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Interdependence of Petrophysical Properties and Depth: Some Implications of Multivariate Solution on Distinction Between the Lower Pontian Hydrocarbon-bearing Sandstone Units in the Western Part of the Sava Depression

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Abstract

Statistical analysis of reservoir data from the Lower Pontian clastics (the most important hydrocarbon reservoir rocks in the Sava depression), supports established knowledge of the interdependence of petrophysical properties and depth. Irrespective of the focus that the reservoir data may be studied and presented, depth always emerges as a fundamental reservoir descriptor. This is particularly evident when studying the differences between widely spaced oil and gas fields, when the numerical model completely separates the two sets of descriptor variables, indicating two different sources of their internal variability. Porosity and permeability belong to "intrinsic rock properties" while depth must be ascribed to other sources, e.g. tectonic subsidence. Discriminant function weighted with depth (DF1) has such group centroid values, that zones can be drawn within a particular field that coincide with structural relationships. On the function marked with reservoir properties (DF2), group centroid values are higher close to the axes of palaeotransport channels, where sandstone layers are the thickest and particles are best sorted. Group centroid values on the third function (DF3) depict the areas of relatively higher permeability in the apical parts of structures, possibly caused by fracturing due to folding, or by cementation of other parts of reservoirs, where the circulation of pore waters was more pronounced. In the case of the most thoroughly investigated Žutica field, the inverse relationship between depth and porosity becomes evident when compared with the direction of palaeotransport and thickness of reservoir rocks on the respective structure and thickness maps.

Sažetak

Numerički modeli izračunati na osnovi podataka o kolektorskim svojstvima donjopontskih klastičnih stijena kao važnih stijena nosioca ugljikovodika u području Savske depresije u skladu su s činjenicama o međusobnoj ovisnosti fizičkih svojstava i dubine. Neovisno o pristupu analizi varijacija kolektorskih svojstava, dubina se uvijek ističe kao najvažnija varijabla koja opisuje ležište. To osobito vrijedi pri proučavanju razlika između međusobno udaljenih ležišta nafte i plina. U tom slučaju numerički model u potpunosti razdvaja dva skupa pokazatelja, ukazujući na dva različita izvora njihove unutarnje varijabilnosti. Porozost i propusnost pripadaju području inherentnih svojstava samih stijena, dok dubinu treba pripisati drugim uzročnicima, poglavito subsidenciji. Centroidi grupa na funkciji obilježenoj dubinom (DF1) imaju takve vrijednosti da se unutar jednoga polja može ocrtati zone koje su u skladu sa strukturnim odnosima. Povišene vrijednosti centroida na funkciji obilježenoj kolektorskim svojstvima (DF2) nalaze se uz osi paleotransportnih kanala gdje su pješčenjaci najdeblji, a zrnca najsortiranija. Vrijednosti centroida grupa na trećoj diskriminantnoj funkciji (DF3) ukazuju da je propusnost najveća u tjemenima struktura uzrok čemu mogu biti pukotine nastale uslijed boranja, te cementacija u ostalim dijelovima ležišta s izraženijom cirkulacijom slojne vode. U slučaju najpotpunije istraženog polja Žutica, obrnuto proporcionalan odnos između dubine i poroznosti posebno je naglašen kad se matematički model usporedi sa smjerom paleotransporta i promjenama debljine kolektorske stijene na odgovarajućim strukturnim kartama.

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1. INTRODUCTION AND PREVIOUS INVESTIGATIONS

Analyses of well cores are surely among the most important procedures during exploration for hydrocarbon accumulations and also during the subsequent production phase. Data obtained by laboratory measurements are the most straightforward measure of reservoir rock properties, i.e. of the porous medium. The first parameter is the "storage capacity" or porosity, and the second one is the "circulation capacity" or permeability. In their systematisation of laboratory measurements during the various phases of development and production, GORIČNIK et al. (1985) have put the determination of porosity and permeability in first place within the phase of reservoir development. In this phase, together with other analyses, it enables the quantitative description of a reservoir, calculation of reserves and its techno-economical evaluation. The most realistic values of relative permeability are vital for such calculations (KRIZMANIĆ et al., 1976), and this can be achieved by a very carefully chosen set of core samples. Samples have to be representative and of homogeneous composition and structure, because the permeability varies with the lamination of sandstones. Furthermore, the rigorous x-ray examination of homogeneity is required. It was also observed that, if a core is only weakly layered perpendicular to the flow direction, it doesn't necessarily affect the relative permeability. Conversely, if a core is layered parallel to the direction of flow, it has a large effect on permeability. It was also proven by KRIZMANIĆ (1980) that significant differences in measured permeability can occur between laboratories and even within a single laboratory, if there was a change of instrument, measurement media or laboratory conditions.

As for the further processing of measured data, numerous reservoir management investigations have shown that the architecture and properties of the hydrocarbon-saturated layers may show great spatial variability that often renders the available data unfit for obvious geological interpretation. Much uncertainty is thus introduced from the start in the prediction of reservoir performance on a regional or even local scale. However, the abundance of data, including core and well log data, can provide a more or less integrated picture of the reservoir attributes if multivariate geostatistical techniques are used. Such techniques are indispensable, not only because reservoir data are essentially of a multivariate nature, but also because this method allows their reduction into an integrated model. Reservoir performance is a result of the interdependency of its various characteristics. Method which differentiates between reservoirs or units pertaining to various fields, usefully emphasises the differences between depth, rock properties, or some other available reservoir data. Of these, discriminant analysis is a very advantageous multivariate method because one can directly ponder on differences between the groups and simultaneously infer the predictor variables that are the most responsible for these differences in the study area.

In this study, porosity and permeability were statistically analysed, because these are the two properties that have the most influence, both on oil and gas recovery and on the methods utilised to increase this recovery. There is a certain proportion of hydrocarbons that are going to remain in the known reservoirs, both on a macro and micro scale. The percentage of the oil remaining in place is mostly dependent on the complexity of a reservoir and on its lithology, especially the distribution of flow barriers. It is with new procedures of reservoir management that the quantities of remaining oil in certain pools are reduced. Advances in technology, such as 3D-seismics or horizontal wells, enable discoveries in places where hydrocarbons still remain, where they were by-passed in initial saturation, or in reservoirs that would have been regarded as depleted according to the usual standards (BASSIOUNI & VELIĆ, 1996).

1.1. Improvements to the recovery ratio

Croatian literature that directly or indirectly discusses the relationship between porosity and permeability comprises papers that are concerned with methods to improve oil recovery, or these that are based on statistical methods of analysis.

It has already been stated that large amounts of hydrocarbons remain in reservoirs at the end of the primary depletion period. In fact, this is usually more than 60% of the original oil in place (OOIP). According to production data published by SEČEN (1979), the average oil recovery in Croatia, achieved in the primary production stage for solution gas drive was in the range of 16-20%, and for the gas cap drive it was between 20-25%, while the water-drive resulted in recovery of 30-50%. The average oil recovery in 1970 was 25%, while the most unfavourable 16% occurred in the largest reservoirs of the Ivanić-Grad and Žutica fields. An average recovery of 35% was achieved post 1975 (SEČEN, 1979, 1980, 1987; BAUK et al., 1988).

There was a sustainable growth in oil production in Croatia until 1980, the year when it crossed the 3 mil.t/yr., after which it remained more or less stable throughout the following decade. Subsequently, the production started to decline because of lost reservoir energy and there were no new compensating discoveries (PERIĆ, 1992).

Production histories from around the world reveal that waterflooding is the most adequate and economic method for improving oil recovery. It was actually discovered by chance back in the 1870's in Pennsylvania. In Croatia, the method of conventional waterflooding was first implemented in 1972, in one layer of the Ivanić-Grad oil field. Due to the fact that this is usually applied after the primary production stage, waterflooding is regarded as a secondary phase of depletion i.e. as a secondary method of production, together with a method of gas injection in primary gas caps. This second method (gas injection) has been applied in Croatia since 1982, when it was initialised in some layers (A_{1-3}) of the Žutica oil field (PERIĆ, 1992). From reservoirs with water injection, oil recovery in the range of 40-54% was achieved, primarily due to a favourable oil viscosity of 0.64-1.31 mPa s (SEČEN, 1980). Nine reservoirs in total were injected with water, and these were the reservoirs that contained 58% of the OOIP in Croatia (SEČEN et al., 1988; BAUK et al., 1988). Gas was injected into two reservoirs with primary gas caps. Between 1982-1987, these methods resulted in the production of an additional 16 mil. t of oil. In the late 1980's, the amount of oil produced from the water-injected pools accounted for 50% of the total annual production.

Approximately 50 years ago, further new methods of increasing oil recovery were developed and tested. According to their planned implementation in the third phase, they were called "tertiary recovery techniques". Some of the techniques involved were aimed at producing oil remaining in the part of the reservoir already swept by displacing fluid (called increasing displacement efficiency). Conversely, increasing sweep efficiency relates to techniques used to extract the oil remaining in the part of the reservoir not swept by displacing fluid. Some techniques, of course, can increase both displacement and sweep efficiency. The use of such techniques is called "enhanced oil recovery" (EOR). Technically, EOR consists of methods aimed at increasing the ultimate oil recovery by injecting appropriate agents not normally present in the reservoir, chemicals, solvents, oxidizers and heat carriers, in order to induce new mechanisms for displacing oil.

These methods are based on the fact that a low oil recovery by conventional methods results from the combined action of several physico-chemical factors (GORIČNIK, 1981; SEČEN, 1979, 1980, 1987; BAUK et al., 1988). These factors are: the interfacial tension between the oil and injected fluids, varying viscosity of oil, water and especially of gas (resulting in injection fluids rapidly bypassing the viscous oil), capillary attraction between rocks and fluids, as well as heterogeneity in the petrophysical properties of reservoir rocks in both a vertical and horizontal direction. Displacement of the remaining oil from reservoirs can be achieved by the reduction of interfacial tension between oil and water and by reduction of capillary forces. These processes can be divided into three groups according to the procedures applied - thermal, chemical and gas injection in miscible, near-miscible or non-miscible conditions (SEČEN, 1980; BAUK et al., 1988). A preliminary decision in the selection and use of tertiary methods (GORIČNIK, 1981) is dependent on technological and economic factors (particularly the price). Among others, technological factors such as lithology, depth and thickness of reservoir rocks, pressure and temperature, gravity and viscosity of oil, and also the (average) permeability of the reservoir are the screening criteria for selection of the main EOR processes. SEČEN et al. (1988) emphasised that in order to obtain good connections between the injection and production wells, it is of primary importance to thoroughly study the reservoir continuity and distribution of the porosity, permeability and saturations within a reservoir. From the thermodynamic point of view, research was undertaken on the injection of dry gas in the Žutica oil field in order to achieve miscibility conditions between injected dry gas and oil in place (JÜTTNER, 1996).

