

3.1. Helium and Mercury Porosity

Both helium and mercury porosity were measured for the studied core samples and an attempt was made to relate them in order to outline one from the other. Figure 2, shows marl and siltstone cores with blue and green colours are of lower porosity than Sandstone samples (red colour). The Helium porosity for each core sample is usually greater than the mercury one because Helium can enter in the pores of a very small radius (0.0075\( \mu \)); however, the mercury has no access due to its large molecules. The Szolnok sandstone reservoir exhibits a dual porosity relationship as:

\[
\phi_H = 0.9228 \phi_M + 3.612
\]  

(7)

where: \( \phi_H = \) Helium porosity, fraction.
3.2. Porosity–Permeability Relationships:
Petrophysicists are interested in how porosity and permeability relate to pore throat size distribution especially in reservoir rocks.

![Figure 2. Helium versus mercury porosity relation](image)

However, exploration geologists are interested rather in using pore aperture size derived from mercury injection-capillary pressure tests to evaluate the reservoir efficiency and/or sealing capacity of cap rocks. Both Helium and Mercury porosity were measured for selected samples obtained from the Szolnok Formation and related to the sedimentary sequence of the Pannonian litho-facies. Figure 3, elucidate that porosity–permeability relation of the Upper Pliocene samples is characterized by the highest coefficient of correlation ($R^2 = 0.97$), followed by Miocene samples ($R^2 = 0.87$) and then Lower Pliocene samples ($R^2 = 0.805$) respectively. However, the highest sample porosity was recorded for the Miocene in age followed by the Lower Pliocene and then for the Upper Pliocene samples respectively. The porosity and permeability of analyzed sandstones have bimodal character indicating two main lithologic populations. The bimodality is caused by grouping rock bodies with similar electro-facies. The calculated relationships for these are:

$$\Phi_H = 0.1826 K_g^{0.2011}$$  for Miocene samples \hfill (8)

$$\Phi_H = 0.1156 K_g^{0.1526}$$  for Lower Pliocene samples \hfill (9)

$$\Phi_H = 0.081 K_g^{0.2223}$$  for Upper Pliocene samples \hfill (10)

where: $K_g =$ gas Permeability, mD.

These relationships are reliable enough to be applicable for outlining gas permeability from routine Helium porosity.
3.3. Vertical and Horizontal Permeability:
In general, the horizontal permeability in clastics has larger value than that in vertical direction for several causes such as lamination parallel to bedding plains and grain orientation. Laminas are mainly made of siltstone and claystone. There are only a few claystones and siltstones samples because the rock bodies composing the Szolnok Formation is mostly consisting of sandstones and the core recovery also is an additional reason (figure - 4). The vertical permeability versus horizontal permeability was plotted and shown in figure-5, indicates that several samples have reasonable horizontal permeability reaching up to 50 mD and their vertical permeability ranged from 0.01 up to 0.1 mD. This fact is confirming the siltstone and/or claystone laminations (figure 4) of a very minute permeability. On the other hand, there is couple of data points having a horizontal permeability of 0.01 up to 0.04 mD and their vertical permeability reaches 4.0 mD. This could be interpreted by the existing of some minor vertical fractures. The power type equation representing the relation (figure 5) is;

\[
K_v = 0.486 \ K_h^{0.8569} \quad \text{R}^2 = 0.72
\]

where: \( K_v \) = vertical permeability, mD and \( K_h \) = horizontal permeability, mD.
3.4. Porosity – Sonic Velocity
The relation between sonic velocity and rock porosity depending on several parameters such as temperature, pressure, fluid saturation and their types, mineralogy, rock digenesis, pore space framework and acoustic wave frequency. The cross-plot (figure 6) exhibits a relationship between both longitudinal velocity \((V_p)\) and Shear velocity \((V_s)\) from one side and rock porosity for some selected dry core samples obtained from Szolnok Formation and representing the Upper and Lower Pliocene and Miocene rocks. The sonic velocity increases by decreasing porosity value but the Miocene samples exhibit low clay content followed by Lower Pliocene samples because they have higher sonic velocity \((V_p \text{ and } V_s)\) than the Upper Pliocene samples. The obtained relations for both Pliocene and Miocene sediments are characterized by robust and reasonable coefficients of correlation \((R^2\) ranges from 0.76 up to 0.97) which prove the applicability of the obtained mathematical equations to estimate acoustic velocity from routine porosity measurements.

