

Geologia Croatica	55/1	11 - 23	10 Figs.		ZAGREB 2002
--------------------------	------	---------	----------	--	-------------

Chronohorizons Based on Resistivity Curve Variations - Upper Miocene Sediments of the Ivanić Grad Formation in the Sava Depression (NW Croatia)

Boris VRBANAC

Key words: Resistivity curve, Chronohorizons, Single cycle, Upper Miocene, Ivanić Grad Formation, Sava Depression, Croatia.

Abstract

Regional definition of chronohorizons represents a fundamental and most difficult problem in geology. Adequate precision of dating can only be obtained from biological evolution, radioactive decay and from the key surfaces of the sequence stratigraphic concept (MFS, TSE, and LSE). It is concluded in this paper that the variation of formation resistivity values (R_a curve), as measured in wells located in the Croatian part of the Pannonian Basin System, is also a criterion for the stratigraphic definition of concurrently deposited sediments. This enables the construction of a sequence of lithogenetic units related to very small time-intervals.

The morphology of the resistivity curve measured in well sections composed of massive marls (that were deposited in a quiet environment of moderate water depth), is regionally exceptionally well defined. This pattern consists of a succession of peaks of lower and higher resistivity values that are in the same relative position regionally, which results in similar form of the resistivity curves of the wells in the study area. On the curve, one peak of higher values together with the next (overlying) peak of lower ones composes a single cycle (SC). Marls of a single cycle were regionally deposited at the same time, thus enabling the points of both the maximal and minimal resistivity values of each SC to be considered as time-markers (chronohorizons). Variation of the resistivity reflects fine changes of petrographic and granulometric composition which can be associated with cyclic water-level fluctuations (Milankovitch cycles).

For future exploration of the remaining, potential hydrocarbon accumulations in the sandstone reservoirs of the Ivanić Grad Formation in the Sava Depression, spatial modelling of the distribution, geometry, facies and palaeocurrent structure of separated depositional episodes and genetic units is suggested. This should be done with special emphasis on the spatial definition of channel sandstones that are the most important hydrocarbon reservoirs (according to current interpretations).

1. INTRODUCTION

Regionally recognisable sections of motifs (sequences of equally developed peaks) on resistivity curves of wells drilled in the Croatian part of the Pannonian Basin System were as early as the 1960's (e.g. ŠIMON, 1963, 1970, 1973; PLETIKAPIĆ, 1965). In well intervals composed of marls, the EK-markers within these motifs were placed on the characteristic points of resistivity curves that were best traced over almost the entire area of the Croatian part of the Pannonian Basin. These EK-markers enabled regional correlation of the sediments, using the markers to construct a framework of lithostratigraphic subdivisions. However, a more comprehensive explanation of what the EK-markers actually indicate was omitted. Are they thin layers of specific characteristics, or is it a certain physical property of marls that produces these regionally recognizable motifs composed of resistivity peaks? A third possibility is that they reflect sequence surfaces of some kind. ŠIMON (1980) stated that: "Their proved regional uniformity and stability gave them the characteristic of chronohorizons, ...". In a more recent, unpublished report (BANKS et al., 1990¹) the markers are treated as facies boundaries.

In order to define a depositional model for the Ivanić Grad Formation in the Sava Depression, the first task was to resolve the nature of the resistivity curve motifs, i.e. to establish the reasons for their repetition, thus also facilitating definition of the stratigraphic meaning of the EK-markers.

2. GEOLOGIC FRAMEWORK

The Sava Depression is the southernmost part of the Pannonian Basin System. It extends in a NW-SE direction, around 90 km in length and 25 km in width (Fig. 1). The Ivanić Grad Formation comprises part of the

INA - Naftaplín, Exploration Department, Šubićeva 29, HR-10000 Zagreb, Croatia.
e-mail: boris.vrbnac@ina.hr

¹ BANKS, N.L., CORNFORD, C. & TUBB, S. (1990): Pannonian basin (Phase II - Final Report).- Unpublished report, Ina-Naftaplín - ECL (World Bank Project), FSD Ina-Naftaplín, Zagreb.

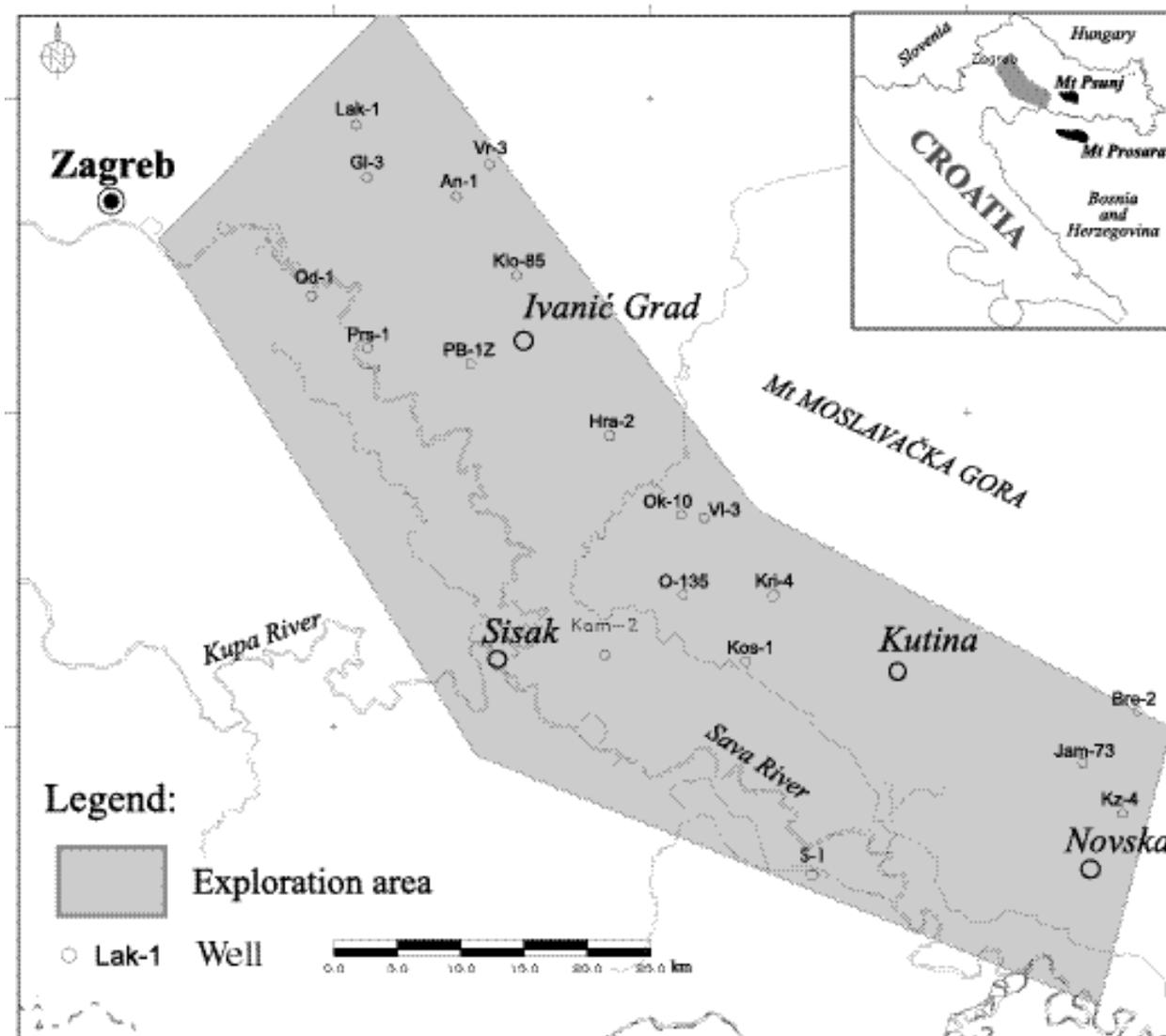


Fig. 1 Location map of the studied area.

