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Qualitative–Quantitative Analyses of the Influence of Depth and Lithological Composition on Lower Pontian Sandstone Porosity in the Central Part of Bjelovar Sag (Croatia)

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Key words: Porosity, Sandstones, Lithological variability, Oil reservoirs, Calculation of average φ, t-test, F-test, Pearson's R, Lower Pontian, Bjelovar sag, Pannonian basin, Croatia.

Abstract

Results of several tests (porosity–depth graphic relation, t-test, F-test, Pearson's R), were used to analyse and interpret the regularity in porosity values of Lower Pontian oil-bearing sandstones from the central part of Bjelovar sag. Data came from 7 cored intervals within 5 wells in the Pepelana member and from 6 cored intervals (in 4 wells) in the Poljana member. The expected porosity decrease with increasing depth was checked against lithological variations.

Sandstones are mostly fine-grained lithoarenites. The detritus is composed of quartz, various micas, carbonate fragments and feldspars. Across the study area, the depth range of the sandstones varies from 430 m (top of the Pepelana member near Šandrovac) to 2046 m (base of the Poljana member near Velika Ciglena). Cores included in the analyses vary between 2.75 to 15.5 m in length.

Mean porosity and relative depth data were collected for two groups: Group 1 comprised wells Pav–1, Pav–2, Rov–1, Ša–5, Ša–35, and Group 2 included well VC–1. These groups were subdivided for analysis into two (litho)stratigraphic units (Pepelana and Poljana ss.). Porosity variation within each group is explained with reference to the silt or clay fraction. Differences between the porosities of the two groups (~10% lower absolute porosity near Velika Ciglena) is the result of compaction and other processes.

Interval of 400 m thickness in particular sandstone member is set as minimum value for observing influence of compaction. Such statement is based on sandstone's tops and bottoms comparison as well as graphical presentation of relation core porosity–relative depth interval. The analysis was improved by statistical calculation of Pearson's R, t-test and F-test, which more precisely described the relationship between porosity and depth. Using these statistical tests and regression equitation, the depth difference is calculated as 621 m in the Pepelana and 667 m in the Poljana sandstones, as the limits when the influence of compaction in the porosity–depth relationship could be noticed.

Compaction was observed, in the study area, when data from Velika Ciglena are compared to data from the other wells.

1. INTRODUCTION

Reservoir characterization mostly comprises detailed evaluation of petrophysical parameters, i.e. porosity, permeability and saturation. Accuracy depends on the source, amount of data, and method applied for their comparison and evaluation in places where the parameters are not measured. Porosity is selected as the most important variable for reservoir characterization as it has a direct influence on permeability and saturation values.

Input data were porosity values measured in vertical cores, performed in the INA-Naftaplin laboratory and noted in well files. Also, data are selected and classified regarding their (litho)stratigraphic position in a database (MALVIĆ, 2003a). The majority of the data in Bjelovar sag (SW margin of Pannonian basin), belongs to the Pepelana and Poljana sandstones (Kloštar-Ivanić formation, of approximate Lower Pontian age, Figs. 3 and 4). These units were chosen for analysis because they occur in the central part of the sag.

The analysed cores have different lengths, number and position of measurements. For previous geostatistical (variogram) analyses (MALVIĆ, 2003a, b), only cores where it was possible to select a minimum of 10 intervals of 0.25 m or 0.5 m were used. In intervals with several measurements the mean value was calculated. Each interval was represented by a single calculated value in order that equal importance could be given to intervals with low or high amounts of data. In intervals without data, interpolated porosity curves were constructed and the mean value determined from such curves.

The same criteria are accepted in this analysis. The goal was to collect sufficient amounts of reliable and equally "valid" input data. "Valid" means that it would be incorrect to give the same importance to a cluster of 8 values measured over 40 cm of core and of 5 values measured from perhaps the next 2 metres. Reliability is a consequence of a selected core size, and is important for the calculation of representative interval values.

The main aims of this paper are to:

– apply graphical and statistical analysis to determine the range (depth difference), over which depth influ-

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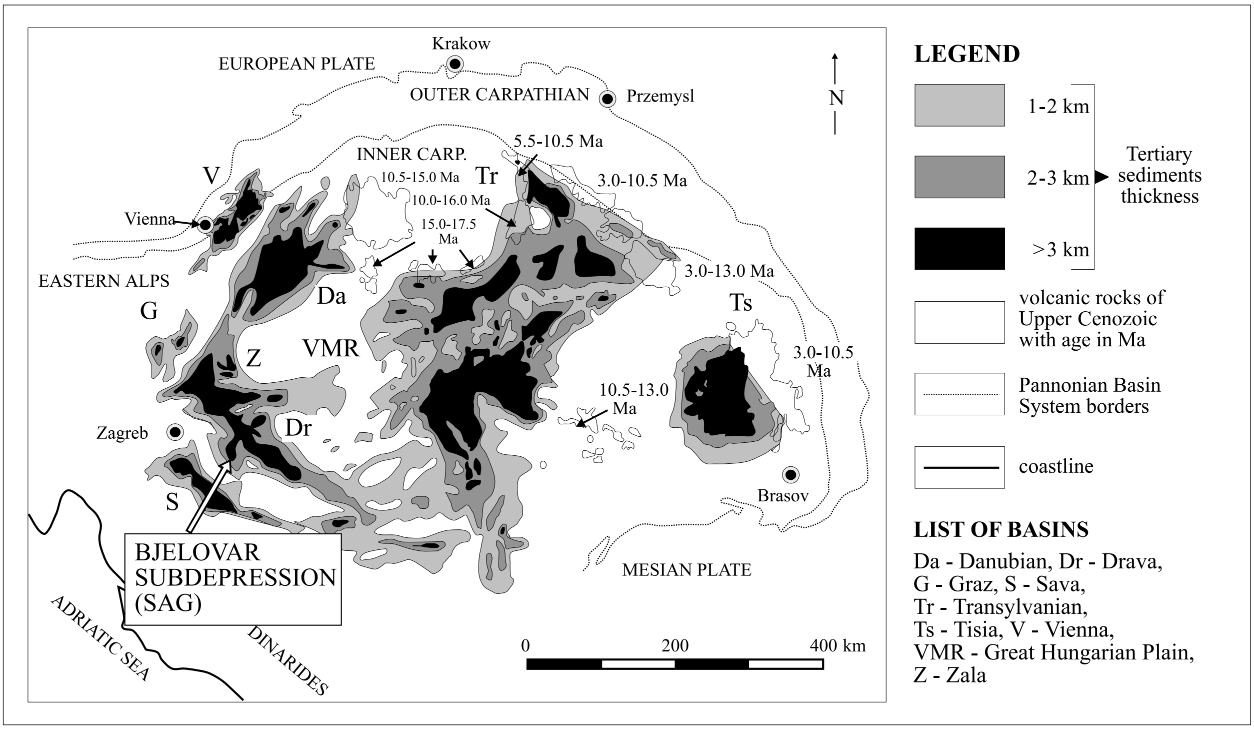

Fig. 1 Main regional structural–stratigraphic units in Pannonian basin system (after ROYDEN, 1988).

ences the decrease in porosity, for both the Lower Pontian Poljana and Pepelana sandstones, and

- describe the range in porosity values, with regard to their depth of location.

