Facies and Facies Architecture of the Ivanić Grad Formation (Upper Pannonian) - Sava Depression, NW Croatia

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Abstract

Four facies were distinguished within the Ivanić Grad Formation of the Sava Depression: massive marl facies (F_1), thick-bedded to massive sandstone facies (F_2), thin-bedded sandstone facies (F_3) and thin-bedded sandstone, siltite and marl facies (F_4). Interpretation of the depositional mechanisms confirmed the presence of two basic sedimentary processes. Hemipelagic deposits are represented by fine-grained detritus. The lithification of these produced a massive marl (facies - F_1). Sand detritus was transported into the depression by turbidite currents (facies - F_2-F_4), and formed a narrow elongated sedimentary body.

By comparing the facies defined on the basis of core samples, the spontaneous-potential curve (SP) and the resistivity curve (R_a) of identical intervals, four facies associations were defined on well log diagrams: channel filling (F_A), depositional lobe (F_B), lateral and distal turbidites (F_C) and massive marls (F_D).

1. INTRODUCTION

The Sava depression represents the most southern part of the Pannonian basin (Fig. 1). After the Middle Eocene, a long continental phase started in the area represented by the present depression, during which tectonic movements occurred and a fault network was created along which the basin subsided by extension. The oldest proven sediments belong to the fresh-water Ottnangian deposits which are overlain by Carpathian, Badenian and Sarmatian clastic marine sediments. Pannonian and Pontian sediments were deposited in a brackish to fresh water environment, while Pliocene sediments represent fresh water-lacustrine deposits. The thickness of this clastic complex exceeds 4,000 m in the deepest parts of the depression. The complex was interpreted by FILJAK et al. (1969) as a single sedimentary

macro-cycle that can be subdivided in three distinct parts. The oldest is composed of coarse clastics (breccias, conglomerates and sandstones), overlain by clays, marls, limestones and biogenic limestones deposited in fresh-water and marine environments with occasional intercalations of effusives. This part of the macro-cycle comprises sediments of Ottnangian, Badenian and Sarmatian age. The middle part of the complex is composed of marls and sandstones that were deposited in a brackish to fresh-water environment, and is of Pannonian and Pontian age. These sediments represent several turbidite cycles. The final part of the macro-cycle constitutes Pliocene and Quaternary sediments of a mixed lithological composition - sands, gravels, clays and lignite. They were deposited in an alluvial environment, either within the river bed or in the large swamps extending along the rivers, following the elongation of marginal depressions.

The studied sediments of the Ivanić Grad Formation (Fig. 2) form part of this clastic complex. The Formation contains sandstone bodies in the central parts of the depression, while the marginal and external parts are represented exclusively by massive marls. The upper boundary of the formation in the marginal parts of the depression occurs at a depth of 300-400 m; in the central parts this boundary is below 3,000 m. The total thickness of this formation in the marginal parts is from 150-250 m, while in the central sections it reaches 800 m (Fig. 3). Part of the sedimentary body composed of turbidite sediments has an elongated narrow fan morphology extending NW-SE, 100 km long and 25 km wide. Although the exact relationship between the lithostratigraphic and chronostratigraphic units was not determined, the fossil content shows that most of this formation, if not the whole, is Upper Pannonian in age (Fig. 4).

The cored material from the central parts of depression, that coincide with the deepest parts of the depositional basin during the Late Pannonian, is, as a rule, either barren of fossils, or contains fragments of unidentifiable ostracods. In the cores taken from the marginal parts of depression (which were the subsurface uplifts), the Upper Pannonian sediments are mostly represented by marls occasionally interbedded with thin sandstones. These marls were found to contain fossils. The Upper Pannonian sediments were also investigated