Neogene clastic sedimentary complex and is composed of a sequence of sandstone, marl and siltstone layers. The approximate age of the sediments of this formation is Late Pannonian (Late Miocene). In the deepest parts of the depression the Neogene complex is more than 5,000 m thick. The basement consists of metamorphic, eruptive and clastic Palaeozoic rocks (PANDŽIĆ, 1980; NAJDENOVSKI et al., 1983). In the marginal parts of the depression, the thickness of the Ivanić Grad formation ranges from 150-250 m, and it is almost exclusively composed of marls. In the central parts, where marls are interbedded with sandstone and siltstone layers, the total thickness occasionally reaches 800 m.

In accordance with the sedimentological characteristics of the cored material (lithology, bedding, sedimentary structures, sand/shale ratio), the geometry of sandstone bodies and interpretation of the well-logs, the explored formation was found to be composed of hemipelagic muds and sediments of turbidite origin

(VRBANAC, 1996). The following facies were determined: massive marls facies (F_1), thick-bedded to massive sandstones (F_2), thin-bedded sandstones (F_3) and facies of thin-bedded sandstones, siltstones and marls (F_4). Hemipelagic muds are represented by massive marl facies (F_1). The massive marls facies (F_1) is located in whole parts of the sedimentary basin. The F_2 - F_4 turbidite facies are exclusively located in the central part of the depression, where they form an elongated sedimentary body that extends over 90 km in length, and is up to 15 km wide. In a NE direction, the Sava depositional basin was separated from the Drava basin by a submerged tectonically uplifted ridge. Towards the east, the sandstone sedimentary bodies thin out when reaching the uplifted tectonic block that connected Mt. Psunj with Mt. Prosara (Fig. 1). In spite of the fact that the Upper Pannonian marls crop out in the Banovina region, south of the Sava Depression, the contemporary extension of the depositional basin in this direction can only be supposed. Furthermore, the general mechanism

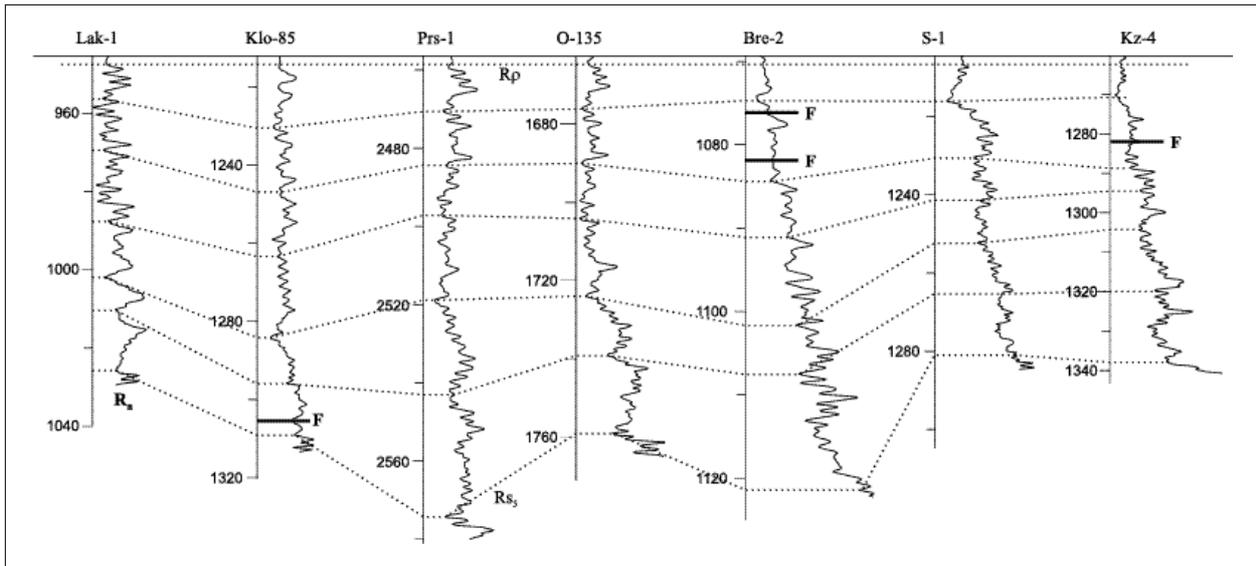


Fig. 2 The identical structure of peaks on the resistivity curve (Ra) within the massive marls facies association. The chosen logs are from the wells located in the marginal parts of the Sava Depression where the facies of massive marls is exclusively developed. The interval between the EK-markers Rs5 and R is shown (F - fault).

of infilling can be regarded as aggradational, although smaller progradational and retrogradational phases have been identified by the detailed mapping of sandstone bodies within the lithostratigraphic members (the Iva and Okoli sandstones, respectively). The progradational phases are interpreted as periods when sandstone bodies gradually spread more and more from NNW to ESE, while the retrogradational ones pertain to periods of sandstone retreat in a NW direction (VRBANAC, 1996).

3. RESISTIVITY CURVE ANALYSIS

Comparison between the core material and resistivity curves leads to the conclusion that the regionally recognisable motifs on the resistivity curve are exclusively connected with the massive marls facies (F₁). This facies is composed of homogeneous and massive, mostly unstratified marls. Occasional traces of stratification are mostly observed through a change of colour or by the occasional thin interbed of siltstone or sandstone. The observed homogeneous appearance and petrographic composition of massive marls still results in variation of certain physical properties that are reflected in a succession of characteristic peaks on the resistivity curve. These peaks represent 1-3 m thick packages of marls, and their sequence, with major or minor variations, forms the regionally recognizable structure both in the marginal and central parts of depression.

The resistivity curves of the wells in the marginal parts of the depression (Fig. 1) clearly illustrate the identical motifs of peaks in all of the wells, as shown in Figs. 2 and 3. Selected peaks are connected by dotted lines in order to facilitate the correlation of shapes with-

in the intervals. It can be observed that each and every one of the peaks on one curve has a corresponding peak on other curves, thus making a characteristic succession of peaks with identical shape and relationship to preceding and succeeding peaks. In this way, the sequence of peaks identify and characterise shape of the resistivity curve. The amplitude of peaks is not always the same, which means that they are not equally well marked in all of the wells, but most importantly they do exist. Their constant shape and relative relationships between peaks that laterally remain unchanged are also important. So, the marginal parts of depression are exclusively composed of the massive marls that have a regionally identical structure of peaks on the resistivity curve. In order to illustrate the almost ideal sequence of the regionally recognizable peaks, a type-curve was constructed (Fig. 4) by amalgamating of the resistivity curves measured in two wells (O-135 and Hra-2).

An overview of the resistivity curves from the wells located in the central part of the depression resulted in the interpretation of three turbidite facies, mostly represented by sandstone bodies, being interlayered with the massive marls that are identified by the characteristic peaks (Figs. 5-8). These peaks allow the massive marls to be distinguished from the marl that was deposited from the tail of the turbidity current. A similar situation can be observed on the resistivity curves of 1700 wells in the central part of the depression, whereby the location of the well in the depression roughly defines which of the peak sequences of massive marls will be more pronounced. It is imperative to explain the cause of the observed regularity of peak structure on the resistivity curve in the massive marls intervals.