Here, the t-test, F-test and areal comparison of porosity values from different locations and depths were used as the main analytical tools. The results are partially comparable with those of statistical analyses published by JÜTTNER et al. (2000) and SAFTIĆ et al. (2001). In these two papers porosity behaviour is also statistically analysed in rock units from the Sava depression, which are lithostratigraphic equivalent to the Lower Pontian sandstones of the Bjelovar sag. A comparison and discussion of the results is given in more detail below.

Additionally, some interesting results on the porosity behaviour and compaction influence in sedimentary rocks can be found in papers written by BURYAKOVSKIY et al. (1991) and REED et al. (2005).

2. DELIMITATION OF THE ANALYZED AREA AND BASIC GEOLOGICAL SETTINGS

The area explored is part of the Pannonian basin system, which was covered by the Paratethys palaeosea and deposits of younger lacustrine and fluvial environments (ROYDEN, 1988). The borders of this basin system, as the largest regional structural–stratigraphic unit, have been determined based on the extent of Neogene sediments (Fig. 1).

The basin system comprises lower structural–stratigraphic units in a range of basins or depressions (in Croatia these are the Drava, Sava, Mura and Slavonian–Srijem depressions). The smallest regional units are named as sag or subdepression. The Bjelovar sag, which is the southwestern branch of the Drava depression, is such a subdepression (Fig. 1).

The study area covers the central part of the Bjelovar sag (Fig. 2), its borders being determined on the basis of a palaeorelief map after MALVIĆ (2003a). An unconformity between Palaeozoic and Mesozoic rocks in the palaeorelief and Neogene sediments ("*temeljno gorje*" – Tg, or "*podloga tercijara*" – Pt) often comprises very characteristic forms (faults, "buried hills", negatively inversed relief areas). The influence of this can also be observed in Badenian, Sarmatian, Pannonian and sometimes even in younger sediments. This boundary was considered very useful for separation of particular blocks in regional units, which is also done here. Borders of analysed block are represented by (clockwise from southwest) the 2300/2400 m isobates, the Bilogora normal fault on the north, the 2500 m isobate north from this fault, and northeast from Šandrovac, the 2800 m isobate to the east and the main reverse fault to the south (Fig. 2).

The following localities (with one or more wells), belong to analysed block and are approximately west to east: Rovišće (well Rov–1), Galovac–Pavljani (Pav–1, Pav–2), Šandrovac (Ša–5) and Velika Ciglena (VC–1). Available cores produced 213 porosity values in total from intervals of 0.5 or 0.25 m (Tables 1, 2) in the Pepelana and Poljana sandstones. The relatively large dis-

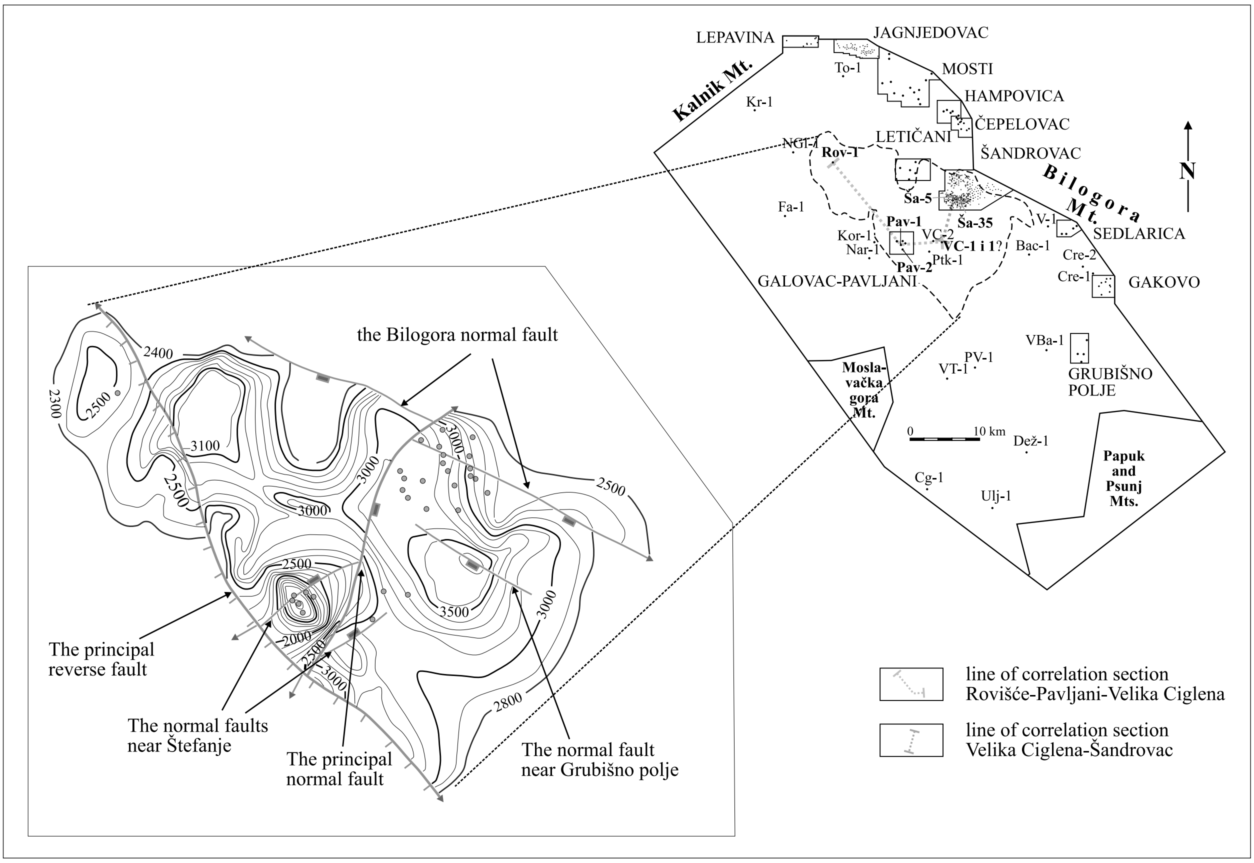

Fig. 2 Borders of the central Bjelovar sag part determined from palaeorelief map.

tance between the Rovišće and Pavljani localities (Fig. 2) is considered as a shortfall in the well net, because there is no data over distances greater than 15 km.

Basic geological, i.e. **lithological characteristics**, from the oldest to the youngest lithostratigraphic units, are shown in Figs. 3 and 4 and described together with their dominant rock types. Palaeozoic schists and Middle Triassic carbonates were drilled at nearby Rovišće, a gneiss–granite complex by Galovac–Pavljani, and Middle Triassic carbonates and carbonate breccia in the Velika Ciglena wells. The pre-Neogene basement is not clearly determined near Šandrovac, because very few wells reached these rocks. It is supposed that the basement is mostly represented by carbonates in contact with Palaeozoic schists on the south/southwest part of the field.