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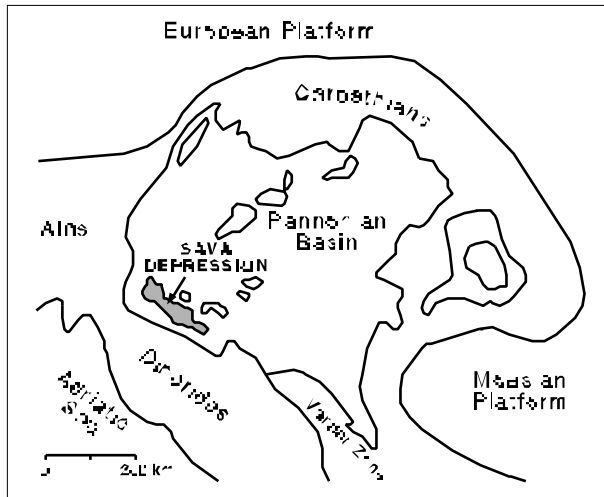 e-mail: boris.vrbanac@ina.hr

Fig. 1 Location map of the Sava depression.

at outcrop, on Mt. Medvednica, Mt. Moslavačka gora and elsewhere. The presence of macrofossils was also determined. However, no publication describing this Upper Pannonian fossil fauna, from either outcrops or cores, explains the possible environment habitat of the fauna. It is usually only stated that deposition took place in a protected low-energy environment.

Over almost the entire area of the Sava depression, the Ivanić Grad Formation overlies the Lower Pannonian sediments of the Prkos Formation. Only in a narrow strip of Dinaridic strike, located in the SW part of depression, does the Ivanić Grad Formation directly overlie the Badenian sediments. The lithological composition of the Prkos formation is mainly of shallow-water thin or thick-layered marls, calcareous marls and marly limestones. Sandstones are only rarely found in the form of millimetre-thick layers or laminae. The Lower/Upper Pannonian contact has not been precisely defined, but it can be concluded that it roughly corresponds with the contact between the lithostratigraphic units. The Prkos formation is relatively easily identified on the well logs, but its age is rarely palaeontologically documented, due to the very scarce fossil content of the cores. Nevertheless, the cored material of the Prkos Formation contains a Lower Pannonian fauna without exception, while the cores taken from the overlying Ivanić Grad Formation mostly contain an Upper Pannonian fauna, if any. Similarly, the sediments of the Kloštar Ivanić Formation, overlying the Ivanić Grad Formation over the entire exploration area, exclusively contain a Lower Pontian fauna. The Kloštar Ivanić Formation bears lithological and depositional similarities with the Ivanić Grad Formation which means that such lithostratigraphic subdivision was conditioned by the practical, petroleum-geological reasons.

Two basic concepts have been postulated to explain the depositional environment of these sediments. According to PLETIKAPIĆ (1965) the water depth was shallow, and the cyclic character of the sediments was due to frequent moving of the shore line and a high energy area. Only in limited area and the constant subsidence of blocks along active tectonic lines, could the water depth have increased significantly in very narrow channels where turbidite currents could have developed. According to MILJUŠ & VUGRINEC (1977) the Ivanić Grad Formation was deposited during a regressive phase. In zones of shallow water coasts pelites were mostly deposited, while sandstones were deposited in the places of higher energy such as channels. LUČIĆ (1994) interpreted the facies as coastal sediments, bar and beach sediments, interbar shoals, lagoon sediments and tidal channel sediments of coastal plains. The results of palynological analyses are contained in an unpublished work (LUČIĆ & KRIZMANIĆ, 1993[1]). The established palyno flora is composed of environmentally different phytoplankton fossils. The genus *Spiniferites* is very common and is characteristic of shallow environments. Alternatively, *Impaginidium* and *Gonyaulax* are phytoplankton that lived in deep water. Despite the possibility that such an association can be interpreted in terms of the deep water environment wherein the shallow water organisms were transported by resedimentation, the authors express the opinion (after SÜTÖ-SZENTAI, 1982) that this was the case of a shallow environment with occasional transport of the deep water organisms by the sea currents, which means that they were mixed with other fossils in the littoral zone. There are significant differences in the age determination between the palynological analyses of the core material from the three major oil fields - Ivanić, Žutica and Okoli. These results remained unpublished in professional studies within the Department of the Central Laboratory. The samples from the Ivanić Grad Formation were found to pertain the Lower and Upper Pontian, and Upper Pannonian. It has to be noted that not a single sample with palynological findings has also been documented by macrofossils. DALIĆ (1996) singled out five different lithofacies - offshore homogeneous marl deposits; well sorted marl intercalated with siltstones and marl deposited as progradational shoreface and/or as barrier bar; marl with coal laminae and lithoarenite layers deposited on tidal flat in estuaries; marl intercalated with siltstone and fine grained sandstones were interpreted as shallow shelf deposits with lagoonal characteristics; well sorted lithoarenites as a subtidal barrier bar.