According to PERIĆ (1992) up to 80% of the known geological reserves in production, and around 75% of the total "balance reserves" (the fraction that can be economically produced with existing technology - see BAUK, 1996) of oil in the Croatian part of Pannonian Basin occur in sandstone reservoirs. Therefore, the study of porosity and permeability of these sandstones is of primary importance in the selection of methods for enhanced oil recovery. Results of various studies (GORIČNIK et al., 1978, 1980, 1993; BAUK et al., 1988; PERIĆ et al., 1991) have indicated that the optimal method would be the displacement of oil by CO_2-injection in almost totally miscible conditions. The best candidates for this method are the reservoirs of the Ivanić-Grad and Žutica fields, where between 50-60% of the residual oil could be produced (BAUK et al., 1988). Recently (JÜTTNER & RAJKOVIĆ, 2001), economic, and especially environmental factors have been emphasised as the most important in the management of reservoirs.

1.2. Previous statistical analyses

Few papers published in Croatia document the use and results of mathematical methods in geology, especially in the field of subsurface geology. HERNITZ & JURAK (1973) where pioneering in their statistical proof that, in the region of Ivanić-Grad, there is a clear stochastic dependence between the thickness of lithostratigraphic units - formations and depth of marker horizons that define them. An average correlation index of 0.8 was calculated.

MOLAK (1977) statistically analysed thousands of laboratory measurements of porosity and permeability, altogether 5,921 core sample taken from 11 oil and gas fields. The Okoli, Stružec and Žutica fields were also contained in this data set. In all cases, these were the sandstones with hydrocarbon accumulations. As has been found elsewhere, several conclusions were reached: porosity is characterised by a normal distribution, permeability by log-normal distribution, both these properties reduce with depth and there is a strong (functional) correlation between the porosity and permeability. Based on the correlation between the porosity and permeability, the permeability can be comparatively reliably determined on the basis of porosity data - good correlation was achieved by the square and linear function of porosity in the 14-34% range. It is assumed that certain statistical procedures were also used in papers where values of average permeability were published (SEČEN, 1979; BAUK & KEBER, 1980; GORIČNIK, 1981).

In a sense, the statistical analyses of JÜTTNER et al. (1999, 2001) are a continuation of the study undertaken by MOLAK (1977). They were governed by the aim of studying interdependence between the porosity and permeability of the Lower Pontian sandstones in the western part of Sava depression, and the stratigraphic architecture of these sediments together with palaeotectonics. The results partly supported the earlier work, except that, when the high-resolution stratigraphy of reservoirs is taken in account, there are significant differences between the fields. For example, there is no correlation between the depth and porosity and depth and permeability in the sandstones of GSS Poljana at the Stružec field. Similar correlations for the Okoli field were moderately to well expressed.

2. GEOLOGICAL SETTING

Statistical analysis of the porosity, permeability and depth was undertaken on measurements from the Lower Pontian clastics. These, together with the Pannonian sandstones, are the most important HC reservoir rocks in the Sava depression. The typical composition of these sediments is a sequence of grey, fine-grained sandstones and clayey-silty marls that were deposited in a brakish marine environment. Sandstone layers in the deeper parts of the depression are intercalated with and embedded within the marls.

Lithostratigraphically, these sediments form the Kloštar Ivanić Formation, encompassing all the strata between the E-log markers Z' (base) and Rϕ (top), as explained by ŠIMON (1970). The formation is subdivided into three smaller units - genetic stratigraphic sequences (GSS) which in geochronological order are the Poljana, Graberje and Bregi units (Fig. 3). Each GSS represents one depositional pulse starting with a progradational phase, a middle aggraddational section, and ending with retrogradation and a subsequent marine flooding surface followed by the overlying sequence (SAFTIĆ, 1998). Sandstone bodies in all of the three genetic sequences are elongated in the NW-SE direction, and according to their maximal thickness axes demonstrate a translation of the depocentre in a southwest and westerly direction.

Reservoir properties were measured on horizontal core plugs from the productive intervals of 4 fields in the western part of the Sava depression. Porosity was measured at a 10-cm spacing and permeability at 1 m. These fields are, from NW-SE (Figs. 1 and 2), the Dugo Selo field (wells marked with Gl- which stands for "Glavničica"), Žutica (wells marked with Žu-), Okoli (Ok-) and Stružec (wells marked O- which stands for "Osekovo"). The nature of the data that were available limited the possibilities for analysis and interpretation. There were no petrographic data - details of the composition and texture of sandstones. It can only be said that they are mostly fine-grained, laminated and interlayered with thin marls and that there is an internal architecture of sandstone bodies in the shape of a submarine fan (SAFTIĆ, 1998). Another limitation was that there were no pressure data to be analysed. A general constraint is that no overpressure zones were found in these sediments, which is presumed to result from both the numerous sandstone layers and at least three intersecting fault systems that were reactivated in several tectonic phases and enabled the migration of pore water (VELIĆ, 1980, 1983; PRELOGOVIĆ et al., 1998; LUČIĆ et al., 2001). Finally, there was no measure of the primary vs. secondary porosity, which limited the possibilities for interpretation. Also, the entire area is under an active wrench tectonic regime in Neotectonic phase, characterised by the general orientation of the maximal horizontal stress N-S, with significant local variation in the vicinity of active faults (PRELOGOVIĆ et al., 1998).

The generalised structure map of the E-log marker Z' (base of Kloštar Ivanić Formation) given in Fig. 4, also shows the shaded outlines of the three fields that are comparatively closely spaced - Žutica, Okoli and Stružec. The Dugo Selo field lies 24 kilometres NW of the Žutica field. Looking at the structure contours of this map, simplified structures can be observed, and also the fact that the reservoirs of these fields lie at various depths. The contours of the Žutica and Stružec fields coincide with anticlines, while the deepest, Okoli field lies on the plunging nose of an anticline. The shallowest samples are from the Dugo Selo field (882-1,013 m), the deepest from Okoli (1,700-2,015 m), those from Žutica lie in the range of 1,492-1,842 m, and 1,047-1,949 m from Stružec. These depth ranges can be seen in the schematic cross-section given in Fig. 3.

Significant differences in the thickness of the Kloštar Ivanić Formation can be observed over short distances (Fig. 5, VELIĆ, 1980). The maximum of more than 700 m occurs south of the Okoli field. The unit gradually thins in a NE direction, towards the margin of the Sava depression. It is also significant that there is a reduction of thickness that coincides with the apical parts of the Žutica, Okoli and Stružec structures. This can be attributed to a palaeostructural influence, i.e. to synsedimentary tectonics that uplifted these structures and partly to differential compaction in the areas where less or no sandstones were deposited on top of the structures. The Žutica structure is characterised by tectonic movements of inherited character. In the Neogene, the structure of the Stružec field was partly renewed and partly inherited, while the Okoli field

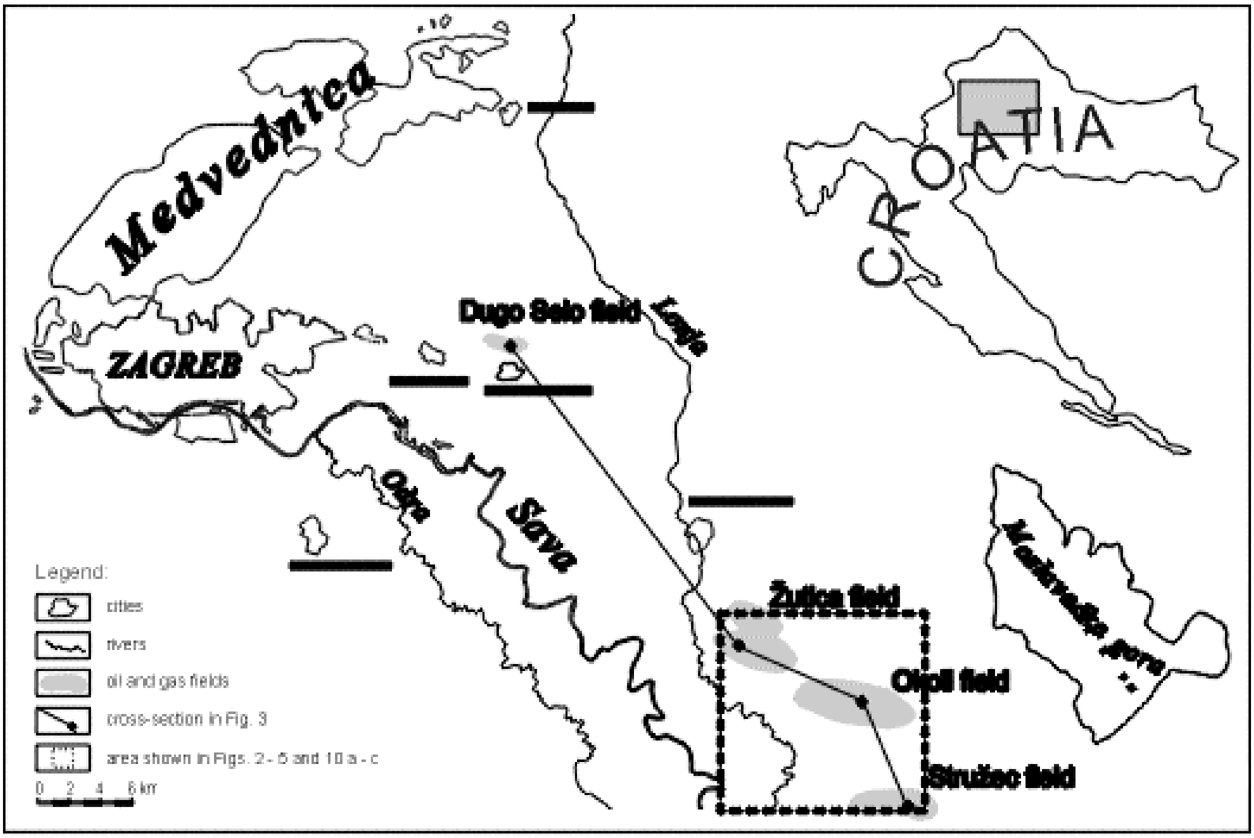


Fig. 1 Situation map.

