Calculation of Pore Throat Radius Percentiles (25, 50 & 75) From Porosity and/or Permeability: Algyo Oil and Gas Field, Hungary

Nahla A. El Sayed¹, Abdel Moktader A. El sayed²

¹Egyptian Petroleum Research Institute, Nasr City, Egypt
²Department of Geophysics, Ain Shams University, Cairo, Egypt

moktader@sci.asu.edu.eg

Abstract. Pore throat size distribution of reservoir rocks has a great importance in hydrocarbon migration and entrapment. It is used for study permeability barriers, reservoir characterization and stratigraphic traps. In the present study 51 core samples obtained from Algyo oil and gas field were conducted to MICP laboratory technique to study pore throat size distribution. The inclusive graphical measures of gain size analysis were borrowed for pore throat size examination. Various pore throat radius percentiles such as 25, 50 and 75 were calculated and related to both rock porosity and permeability. The obtained models were robust and reliable to use for pore throat radius percentiles (25, 50 and 75) calculation. One of these models which is predicting the 50 percentiles was verified. It shows reliable coefficients of correlation \( R^2 = 0.77 \) and 0.79 as it is estimated from permeability and porosity, respectively.

1. Introduction

The studied area is in Central Europe, in the Pannonian basin, South-East Hungary. The Algyő Field is the largest Hungarian hydrocarbon accumulation consisting of several oil and gas bearing reservoirs (Figure 1). A comprehensive description of the structural and geological setting of the field is given in [1]. The Algyő field produces from fractured Palaeozoic metamorphic, basal Pannonian conglomerate, and overlying Miocene sandstones. The upper members of these reservoirs have developed in a Pannonian delta system due to complex lateral shifting and prograding phases. They can be subdivided into slope (Algyő Formation) and delta plain (Újfalui Formation) rock bodies. The sills of the individual reservoirs were formed during the delta abandonment phases. Consequently, they can be accepted as time horizons in modelling studies. Below these series, the lower reservoirs are regarded as turbidity rock bodies (Szolnok Formation) of partly prodelta fans and partly deep basin origin [2]. Besides the evident economic importance, the rock bodies comprising the Algyő Field can be considered as an almost complete sequence of general Pannonian (s. l) basin filling accumulation [3, 4].

Here, according to the Hungarian Neogene geochronological terminology we use ‘Pannonian (s. l)’ for Late Miocene-, Pliocene sequences in the Algyő Field, the Pannon filling delta-systems (Figure 2). The most recent results have shown that self-margins reached the vicinity of the Algyő Field about 5.7 million years ago [5]. Neogene rocks of Miocene age are the principal source for oil and gas in most of the province. They are generally middle to upper Miocene shale, clay-marl, and marl. [6] indicate that potential source-rock thickness in the Hungarian part of the Pannonian Neogene Basin system ranges
from less than 1 m to 4 km, but the rocks are generally of low quality. These rocks contain mostly type-II and type-III kerogen. However, middle Miocene shale and marl locally contain the richest source rocks (TOC as high as 5.0 weight percent), and upper Miocene rocks, in particular lower Pannonian lutites, locally contain good source beds, as the Tótkomlós Formation of the Békés Basin (as much as 2 weight percent TOC, of mostly type-III kerogen). Seals are provided by associated fine-grained rocks and by overlying Tertiary sediments, such as mudstones and marls of Sarmatian and early Pannonian age, which are often overpressure.

