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RELATIONSHIP OF POROSITY AND PERMEABILITY TO MERCURY INJECTION DERIVED PARAMETERS FOR SANDSTONES OF THE TÖRTEL FORMATION, HUNGARY

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Mercury injection-capillary pressure tests are expensive and, therefore, are not extensively used. However various petrophysical parameters derived from them are valuable with regard to both reservoir geology and engineering. Pore aperture size estimated from mercury injection tests has been used to evaluate seals for stratigraphic hydrocarbon bearing traps. Mercury injection-capillary pressure curves of 45 sandstone core samples obtained from the Törtel Formation (Algyő oil and gas field) were investigated.

This paper develops empirical equations for estimating pore aperture size and some important reservoir parameters from routine core analysis (porosity and/or permeability). Pore aperture sizes r_{36} and r_{50} were estimated. Size r_{50} seems to be critical and the most effective pore size for delineating hydrocarbon traps in the Törtel Formation. In addition, the mercury recovery efficiency could be estimated.

Keywords: capillary pressure, porosity, permeability, Törtel Formation, Hungary

1. Introduction

The Törtel Formation (Pannonian s.l.) is mainly composed of bedded sandstones intercalated with siltstones, marls, lignites and carbonified plant fragments. Sandstone bodies were interpreted as distributary channel, barrier and mouth bars, and deltaic fringe deposits [EL-SAYED 1981, BÁN, EL-SAYED 1987, JUHÁSZ 1991]. Limonitic concretions are common in the stratified laminated and cross-laminated medium of fine grained sandstones and siltstones. The environment of deposition of the Törtel Formation varies from

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shallow lake and fluvial marsh to terrestrial and fluvially dominated delta [MUCSI, RÉVÉSZ 1975, EL-SAYED 1981, BÉRCZI, PHILLIPS 1985].

The Törtel Formation in the Great Hungarian Plane is underlain by the Algyő Formation and overlain by the Zagyva Formation. In the Algyő field it is penetrated by more than 900 drilled holes. Five superimposed hydrocarbon bearing reservoirs were attributed to the Törtel Formation. They are, from bottom to top: Algyő-1, Algyő-2, Szeged-1, Szeged-2 and Szeged-3. The Algyő-2 reservoir sequence was petrophysically studied by EL-SAYED [1981 and 1983], and classified into three deltaic rock genetic types. The previously mentioned reserviors are considered as the most important oil producing sequences in the Algyő field. The reservoir characteristics of them are available in the literature [EL-SAYED 1991, EL-SAYED, VOLL 1992].

Petrophysicists are interested in how porosity and permeability relate 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 sealing capacity of cap rocks [BERG 1975, MAGARA 1978]. Hydrocarbon migration problems have been discussed by number of authors [e.g. SOMFAI 1976, WARDLAW, CASSAN 1979, SCHOWALTER 1979, SWANSON 1981]. Hydrocarbon migration and entrapment result from the interaction between buoyant pressures and capillary forces.

In reservoir rocks, the minimum pressure necessary to force the oil (usually the non-wetting phase) to enter the rock pores is known as displacement pressure [SCHOWALTER 1979]. It is defined as the pressure at 10 % mercury saturation on the mercury injection-capillary pressure curve. However, the pore aperture size corresponding to it can be determined. It is used for both reservoir and sealing capacity evaluation. Therefore a readily available estimation of displacement pressure from routine core analysis would be helpful.

Another parameter of interest is the pore aperture size that corresponds to the apex of a hyperbola on the mercury injection-capillary pressure plot [THOMEER 1960]. This parameter has the potential for depicting stratigraphic oil bearing traps [SWANSON 1977, PITTMAN 1989 and 1992]. PITTMAN [1992] showed that the net thickness of sandstone reservoirs having the 36th percentile of mercury saturation, which corresponds to a pore aperture size greater than 0.5 μm (5000 Å), was useful for delineating the charged stratigraphic traps. He introduced useful empirical equations for estimating various reservoir parameters especially for sandstones.