Let us analyse the factors that influence the shape of resistivity curves and the vertical change of the resistiv-

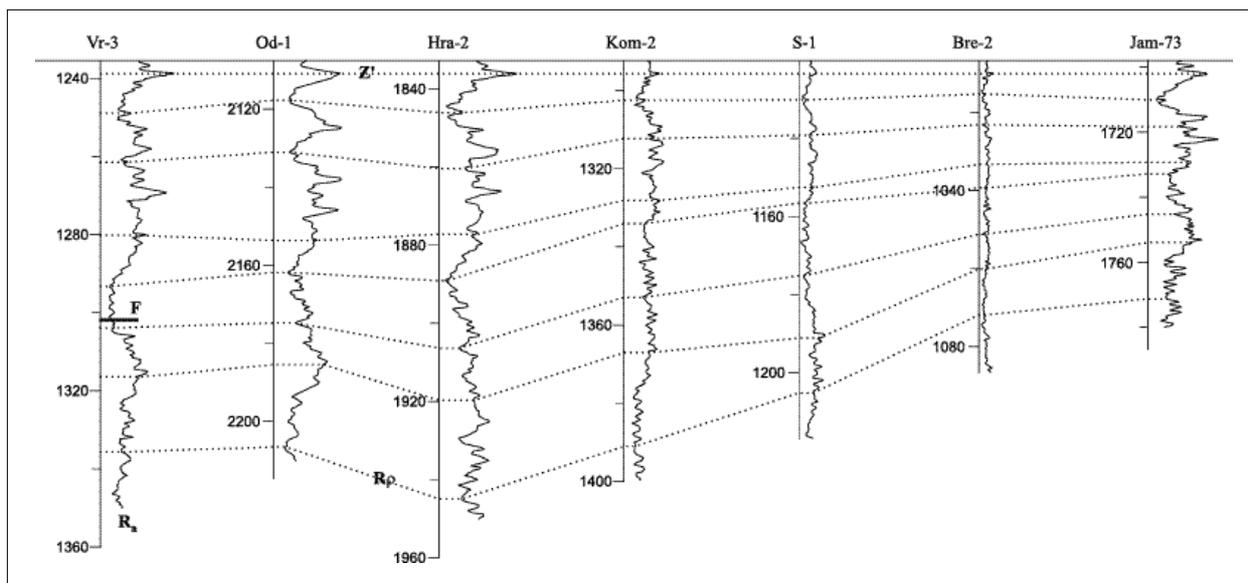
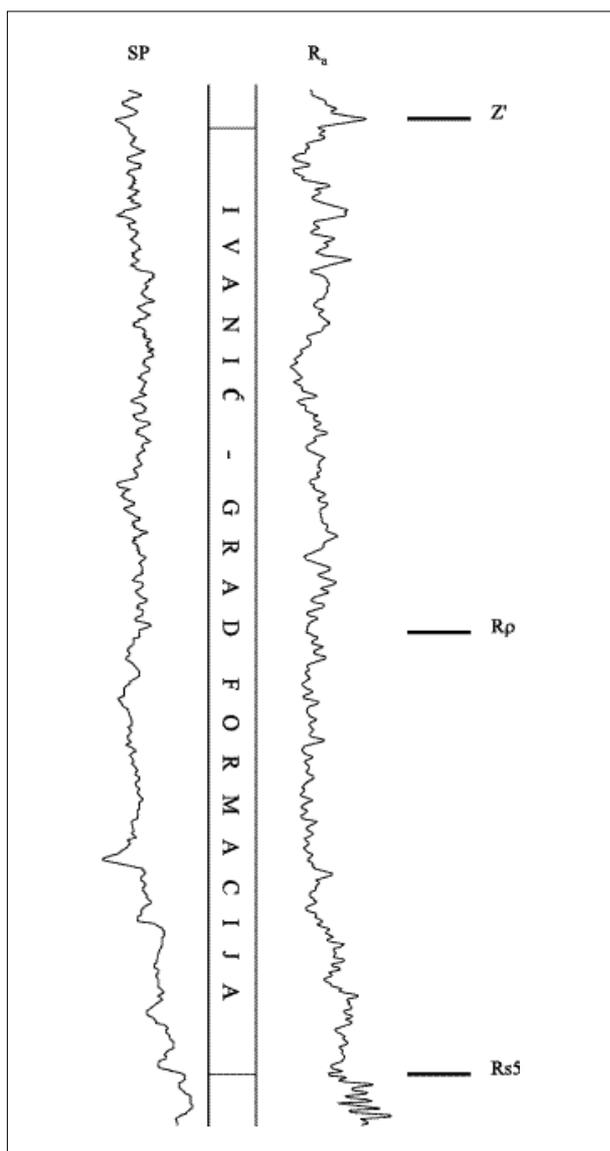


Fig. 3 The identical structure of peaks on the resistivity curve (R_a) within the massive marls facies association. The chosen logs are from the wells located in the marginal parts of the Sava Depression where the facies of massive marls is exclusively developed. Interval between the EK-markers R and z' is shown (F - fault).



ity of clastic sediments. The first group of factors consists of the ones that are preconditions in order to measure the quality of the resistivity curve. For instance, the well should be of either the nominal or a slightly greater diameter, the degree of the mud infiltration into the formation should be minimal, etc. Factors determining the average resistivity of a formation or lithological member are located in the second group. The following can be quoted: formation water resistivity, mud resistivity/formation water resistivity ratio, bedding thickness, sedimentary structures that influence the permeability, type and degree of cementation, lithologic composition, formation resistivity and hydrocarbon saturation. The factors of this group exhibit insignificant vertical changes in the intervals of massive marls. This is because of the impermeability and lithological homogeneity of marls, the weakly expressed bedding, lack of hydrocarbons and constant formation resistivity. Therefore, the factors of the second group do not influence the variation of resistivity at every point, but the variation of an average value instead. A third group is composed of factors that affect the variation of resistivity at every point around the trend-line of the average value. These are: the average grain-size at certain points, the ratio of clay particles, level of sorting and the packing of grains that depends on it, grain-supported or mud-supported structure, type and degree of cementation and compaction level as well as the relationship between cementation and compaction and the shape of sedimentary body.

Fig. 4 The type resistivity curve with characteristic peaks in the massive marls facies. It is composed by amalgamating the resistivity curves from the O-135 well ($R_{s5} - R$) and the Hra-2 well ($R - z'$).

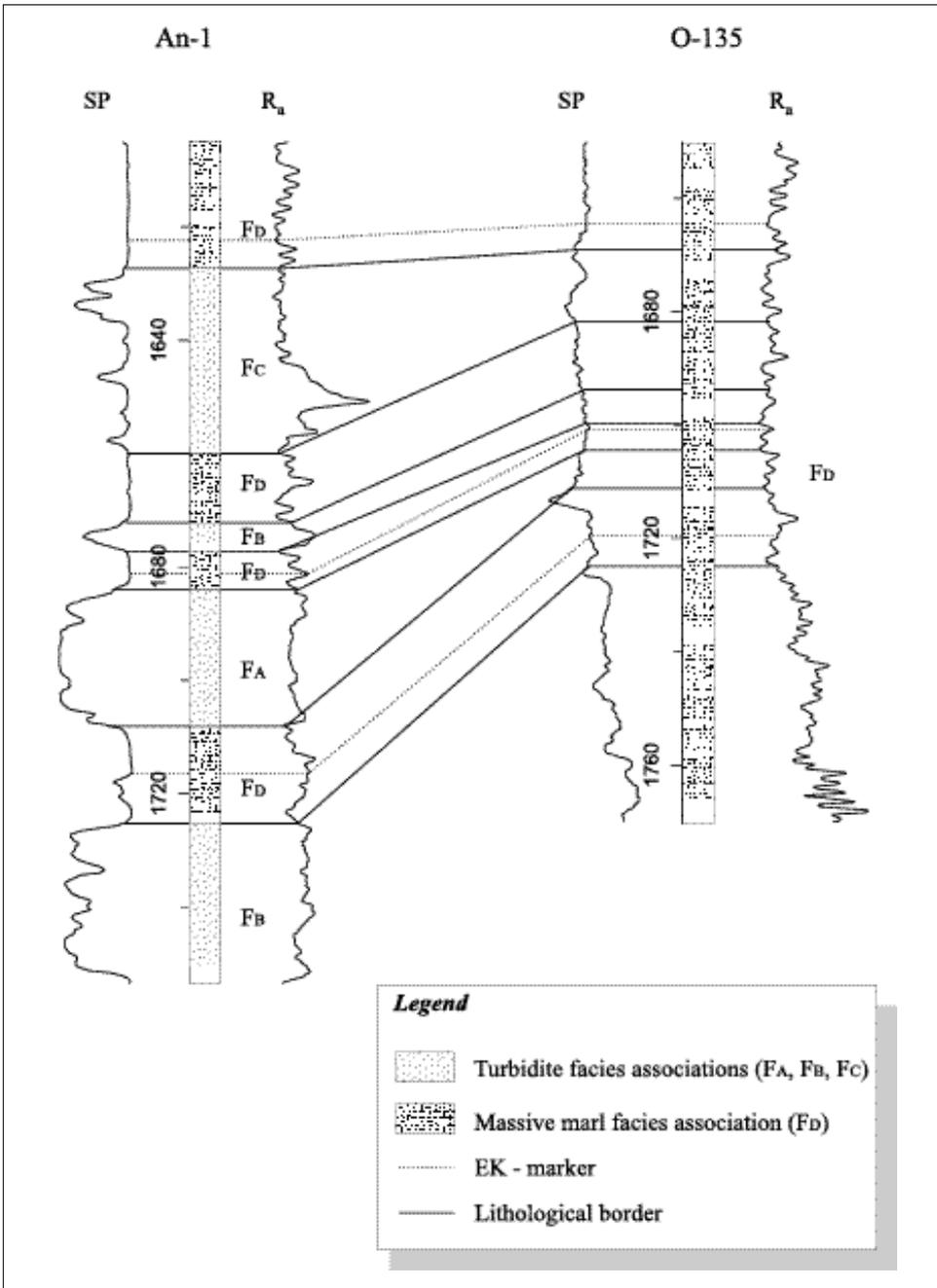


Fig. 5 EK-marker correlation in the massive marls of the An-1 and O-135 wells.