Neogene sediments were deposited over the entire area. They begin with the Mosti member of the Moslavačka Gora fm. (approximately Middle Miocene age, including the Sarmatian), composed of mostly marine facies including siliciclastic and carbonate breccia, conglomerates and sandstones. Deepwater sediments with a prevalence of carbonate detritus and silt characterize the Velika Ciglena area, elsewhere siliciclastic detritus predominates. There is a fining-upward sequence from coarse-grained sediments into limestone. The younger Križevci member (approximately of Lower Pannonian age) is represented by calcareous marlstones and clayey limestones.

The Ivanić-grad formation (approximately of Upper Pannonian age) was deposited in brackish environments of the closed lake. Within this, the Lipovac marlstone (missing at the top of Galovac–Pavljani structure, in well Pav–1, Fig. 3) is the oldest member, followed by the Zagreb member (or lateral equivalent Okoli sandstones in the Velika Ciglena area), both represented by repetitions of sandstones and marlstones.

The Kloštar-Ivanić formation (of approximate Lower Pontian age) represents a lacustrine environment and is composed of a number of members. The oldest is the Lepsić marlstone, medium hard and sporadically sandy in the upper part. It is overlain by the Poljana sandstone, often marly or with pure marlstone intercalations. The Graberje marlstone is a middle marly member, with localised sandy intercalations. The Pepelana sandstone is the younger sandstone member. Mostly composed of fine-grained, quartz-mica, medium hard content, it often contains clayey marlstones or marly clays intercalations. The youngest Cabuna marlstone is represented by clayey marlstone or marly clay.

Fresh-water, lacustrine and deltaic environments represent the depositional setting of the Bilogora formation (approximately of Upper Pontian age). This formation is not divided into members. Generally, sediments are

PEPELANA	Pav–1	Rov–1	Ša–5	Ša–35	VC–1 (a)	VC–1 (b)	VC–1 (c)
(Rel. depth of unit)	**(827–882 m)**	**(≈1045.0–1167.1 m)**	**(≈430–820 m)**	**(≈616.5–884 m)**	**(1401–1715 m)**		
Rel. depth of anal. core (m)	850–856	1047–1053	680.3–687.3 810.6–816.6	797.7–810.2	1479.25–1482.5	1536–1542	1579–1583.5
Averaging interval (m)	0.5	0.5	0.5	0.5	0.25	0.5	0.25
Min.–Max. φ (%)	17.9–31.0	7.7–33.1	28.1–33.1	15.4–31.4	8.4–16.4	13.6–16.0	6.9–25.6
Arithmetical mean φ (%)	25.03	22.54	31.15	23.15	14.63	15.02	19.91
No. of data	12	12	26	51	13	12	18

Table 1 Descriptive statistics for the Pepelana sandstones.

POLJANA	Pav–1	Pav–2 (a)	Pav–2 (b)	Rov–1	VC–1 (a)	VC–1 (b)
(Rel. depth of unit)	**(911–1040 m)**	**(948–1195 m)**		**(1190.9–1333.8 m)**	**(1748–2046 m)**	
Rel. depth of anal. core (m)	913–928.5	977–986	1071–1075.5	1311–1316	1747–1751	1843.5–1846.25
Averaging interval (m)	0.5	0.5	0.5	0.5	0.25	0.25
Min.–Max. φ (%)	20.5–33.0	13.0–24.7	19.9–27.7	6.9–25.5	6.2–17.4	9.6–24.6
Arithmetical mean φ (%)	27.17	20.44	25.23	21.43	12.58	16.39
No. of data	31	9	18	10	16	11

Table 2 Descriptive statistics for the Poljana sandstones.

composed of marly clays, clays and sandstones, with a prevalence of impermeable or poorly permeable sediments.

The youngest Lonja formation (approximately of Pliocene and Quaternary age) was deposited in numerous fresh-water lakes, and (in the Quaternary), in fluvial and swamp environments as well as on the land. Marly clays, clays, sands, gravels and loess were deposited, and, close to the modern surface, unconsolidated Holocene sediments.

Lower Pontian sandstones were analysed with regard to their available depositional, granulometric and mineralogical data. All available cores were mostly taken from the most favourable parts of these reservoir units. These are lithologically very similar units – light grey, fine-grained, and mostly medium to very hard, quartz-mica sandstones, with different portions of silt and/or clay.

All the studied units need to be observed in the context of the entire sag with respect to their environmental interpretation. MALVIĆ (2003a) gives a short review of the Neogene depositional environments in the Bjelovar sag, as a compilation of currently accepted interpretations of the entire Croatian part of the Pannonian basin. The author has mentioned that a significant part of the permeable sediments is mapped in the deepest parts. Such sediments were probably transported by strong and multiple turbidity currents, which originated in the Alps and flowed toward the southeast. The surrounding land was probably the source of a smaller proportion of material. Such a transport mechanism of very dense turbidite currents, able to carry huge quantities of material for a hundred kilometres, has been described elsewhere, e.g. by TIŠLJAR (1994) and VRBANAC (1996). Normal, deepwater pelitic sediments, mostly marlstones, were deposited between the activities of such currents. Turbidites were active periodically through subaqueous channels, probably of kilometre dimensions. The salinity of water changed from brackish to fresh (VRBANAC, 1996; RÖGL, 1996, 1998), as indicated by the fauna found in the cores.

The sedimentary environment is interpreted as part of a subaqueous channel, probably of kilometre dimensions. Regarding the present-day depths and thickness, as well as the observed horizontal lamination in Velika Ciglena cores, the axis of the depositional channel runs through the areas of Šandrovac and Velika Ciglena, striking in a northwest/southeast direction. Rovišće and Pavljani were located on its margin. The total thickness of the Pepelana and Poljana sandstones taken together is about 400–600 m in the central part of the channel (Šandrovac and Velika Ciglena), and about 200–300 m on the margins (Rovišće and Galovac–Pavljani). Neogene pelitic sediments were deposited during specific periods in places with lower current energy, i.e. shallower or uplifted parts of sedimentational area (after ŠIMON, 1980).

Intervals of particle diameters were determined from granulometric analyses (collected from well files Rov–1, Pav–1, Pav–2 and VC–1). These values, regarding the core, vary between 0.05–0.115 mm, 0.100 mm on average. Analysis of particle sizes showed the prevalence

