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Reservoir diagnosis for the Szolnok Formation in the middle part of the Great Hungarian Plain

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The Szolnok Formation encountered in all drilled wells in the middle part of the Great Hungarian Plain is composed mainly of turbidite clastic deposits while the siltstones present are intercalated by sandstone beds and streaks of marls. For this study, 494 core samples were collected and subjected to laboratory investigations using various petrophysical techniques. The capillary pressure technique was utilized to outline pore throat size distribution, pore space volume corresponding to pore radius of different dimensions (*pvc*), and effective porosity. On the other hand, both the horizontal and the vertical permeability were measured for reservoir parameter correlation purposes and the helium porosity was also measured.

The petrophysical data obtained were handled as one population for all studied samples regardless of lithology. Moreover, each lithologic facies of the Szolnok Formation was treated separately in order to calculate reliable mathematical relations of high significance for reservoir diagnosis. A new technique was used for pore throat size measurements; this technique allows enhancement and evolution pathways of pore space characterizing the Szolnok deposits to be detected and/or predicted through different stages of reservoir sedimentation and lithification.

In the case of sandstone facies, cross-plots performed for pore throat size measurements indicated that we have two different genetic types whereas this phenomenon does not clearly appear by using either porosity or permeability data. On the other hand, both horizontal and vertical permeability give clear diagnostic features for reservoir heterogeneity in case of marls and siltstones. Both porosity and permeability versus some special sizes of pore spaces usually elucidate reservoir heterogeneity in all types of lithologic facies of the Szolnok Formation. Lithologic facies in the Szolnok Formation were distinguished and a number of reservoir parameter combinations were proved to be effective. In addition, reliable relations were obtained for reservoir effective pore radius, porosity and or permeability prediction.

Keywords: reservoirs, Szolnok Formation, porosity, permeability

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1. Introduction

The results of pore throat size distribution in combination with porosity and permeability can be used by geologists, petrophysicists, and petroleum engineers to evaluate reservoir genesis, heterogeneity, and pore space history through the time of deposition and lithification. On the other hand, based on the correlation of these data reservoir quality as well as reservoir classification can be determined. Correlation of pore throat size with either reservoir porosity or permeability is important because pore throat distribution governs all reservoir parameters. Investigation of pore space evolution is very difficult task while an understanding of its evolution paths is of great significance for outlining reservoir behaviour. Even a partial understanding of pore throat evolution and their recent distribution helps in reservoir performance and enhancement projects. The Szolnok Formation of the Great Hungarian Plain was the target of the present study; it is penetrated by a great number of drilled wells. The Great Hungarian Plain, attributable to the Late Miocene in age (Pannonian s.l.), lies in eastern part of Hungary (*Fig. 1*). It comprises

Fig. 1. Location map of the study area
1. ábra. A vizsgált terület helyzete

an area of approximately 40,000 sq. km. The term Pannonian is mainly related to sedimentary facies, which range in age from the Miocene to the Pliocene, and are distributed throughout the Pannonian basin. The structural pattern of the basement was most likely formed by the Neo-Alpine orogeny which took place during the Miocene and extended in some parts to Pliocene times.

The Pannonian basin is of large extension especially in the eastern part of Hungary; it is characterized by various sedimentary environments through time and space, while near the edges, fluvial, alluvial and deltaic facies were the most predominant. The Pannonian basin is composed mainly of a series of different sizes sub basins, therefore some formations are not of uniform thickness or may even be discontinuous. These sub basins are more or less connected to each other. The sedimentary sequence of the Pannonian basin in the Great Hungarian Plain has been studied from the geological viewpoint and stratigraphically classified by a number of authors [e.g. SZELES 1962, 1966; KÖRÖSSY 1968, 1971; MUCSI and RÉVÉSZ 1975; MAGYAR and RÉVÉSZ 1976; JÁMBOR 1980 and 1989; EL SAYED 1981; GAJDOS et al. 1983; BÉRCZI and PHILLIPS 1985; BÁN and EL SAYED 1987; RÉVÉSZ et al. 1989; and JUHÁSZ 1991 and 1994]. Periodic rapid sedimentation and huge amount of sediments occurred during Late Miocene times (Pannonian s.l., 2.4–12 Ma).

The sedimentary sequences (*Fig. 2*) developed in the Pannonian basin during late Miocene times, having characteristic depositional environments which seem to be unchanged through that long time. The lithologic associations formed in the Pannonian sub basins are almost similar to each other although they become younger in the south-eastern part of Hungary. The sedimentary sequences attributed to the Late Miocene (Pannonian s.l.) in the Great Hungarian Plain can be summarized from top to bottom as;

Bükkalja Formation: composed of lignite and brown coal beds especially in the northern part of the Great Hungarian Plain.

Zagyva Formation: mainly a thick clastic association of fluvial origin and partly of limited extent in the basin. It contains thin beds of siltstones, marls and sandstone intercalations. Thin lignite beds are frequently present. The uppermost part of the Zagyva Formation contains variegated clays and terrestrial fauna. The most likely depositional environment is alluvial plain sediments.

Törtel Formation: this is mainly composed of embedded sandstones intercalated with siltstones, marls, lignite and carbonized plant fragments. Sandstone bodies were interpreted as distributary channel, barrier and mouth

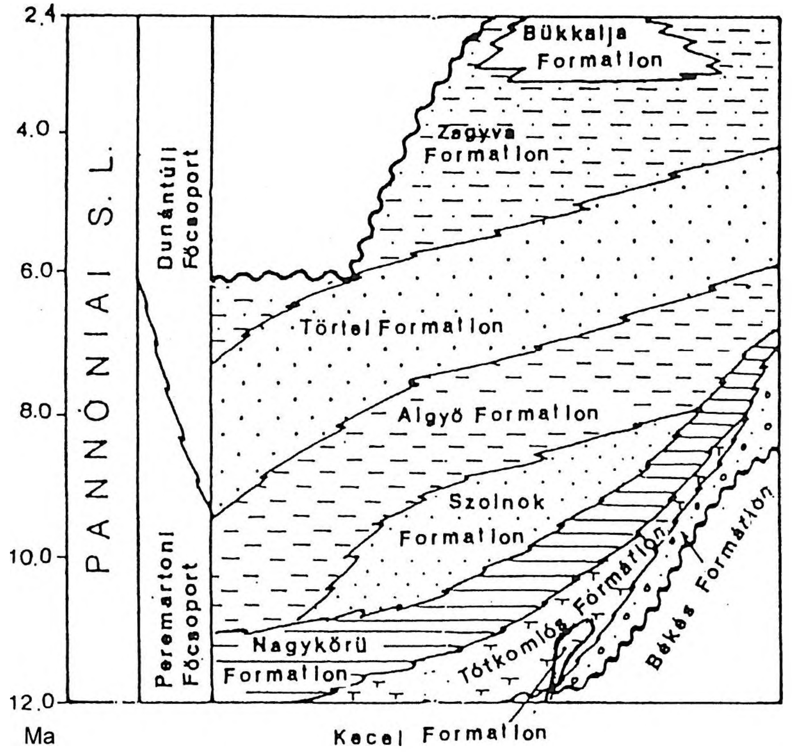


Fig. 2. Stratigraphic classification of the Pannonian s.l. [after GAJDOS et al. 1983]
2. ábra. A pannon s.l. rétegtani felosztása [GAJDOS et al. 1983 nyomán]

bars, and deltaic fringe deposits [EL SAYED 1981]. The environment of deposition of the Törtel Formation varies from shallow lake and fluvial marsh to terrestrial and fluvially dominated delta. The Törtel Formation is conformably underlain by the Algyő Formation. It is classified into five superimposed reservoir bodies, in the Algyő field, from bottom to the top as: Algyő-1, Algyő-2, Szeged-1, Szeged-2, and Szeged-3. Both the Algyő-2 reservoir sequence as well as the Törtel Formation were petrophysically studied by EL SAYED [1981, 1993 and 1994]. The previously mentioned reservoir sequences of the Törtel Formation are considered as the most important oil producing zones in the Algyő field, while their reservoir characteristics have been outlined by a number of authors, e.g. EL SAYED [1991] and EL SAYED and VOLL [1992].