Subdivided the Algyő -2 sedimentary section in the Algyo field into three deltaic rock genetic types based on their geological and petrophysical properties. The obtained three deltaic rock genetic types were distributary channel, barrier bar and deltaic fringe deposits. He studied the rock porosity, permeability, electrical properties, pore throat size distribution, SEM and XRD for Algyő -2 reservoir characterization. The aim of the present study is to use the porosity and/or permeability for assessing the pore throat radii 25%, 50%, and 75% usually measured through the MICP technique, which is expensive and rock sample destroying. [7]

![Figure 1. Location Map of Different Oil and Gas Fields in Hungary, After [8]](image)

2. Methodology
The gas permeability of the studied samples was measured by using the Ruska Gas permeameter. The measuring technique is outlined by [9]. Mercury porosimetry is used to approximate reservoir conditions, and allows accurate determination of the petrophysical properties of sandstones of the
Algyo-2 Formation. For the 49 sandstone core samples under investigation, the capillary pressure (Pc) is calculated using the equation (modified by [10]; from [11, 12]):

\[ P_c = \frac{2\gamma \cos \Theta}{r} \]  

(1)

where \( \gamma \) = surface tension of Hg (485 mN/m), \( \Theta \) = contact angle of mercury in air (140 °), and \( r \) = radius of pore aperture for a cylindrical pore.

Figure 2. Lithostratigraphic chart of the Pannonian Basin Neogene with the regional central Paratethyan stages, Picha, eds., The Carpathians, and their foreland: geology and hydrocarbon resources: AAPG Memoir 84, p. 619 – 632. After [1]. 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 resulting in the injection curve. These were generated by displacing the wetting phase (a partial vacuum) with the nonwetting phase (mercury) at increasing pressures. This is analogous to the drainage curve with hydrocarbon/brine system.

The water saturation was estimated as the percentage of pore spaces volume filled with mercury. On the other hand, data from the mercury injection curve is used to approximate the distribution of pore throats using the equation:
The graphical measures introduced by [13] have been employed to define pore throat size distribution curves in statistical terms. The various measures are simple to obtain in conjunction with cumulative pore throat size distribution curves. This technique [13, 14] gives a reasonable representation of the whole length of the unimodal distribution curve and may even be used for bimodal curves. Various pore throat percentiles (5%, 16%, 25%, %50, 75%,84%, 95%) are read directly from the cumulative pore throat size distribution curve [15] and substituted in the following equation to calculate the pore throat radius measures (Table 1 and 2) as:

\[
M_z = \frac{16\% + 50\% + 84\%}{3} 
\]

(3)

Where \(M_z\) = the measure of average pore throat size, \(\mu m\).

\[
6I = \left( \frac{84\% - 16\%}{4} \right) + \left( \frac{95\% - 5\%}{6.6} \right) 
\]

(4)

Where \(\sigma_i\) = stander deviation measure of the pore throat size, \(\mu m\).

\[
SK_1 = \frac{((84\% + 16\% - 2 \times 50\%))/(2 \times (84\% - 16\%)))}{2.44(75\% - 25\%)} 
\]

(5)

Where SK\(_1\) = skewness as a measure of the non-normality of the pore throat size distribution where positive values indicate that the curve has a tail in the small pores, while negative values indicate the tail in the larger pores.

\[
KG = \left( \frac{95\% - 5\%}{2.44(75\% - 25\%)} \right) 
\]

(6)