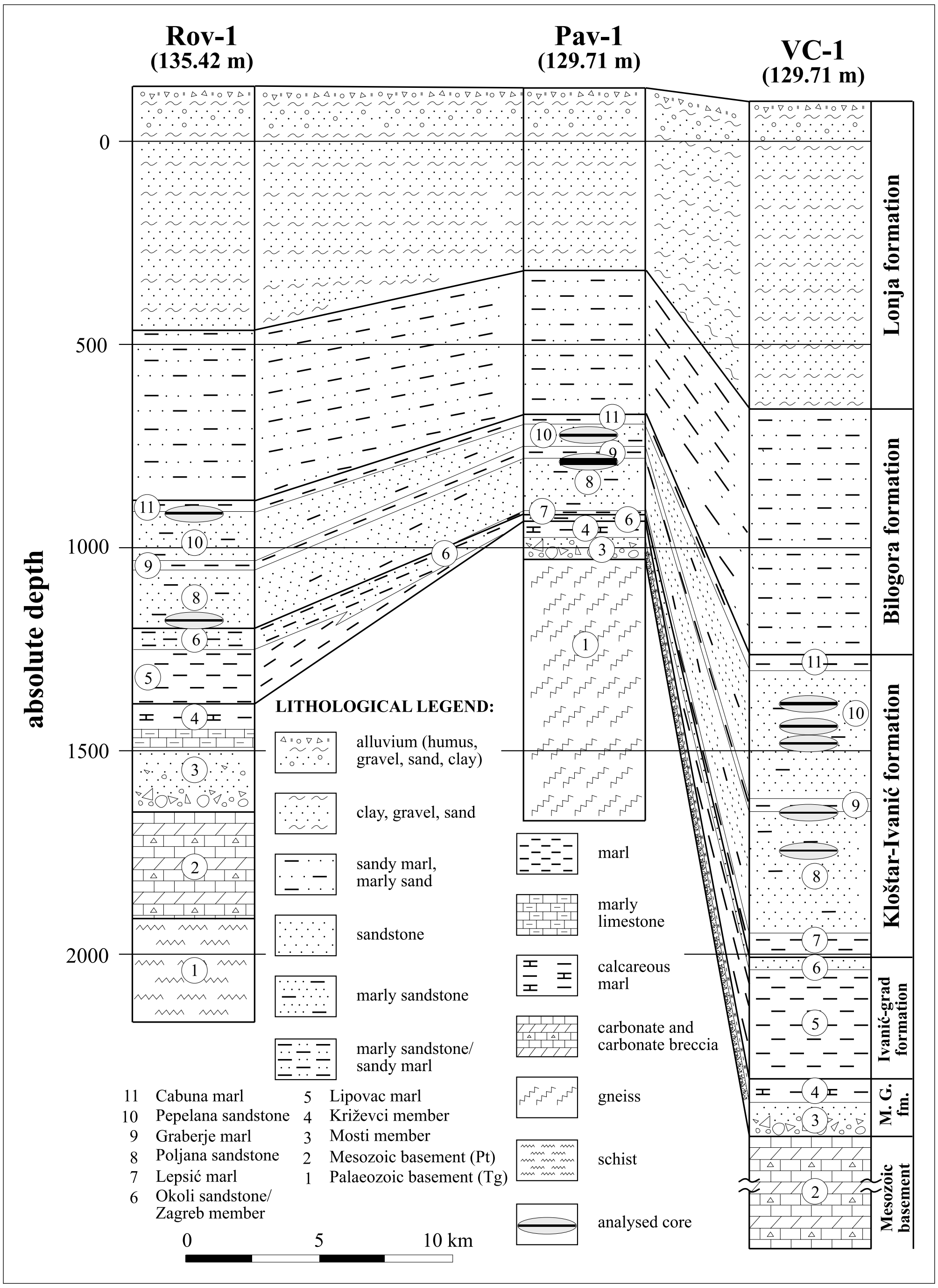

Fig. 3 Lithostratigraphic correlation section Rovišće–Pavljani–Velika Ciglena.

of sand (about 70%), followed by coarse-grained silt (about 20%), with the remainder being fine-grained silt and clay. The fraction of particles less than 0.125 mm in diameter accounts for more than 50%. Again, sand predominates with about 40–50 wt.%, followed by coarse-grained silt (about 15–25%) and a high proportion of calcite (about 30–35%). The rest is fine-grained silt and clay. There is a good degree of sorting.

Sandstones are classified as lithoarenites, according to their detrital origin. The mineral composition of the Lower Pontian sandstones was meticulously analysed in the cores of the well VC–1 (VLAHOVIĆ et al., 1991[4]), and the following minerals were determined: quartz, various micas (muscovite, sericite, chlorite and biotite), rock fragments (mostly carbonate, lesser low-grade metamorphic schists) and feldspars. Accessory minerals described included zircon, tourmaline, opâque minerals and (rarely) glauconite. The intergranular space is filled with ferroan and calcite cement, and sporadically with organic matter. Horizontal lamination observed at Velika Ciglena is a result of grain size variations as well as an

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[4] VLAHOVIĆ, T., STANKOVIĆ, D., RAŠKAJ, N. & BAN, D. (1991): Biostratigrafija, litofacijesi i okoliši sedimentacije bušotine VC–1 [*Biostratigraphy, lithofacies and depositional environments of the VC–1 well* – in Croatian].– Unpublished report, Archive of INA-Naftaplin professional documentation, Zagreb.