ŠIMON (1980) believed, on the basis of the geometry and lithological properties, that these sediments belong to "the family of redeposited coarse clastics". He applied the concept of "submarine-sublacustrine fan" to explain deposition. In defining the depositional environment of the Okoli sandstones (the youngest

[1] LUČIĆ, D. & KRIZMANIĆ, K. (1993): Završno izvješće, bušotina Okoli-57, Biostratigrafska, litofacijesna i sedimentološka interpretacija.- Unpubl. report, INA-Naftaplin Archive, Zagreb.

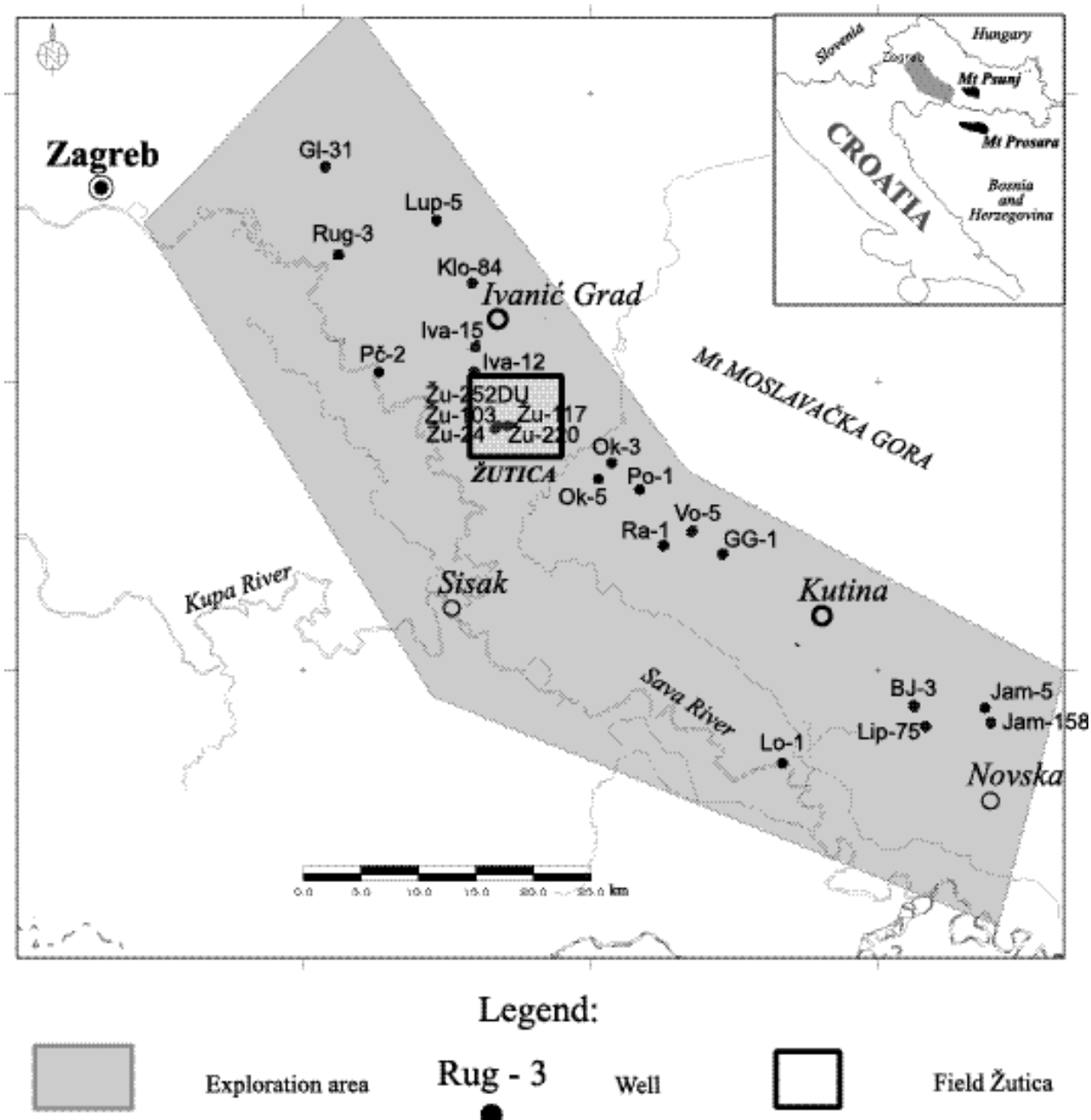Vrbanac: Facies and Facies Architecture of the Ivanić Grad Formation...