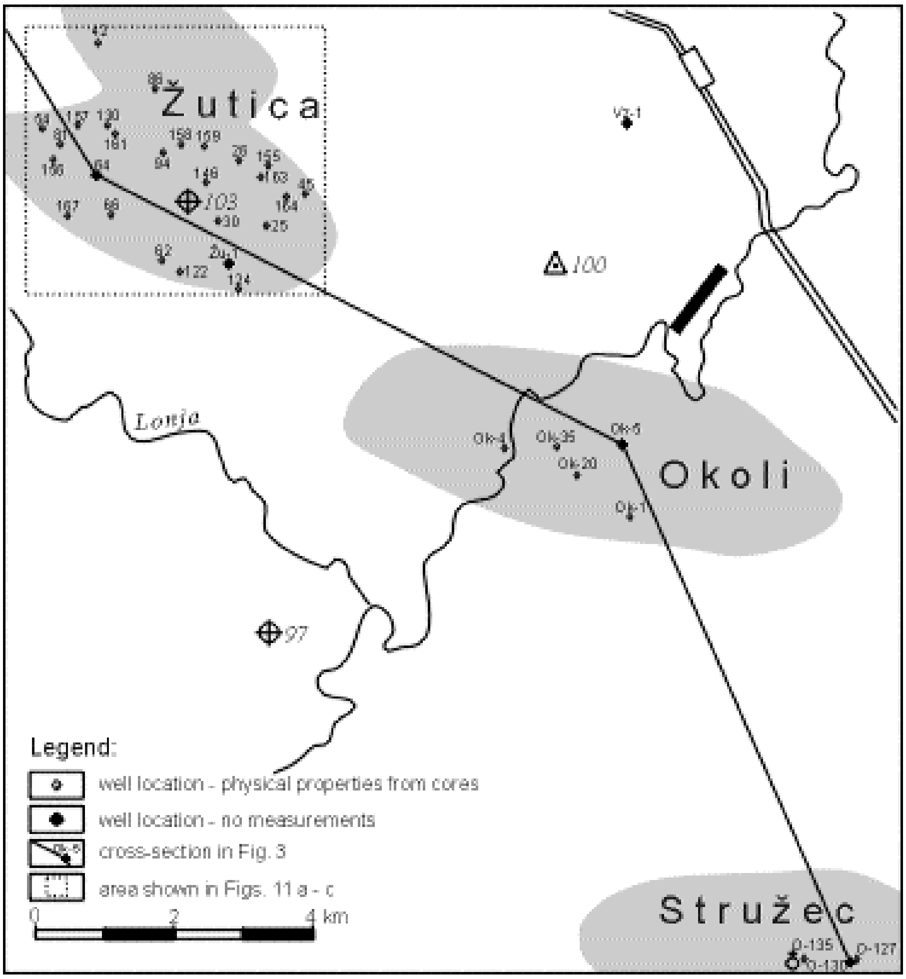


Fig. 2 Index map showing locations of field areas.

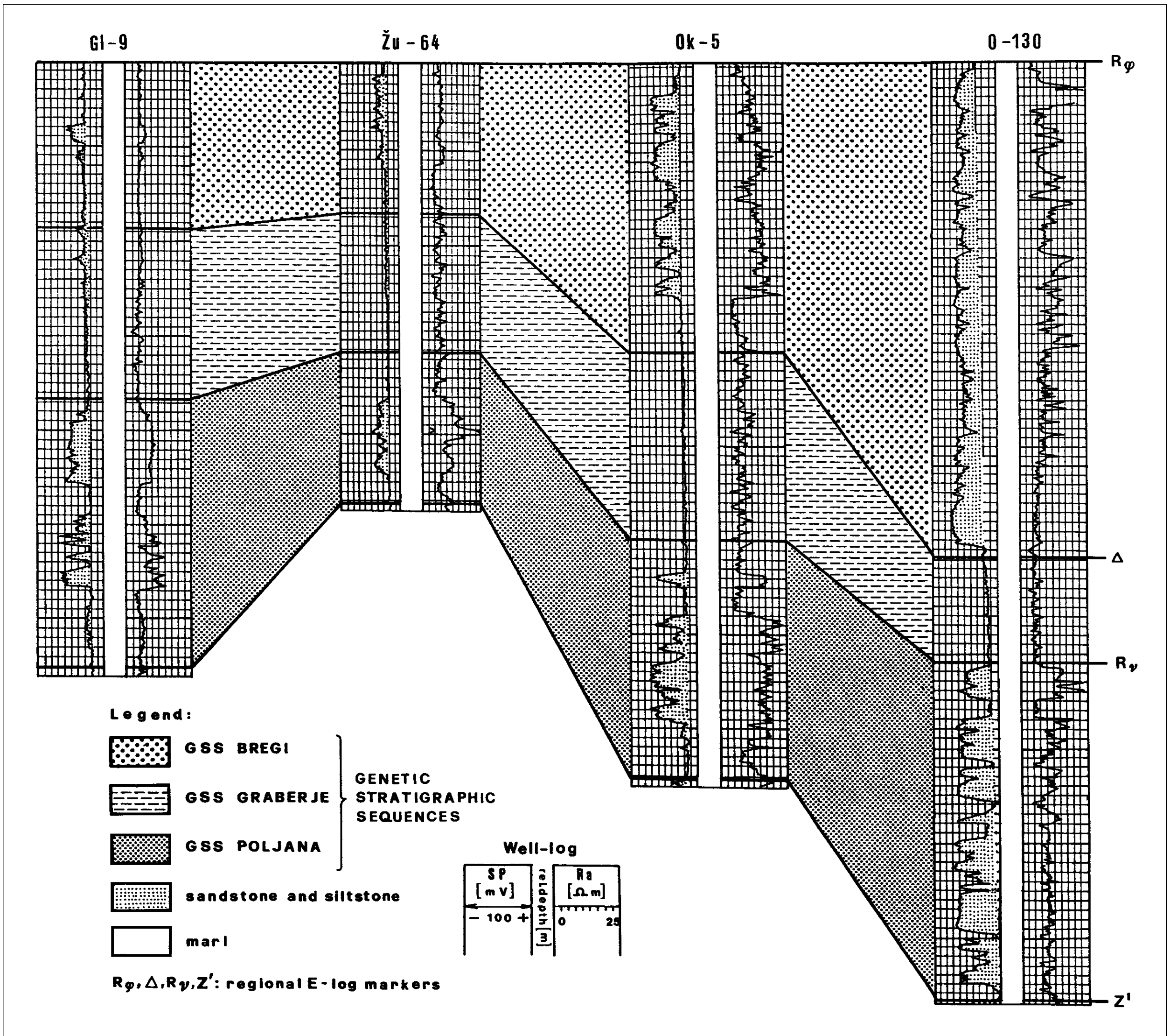


Fig. 3 Cross-section Dugo Selo-Žutica-Okoli-Stružec.

structure experienced diversification into three smaller anticlines (VELIĆ, 1979, 1983).

The thickness of the oldest of the three genetic stratigraphic sequences within the Kloštar Ivanić Formation - GSS Poljana is illustrated in Fig. 6, primarily based on well data. Thorough wireline log correlation across the western part of the Sava depression (SAFTIĆ, 1998) confirmed that the areas of maximal thickness of this unit coincide with the maximal thickness of the sandstone reservoirs. These elongated sedimentary bodies were formed by accumulation of sandy material within the submarine channels that formed conduits for the sedimentary transport. This explains why the generally NW-SE trending palaeodrainage axes are drawn through the areas of maximal thickness of GSS Poljana. Two main channels can be distinguished in the mapped area - the main palaeotransport axis of the Sava depression, and a main local transport channel that is located to the north.

3. MULTIVARIATE ANALYSIS OF THE WELL DATA

Exploratory multivariate analysis is a powerful statistical tool when dealing with a volume of numerical data as, for example, various measurements from wells across the oil fields. Through the process of data contraction it can reduce problems of structuring, distinguishing or comparison of data to scale providing a clearer insight into the underlying geological control. Also, it helps to organise the data into a mappable form which clarifies interrelationships more clearly.