The pore/throat size ratio is a parameter thought to be related to the microscopic recovery efficiency of the non-wetting phase in sandstone reservoirs [WARDLAW 1980, KOPASKA-MERKEL, FRIEDMAN 1989, MORAES 1991]. The oil recovery efficiency decreases while the pore/throat size ratio increases. On the other hand, the opposite regime is obtained for the recovery efficiency of the rock-saturating wetting phase. The purposes of this study are (1) to detect which percentile of cumulative mercury saturation is able to give reliable results in trap delineation for the sandstones of the Törtel Formation,

(2) to present empirical relationships between porosity (Φ), permeability (k) and capillary pressure derived parameters.

2. Methodology

Forty five porosity and nitrogen permeability analyses were available in Hungarian Hydrocarbon Institute (SZKFI) files on plugs that had also been used for mercury injection tests of sandstone samples obtained from the Törtel Formation. The porosities and permeabilities of the data set ranged from 8.1 % to 30 % and from 0.03 md to 3000 md respectively. The studied samples were mainly of calcareous and argillaceous sandstones and siltstones.

The displacement pressure is determined graphically from the mercury injection curves, whereas the corresponding pore aperture radii were calculated by using the equation adapted from WASHBURN [1921]:

$$P_c = -2\,\gamma\cos\Theta/r \quad (1)$$

where P_c is capillary pressure (dynes/cm^2), γ is the surface tension of mercury (480 dynes/cm), Θ is the contact angle of mercury in air (140 °C) and r is the radius of pore aperture for a cylindrical pore. Thus, r (μm) = $107/P_c$ (psia).

The mercury recovery efficiency (Re) is calculated in accordance with the equation introduced by HUTCHEON and OLDERSHAW [1985]:

$$Re = (S - S_r)/S \quad (2)$$

where S is the volume of mercury injected at maximum pressure (cc) and S_r is the volume of mercury retained in the pore system at minimum pressure (cc). Both S and S_r are measured on capillary curves. However, the microscopic oil recovery efficiency (Re_o) was calculated by MORAES [1991] for oil-saturated samples as:

$$Re_o = (So_{\max} - Sor_{\min})/So_{\max} \quad (3)$$

where $So_{\max}$ is the maximum oil saturation and Sor_{min} is the minimum residual oil saturation.

The apex of the curves of *Fig. 1A* was calculated graphically by using SWANSON's method [1977]. He determined that the 45° line is tangential to the hyperbola of a log-log plot at the apex. Consequently, the average apex of the sandstone samples of the Törtel Formation is calculated by plotting the mercury saturation at the defined apex divided by the mercury saturation pressure on the y axis against the mercury saturation on the x axis for each mercury injection curve (*Fig. 1B*). A regression analysis program [STOODLEY 1984] was used to establish various empirical relationships.

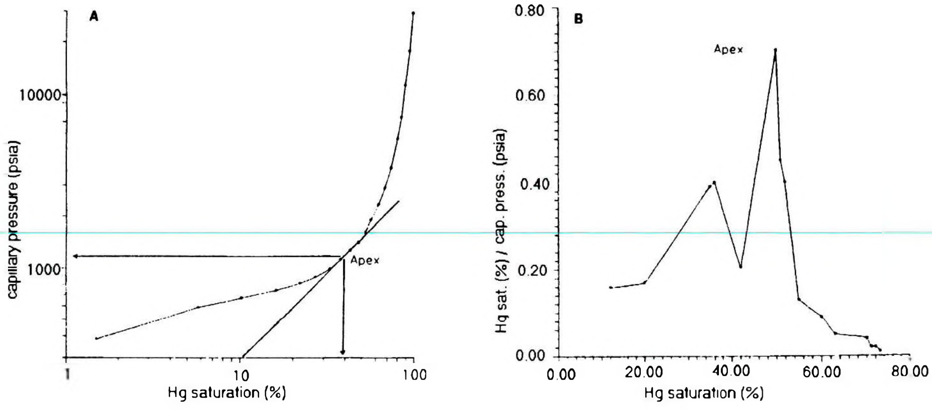

Fig. 1. A—Log-log hyperbolic plot of mercury injection data. Φ=13.07 %, *Re*=98.43 %, *k*=12.981 md, mean pore throat size=14.15 phi; B—Plot of mercury saturation/capillary pressure versus mercury saturation