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Fig. 2 Location map of the explored area.

member of the Ivanić Grad Formation), in part of the Žutica oil field, VRBANAC (1989, 1990) believed that they belonged to the channelised part of a submarine fan (to its middle proximal part). The detritus was carried by gravitational flows which could be compared to turbidity flows. In his later work VRBANAC (1996) reconstructed a palaeogeographic view of the Sava depression during the Upper Pannonian, and concluded that it was a marked sub-sea (sub-lake) palaeorelief, the major feature of which was a central tectonic graben surrounded by submarine highs - the Medvednica horst in the NE, Moslavačka Gora horst in the north, Martinska Ves horst in the south, and the Psunj-Prosara ridge in the east (Fig. 2). The bottom of this graben was irregular and mildly inclined in a SE-E direction, with some

occasional steepening. He also concluded that this was a calm, low-energy environment, with a sedimentary basin large and deep enough to ensure a stable depositional environment, to compensate for the variations of the factors that respectively influence depositional mechanisms in a tectonically active basin.The source area of the clastic material was N-NW from the area named the "Alps mineral association", and it can be concluded that there was lengthy transport of the probably extensively resedimented material (ŠĆAVNIČAR, 1979).

Although they did not directly study the areas of the Drava and Sava depressions, Hungarian authors also think that during the Pannonian (Pannonian s.s.) a deep water system existed with early turbidites, and later
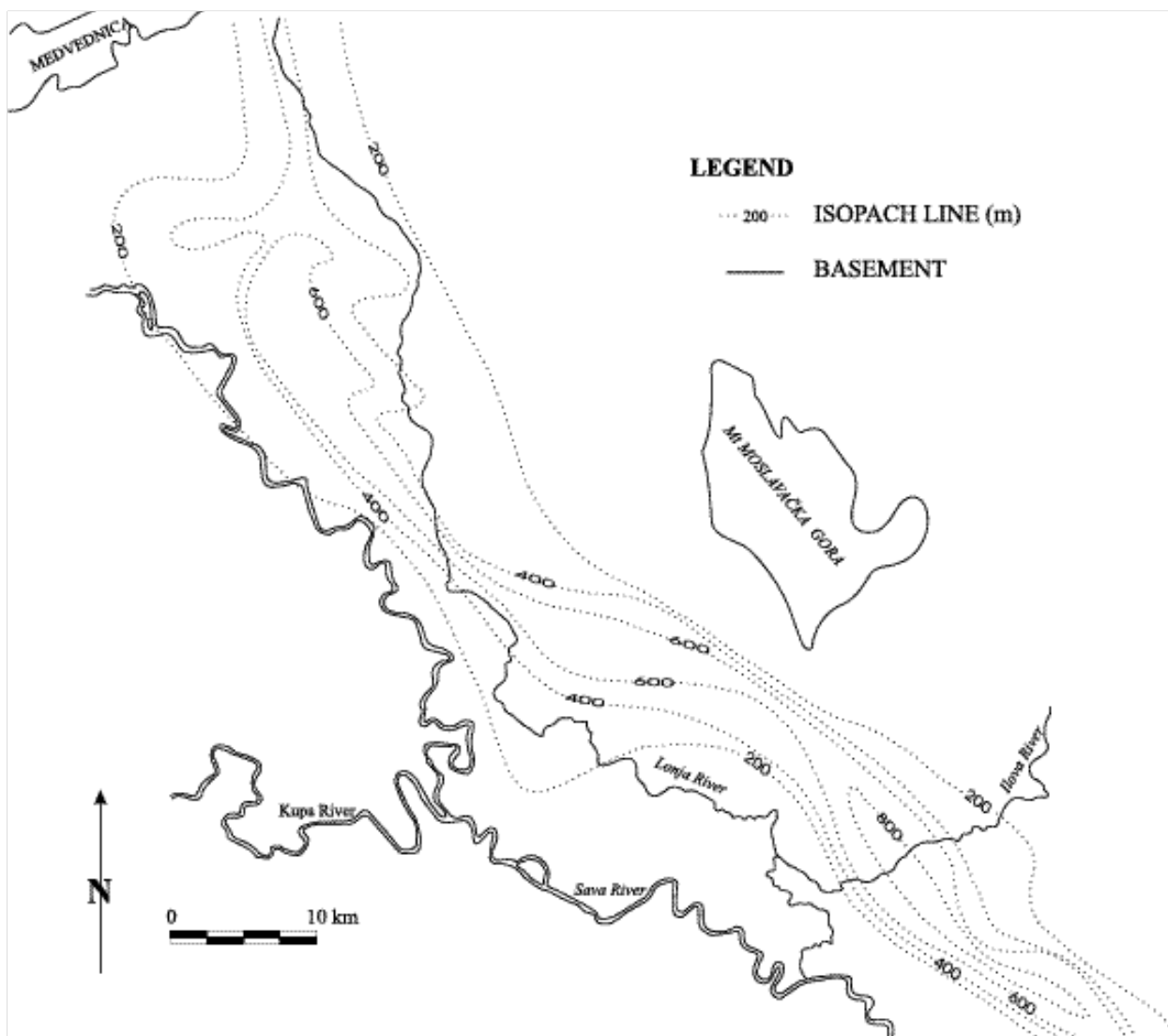