Since any change in the physical properties of sediments or any kind of external influence results in a change of the resistivity (respectfully, the electric conductivity), the true formation resistivity can only be measured in undisturbed sediments. In a “clean formation” of the water-saturated sandstone with no clay, the resistivity is a function of the porosity, pore geometry (reflected in the cementation factor) and of the mineralization of the formation water²:

$$R_a = R_w / m \quad (1)$$

where: R_a - resistivity of formation 100% saturated with water ($S_w = 1$), R_w - resistivity of formation water, m - porosity, m - cementation factor.

The porosity depends on grain dimensions, type of packing and on the sorting level. The cementation factor depends on the pore geometry. The more complex the geometry, the higher is the cementation factor. Types of packing and pore geometry are also dependent on the compaction level, i.e. on the pressure that is acting on the bed. Experience indicates that the resistivity curves in clastic sediments exhibit a general linear increase with depth due to compaction, in other words, that the compaction of sediments causes the resistivity to increase. At the same time, the relationship between

² Schlumberger Ltd., Log Interpretation, Vol. 1 - Principles, 1974.

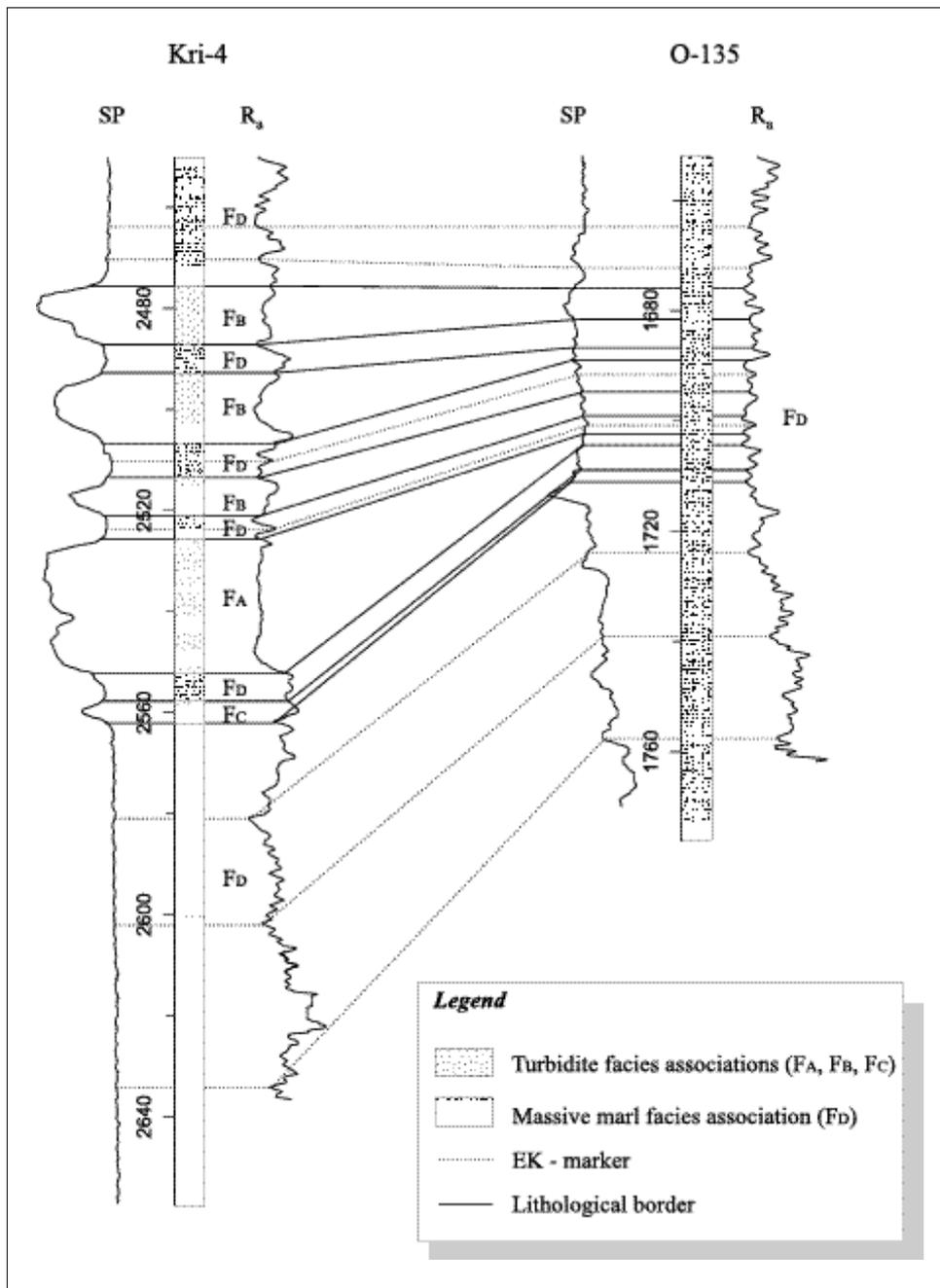


Fig. 6 EK-marker correlation in the massive marls of the Kri-4 and O-135 wells.

the resistivity of two layers in contact always remains the same. This means that the shape of the resistivity curve still remains the same and curve is only shifted to a range of higher values.

A sandstone itself has no electrical conductivity. Its resistivity is unmeasurable. The only conduit of electric current is the formation water. The resistivity of formation water is a function of its mineralization. Since the mineralization exhibits no significant change even over larger depth intervals, this factor does not affect the shape of the resistivity curve, only its position, or the average value. Saturation with oil or gas results in an increase of resistivity proportional to the quantity of hydrocarbons that fill the pore space together with the

formation water. Resistivity of sandstone layers that contain certain amounts of silt and clay-size particles can be calculated from the following equation²:

$$R_t = R_{sh} / V_{sh} + R_w / {}^m (1 - V_{sh}) S_w^n \quad (2)$$

where: R_t - true resistivity of formation, R_{sh} - resistivity of marls (shales), V_{sh} - relative proportion of marls (shales) per volume unit, S_w - water saturation, n - saturation exponent.