1. ábra. A—A higanyinjekciós adatok log-log hiperbolikus ábrázolása Φ=13,07 %, *Re*=98,43 %, *k*=12,981 md, átlagos pórusnyílás méret=14,15 phi; B—A higanytelítettség/kapilláris nyomás ábrázolása a higanytelítettség függvényében

Рис.1. A–Гиперболическое изображение данных нагнетания ртути в логарифмическом масштабе. Φ=13,07 %, *Re* =98,43 %, *k* =12,981 md, средний размер отверстия пор=14,15phi; B–Зависимость отношения насыщенности ртутью и капиллярного давления от насыщенности ртутью

3. Analysis of apex

The distribution of mercury saturation (*Fig. 1B*) reveals two major apexes (r_{36} and r_{50}) that are generally present and characterize the sandstones of the Törtel Formation. The most predominant apex is the r_{50}. These apexes are defined as the pore aperture sizes corresponding to the mercury saturation of 36 % and 50 % respectively. Although PITTMAN [1992] pointed out that the mean apex calculated for 196 sandstone samples had a mercury saturation of 36 % (r_{36}), the calculated apex (r_{50}) proves that this latter is appropriate and convenient for sandstones of the Törtel Formation. This is confirmed by the relationships between the pore aperture radii (r_{36}, r_{50}) and the rock porosity (*Figs. 2A* and *2B*).

Based on regression analysis with r (apex) as the dependant variable, the relationship between the pore aperture size corresponding to the apex (r_{36} in Å) and porosity (Φ in %) is:

$$r_{36} = 466.82\, e^{0.193\Phi} \tag{4}$$

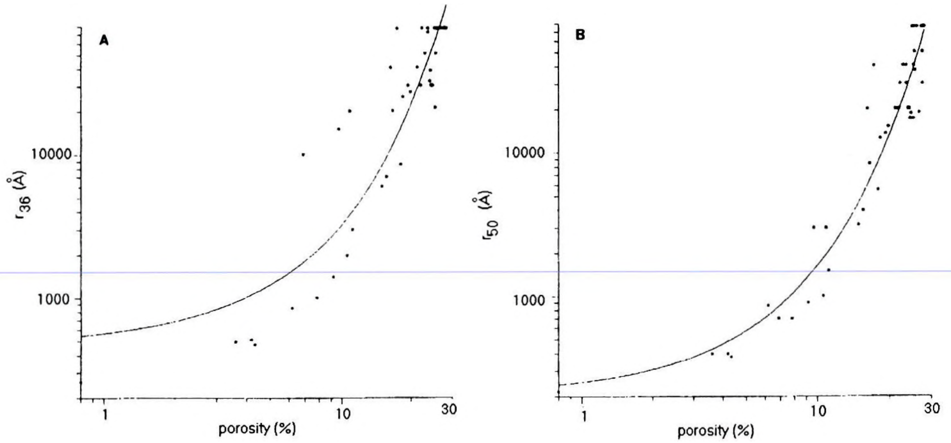

Fig. 2. Pore aperture radii versus porosity. A—r_{36}; B—r_{50}
2. ábra. Pórusnyílás sugarak a porozitás függvényében. A—r_{36}; B—r_{50}
Рис. 2. Зависимость радиуса отверстия пор от пористости. A—r_{36}; B—r_{50}

This equation yields a correlation coefficient of 0.901. On the other hand, the relationship (Fig. 2B) considering r_{50} as the mean apex characterizing the sandstone of the Törtel Formation is:

$$r_{50} = 203.97\, e^{0.207\Phi} \tag{5}$$

This equation is characterized by a high correlation coefficient (0.96).