### Table 1. Measured and calculated parameters for outlining pore throat radius (50%) verification

| S. No. | Depth, m | Ot, % | \(K, \mu m^2\) | Lab. G. m, \(\mu m\) | G. m, \(\mu m\) | G.M.O.A. Error | Lab. G. m, \(\mu m\) | G. m, \(\mu m\) | G.M.K.A. Error |
|--------|----------|------|---------------|-----------------|--------------|----------------|-----------------|--------------|---------------|
| 194    | 1951.15  | 12.2 | 0.0003        | 0.03809         | 0.0558       | -0.001         | 0.038099        | 0.0908       | 0.00052       |
| 338    | 1971.84  | 28.58| 1.418         | 11.0485         | 7.8674       | 0.0318         | 11.04854        | 11.4600      | 0.00412       |
| 200    | 1931.48  | 21.6 | 0.0136        | 1.29754         | 0.9551       | 0.0034         | 1.297544        | 0.8043       | -0.0049       |
| 404    | 1916.24  | 20.87| 0.077         | 1.29754         | 0.7660       | 0.0053         | 1.297544        | 2.1672       | 0.00869       |
| 174    | 1952.9   | 22.1 | 0.007         | 1.50085         | 1.1108       | 0.0039         | 1.500854        | 0.5502       | -0.0095       |
| 174    | 1950.48  | 21.83| 0.0245        | 2.09330         | 1.0238       | 0.0106         | 2.093307        | 1.1261       | -0.0036       |
| 314    | 1925.27  | 24.8 | 0.5334        | 4.39475         | 2.5112       | 0.0188         | 4.394759        | 6.5533       | 0.02158       |
| 314    | 1925.65  | 27.24| 0.593         | 4.61325         | 5.2483       | -0.006         | 4.613252        | 6.9624       | 0.02349       |
| 6      | 1968.2   | 24.1 | 0.1821        | 4.80915         | 2.0326       | 0.0277         | 4.809157        | 3.5456       | -0.0126       |
| 6      | 1968.8   | 27.31| 0.0194        | 6.70754         | 5.3605       | 0.0134         | 6.707542        | 6.4544       | -0.0025       |
| 402    | 1927.41  | 26.59| 0.42          | 2.35509         | 4.3126       | -0.019         | 2.355093        | 5.7163       | 0.03361       |
| 402    | 1928.34  | 24.56| 0.027         | 0.93678         | 2.3536       | -0.013         | 0.936781        | 1.1904       | 0.00253       |
| 415    | 1908.12  | 26.55| 0.1095        | 3.19492         | 4.2608       | -0.010         | 3.194929        | 2.6505       | -0.0054       |
| 415    | 1913.79  | 24.48| 0.137         | 3.49619         | 2.2798       | 0.0121         | 3.496191        | 3.0128       | -0.0048       |
| 306    | 1905.03  | 28.68| 0.103         | 2.35509         | 8.1087       | -0.057         | 2.355093        | 2.5594       | 0.00204       |
| 306    | 1907.3   | 24   | 0.054         | 5.01338         | 1.9721       | 0.0304         | 5.013382        | 1.7693       | -0.0324       |

where: \(r_c (\mu m)\) is the pore throat radius and \(P_c\) is the capillary pressure (kPa).
### Table 2. Calculated parameters for outlining graphical measures of pore throat radius

| S.No. | Mz,μm | Ol,μm | Skl | KG | S.No. | Mz,μm | Ol,μm | Skl | KG |
|-------|-------|-------|-----|----|-------|-------|-------|-----|----|
| 194   | 52.19299 | 152.0903 | 0.1311 | 1.127 | 304  | 62.5 | 201.3811 | 0.172 | 1.05 |
| 338   | 124.1366 | 101.884 | 0.0609 | 1.454 | 331  | 50.765775 | 250.5204 | 0.2079 | 2.049 |
| 200   | 49.37758 | 141.1206 | 0.0905 | 0.85 | 331  | 42.393885 | 234.5553 | 0.1658 | 1.489 |
| 404   | 106.5794 | 139.7577 | 0.1105 | 1.002 | 210  | 37.94359 | 97.93715 | 0.0675 | 1.481 |
| 174   | 41.81024 | 145.4908 | 0.1084 | 0.845 | 321  | 70.316155 | 141.7087 | 0.1086 | 1.161 |
| 174   | 105.1121 | 130.0375 | 0.1093 | 1.178 | 240  | 71.297732 | 246.9002 | 0.1649 | 1.347 |
| 314   | 126.7449 | 127.4497 | 0.1089 | 1.131 | 240  | 66.523136 | 137.3568 | 0.1208 | 1.256 |

N.B.:  Ot = total porosity, %, K = Gas permeability, μm², Lab. G.M.= Laboratory measured Graphical mean of pore throat radius (50%), μm, G.M. Ø = Graphical mean calculated from porosity., G.M. K = Graphical mean calculated from permeability, G. MÖA. Er. = Absolute Error for G.M. from por., G.MKA. Er. = Absolute Error for G.M. from permeability.
3. Results and Discussions