According to the above formula, the proportions of the silt and clay-size particles, as well as their resistivity, significantly influence the bulk resistivity of rock. The clay particles possess a certain level of electric

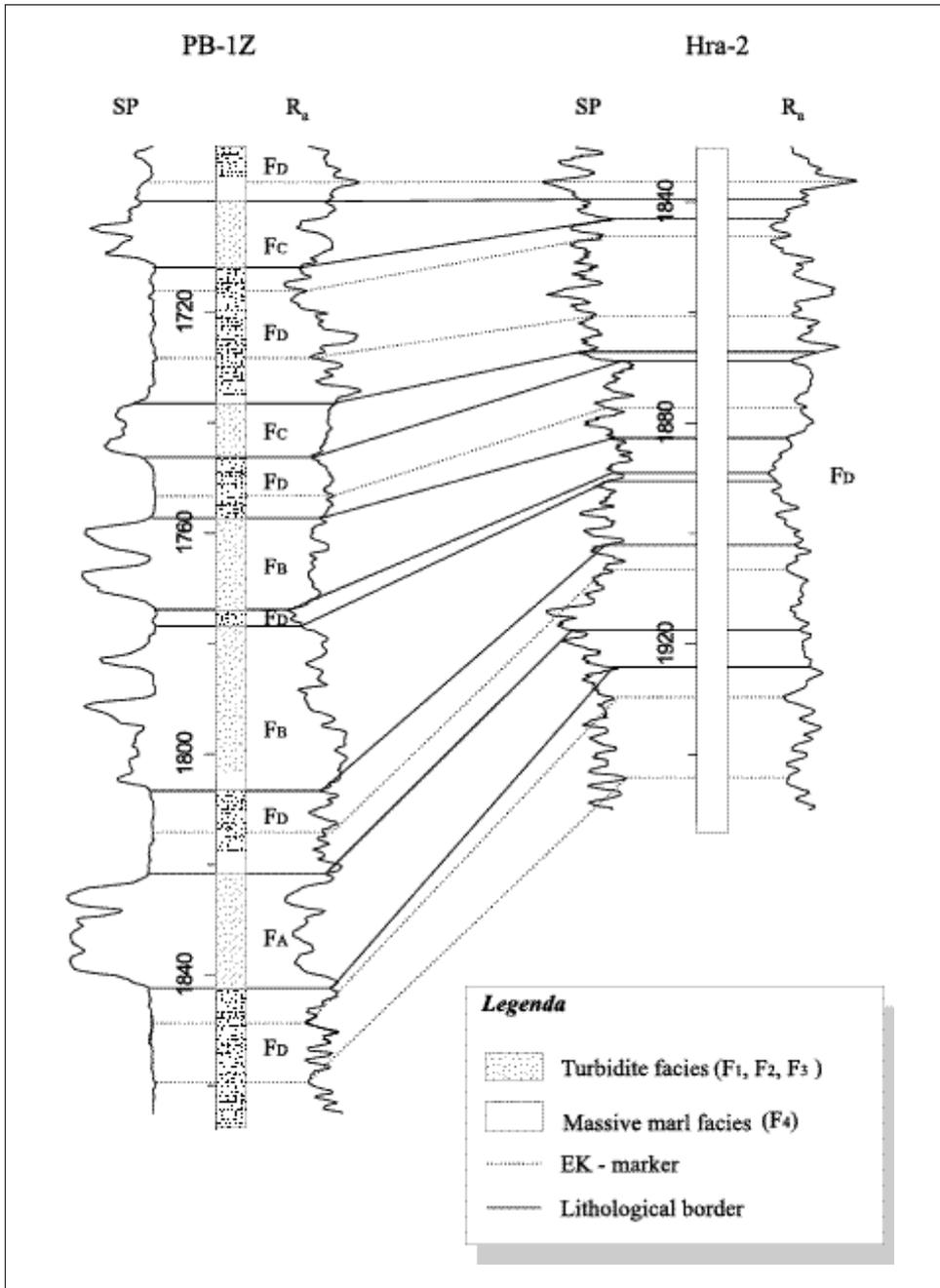


Fig. 7 EK-marker correlation in the massive marls of the PB-1Z and Hra-2 wells.

conductivity due to the presence of crystal water. This electrical conduit is independent of the one provided through the water in pores, meaning that the conductivity remains even if the pore water is totally replaced by hydrocarbons. It can thus be concluded that the average granulometric composition, presence of clay minerals and the type of grain packing, the factors that jointly influence the porosity and permeability of rock, are also the factors that significantly influence the amplitude of every peak on the resistivity curve, and in fact the shape of the curve itself. In spite of the fact that these formulae describe the relationships in sandstones without clay particles (1) and the ones with a certain amount of clay (2), they can also be used for the calculation of resistivity in the marl intervals. Naturally, the range of average

values will then be lower. The marls of this formation largely have the same mineral composition as the sandstones: quartz, feldspar, mica, chlorite and rock fragments (dominated by dolomite and with smaller proportions of limestone, chert and quartzite), but they contain less quartz and more carbonates and clay particles. They are classified as the siltstones and silty marls.

Within the massive marls intervals there is a regionally recognisable pattern of peaks on the resistivity curve and therefore it is likely that the variations of the above mentioned factors were also regional. This means that there were similar conditions of transport and deposition of clastic material and that the deposition of sediments corresponding to one characteristic

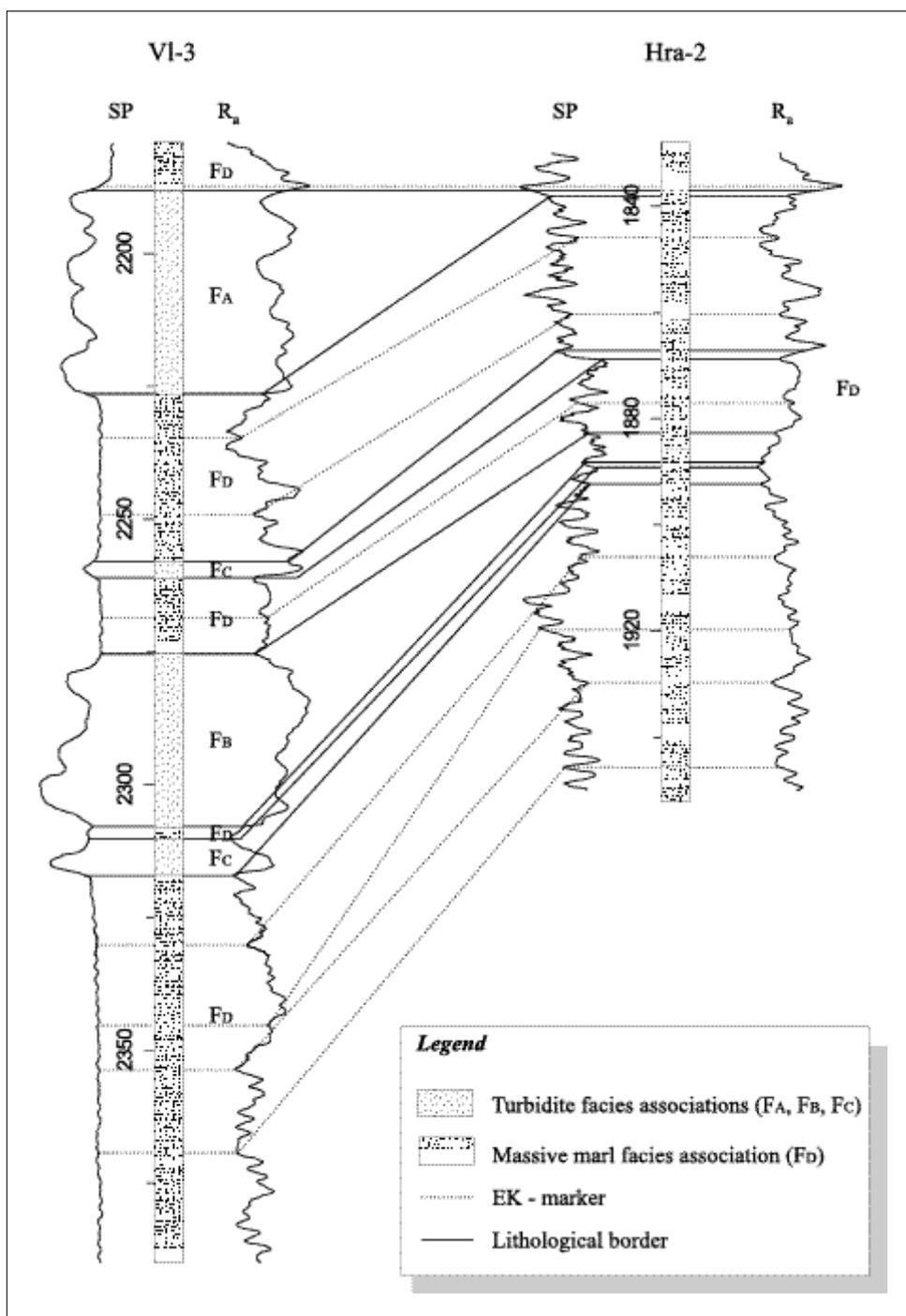


Fig. 8 EK-marker correlation in the massive marls of the VI-3 and Hra-2 wells.

peak happened **concurrently and in the same time interval**. Therefore, the factors influencing the resistivity variations do not reflect the changes in depositional environment, but rather the minor variations of the relative water level and the related small changes of energy of the transport media that conditioned the composition of clastic material brought into the basin.