Algyő Formation: mainly of argillaceous marls, siltstones and sandstone of deltaic slope and neritic environments [Juhász 1994]. It conformably overlies the Szolnok Formation especially in the deep parts of the basin.

Szolnok Formation: composed mainly of sandstone beds intercalated with marls and siltstone laminations while grain size increases downward. Direct contacts between sandstones and siltstone beds are frequently present. Coal seams, plant debris and fragments are recorded. Turbidite deposits characterizing the Szolnok Formation in the Great Hungarian plain were created in a prodelta subenvironment while the north western direction of delta system was prevailing. This formation is conformably underlain by calcareous marls of the Nagykörű Formation [Gajdos et al. 1983]. The encountered thickness of the Szolnok Formation in the Szarvas area increases with increasing depth; its minimum thickness was about 449 m [Juhász 1991]. The Szolnok Formation is underlain from place to place by two diachronous marl units (Nagykörű and Tótkomlós formations). These units are underlined by the basement.

Nagykörű Formation: this is composed mainly of argillaceous facies and gradually changes downward to calcareous marls of the Tótkomlós Formation; the coastal conglomerates are of very limited extension around the pre-existing islands and represent what is known as the Békés Formation.

The main aim of the present study is an attempt to introduce a new technique of reservoir data manipulation for diagnosing the Szolnok reservoir on the basis of pore throat, permeability and porosity measurements.

2. Methods and techniques

In natural hydrocarbon reservoirs at least two fluids are present, viz. water and oil and/or gas. If the reservoir rock was wet (with water), most grains will be surrounded by a thin film of water, whereas the oil does not usually come into contact with grains but it will be in contact with the water which surrounds the rock grains. When the rock grains are fine, they are closely packed with very small pore throats. Oil will not move in the pores until it develops a sufficient pressure to overcome capillary forces. The best method to determine effectively the minimum size of rock pore throats is the mercury injection technique [Mapstone 1973; El Sayed 1981 and 1994; Kiss 1994].

In the present study, 494 core samples obtained from the Szolnok Formation, which were encountered in some small fields in the middle part of the Great Hungarian Plain (*Fig. 3*) have been prepared (sample size of 1.0 cm diameter and 5.0 cm length). The prepared clean (hydrocarbon free)

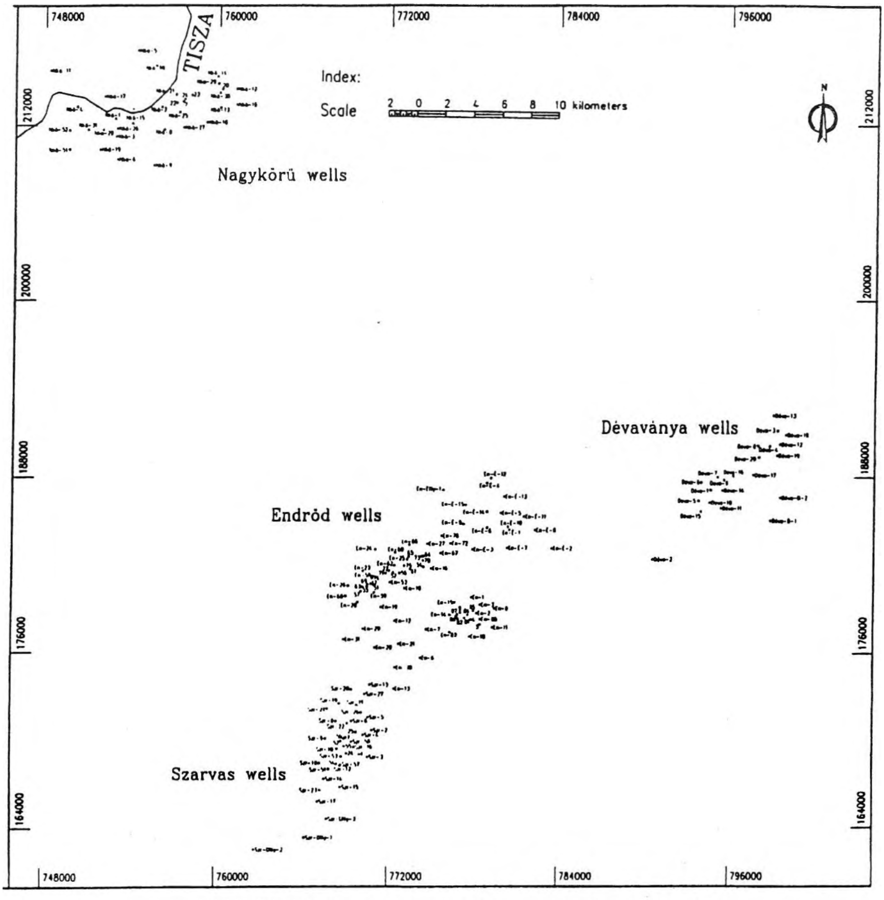


Fig. 3. Location map of the studies wells
3. ábra. A vizsgált kutak elhelyezkedése

sample is placed in a metal chamber of a Carlo Erba porosimeter (model 2000) and then evacuated. Mercury is forced into the evacuated core sample at low pressure starting with 1.0 kg/sq.cm, which is maintained until no more mercury enters the sample. The volume of mercury entering the sample at this pressure level is recorded by the pressure measuring circuit of the porosimeter. The process is repeated through a range of pressure (1.0–2000.0 kg/sq.cm) while the recorded volume of mercury injected with each pressure increment step is used to calculate directly the percentages of total pore spaces which can be saturated. The fraction of the one volume accounted for by all pore sizes between 75,000 Å and 37 Å is calculated according to the following equation:

$$Vp = (Hp_{\max} - Hp_r)/Hp_{\max} \tag{1}$$

where Hp_{max} = corrected value of mercury level displacement in mm at maximum pressure, Hp_r = corrected value of mercury level displacement in mm at the pressure step recorded.

The sample mercury porosity, in the present work, is determined according to the equation

$$\Phi = (aHp_{\max} . Q)/A.L \tag{2}$$

where Φ = porosity; fraction a = the instrument dilatometer cross-sectional area (sq.mm); Q = sample weight (g), referred to as one gram of sample; A = core sample cross-sectional area, (sq.mm); L = core sample length.

On the other hand, the sample helium porosity is determined by use of both mercury pump porosimeter for bulk volume (Vb) and the helium porosimeter with matrix cup core holder for grain volume (Vg). Hence, porosity is calculated as;

$$\Phi = 1.0 - (Vg/Vb) \tag{3}$$

The sample permeability was measured in the laboratory using a Hassler type core holder in which the sample was subjected to dry nitrogen gas at a pressure of 1378.9 kPa. The gas permeability is calculated as ;

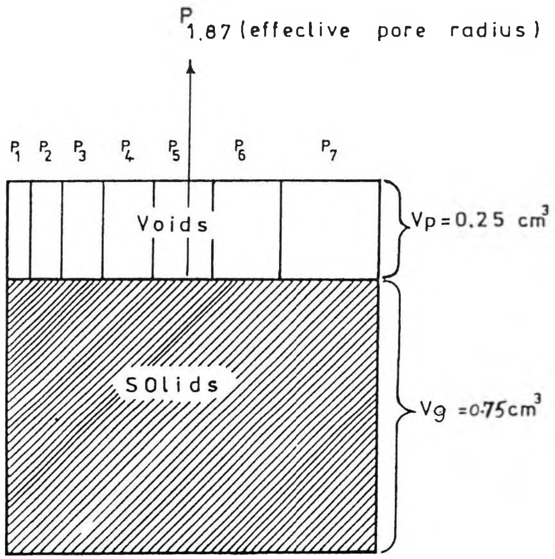
$$K = \{(C.Q.hw.L)/200.Vb\} \tag{4}$$

where: K= permeability (μm^2); C = value of mercury height (mm); Q = orifice value; hw = orifice manometer reading (mm); L = sample length (cm); Vb = sample bulk volume (cubic cm).

