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Experimental investigation of the fractal dimension of the pore surface of sedimentary rocks under pressure

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Dedicated to Dr. Károly Posgay, on his 75th birthday

A new experimental technique has been developed and applied to study the changes in the fractal dimension of the pore surface of sedimentary rocks under increasing confining pressures. Twenty sandstone, and twenty limestone reservoir rock samples were studied; the pressure was step-wise increased from 4 to 83 MPa. At any given pressure step, and for a given lithology, the porosity Φ and hydraulic permeability k were found related as a power law $k \propto \Phi^{\nu}$. For sandstone, the exponent ν smoothly increased from ≈ 2 to ≈ 3 as the pressure increased from 4 to 83 MPa. For limestone, for the same pressure range ν smoothly decreased from ≈ 5.7 to ≈ 5. Assuming two plausible fractal models of fluid flow in rocks, the exponent ν was converted to pore-surface dimension D, and it was found that D increases with pressure from $D \approx 2$ to $D \approx 2.5$ for sandstone, and decreases from $D \approx 2.7$ to $D \approx 2.65$ for limestone. The difference between the pressure-dependencies of the fractal dimension of the pore surfaces in case of the two lithologies is due to the different mechanisms governing compression in the various rock types.

Keywords: porosity, permeability, fractal dimension, sedimentary rocks

1. Introduction

In the last fifteen years the fractal structure of the pore space of sedimentary rocks has been experimentally verified over a wide length range with different techniques [FEDER 1988; KORVIN 1992; RADLINSKY et al. 1999]: in the range from 1 Å to ≈ 100 Å by chemical adsorption [AVNIR et al. 1985]; for 10 Å to ≈ 1000 Å by SAXS or SANS (i.e. Small Angle X-Ray Scattering, and Small Angle Neutron Scattering, respectively: THOMPSON

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et al. [1987]); for the range from 10 Å to ≈ 100 μm by image processing of the SEM or optical micrographs [KATZ and THOMPSON 1985]. Quite recently [RADLINSKY et al. 1999] SANS and USANS (Ultra-Small-Angle Neutron Scattering) studies established the fractality of the pore/matrix interface of a hydrocarbon source rock over three decades of scale, from 6 nm to 7 μm (with a resulting fractal dimension $D_S = 2.82$). None of these experimental techniques however can be readily applied to determine the fractal dimension of the pore/matrix interface in rock samples under varying pressure. In this paper an experiment is reported where the pressure-dependent pore-surface dimensions of twenty sandstone and twenty limestone reservoir rock samples were indirectly determined from the permeability vs. porosity relations established at the different pressure steps.

2. Fractal aspects of permeability

As well known, the porosity and hydraulic permeability of sedimentary rocks are connected by the classical Kozeny–Carman law [WALSH and BRACE 1984]

$$k = (1/b)\,\Phi^{3}(V/A_s)^2(1/\tau^2), \tag{1}$$

where b is a constant, A_s/V is the *specific surface* S_{spec} (i.e. total surface area per unit volume of rock), and τ is hydraulic tortuosity.

In another theoretical expression [GOODE and SEN 1988]

$$k = C\Phi^{m}(\Omega_+^{2}/Q_V^{2}) \tag{2}$$

(where C is a constant, m the electric tortuosity, Ω_+ is the surface charge density of clay, Q_V is charge per unit pore volume). These, and similar, theoretical and empirical laws all share the power-law form [KORVIN 1992]

$$k \propto \Phi^{\nu} \tag{3}$$

with different exponents ν. Therefore, it is a good practice [SERRA 1984] to always plot the k–Φ data on a double logarithmic grid and (if the points form a linear cluster) to find ν of Eq. (3) from the slope.

An intriguing aspect of these exponents is their *non-integer value*, which has obviously called for a derivation of Eq. 13 from simple *scaling arguments* [KORVIN 1992, pp. 292–298]. One possible scaling derivation

[MOSOLOV and DINARYEV 1987] of the rule (3) starts out from the D'Arcy law of flow in porous media

$$\boldsymbol{u} = -(k/\mu) \text{ grad } P \tag{4}$$

where $\boldsymbol{u}$ is the velocity of the flow, P is pressure, μ viscosity of the fluid, k permeability. Assuming that $\boldsymbol{u}$ does not depend on the spatial position x, the discharge Q in one second through a cross section A of linear size a perpendicularly to $\boldsymbol{u}$ is

$$Q \propto \rho\Phi \, |\boldsymbol{u}| \, a^2 = \rho\Phi \, (k/\mu) \, a^2 \, |\text{grad } P| \tag{5}$$

Suppose the porosity is built up of channels of characteristic width (say, radius) r, and that the number of channels of radius r are distributed with respect to some probability density function $n(r)$. Following KATZ and THOMPSON [1985] assume that the porosity Φ fractally scales with r between two characteristic length scales l_1 (20 Å)$< r < l_2$ ($\approx 50 - 100\mu$) as

$$\Phi \, (r) \propto \, (l_1/r)^{3-D} \tag{6}$$

where D is the fractal dimension of the pore space. The contribution of the channels of radius r to total porosity is $\Phi(r) \propto \, n(r) \, r^2$ that is by Eq. 6, putting $\delta = 3-D$,

$$n(r) \propto \, r^{\delta-2} \tag{7}$$

The discharge can also be expressed by Poiseuille's law:

$$Q \propto \rho \, (a^2/\mu) \, n(r) \, r^4 \, |\text{grad } P \, | \tag{8}$$

Matching Eqs. (5) and (8) yields

$$k(r) \propto n(r) \, r^4/\Phi \, (\, r \,) \propto \Phi^{\,2/\delta} \tag{9}$$

that is Eq. (3) becomes

$$k \propto \Phi^{\,2/\delta} = \Phi^{2/(3-D)} \tag{10}$$

A quite different power-law rule could be arrived at if we start out from the classical Kozeny–Carman equation [KOZENY 1927; CARMAN 1956; WALSH and BRACE 1984]

$$k = \Phi^{\,3}/(b \, S^2_{spec} \tau^2)$$

(see Eq. 1) where b is a shape factor of order one, τ is the tortuosity i.e. the ratio of the hydraulic path to the straight-line path [KORVIN 1992a]. The specific surface area of granular materials of surface-dimension D_S scales with particle size as [VAN DAMME et al. 1988; KORVIN 1992a]

$$S_{spec} \propto R^{D_S-3} \tag{11}$$

For the estimation of τ let us simply assume [following PAPE et al. 1987a] that the hydraulic path follows the cross-sectional outline of the pore wall. (This assumption is only justified in clay-free sediments. In clayey sandstones percolation-theoretical arguments give a more complicated scaling law [KORVIN 1992 pp. 17–33; 1992 a].) Consider a domain of characteristic size R. The hydraulic path-length $L(R)$ over a domain of linear size R scales as

$$L(R) \propto R^{D_S-1}$$

and we get

$$\tau \propto \frac{L(R)}{R} \propto R^{D_S-2} \tag{12}$$

Using Eqs. (11, 12) and assuming [as in KATZ and THOMSON 1985] that the fractal dimensions of the pore space (D in Eq. 6) and of the pore surface (D_S in Eq. 11) are the same, $D = D_S$, we get a power law with an exponent different from that in Eq. (10):

$$k \propto \Phi^{(D-1)/(3-D)} \tag{13}$$

(Note that RADLINSKY et al. [1999] recently suggested another scaling law

$$S_{spec} \propto R^{2-D_S}$$

for the specific surface area of rocks. However, this scaling leads to $k \propto \Phi^3$ which is not consistent with measurements.)

From Eqs. (10) and (13) two different possible relations can be derived between the exponent ν (in the rule $k \propto \Phi^\nu$) and the fractal dimension D of the pore surface. It is convenient to distinguish these two fractal dimensions as D_1 and D_2:

—For the first permeability model [MOSOLOV and DINARYEV 1987] $\nu = 2/(3-D)$ and

$$D_1=(3\nu-2)/\nu \tag{14}$$

—For the second permeability model [PAPE et al. 1987a; KORVIN 1992] $\nu = (D-1)/(3-D)$ and

$$D_2=(3\nu+1)/(\nu+1) \tag{15}$$

In order to experimentally establish a $k \propto \Phi^{\nu}$ trend for some rock type one has to measure porosity and permeability on a suit of representative rock samples belonging to the same lithology, age and depth range [ROBERTS and SCHWARTZ 1985]. From the obtained ν exponent, one can then estimate the fractal dimension D of the pore space by either of the Eqs. (14) or (15). As will be shown below (Section 4), the dimensions D_1 and D_2 belonging to the same ν value are quite different. Until further theoretical studies would more precisely define the exponent in the $k \propto \Phi^{\nu}$ law in terms of pore-surface dimension, both fractal dimensions should be accepted as possible values.

3. Measurement of porosity and permeability

The porosity and permeability measurements had been carried out on 20 sandstone and 20 limestone samples from Saudi Arabian reservoir rocks, and for a series of effective pressures ranging from 4 to 83 MPa (experimental details and porosity-, resp. permeability vs. pressure plots have been published in ABDULRAHEEM et al. [1999]). The samples were of cylindrical shape with 1.5 inch (3.81 cm) diameter and 1.0 inch (2.54 cm) length. For every sample, the confining pressure was increased from 4 MPa to 82 MPa in suitable increments. Sufficient time was left at every pressure step to ensure that the corresponding strains were fully developed. The porosity and permeability of the rock specimens were measured simultaneously at every pressure step. A combined porosity and permeability measurement apparatus was assembled for this purpose. The porosity was measured using the Helium gas expansion method (*Fig. 1*). The permeability was measured either by the steady state method (*Fig. 2*) or by the pressure pulse decay technique (*Fig. 3*) for some very tight samples. The procedure and theory for measuring the porosity by gas expansion method and permeability by steady state method are well known [GATLIN 1960; TIAB and DONALDSON 1996]. However, a brief review of determination of permeability by pressure pulse method seems necessary.

The schematic diagram showing the experimental arrangement of the transient pressure pulse test is shown in Fig. 3. The procedure consists of the following steps:

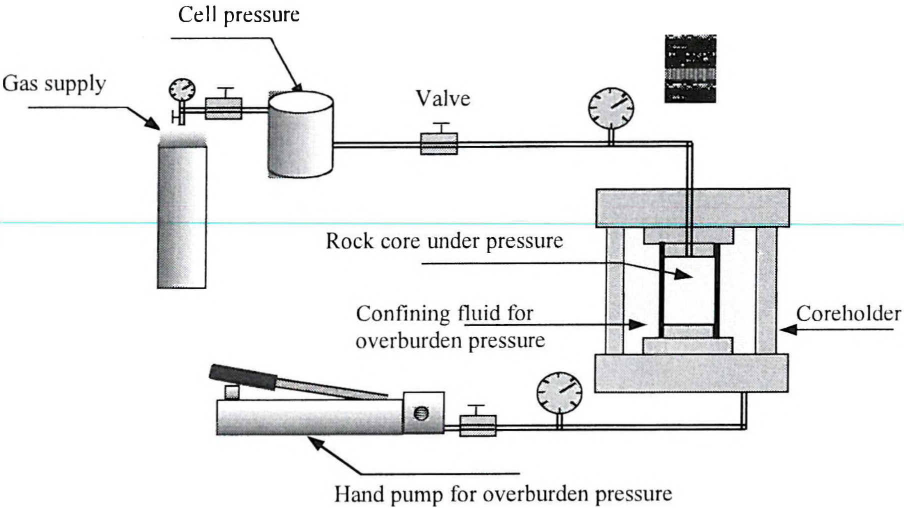

Fig. 1. Schematic of the porosimeter (Helium gas expansion method)
[From ABDULRAHEEM et al. 1999]
1. ábra. A porozitásmérő berendezés vázlata (Hélium gáz kiterjedéses módszer)
[ABDULRAHEEM et al. 1999 nyomán]

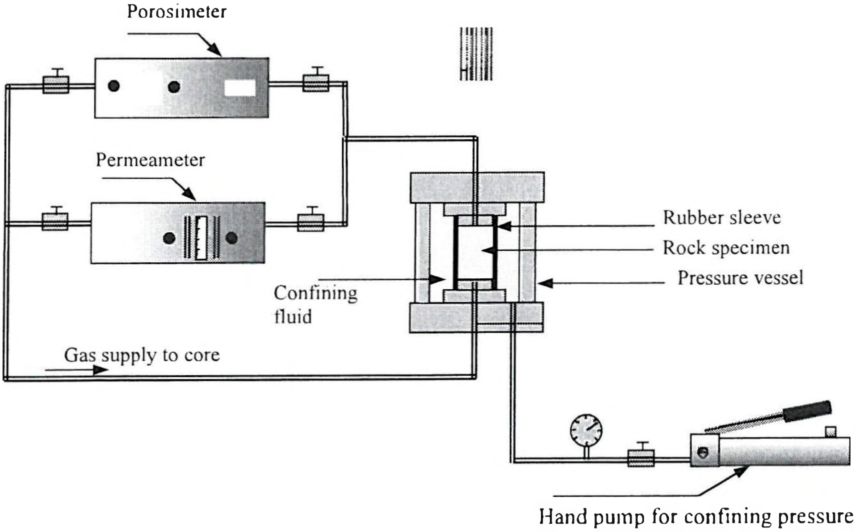

Fig. 2. Schematic for steady state method for permeability measurement
[From ABDULRAHEEM et al. 1999]
2. ábra. Permeabilitás mérése az állandósult fázis módszerével
[ABDULRAHEEM et al. 1999 nyomán]