Discrimination functions can be particularly convenient when applied to a problem involving several thousand of data scattered within and across different boundaries such as wells, geological units or HC fields, and which contain the same set of observed qualities. Their primary purpose is to separate the *a priori* defi-

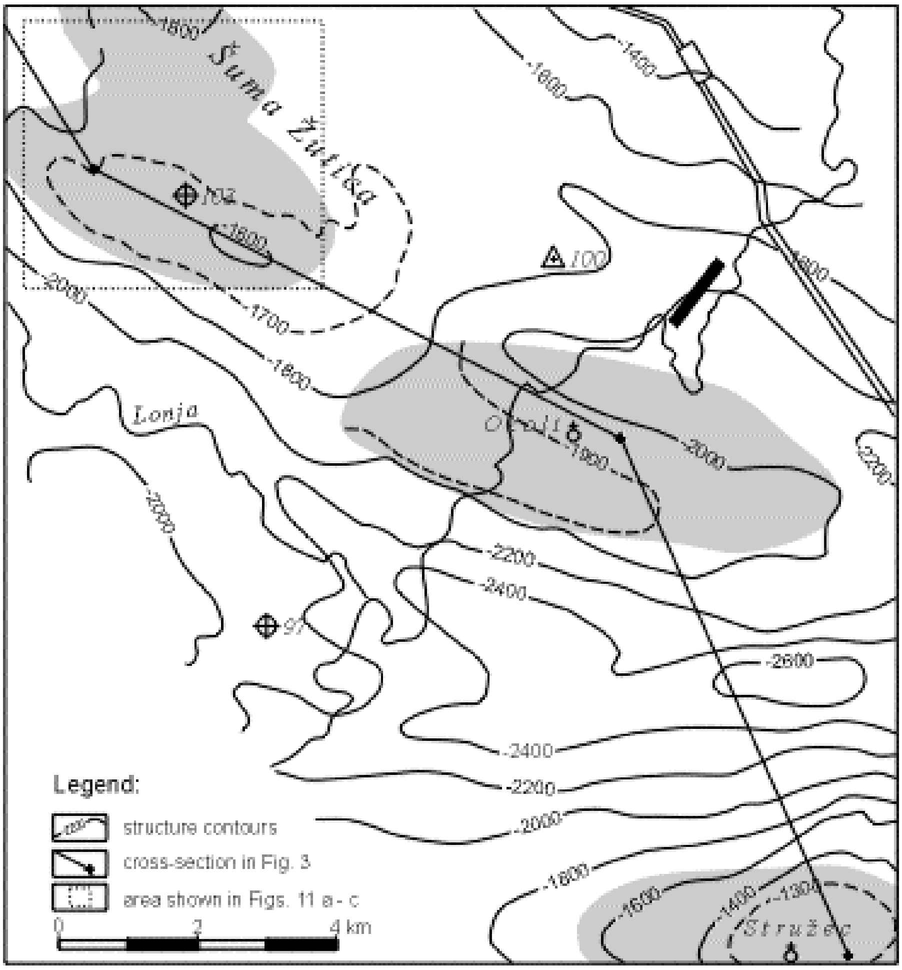


Fig. 4 Structure contour map - base of Kloštar Ivanić Formation.

ned clusters or groups in such a way that inter-group variance is maximised in comparison to the variance within each group (DILLON & GOLDSTEIN, 1984). Truly, the process of discrimination transforms the original set of data into a number of discriminant scores that place each object or group (represented by its mean) along one or more lines defined by the computed linear discriminant functions (DAVIS, 1986). Simultaneously, the multivariate problem simply collapses to the least-dimensional solution that is dependent on the number of groups or variables, whichever is the smaller.

3.1. The strategy of analysis

The data collected from a great number of wells through the Kloštar Ivanić Formation can be organised in several ways, as the grouping criteria are subject to different conceptions. The most obvious manner of grouping follows the trends of depth and area after which the two types of clusters can be formed, namely the FIELDS and (stratigraphic) UNITS. Such *a priori* formed groups are quite “natural”, and basic differences between them can be easily inspected provided that the data variability is great enough to disclose them.

However, merely three or four or even more (combining fields with units) groups of data, thus formed, do not allow their mutual relationship to be meaningfully represented on relevant field maps since there are insufficient mappable points to produce a grid. Also, only the lowest unit - the GSS Poljana - contains the entire body of measured data across the investigated area, and in most of the wells. On the other hand, the well data are arranged in intervals rendering their representation, unless depicted in a cross-section, largely abstract. To avoid this problem and, possibly, to focus on a narrower stand such as a single field, the groups can be reshaped by combining the wells with units or fields, or both. Thus, each well might be portrayed as a group with its intervals as objects. Through this rearrangement, new groups can be created and represented on a map via the relevant well locations. These groups though, being arbitrarily created, can introduce a form of artificiality into the “naturalness” of the original data. In such a case interpretation must be exercised with great care as differences between larger groups, such as fields or units, can easily be offset by variations within the smaller ones, such as wells.

Three discriminant exploratory analyses can be performed following the observed methods of grouping the

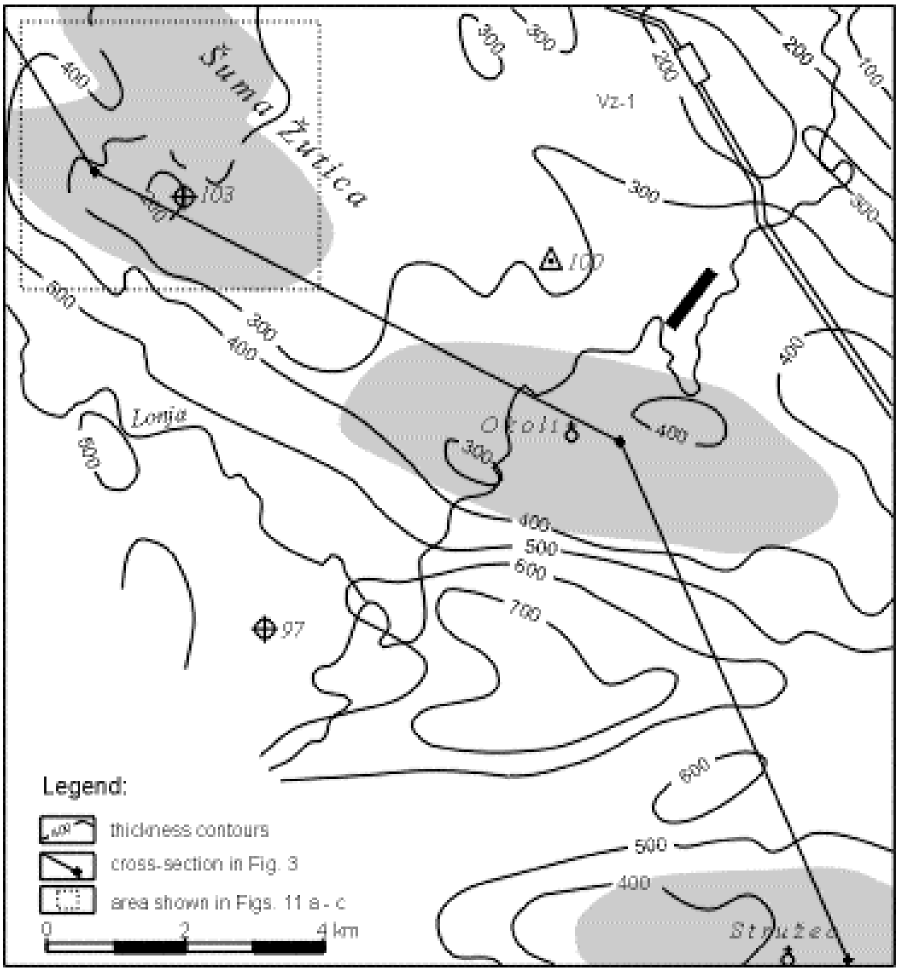


Fig. 5 Isopach map of Kloštar Ivanić Formation.

well data. In the first case, the data are arranged in such a way that sources of variation between the hydrocarbon-bearing fields - Dugo Selo (wells labelled Gl-), Okoli (wells labeled Ok-), Stružec (wells labeled O-) and Žutica (wells labeled Žu-) can be examined. The second case deals with differences between the three units containing the sandstone reservoirs - the GSS Poljana, GSS Graberje and GSS Bregi units, that always appear in the same superpositional sequence. The third possibility was a well-field combination that is narrowed to the Poljana unit and contains 31 groups (wells). This last attempt was aimed at highlighting possible variations within a single unit.

In all three cases, the same set of four variables is utilised, namely depth (D), vertical permeability (K_v), horizontal permeability (K_H), and porosity (Φ).

4. RESULTS

4.1. Case 1 - "FIELDS"

Discriminant analysis performed on the data matrix of four groups containing 1,401 valid objects and four variables resulted in three discriminant functions, the first of which explains almost 94% of the total system variability. The results, arranged in Table 1, portray the structure matrix of correlation between discriminant functions and observed variables.

The first discriminant function (DF1) has a strong loading on only one variable, namely the descriptor of depth, while the remaining three variables can be deemed irrelevant. According to its structure it can be properly labelled the depth function. The other two functions can be interpreted as reflecting the relationships among the basic physical properties. Of these, the second (DF2) is loaded heavily with porosity, while the

	DISCR. FUNCT.		
VARIABLE	**DF1**	**DF2**	**DF3**
DEPTH	-0.86*	-0.28	-0.41
HORIZ. PERMEABILITY	0.02	0.45	0.74*
VERT. PERMEABILITY	0.04	0.42	0.91*
POROSITY	0.06	0.97*	0.25
% explained	**93.66**	**5.91**	**0.42**

Table 1 The structure matrix for FIELDS.

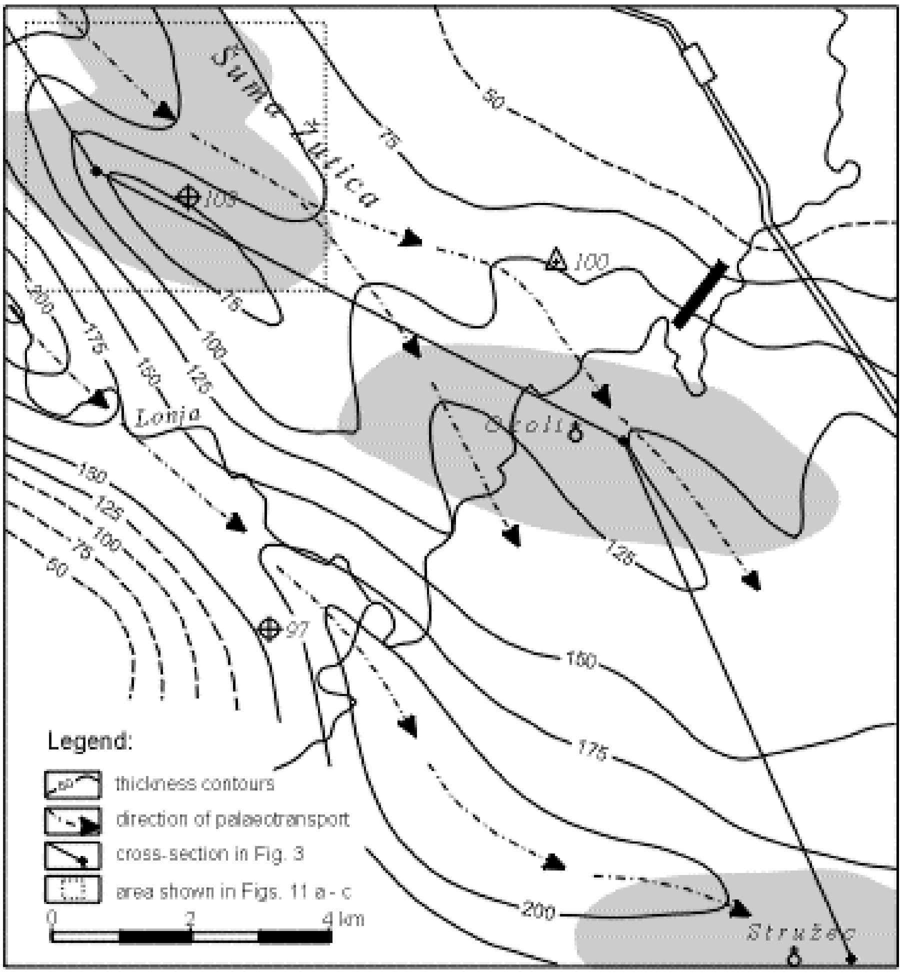


Fig. 6 Isopach map of GSS Poljana with directions of palaeotransport.

third (DF3) deals with indices of permeability. Both are slightly bipolar as their predictor variables are negatively associated with depth, although the relation is weak. Thus the sequence depth-porosity-permeability in decreasing order of variability and interpretability can be established through the FIELDS.