3.1. Total Porosity Versus Pore Throat Percentiles

An attempt was made to relate total porosity to pore percentiles (Table-1) to outline which one is reliable for reservoir evaluation. Figure 3 shows that total porosity increases by increasing pore radius value measured as 25%, 50% and 75% measured on the cumulative curve of pore throat size distribution. The relationship function between each pore throat radius percentile versus porosity in reservoir storage capacity is different. Each of which is characterized by a certain coefficient of correlation value. It equals \( R^2 = 0.71, 0.79 \) and 0.78 for 25%, 50% and 75% respectively. This means that \( r_{50}\% \) is the most effective percentile in reservoir storage capacity calculation. Because of the pore throat radius measurement needs core samples, MICP of highly cost and time consuming, the obtained relation can be used to outline it from total porosity as:

\[
r_{50} = 0.006 e^{0.2352\varnothing} \tag{7}
\]

\[ R^2 = 0.79 \]

Where: \( r_{50} \) by \( \mu m; \varnothing, \% \).
Each of which is characterized by a certain coefficient of correlation value. It equals \( R^2 = 0.71 \), 0.79 and 0.78 for 25%, 50% and 75% respectively. This means that \( r_{50} \) is the most effective percentile in reservoir storage capacity calculation. Because of the pore throat radius measurement needs core samples, MICP of highly cost and time consuming, the obtained relation can be used to outline it from total porosity as:

\[
r_{50} = 0.006 e^{0.2352\phi}
\]

[\( R^2 = 0.79 \)]

Where: \( r_{50} \) by \( \mu m \); \( \phi \), %.

### 3.2. Permeability Versus Pore Throat Percentiles

Figure 4 exhibits the gas-permeability – pore throat percentiles relationships while each of which is characterized by a reliable coefficient of correlation. The highest one \( R^2 = 0.76 \) characterizes the 50% percentiles of pore throat radius. It is controlled by a regression power equation:

\[
r_{50} = 7.7082 K0.5953
\]

[\( R^2 = 0.78 \)]

Where: K by \( \mu m^2 \)

Equation (8) can be used to outline \( r_{50} \) from permeability measurements.

### 3.3. Absolute Error of \( r_{50} \):

The absolute errors of \( r_{50} \) calculated from porosity and permeability using equations (7&8) respectively (Table-1) are plotted as frequency distribution polygons (Figures 5, 6). These polygons indicated that in case of using porosity data to calculate \( r_{50} \), the absolute error of most samples (24
samples) is 0.00091µm. It is equal to 0.0089µm for the percentile r50 calculated from permeability data (23 samples).

![Graph showing Gas Permeability Vs. Pore Throat Radius Percentiles](image)

**Figure 4.** Gas-Permeability versus Pore Throat Percentiles.

![Graph showing Absolute Error of Pore Throat Percentiles](image)

**Figure 5.** Absolute Error of Pore Throat Percentiles (r50%) Calculated from Porosity.
Figure 6. Absolute Error of Pore Throat Percentiles (r50%) Calculated from Permeability.

4. Pore Throat Sorting Versus Skewness
The pore throat sorting is plotted against skewness (Figure 6) shows excellent relationship allowing the calculation of pore throat sorting from its skewness or vice versa. The equation controlling this relation is characterized by very high coefficient of correlation ($R^2 = 0.87$). (Figure 7)

$$SkI = 0.0507 e^{0.0051 \chi}$$  \hspace{1cm} (9)

Figure 7. Pore Throat Sorting Versus Skewness.

5. Conclusions
1. The pore throat radius r50 has a reliable relation with either rock porosity or permeability.
2. The percentile (r50%) can be calculated from either porosity or permeability.
3. Pore throat sorting has a very reliable relation with its skewness.
Acknowledgment
Authors wishing to acknowledge MOL Rt (Hungary) for allowing the publication of these data.