Let us analyse the structure of a set of massive marls, represented on the resistivity curve by a number of characteristic peaks (Fig. 9a). Since the resistivity variation is an indirect function of the average grain-size and the type of packing, the curve will also reflect

the changes of average grain-size. The line drawn through the inflection points of the curve reflects the trend of the average resistivity values. The peaks above and below this line reflect the variation of the maximal (dotted line), and the minimal resistivity values (hatched line). In this way, the exceptionally regular sequence of peaks of higher and lower resistivity values is illustrated; this reflects a sequence of massive marls packages with the same thickness but different resistivity values due to the variable average grain-size, sorting level, type of grain packing and content of clay particles. It can be concluded that the regular sequence of

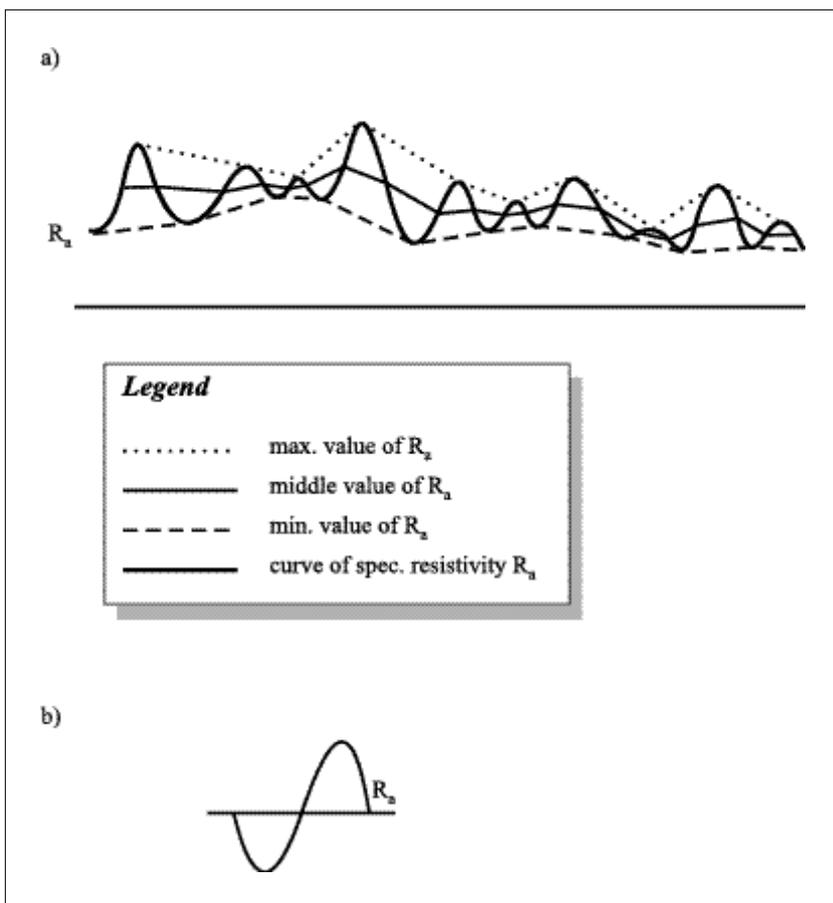


Fig. 9 a) Cyclic variation of the granulometric composition of massive marls in accordance to the resistivity curve; b) a single cycle.

peaks reflects a sequence of high-order cycles where one of the cycles encompasses one peak of higher and one of lower resistivity values. The sediments of one cycle on the resistivity curve will be regarded as a single cycle (Fig. 9b). In this way, the single cycle (SC) is the thin stratigraphic unit composed of hemipelagic sediments that were deposited during one cycle of the relative water level fluctuation in the basin. A cycle is composed of concurrently deposited sediments and the extreme point of resistivity values within every SC have the character of chronohorizons.

The relationship between the massive marls and the sandstone bodies presents another problem that has to be explained. According to the spontaneous potential curve of the GI-33 well (Fig. 10) the sandstone body "I" is easily observable. The resistivity curve clearly shows that the sandstone body lies within the obvious marked succession of SC-s. A comparison between the SC-s below and above the "I" sandstone in the GI-33 well with those in the O-135 well (taken for reference in this part of the SC-succession), results in a correlation of the sandstone body "I" in the GI-33 well with the SC named "I" in the O-135 well. It can be observed from the spontaneous potential curve that the sandstone body "I" is not homogeneous, but rather characterised by a variation of the SP that results from a number of thin marl interbeds. Illustrated in this example, but based on very numerous cases that can be observed on the logs

of almost every well, it can be concluded that a set of massive marls represented by one SC, corresponds to a sequence of depositional events caused by the intermittent activity of the turbidity currents that deposited thinner and thicker layers of sandstone, siltstone and marl in the central parts of the depression. The massive marls represented on the resistivity curve by a succession of SC-s are therefore interpreted as having been formed by deposition of muddy material that was transported into the depression by the permanent and weak, surface, internal and bottom-currents. In the parts of depression characterised by deposition from the intermittent turbidity currents in the same time interval, the SC is correlated with a corresponding "depositional episode". The episode is composed of a set of sandstone, siltstone and marl layers, each of which was formed by deposition of clastic material transported by a single turbidity current. Each of these turbidity currents is an independent event, it transported its own quantity of clastic material and deposited it in a specific area where it has a certain thickness that is laterally variable. There are differences in a number of turbidity currents that form one depositional episode in different parts of the depression, as well as in the surfaces covered by the clastic material of single turbidity currents. Under optimal conditions, the maximally obtainable vertical resolution would be to correlate the sediments of one depositional episode.