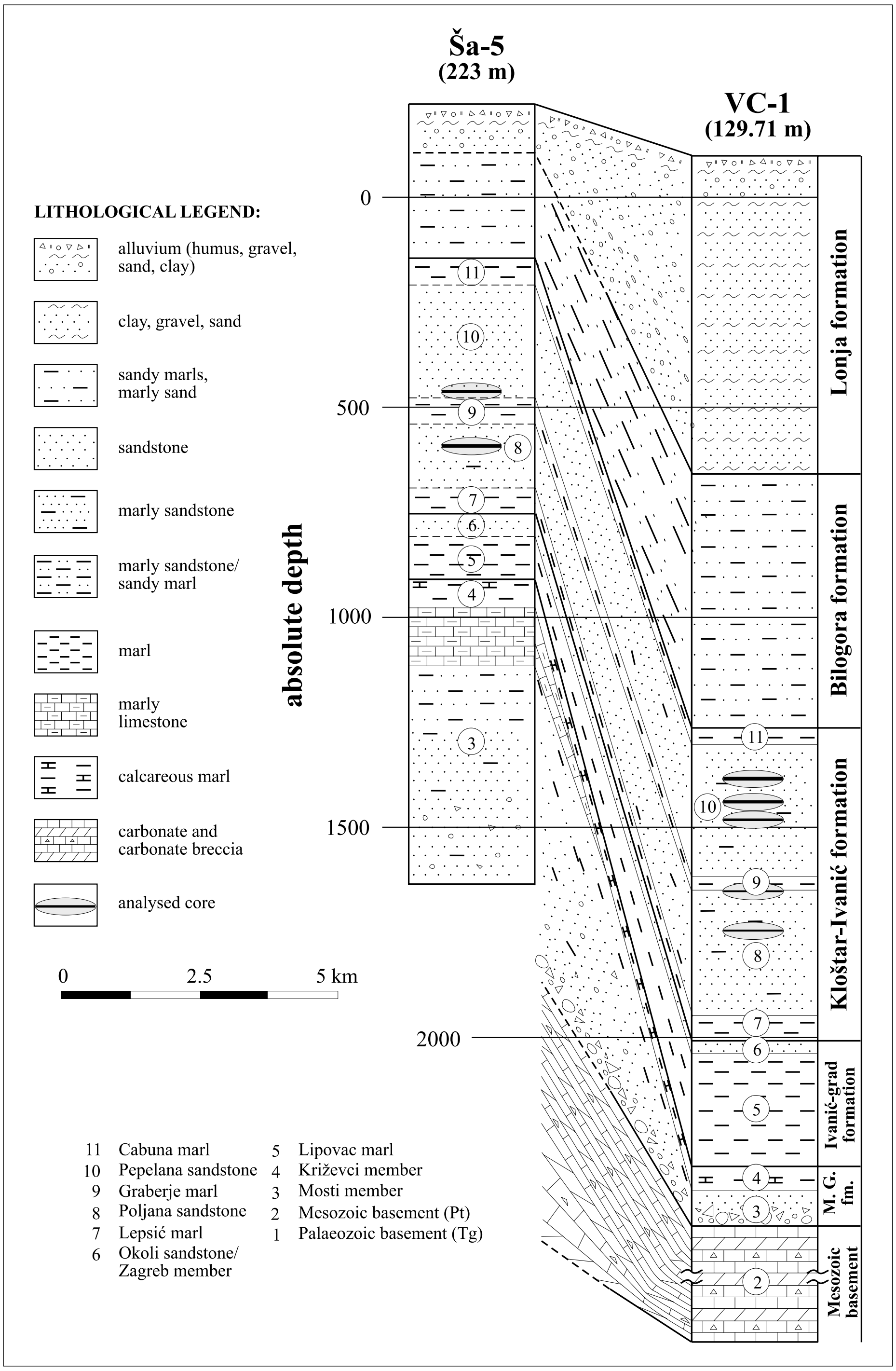

Fig. 4 Lithostratigraphic correlation section Šandrovac–Velika Ciglena.

increase in the proportion of mica minerals/organic matter.

The well Ša–5 was completed in 1964 and this is why some lithostratigraphic borders are only assumed (Fig. 4). At that time stratigraphic units were described according to the biostratigraphic nomenclature (*Rhomboidea*-, *Abichi*-, *Banatica*- and *Croatica*-strata). Documentation of the informal lithostratigraphic data of particular members and reservoirs (pools) was rare. At the end of the nineteen-sixties, biostratigraphic units started to be replaced with lithostratigraphic units of formation range, which were approximately co-depositional. At the same time, standard procedures during geological observation also comprised determination of lithostratigraphic members. The first comprehensive lithostratigraphic nomenclature for the Croatian part of the Pannonian basin was introduced by ŠIMON in 1968[5].

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[5] ŠIMON, J. (1968): Informativne litostratigrafske jedinice tercijarnog kompleksa u profilima dubokih bušotina na području Dravske potoline [*Informative lithostratigraphic units of the Tertiary complex in profiles of deep wells in the Drava Depression* – in Croatian].– Unpublished report, Archive of INA-Naftaplin professional documentation, Zagreb.

It is important to mention the work of VELIĆ et al. (2002) where Neogene lithostratigraphic formations are divided into 3 depositional megacycles of the second order. Each of these megacycles is composed of clearly recognisable lithological units corresponding to formations and members. According to the Drava depression nomenclature, the 1st depositional megacycle comprises the oldest Miocene sediments including the Sarmatian, i.e. the Mosti member. The 2nd depositional megacycle comprises the Križevci member as well as the Ivanić-Grad, Kloštar-Ivanić and Bilogora formations, i.e. sediments of Pannonian and Pontian ages. The last, 3rd depositional megacycle comprises the Pliocene–Quaternary sediments of the Lonja formation.

The analysed Lower Pontian sandstones belong to the 2nd depositional megacycle, characterised by a relatively uniform alternation of sand/sandstones and silts/marlstones, in different proportions.

3. QUANTITATIVE ANALYSIS OF THE PEPELANA AND POLJANA SANDSTONES

There is a general rule concerning the negative correlation between porosity and depth, but only on the condition that large enough vertical intervals are observed. The question is: How large is this depth difference in the central part of Bjelovar sag?

An increase in depth will usually result in a decrease in porosity, mostly due to compaction. Also, compaction is only one of several factors that have an effect in phases of early diagenesis and diagenesis. Early diagenesis is characterized by the mechanical influence of compaction as well as chemical effects resulting from water circulation, mineral dissolution (mostly carbonates) and secondary porosity creation. The diagenesis phase includes plastic rock deformation, overpressuring with fracturing and fissure creation. Also grain deformation and strong compaction take place, and increased temperatures cause additional cementation.

Available data on the sandstone members and cores are listed in Tables 1 and 2. Pepelana sandstones values are collected from 5 wells (7 cored intervals) and Poljana sandstones from 4 wells (6 cored intervals). These datasets were the input for statistical correlation (t-test and F-test) analyses.

3.1. Correlation analysis and interpretation of depth differences

Pearson correlation coefficients (R) between all porosity and depth values for each member are calculated. Also minimum and maximum depth and porosity values as well as standard deviation values are listed in Table 3. It is noticeable that the R-value for each intra-member group (Velika Ciglena and other locations) selected in the Pepelana and Poljana sandstones are significantly correlated (this analysis is extended with Student's t-test in subsection 3.3). Also, Velika Ciglena data are positively correlated, which indicated a local deviation from the expected behaviour (see section 3.2). Data from other locations are negatively correlated with depth.

Results published by JÜTTNER et al. (2000), regarding the correlation of porosity and depth show values of porosity–depth correlation of -0.19 at Stružec and -0.57 at Okoli in the Sava depression. They statistically analysed four parameters; φ, horizontal and vertical permeability and depth. Although no significance test was performed, the Okoli result describes a strong negative correlation between porosity and depth. Based on such correlations, compaction was assumed at significant lower depth differences (150 m at Okoli field) than it was supposed for equivalent lithostratigraphic members in the central part of Bjelovar sag. This is a result of the relatively large depth of these members at Okoli field (1850–2000 m).

Similar analysis was the main goal of this paper, i.e. determination of the range, as precise as possible, where compaction and depth have influence on the decrease in porosity.

Cores were taken in stratigraphically very different parts of the analysed members, from the youngest part of the Pepelana sandstones to the oldest part of the Poljana sandstones (Figs. 3 and 4). The mean porosity of the cored intervals is mostly very similar despite strati-

Sandstone member	N	Mean	Min	Max	Std. dev.	R	p
D_{PE}	101	823.845	680.30	1052.50	95.8419		
φ_{PE}	101	24.313	6.80	33.10	6.5837	−0.2631	0.008
D_{PEVC}	43	1538.953	1479.25	1583.25	42.5746		
φ_{PEVC}	43	16.951	6.90	25.60	4.0242	0.5468	0.000
D_{PL}	68	1014.750	913.50	1315.50	134.6637		
φ_{PL}	68	24.921	6.90	33.00	4.3558	−0.4974	0.000
D_{PLVC}	27	1787.935	1747.00	1846.00	48.0170		
φ_{PLVC}	27	14.133	6.20	24.60	4.3935	0.4381	0.022

Table 3 Descriptive statistics for depth and porosity in both sandstone members.
Legend: PE = Pepelana, PL = Poljana, PEVC = Pepelana (Velika Ciglena), PLVC = Poljana (Velika Ciglena), D = depth, φ = porosity.

graphic position and location (Tables 1 and 2) – average is 24.5%, and maximum about 30%. Exceptions include data from well VC–1, where the average is 15.7%, and the maximum average was 25%. Interestingly, the total mean porosity in both sandstone members is exactly the same at 21.8%.