References
[1] I. Magyar, and A. Fogarasi, G. Vakarc, L. Buko, and G. C. Tari, The largest hydrocarbon field discovered to date in Hungary: Algyo, in J. Golonka and F. J.Picha, eds., The Carpathians and their foreland: geology and hydrocarbon resources: AAPG Memoir 84, p. 619 – 632, 2006.
[2] I. Revesz, Az Algyő-2 telep földtani felépítése, üledéfkőföldtani heterogenitása és ösföldrajzi viszonyai [Hydrocarbon deposits Algyő -2: geological structure, sedimentological heterogeneity and paleogeographic features – in Hungarian].– Földtani Közlöny,110, 512–539, 1980.
[3] I. Berczi, and R. L. Phillips, Process and depositional environments within Neogene deltaic-lacustrine sediments,Pannonian Basin, southeast Hungary: Geophysical Transactions, v. 31, p. 55–74, 1985.
[4] I. Berczi, Preliminary sedimentological investigation of a Neogene depression in the Great Hungarian Plain, in L. Royden and F. Horvath, eds., The Pannonian Basin: A study in basin evolution: AAPG Memoir 45, p. 107–116, 1988a.
[5] I. Magyar, A Pannon medence ösföldrajza és környezeti viszonyai a késő miocénben [Paleogeographical and paleoenvironmentological characters of the Pannonian basin in the Late Miocene – in Hungarian].– GeoLitera, Szeged, 140 p., 2010.
[6] A. Szalay, and I. Koncz, Migration and accumulation of oil and natural gas generated from Neogene source rocks in the Hungarian part of the Pannonian Basin, in A. M. Spencer, ed., Generation, accumulation and production of Europe’s hydrocarbons III: European Association of Petroleum Geoscientists Special Publication 3, p. 303–309, 1993.
[7] A.M.A. El Sayed, Intercorrelation of capillary pressure derived parameters for sandstones of the Tortel Formation, Hungary, Journal of Petroleum Science and Engineering, 10 (1993) 47-53, Elsevier Science Publishers B.V., Amsterdam, 1993.
[8] L. Dolton Gordon, Pannonian Basin Province, Central Europe (Province 4808) - Petroleum Geology, Total Petroleum Systems,and Petroleum Resource Assessment U.S. Geological Survey, Reston, Virginia: 2006.
[9] A.M.A. El-Sayed, and L. Voll. Empirical prediction of porosity and permeability in deltaic sandstones of the Tortel Formation, Hungary. Ain Shams Sci.Bull., 30: 461-487.
[10] Wardlaw, N.C., 1976. Pore geometry of carbonate rocks as revealed by pore casts and capillary pressure. AAPG Bull., 60: 245-257, 1992.
[11] E.W. Washburn, Note on a method of determining the distribution of pore sizes in a porous materials.Proc. Natl. Acad. Sci. (USA),, 7:115-116, 1921.
[12] R.R. Berg, Capillary pressure in stratigraphic traps.AAPG Bull., 59: 939-956, 1975.
[13] R.L. Folk, and W.C. Ward, Brazos river bar: A study in the significance of grain size parameters. J. Sed. Pet. Vol. 27, No. 1, PP. 3-26, 1957.
[14] M. Kashif, Y. Cao, G. Yuan, M. Asif, K. Javed, J.N. Mendez, D. Khan, and L. Miruo. Pore size distribution, their geometry and connectivity in deeply buried Paleogene Es1 sandstone reservoir, Nanpu Sag, East China. Pet Sci 16:981–1000, 2019. https://doi.org/10.1007/s12182-019-00375-3.
[15] A.M.A. El-Sayed, and A. Nahla El Sayed, Pore aperture size (r36) calculation from porosity or permeability to distinguish dry and producing wells, Arabian Journal of Geosciences. 14:866, P.1-11, 2021. https://doi.org/10.1007/s12517-021-07185-1.