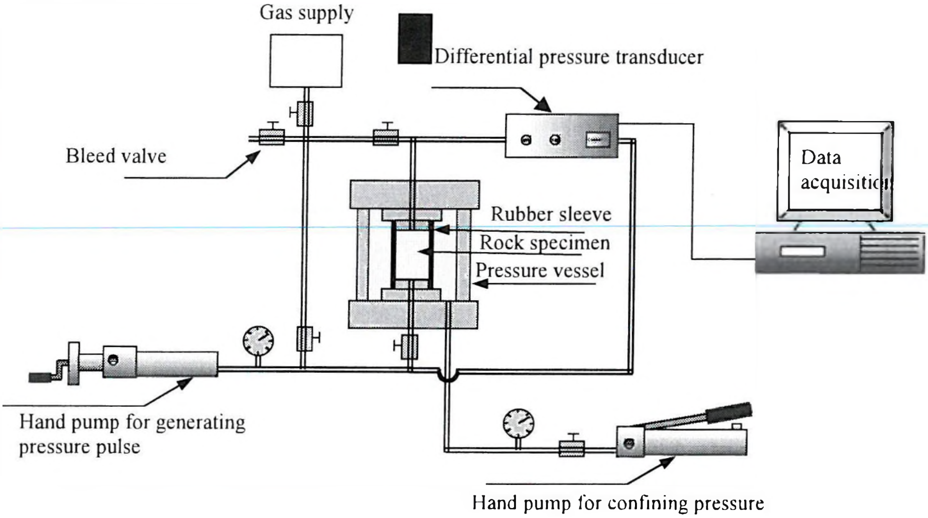

Fig. 3. Schematic for pulse decay method. [From ABDULRAHEEM et al. 1999]
3. ábra. Permeabilitás mérése a pulzus csillapodás módszerével [ABDULRAHEEM et al. 1999 nyomán]

- The system consisting of the core holder and the upper and lower reservoirs is brought to a certain pressure called the system pressure.
- The upper reservoir is isolated and its pressure is increased by about 2–3% of the system pressure.
- The pressure pulse is made to flow through the rock specimen and its decay with time is recorded by the data acquisition system. The pressure decay data can be used to determine the permeability of the rock specimen [BRACE et al. 1968; JONES 1994; TIAB and DONALDSON 1996].

4. Determination of the pore surface fractal dimension

For all pressure steps, and for both sandstones and limestones, the measured air permeability k as a function of porosity Φ followed a power law $k \propto \Phi^{\nu}$ (see *Tables I, II*). The exponent ν showed a smooth dependence on pressure P (*Figs. 4, 5*). Using Eqs. (14, 15), we converted the $\nu(P)$ relations to $D(P)$ relations which thus describe the *behavior of the fractal dimension D of the pore surface as function of effective pressure P.* Both possible mechanisms, $D_1(P)$ and $D_2(P)$, yielded physically plausible fractal pore surface dimensions (i.e. between 2 and 3). For all pressure steps $P \in [4MPa, 84MPa]$ the dimensions satisfied

$$2 < D_1^{sandstone}(P) < D_2^{sandstone}(P) < 2.5 \text{ and } 2.5 < D_1^{limestone}(P) < D_2^{limestone}(P) < 2.7.$$

P(MPa)	ν	$D_1=(3\nu-2)/\nu$	$D_2=(3\nu+1)/(\nu+1)$
04.13	2.10	2.048	2.355
13.79	2.30	2.130	2.394
24.13	2.45	2.184	2.420
34.47	2.47	2.190	2.424
44.81	2.58	2.225	2.441
55.15	2.90	2.310	2.487
65.50	2.78	2.281	2.471
75.84	2.93	2.317	2.491
82.73	2.95	2.322	2.494

Table I. Permeability exponent ν and fractal dimensions D_1 and D_2 for sandstone samples
I. táblázat. A ν permeabilitás kitevő és D_1 és D_2 fraktál dimenziók homokkövekre

P(MPa)	ν	$D_1=(3\nu-2)/\nu$	$D_2=(3\nu+1)/(\nu+1)$
04.13	5.68	2.648	2.701
13.79	5.71	2.650	2.702
24.13	5.59	2.642	2.697
34.47	5.59	2.642	2.697
44.81	5.60	2.643	2.697
55.15	5.42	2.631	2.688
65.50	5.25	2.619	2.680
75.84	5.14	2.611	2.674
82.73	4.94	2.595	2.663

Table II. Permeability exponent ν and fractal dimensions D_1 and D_2 for limestone samples
II. táblázat. A ν permeabilitás kitevő és D_1 és D_2 fraktál dimenziók mészkövekre

The behavior of the fractal dimensions D_1 and D_2 as functions of pressure is shown in Tables I, II and *Figs. 6* and *7*. Note that both kinds of fractal dimension are increasing with pressure for sandstones and decreasing with pressure for limestones. The higher values provided by the D_2 dimen-

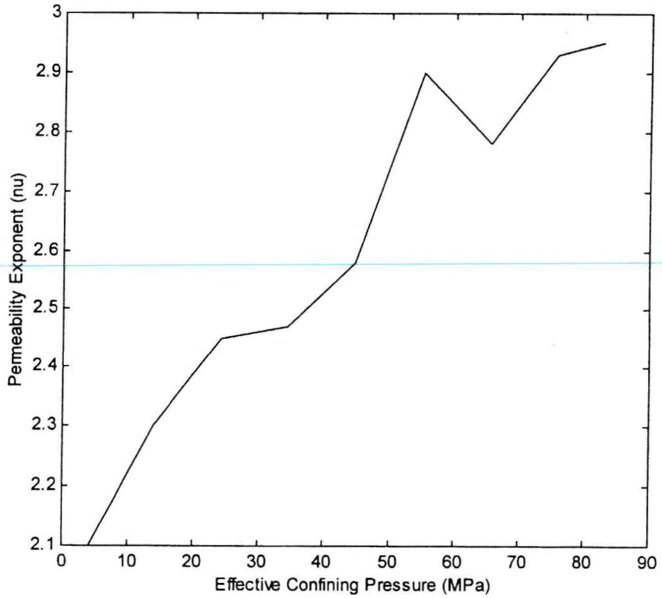

Fig. 4. The permeability exponent ν as function of pressure for sandstone samples
4. ábra. A permeabilitás hatványkitevő (ν) a nyomás függvényében homokkő minták esetében

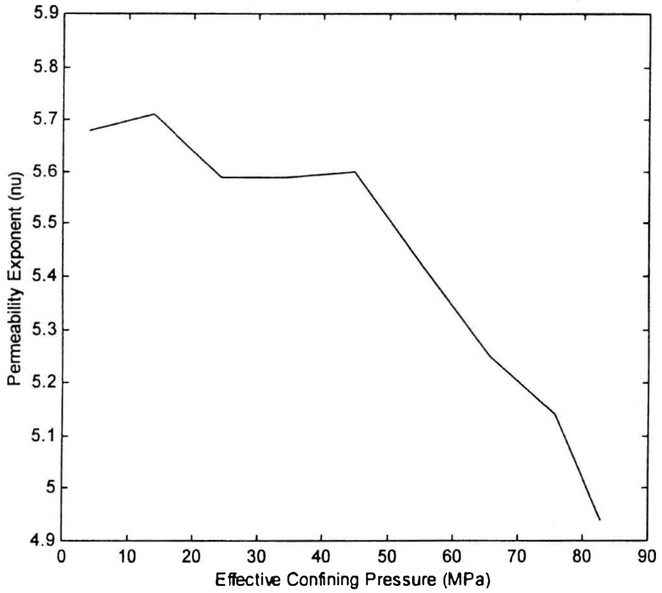

Fig. 5. The permeability exponent ν as function of pressure for limestone samples
5. ábra. A permeabilitás hatványkitevő (ν) a nyomás függvényében mészkő minták esetében

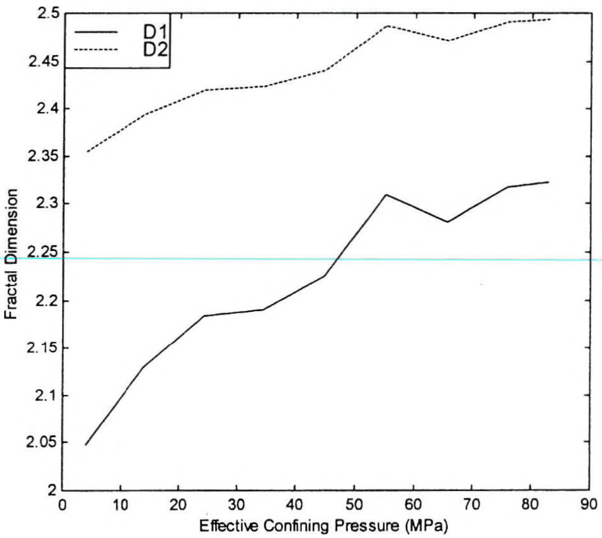

Fig. 6. The fractal dimensions D_1 and D_2 (Eqs. 14, 15) as functions of pressure for sandstone samples

6. ábra. A D_1 és D_2 fraktál-dimenziók (v.ö. 14, 15 egyenletek) a nyomás függvényében homokkő minták esetében

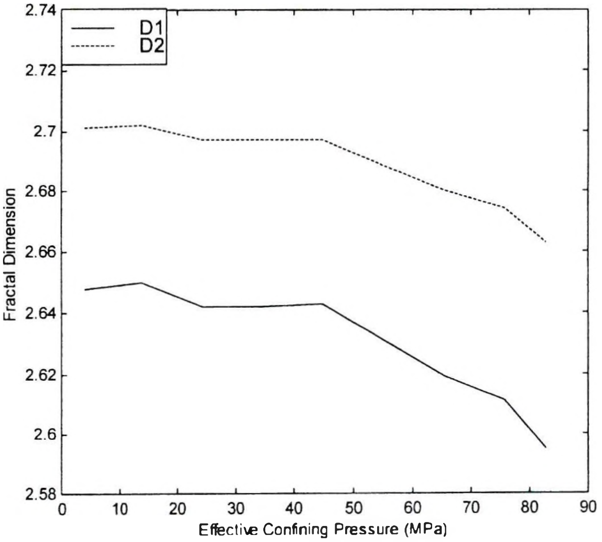

Fig. 7. The fractal dimensions D_1 and D_2 (Eqs. 14, 15) as functions of pressure for limestone samples

7. ábra. A D_1 és D_2 fraktál-dimenziók (v.ö. 14, 15 egyenletek) a nyomás függvényében mészkő minták esetében sions make this mechanism more plausible, but even these values are somewhat lower than most of the published D_S values [AVNIR et al. 1985; THOMPSON et al. 1987; KATZ and THOMPSON 1985; RADLINSKY et al. 1999]. The relatively low pore surface dimensions found in this study are likely due to the almost clay-free nature of the samples (less than 2% clay according to XRD, or to analysis by the pipette method [LEWIS and McCONCHIE 1994]). In reservoir rocks, low fractal dimensions correspond to the original unaltered pore surface [PELEG and NORMAND 1985; PAPE et al. 1987b], while the higher (≥ 2.7) values are related to the growth of diagenetic clay along the rock/pore interface [KROHN and THOMPSON 1986; WONG et al. 1986; WONG 1987] — which is absent in our samples.