Uncorrected gas permeability is plotted against both of r_{36} and r_{50} (*Figs. 3A and 3B*). These relationships were characterized by slightly low correlation coefficients (0.54 and 0.62 respectively). The regression equations representing these relations are:

$$r_{36} = 2277.5\, K^{0.542} \tag{6}$$

$$r_{50} = 993.5\, K^{0.61} \tag{7}$$

where K is the gas permeability (md).

Results showed that there is a favourable comparison with either r_{36} or r_{50}. However, results obtained with r_{36} are somewhat optimistic (*Fig. 4*) especially in sandstones of the Törtel Formation. An examination of 12 nonproductive wells in the Algyő field using both r_{36} and r_{50} gave complete agreement for 10 dry wells (83.3 %), while they have a pore aperture size < 0.5 μm (5000 Å). Another examination of 33 producing wells in the Algyő field indicated that r_{50} gives 100 % reliable results; r_{36} gave 95 % reliable results. Therefore r_{50} could be considered as the most effective tool for distinguishing nonproductive from productive wells in respect of the lithological traps of the Törtel Formation in the Great Hungarian Plane.

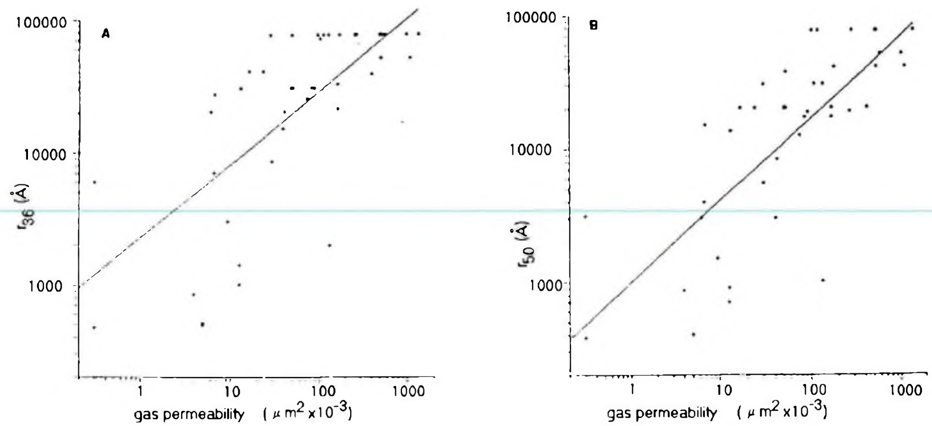

Fig. 3. Pore aperture radii versus gas permeability. A—r_{36}; B—r_{50}

3. ábra. Pórusnyílás sugarak a gáz permeabilitás függvényében. A—r_{36}; B—r_{50}

Рис. 3. Зависимость радиуса отверстия пор от проницаемости газа. А—r_{36}; В—r_{50}

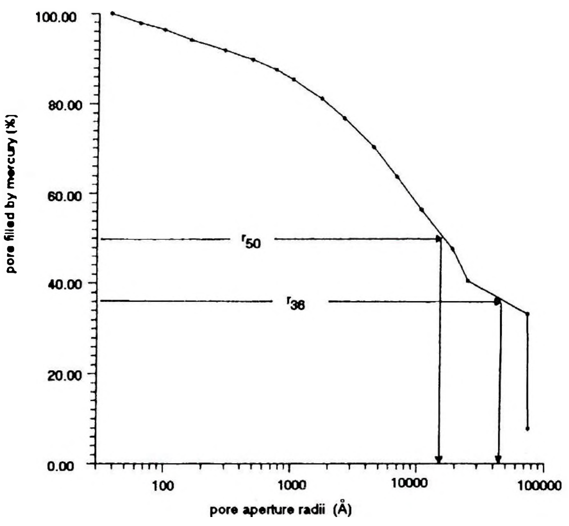

Fig. 4. Semilog mercury injection plot with pore aperture size plotted on the logarithmic axis. Φ=12.38 %, k=6.38 md

4. ábra. Higanyinjektálás ábrázolása féllogaritmikus rendszerben, a pórusnyílás méret a logaritmikus tengelyen ábrázolva. Φ=12,38 %, k=6,38 md