Generally, the Pepelana and Poljana sandstones (eliminating the two extremes) are approximately 550–900 m deeper in Velika Ciglena (well VC–1) than elsewhere (Tables 1 and 2, Figs. 3 and 4). Minimum and maximum differences between the top and bottom of the analysed members are:

- the top of the Pepelana sandstones in the VC–1 well is 356 m deeper than in the Rov-1 well, and approximately 971 m below the top in well Ša–5;
- the base of the Pepelana sandstones in VC-1 is 547.9 m deeper than in Rov–1 and 895 m (Ša–5);
- the top of the Poljana sandstones in VC-1 is 557.1 m deeper than in Rov–1 and 837 m (Pav–1);
- for the base of the Poljana sandstones these figures are 712.2 m (Rov–1) and 1006 m (Pav–1).

It is clear that such depth differences have to be reflected in the compaction rates as well as in porosity decreases. Locally, it was described that the mean porosity value was about 10 (absolute) % lower in well VC–1 than elsewhere.

These listed differences between the top and bottom of the sandstone members show an approximate range of 400 m as the range when compaction starts to have a measurable influence on porosity values.

3.2. Analysis of vertical porosity within and among the single wells

The possible decrease in the mean core porosity was also analysed within both an individual member and a single well. It was only possible to perform this for those wells with two or more cores from the same member, e.g. well VC–1 with three cores in the Pepelana sandstones, and wells Pav–2 and VC–1 with two cores each in the Poljana sandstones.

All three cores in the Pepelana sandstones (well VC–1) showed a simultaneous increase of mean porosity and depth, although the mid points of the shallowest and deepest cored intervals are 100.4 m apart (Table 1, well VC–1). An identical result is given for cores taken from the Poljana sandstones. In the Pav–2 well, the mean porosity in the deeper core is higher by 5%, although the distance between the shallow and deeper cores is 91.75 m. Very similar results were obtained for well VC–1, where the porosity is higher by 3.81% in the core that is 95.9 m deeper (Table 2).

It is obvious that porosity decrease as result of compaction was not observed at all here, i.e. the depth difference of 100 m was not large enough to be significant in this way. In contrast, there is locally higher mean porosity observed in the deeper cores.

This is why separate porosity–depth diagrams were constructed for each member (Figs. 5 and 6).

Figures 5 and 6 show simple porosity variation curves. The interval mean porosity values in the analysed cores of Pepelana (5 wells, 7 cored intervals) and Poljana sandstones (4 wells, 6 cored intervals) are placed on the horizontal axis, while relative depths are placed on the vertical axis. This shows the trend of porosity variations with depth to be compared for both members.

It is possible to visually evaluate the behaviour of mean porosity in different cores regarding depth. Figures 5 and 6 present similar regularity, i.e. data are grouped in two sets. Mean porosities calculated for the cores from Šandrovac, Galovac–Pavljani and Rovišće represent the first (shallower), while porosities from Velika Ciglena represent the second group. The same approach is applied for both the Pepelana and Poljana sandstones.

It is clear that the depth difference of the cores in each group falls within the range of 100–400 m. The variability of porosity in each group is not explained by compaction, but by another mechanism. High lithological variability could be clearly observed in the core descriptions of the analysed fine- and medium-grained sandstones. Such variability is the result of the very different and occasionally high proportion of silts, marlstones or clays. It is why the unexpected, simultaneous increase of porosity and depth could be explained by a sedimentological mechanism. Such a mechanism is also the reason for the variability in porosity within the groups.

In contrast, the influence of compaction could only be determined by comparison of Velika Ciglena with other data from shallower groups, i.e. in the porosity decrease as a result of inter-group variation. Such variations could be observed after comparing cores among the groups. Depth differences between the deepest core in the first, and the shallowest core in the second group are compared. In the Pepelana sandstones the vertical distance of cores in wells Rov–1 and VC–1 is 430.9 m (Fig. 5). In Poljana sandstones this distance (the same wells) is 435.5 m (Fig. 6).

Also, the differences between the shallowest and deepest cores inside the same group are compared. In the first group this distance in the Pepelana sandstones amounts to 366.2 m (wells Ša–5 and Rov–1), while in the Poljana sandstones it is 392.75 m (Pav–1 and Rov–1). In the second group (Velika Ciglena) these differences are significantly lower – 100.25 m (Pepelana sandstones) and 96 m (Poljana sandstones).

Compaction is not observable from the data within the groups, although the maximum distance between cores is 392.75 m, determined in the first group of Pepelana sandstones. However, the compaction effect is recorded by comparing the data from different groups, i.e. comparing data from depth differences of 400–500 m.

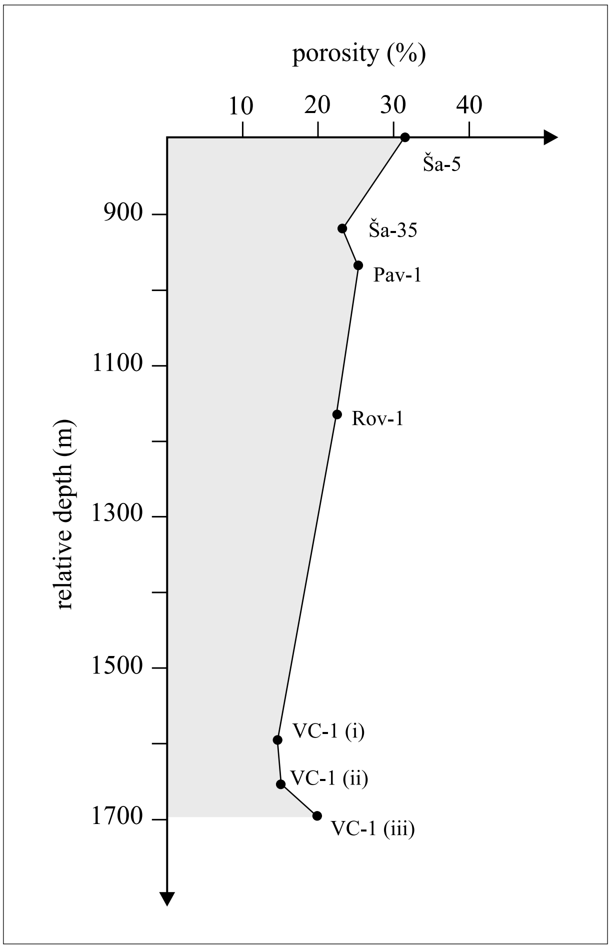

Fig. 5 Mean analysed core porosities and depth differences in Pepelana sandstones.