Relationships among the descriptor variables and related groups can best be represented diagrammatically, in which case the discriminant functions are viewed as axes in the reduced discriminant space. However, diagrams can not be directly compared as different scales are used in both cases. Discriminant axes on the scatterplot of variables (Figs. 7a-b) are drawn as normalised vectors, while on the scatterplot of canonical means (centroid values for FIELD groups) these indicate an altogether different scale (Figs. 7c-d). Thus, the interpretation of interdependence between variables and groups is always based on their shared position along the appropriate axis. The points placed close to the axis intersection (main centroid) are subject to little or no discrimination whatsoever.

The interpretation of diagrams is straightforward. Comparing the pairs of scatterplots it is easily observed that, according to DF1, the fields are arranged in the sequence of Okoli - Žutica - Stružec - Dugo Selo (Glavničica), of decreasing depth. The Žutica field is marked with an almost zero value (Table 2) of its centroid (group mean) functioning as the average depth value for fields. Regarding DF2, the diagram (Fig. 7c) is indicating increasing porosity with Dugo Selo field and decreasing porosity with the Stružec and, particularly, the Okoli fields. In the case of DF3 only the Dugo Selo field is clearly discriminated (Fig. 7d) on account of its lower permeability, while other fields remain virtually indistinguishable.

A classification matrix (Table 3) helps to understand the accuracy of discrimination results via the rela-

	DISCR. FUNCT.		
GROUP	DF1	DF2	DF3
DUGO SELO	9.09	0.41	-1.70
OKOLI	-1.64	-0.84	-0.05
STRUŽEC	3.99	-0.50	0.09
ŽUTICA	-0.09	0.09	0.00

Table 2 Group centroids for FIELDS.

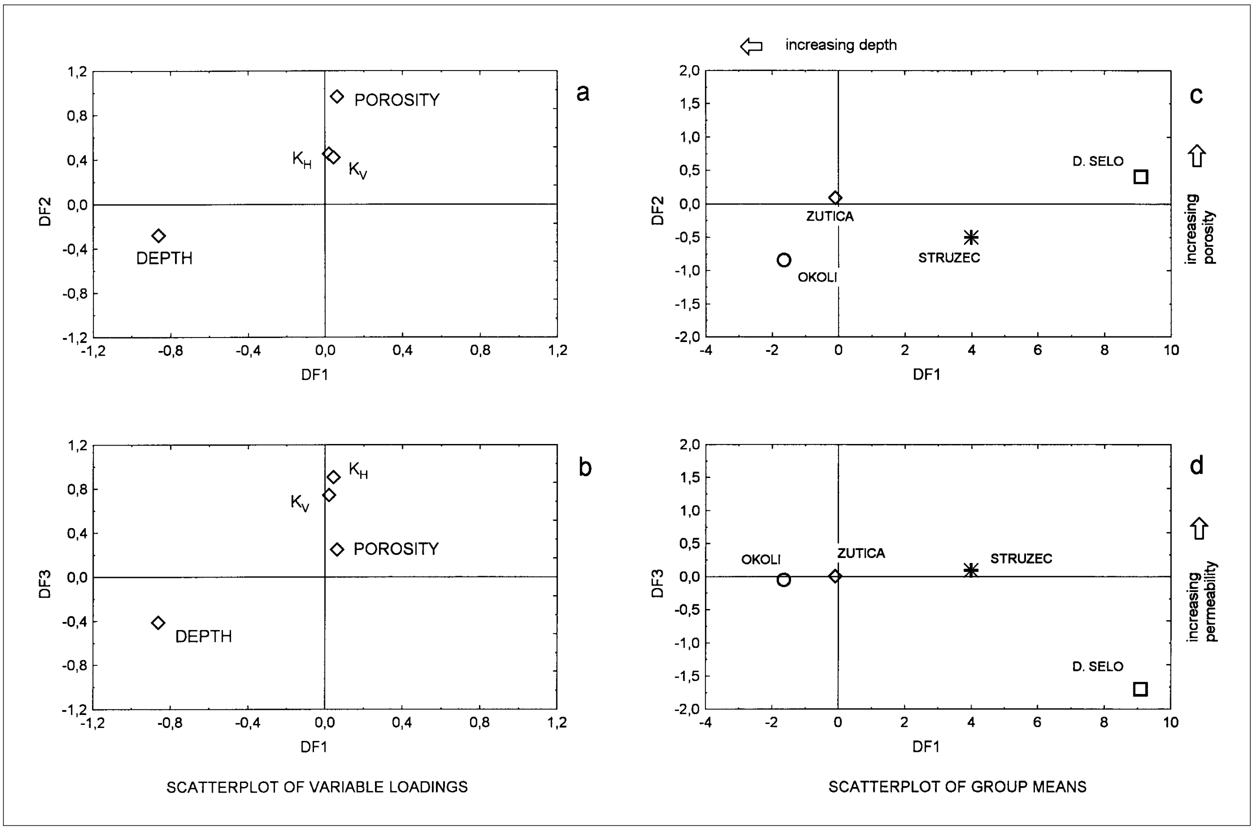


Fig. 7 Comparison of variables and fields: scatterplots of variable loadings (a, b) and of group means (c, d).

tionship between the *a priori* defined and mathematically computed groups. Discrimination efficiency exceeds 92% of a combined sample although it is unevenly distributed among the groups. The Okoli field displays the lowest classification results as most of its samples proved to be more akin to the Žutica field. The correctly classified groups are placed diagonally across the table.

4.2. Case 2 - "UNITS"

As in Case 1, discriminant analysis is carried out on the same data matrix but with only three groups representing the three units through all fields (GSS Poljana, GSS Graberje and GSS Bregi, superimposed as in Fig. 3). The analysis resulted in two discriminant functions as can be seen in the structure matrix (Table 4). Although the depth variable is an obvious predictor due to the fact that the sandstone units are always bedded in the same sequence of increasing depth, GSS Bregi - GSS Graberje - GSS Poljana, it is nevertheless included into the analysis for the possible interrelations with physical properties of rocks.

In contradistinction to the discrimination among FIELDS, the first discriminant function (DF1) is of a prominently bipolar nature, weighting the strongly loaded depth variable against the moderately loaded set of physical properties (K_H, K_V and porosity), as can be seen from Table 4. It accounts for almost the total variability (99.9%) of the UNITS system. The second discriminant function (DF2) is essentially concerned with a single variable, namely that of porosity, but having almost negligible interpretative worth (0.1%) it can be

GROUP	MATHEMATICALLY DEFINED GROUP D.S.	Ok.	Str.	Žu.	TOTAL	% correct
DUGO SELO	2	0	0	0	2	100.00
OKOLI	0	8	0	87	95	8.42
STRUŽEC	0	0	60	4	64	93.75
ŽUTICA	0	1	20	1219	1240	98.31
TOTAL	**2**	**9**	**80**	**1310**	**1401**	**92.01**

Table 3 Classification matrix for FIELDS.

VARIABLE	DISCR. FUNCT. DF1	DF2
DEPTH	0.92*	0.02
HORIZ. PERMEABILITY	-0.39	0.21
VERT. PERMEABILITY	-0.46	-0.10
POROSITY	-0.37	0.70*
% explained	**99.90**	**0.10**

Table 4 Structure matrix for UNITS.

GROUP	DISCR. FUNCT. DF1	DF2
GSS Bregi	-2.18	-0.00
GSS Graberje	2.19	-0.70
GSS Poljana	-0.64	0.00

Table 5 Group centroids for UNITS.

excluded from further considerations. Thus, the interpretation of results in the case of UNITS is very simple, particularly when inspecting the diagrammatic representation of variable-unit association (Figs. 8a-b). The GSS Bregi unit is placed on top of the others as expected, with a slight increase of K_H, K_V and porosity values, but the Graberje unit instead of Poljana shows the inverse relationship of their natural sequence (Table 5, Fig. 8b) which requires further consideration. With regard to DF2, the GSS Bregi and GSS Poljana are quite indistinctive, while GSS Graberje is assigned with decreased porosity.

The classification matrix (Table 6) reveals the apparent misclassification of the Graberje unit which is, according to all its properties, most similar to the lowest, Poljana unit. The overall classification accuracy exceeds 94% of a combined sample (1,401 valid cases). Discriminaton analysis for both FIELDS and UNITS represents a great error in classifying samples from the Okoli wells drilled through the GSS Graberje sandstone layers, the middle of the three units. The canonical mean (group centroid) for GSS Graberje in Table 5 is highlighted, which is excessive, indicating deeper emplacement, when compared to the sandstones of GSS Poljana. This may be the result of different or changed physical properties that caused the reduction of reservoir quality of the unit in question.