5. Discussion

We cannot explain yet why $D(P)$ increases with P for sandstones while it decreases for limestones. In the pressure range of the experiments (<85 MPa) both porosity and permeability decreased with pressure for sandstone and limestone as well (*Figures 8* and *9* — the sandstone curves are convex from upwards, the limestone curves from downwards, as discussed in ABDULRAHEEM et al. [1999].) Conventional pore-space compression theory assumes non-interacting isolated spheroidal pores [ZIMMERMANN 1991]. In these rock models pore compressibility is inversely related to pore aspect ratio α as

$$C = 2(1-\nu)/\pi\alpha G + O(\alpha) \tag{16}$$

for small α, where the aspect ratio is $\alpha = b/a$, that is the pore's semi-minor axis divided by its semi-major axis; G is the solid rock component's shear modulus, ν (in this equation only) is its Poisson ratio. Consequently, the closing pressure of pores of different shape is proportional to α. With increasing pressure first the pores with small aspect ratio will close up, then gradually the more rounded ones. To apply this theory to sedimentary rocks, consider a fractal pore surface model where, on the analogy with the classical Von Koch snowflake construction, an initially smooth 2-dimensional surface is iteratively decorated with smaller and smaller-sized 'pigeonholes' [PAPE et al. 1987a, 1999] or 'pits' [DE GENNES 1985]. If the 'decorations' have a broad aspect ratio distribution and they are compressed in accordance with Eq. 16 then under increasing pressure the most

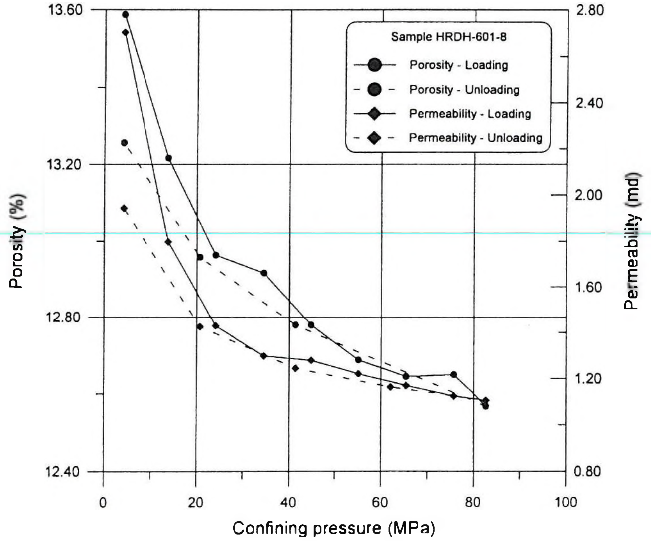

Fig. 8. Porosity and permeability as a function of confining pressure for sandstone sample [From ABDULRAHEEM et al. 1999]

8. ábra. A porozitás és permeabilitás nyomásfüggése homokkő mintára [ABDULRAHEEM et al. 1999 nyomán]

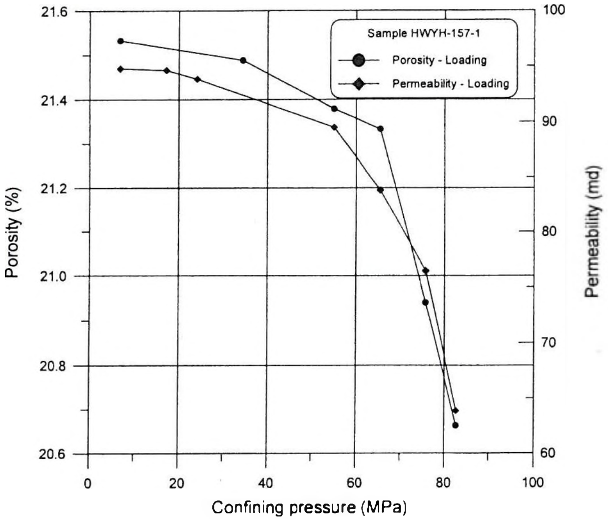

Fig. 9. Porosity and permeability as a function of confining pressure for limestone sample [From ABDULRAHEEM et al. 1999]

9. ábra. A porozitás és permeabilitás nyomásfüggése mészkő mintára [ABDULRAHEEM et al. 1999 nyomán] elongated ones will close up first and the mean aspect ratio would shift to higher α values. In this case — as follows from the details of the Von Koch construction [FEDER 1988; KORVIN 1992] — the fractal dimension D_S would decrease with increasing P because the more elongated decorations, which had significantly contributed to the surface area, quickly close up and are no longer available at high pressures.

While this model (qualitatively, at least) explains the decreasing $D(P)$ in limestone where cracks and penny-shape pores with small aspect ratio are more frequent [PITTMAN 1984], it contradicts the increasing $D(P)$ trend in sandstone. In unstressed sandstone the pore aspect ratio distribution is much narrower [ZIMMERMANN 1991] and most of the 'decorations' are half-spherical. Under pressure however, if we wait long enough for the strains to fully develop, the pore surface will be in statistical equilibrium with the stress field. By Boltzmann's maximum-entropy principle [KORVIN 1984] the equilibrium pore configuration would necessarily contain some elongated pores as well. Their larger contribution to surface area, and additional phenomena like stress-induced relative grain displacements and the natural tendency of the pore surface to maximize itself [COHEN 1987] lead to surface roughening which could then result in an increasing $D(P)$ like in Fig. 6.

As one of the Reviewers rightly pointed out, this explanation is not very convincing. In a sequel to this paper [KORVIN et al. 2001], an other explanation is proposed, based on the statistical geometry of crumpled paper balls, and a modified Kozeny-Carman relation.

6. Conclusions

A new experimental technique has been developed to indirectly determine the fractal dimension of the pore surface of sedimentary rocks under varying pressure. In this technique, one first establishes a permeability vs. porosity relation on a suit of samples of the same lithology at each different pressure step. The fractal surface dimension is then estimated from the exponent ν figuring in the power law $k \propto \Phi^{\nu}$ describing k vs. Φ for the corresponding lithology and pressure.

A deficiency of the technique is that at present the physics of flow in fractal media is not properly understood. To date, at least three different scaling rules have been proposed to connect Φ, k, and D_S: MOSOLOV and DINARYEV's Eq. 10; PAPE et al.'s Eq. 13; and RADLINSKY et al.'s $k \propto \Phi^3$ law. The simple cubic law is inconsistent with measurements. Both Eqs. 10 and 13 are viable mechanisms, though Eq. 13 is more plausible in light of published pore surface dimensions. Alas, the present set of measurements could not be used to decide between the competing theories.

It has been found that as the confining pressure increased from 4 to 83 MPa, the surface fractal dimension of sandstone increased from 2 to 2.5, while for limestone it decreased from 2.7 to 2.65. The different pressure-dependencies of the fractal dimension of the pore surface in case of the two lithologies are due to the different factors governing compression in the various rock types.

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REFERENCES

ABDULRAHEEM A., MOHIUDDIN M. A., KORVIN G., AWAL M. R., KHAN K, KHAN M. S, AL-GHAMDI A. 1999: Parametric study of ultrasonic velocity using reservoir cores for enhancing seismic signatures for improved reservoir definition. Soc. Petr. Engs. Saudi Arabian Section Proceedings (Oct. 24–27, 1999), pp. 111–120

AVNIR A., FARIN D., PFEIFER P. 1985: Surface geometric irregularity of particulate materials: the fractal approach. J. Colloid Interf. Sci. **103**, pp. 112–123

BRACE W. F., WALSH J. B., FRANGOS W. T. 1968: Permeability of granite under high pressure. J. Geoph. Res. **73**, pp. 2225–2236

CARMAN P. C. 1956: Flow of Gases through Porous Media. Butterworth, London

COHEN M. H. 1987: The morphology of porous sedimentary rocks. *In:* BANAVAR J. R, KOPLIK J., WINKLER K. W. (*eds.*), Physics and Chemistry of Porous Media, II. AIP Conf. Proc. **154** (AIP, New York), pp. 3–16

DE GENNES P.-G. 1985: Partial filling of a fractal structure by a wetting fluid. *In:* ADLER D. et al. (*eds.*), Physics of Disordered Materials, Plenum, New York, pp. 227–241

FEDER J. 1988: Fractals. Plenum Press, New York

GATLIN C. 1960: Petroleum Engineering: Drilling and Well Completion. Prentice Hall, New York

GOODE P., SEN P. S. 1988: Charge density and permeability in clay-bearing sandstones. Geophysics **53**, pp. 1610–1612

JONES S. C. 1994: A technique for faster pulse-decay permeability measurements in tight rocks. SPE #28450, SPE 29th Ann. Technical Conf. and Exhibition, New Orleans, LA, 25–28 September, 1994.

KATZ A. J., THOMPSON A. H. 1985: Fractal sandstone pores: Implications for conductivity and pore formation. Phys. Rev. Lett. **54**, pp. 1325–1328

KORVIN G. 1984: Shale compaction and statistical physics. Geophys. J. R. Astron. Soc. **78**, pp. 35–50

KORVIN G. 1992: Fractal Models in the Earth Sciences. Elsevier, Amsterdam, 396 p.

KORVIN G. 1992a: A percolation model for the permeability of kaolinite-bearing sandstones. Geophys. Trans. **37**, pp. 177–209

KORVIN G., AKBAR N., MOHIUDDIN M. A., ABDULRAHEEM A. 2001: Changes in the fractal dimension of the pore surface of sedimentary rocks under pressure. 1st Saudi Sci. Conf. Proc., Dhahran, Saudi Arabia **3**, pp. 217–228

KOZENY J. 1927: Über die kapillare Leitung des Wassers im Boden (Aufstieg, Versickerung und Anwendung auf die Bewässerung). Sitzungsber. Akad. Wiss. Wien, Math. Naturwiss. (Abt. 2a) **136a**, pp. 271–306

KROHN C. E., THOMPSON A. H. 1986: Fractal sandstone pores. Phys. Rev. B **33**, pp. 6366–6374

LEWIS D., MCCONCHIE D. 1994: Analytical Sedimentology. Chapman & Hall, New York

MOSOLOV A. B., DINARYEV O.Yu. 1987: Fractal models of porous media (In Russian). J. Techn. Phys. **57**, pp. 1679–1685

PAPE H., RIEPE L., SCHOPPER J. R. 1987a: Theory of self-similar network structures in sedimentary and igneous rocks and their investigation with microscopical and physical methods. J. Microsc. **148**, Pt. 2, pp. 121–147

PAPE H., RIEPE L., SCHOPPER J. R. 1987b: Interlayer conductivity of rocks — a fractal model of interface irregularities for calculating interlayer conductivity of natural porous mineral systems. Colloids Surf. **27**, pp. 97–122

PAPE H., CLAUSER CH., IFFLAND J. 1999: Permeability prediction based on fractal pore-space geometry. Geophysics **64**, pp. 1447–1460

PELEG M., NORMAND M. D. 1985: Mechanical stability as the limit to the fractal dimension of solid particle silhouettes. Powder Technol. **43**, pp. 187–188

PITTMAN E. D. 1984: The pore geometries of reservoir rocks. *In*: JOHNSON D., SEN P.N. (*eds.*). Physics and Chemistry of Porous Media. AIP, New York, pp. 1–30

RADLINSKY A. P., RADLINSKA E. Z., AGAMALIAN N., WIGNALL G. D., LINDNER P., RANDL O. G. 1999: Fractal geometry of rocks. Phys. Rev. Lett. **82**, pp. 3078–3081

ROBERTS J. N., SCHWARTZ L. M. 1985: Grain consolidation and electrical conductivity in porous media. Phys. Rev. B **31**, pp. 5990–5997

SERRA O. 1984: Fundamentals of Well-Log Interpretation. I. The Acquisition of Logging Data. Elsevier, Amsterdam, 423 p.

THOMPSON A. H., KATZ A. J., KROHN C. E. 1987: The microgeometry and transport properties of sedimentary rock. Adv. Phys. **36**, pp. 625–694

TIAB D., DONALDSON E. 1996: Petrophysics: Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties. Gulf Publishing, Texas, USA

VAN DAMME H., LEVITZ P., GATINEAU L., ALCOVERE J. F., FRIPIAT J. J. 1988: On the determination of the surface fractal dimension of powders by granulometric analysis. J. Colloid Interf. Sci. **122**, pp. 1–8

WALSH J. B., BRACE W. F. 1984: The effect of pressure on porosity and the transport properties of rock. J. Geoph. Res. **89B**, pp. 9425–9431

WONG P. –Z. 1987: Fractal surfaces in porous media. *In*: BANAVAR J.R., KOPLIK J., WINKLER K.W. (*eds.*), Physics and Chemistry of Porous Media, II. AIP Conf. Proc. **154**, AIP, New York, pp. 304–317

WONG P. –Z., HOWARD J., LIN J.-S. 1986: Surface roughening and the fractal nature of rocks. Phys. Rev. Lett. **57**, pp. 637–640

ZIMMERMAN R. W. 1991: Compressibility of Sandstones. Elsevier, Amsterdam, 1991

Kísérleti módszer az üledékes kőzetek fraktális porozitásának tanulmányozására a nyomás függvényében

KORVIN Gábor, Mohammed A. MOHIUDDIN és Abdulazeez ABDULRAHEEM

A dolgozat egy új kísérleti módszert ismertet amellyel fokozatosan növekedő nyomásnak alávetett üledékes kőzetek pórusfelszinének fraktál dimenzióját tanulmányoztuk. Húsz-húsz, Szaudi Arábia-i tárolókőzetekből származó homokkő és mészkő mintát vizsgáltunk; a nyomás 4 MPa -tól 83 MPa-ig változott. Minden egyes nyomásértéknél, és mindkét kőzetfajtára, a porozitás és permeabilitás között $k \propto \Phi^{\nu}$ alakú hatványfüggvény összefüggés volt. Homokkövekre a ν kitevő folytonosan növekedett kb. 2-ről kb. 3-ig, ahogy a nyomás 4-ról 83 MPa-ra nőtt. Mészkövekre ugyanebben a nyomástartományban a ν kitevő monoton csökkent kb. 5,7-ről kb. 5-re. Ha elfogadjuk a két, az irodalomból ismert fraktál modell valamelyikét a közetekben való folyadékáramlás leirására, a hatványkitevőből meghatározható a pórusok felszinének D fraktál-dimenziója. Úgy találtuk, hogy D növekszik a nyomással $D \approx 2$-ről $D \approx 2.5$-re homokkövekre, és csökken $D \approx 2.7$-ről $D \approx 2{,}65$-re mészkövek esetében. A fraktál-dimenzió nyomásfüggése azért különbözik a két kőzetfajta esetében, mert a kőzetek kompressziójanak mechanizmusa is teljesen különböző jellegű.