Рис.4. Изображение нагнетания ртути в полулогарифмическом масштабе. Размер пор изображен в логарифмическом масштабе. Φ=12,38 %, k=6,38 md

4. Displacement pressure

A relationship between the displacement pressure measured graphically on the capillary pressure-mercury injection curve [SCHOWALTER 1979] and porosity is shown in *Fig. 5A*. The relationship is represented by regression line equation:

$$\Phi = 30.5\ Pd^{-0.312} \tag{8}$$

where *Pd* is the displacement pressure (psia).

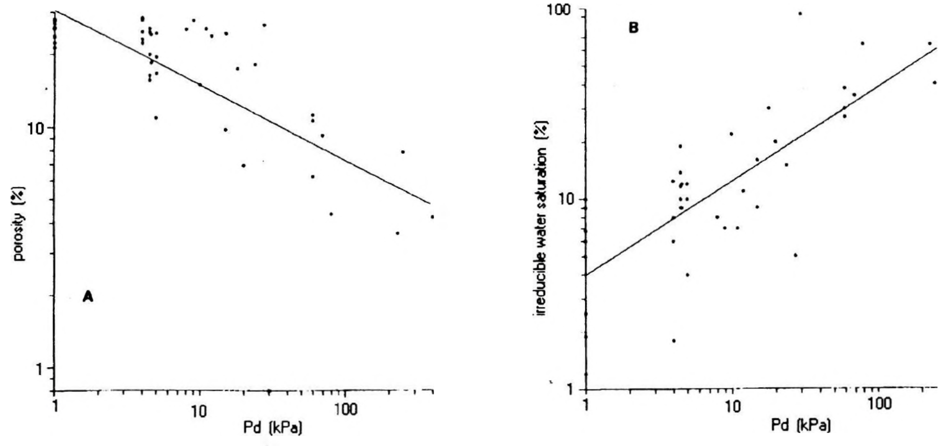

Fig. 5. Porosity (A) and irreducible water saturation (B) versus displacement pressure
5. ábra. Porozitás (A) és nem redukálható víztelítettség (B) az elmozdulási nyomás függvényében
Рис.5. Зависимость пористости (A) и остаточной водонасыщенности (B) от давления смещения

This equation has a correlation coefficient of -0.85. *Fig. 5B* exhibits a relationship berween the irreducible water saturation calculated from capillary pressure curves and the displacement pressure. This relationship is provided with a reliable correlation coefficient (0.81) governing the equation:

$$S_{wir} = 3.99\ Pd^{0.49} \tag{9}$$

where S_{wir} is the irreducible water saturation (%).

Hence, the displacement pressure could be estimated from the measured rock porosity which usually obtained during the conventional core analysis.

5. Recovery efficiency

EL-SAYED [1988] studied the recovery efficiency of 27 sandstone core samples obtained from the Algyő-2 reservoir formation of the Algyő field. He concluded that the recovery efficiency of these deposits is influenced mainly by tortuosity and matrix conductivity, or tortuosity and permeability per porosity ratio.

Figure 6A reveals a negative relationship between mercury recovery efficiency and rock porosity of sandstones of the Törtel Formation. In some cases — especially in carbonate reservoirs (e.g. limestones and dolomites) — positive relations have been recorded in dolostones [WARDLAW 1976 and 1980] and in oolitic limestones of Jurassic age [MELAS, FRIEDMAN 1992]. This phenomenon depends mainly on the wettability of mineral grains forming the rock-pore network. The obtained relationship (Fig. 6A) is presented by the regression line equation:

$$Re = 106.86 - 1.62\Phi \tag{10}$$

where *Re* is the mercury recovery efficiency (%) and Φ is the porosity (%).

This equation is characterized by a correlation coefficient of -0.7. It is worth mentioning that an insignificant correlation coefficient has been obtained for the relation between mercury recovery efficiency and gas permeability.