Fig. 3 Isopach map of the Ivanić Grad Formation.

delta slope sediments (MATTICK et al., 1985, 1988; SZENTGYÖRGYI & JUHÁSZ, 1988; CLAYTON & KONCZ, 1994; HÁMOR & BÉRCZI, 1999).

2. SEDIMENTOLOGICAL ANALYSES OF CORE SAMPLES

Detailed sedimentological analysis, layer-by-layer, was carried out on the cores from 29 wells distributed throughout the Sava depression. The 61 cored intervals were analysed with a total length of 569 m that covers almost the entire interval of the studied formation. The cores are mostly in isolated intervals that are not more than 6 m length. Only 6 wells were found to have continuous coring ranging from 27-82.1 m in length. Since most of the cores were taken 20 or more years ago, lots of the core material was either missing or was found fragmented in irregular small pieces that were unsuitable for sedimentological analysis.

2.1. Petrography

Sandstone, siltite and marl alternate with each other. Data on the petrographic, mineralogical and physical properties of the sediments are provided by experts from INA-Naftaplin's Central Laboratory.

Sandstones are present only in the central part of the depression, pinching out towards the edges. They are grey (mostly light grey) in colour, only those saturated with oil are brown. Sandstone bedding is well expressed in parts where they are interbedded with marl; bed thickness may reach several metres. They belong to a group of very fine to fine-grained sands with average grain size of 0.08-0.2 mm, rarely medium grained (0.5mm). Roundness varies between 0.2-0.3, belonging to the group of subangular grains. Sphericity grade values are balanced and vary between 0.68-0.74, making them highly spherical particles.

