

## Research Article

# Reservoir Characteristics of Szolnok Formation, End Rod 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 petro physical data correlations. Study of the Szolnok Formation in is our target. It 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 petro physical 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 exhibit relative clay free followed by Lower Pliocene samples because they have higher sonic velocity ( $V_p$  and  $V_s$ ) 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 End rod field. Several regression line equations with high coefficient of correlation have been calculated to predict Szolnok reservoir parameters.

### Introduction

The End Rod 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 (Sari, 2013) [1]. 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 [2]. The Pannon Basin System was formed because of the tensions caused by sub-

duction. 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 [3]. In such environment the salinity fluctuated extremely, and eventually regionally decreased when it became brackish with 8-15% of 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 sedi-

ment 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 paleo environments active in the Lake Pannon, also highly influenced by paleo morphology [4]. 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 turbidities. On the slope, coarse grain sediment was eroded far away, and mostly clay stones 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 distal part mainly consists of siltstones and Clay stones, and its proximal part made of fine sands, that can be separated to channel and lobe facies. The maximal thickness of the formation is 1000 m. The Szolnok Formation is underlain by End Rod hemiplegic marlstone and overlain by Algyő clay-marlstone silt and sandstone sediments [5,6].

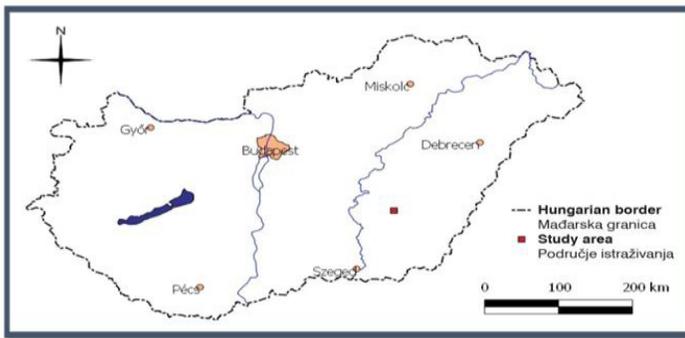


Figure 1: Location map of End Rod Field.

The sedimentary sequence of the Pannonian basin in the great Hungarian plain were geologically and Geophysical studied by a number of authors such as Ban and El Sayed, 1987; El Sayed, 1997; El Sayed and Kiss, 1997; Juhaz, 1998; Muller, 1998; Geiger et al, 2004; Thamone et al, 2006; Juhaz et al, 2006; Magyar, 2010; Uhrin, 2011, and Sari, 2013 [1-12]. 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 Szolnok reservoir rocks.

## Methodology

Two hundred - thirteen core samples were cut 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 El Sayed (1981), API (1998) and El Sayed et al, (2017) [5,13,14]. Horizontal and vertical permeability were conducted using Hassler type core holder and dry Nitrogen gas with pressure of 2.0 Mpa [15]. 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:

$$\emptyset = (V_p / V_b) .100 \quad (1)$$

Where:

$\emptyset$  = porosity, percent;  $V_p$  = pore volume, cc;  $V_b$  = rock bulk volume, cc

Gas Permeability is calculated using the following equation;

$$K = c. Q. h_w. L / 200 \quad (2)$$

Where:

$K$  = gas permeability,  $\mu\text{m}^2$ ;  $h_w$  = orifice manometer reading, mm;  $L$  = sample length, cm.

The term 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 the equation [8]

$$P_c = 2\gamma \cos \theta / r \quad (3)$$

Where:  $\gamma$  is the surface tension of Hg (845 dynes/cm),  $\theta$  is contact angle of mercury in air ( $140^\circ$ ) 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 El Sayed (1994);

$$r = 107.6 / P_c \quad (4)$$

Where:  $r$  is pore throat radius,  $\mu\text{m}$

The effective pore radius ( $R1.87\mu$ ) introduced by El Sayed and Kiss (1997) [6] has 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 widen its applicability to weak signals. The P-wave and S-wave velocities have been measured at ultrasonic frequencies of 63 and 33 KHz respectively. Dynamic mechanical properties were calculated as,

$$V_p = [(k + (4/3) \cdot G) / \rho_b]^{1/2} \quad (5)$$

$$V_s = (G/\rho_b)^{1/2} = \{E/\rho_b \cdot 1 / [2(1+\nu)]\}^{1/2} \quad (6)$$

Where:  $\rho_b$  = bulk density, gm/cc; G = rigidity (shear) modulus of the medium, Kg/cm<sup>2</sup>