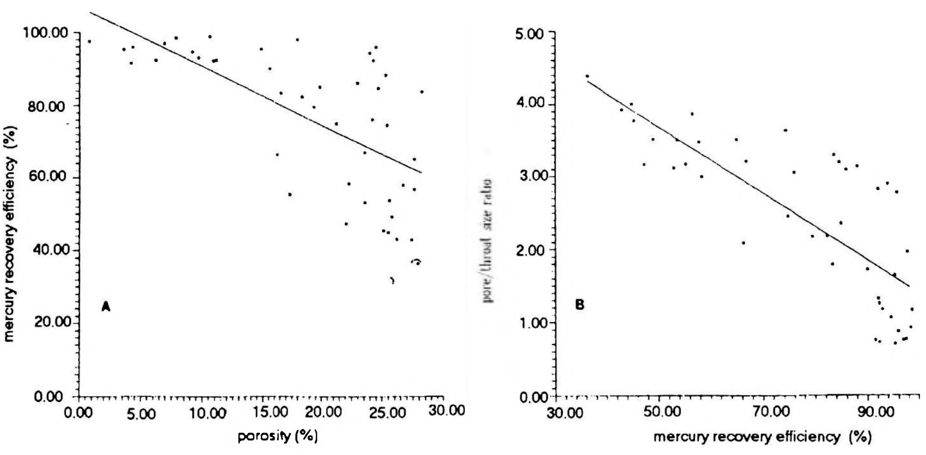

Fig. 6. Mercury recovery efficiency versus porosity (A) and pore/throat size ratio (B)

6. ábra. Higany visszanyerési hatékonyság a porozitás (A) és pórus/nyílásméret arány függvényében

Рис.6. Зависимость эффективности извлечения ртути от пористости (A) и от отношения размера пор и отверстий (B)

Therefore, rock porosity from routine core analysis could be used for delineating the oil recovery efficiency in the sandstones of the Törtel Formation.

The calculated mercury recovery efficiency is plotted against the pore/throat size ratio (*Fig. 6B*). The graph displays a negative relationship, while recovery efficiency decreases with increasing pore/throat size ratio. This is completely consistent with the relations introduced by WARDLAW and CASSAN [1979]. The calculated average pore/throat size ratio for the sandstones of the Törtel Formation was found to be 2.7, while the mean pore throat size was measured by phi units. This average value, when plotted on the graph of Fig. 6B, gives a mercury recovery efficiency of around 70 %.

6. Conclusions

Porosity and permeability of sandstones of the Törtel Formation, from routine core analysis could be used to estimate various reservoir parameters derived from mercury injection.

Among 45 sandstone core samples, the mean apex of log-log mercury injection plots was at a mercury saturation of 50 %.

The apex of mercury saturation distribution exhibits bimodal type (r_{36} and r_{50}). The empirically derived relationships between porosity and the pore aperture radii of r_{36} and r_{50} are presented by Eqs. (4) and (5). They are reliable enough for estimating the apexes and then for delineating the productive and nonproductive wells in this trap.

Displacement pressure derived from mercury injection tests could be estimated from either porosity or irreducible water saturation data by using empirical equations (Eqs. 8 and 9). Although mercury recovery efficiency reveals negative relationships with both porosity and pore/throat ratio, it could be estimated from rock porosity using the calculated empirical equation (Eq. 10).

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REFERENCES

BÁN Á., EL-SAYED A. M. A. 1987: Genetic delineation of deltaic rock types in terms of log curve shape in the Algyő-2 hydrocarbon reservoir, Hungary. Acta Geol. Hung. **30**, 1-2, pp. 231-240

BÉRZCI I., PHILLIPS R. L. 1985: Processes and depositional environments within Neogene deltaic-lacustrine sediments, Pannonian Basin, Southeast, Hungary. Geophysical Transactions **31**, 1-3, pp. 55-74

BERG R. R. 1975: Capillary pressure in stratigraphic traps. AAPG Bulletin **59**, pp. 939-956