2.1. Suggested reservoir model

The suggested new technique for pore throat measurements is based mainly on the reservoir model shown in *Fig. 4*, the total volume of the proposed cube simulating the reservoir rock is 1.0 cubic cm and comprises:

1. grain volume (total volume of solids) = 0.75 cm^3
2. pore volume (total volume of voids) = 0.25 cm^3.



$P_1 = pvc_1$ (0.0075 μm)

$P_2 = pvc_2$ (0.01 μm)

$P_3 = pvc_3$ (0.075 μm)

$P_4 = pvc_4$ (0.25 μm)

$P_5 = pvc_5$ (0.75 μm)

$P_6 = pvc_6$ (2.5 μm)

$P_7 = pvc_7$ (7.5 μm)

$Vg = 0.75\ cm^3$ Grain Volume

$Vb = 1\ cm^3$ Bulk Volume

$Vp = 0.25\ cm^3$ Pore Volume

$$Pv = TTh(np_1 r^2 p_1 + np_2 r^2 p_2 + np_3 r^2 p_3 + np_4 r^2 p_4 + np_5 r^2 p_5 + np_6 r^2 p_6 + np_7 r^2 p_7)$$

$$\sum P_1 + P_2 = \text{Pore Volume} < pvc_2$$

$$\sum P_1 + P_2 + P_3 + P_4 = \text{Pore Volume} < pvc_4$$

Fig. 4. Suggested reservoir model

4. ábra. A javasolt tároló modell

Therefore, the rock porosity in this case should be equal to 0.25. In fact, this is the summation by product of all sizes of pore spaces present while both the number and radius of these clusters of pores are usually different. The measured pore throat size distribution data of the Szolnok Formation are classified into seven groups (from P_1 to P_7) each of which covers a subgroup of pore clusters having a small range of pore radius. The volume of voids making up a cluster of a certain pore radius can be calculated as

$$P = \Pi r^2 \cdot h \tag{5}$$

where r = average pore radius of the cluster of pore cylinders (cm), having height (h).

The volume of a pore space subgroup can be determined as;

$$pvc = \Pi r^2 \cdot n \cdot h \tag{6}$$

where pvc = volume of pore radius corresponding to a certain size of pore space subgroup (cubic cm) and n = number of pores of the same radius in the reservoir rock model. The relative pvc (%) = (pvc/Vp) . 100

Thus, the total pore volume is given by

$$Vp = \Pi h\left(r_1^2 n_1 + r_2^2 n_2 + r_3^2 n_3 + r_4^2 n_4 + r_5^2 n_5 + r_6^2 n_6 + r_7^2 n_7\right) \tag{7}$$

or

$$Vp = pvc_1 + pvc_2 + pvc_3 + pvc_4 + pvc_5 + pvc_6 + pvc_7 \tag{8}$$

where Vp = sample total pore volume, h = height of pore cylinder, all pores in this model are suggested to be of circular cylindrical shape, and n is the distribution parameter as function of pore number of each subgroup pore type. The pore radius in sandstone reservoirs usually ranges from 0.0075 μm up to at least 4.2 μm or more. The effective pore radius for hydrocarbon production is identified as 0.5 μm [Pittman 1992] while the suggested size in the present study is 1.87 μm and is known as $P_{1.87}$ [El Sayed 1991].

3. Results and discussion

All core samples under investigation were petrographically studied by the staff of MOL plc, OGIL Lab. and classified into two main groups: (a) sandstones (324 samples) and (b) siltstone and marl (170 samples). The petrophysical data including porosity, permeability, and pore throat size distribution for the above-mentioned two groups are treated as one sample population. On the other hand, each group was treated separately in order to investigate the efficiency of the suggested reservoir model (Fig. 4) to discriminate between sandstone and siltstone–marl lithologic facies. The following part is devoted to discussing the cross plots regarding the reservoir diagnostic features and validity of the suggested model.

3. 1. Helium versus mercury porosity

The cross plots (*Fig. 5a, b,* and *c*) elucidate the relationships between helium porosity and mercury porosity for sandstone (Fig. 5a), siltstone–marl facies (Fig. 5b) and all samples (Fig. 5c). In fact, the sandstone porosity (Fig. 5a) seems to start its lower limit from $\Phi H = 7.0\%$ and $\Phi M = 6.0\%$. The lowest porosity values of the sandstone facies are mainly represented by samples belonging to the Déva and Endrőd wells. The samples of Kisújszállás are characterized by higher porosity values while both porosity types (ΦH and ΦM) are more than 25%. The calculated regression line equation characterizing this relation is;

$$\Phi H = 0.999\,\Phi M + 2.326 \tag{9}$$

where ΦH = helium porosity (%), and ΦM = mercury porosity (%).

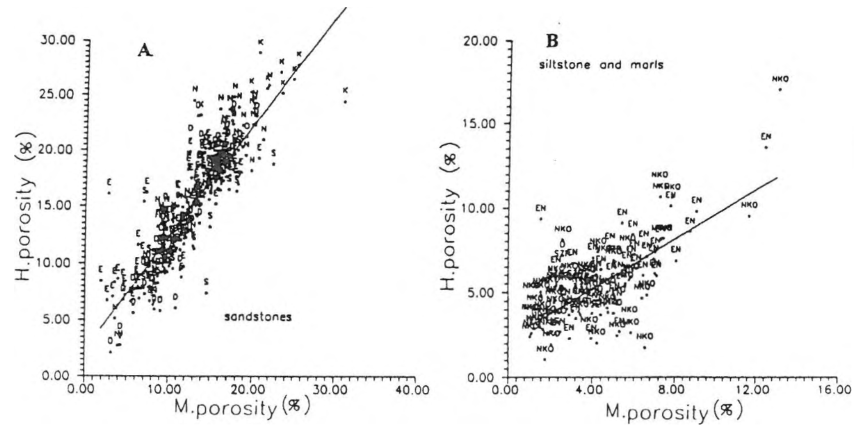
This equation is supported by a high correlation coefficient ($r = 0.9$) which enables it to be used to predict one porosity from the other. The maximum recorded porosity of the siltstone–marl facies is generally lower than 8% (Fig. 5b); most of these samples are attributed to the Nagykörű and Endrőd wells. The regression line equation recognizing this relation is

$$\Phi H = 0.74\,\Phi M + 2.26 \tag{10}$$

The relationship governing all the samples (Fig. 5c) is calculated as;

$$\Phi H = 1.054\,\Phi M + 1.54 \tag{11}$$

This equation contains a high correlation coefficient ($r = 0.9$) enabling porosity to be predicted and the costs and time of laboratory measurements to be reduced. It is worthy of mention that both of the defined siltstone and sandstone areas (Fig. 5c) could be beneficial during lithofacies studies of the Szolnok Formation.



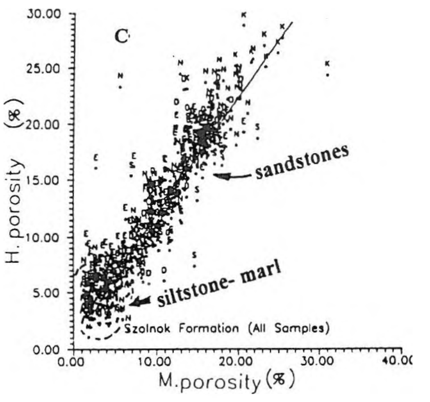


Fig. 5. Relationships between helium porosity and mercury porosity. A—sandstones; B—siltstone-marls; C—all samples

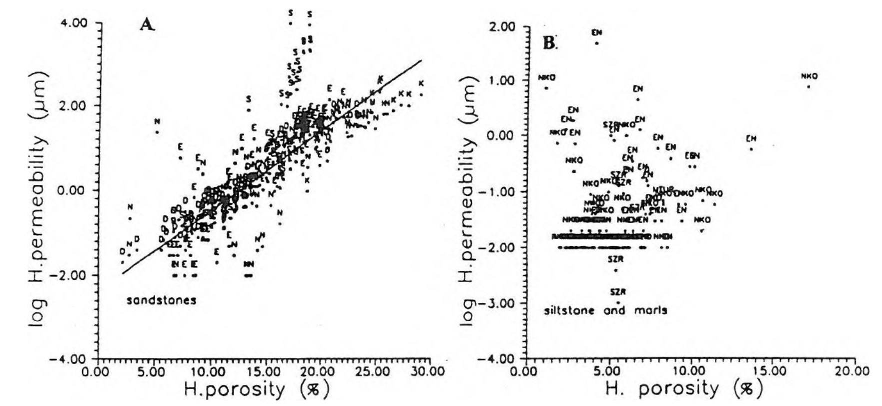
5. ábra. A hélium porozitás és a higany porozitás közötti összefüggések. A—homokkövek; B—aleurolit-márga;C—minden minta

3. 2. Porosity versus permeability

The relationships between helium porosity and horizontal permeability for sandstones, siltstone-marl facies and all samples are shown in *Figs. 6a, b*, and *c* respectively. Figure 6a exhibits a linear relation with reliable coefficient of correlation (r = 0.75), while a sandstone subtrend of abnormally high permeability is observed (*s* or *sz* symbol on graphs). The calculated regression line equation for sandstones facies is

$$\log Kh = 0.189\,\Phi H - 2.37 \qquad (12)$$

where Kh = horizontal permeability (μm^2).