Sandstone porosity is 10-33%, with significant differences in these values regarding the regional spatial

M a	REGIONAL STAGES	LITOSTRATIGRAPHIC UNIT OF SAVA DEPRESION (by PLETIKAPIĆ, 1965; ŠIMON, 1970, 1980)			EK - marker
9	UPPER PANNONIAN	SAVA - GROUP	IVANIĆ - GRAD FORMATION	OKOLI SANDSTONES	ZAGREB MEMBER	Z'
10				GORNJOŠARAMPOVO MARL	LIPOVEC MARL	Rρ
11				IVA SANDSTONES		
				DONJEŠARAMPOVO MARL		Rs5
12	LOWER PANNONIAN	MOSLAVAČKA GORA - GROUP		PRKOS FORMATION		
13	OTTNANG			PREČEC FORMATION		

Fig. 4 Correlation table of the chronostratigraphic and lithostratigraphic units and position of the EK markers.

distribution of sandstones in relation to the source area of the detrital material and different facies. Parallel presentation data of porosity on several oil fields (BOKOR et al., 1979) show a distinct decrease of these values from northwest to southeast. Great differences in porosity and permeability values are also statistically proven in Ivanić Grad sandstones which belong to different facies. Maximum values are determined in the distributory channel sandstones, while sandstones of levees and lobes have considerably lower values (ĐUREKOVIĆ, 1995).

The petrographic uniformity of the Upper Pannonian sandstones has long been noted (ŠĆAVNIČAR, 1979). Quartz is the main component, together with rock fragments, micas and feldspars. Quartz does not exceed 60% of the detritus. Among rock fragments (18-35% of composition), the most dominant are limestone and dolomite, while grains of cherts, quartzite, clay shale, chloritic and sericite shales, quartz-muscovitic shale and gneiss, with rare fragments of granite and tuff are also present. The clay mineral content is very low (<5%, mostly 1-2%). Cement is formed by a mixture of prevailing calcite and detritic silt-clayey matrix. The detrital matrix contains illite, kaolinite, quartz, chlorite, plagioclase and mica. Sandstone cementation is not always complete, so many sandstone beds are poorly cemented and friable. According to their composition, they are litharenites, respectively calclithoarenites since in rock cuttings carbonate sediments are dominant[2]. Relatively large quantities of unstable grains indicate the low maturity of sandstones (ŠĆAVNIČAR, 1979).

The best indicator of the petrographic uniformity of this formation is the identical composition of accessory heavy minerals, with the dominance of chlorite and garnet and to a lesser extent biotite, staurolite, disthene, epidote, zoisite, apatite, tourmaline, zircon and rutile. Such an association of heavy minerals indicates that the source areas of the detritic material were probably the Alps with metamorphic rocks of epi and mezzo zones, as well as with limestones and cherts (ŠĆAVNIČAR, 1979).

A great number of sandstone beds contain dark grey marl clasts. Clasts are mostly of an irregular and subangular shape. Their dimensions vary considerably; more often to 1-2 cm, very rare to 10 cm. They are found either dispersed, scattered in great numbers, or massively. They can be scattered irregularly but mostly appear so that their longer axis is parallel or subparallel to the bedding plane. They are mostly found in the lower parts of sandstone beds, although they can also be present in the central and upper parts.

The mineralogical composition of siltites is identical to that of the sandstones except for a higher mica content. Flat and/or cross-lamination is almost always present, and visible due to presence of organic matter or mica. Burrows of ichnofossils are frequently noticed, as well as tiny marl clasts. Siltite porosity is mostly below 5%; permeability is also very poor, less then $10\ \mu m^{-2} \times 10^{-3}$.

Marls are grey brown, brown, dark grey and often almost black in colour. They are mostly hard, fissile and show parallel bedding planes where numerous carbonised plant remnants are frequently obseved. These remnants are mostly particle-sized but can be larger than 10 cm. Bioturbation is sporadically strongly

expressed. Ichnofossils look like winding tubes filled with sand or marl material. Petrographic analyses show that the marls consist of a clay-carbonate and cryptocrystal base with more or less fine grained quartz and mica of silt or sand dimensions. The $CaCO_3$ content is about 60%.