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Compaction of sediments with great thickness in the Pannonian Basin

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Horizontal and vertical distribution of the geophysical parameters measured in borehole include valuable information. Sediment filling the Pannonian Basin is analysed by means of density and velocity data from boreholes. Special attention is paid to the compaction relationships of rocks and discovering the sites of discordance developed during deposition. In addition, the possibilities of determining the subsidence and uplifting phases of deposition are shown.

A subsidence map is given to illustrate the area of the country where the boreholes belonging to the present research are located.

Keywords: density, velocity, deposition, subsidence, uplifts, compaction, discordance

1. Introduction

By virtue of its measuring methods borehole geophysics is directly linked with the given rock. A wide range of geological information is available from borehole geophysics, and mineralogy, petrology and palaeontology characteristics are given by analysing cores in the laboratory.

One of the advantages of borehole geophysics is that it gives so much additional information by virtue of its ability to measure the depth trend of geophysical parameters; this is not generally the case with core investigations. In addition to the sedimentary geological cycles — regression, transgression — other 'trendlike' physical changes connected with the mechanical state of a rock can be obtained.

Well logs give valuable information on the reconstruction of events of geological history by recognition of special attributes of the rocks from the borehole. Analysis of horizontal and vertical distribution relations of petrophysical parameters gives a possibility to determine the rate of basic deposition phases (subsidence, uplift).

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A knowledge of the physical properties of rock is of essential importance in investigating earthquake hazards. In the event of an earthquake with a given strength the effective accelerations primarily depend on the attributes of deeply lying rocks. For instance consolidation can be characterized by the density and velocity data from well logs, depth trends and their gradient according to the depth.

With the help of well log data the temporal formation of compaction can be followed. Temporal formation is equivalent to the succession of events and it can be investigated on the basis of the discordances. In a borehole there are several compaction trend sections among the discordances.

The discordance depth spots based on the compaction can be revealed by changes of density and velocity with the depth. By definition, a break in the depth trend corresponds to a discordance site. Discordance does not necessarily mean a discordance stratigraphically: it is sufficient if there is only a drastic change in the rate of subsidence.

If we consider the sediment as being in equilibrium — in other words if subsidence does not continue it is not expected that further compaction will take place solely because of the weight of the sediment — the maximum buried depth can be estimated by comparing the unique and countrywide depth trends.

Knowledge on the extent of movements that took place during the Earth's history can also be linked with the tectonic units of a given basin — in our case, the Pannonian.

2. Depth related increase in density and velocity in the Pannonian Basin

The Pannonian Basin is filled with sediment of great mass, spreading horizontally and vertically. The time and the pressure from the weights of the beds deposited one on top of the other played a significant role in the evolution of the Basin's physical characteristics. Borehole geophysics gives in situ information about the physical characteristics of the sedimentary rock complex of the basin. Those well logs from boreholes deeper than 1000 m are advantageous from the point of view of analysing depth trends. Hydrocarbon prospecting over the last four decades has created a fortunate situation in that borehole geophysical measurements carried out in hydrocarbon wells can be utilized to study the evolution and internal structure of the basin.

The rock structure has an effect basically on the values of density, porosity and longitudinal velocity. All three parameters are measurable in the boreholes well. The effect of compaction on the porosity was investigated by KISS B. et al. [1990]. In the case of 100 % water saturation and constant matrix density the relation between density and porosity is unambiguous. In our study a phenomenon is presented which is independent of porosity and to some extent the cementation effects. The above mentioned phenomenon mainly influences the velocity of the sonic waves through the rock (V_P). The increment of sonic velocity is partly connected with the increment of pressure too. This phenomenon is well recognizable in the near-surface loose sediments and in the Lower Pannonian sediments which are well consolidated with regard to porosity and cementation. In both cases the basis of the V_P changes is the increment of shear modulus versus increment of geostatic pressure. Therefore the velocity depth trend is to some extent independent of the changes in porosity and cementation connected with diagenesis.

It is due to the different physical effects taking place during the sedimentation process, a process with a time span of millions of years during which layers of eroded rock material are deposited on each other. Simultaneously with the thickening of the sedimentary rock the increasing weight of the rock gradually drives out water from the pores. The result is that the rock will be more compact and its density increases. In consequence of the decreasing distance between the rock grains the propagation of elastic waves is advanced: the wave velocity increases in the rocks. Consequently the distance from the surface, i.e. the depth, affects each and every parameter.

In order to clarify the role of depth we collected borehole details from various parts of the country, that satisfy the following conditions:

— the sediment was bored to a depth of at least 1000 m because there is high probability that the effective error caused by borehole structure changes became negligible and a systematic difference from the true parameters was thus unlikely.

— there are density and velocity logs in it,

— its co-ordinates are advantageous from the point of view of the examination.

The aim was to cover the whole country with boreholes.

The end result of data collection was that we were able to utilize 30 boreholes; the territorial distribution of these boreholes is shown in *Fig. 1*. Ten boreholes are situated in Transdanubia, the others are located east of the Danube. (It is mentioned that in boreholes Hercegszántó–2 and Nagykökényes–I the thickness of the sediment is less than 1000 m, but as their territorial coordinates are advantageous they were used in the detailed investigations). Uniform coverage of the country with boreholes has not been solved. Apart from the Northern Central Range and Transdanubian Central Range there are no boreholes on the territory between the Lake Balaton and the Danube, and the northern part of the Hungarian basin.

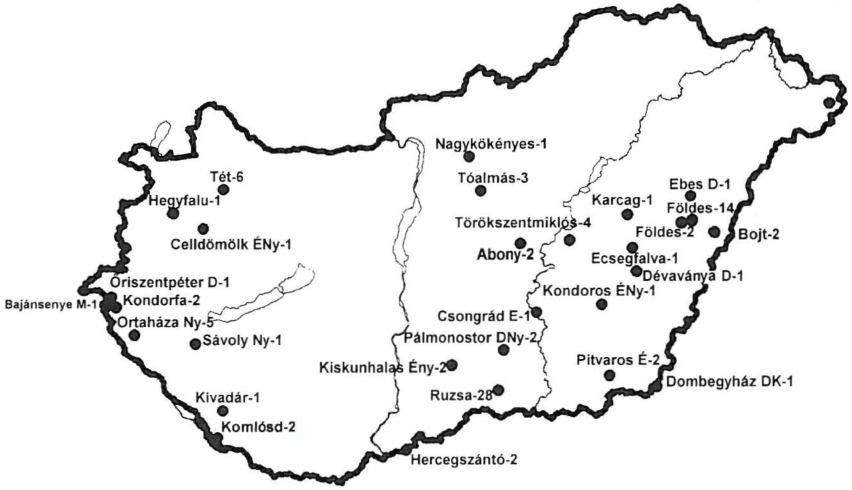

Fig. 1. Territorial distribution of 30 boreholes
1. ábra. A 30 fúrás területi eloszlása

We used a sampling of 10 m instead of the original one of 10–20 cm, which is more appropriate for investigating comprehensive trends. As a result of averaging the number of data decreased by 50 % thereby facilitating data handling.

The boreholes of interest are presented in *Table I.* divided into geological ages down to Lower Pannonian. Most of the boreholes bored the Lower Pannonian in total thickness. Two boreholes (Kondoros ÉNy–1 and Törökszentmiklós–4) stopped in the Lower Pannonian for some reason, but the logged thickness of the sediments is near 1000 m.

No.	Great Hungarian Plain Borehole names	Q	Q+UPL	UPL	UPL+UP	UP+ younger	UP	LP
1	Abony-2	55-235	_	235-465	_	_	465-955	965-2065
2	Bojt-2		_	46-486	_	_	496-1356	1356-2786
3	Csongrád É-1	55-345	_	355-645	_	_	655-1905	1915-2705
4	Dévaványa D-1	85-595	_	595-1155	_	_	1155-1955	1965-2915
5	Dombegyház DK-1	50-150	_	160-450	_	_	460-790	790-1120
6	Ebes D-1	32-112	_	122-552	_	_	562-1172	1182-1502
7	Ecsegfalva-1	60-470	_	480-870	_	_	870-1550	1560-2540
8	Földes - 2	75-375	_	_	_	_	385-1765	1775-3135
9	Földes -14	55-345	_	_	355-1715	_		1725-3115
10	Gacsály-1	35-45	_	_	_	_	45-1105	1115-1305
11	Hercegszántó-2	_	_	_	_	_	90-530	540-960
12	Karcag-1	_	160-400	_	_	_	410-920	930-2497.5
13	Kiskunhalas ÉNy-2	_	_	_	_	_	35-735	735-1665
14	Kondoros ÉNy-1	113-423	_	433-973	_	_	983-2013	2023-2999
15	Nagykökényes-1	_	_	_	_	_	62-602	612-942
16	Pálmonostor DNy-2	_	_	_	_	_	35-1705	1715-2125
17	Pitvaros É-2	155-335	_	345-765	_	_	775-1365	1375-1885
18	Ruzsa-28	_	_	_	_	_	505-1285	1295-2455
19	Tóalmás-3	_	_	_	_	_	159.5-624.8	624.8-1344.
20	Törökszentmiklós-4	34-314	_	324-654	_	_	664-1054	1064-1900
No.	TRANSDANUBIA Borehole names							
1	Bajánsenye-Mély M-1	_	_	_	_	305-1525	_	1525-2255
2	Celldömölk ÉNy-1	_	_	_	_	95-1045	_	1055-1605
3	Hegyfalu-1	_	_	_	_	110-1240	_	1240-1830
4	Kivadár-1	_	_	_	_	55-1345	_	1355-2143.5
5	Komlósd-2	_	_	_	_	555-1355	_	1365-2865
6	Kondorfa-2	_	_	_	_	55-1475	_	1485-2185
7	Ortaháza Ny-5	_	_	_	_	70-1600	_	1600-2670
8	Őriszentpéter D-1	_	_	_	_	305-1485	_	1485-2155
9	Sávoly-Nyugat-1	_	_	_	_	35-825	_	825-1565
10	Tét-6	_	609-1448	_	_	_	_	1458-2328
	Q=Quaternary, UPL=Upper Pliocene, UP=Upper Pannonian, LP=Lower Pannonian							

Table I. Depth intervals of sedimentary complexes

I. táblázat. Üledékes kőzetek mélység intervallumai

Density-depth trends in the Pannonian Basin

The measured density curves can be fitted by a $y=ax+b$ line, but this linear approach does not fully describe the density–depth function. Judging from experience it would be more practical to divide the measured density curve into two or more sections and to fit lines of different slope on every section. In spite of the good correlation coefficient (r^2~0.9) the linear fitting line is not suitable for extrapolation towards the surface nor towards greater depths. In the latter case the density values may increase abnormally with the depth [MÉSZÁROS, ZILAHI 1998].

The density of sediments is determined by the density of fluid and gas in the rock matrix and pore volume. The dimensions of the pore volume are limited in nature therefore the density of sediments is between a minimum and a maximum value. Under ideal conditions when the grains are homogeneous, uniform and spherical, the theoretical value of porosity is 47% [VENDL 1953]. Assuming that the fluid in the pores is water this porosity corresponds to a density of 1.87 g/cm^3. In reality this is not true in the majority of cases. The occupation of the space is larger in general, thereby porosity decreases and density increases. The density of a sediment at 100% water saturation — apart from extreme cases such as bentonite, pumice and gravel — is limited from below and above. Based on experience a $y=a-b\,e^{(-cx)}$ function correctly describes the special behaviour of the density. The physical meaning of the function coefficients are:

a: maximum density of the sediments

b: domain of the parameter change compared to the extrapolated density of the surface

c: rate of increase.

The 'b' and 'c' coefficients of the countrywide density–depth trend are determined by median values of 'b' and 'c' coefficients of the density–depth trends for the individual boreholes. The trend of the borehole Komlósd–2 strikingly differs from the average. In view of the robust estimation approach this trend was not included in the calculations of the countrywide and Transdanubian trends. On the basis of 29 boreholes the analytical form of the ORSZÁGOS (countrywide) density–depth trend is:

$$\rho = 2.7-0.80\,e^{(-0.00071h)}$$

The coefficient $a = 2.7$ represents the maximum density of the sedimentary rocks. As soon as the depth increases the sediment becomes more cemented and its lime content increases [FÜLÖP J. 1989]. The function describes with good approach the measurable density relations at different borehole locations.

The analytical form of the ALFÖLD (Great Hungarian Plain, i.e. GHP) density–depth function determined for the eastern part of the country on the basis of 20 boreholes — the intermediate space between the Danube –Tisza and the territory east of the Tisza — is

$$\rho = 2.7 - 0.81\, e^{(-0.00068h)}$$

In a similar way the DUNÁNTÚL density–depth trend for Transdanubia is:

$$\rho = 2.7 - 0.74\, e^{(-0.00087h)}$$

Figure 2 shows the graphical forms of the three function trends.