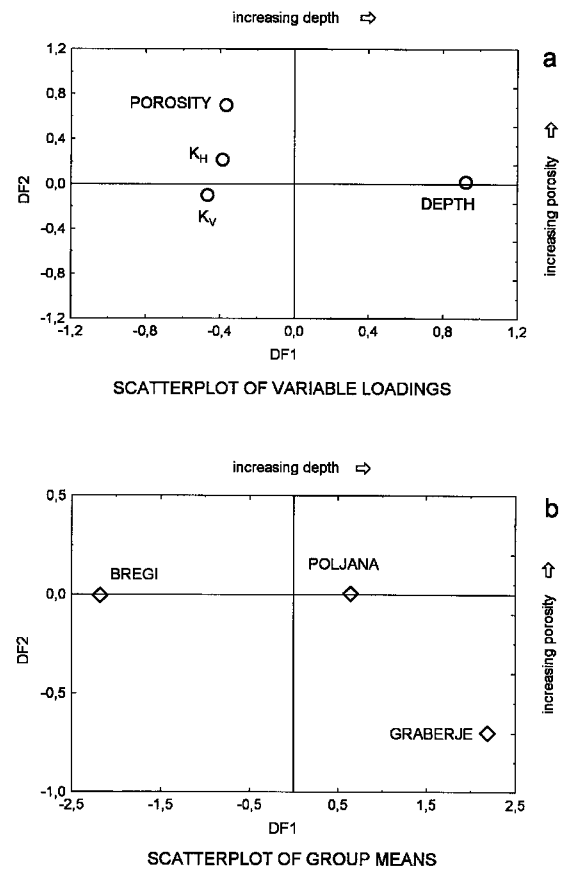


Fig. 8 Comparison of variables and units: scatterplots of variable loadings (a) and of unit means (b).

4.3. Case 3 - 'WELLS"

Discriminant analysis performed on 31 combined groups (associating the wells from all fields with the lowest unit, GSS Poljana) with 1,069 valid objects and the same four variables, resulted in four discriminant functions, the first three of which can be meaningfully interpreted. The results are similar to Case 1, with one

GROUP	MATHEMATICALLY DEFINED GROUP Bregi	Graberje	Poljana	TOTAL	% correct
GSS Bregi	295	0	26	321	91.90
GSS Graberje	0	0	4	4	0.00
GSS Poljana	53	0	1023	1076	95.07
TOTAL	**348**	**0**	**1053**	**1401**	**94.08**

Table 6 Classification matrix for UNITS.

VARIABLE	DISCR. FUNCT. DF1	DF2	DF3
DEPTH	-0.99*	0.09	-0.06
HORIZ. PERMEABILITY	0.03	0.70	0.70*
VERT. PERMEABILITY	0.02	0.60	0.56*
POROSITY	0.04	0.96*	-0.24
% explained	**98.26**	**1.11**	**0.54**

Table 7 Structure matrix for WELLS.

exception that much greater importance is placed on the first discriminant function (over 98%) which is weighted with the single variable of depth. Explaining almost the entire variability potential of the WELLS system, DF1 acquires the quality of a fundamental discriminator indeed within the area of investigation (Table 7). Far behind lie the two remaining functions (explaining together less than 2% of the system's variance) which, nevertheless, are still capable of elucidating some nuances that may appear across relatively short distances, that is, within the same field.

The first discriminant function strongly separates the *a priori* established groups on the basis of their relative depth, as can be seen from close inspection of the group and variable scatterplots (Figs. 9a-d). The arrays of group centroids are strewn diagonally across the diagrams, emphasising the distinct position of the Dugo Selo and Stružec fields (Gl- and O- wells). Obviously, the pertinent fields are placed less deeply in respect to the remaining field-unit assemblage. Alternatively, the points representing the Žutica wells are concentrated around the main centroid (axis intersection) indicating intermediary depths at regional scale, while the Okoli points are placed somewhat deeper. Moreover, one can

GROUP	DISCR. FUNCT. DF1	DF2	DF3
Gl-16	57.86	-1.65	-1.95
Ok-1	-10.40	-0.83	0.33
Ok-4	-5.91	0.26	0.61
Ok-20	-7.67	-0.39	1.46
Ok-35	-8.98	-0.63	0.31
O-127	25.22	-2.00	0.58
O-135	25.83	-0.33	-0.71
Žu-25	5.94	0.61	-0.52
Žu-26	-1.37	0.01	-0.17
Žu-30	6.55	0.91	0.43
Žu-42	0.91	1.99	0.96
Žu-45	-0.30	-0.21	0.33
Žu-54	-3.13	-0.03	-0.32
Žu-62	-0.14	-1.56	0.51
Žu-66	1.34	-1.32	0.86
Žu-81	3.25	0.34	0.77
Žu-86	1.04	1.10	0.38
Žu-94	0.51	0.68	0.58
Žu-122	-0.57	-0.89	0.09
Žu-124	1.40	0.06	-0.57
Žu-130	0.31	0.18	-0.44
Žu-146	4.11	1.37	1.11
Žu-155	-1.79	0.09	-0.46
Žu-156	-0.56	-0.47	-0.63
Žu-157	-0.95	0.03	-0.81
Žu-158	-0.76	0.95	-0.50
Žu-159	-0.59	0.39	-0.23
Žu-161	-0.54	-0.16	-0.59
Žu-163	-0.26	0.94	-0.73
Žu-164	0.34	0.13	-0.51
Žu-167	-0.53	-0.24	-0.05

Table 8 Group centroids for WELLS.

GROUP	No. of cases	% correct
Gl-16	2	100.00
Ok-1	5	0.00
Ok-4	3	0.00
Ok-20	15	46.67
Ok-35	64	100.00
O-127	16	93.75
O-135	26	80.77
Žu-25	6	0.00
Žu-26	132	46.97
Žu-30	91	98.90
Žu-42	7	42.86
Žu-45	16	0.00
Žu-54	326	82.21
Žu-62	58	68.97
Žu-66	30	53.33
Žu-81	3	0.00
Žu-86	34	41.18
Žu-94	35	17.14
Žu-122	5	0.00
Žu-124	10	20.00
Žu-130	12	0.00
Žu-146	32	50.00
Žu-155	28	0.00
Žu-156	12	0.00
Žu-157	16	0.00
Žu-158	22	9.09
Žu-159	13	0.00
Žu-161	5	0.00
Žu-163	7	0.00
Žu-164	27	22.22
Žu-167	12	0.00
TOTAL		**59.31**

Table 9 Efficacy of classification for WELLS.

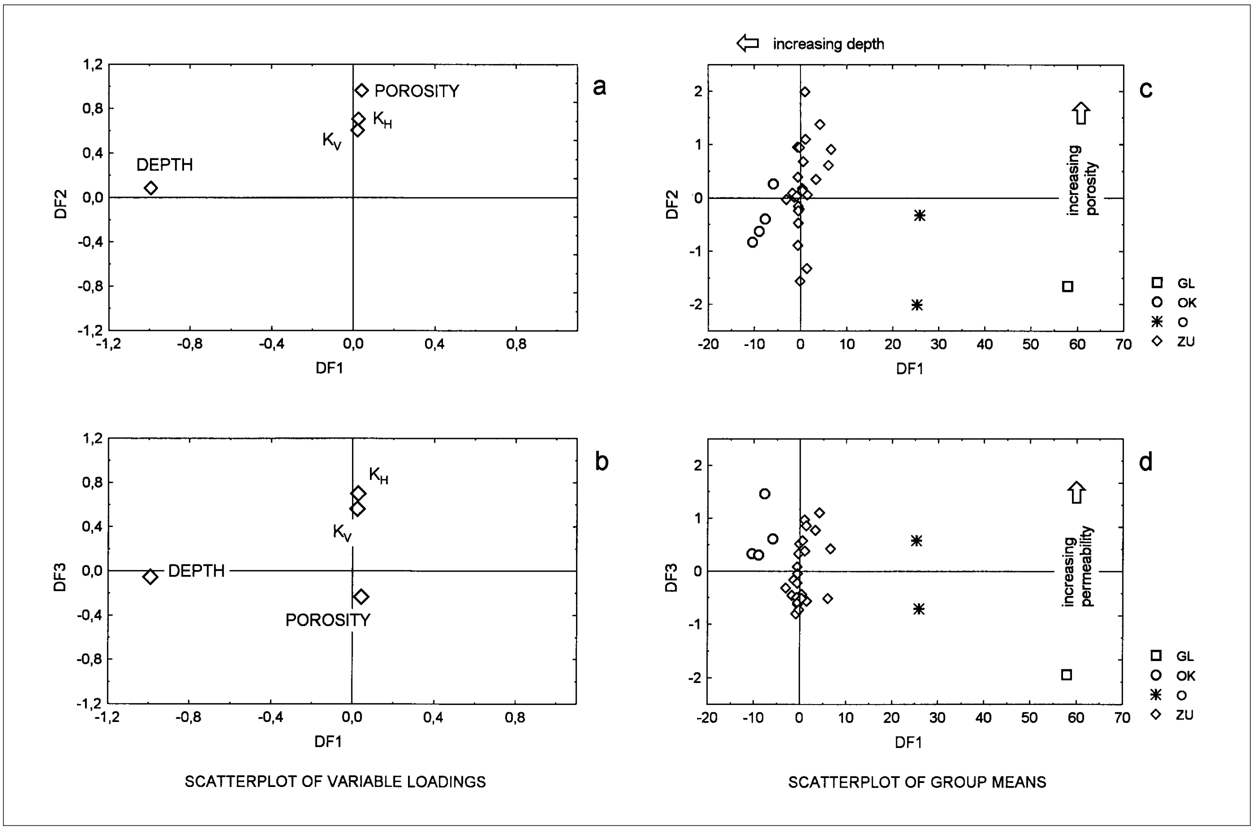


Fig. 9 Comparison of combined groups within GSS Poljana: scatterplots of variable loadings (a, b) and of group means (c, d).

observe that Žu- points are not dispersed widely along the axis, which is a positive indicator of their rather constant depth at their respective level.

The second and third discriminant functions separate the groups with much less efficacy than the first one, because porosity and permeability are much poorer predictor variables than depth. Such a situation implies that within-group variance may strongly offset the difference among groups, which is why great caution must be exercised in explaining the group separation along these two axes. Their low discriminating capacity may well be the unfortunate result of low data variability concerning the mentioned predictors. Also, the groups markedly differ in size (varying from 2 to 326 objects), which laid too much weight on the large Žu- groups (functioning as average) such as, for example, Žu-54. This has a grave impact on the effectiveness of the classification of the combined samples which becomes much lower (Table 9) and does not exceed 59%.