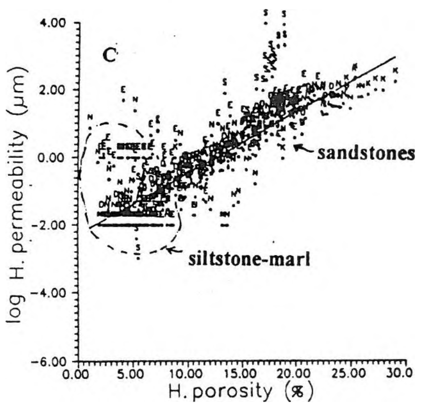


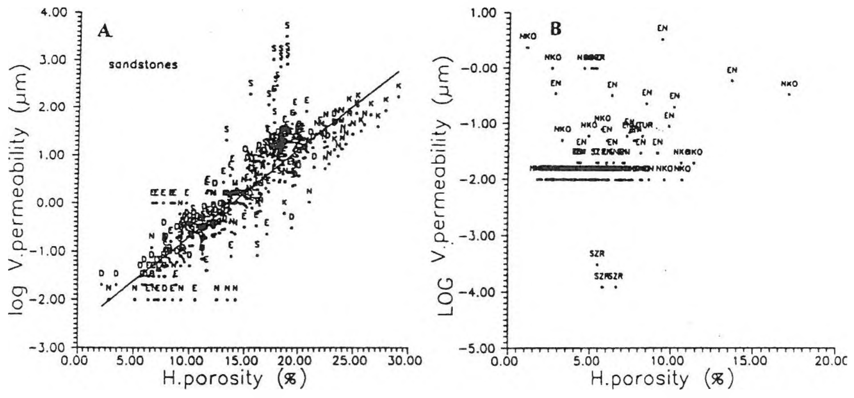
Fig. 6. Helium porosity versus horizontal permeability. A—sandstones; B—siltstone-marl; C—all samples

6. ábra. A hélium porozitás a horizontális permeabilitás függvényében. A—homokkövek; B—aleurolit-márga; C—minden minta

The relationship (Fig. 6b) representing siltstone-marl facies has mainly cloud shaped sample points indicating that permeability does not depend on sample porosity. On the other hand, Fig. 6c shows the probable partitioned areas of both sandstone and siltstone-marl facies. The regression line equation governing this relation, which is supported by a reliable coefficient of correlation ($r = 0.72$) is

$$\log Kh = 0.183\,\Phi H - 2.29 \qquad (13)$$

The helium porosity versus vertical permeability relations (*Figs. 7a, b,* and *c*) exhibit the same features — as was mentioned earlier — while the siltstone-marl area is slightly changed. The sample behaviour of abnormally high permeability which belongs to samples obtained from the Szarvas wells



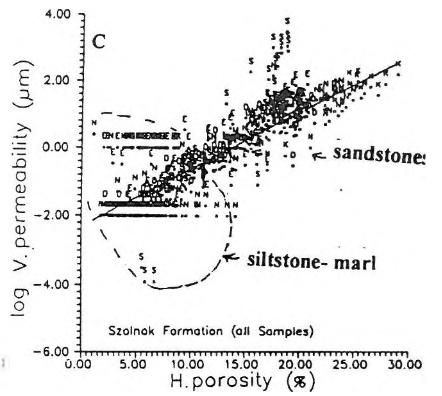


Fig. 7. Helium porosity versus vertical permeability. A—sandstones; B—siltstone-marls; C—all samples

7. ábra. A hélium porozitás a vertikális permeabilitás függvényében. A—homokkövek; B—aleurolit-márga; C—minden minta

still exists. The regression equations calculated for both sandstone facies and all samples are:

$$\log Kv = 0.183\,\Phi H - 2.54 \qquad \text{(for sandstones)} \qquad (r = 0.84) \tag{14}$$

and

$$\log Kv = 0.169\,\Phi H - 2.23 \qquad \text{(for all samples)} \qquad (r = 0.81) \tag{15}$$

where Kv = vertical permeability (μm^2).

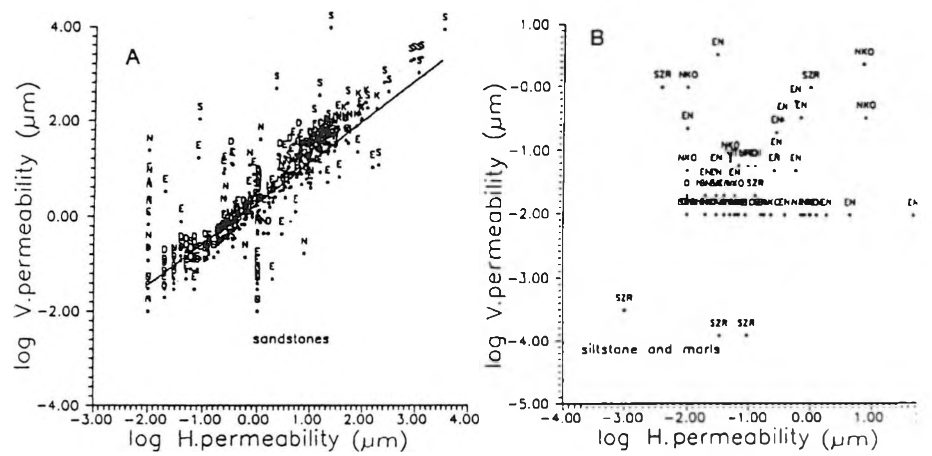
3. 3. Horizontal versus vertical permeability

Figures 8a, b, and *c* show good relations between horizontal and vertical permeability of sandstones attributed to the Szolnok Formation. The calculated formulae representing both sandstone lithologic facies and all studied samples have slightly high coefficients of correlation (r = 0.8 and 0.78) respectively, they are:

$$\log Kh = 0.862 \log Kv + 0.29 \qquad \text{(for sandstones)} \qquad (16)$$

and

$$\log Kh = 0.36 + 0.76 \log Kv + 0.073 \log Kv \qquad \text{(for all samples)} \qquad (17)$$



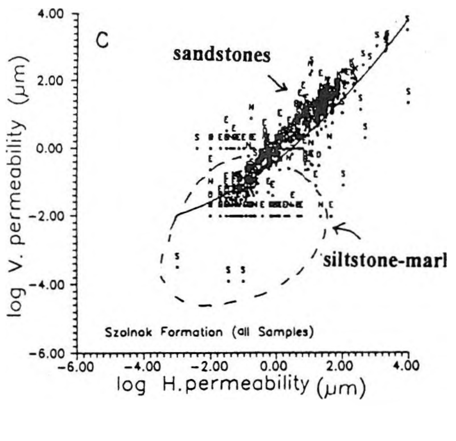


Fig. 8. Horizontal permeability versus vertical permeability. A—sandstones; B—siltstone-marls; C—all samples

8. ábra. A horizontális permeabilitás a vertikális permeabilitás függvényében. A—homokkövek; B—aleurolit-márga; C—minden minta

The correlation between sample plots in Figs. 8b and 8c allows identification of limits of siltstone-marl facies of the Szolnok Formation see Fig. 8c and this therefore facilitates allocation of areas for further reservoir studies.