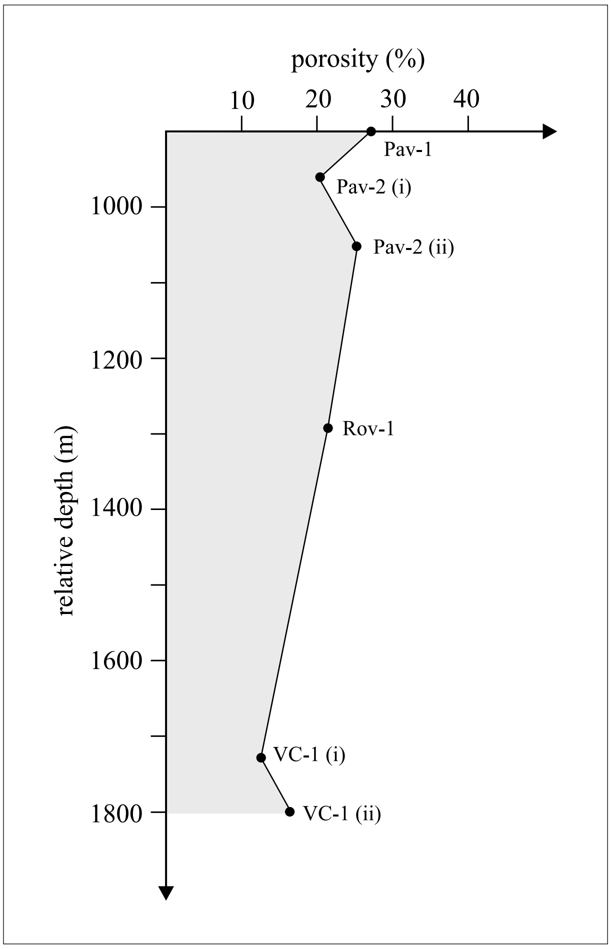

Fig. 6 Mean analysed core porosities and depth differences in Poljana sandstones.

Compiling these results, a minimum depth difference of 400 m is accepted as a limit when compaction will have to take place to influence porosity decrease in the same lithostratigraphic unit.

It is clear that the influence of compaction cannot be observed in the data from a single well, because the thicknesses of the particular members do not exceed the value of 400 m. In the Pepelana member it varies between 55 m (Pav–1) and 314 m (VC–1). In the Poljana member this range is from 129 m (Pav–1) to 298 m (VC–1). Such a result could be very useful regarding the control point values calculation as an input for interpolation. In such a case, the mean porosity value will not depend on the vertical position of the core in a particular member at the same locality. It makes porosity mapping (e.g. MALVIĆ & ĐUREKOVIĆ, 2003) in these units easier, because point values are simply represented by the arithmetical mean of interval values, which are not dependent on the stratigraphic position of the cores.

3.3. Testing the group differences

To compare two sample collections or populations and decide either for, or against their statistical similitude one should perform some specific statistical tests such as, for example, the simple t- and F-tests.

Broadly speaking the t-test is always used for the practical purposes of either: (1) testing hypotheses about the equivalence of two sets of data (equality of means), or (2) establishing the possibility that a given sample could belong to a population having some specific characteristics (DAVIS, 1986). Theoretically, in the presented case both types of analysis could have been performed, namely, testing the differences between the porosity of the two groups of sandstones vertically disposed within the same sandstone formation, and searching for the critical values of reduced porosity which may be indicative of a depth difference between these groups having resulted from the process of compaction. However, there are two assumptions that must be justified before the t-test is run, particularly when referring to the former example. The first assumption prevents the violation of normality, the second requires the homogeneity of variance.

φ	N	Skewness	Kurtosis	K–S	S–W (p)
Pepelana	101	-0.62	-0.46	0.13	<0.000
Pepelana–VC	43	0.22	0.29	0.24	<0.001
Poljana	68	-1.32	3.87	0.13	<0.000
Poljana–VC	27	-0.13	0.10	0.14	<0.138*

Table 4 Distribution characteristics of porosity. Legend: K–S = Kolmogorov–Smirnov test; S–W = Shapiro–Wilk's test; * = normal distribution.

φ	F-value	t-value	df	p
Pepelana/Pepelana–VC	2.68*	-	142	0.000
Poljana/Poljana–VC	1.02*	10.862*	93	0.000

Table 5 F- and t-statistics for two pairs of variates (φ). Legend: * = F- and t-values exceeding critical.

It is common when dealing with most geological problems that normal (and lognormal) distributions are the exception rather than the rule, which poses considerable constraints on the statistical treatment of such data (REIMANN & FILZMOSER, 2000). The distribution characteristics of porosity are in full accordance with this state of affairs, only that in this particular case their distinctive trait is reflected in a typically negative skewness (see Table 4). Negatively skewed distributions are fairly rare in natural systems, generally occurring when many of the observations linger at, or near, an upper limit set by some natural process (KOCH & LINK, 1980). Porosity is expected to attain progressively lower values as the process of compaction develops. Accordingly, the porosity in the shallower parts of some sedimentary complexes would show significant departure from normality, while the deeper parts, in contrast, would tend to normality as the increasing number of observations cluster symmetrically around some lower central value. This is easily seen in the present case where the porosity ratio in the deeper, Velika Ciglena horizons, or series, in both the Pepelana and Poljana sandstone members either approaches (Pepelana–VC), or actually assumes (Poljana–VC) a normal distribution in respect to the shallower horizons (Table 4).

However, in testing the variances and means of samples taken in different geological domains, departure from normality is not usually seen as a problem if the data suite is rather large, with the number of cases N>30 (DAVIS, 1986).

The second assumption though, is critical, and requires that the equality of variances of the two comparison groups is guaranteed before the additional t-test is performed. If variances, ordinarily checked by the simple F-test, are not equal there is no sense in testing the equality of means because the difference between the two groups is already obvious.

To begin with, in this particular case the hypothesis that the two sandstone horizons from the Pepelana and Poljana members, namely, shallower and deeper, belong to the same population is tested. An alternative hypothesis is that they are of a different origin. The premises are the same for the F-test examining the equality of variances as for the t-test checking the equality of means. Thus:

(1) $H_0: \sigma_1 = \sigma_2$
$H_1: \sigma_1 \neq \sigma_2$, and

(2) $H_0: \mu_1 = \mu_2$
$H_1: \mu_1 \neq \mu_2$

The problem tested by the hypothesis and its alternative is simple: is the difference between the group means significant at the selected level (usually $\alpha=0.05$). If the terms in the first set of equations are met and variances between the groups do not differ significantly, then the additional test for equality of means can be safely applied. The results of the test for Pepelana and Poljana sandstones are given in Table 5.

It is clear from the calculated F-statistics that for the first pair of variates (φPepelana/φPepelana–VC) the null hypothesis is rejected, meaning that there is ample statistical evidence to suggest that the porosity ratio in the shallower and deeper horizons of the Pepelana sandstones are significantly different. Obviously, these two series do not represent parts of the same population ($H_1: \sigma_1 \neq \sigma_2$).

In contrast, the second pair of variates (Poljana/Poljana–VC) behaves in a quite different manner, as the F-test does not result in rejection of the hypothesis about the equality of variance ($H_1: \sigma_1 = \sigma_2$). However, using the additional t-test, the hypothesis of equality of their means is nevertheless rejected ($H_1: \mu_1 \neq \mu_2$), which, again, places the deeper region of the Poljana sandstones (Poljana–VC) in different circumstances, with respect to its overlying shallower counterpart (Table 5). Thus, in the final analysis, the hypothesis about the deeper and shallower sandstone series in either area (Pepelana and Poljana) belonging to the same, homogeneous member, at least as regards their porosity, is rejected by both statistical tests.