Figures 9a-d immediately disclose the symmetrical scattering of the Žutica wells along both DF2 or DF3 axes which is in accordance to their permeability/porosity relationship. Care must be taken here with distinction from Case 1 as DF2 and DF3 do not weight depth against physical properties, while porosity on DF3 exerts a slight negative correlation with permeability indices. In Fig. 9c, some wells of the Žutica field show the greatest shift from the group mean (as revealed previously in Fig. 7) into the area of increased porosity/ permeability, while others from the same field are distinguished by the lowest porosity/permeability scores on the second axis. DF3 is even less revealing and more should be expected only through the inspection of the discriminant score maps (created on the basis of Table 8) which will be explained later (Figs. 10a-c and 11a-c). The scattering on the DF2 and DF3 has not much weight because the dwarfed discriminating potential of these axes should be obvious when comparing their relevant scales to that of the depth axis.

5. INTERPRETATION OF RESULTS

The results of all three cases have shown that, regardless of the angle from which the variation of the reservoir data can be studied and presented as a numerical model, depth will always emerge as a fundamental reservoir descriptor. This was to be expected under conditions of normal compaction. It is particularly evident when attempting to establish the interdependence between depth and substantial petrophysical properties over greater horizontal distances that embrace several widely scattered oil fields. In this case, the numerical models will tend to completely separate the two sets of descriptor variables of which one (porosity and permeability) belongs to the realm of intrinsic rock properties while the other (depth) is related to other causes, most likely tectonics. The spatial distribution of the latter obviously has much greater variability when mirrored in the, often subtle, changes of petrophysical data. If one should investigate and predict the reservoir performance solely on the basis of the depth-porosity relationship both internally and between as many as four oil and gas fields, with no linking data (e.g. from exploration wells), the attempt would be highly questionable due to the vast impact of the depth factor which would offset a commonly weak correlation of that variable with other reservoir descriptors. The effect is also aggravated if noise caused by short distance irregularities from wells is introduced into the scheme such as in Case 3.

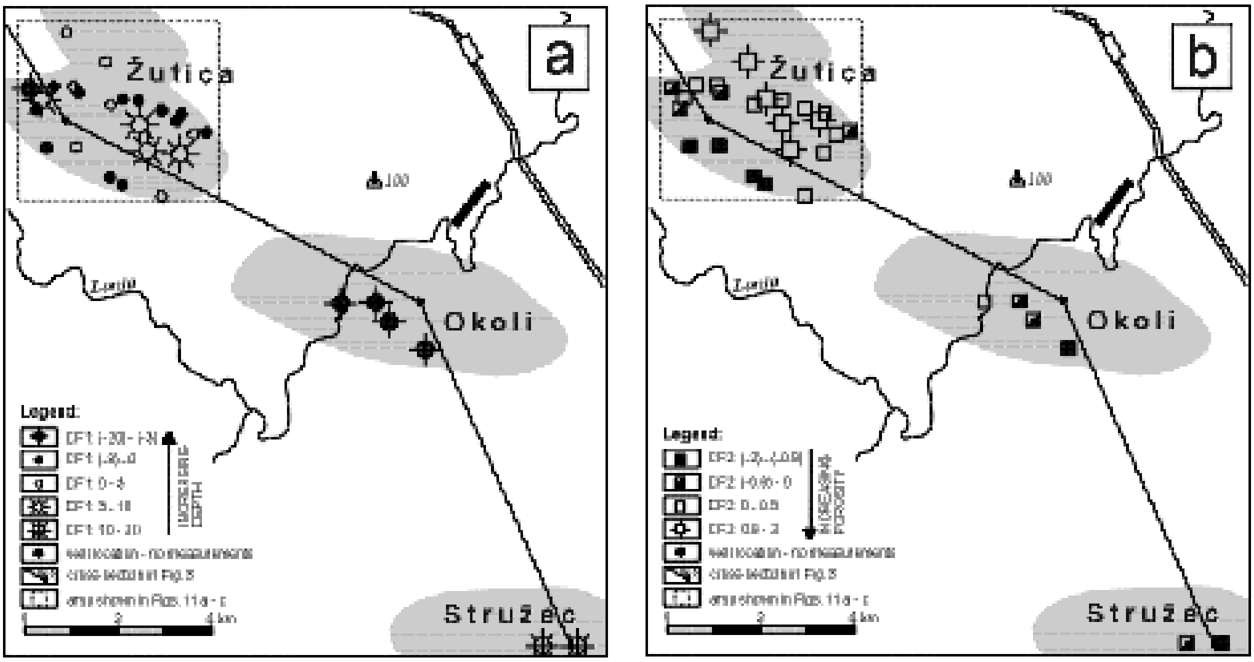
Thus, spatial (between-field) interdependence between depth and porosity/permeability can only be disclosed by a simultaneous review of the two computed functions in discriminant analysis, DF1 and DF2. Case 1 is particularly instructive in this sense; with the Žutica field as a pivot, with no distinctive depth and physical properties, other fields are arranged according to their weak but still observable inverse relationship. Dugo Selo is placed closest to the surface (DF1=9.09) with the highest porosity/permeability indices (DF2=0.41), while Okoli is the deepest (DF1=-1.64) with the lowest petrophysical qualities (DF2=-0.84). Stružec is somewhere in between (DF1=3.99; DF2=-0.50).

When interpretation is focused on vertical instead of horizontal distances, one can assess a more realistic representation of reservoir heterogeneity, because the actual spatial distribution of petrophysical attributes is spread through the same sedimentary sequence. When the sandstone units are correlated, depth and physical properties are directly linked to each other and one can more directly observe their inverse relationship. As expected, porosity and permeability features are reduced with increasing depth, which is directly observable from one and the same function computed in discriminant analysis for UNITS (Case 2).

Symbols in Figs. 10a-c depict the spatial distribution of the wells of three fields - Žutica, Okoli and Stružec, where each symbol depicts the value of the group centroid on one of the three discriminant functions (DF1-DF3). As can be observed from the scatterplot in Fig. 9a, the DF1 function is strongly weighted with depth, which means that data from wells with negative values in Fig. 10a are located at relatively greater depth compared to the entire data set. It can be observed that the cores from the Okoli field wells are the deepest, those from the Stružec field are the shallowest, while the data from the Žutica field have a midrange of values. Since this field is illustrated by the largest number of wells, and the classes with different symbols do not have equal span (see legend in Fig. 10a), a local zonation becomes obvious. More precisely, it is observable that symbols in the centre of the southern part of the Žutica structure correctly correspond to shallower locations than those in the peripheral parts of the field. Exact DF1 values are given in Table 8. It can be presumed that the Okoli and Stružec fields would also exhibit a range of values if a larger number of wells would have been available and if they were more widely spaced.

The map in Fig. 10b depicts the regional distribution of the group centroids on the second discriminant function (DF2). It is weighted with reservoir properties, strongly with porosity and mildly with both horizontal and vertical permeability (see in Fig. 9a). Simplified, this means that the specimens from the wells with increased DF2 values are relatively more porous. In the Okoli and Stružec fields it can thus be observed that there is a porosity decrease in a SE direction, and there is a local zonation in the Žutica field area. In this field, there is a local area of increased porosity that is elongated NW-SE and lies approximately between the southern and northern part of the Žutica structure. There is also an area of reduced porosity along the SW margin of the field. If these relations are compared with the GSS Poljana isopach map (Fig. 6) where the directions of palaeotransport are also marked, it becomes clear that the increased DF2 values are located close to the transport channel axes which were drawn based on the thickness variations of both the entire interval of this genetic stratigraphic unit, and also on the variations of the total thickness of sandstone layers of this unit (SAFTIĆ, 1998; SAFTIĆ & VELIĆ, 2000). This regularity can be explained by the fact that the transport channels were almost entirely filled with sandstones, and the thickest sandstone bodies are at the same time characterised by the highest level of sorting which results in maximal porosity values.

Regional distribution of the group centroids on the third discriminant function (DF3) is illustrated in Fig. 10c. It can be observed from Fig. 9b that these values are proportional to the permeability and inversely proportional (but with less influence) to porosity. This can be read in such way that the increased DF3 values depict the areas of high permeability. In Fig. 10c, this is in the centre of the southern part of the Žutica field, in the SW part of the Okoli field and in the eastern part of Stružec. It appears that DF3 is spatially too variable to allow any conclusions regarding the Okoli and Stružec fields. However, similar layers in the Okoli field (located 600 m deeper) show higher permeability than their counterparts overlying the top of the shallower Stružec structure. It is also apparent that numerous wells of the Žutica field show a distribution of DF3 values which indicates that the most permeable parts are in the centre of the southern part of the field, which also represents the crest of an anticline, while the marginal parts of the field are less permeable. By comparison of this map (Fig. 10c) with structure contours (Fig. 4), isopachs of the Kloštar Ivanić formation (Fig. 5) and of the GSS Poljana (Fig. 6) it can be concluded that the regional distribution of permeability does not coincide with the