3. 4. Permeability versus pvc_7

The pore volume corresponding to pore radius of 4.28 μm in size is defined in the present study (Fig. 2) as pvc_7. The permeability-pvc_7 relations (*Figs 9a, b*, and *c*) seem to be slightly effective for siltstone-marl discrimination. Some sort of sub-facies (probably silty sandstones) which may be assumed petrographically to sandstone facies have appeared and partially overlap siltstone-marl areas in some combinations (Figs. 9a , b & c). These combinations lead to some difficulties in differentiating between silty sand-

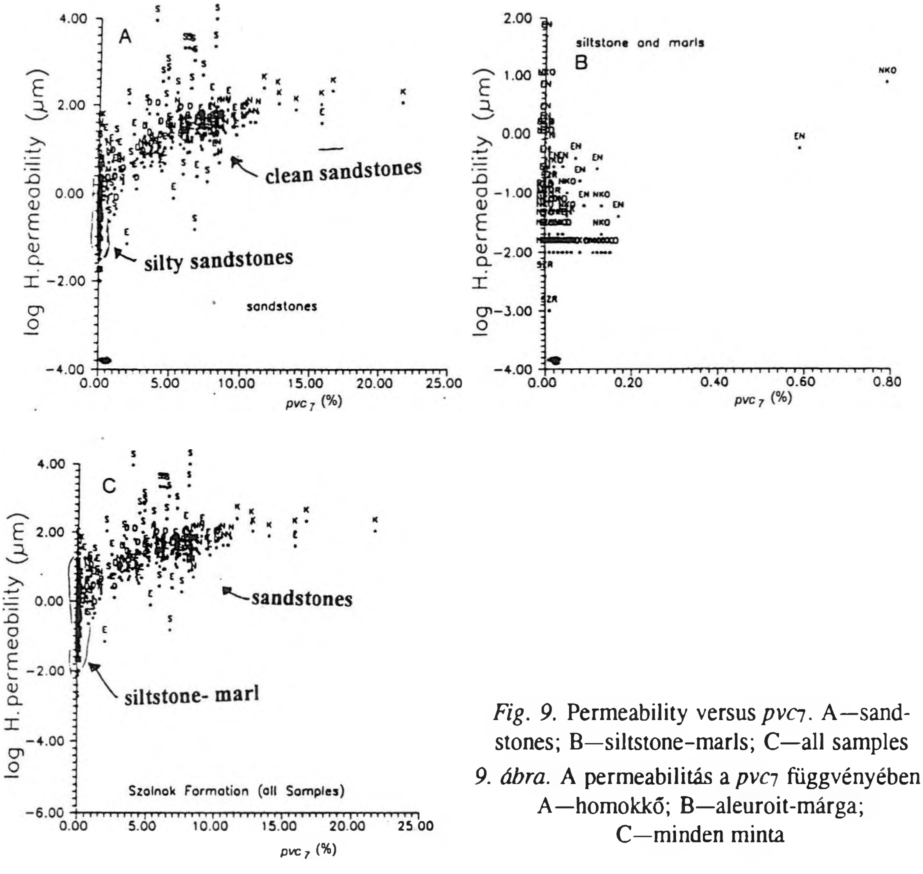


Fig. 9. Permeability versus pvc_7. A—sandstones; B—siltstone-marls; C—all samples

9. ábra. A permeabilitás a pvc_7 függvényében. A—homokkő; B—aleuroit-márga; C—minden minta stone and siltstone–marl facies in view of which either we have to look for another effective cross plot or assume both silty sandstones and siltstone–marl as one petrophysical facies (petrofacies).

3. 5. Mercury porosity versus pvc_2

pvc_2 is defined as the pore volume corresponding to pore radius of 0.01 μm. The combination of mercury porosity and pvc_2 (*Figs. 10a, b* and *c*) proves to be very effective in discriminating between clean sandstones, silty sandstones, and siltstone–marl facies. The obtained inclined V-shaped sample points distribution is a specific feature characterizing this cross-plot. The examination of Figs. 10a, b and c indicates that silty sandstone facies is more or less overlapped in some parts by siltstone–marls. In addition, it can be proved that clean sandstones have a very low pvc_2 %, while silty sandstone

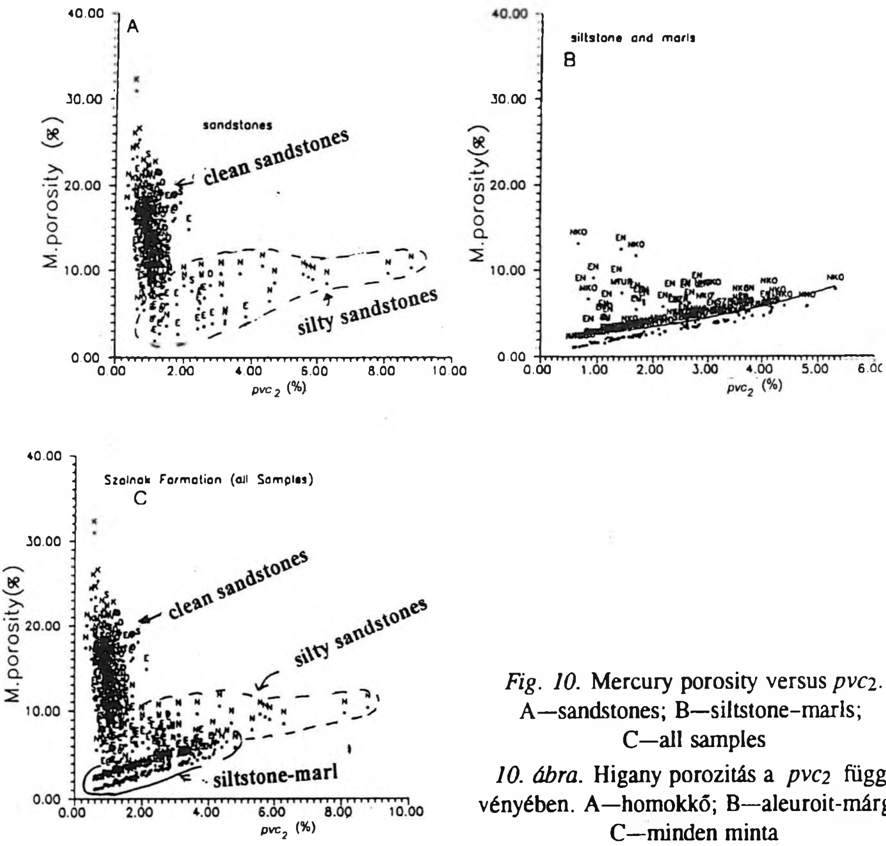


Fig. 10. Mercury porosity versus pvc_2. A—sandstones; B—siltstone-marls; C—all samples

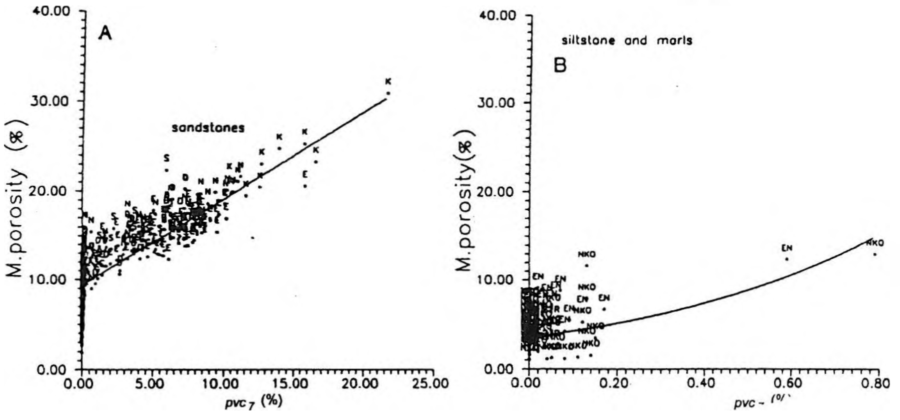
10. ábra. Higany porozitás a pvc_2 függvényében. A—homokkő; B—aleuroit-márga; C—minden minta and siltstone–marls have a range of pvc_2 % from 1.0 up to 10.0 of total pore volume. A linear regression line equation has been calculated for siltstone–marl facies, this being:

$$\Phi M = \exp \cdot (0.259 pvc_2) \cdot 2.06 \tag{18}$$

This equation could be used for either siltstone or clean sandstone determination; while the latter has a pvc_2 value of $<2.0\%$.