EL-SAYED A. M. A. 1981: Geological and petrophysical studies for the Algyő-2 reservoir evaluation, Algyő oil and gas field, Hungary. Ph.D. thesis, Hungarian Academy of Sciences, Budapest, p. 166

EL-SAYED A. M. A. 1983: Skewness-kurtosis crossplot of pore throat size distribution as a discriminating factor for deltaic rock genetic types. 2nd Ann. Mtg., Egyptian Geophys. Soc., pp. 75-85

EL-SAYED A. M. A. 1988: Statistical relationships among some petrophysical parameters for Algyő-2 sandstone, Hungary. Geophys. Res. Bull. (National Geophys. Res. Inst. India) **26**, 3, pp. 96-102

EL-SAYED A. M. A. 1991: Reservoir characteristics of the Upper Pannonian hydrocarbon reservoirs in the Algyő field, Hungary. Internal report of the Hungarian Hydrocarbon Institute (SZKFI), p. 47

EL-SAYED A. M. A., VOLL L. 1992: Empirical prediction of porosity and permeability in deltaic sandstones of the Törtel Formation, Hungary. Scientific Bulletin, Ain Shams Univ., **30**, pp. 461-487

HUTCHEON I., OLDERSHAW A. 1985: The effect of hydrothermal reactions on the petrophysical properties of carbonate rocks. Can. Pet. Geol. Bull. **33**, pp. 359-377

JUHÁSZ GY. 1991: Lithostratigraphical and sedimentological framework of the Pannonian (s.l.) sedimentary sequence in the Hungarian Plain (Alföld), Eastern Hungary. Acta Geol. Hung. **34**, 1-2, pp. 53-72

KOPASKA-MERKEL D. C., FRIEDMAN G. M. 1989: Petrofacies Analysis of Carbonate Rocks: example from Lower Paleozoic Hunton Group of Oklahoma and Texas. AAPG Bulletin **73**, 11, pp. 1289-1306

MAGARA K. 1978: Geological model predicting optimum sandstone percent for oil accumulation. Can. Pet. Geol. Bull. **26**, pp. 380-388

MELAS F. F., FRIEDMAN G. M. 1992: Petrophysical characteristics of the Jurassic Smackover Formation, Jay field, Conecuh embayment, Alabama and Florida. AAPG Bulletin, **76**, 1, pp. 81-100

MORAES M. A. S. 1991: Diagenesis and microscopic heterogeneity of lacustrine deltaic and turbiditic sandstone reservoirs (Lower Cretaceous), Potiguar Basin, Brazil. AAPG Bulletin, **75**, pp.1758-1771

MUCSI M., RÉVÉSZ I. 1975: Neogene evolution of the south-eastern part of the Great Hungarian Plain on the basis sedimentological investigations. Acta Mineral. Petrograph. **22**, 1, pp. 29-49

PITTMAN E. D. 1989: Nature of the Terry sandstone reservoir, Spindle Field, Colorado. *In*: Coalson E. B. (ed.), Petrogenesis and petrophysics of selected sandstone reservoirs of the Rocky Mountain region. Rocky Mount. Assoc. of Geol., Denver, Colorado, pp. 245-254

PITTMAN E. D. 1992: Relationship of porosity and permeability to various parameters derived from mercury injection-capillary pressure curves for sandstones. AAPG Bulletin **76**, 2, pp. 191-198

SCHOWALTER T. T. 1979: Mechanics of secondary hydrocarbon migration and entrapment. AAPG Bulletin **63**, pp. 723-760

SOMFAI A. 1976: Classification of hydrocarbon trap types on the area of the Pannonian Basin (within Hungary) and possibilities of the investigation of lithological and stratigraphical trap types. (in Hungarian) Földtani Kutatás **19**, 4, pp. 11-18

STOODLY K. D. C. 1984: Applied and computational statistics—a first course. Ellis Horwood, New York

SWANSON B. F. 1977: Visualizing pores and non-wetting phase in porous rocks. Ann. Fall. Res. Conf., Soc. Pet. Engs., No. **6857**, p. 10