K= bulk modulus of the medium (incompressibility), Kg/cm<sup>2</sup>;

E = Young's modulus, kg/cm<sup>2</sup>;  $\nu$  = Poisson's ratio

## Results and Discussions

### 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 colors are of lower porosity than Sandstone samples (red color). 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;

$$\phi_H = 0.9228 \phi_M + 3.612 \quad (7)$$

Where:  $\phi_H$  = Helium porosity, fraction.

### Porosity -Permeability Relationships

Petro physicists are interested in how porosity and permeability be relating to pore throat size distribution especially in reservoir rocks. 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. (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.

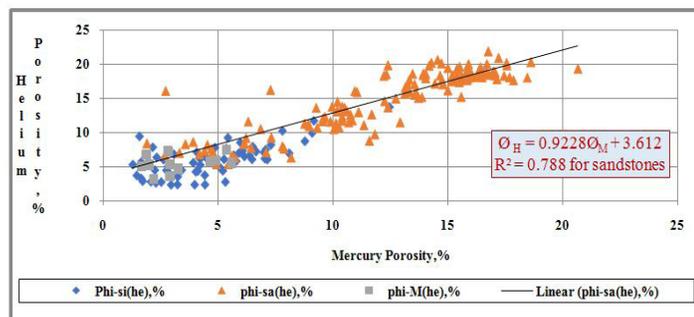


Figure 2: Helium versus Mercury Porosity Relation.

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;

$$\phi_H = 0.1826 K_g^{0.2011} \text{ for Miocene samples} \quad (8)$$

$$\phi_H = 0.1156 K_g^{0.1526} \text{ for Lower Pliocene samples} \quad (9)$$

$$\phi_H = 0.081 K_g^{0.2223} \text{ for Upper Pliocene samples} \quad (10)$$

Where:  $K_g$  = gas Permeability, m D.

These relationships are reliable enough to be applicable for outlining gas permeability from routine Helium porosity.

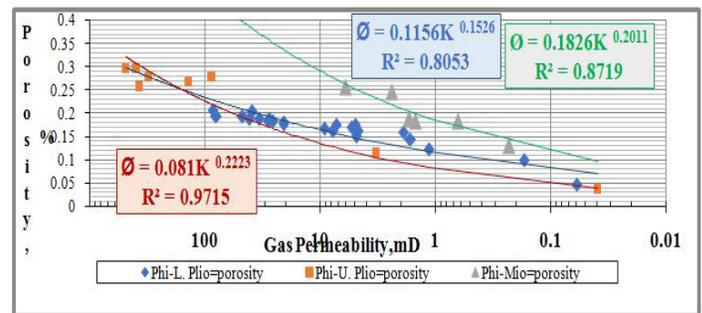


Figure 3: Helium Porosity-Gas Permeability

### Vertical and Horizontal Permeability

In general, the horizontal permeability in Clastic has larger value than that in vertical direction for several causes such as lamination parallel to bedding plains and grain orientation. Laminae are mainly made of siltstone and clay stone. There are only a few clay stones 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 (Figure4) 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.



Figure 4: Laminated Sandstone Core sample [1].

This fact is confirming the siltstone and/or clay stone 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 explained by existing of some minor vertical fractures. The power type equation representing the relation (Figure 5) is;

$$K_v = 0.486 K_h^{0.8569} \quad R^2 = 0.72 \quad (11)$$

Where:  $K_v$  = vertical permeability, mD and  $K_h$  = horizontal permeability, mD

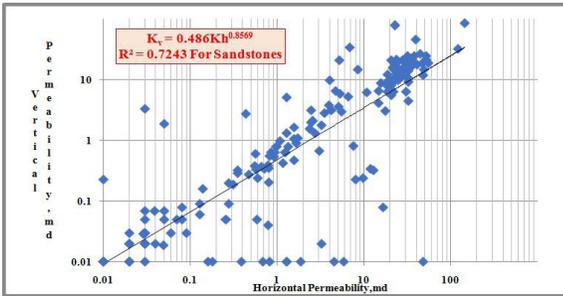


Figure 5: Vertical versus Horizontal Permeability.