3. 6. Mercury porosity versus pvc_7

The relationships between mercury porosity and pvc_7 (*Figs. 11a, b* and *c*) for sandstone, siltstone–marl and all samples have a certain efficiency of lithologic facies differentiation. The siltstone–marl facies have a percentage of pvc_7 ranges from 0.0 to 1.8, while clean sandstone facies attains pvc_7 from



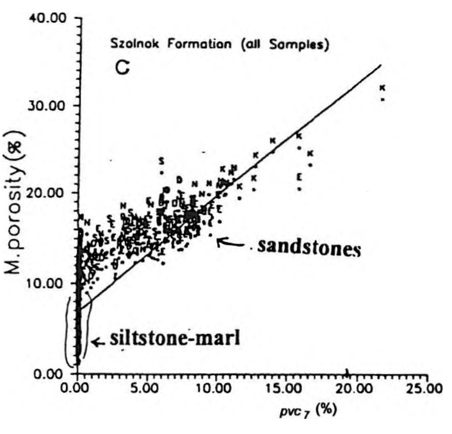


Fig. 11. Mercury porosity versus pvc_7. A—sandstones; B—siltstone-marls; C—all samples

11. ábra. Higany porozitás a pvc_7 függvényében. A—homokkő; B—aleuroit-márga; C—minden minta

2.0 up to 25. In addition, siltstone–marl facies are characterized by low mercury porosity ranging from 1.0 to 9.0 %, the porosity of the silty and clean sandstones ranges from 3.0 to 30.0%. It is mentioned that this combination fails to discriminate silty sandstones. The regression line equations calculated for both sandstones and all samples are supported by reliable coefficients of correlation equal to r = 0.75 and 0.65, respectively. The equations representing these relations are:

$$\Phi M = 0.975(pvc_7) + 9.37 \qquad \text{(for sandstones)} \qquad (19)$$

and

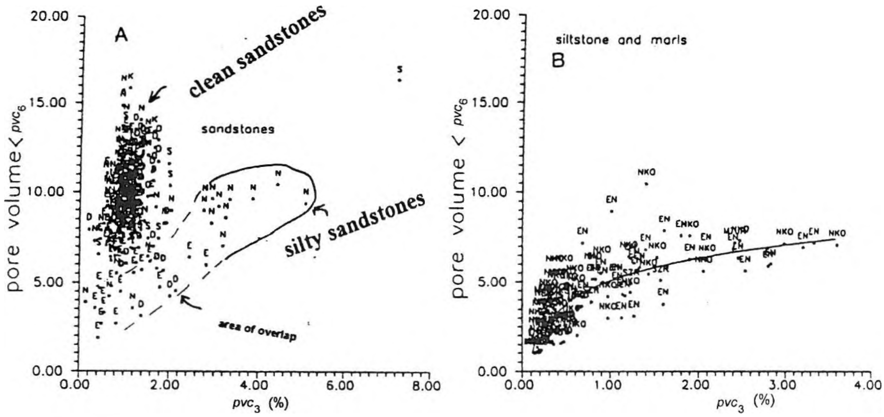
$$\Phi M = 1.3(pvc_7) + 6.82 \qquad \text{(for all samples)} \qquad (20)$$

3.7. (Vp < pvc_6) versus pvc_3

The pore volume (*Vp*) less than pvc_6 is defined in the present study as the summation of all pore volumes corresponding to a pore radius starting from 0.0075 μm (pvc_1) up to 2.5 μm (pvc_6). pvc_3 is defined as the pore volume corresponding to pore space radius of 0.075 μm in size. The relationships (*Figs. 12a, b* and *c*) exhibit a sample point distribution of L-shape. Most siltstone–marl sample points are concentrated in the area with maximum pvc_3 equals 4.0 and (*Vp* <pvc_6) equals 7.0. In fact the silty sandstone facies and the siltstone–marl have a mutual overlapping zone, whereas the clean sandstone facies is sharply isolated and easily identified (Fig. 12c).

3.8. (Vp < pvc_5) versus pvc_5

The pore volume (*Vp*) less than pvc_5 is defined as the summation of all pore spaces, which corresponds to pore radius starting from 0.0075 μm (pvc_1) up to 0.75 μm (pvc_5).The relationships (*Figs. 13a, b* and *c*) elucidate the efficiency of such combinations in lithologic facies discrimination. The correlation between these figures helps in allocating areas of different lithologic facies. The silty sandstones, exposed by different previously examined cross-plots, are usually accompanied in some parts by siltstone–marl facies. As complete separation between them using the present technique seems to be difficult, we suggest to put them altogether as one petrophysical facies.



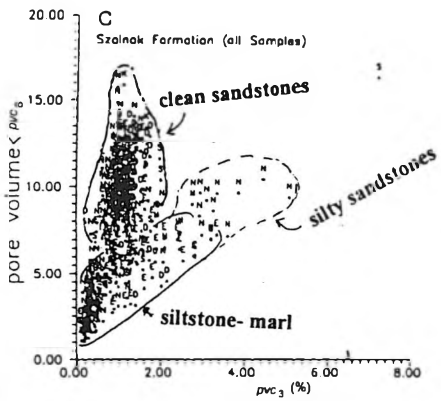


Fig. 12. ($Vp < pvc_6$) versus pvc_3. A—sandstones; B—siltstone-marls; C—all samples

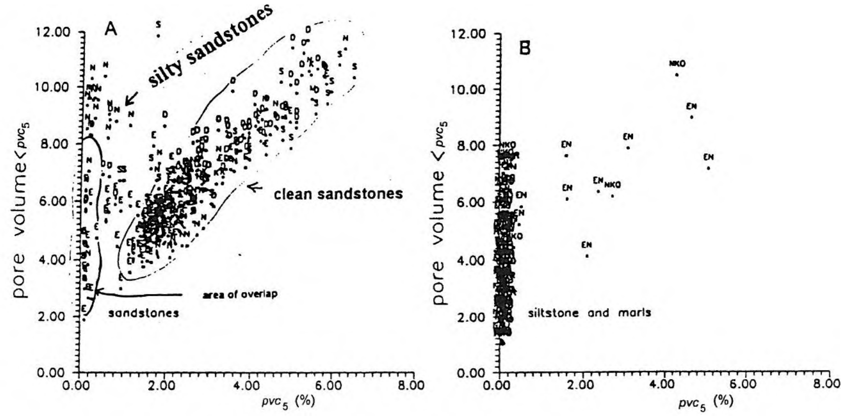
12. ábra. ($Vp < pvc_6$) a pvc_3 függvényében. A—homokkő; B—aleuroit-márga; C—minden minta

3.9. ($Vp < pvc_6$) versus pvc_2

Examination of the relationships (*Figs. 14a, b* and *c*) indicates that we can easily differentiate between sandstones and siltstone–marl facies. Both the siltstone–marl and silty sandstones still have an overlapping area, which represents poor reservoir type in the Szolnok Formation.