SWANSON B. F. 1981: A simple correlation between permeabilities and mercury capillary pressures. J. Pet. Technol., 1981 Dec., pp. 2498-2504

THOMEER J. H. M. 1960: Introduction of a pore geometrical factor defined by the capillary pressure curve. J. Pet. Technol., 1960 March, pp. 73-77

WARDLAW N. C. 1976: Pore geometry of carbonate rocks as revealed by pore casts and capillary pressure. AAPG Bulletin **60**, pp. 245-257

WARDLAW N. C., CASSAN J. P. 1979: Oil recovery efficiency and the rock pore properties of some sandstone reservoirs. Can. Pet. Geol. Bull. **27**, pp. 117-138

WARDLAW N. C. 1980: The effect of pore structure on displacement efficiency in reservoir rocks and in glass micromodels. SPE Paper, Soc. Pet. Engs., No. **8843**, pp. 345-352

WASHBURN E. W. 1921: Note on a method of determining the distribution of pore sizes in a porous materials. Proc. National Acad. Sci., USA, **7**, pp. 115-116

SI Metric conversion factors:

psi · 6.894 575 E+03 = MPa
dyn · 1.0 E-05 = N
md · 9.869 233 E-04 = mm^2
phi unit = $-\log_2 S$, where S is diameter in mm

POROZITÁS ÉS PERMEABILITÁS KAPCSOLATA HIGANYINJEKTÁLÁSBÓL SZÁRMAZTATOTT PARAMÉTEREKKEL, A TÖRTEL FORMÁCIÓ HOMOKKÖVEIRE

Abdel Moktader A. EL-SAYED

A higanyinjektálás-kapilláris nyomás vizsgálatok költségesek, ezért alkalmazásuk nem terjedt el széles körben, bár a belőlük levezetett paraméterek mind tározó-geológiai, mind mérnöki szempontból értékesek. A higanyinjektálásos tesztekből becsült pórusnyílás méret adatokat a sztratigráfiai szénhidrogén csapdák zárórétegeinek kiértékelésére használtuk. A Törtel formációból származó (Algyő gáz- és olajmező), 45 homokkő magminta higanyinjektálás-kapilláris nyomás görbéit vizsgáltuk.

A tanulmány empírikus egyenleteket vezet le a pórusnyílás méretre és néhány fontos tározó paraméterre mindennapos magminta-analízis eljárásokból (porozitás és/vagy permeabilitás). Az r_{36} és r_{50} pórusnyílás méreteket becsültük, mely alapján az r_{50} méret tűnik a legjelentősebbnek és leghatékonyabbnak a Törtel formáció homokköveiben lévő szénhidrogén csapdák leírására. Ezen kívül a higanyvisszanyerési együttható becslését is elvégeztük.

СВЯЗЬ ПОРИСТОСТИ И ПРОНИЦАЕМОСТИ С ПАРАМЕТРАМИ ВЫВЕДЕННЫМИ ПО НАГНЕТАНИЮ РТУТИ ДЛЯ ПЕСЧАНИКОВ ТЕРТЕЛЬСКОЙ ФОРМАЦИИ

Абдел Моктадер А. ЭЛЬ-САЕД

Исследование капиллярного давления при нагнетании ртути является дорогостоящим методом, поэтому он не получил широкого применения, несмотря на ценность получаемых данных как и для геологии резервуаров, так и с инженерной точки зрения. Размер отверстия пор, оцененный по таким исследованиям, применяли для описания закрывающих пластов стратиграфических резервуаров. Были проанализированы кривые нагнетание ртути-капиллярное давление по 45 кэрновым пробам песчаников Тертельской Формации месторождения нефти и газа Альде.

В статье выведены эмпирические уравнения для расчета размера отверстияпор и некоторых важных параметров резервуаров по данным стандартного анализа кэрновых проб (пористость и/или проницаемость). Размеры отверстия пор r_{36} и r_{50} получены путем оценки. Самым значительным является размер r_{50}, который наиболее эффективно применяется для описания резервуаров Тертельской формации. Также выполнена оценка коэффициента извлечения ртути.