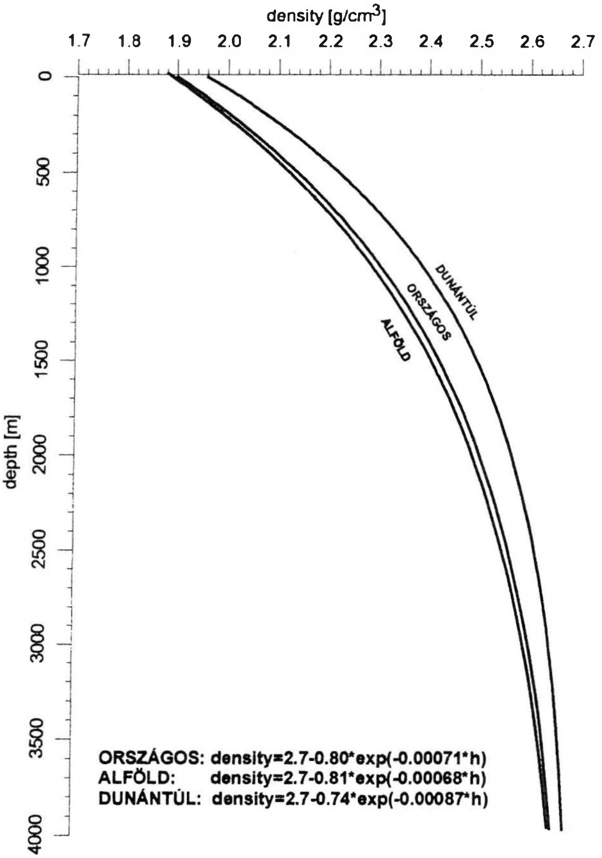

Fig. 2. Density–depth functions of sediment complex in the Pannonian Basin
2. *ábra.* A Pannon-medence üledékes összletének sűrűség–mélység függvényei

Velocity–depth trends in the Pannonian Basin

On the basis of similar considerations we used the previously described exponential function to investigate the relation between velocity and depth. We determined the maximum value of velocity of the elastic wave (a) on the basis of the following:

— the average velocity of the lowest 100 meters measured in 30 boreholes is 4627 m/s

— two boreholes stopped in the Lower Pannonian therefore the rounded average is 5000 m/s.

5000 m/s average velocity is considered to be correct because no metamorphose occurred during the sedimentation. This means the last condition can be obtained only by diagenesis. The meanings of coefficients b and c are the same as those previously mentioned.

Detailed investigations showed that borehole Komlósd–2 also behaves anomalously from the point of view of the elastic wave velocity therefore it was not taken into consideration in the countrywide (ORSZÁGOS) and Transdanubian (DUNÁNTÚL) trends.

The analytical form of the ORSZÁGOS velocity–depth trend from the data of 29 boreholes is:

$$v = 5000-3610\ e^{(-0.00042h)}$$

This function describes the measurable velocity relations with a good approach in different parts of the country.

The ALFÖLD trend estimated for the eastern part of the country is:

$$v = 5000-3620\ e^{(-0.00040h)}$$

The analytical form of the DUNÁNTÚL trend for Transdanubia is:

$$v = 5000-3440\ e^{(-0.00046h)}$$

The three trend functions are shown in *Fig. 3*. In Figs. 2 and 3 it can be seen that the DUNÁNTÚL trend's documented sedimentation history is different from that of the ALFÖLD's. The h=0 in depth trends corresponds to the value of density and velocity on the surface.

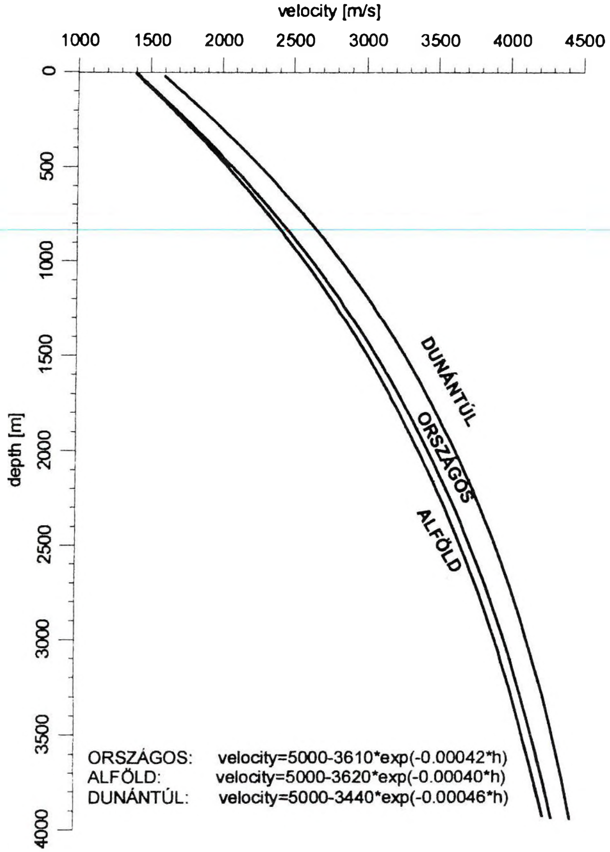

Fig. 3. Velocity–depth functions of sediment complex in the Pannonian Basin
3. ábra. A Pannon-medence üledékes összletének sebesség–mélység függvényei

3. Appearance of discordance depending on the compaction of the depth trend of curves

The depth trends in Figs. 2 and 3 probably do not include the effect of the differently signed anomalies of density and velocity in the coefficients due to the special median averaging. The continuous depth trend functions reflect a uniform, unbroken sedimentation.

The little difference in the two kinds of depth trend indicates that the changes during the sedimentation did not equally influence the increase of the two fundamental parameters. The increase of density as we go deeper starts to slow down — its gradient gets smaller — before the growth of velocity slows down. A significant velocity increase in relation to depth can be observed especially at depth trends of DUNÁNTÚL below 2500 m where the rocks can be considered compact from the viewpoint of density. The most intensive change — the steepest part of the diagram — can be observed in the Quaternary. In the Upper and Lower Pannonian the increase of density and velocity with depth slows down. The behaviour of the two parameters can be tracked by detailed analysis of the density and velocity logs measured in boreholes.

Investigating the density and velocity changes in the Quaternary and Pliocene we can find differences in the behaviour of the two parameters. On the basis of Table I, the separation of Quaternary and Upper Pliocene in the majority of boreholes can only be made for the Great Hungarian Plain. The density versus velocity cross plots unambiguously prove the different behaviour of the density and velocity values from the point of view of compaction. For example the Quaternary formations are, based on our expectations, undercompacted in velocity. This means a greater velocity change belongs to a relatively small density change (*Fig. 4*). The explanation of this can be found in the changes of the rock structure resulting from the effects of the depth. In that pressure increases with depth, the type of the contacts between the grains changes first of all. The looser contacts belonging to smaller pressures will gradually transform. With increasing pressure a closer contact develops between the grains thereby promoting first of all the propagation of the elastic waves, viz. the longitudinal propagation velocity measurable by well logging increases. The change of the contact between the grains has little influence on the density.

This is supported by both the countrywide density–depth and velocity– depth trends. We defined the lower depth boundary of the Upper Pliocene to be 700 m by average values measured in the Great Hungarian Plain boreholes shown in Table I. The changes in density and velocity for 700 m are not the same. The relative velocity growth is 50 % greater than the relative density change.

In *Fig. 5* it can be observed in more detail that up to a certain pressure (depth) the density remains constant or decreases in the regions younger than Upper Pannonian. On the other hand the sonic velocity below a short depth interval of stagnation observable in the smaller depths near the surface shows a definite increasing tendency.

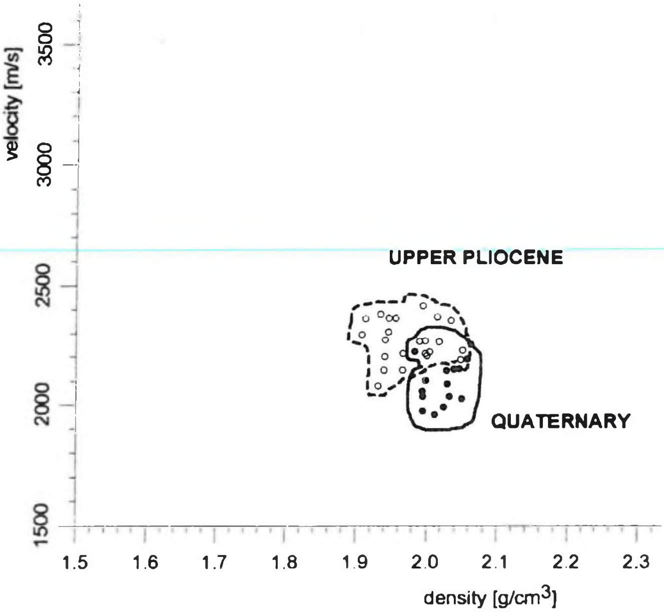

Fig. 4. Differentiation of Upper Pliocene and Quaternary in borehole Abony–2
4. ábra. Felső-pliocén és kvarter elkülönülése az Abony–2 fúrásban

The situation at the boundary between Upper and Lower Pannonian differs from the Q/P boundary. The Pannonian Basin has not fully evolved. The boundary between Lower and Upper Pannonian is not an isochronous surface but rather a lithostratigraphic boundary. According to *Figs. 6* and *7* the Upper Pannonian is settled discordantly on the Lower Pannonian. On the mentioned boundary of the boreholes Pitvaros É–2 and Kondorfa–2 the density curve — proceeding from the surface to greater depths — has an abrupt growth then it continues at a higher level with 0.1 g/cm^3.

A special situation exists in the borehole Törökszentmiklós–4 (*Fig. 8*). The density practically does not change versus depth in the Upper Pannonian, but it begins to increase drastically in the Lower Pannonian. It is possible that the places characterized by sudden decreasing density and velocity indicate the presence of gas.

The velocity logs can also be seen in all three figures, which may support the discordance— though only to a small extent. A break can be observed on the depth trend of the velocity curve; on the other hand the veloc-

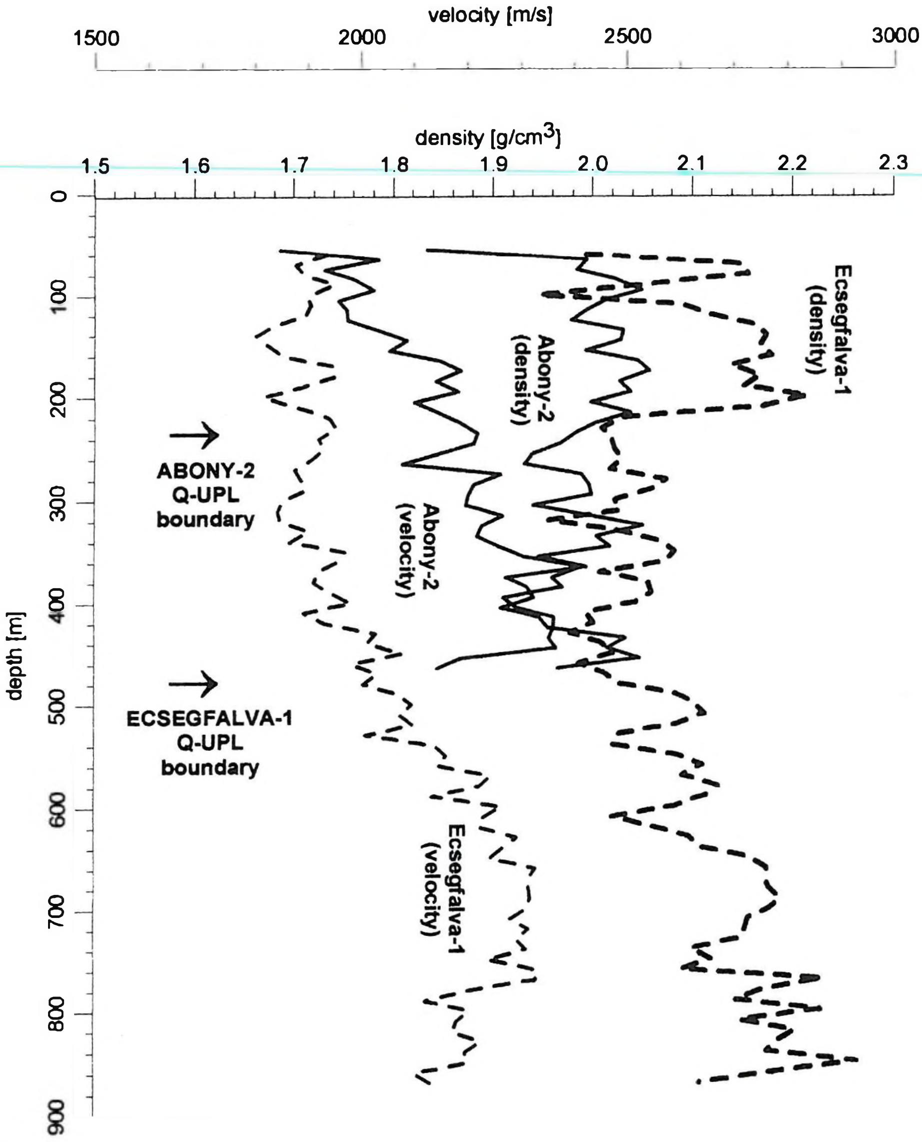

Fig. 5. Compaction based on velocity and density in the Quaternary and Upper Pliocene
5. ábra. Sebesség és sűrűség szerinti kompakció a kvarterben és a felső pliocénben