![Figure 5. Vertical versus Horizontal Permeability](image1)

\[
K_v = 0.486 K_h^{0.8569} \quad R^2 = 0.7243 \text{ For Sandstones}
\]

**Figure 5. Vertical versus Horizontal Permeability**

\[
V_p = 1.5311 \Phi^{-0.38} \quad R^2 = 0.834 \quad (LP)
V_s = 1.0969 \Phi^{-0.389} \quad R^2 = 0.7618 \quad (LP)
V_p = 1.1672 \Phi^{-0.494} \quad R^2 = 0.9674 \quad (UP)
V_s = 0.8303 \Phi^{-0.485} \quad R^2 = 0.9773 \quad (UP)
V_p = 0.9466 \Phi^{-0.798} \quad R^2 = 0.976 \quad (MIO)
V_s = 0.586 \Phi^{-0.874} \quad R^2 = 0.9777 \quad (MIO)
\]

**Figure 6. Porosity versus longitudinal velocity \((V_p)\) and shear velocity \((V_s)\)**
3.5. Permeability – Sonic Velocity
There is no direct relation between acoustic velocity and permeability but the constructed plots (figures 7 and 8) show high coefficients of correlation in case of longitudinal waves (R² = 0.93, 0.70 and 0.68) for Upper Pliocene, Lower Pliocene and Miocene samples respectively, while in figure 8, only the upper Pliocene samples have a high coefficient of correlation (R² = 0.8) in case of permeability-shear wave velocity.

![Figure 7. Permeability versus longitudinal velocity (Vp)](image1)

![Figure 8. Permeability versus shear wave velocity (Vs)](image2)
The reverse relationship between permeability and velocity is similar to that relation existed with porosity and therefore the permeability could be outlined from sonic logs for the Szolnok sediments in the Endrod field.

3.6. Effective Pore Radius, Porosity and Permeability
Effective pore radius in clastic sediments is defined as pore spaces which have pore radius >1.87µm [3] and it is found to be effective for reservoir fluid movements during migration and/or production. Porosity increasing by increasing of the effective pore radius (figure 9) and this relation is governed by the equation:

\[ R_{1.87} = 0.0662 \Phi^2 - 0.6037\Phi + 0.9316 \]  

with \( R^2 = 0.87 \).

The high coefficient of correlation characterizing this relation is acquired to calculate \( R_{1.87} \) from porosity for the Szolnok sandstone reservoir. Figure 10 shows the same parameter (\( R_{1.87} \)) in correlation with permeability. It exhibits similar behaviour while, data points of sample permeability >1.0 mD are represented by linear equation with high coefficient of correlation (\( R^2 = 0.688 \)). The pore radius of clay-marl of the Szolnok Formation is generally of unimodal distribution with mode value equal = 0.0175µm with frequency = 42%, while siltstone exhibits bimodal distribution of mode values = 0.025µm and 1.750µm with frequency = 24% and 10% respectively. The measured pore radius of the Szolnok sandstone facies is of bimodal distribution with mode values = 0.025µm and 3.750µm, while each of which have a frequency = 18%.

3.7. Porosity versus Dynamic Mechanical Parameters
The dynamic mechanical properties of reservoir such as rigidity (G), bulk modulus (K) and young’s modulus (E) are good tools for detection of both fluid saturation and fluid types (oil, water or gas), rock digenesis, stiffness and consolidation as well. Figure 11 shows that Miocene and Lower Pliocene samples have relatively lower dynamic mechanical parameters than Upper Pliocene samples. Therefore, it could be concluded that both of them represent good gas reservoirs in the Endrod field followed by the Upper Pliocene sediments. Each relation is characterized by a regression line equation.
Most of them have robust and high coefficient of correlation permitting calculation of the geomechanical properties of the Szolnok Formation from rock porosity. The measured rock rigidity (G) for the Szolnok sediments is found to be >1.10^4 Kgf/cm² at porosity ranged from 4.0 - 5.0 %, while at Ø > 25.0 % the rigidity was < 4.10^4 Kgf/cm² (figure 11).

4. Conclusions
1. The highest sample porosity was recorded for the Miocene in age followed by the Lower Pliocene and then for the Upper Pliocene samples respectively.
2. Several samples have reasonable horizontal permeability reaching up to 50 mD and their vertical permeability ranged from 0.01 up to 0.1 mD due to siltstone and/or claystone laminations.
3. Miocene samples show low clay content followed by the Lower Pliocene samples because both of them have higher sonic velocity (Vp and Vs) than the Upper Pliocene samples.

4. Effective pore radius R1.87µm can be estimated from either porosity or permeability data.

5. The Miocene and Lower Pliocene samples have relatively lower dynamic mechanical parameters than Upper Pliocene samples. Therefore, it represents good gas reservoirs in the Endrod field followed by the Upper Pliocene sediments.

6. Several regression line models were obtained and characterizing by a high correlation coefficient.

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