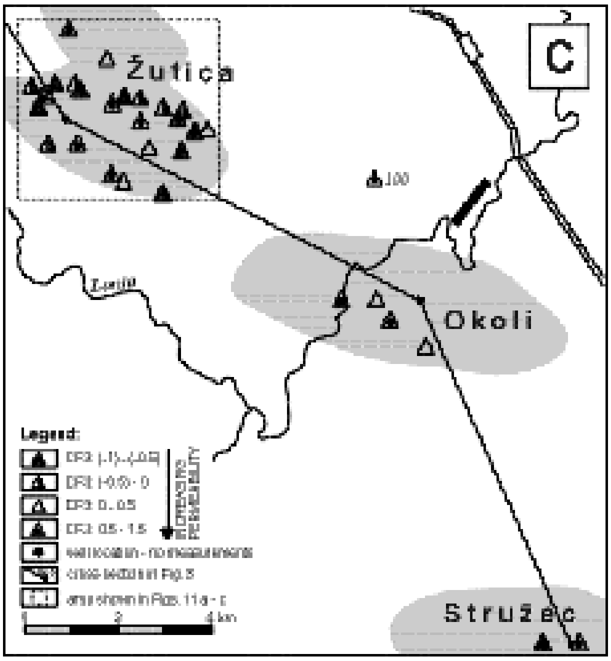
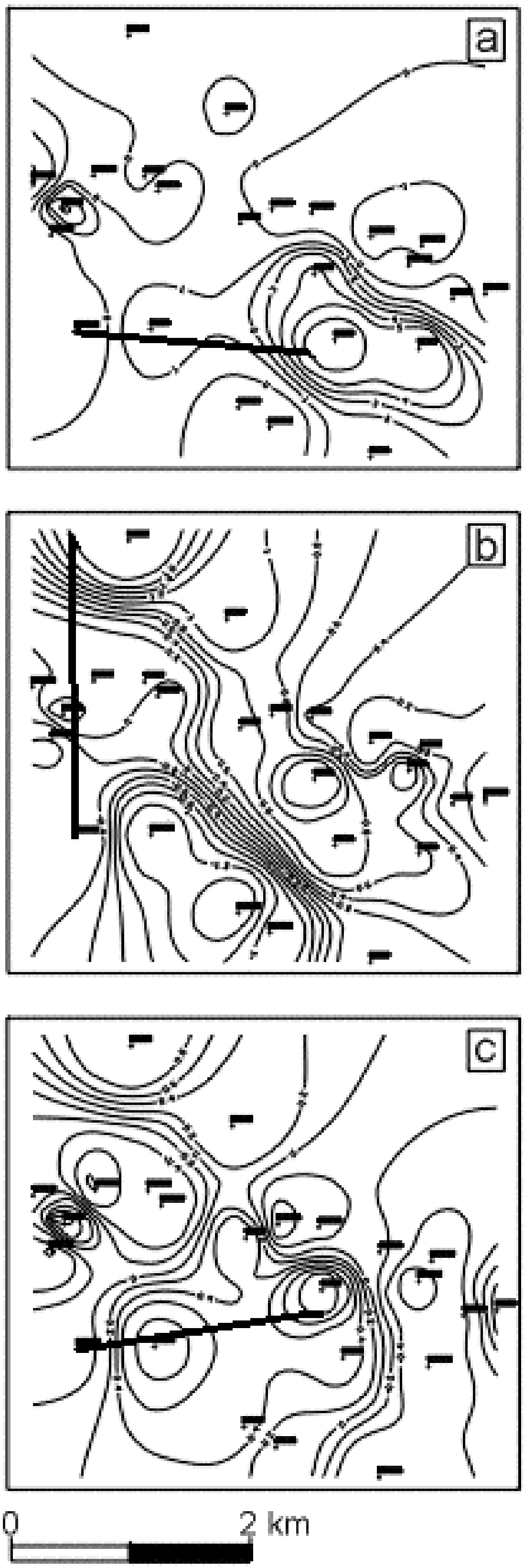


Fig. 10 a) Regional distribution of the group centroids on the first discriminant function (DF1); b) regional distribution of the group centroids on the second discriminant function (DF2); c) regional distribution of the group centroids on the third discriminant function (DF3).

thickness of the unit but rather with structural highs. It is a known fact that the southern part of the Žutica structure is in the GSS Poljana interval covered by only 40 m of sandstones (SAFTIĆ, 1993) and it can be observed from the E-logs that the permeability of these layers is occasionally really high.

In the Žutica field, favourable placement of wells with samples enabled construction of the DF1-DF3 contour maps (Figs. 11a-c) which can actually be read as details of Figs. 10a-c. The maps were created automatically, using PC and geological software. A relatively small area is shown (approx. 4x4 km, Figs. 10a-c), and therefore the values were recalculated in a coarse regular grid of 25x25 nodes. For this calculation, the inverse distance method was used in all three cases. Namely, it appeared that in this way calculated node values maximally honour the original values in the area surrounded by wells. From Fig. 11a, which illustrates depth relations (as for Fig. 10a), it can be observed that contour lines coincide with the structure contours of the southern part of Žutica field as previously illustrated by the structure contour map (Fig. 4). Looking at the detailed spatial distribution of porosity (in Fig. 11b), it is notable that the increased DF2 values depict the extension of sandstone fill of one of the transport channels - named "the main local transport channel", which has already been drawn in the central part of the Žutica field, based on the thickness variations of genetic units



Figs. 11 Maps of Žutica field - spatial variation of the group centroids on discriminant functions DF1 (a), DF2 (b) and DF3 (c).

and of their sandstone isolith (SAFTIĆ, 1993). The spatial distribution of DF3 values (shown in Fig. 11c), which is marked by permeability, is very variable. Even at a local scale, it appears that there is no clear dependence between the permeability distribution and thickness of sandstone bodies. When compared with Fig. 6 it can be seen that, regardless of the extensive area of increased thickness of GSS Poljana in the central part of the Žutica field, there are significant changes of permeability along this “main local transport channel”. Previous correlation indicated that sandstones of this unit are of a relatively homogeneous composition, which allows comparison of the spatial changes in architecture of each sandstone layer, based on the variations of the wireline log response (SAFTIĆ, 1993). Therefore, spatial variations of permeability (Figs. 10c and 11c) could be explained in two ways; either the apical parts of structures are usually slightly fractured due to strain, which causes an increase of permeability through microscopic fractures; or it is the result of the influence of stronger cementation in parts of the reservoir with increased circulation of pore water as opposed to areas at least partly saturated with hydrocarbons, or the permeability is originally smaller. As explained by TADEJ et al. (1996), it is therefore possible that originally “cleaner” and more permeable parts of sandstone layers become less permeable than the parts with a higher proportion of clayey and silty particles.

7. CONCLUSIONS

Analysis of discriminant functions in four oil and gas fields - Dugo Selo, Žutica, Okoli and Stružec (Case 1) has shown the following regularities. 94% of the variability of the entire system is related to depth. This means that differences between the fields are mostly marked with the depth of the studied reservoirs in a particular field. There is also an unusual reduction of the DF2 group centroid values (marked with porosity) in the Stružec field where reservoir layers are shallower in comparison to the deeper Žutica field. No differences in architecture of sandstone layers that could explain this can be observed on the thickness maps or on wireline logs. The study of DF3 (permeability) separated the Dugo Selo field (Gl- wells) on the basis of its reduced permeability. The reservoirs of this field are much shallower than in the other three fields, which means that a substantial proportion of the permeability should have been preserved there. The reduced permeability is therefore explained by two facts - the Dugo Selo field is quite distant from the other three studied fields, and it lies in the marginal part of the Sava depression, where sandstone layers are thinner and are more poorly sorted. It is also interesting why only 8.42% of data from the Okoli field are correctly classified (Table 3). This may be explained by the great depth of the layers in this field, and the potential slowing of certain diagenetic processes. The Okoli data here are more similar to the properties in the 300 m shallower layers of the Žutica field, which means that deeper emplacement did not affect the reservoir properties in this field and the pools retained the properties indicative of shallower layers.

Different properties within the three genetic stratigraphic sequences - GSS Poljana, GSS Graberje and GSS Bregi (Case 2), where only two discriminant functions were calculated, can not be discussed in more detail, because it showed that DF2 has an insignificant interpretative value (only 0.1% of the system's variability), and the rest is connected with the depth. Anyway, the units are in a sequence of superposition. There is a significant difference in classification of data from GSS Graberje in the Okoli field. They appear to be either the deepest or of the poorest reservoir properties. This is caused by the different lithology of GSS Graberje, which is, in the Okoli field area, composed of clay- and silt-sized particles and contains no significant sandstone layers. In the lithostratigraphic system of units this is the area where, instead of the Graberje Member, its lateral equivalent named the Graberje Marl is present. This congruence is considered as an independent proof of the validity of this kind of statistical analysis.

A combination of fields and wells (Case 3) was aimed at depicting the regional distribution of the group centroids on three discriminant functions - DF1 (marked with depth), DF2 (porosity) and DF3 (permeability). It was established that DF1 strongly separates the *a priori* defined groups, and that DF2 and DF3 have very weak influence (less than 2% of the system variance) which hinders any comparison apart from the ones within the margins of one particular field.

Certain regularities can also be spotted on the maps of regional distribution of the group centroids on all three discriminant functions. The values on the function which is marked with depth (DF1) are such that, providing there are data from a larger number of wells, a zonation can be made within a particular field which conforms to structural relations. Increased values of group centroids on the function which is marked with reservoir properties (mostly with porosity - DF2) are located close to the axes of palaeotransport channels. These channels were filled with the thickest sandstone bodies, with the highest level of particle sorting (coarsest grains) and the highest porosity. Values on the third discriminant function (DF3 - proportional to permeability and inversely proportional to porosity but with lesser influence) show that permeability is not high in the areas where the genetic stratigraphic unit is the thickest but rather in the areas that coincide with the apical parts of structures. The differences may have been caused in two ways: either the crestal parts of the anticlines were fractured due to folding, or the lower parts experienced increased circulation of pore waters and therefore faster and stronger cementation.

The distribution of group centroids and possibilities for zonation of these values much depend on the available number of wells (number of valid data and analysed samples). The spatial distribution of well data strongly affects interpretability, which means that it would be advisable to "activate" all the existing data and to systematically collect newly acquired information. There is a large data set of reservoir properties measured on horizontal cores in the INA Naftaplin archives, but only the data that were within 10 cm vertical spacing were regarded as a set of three measurements - porosity, horizontal and vertical permeability, that could be used in calculation, thus invalidating a large part of the data.

Experience has proved that many failures encountered in EOR are due to poor understanding of the reservoir, particularly because of insufficient characterization. Therefore the analysis of the spatial distribution of porosity and permeability is the most important issue in the description of the reservoir architecture, and in understanding of the geological model and fluid movement in the reservoir. A comparison between the regional distribution of petrophysical characteristics with lithological composition of the genetic stratigraphic units and with the interpreted palaeodrainage pattern of a submarine fan system, could be potentially useful in predicting both the reservoir behaviour and prospective areas for further exploration or infill drilling.

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