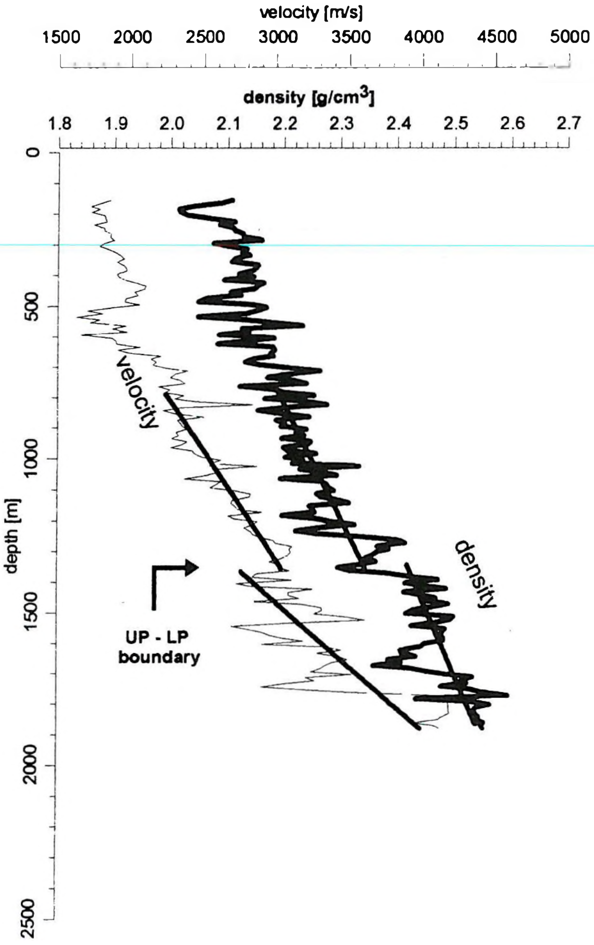

Fig. 6. Discordance on the boundary of Lower Pannonian–Upper Pannonian in borehole Pitvaros É–2

6. ábra. Diszkordancia az alsó pannon felső–pannon határon a Pitvaros É–2 fúrásban

ity values show much greater fluctuations in the Lower Pannonian than in the Upper Pannonian.

The individual geological ages are approached by lines in order to able to survey the density and velocity curves easily. In Kondorfa–2 borehole (Fig. 7) this can only be seen in the Lower Pannonian because we do not have exact information about the boundary between the Upper Pannonian and the younger beds above them. This boundary can be marked with great

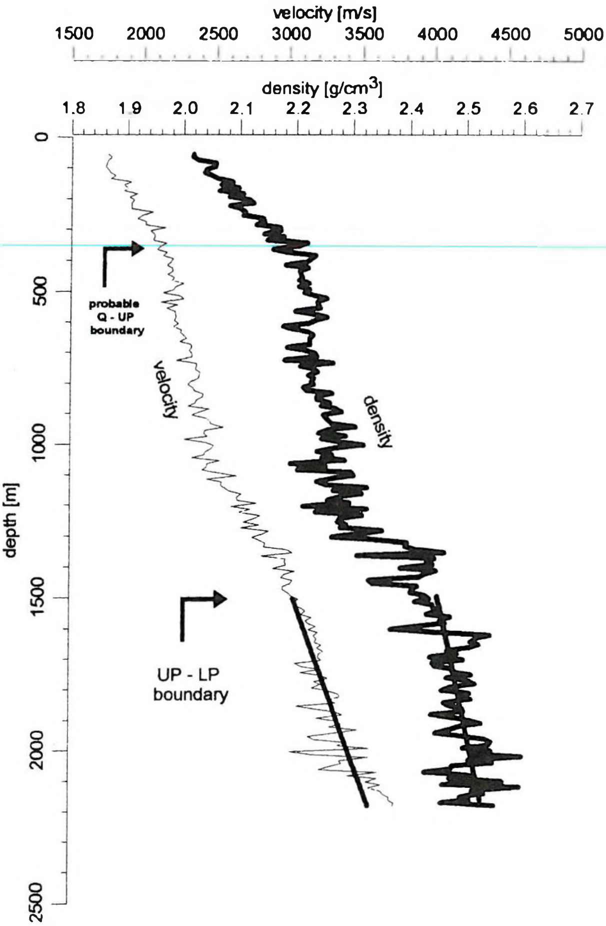

Fig. 7. Discordance on the boundary of Lower Pannonian–Upper Pannonian in borehole Kondorfa–2

7. ábra. Diszkordancia az alsó pannon felső–pannon határon a Kondorfa–2 fúrásban

probability on the two well logs at 350 m. Upwards, a drastic density and velocity decrease can be observed above the upper boundary of Lower Pannonian indicating the fact of discordance.

Summarizing the density of the rocks and the longitudinal wave propagation velocity in it, noticeable changes are apparent on the boundary between the Upper and Lower Pannonian. The greater values measured in the Lower Pannonian may be linked with increased compaction and consolidation of the rocks of the Lower Pannonian. In the Upper Pannonian the rock

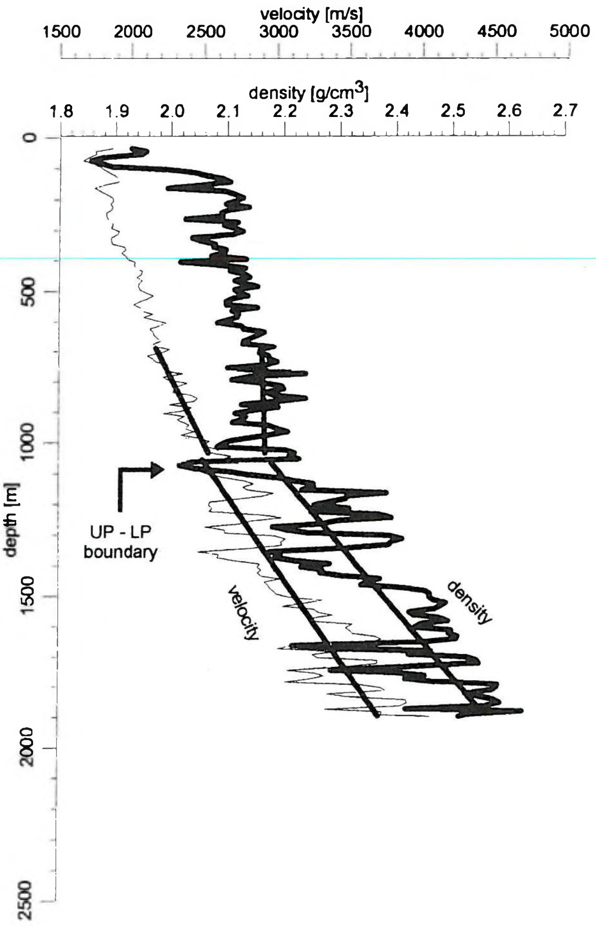

Fig. 8. Discordance on the boundary of Lower Pannonian–Upper Pannonian in borehole Törökszentmiklós–4

8. ábra. Diszkordancia az alsó pannon felső–pannon határon a Törökszentmiklós–4 fúrásban

grains become closer solely because of the effect of increasing pressure; in contrast, a qualitative change takes place in the Lower Pannonian. Chemical diagenesis may have a significant role in the cementation, inducing the sudden increase of the density and velocity values. Because of the greater lime content and marly character of the Lower Pannonian we would consider the boundary as a discordance if it were to be a continuous sediment.

On the velocity–density cross plot in *Fig. 9* the separation of formations of the two geological formations according to density and velocity

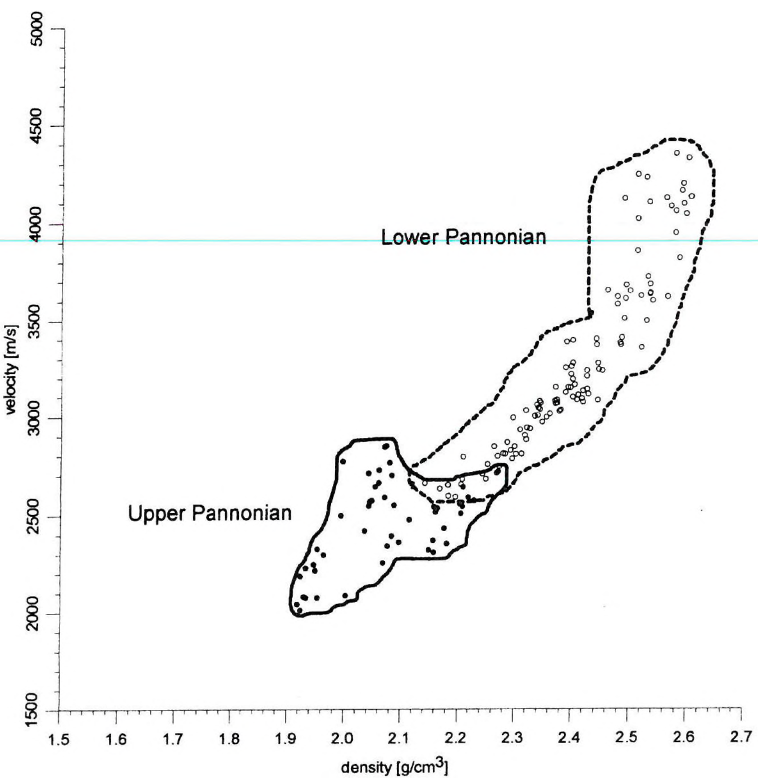

Fig. 9. Differentiation of Lower Pannonian–Upper Pannonian based on velocity and density in borehole Abony–2

9. ábra. Alsó pannon–felső pannon elkülönülés sebesség és sűrűség szerint az Abony–2 fúrásban

can be observed unambiguously. In the transitional zone near the boundary the density and velocity values are nearly the same, but from it both upwards and downwards the separation is dominant. The cross plot illustrates that the velocity increases most quickly — moreover under the influence of very small density changes, too — in those rocks which are nearly consolidated from the density point of view. This can be attributed to the combined effects of the increase of cementation and geostatical pressure. Both effects increase the actual contact surface of the grains, but it causes only a small density increase because the rock porosity is near the minimum.

4. Subsidence history conclusions based on depth trends of density and velocity curves

The relationship between the formation of the sediment complex filling the Pannonian Basin and the world's oceans has not been clarified unambiguously. Certain opinions have it that the Pannonian Basin gradually became isolated from the world's oceans in relation to the uplift of the Alps and Carpathians [BÉRCZI 1998]. It follows from this that the sedimentary and tectonic evolution of the Pannonian Basin differs from the surrounding European territories. On the other hand certain research results suggest that a correlation can be observed between the sinking of the water level of the Pannonian inland sea and the rising of the global sea level [POGÁCSÁS 1989]. Certainly the fact is that subsidences and uplifts alternate over a period of millions of years. Based on well logging results the thickness of the sediment complex varies considerably. In accordance with Table I, the greatest thickness — about 2500–3100 m — is in the eastern part of the Great Hungarian Plain (boreholes Földes, Karcag, Ecsegfalva). Near the Dráva from Lake Balaton to the south (Kivadár, Komlósd) a sedimentary complex can be found in the depression with relatively greater thickness (2100–2800 m).

Certain phases of the processes of deposition of sedimentary formation of the basin may be concluded from the detailed analysis of depth trends of density and velocity values measured in the boreholes.

Due to the increasing pressure with increasing depth the compaction in the beds is enhanced and because of its effect part of the pore content of the rocks will be squeezed from it. The grains of the rock become closer to each other and the proportion of the space filled up by fluid decreases. The result is that the values of the physical parameters characterizing the rock, — viz. density and velocity, — increase with increasing depth.

In consequence of the tectonic movements the beds uplifting from the greater depths are forced into an environment of lower pressure. In spite of the pressure decrease the rock grains do not recover their original shape or structure, nor does their porosity change. The rock has a structure as though it would be continuously under great pressure at greater depths [MESKÓ 1994]. It follows from this that if a greater average density is observed in smaller depth on the density curve measured in the borehole and it is definitely not a result of a local diagenetic change, then it proves the uplifting tendency of the beds. Otherwise subsidence will dominate.

In practice the subsidence history consists of a comparison of individual data measured in boreholes, and countrywide and regional trends. The countrywide (ORSZÁGOS) and regional (DUNÁNTÚL, ALFÖLD) trends are free from extreme anomalies and with a good approach represent average, normal compact sedimentation.

In borehole Kivadár–1, which was drilled in the deep basin near the Dráva, the density and velocity curves show uplifting and downlifting sections (*Fig. 10*). The density and velocity values of the formations in Lower Pannonian are higher than the countrywide average which suggests uplifting. An approximately uniform downlifting sedimentary formation process took place about in the lower 800 m of the Upper Pannonian. On the two trends it can be observed that the velocity increases over the countrywide average in smaller depth about with 200–250 m as the density. This stems from the earlier mentioned velocity increasing tendency of greater degree.

In the borehole Sávoly Ny–1 the measured logs are over countrywide trends indicating this region is characterized by an uplifting tendency in the past and in the present, too (*Fig. 11*).