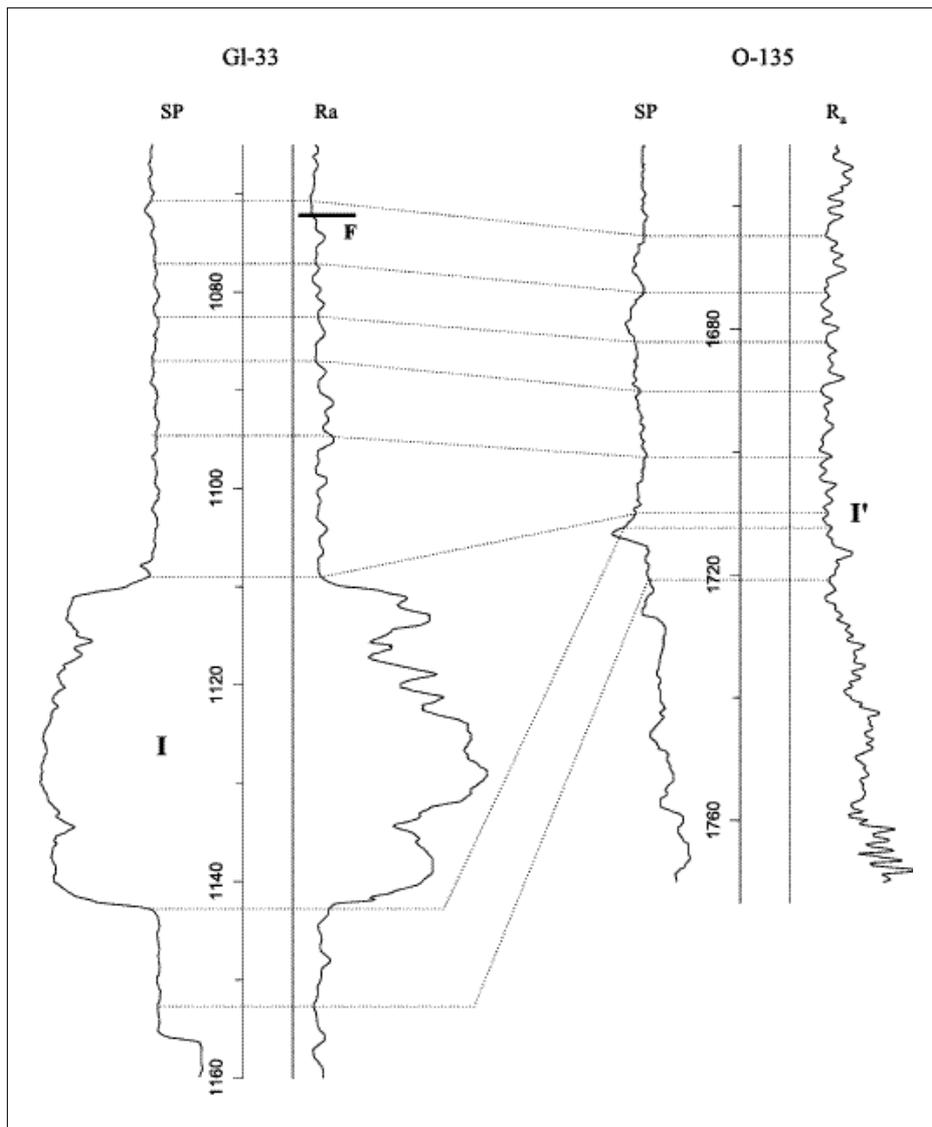


Fig. 10 Correlation of depositional episode A in the GI-33 well with the single cycle A' in the O-135 well, obtained by the precise correlation of the succession of single cycles within the massive marls in both wells.

4. DISCUSSION

The single cycle (SC) forms the fundamental genetic unit in the sedimentary sequence, i.e. the one of lowest rank. It consists of massive marl of a particular composition and grain packing, and it encompasses the complete cycle of the variation of granulometric composition. The regularity of the sequence of this genetic unit indicates that every single SC forms only part of a larger stable system that functioned and oscillated throughout deposition of the studied sediments. This oscillation is reflected in the cyclic changes of granulometric composition. Although it is within a single lithological member (marl), the cyclicity is seen in the sequence of marl sets characterised by roughly equal thickness, that resulted from the minor and permanent cyclic changes in granulometric composition of the transported muddy material, and in connection with the relative water level variations. According to the rule that relates the thickness of sediments with the time-interval of their deposi-

tion (SANDER, 1936) it is most likely that, under normal stable depositional conditions, the cycles marked by the sediments of equal thickness that are continuously deposited within the studied statistical (time) intervals, also represent equal time-intervals. Therefore, it is difficult, if not impossible to imagine depositional mechanisms that lead to such changes in the rate of deposition in different time-intervals which result in the same thickness of sediments. Alternatively, the rule states that the same time-intervals are likely to be represented by sediments of various thickness, which results from the changes in the rate of deposition. Such changes almost always exist, except in the case of a marked stability of the system. It can be observed from the well-logs (Figs. 2-8), that the thicknesses of the SCs are roughly equal in all the wells. There is insignificant variation between the wells, depending on their location within the depression - in other words, variation with the distance from the source area and sedimentation axis, and the position relative to the palaeore-

lief, as well as to compaction (differences in petrostatic pressure and thickness of sedimentary cover). Since the deposition of hemipelagic sediments that were the source material for the massive marls occurred in the deeper water environment, it can be concluded that the system was stable for a long period of time. It can also be stated with a degree of confidence that the thickness cyclicity reflects higher time cyclicity. This is a case of a specific type of cyclicity which is not based on cycles of repetition of various depositional environments and their corresponding lithological composition, but rather on small, temporally levelled (cyclic) variations of the granulometric composition of clastic material. This material was brought into the depositional basin by the permanent surface, internal and bottom-currents that were active in the generally stable depositional environment over a long time-interval. The occasional "break-throughs" of turbidity currents, although contributing more material to the depositional area, acted in a limited area and over a very short time-span, and the syngenetic tectonic movements were, according to evidence shown in the massive marls, very slow, and therefore did not influence the stability of the environment and depositional conditions. However, the relative water depth was always deep enough to compensate for water-level variations due to either tectonics, or the influences of climate change.

The sedimentary cycle is related to three categories of regularity - the regularity in the repetition of either the lithology or the sedimentary structures, the regularity in variation of the thickness of sediments pertaining to one cycle, and the regularity of the time interval that forms the depositional cycle (SCHWARZACHER, 1993). Let us analyse the SC-s in respect of these regularities. The first regularity is related to the cyclic changes of granulometric composition and the type of packing. The second is related to the SC thickness variation that results from the oscillation process. In areas where it is exclusively composed of the massive marls facies with characteristic SC-s, the thickness of the Ivanić Grad Formation is in the order of 150-250 m. Comparison of the resistivity curves of a large number of wells resulted in a total number of 82 SC-s as the minimal number of intervals that comprise the complete marl succession of sediments of the studied unit. Since the SC-s within a single well are of approximately the same thickness, it can be easily calculated that the average SC thickness is in the range of 1.1 to 3 m. Considering the rule that relates the thickness of sediments with the time-interval of deposition (SANDER, 1936), an approximate calculation of the time-span of a single cycle can be performed. The Pannonian interval on the absolute radiometric age scale is between 11.5 and 8.5 Ma. Supposing that the deposition of the studied sediments, mostly of Upper Pannonian age, lasted for the one half of this time-span, the calculated duration of the single SC deposition is around 18.3×10^3 years. In other words, deposition occurred in 18.3×10^3 years cycles.

From the approximate determination of the single cycle time-interval, the logical succession of further speculative considerations is in definition of the origin of these cycles. There are two types of oscillating systems that can be applied to solve the question of how the sedimentary cycles were generated. The first type is represented by the self-oscillating systems, among which the so-called tectonic model (BOTT, 1964) is very interesting and applicable to the studied sediments. A number of factors indicate that this system could have produced the cyclic variation of the relative water level; basin subsidence over a lengthy period, the existence of marginal faults, existence of the shelf and source area that were undoubtedly uplifting, and differences in the temporal pulsation of the prevailing uplift of the source and shelf area with respect to the basin subsidence. Since this was environment of moderate water depth, the cyclic changes of the relative water level could not have significantly influenced the depositional conditions. This means that minor cyclic changes in the granulometric composition of the massive marls reflect small variations of the relative depth of water caused by a time-delay between the tectonic movements on the shelf and in the basin area. The large number of the turbidity currents that entered the basin over the duration of single depositional episode results in a number of sandstone interbeds within one episode. This implies that the discontinuous transport of sand-size material from the shelf into the basin area probably was not caused by the aforementioned cyclic variations of the relative water level, but by tectonic activity that led to the continuous uplift of the shelf area. An important aspect of every oscillating system is the question of domain - the area of the system's activity. The registration of recognisable SC-s is taken as the fundamental criterion for definition of the system's area. Therefore, it is without doubt that the area of this system extended throughout the entire Sava Depression, the whole region between the Sava and Drava Depressions, and over the larger, western part of the Drava Depression (VRBANAC et al., 2000). The size of the domain, together with the long period of time over which the oscillating system was active, indicates the influence of supporting processes at least regional if not global in scale. Applying the tectonic model to the Sava Depression example, the driving and supporting mechanism would be found in the temperature induced extensional subsidence movements (ROYDEN, 1988). Nevertheless, the acceptability of the tectonic oscillating system has to be assessed very carefully. Although the convection currents represent the supporting force of the oscillating system that is very adequate in terms of dimensions and permanency, the most important factor is something else. It is hardly conceivable in this model, that supposed consequent tectonic activities of opposing character, which were active in several separate basins over a large area and of lengthy duration, could have been so ideally composed and equally measured, to have the time-delays between the uplift and subsi-

dence tectonic movements necessary for almost ideal cyclic variations of water level of the lowest rank.