### 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 diagenesis, 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 relative clay free followed by Lower Pliocene samples because they have higher sonic velocity ( $V_p$  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.

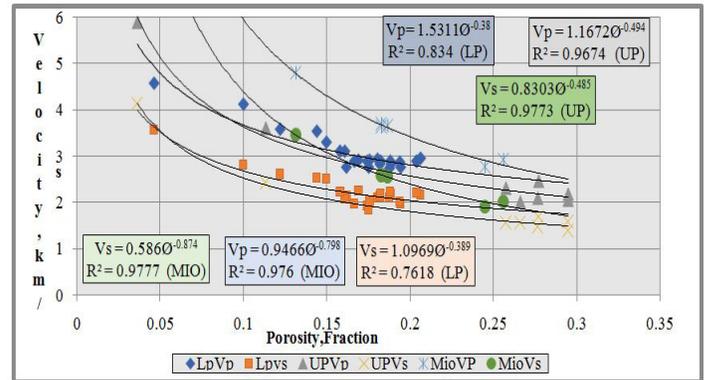


Figure 6: Porosity versus longitudinal velocity ( $V_p$ ) and shear velocity ( $V_s$ ).

### 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 ( $R^2 = 0.93$ , 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 ( $R^2 = 0.8$ ) in case of permeability-shear wave velocity. The reverse relationship between permeability and velocity is similar to that existed with porosity and then permeability could be outlined from sonic logs for Szolnok sediments in the End rod field.

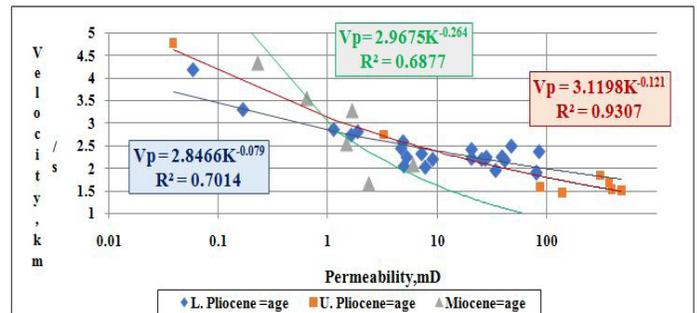


Figure 7: Permeability versus longitudinal velocity ( $V_p$ ).

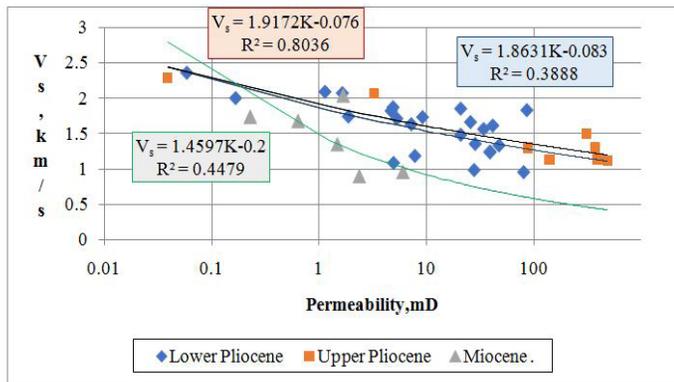


Figure 8: Permeability versus shear wave velocity (Vs).

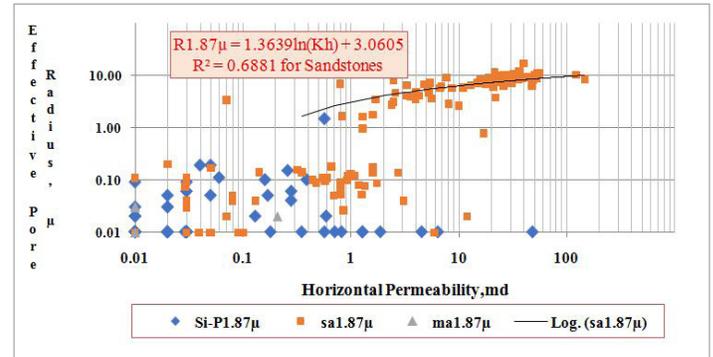


Figure 10: Permeability versus pore radius R1.87µm.