The second method of utilizing the t-test can be safely applied after the previous analysis had established the clear statistical difference between the compared groups. The problem emerging in this instance is to find the critical value of porosity for the depth where the process of compaction has significantly changed the physical characteristics of the shallower sandstone series. In other words, as seen in the light of negative correlation between depth and porosity, one must propose a porosity ratio that would not belong to the parent population (the shallower sandstone member), but must be significantly lower. This value can be tested by the standard one-tailed t-test ($\alpha=0.05$), which is appropriate on this occasion because only one critical region of the population is examined – that with decreasing porosity (increasing depth). In the shallower part of the Pepelana sandstones the mean value of porosity ratio equals 24.313% (see Table 3), but to compute the critical t-value that discriminates the two sandstone series, a hypothesis and its alternative must be tested which state that:

$$H_0 : \mu = \mu_0 \text{ and } H_1 : \mu < \mu_0$$

which is accepted for:

$$\frac{\bar{x} - \mu_o}{\sigma}\sqrt{N} \le t_c$$

or:

$$\mu_0 \ge \bar{x} - t_c \frac{\sigma}{\sqrt{N}}$$

where the symbols are as follows: $\bar{x}$ = mean porosity of the parent population (shallower series), σ = standard deviation of the parent population, and N = number of observations (Table 3); t_c = critical t-value; μ_0 = hypothetical mean of a deeper population.

As the procedure of finding the critical value is tentative, by consecutive decreasing of the proposed porosity ratios during the test one can eventually find a number for which the computed t-value is critical. In practice, it means that the hypothetical sandstone series with the porosity ratio thus computed (representing its mean) do not belong to the parent population (the shallower Pepelana sandstones), but neither to the deeper Velika Ciglena member distinguished by much lower values. A decision can be made that, according to the t-test, the proposed porosity ratio on the verge of the critical region represents those samples in the upper part of the Pepelana sandstones where compaction becomes significantly observable. The critical t-value and critical porosity found by the t-test are thus 23.022% and 1.971, respectively (Table 6).

A similar procedure was carried out for the deeper member of the Pepelana sandstones (Velika Ciglena) where the process of compaction has resulted in a much lower porosity represented by the mean value of 16.951%. If the natural law of the decrease of porosity with depth is applied on this occasion, one would expect further reduction of porosity with depth which would place the Velika Ciglena member in some intermediate position. However, due to the variable proportions of clay in different parts of the sandstones, porosity actually can become higher with depth (positive correlation in Table 3). This phenomenon requires a different approach applying an inverse procedure: it would be reasonable to expect the compactness being still greater in a limited region immediately above the porosity ratios represented by the mean for the deeper Velika Ciglena population. Thus a lower porosity can be proposed for a somewhat shallower hypothetical sample for which the computed t-value would be critical. In this case the hypothesis and its alternative only change their signs with respect to the former case. The computed critical t-value of 1.988 is found for the respective porosity ratio of 15.731% (Table 6), and it can be deemed to be the representative value for maximum compaction in the Pepelana sandstones. The range between the area with significantly observable compaction and maximum compaction would thus be the range between the two critical margins, namely 23.022% and 15.731%, which equals 7.291% for the Pepelana sandstones. To recalculate these values into depths is a simple task using the regression lines between porosity and depth. In the case of Pepelana the regression lines are:

$$D_{PE} = \frac{39.202 - \phi_{PE}}{0.0181}$$

$$D_{PEVC} = \frac{\phi_{PEVC} + 62.58}{0.05168}$$

The recalculated range of compaction thus spans between 893.92 m and 1515.31 m, or 621.39 m in total (Table 6).

An identical procedure is repeated for the Poljana sandstones. From Table 6 it is clear that the range of compaction is considerably wider in the light of porosity, from 23.877% to 12.437% (11.44% in total), due to the lower values in the deeper member of the Poljana sandstones (Velika Ciglena). However, after recalculating porosity into corresponding depth using the regression lines for these sandstones:

$$D_{PL} = \frac{\phi_{PL} - 41.248}{-0.0161}$$

$$D_{PLVC} = \frac{\phi_{PLVC} + 57.54}{0.04008}$$

φ	t-critical	df	p	φ-critical	depth	range
Pepelana	1.971	100	0.05	23.022	893.92	
Pepelana–VC	1.988	42	0.05	15.731	1515.31	621.39
Poljana	1.977	67	0.05	23.877	1078.94	
Poljana–VC	2.006	26	0.05	12.437	1745.93	666.99

Table 6 F- and t-statistics within members.

the range appears only slightly wider, spanning between 1078.94 m and 1745.93 m, which is 666.99 m.

The procedure described in this subsection could be considered as a more precise extension of the determination of the compaction depth difference given in subsection 3.2. The minimal depth difference of 400 m estimated graphically (Figs. 5 and 6) is numerically recalculated at 621.4 m (Pepelana) and 667.0 m (Poljana).

One must be aware, though, that porosity values (as well as depth) with two or three decimals are statistically valid and appear as a result of statistical computations, which is the only reason for being written in this manner throughout the text. In the last analysis, such precisely calculated numbers are not geologically meaningful and can be soundly reduced to one decimal (φ), or given to a round figure (depth).

4. CONCLUSIONS

A detailed study of porosity and depth in the sandstone members of the Kloštar-Ivanić formation (Lower Pontian) was performed using the data obtained from core analysis. This is supported by other available data gathered from several well files from the sedimentary environment, together with granulometric analysis and electric log interpretations.

Generally, the data were treated in two ways. Firstly, the diagrammatic representation of both investigated variables was amply utilized in analysis – depth differences from the cores and porosity–depth plots were drawn for both sandstone members. Secondly, a detail statistical analysis of porosity was carried out separately for two groups, or series, within the same sandstone member – shallower and deeper (the latter known as Velika Ciglena group). Comparison of the results from the two approaches (graphical and statistical) allow the following conclusions to be drawn:

- Porosity values in these Lower Pontian sandstones are negatively correlated with depth in the shallower series, but, in contrast, a good positive correlation is found between these variables in the deeper, Velika Ciglena group.
- The qualitative aspect is expressed through lithological variability of the sandstones, as result of their very different and occasionally high proportion of silts, marlstones or clays. This is why the porosity within a particular group varies and even increases with depth.
- Dependence between porosity and depth is established in two ways: (a) graphically, with more than 400 m of depth difference at the same location, and (b) by the use of statistical tests which set the limits for the influence of compaction at a minimum of 621 m in the Pepelana, and 667 m of depth difference in the Poljana sandstones.
- There is no single location (well), where the thickness of the Pepelana and Poljana sandstones exceeds 400 m. Because of the latter, it is appropriate to calculate the porosity value as an arithmetic mean of interval core porosities at a particular location regardless of the influence of compaction.
- The mean porosity value is not dependent on the vertical position of the core in a particular member at a given locality. This allows the calculation of simple arithmetic means to be used as possible mapping and, consequently, easier porosity interpolation.
- Analysed sandstones are located more than 400 m deeper in the Velika Ciglena area than in other wells. A compaction-related porosity decrease is clearly reflected only in the case where the porosity values of Velika Ciglena are compared with other locations.

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