The second type of oscillating system is the planetary system. Its most important characteristic is a greater potential for stability than for any other system that can influence sedimentary processes. This stability is based on well-defined physical laws. The system's stability is not absolute, there are minor internal variations that can have strong geological effects. It was proved (MILANKOVIĆ, 1941) that small cyclic variations of orbital elements (eccentricity, precession, obliquity) influence the amount of solar radiation that reaches the Earth's surface and its atmosphere and in this way indirectly determine the climate. The previously calculated 18.3×10^3 year period of the single SC time-interval is very close to the cycle amplitude of precession of 18.9×10^3 years calculated by MILANKOVIĆ (1941) and BERGER (1978). Taking in account the exceptionally regular and marked cyclicity of sediments that were surprisingly undisturbed, it is more likely that the variations of water level are directly connected with climate changes, namely with the warmer and colder periods in Earth history. There is also the possibility that these cyclic climate variations resulted in cyclic variations of the water temperature and in changes of the energy level at the floor of depositional basin, which caused the variation in granulometric composition. Naturally, it has to be noted that there is the possibility that all three factors influenced the aforementioned variations in a certain way.

The only measurable value based on which the cyclicity of the studied sediments is supposed, are the thicknesses of the SC-s, and relative to certain cyclic changes in the physical characteristics of sediments. These variations are regrettably not substantiated by adequate analyses, e.g. of the mineral, granulometric and chemical composition. The Milanković theory was accepted after measurement of isotope signals in deep-water sediments, testing in accordance to the changes of magnetic poles, radiometric age measurement by C_{14} and spectral analysis. None of these measurements were performed in this case. Therefore, it can only be supposed that each SC is a reflection of one complete cycle of the rising and lowering of the water level, or energy level fluctuations, or temperature changes of the water. In this way the coarser clastic part of the single cycle represents the low water phase, and the part with finer grains corresponds to the high water phase. Although almost insignificant, these fine changes of granulometric composition were inevitably reflected in the type of grain packing. It can be stated that this consideration is a speculative one, for it has observable and clear consequences, but the positive and scientifically acceptable definition of the causes would only be possible after the aforementioned measurements have been taken and analysed.

5. CONCLUSIONS

- (1) The dual mechanism of transport and deposition of clastic material in the depression (by turbidity currents and from normal basin currents) is recognised from the resistivity and the spontaneous potential curves.
- (2) Within the massive marls facies, formed by deposition of fine-grained clastic material from the permanent basin currents, **single cycles** (SC) are distinguishable on the resistivity curve. Each SC encompasses one cycle of changes of granulometric composition, and these changes result from the cyclic water-level fluctuation and/or changes in water temperature and energy level on the basin floor.
- (3) The SC is a basic genetic depositional unit of extremely short time-span (close to the 20,000 years).
- (4) On the spontaneous potential curve, the sandstone, siltstone and marl layers formed by lithification of clastic material that was brought in by the turbidity currents in the time-interval of one SC deposition (within the cycle of a SC) comprise a **depositional episode**.
- (5) The sandstone bodies are composed of sandstone layers of one, two or more depositional episodes. The numbers of sandstone bodies and of depositional episodes forming each body varies along the basin. The distribution and thickness of every sandstone layer was influenced by the mass of transported clastic material, the energy of each turbidity current, the contemporary inclination of slope and by the palaeorelief of the basin bottom.
- (6) Such heterogeneous composition of the sandstone bodies (and respectively of the sandstone reservoirs), explains the very common irregular oil-water contacts in the existing oil fields and the irregular outer contours of the pools.
- (7) Since the majority of the already proven hydrocarbon reserves is contained in the facies of the thick-layered channel sandstones and the lobe sandstones, and to a lesser extent in marginal or distal sandstones, in order to further search for the potential oil and gas fields it is firstly necessary to define the palaeocurrent pattern.
- (8) The construction of a set of 82 maps of the Upper Miocene sediments of the Ivanić Grad formation, where the area of every single cycle would be separated from the area of depositional episodes with marked facies and palaeocurrent channels, supplemented by the structural and tectonic elements, would provide exceptionally precise input for three-dimensional modelling of regional sandstone reservoirs and of their depositional system within the depression.

Acknowledgements

An earlier version of this paper was critically read by Dr. Jožef ŠIMON, Ina-Naftaplin, Zagreb, Dr. Bruno SAFTIĆ, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Prof. H.G. READING, University of Oxford, and Dr. Györgyi JUHASZ, Geological Institute of Hungary, Budapest, who contributed extensive and valuable suggestions. I am also grateful to Gordan BRZICA, Gordana RAFFAEL-GUJIĆ and Neven BUTINA (INA-Naftaplin) on graphic outfit of the paper.

6. REFERENCES

- BERGER, A.L. (1978): Long-term variations of daily insolation and Quaternary climatic changes.- *Jour. Atmos. Sci.*, 35, 2362-2367.
- BOTT, M.H.P. (1964): Formation of sedimentary basins by ductile flow of isostatic origin in the upper mantle.- *Nature*, 201, 1082-1084.
- MILANKOVIĆ, M. (1941): Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitproblem.- *Akad. R.S.*, 133, 1-633.
- NAJDENOVSKI, J., HERNITZ, Z. & BLAŠKOVIĆ, I. (1983): A review on the geological relations of Variscides in the Southeastern part of the Pannonian basin.- *Newsletter IGCP (UNESCO)*, 5/5, 108-117, Padova.
- PANDŽIĆ, J. (1980): Pretercijar jugozapadnog dijela Panonskog bazena (Geology of the pre-tertiary base of southwestern part of the Pannonian basin).- Unpublished PhD Thesis, University of Beograd, 183 p.
- PLETIKAPIĆ, Ž. (1965): Stratigrafija, paleogeografija i naftoplinonosnost Ivanić Grad formacije na obodu Moslavačkog masiva (Stratigraphy, paleogeography and oil gas possibilities of the Ivanić Grad formation on the border of the Moslavačka gora range).- Unpublished PhD Thesis, University of Zagreb, 71 p.
- ROYDEN, L.H. (1988): Late Cenozoic Tectonics of the Pannonian Basin System.- *AAPG Mem.*, 45, 27-48.
- SANDER, B. (1936): Beiträge zur Kenntnis der Anlagerungsgefüge (Rhythmische Kalk und Dolomit aus der Trias).- *Mineral. Petrogr. Mitt.*, 48, 27-209.
- SCHWARZACHER, W. (1993): Cyclostratigraphy and Milankovitch Theory.- Elsevier, Amsterdam, 225 p.
- ŠIMON, J. (1970): Prilog stratigrafskoj analizi tercijarnih sedimentata na sjeverozapadnom predjelu Savske potoline.- VII kongr. geol. Jugosl., 1, 347-360, Zagreb.
- ŠIMON, J. (1973): O nekim rezultatima regionalne korelacije litostratigrafskih jedinica u jugozapadnom području Panonskog bazena (Some results of regional correlation of lithostratigraphic units in the southwestern part of the Pannonian Basin).- *Nafta*, 24/12, 623-630, Zagreb.
- ŠIMON, J. (1980): Prilog stratigrafiji i taložnom sustavu pješćanih rezervoara Sava-grupe naslaga mlađeg tercijara u Panonskom bazenu sjeverne Hrvatske (Contribution to stratigraphy and depositional system of sandstone reservoirs of Sava group younger Tertiary deposits in Pannonian basin, Northern Croatia).- Unpublished PhD Thesis, University of Zagreb, 66 p.
- VRBANAC, B. (1996): Paleostrukturalna i sedimentološka analiza gornjopanonskih naslaga formacije Ivanić Grad u Savskoj potonini (Paleostructural and sedimentological analysis of the Upper Pannonian deposits of Ivanić Grad formation in Sava depression).- Unpublished PhD Thesis, University of Zagreb, 125 p.
- VRBANAC, B., ŠIMON, J. & HERNITZ, Z. (2000): Sjeverna Hrvatska tijekom gornjeg panona - plitkovodni ili dubljvodni taložni bazen?- In: VLAHOVIĆ, I. & BIONDIĆ, R. (eds.): 2nd Croatian Geological Congress, Cavtat - Dubrovnik, Proceedings, 469-474, Zagreb.

Manuscript received September 1, 2000.

Revised manuscript accepted May 20, 2002.