### Effective Pore Radius, Porosity and Permeability

Effective pore radius in Clastic sediments is defined as that has pore radius of  $>1.87\mu\text{m}$  [6] and it is found to be effective for reservoir fluid movements during migration and/or production. Porosity increases by increasing of effective pore radius (Figure 9) and this relation is governed by the equation

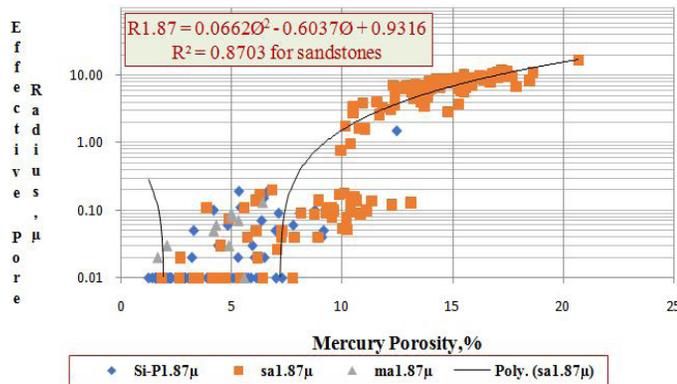


Figure 9: Porosity versus effective pore radius r1.87µm.

$$R_{1.87} = 0.0662 \text{ } \phi^2 - 0.6037\phi + 0.9316 \quad (12) \quad \text{with, } R^2 = 0.87$$

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  $>1.0\text{mD}$  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 =  $0.0175\mu\text{m}$  with frequency = 42%, while siltstone exhibits bimodal distribution of mode values =  $0.025\mu\text{m}$  and  $1.750\mu\text{m}$  with frequency = 24% and 10% respectively. The measured pore radius of the Szolnok sandstone facies is of bimodal distribution with mode values =  $0.025\mu\text{m}$  and  $3.750\mu\text{m}$ , while each of which have a frequency = 18%.

### 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 indicators utilizing for detection of 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 End Rod 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  $>14.10^4\text{kgf/cm}^2$  at porosity ranged from 4.0 -5.0 %, while at  $\phi > 25.0\%$  the rigidity was  $< 4.10^4\text{kgf/cm}^2$  (Figure 11).

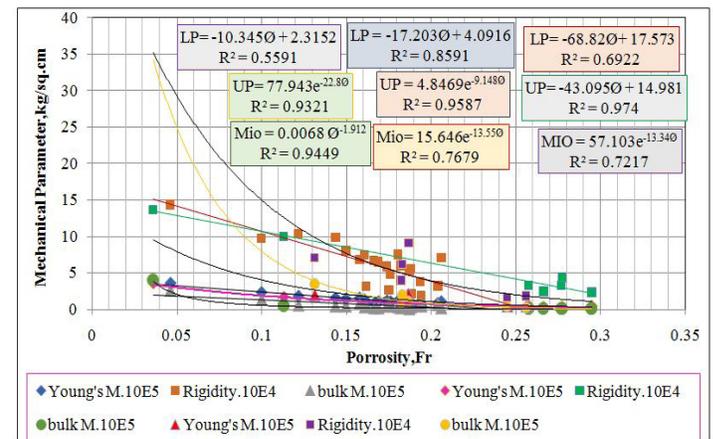


Figure 11: Porosity versus dynamic mechanical parameters.

### Conclusions

- The highest sample porosity was recorded for the Miocene in age followed by the Lower Pliocene and then for the Upper Pliocene samples respectively.

- 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 Clay stone laminations.
- Miocene samples exhibit relative clay free followed by Lower Pliocene samples because they have higher sonic velocity ( $V_p$  and  $V_s$ ) than the Upper Pliocene samples.
- Effective pore radius  $R_{1.87\mu m}$  can be estimated from either porosity or permeability data.
- The Miocene and Lower Pliocene samples have relatively lower dynamic mechanical parameters than Upper Pliocene samples. Therefore, it represents good gas reservoirs in the End Rod field followed by the Upper Pliocene sediments.
- Several regression line models were obtained characterizing by high correlation coefficient.

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