Figure 12 shows the results of investigations accomplished in borehole Bojt–2. The measured curves represent the subsidence process, which would have been greater than average at least based on the density curve in the Upper Pannonian and in the upper 300–400 m of the Lower Pannonian. Within this depth interval, at some places the density is lower by 0.15 g/cm^3 than the countrywide average. It is possible that this lower density may originate from lack of compaction; in other words, the sediment deposited in a geologically relatively young trough — viz. the deep zone of Derecske — has not been in equilibrium.

The final result of individual investigations of boreholes of Transdanubia and the GHP can be seen in *Fig. 13* as a subsidence sketch map. It can be stated that subsidence (S) played a significant role in the regions situated east of the Danube. The surroundings of boreholes Ebes D–1, Ruzsa–28 and Gacsály–1 (Fig. 1) may be characterized by a partial uplifting tendency (S, U). Among the boreholes of Transdanubia the data of Hegyfalu–1 and Sávoly Ny–1 suggest uplifting for the most part, but in the other ones subsidence plays a significant role (S, U).

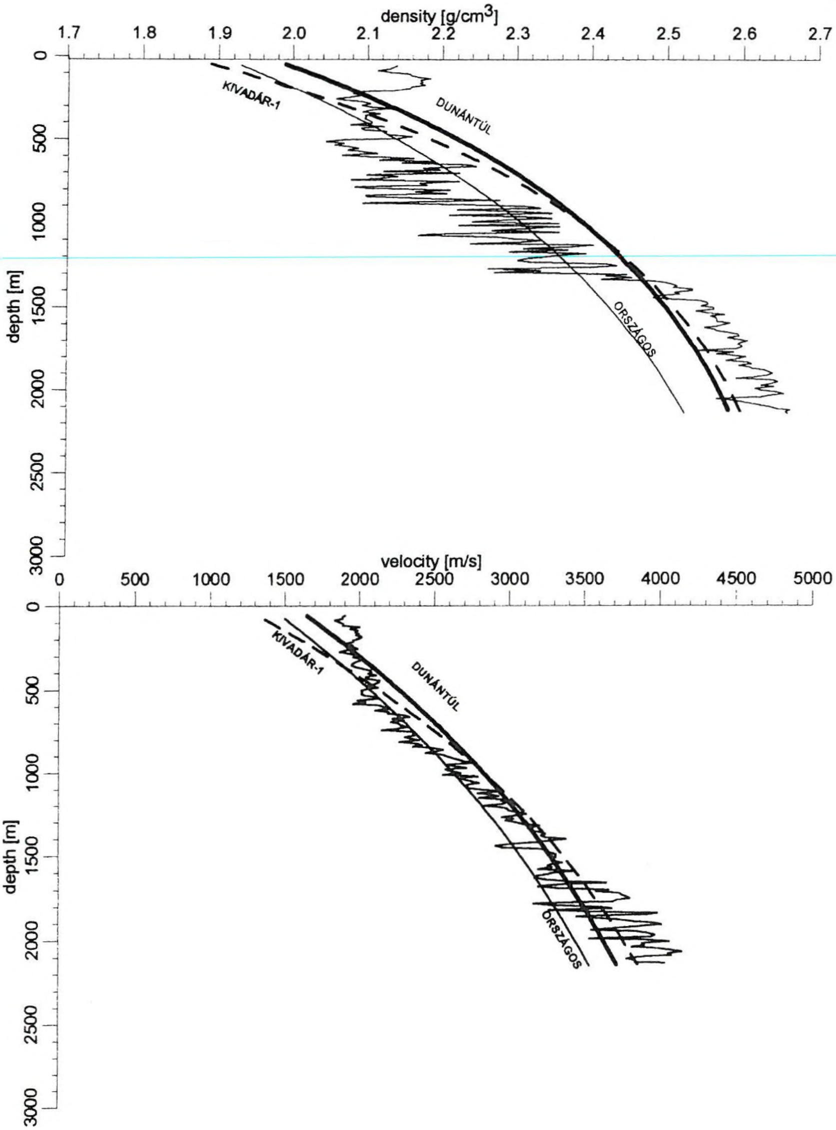

Fig. 10. Comparison of ORSZÁGOS density and velocity depth trends with those of borehole Kivadár–1

10. ábra. Az ORSZÁGOS sűrűség- és sebesség-mélység trend összehasonlítása a Kivadár–1 jelű fúrással

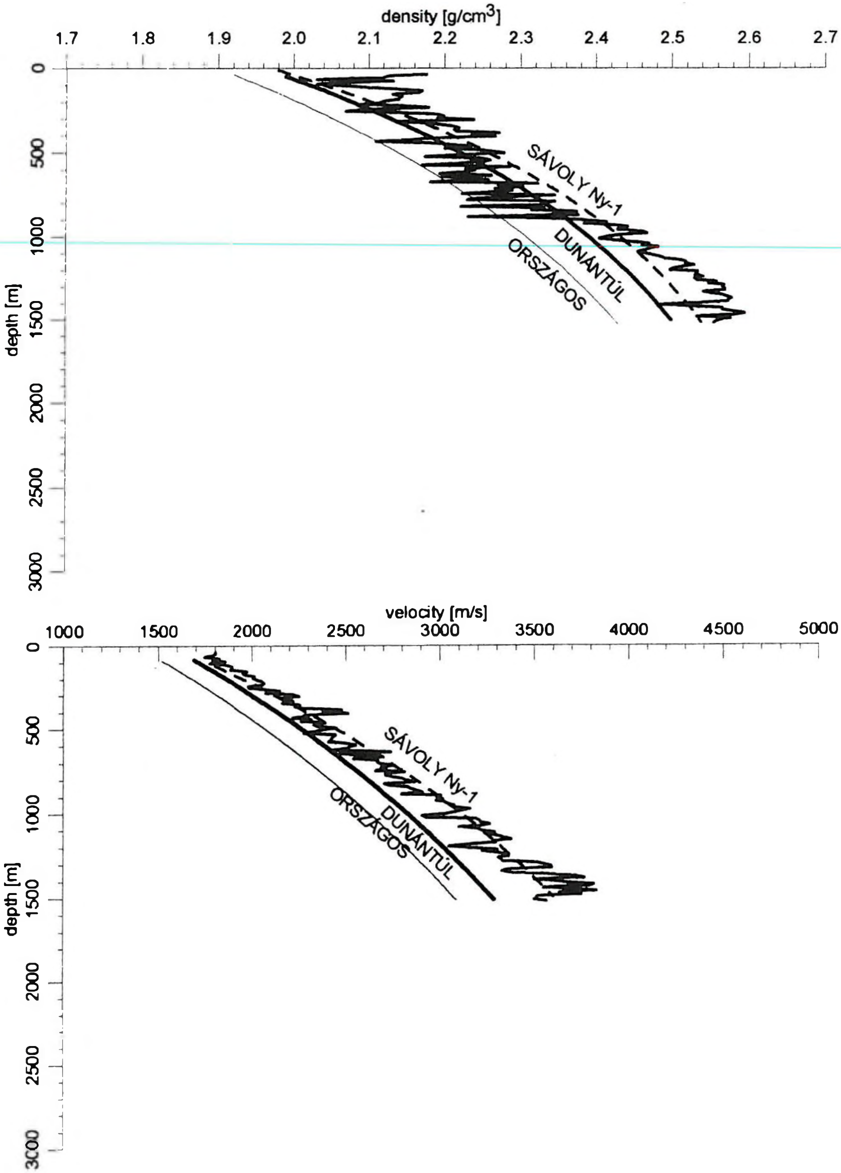

Fig. 11. Comparison of ORSZÁGOS density and velocity depth trends with those of borehole Sávoly Ny–1

11. ábra. Az ORSZÁGOS sűrűség- és sebesség-mélység trend összehasonlítása a Sávoly Ny–1 jelű fúrással

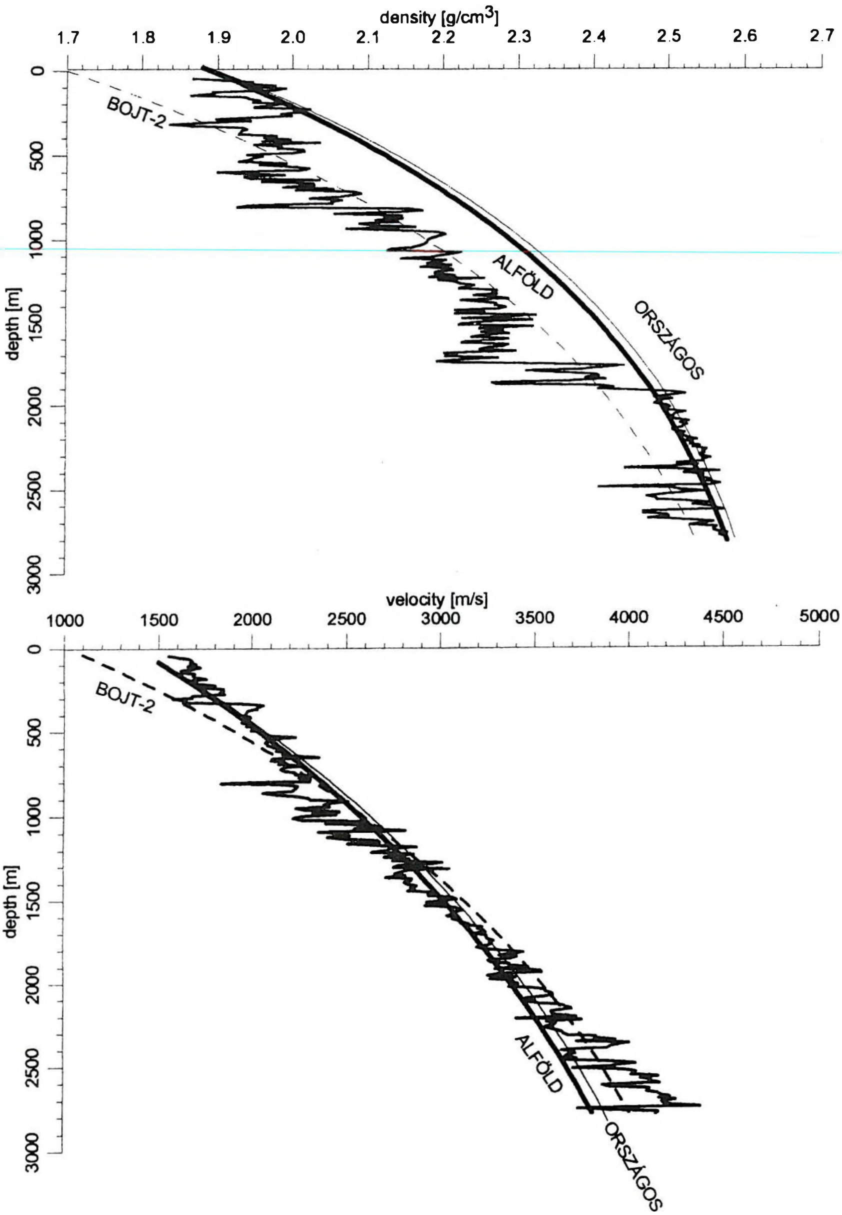

Fig. 12. Comparison of ORSZÁGOS density and velocity depth trends with those of borehole Bojt–2

12. ábra. Az ORSZÁGOS sűrűség és sebesség–mélység trend összehasonlítása a Bojt–2 jelű fúrással

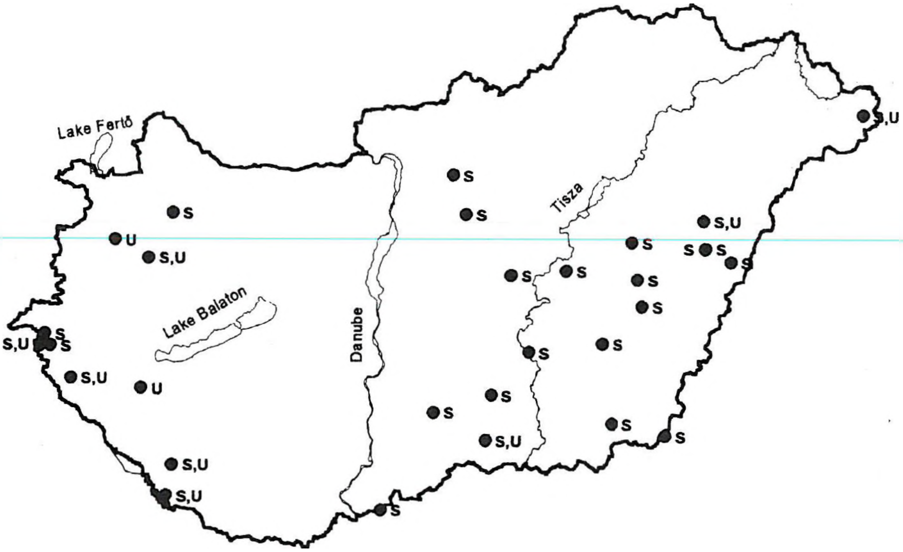

Fig. 13. Subsidence map based on borehole geophysical investigations.
S=subsidence; U=uplift
13. ábra. Süllyedéstörténeti helyzetkép a karotázs visgálatok alapján.
S=süllyedés; U=emelkedés

The difference between the two parts of the country regarding the state of sediment compaction is probably linked with the vertical movements caused by force originating as a consequence of collisions of horizontal movements of lithospheric plates. In a general sense this difference is related to the collision of the African and Eurasian lithospheres.