3. 10. Effective radius versus mercury porosity

Here, the effective pore radius, is defined as the pore volume corresponding to pore radius of 1.87 μm in size. The relationships (*Figs. 15a, b* and *c*) between effective pore radius and mercury porosity for sandstones, siltstone–marls and all samples are useful for facies discrimination despite exhibiting linear trends in the case of clean sandstone samples. It is clear that



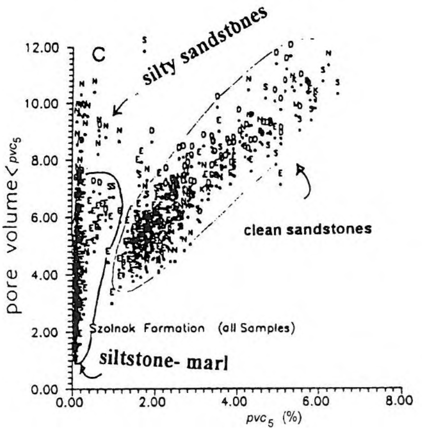


Fig. 13. ($Vp<pvc5$) versus $pvc5$. A—sandstones; B—siltstone-marls; C—all samples

13. ábra. ($Vp<pvc5$) a $pvc5$ függvényében. A—homokkő; B—aleuroit-márga; C—minden minta

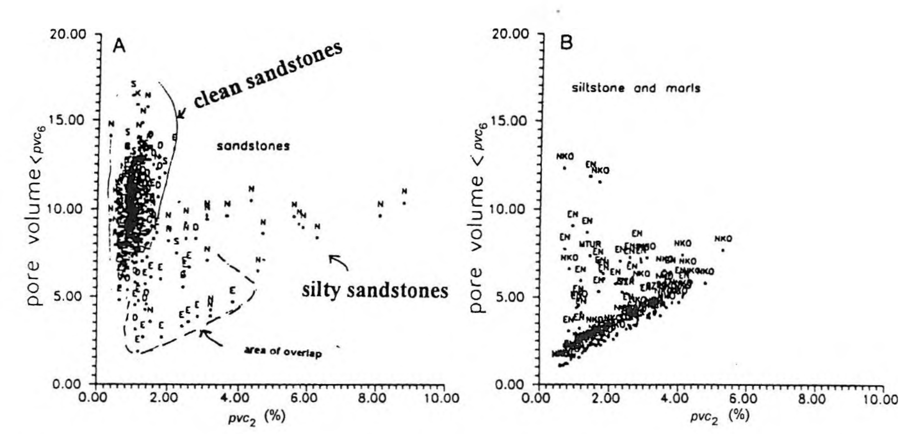
effective pore radius has little or no positive contribution to increase porosity in the case of both silty sandstones and siltstone-marl facies of the Szolnok Formation. The regression line equations calculated are distinguished by reliable coefficients of correlation: $r = 0.86$ and 0.71 for sandstones and all samples respectively. The equations are;

$$\Phi M = 0.902(P_{1.87}) + 8.95 \qquad \text{(for sandstones)} \qquad (21)$$

and

$$\Phi M = 1.187(P_{1.87}) + 6.48 \qquad \text{(for all samples)} \qquad (22)$$

where $P_{1.87}$ = effective pore radius (μm).



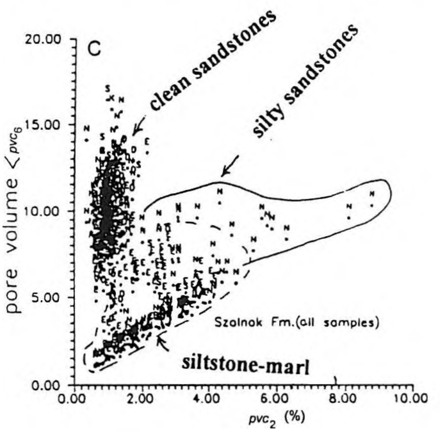


Fig. 14. ($Vp < pvc_6$) versus pvc_2. A—sandstones; B—siltstone-marls; C—all samples

14. ábra. ($Vp < pvc_6$) a pvc_2 függvényében. A—homokkő; B—aleuroit-márga; C—minden minta

By using these relations one can determine the effective pore radius, which is difficult in measurements as well as being expensive, from the routine porosity data of the Szolnok Formation.

3. 11. Effect of calcite content on pore structure

During the sedimentary history, both chemical and physical diagenetic processes have a great effect on the rock pore space framework. Therefore, the today's rock pore space structures are mainly the net product of either syn-sedimentary or post-sedimentary processes. Study of the primary porosity is not enough for pore structure investigation, while the chemical diagenetic processes (solution, cementation, etc.) can negatively or positively affect reservoir parameters such as pore structure, porosity and permeability.

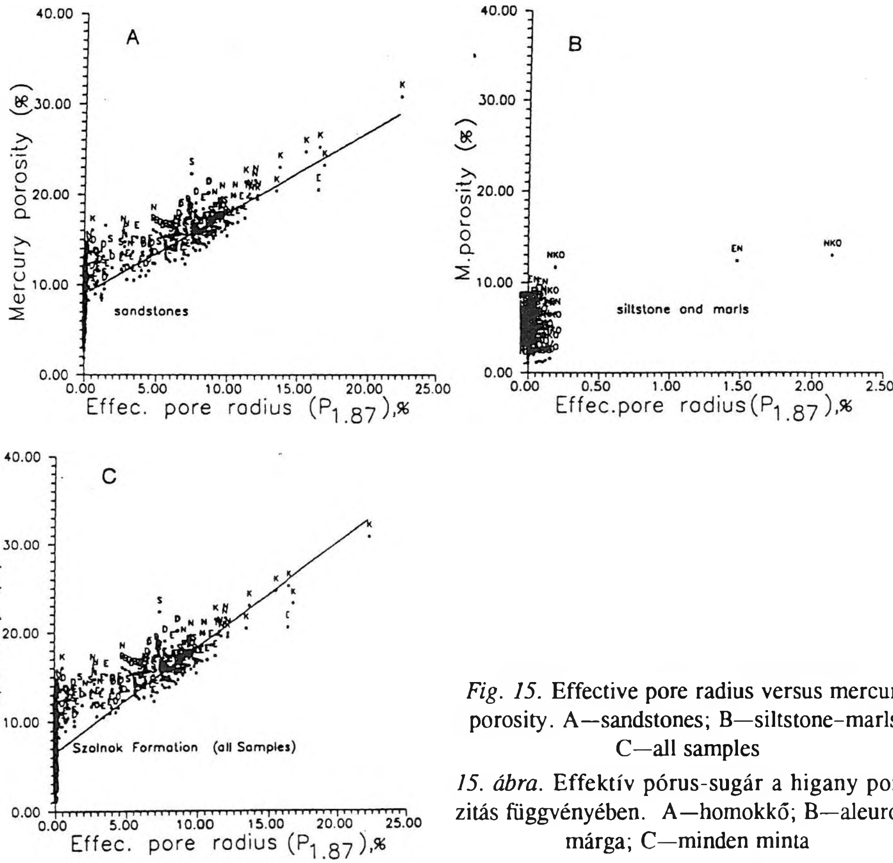


Fig. 15. Effective pore radius versus mercury porosity. A—sandstones; B—siltstone-marls; C—all samples

15. ábra. Effektív pórus-sugár a higany porozitás függvényében. A—homokkő; B—aleuroit-márga; C—minden minta

The low percentages of calcite content as a rock formation fines occurring in the pore spaces usually occupy the larger pore throat size fractions (*Fig. 16*). On the other hand the percentages of calcite content increase at the expense of the large pore throats. Figure 16 elucidates that the large pore size fractions have been destroyed step by step from the largest size fraction downward by the gradual increase of the percentages of the calcite content in the pore space framework of the sandstones belonging to the Szolnok Formation. We can conclude that the increase in the percentages of calcite contents up to 22% can destroy all pore throats having a radius larger than 0.25 μm, in this case the sandstone reservoir could not be suitable for storing fluids.

An attempt was made to investigate the calcite cement and its effect on reservoir fluid production. For this purpose some sandstone samples were acidified with 15% HCl acid while both porosity and pore throat size

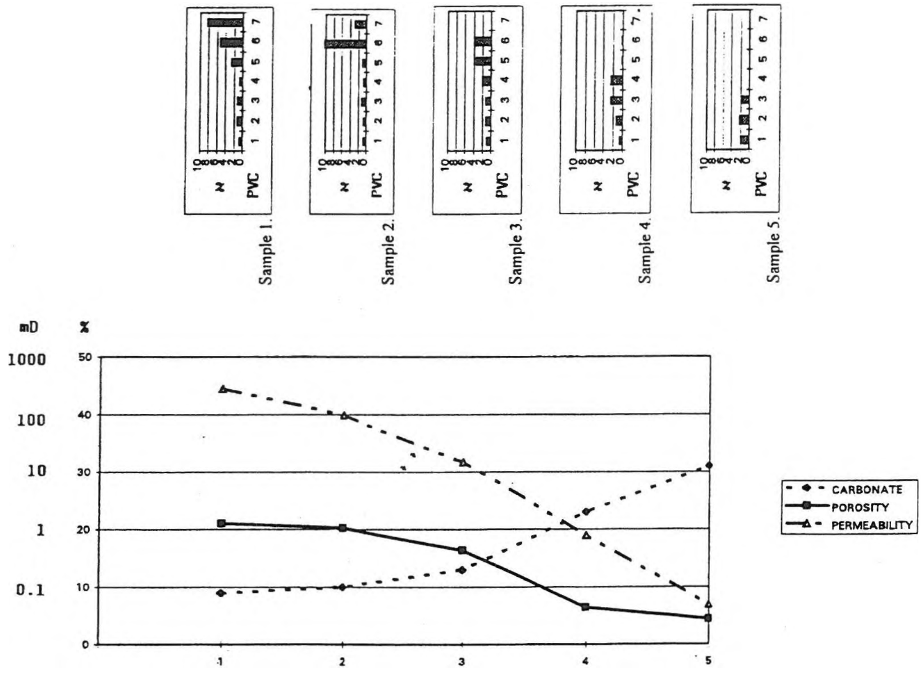
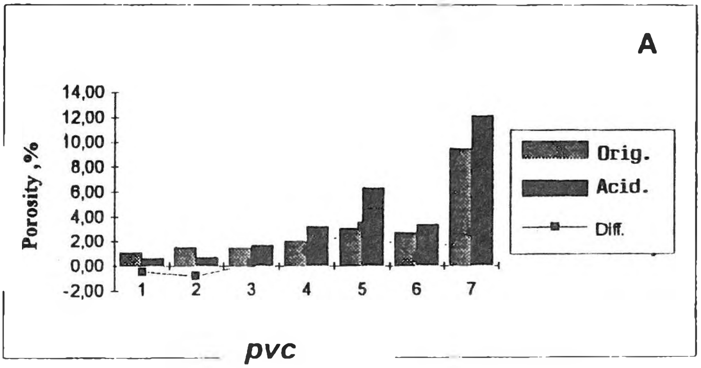


Fig. 16. Permeability, porosity, and *pvc* interrelationships for some selected samples from Szarvas area

16. ábra. Permeabilitás, porozitás és *pvc* összegüggések néhány Szarvas környéki mintára

parameters are measured before and after the acidification (*Figs. 17a* and *b*). Based on the data presented in Figures 17a and b, we can find two different types of sandstone reservoir behaviour in the Szolnok Formation. The first type (Fig. 17a) exhibits that the enhancement of the rock porosity after acidification goes in accordance with that before acidification. This can be explained by the dissolving of the calcite without any major changes in the shape of the original rock pore structure. The permeability of this sandstone type is slightly increased. The second reservoir type (Fig. 17b) shows that the largest pore throat size (pvc_7) is drastically increased at the expense of pvc_5 and pvc_6, while the permeability of this type is greatly enhanced after the acidification processes. Therefore, we can conclude that the formation fines were only calcite in the pore throats which are now completely dissolved



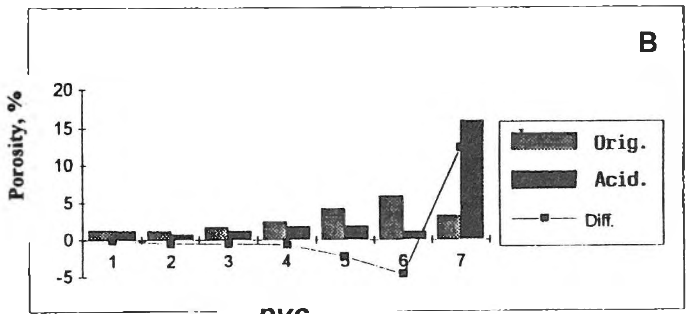


Fig. 17. Effect of calcite cement on both porosity and permeability before and after acidification (Szarvas area). A—sandstone reservoir type-1; B—sandstone reservoir type-2

17. ábra. A kalcit cement hatása a porozitásra és a permeabilitásra savazás előtt és után (Szarvasi terület). A—1-es típusú homokkő tározó; B—2-es típusú homokkő tározó

and thus they enhance pore throat size as well as porosity and permeability. It is mentioned that reservoir enhancement using acidification of sandstones depends mainly on the nature of pore throats, pore spaces and mode of occurrence of formation fines and its mineralogy .

4. Conclusions

The petrophysical data obtained for the Szolnok Formation have been treated as one population for all samples. However, both sandstone and siltstone-marl facies were processed separately. The application of the suggested reservoir model permits lithologic discrimination with high efficiency using some graphical combinations. This technique is extremely important for Szolnok reservoir diagnosis. It facilitates separation and identification of the present lithofacies.

The pore throat size classification based on the proposed model proves its appilicability for lithologic facies discrimination as well as for prediction of some important reservoir parameters. Cross-plotting of the petrophysical measurements has indicated that the Szolnok Formation comprises two main lithologic groups: (a) clean sandstone, (b) silty sandstone, siltstone and marls. It means that by using these plots one can easily differentiate between very good and intermediate or even bad reservoirs; each lithologic facies has a characteristic trend.

The prediction of one type of porosity and/or permeability from another using the least squares fitting method has great significance for Szolnok reservoir evaluation. Both the porosity and permeability variation range characterizing the detected lithologic facies of the Szolnok Formation are useful for reservoir zonation.

Some pore volume sizes — especially pvc_2 and pvc_7 as defined by the suggested reservoir model — could be predicted from either measured permeability or porosity. Intercorrelation between some pore space volumes is very effective for lithologic facies separation and identification.

It should be mentioned that reservoir enhancement using acidification processes depends mainly on the nature of pore throats, pore spaces, and the mode of occurrence of formation fines and its mineralogy.

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A Szolnoki Formáció tárolóinak diagnózisa az Alföld középső részén

A. M. A. El SAYED és KISS Balázs

Az Alföld középső részén minden mélyfúrásban megtalálták a Szolnok Formáció képződményeit többnyire turbidites törmelékes üledék alakjában. Az aleuritban közbetelepülő homokkő rétegek és márga csíkok is vannak. Jelen tanulmány céljára 494 db magmintát gyűjtöttek össze és vetették alá különböző kőzettani laboratóriumi vizsgálatoknak. A kapilláris nyomás módszerét (MICP) alkalmazták a pórusnyílás méreteloszlásának, a különböző dimenziójú pórus átmérőknek megfelelő pórustérfogat (*pvc*) és az effektív porozitás vizsgálatára. Másrészről a tároló paraméterének korrelációja céljából mind a horizontális, mind a vertikális permeabilitást és a hélium porozitást is mérték.

A kőzetfizikai adatokat a litológiától függetlenül minden mintára egyetlen halmazként kezelték. Továbbá, a Szolnoki Formáció minden litológiai fáciesét külön kezelték azért, hogy megbízható, nagy pontosságú matematikai összefüggéseket állíthassanak fel a tároló értékeléséhez. Új eljárást alkalmaztak a pórusnyílások mérésére; ez a módszer lehetővé teszi a szolnoki üledékeket jellemző pórusterek keletkezésének és fejlődésének becslését a tároló üledékképződésének és kőzetté válásának során.

Homokkő fáciesek esetében a pórusnyílás mérések korrelációja jelzi, hogy két genetikai típus létezik, míg ez a jelenség nem ilyen egyértelmű, ha csak porozitási vagy permeabilitási adataink vannak. Másrészt mind a horizontális, mind a vertikális permeabilitás világosan jelzi a tároló heterogenitását márgák és aleurolit esetében. Mind a porozitás, mind a permeabilitás ábrázolása a különböző pórustér méretek függvényében világossá teszi a tároló heterogenitását a Szolnoki Formáció minden kőzetfácies-típusában. A Szolnoki Formációban a litológiai fácieseket elkülönítették és egy sor tároló-paraméterkombináció hatékonyságát a gyakorlatban is bizonyították. Továbbá, megbízható összefüggéseket kaptak a tároló effektív pórusátmérője, porozitása és/vagy permeabilitása becslésére.