Let us consider the formations of examined boreholes in upper sections near the surface down to a depth of some 100 m. In this depth interval, it is mainly the density values that hardly change according to the increasing depth. This means that there is not an unambiguous, definite relationship between the depth and the density in the Quaternary formation. At smaller depths the compaction means a compaction above all based on the velocity, which originates from the grains being forced against each other more and more by the influence of the pressure. This pressure is not enough to rearrange the grains in accordance with the maximum filling of the space. The rearrangement is sufficient to overcome the inner viscosity only above a certain geostatic pressure threshold. Sometimes the longitudinal propagation velocity also behaves similarly (e.g. Kivadár–1, Dévaványa

D–1). In view of this, the subsidence investigation method needs to be applied to this section extremely carefully. In other words, the shape of the calculated depth trends is determined basically by the density relations of greater depths.

On the other hand the behaviour of the density curves in the Quaternary reflects the energy relations of the paleoenvironment during the given period, too. The dynamic density changes with great amplitude refer to the existence of a high energy environment enabling the coarser sediments with larger grain diameter to be carried and deposited. The density curve characterizable by smaller changes shows sedimentation in a low energy environment in which first of all fine grain sediments (clay, fine grain sand) were deposited. On the other hand this can hinder the velocity increasing trend at smaller depths because the clayey formations differ from the sands both in density and depth trend of velocity.

5. Estimation of maximum buried depth

During the sedimentation process taking place over millions of years the deposits constantly filled a subsiding basin. A bed which had been situated on the surface or near the surface became deeper and deeper because newer and newer sedimentary masses settled on each other. Tectonic forces may temporarily stop the subsidence and under their effects begin a slow uplifting; a bed situated at a relatively greater depth could get higher, and destructive processes could took place on its surface.

These processes might be reconstructed with the help of density logs measured in boreholes. In Section 4 we mentioned that if a bed was uplifted from a greater depth to one that was not so great it retains the density belonging to the greater depth in a peculiar way. The bed 'remembers' the former depth. Using the density–depth trends we have the possibility to estimate the maximum degree of uplift or, in other words, to estimate the maximum buried depth. The process does not work the opposite way, i.e. if the subsidence was not followed by an uplift the degree of subsidence cannot be determined. The beds that sank to greater depths are obviously of greater density than they were initially.

Based on the subsidence map (Fig. 13) we examined boreholes in which an uplifting tendency — or subsidence and uplift — took place.

The method of calculating maximum buried depth is presented through the example of well logs of borehole Gacsály–1 (*Fig. 14*). The ORSZÁGOS and ALFÖLD trends are not completely the same therefore the buried depths calculated from them are not the same either. The intensive uplifting interval can be found between about 700 and 1230 m. The

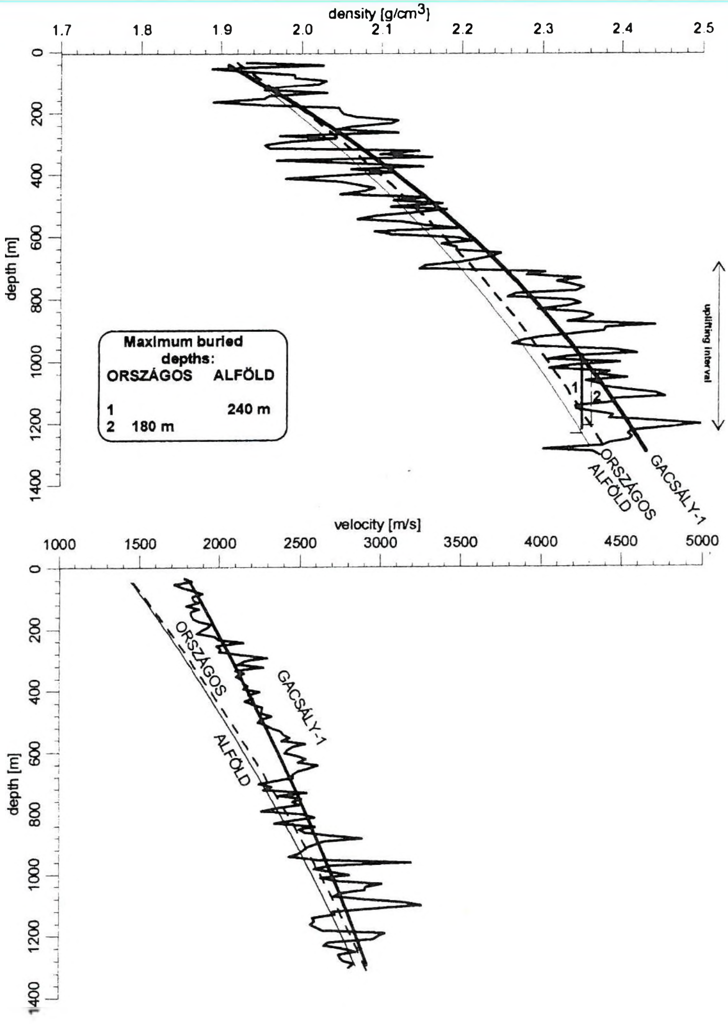

Fig. 14. Estimation of maximum buried depth in borehole Gacsály–1
14. ábra. Maximális eltemetődési mélység számítása a Gacsály–1 fúrásban

two vertical line sections marked by arrows represent the buried depth (uplifting height) estimated from the two trends. Within the uplifting interval, buried depths with different degrees can be estimated by virtue of the character of the exponential curves. The two values marked on the figure are situated near the points with greatest depth of the uplifting interval therefore they correspond to the maximum buried depth. The average value calculated from the two trends gives a maximum buried depth which is greater by 210 m than the present day for borehole Gacsály–1 and its immediate neighbourhood. In the same way the estimated values are about 100 m for borehole Ebes D–1 and about 350 m for borehole Ruzsa–28.

The uplifting height values calculated from 6 boreholes in Transdanubia compared with maximum buried depth can be seen in *Table II*.

Borehole name	**ORSZÁGOS (countrywide) trend**	**DUNÁNTÚL (Transdanubian) trend**
Hegyfalu–1	~ 580 m	~ 230 m
Celldömölk ÉNy–1	~ 300 m	~ 0 m
Ortaháza Ny–5	~ 450 m	~ –50 m
Sávoly Ny–1	~ 500 m	~ 250 m
Kivadár–1	~ 600 m	~ 180 m
Bajánsenye M–1	~ 400 m	~ 0 m

Table II. Calculated uplifting values from boreholes in Transdanubia
II. táblázat. Dunántúli fúrások számított emelkedési értékei

Because of the difference between DUNÁNTÚL and ORSZÁGOS density trends the calculated buried depths differ from each other, too. Based on comparison of the two trends an uplift of approximately 350 m is presumable for Transdanubia compared to the countrywide trend. This value is also in agreement with the present geomorphological difference between Transdanubia and the Great Hungarian Plain.

Compared to the countrywide trend — if the borehole Celldömölk ÉNy–1 is omitted — the uplifting is, on average, 500 m. The divergence from the average can practically be considered as being within the limits of experimental error. The borehole Celldömölk ÉNy–1 belongs to another tectonic unit therefore there are also other aspects to its past subsidence history.

6. Examination of boreholes according to tectonic units on the basis of compaction trends

During the development of the Pannonian Basin the epirogenetic movements generated by internal forces were dominant. The sedimentation could be characterized by uplifting and subsiding vertical movements [JÁMBOR et al 1988].

The result from estimating the buried depth based on the borehole measurements is that one part of the Pannonian Basin is characterized by subsidence but on the other parts of it uplifting tendencies could be observed. Those parts of the basin where the degree of uplifting or subsidence is approximately the same, form a tectonic unit or block. The important character of these is that the sediment complex moves together during the vertical movement.

The boreholes Ebes D–1 and Ruzsa–28 show both uplifting and subsidence tendencies but because of the great dispersion of data (100–350 m) and the great distance between them one cannot unequivocally speak about a tectonic unit. Of the Transdanubian boreholes examined the Ortaháza Ny–5 and Sávoly Ny–1 probably belong to the same tectonic unit. On the one hand they are relatively near to each other (30–40 km), on the other hand the uplifting heights calculated from geophysical data measured in them are similar.

The major difference between the uplifting values of the Hegyfalu–1 and Celldömölk ÉNy–1 boreholes proves unambiguously that they belong to different tectonic units. There is a characteristic fact that two marked geomorphologic units — Rába valley and Kemeneshát — can be found between the two boreholes on the surface. Though the borehole Kivadár–1 possesses similar parameters, the borehole that was drilled on the brink of the Dráva depression belongs to another tectonic unit.

7. Conclusions

- It is clear that there is a close relationship between borehole geophysical parameters and the internal structure of rock.
- The compaction relations of rock can be deduced from the depth distribution of the borehole's geophysical parameters.

—The depth places of beds of settled discordance could be indicated on the depth trends of density and velocity.

—The vertical and horizontal distribution of the geophysical parameters measured in boreholes in advantageous geographical locations carries evolution history information in relation to the sedimentation.

—The importance of such investigations is enhanced by the fact that the slow movements during the sedimentation and the state of consolidation are closely linked with the risk of earthquake of a given territory.

REFERENCES

BÉRCZI I., JÁMBOR Á. 1998: The stratigraphy of geological formations of Hungary (in Hungarian). MOL Rt and MÁFI, Budapest

FÜLÖP J. 1989: Introduction to the geology of Hungary. Akadémiai Kiadó, Budapest, pp. 203–211

JÁMBOR Á., BALÁZS E., BALOGH K., BÉRCZI I., BÓNA J., HORVÁTH F., GAJDOS I., GEIGER J., HAJÓS M., KORDOS L., KORECZ A., KORECZNÉ L. I., KORPÁSNÉ H. M., KŐVÁRI J., MÉSZÁROS L., NAGY E., NÉMETH G., NUSSZER A., PAPP S., POGÁCSÁS GY., RÉVÉSZ I., RUMPLER J., SÜTŐNÉ SZ. M., SZALAI Á., SZENTGYÖRGYI K., SZÉLES M., VÖLGYI L. 1988: Short geological characterisation of Hungarian Pannonian Formations (in Hungarian). M. Áll. Földtani Intézet Évi Jelentése 1986. évről, pp. 311–326

KISS B., CSATÓ I., BALLA GY. 1990: Compaction trend analysis of the sediments in the Pannonian Basin. Transactions of the Thirteenth European Formation Evaluation Symposium, October 22–26, Budapest, AAA 14 p.

MESKÓ A. 1994: Elastic waves in the Earth (in Hungarian). Akadémiai Kiadó, Budapest, pp. 118–139

MÉSZÁROS F., ZILAHI-SEBESS L. 1998: Risk of earthquakes in Hungary. Analysis of density and velocity data from boreholes (in Hungarian). Report, ELGI

POGÁCSÁS GY., JÁMBOR Á., MATTICK R. E., ELSTON D. P., HÁMOR T., LAKATOS L., LANTOS M., SIMON E., VAKARCS G., VÁRKONYI L., VÁRNAI P. 1989: Chronostratigraphic framework of the Neogene formation in the Great-Hungarian Plain as revealed by combination of seismo- and magnetostratigraphy (in Hungarian). Magyar Geofizika **XXX,** 2–3, pp. 41–62

VENDL A. 1953: Geology. University coursebook (in Hungarian). Tankönyvkiadó, Budapest Vol.I, 228 p.

Nagyvastagságú üledékek kompakciója a Pannon-medencében

MÉSZÁROS Ferenc és ZILAHI-SEBESS László

A fúrólyukban mért geofizikai paraméterek horizontális és vertikális eloszlása értékes információkat tartalmaz. A tanulmány mélyfúrásokból származó sűrűség és sebesség adatok elemzésével vizsgálja a Pannon medencét kitöltő üledékösszletet. Különös figyelmet szentel a köze-

tek kompakciós viszonyainak illetve az üledékképződés során kialakuló diszkordancia helyek feltárásának. A fentieken kívül bemutatja az üledékképződés süllyedési és emelkedési fázisainak meghatározási lehetőségeit. Süllyedéstörténeti térképet közöl az ország azon területére, ahol a vizsgálatokba bevont fúrások helyezkednek el.

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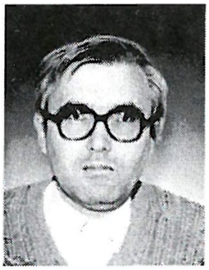
Ferenc Mészáros graduated as a geophysicist at Eötvös Loránd University, Budapest, in 1964. After graduation he joined ELGI. His main field of interest is borehole geophysics. In the 1960s he worked as a field geophysicist carrying out geophysical measurements in boreholes to determine the main parameters of various raw materials (coal, water, bauxite, ores, etc.). From the beginning of 1970 onwards, his main field of interest was computer-aided geophysical interpretation of borehole measurements. He played an active part in developing log interpretation methods. For the last ten years or so, he has mainly been dealing with the relationship between the risk of earthquakes and the distribution of petrophysical parameters. A further topic he deals with is examining evolutionary aspects of the Pannonian Basin by analysing density and velocity logs. Currently, he is a member of ELGI's research department.



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