2.2. Facies

According to the sedimentological properties of the cored deposits (lithology, bedding, texture, relation between lithological members) four facies were identified: massive marl facies (F_1), thick bedded to massive sandstone facies (F_2), thin bedded sandstone facies (F_3), and laminated sandstone, siltite and marl facies (F_4)

2.2.1. Massive marl facies (F_1)

This facies consists of homogenous and massive, mostly unbedded marls, dark grey to almost black in colour (Fig. 5a). Sporadically preserved signs of bedding and lamination are mainly expressed by a colour change, and occasionally by thin siltite or sandstone laminae or beds. The massive homogenous appearance is sporadically disturbed by burrows, but those traces of organism activities did not disturb rare primary internal structure and textural properties.

Massive marls are the "normal" basin deposit, as hemipelagic muds which covered the basin floor relief under stable conditions. The uniform petrographic structure of detrital material indicates material transported by turbidity currents, but the transport mechanism and mode of deposition is different. Thickness of massive marls in the marginal, morphologically higher parts of the depression, reaches 150-250 m, and up to 250 m in the central lower parts. Thin siltite and sandstone intercalations and laminae in the massive marl are of turbidite origin, reflecting the enlargement of turbidity flow area in the direction of movement as well as in their lateral spreading.

2.2.2. Thick bedded to massive sandstone facies (F_2)

This facies is represented by thick-bedded to massive homogenous sandstones with a few siltite and marl intercalations which can be compared to massive sandstone facies (WALKER, 1978). The thickness of individual sandstone beds from the cored intervals is from 0.5-6 m (Fig. 5b). Amalgamation is frequently present. It is expressed by sharp changes in colour nuance within homogenous sandstone beds, or by sharp changes in grain size of sandstones. Frequently, several metre long intervals of sandstone cores were broken into pieces only a few cm long or even smaller, making sedimentological analysis impossible. It is debatable whether these significant thicknesses of sandstone beds could be

the consequence of amalgamation which, due to the identical content and physical properties of sand detritus, and broken of cores, can not always be determined. This facies appears exclusively within distributory channels where the energy of turbidity flows was the highest and where the effects of erosion on the base by mud flows were most strongly expressed.

Lower bedding planes are sharp and with more or less expressed traces of erosion. Sandstones of this facies can be of different structure. A lot of beds are massive and homogenous. Normal gradation can be noticed only in a few beds, in their upper part, while it is less frequent in their lowest part or within the bed. Even though there is usually no gradual transition between a sandstone bed and overlying marl, some sandstones gradually grade into siltite and marl. In such beds horizontal and lateral siltite lamination can be noticed, as well as convolution. The thickness of these seal marls does not exceed several centimetres. Less commonly there are cases of inverse gradation. Lamination is very seldom present. Frequently, horizontal or wavy lamination within sandstones which are abruptly cut off on the upper side by a massive sandstone with no texture, points to amalgamation, during which the upper laminated part was carried away, probably together with the capping marl.

Deformed bedding and lamination, and convolute bedding or lamination is common. This is the result of hydroplastic deformation of unconsolidated deposits over which strong water flows passed during sedimentation (SANDERS, 1965), as well as in the post-sedimentation phase as the result of the sudden displacement of pore water (LOWE, 1975). In this way dish structures and sand dikes are formed. Frequently, flame structures occur on the lower surface of sandstone layers, and it could be established for some clasts that they were formed by the breaking of thin marl beds due to the sudden displacement of pore water, and their "intrusion" into overlying sandstone or even siltite beds. Some deformations are probably the result of sliding of poorly compacted material down the slope. Due to expressed lamination, sinsedimentary faults of small dimensions are often noticed, both normal and reverse. On lower bedding surface visible traces were left by erosion of the flow itself and/or traces of erosion by objects moving over the bottom: clasts, plant parts etc. Marl clasts of different dimensions and different roundness grades and carbonised plant remnants are quite common. While carbonised plant remnants of different dimensions originate from continental regions, marl clasts were formed by the erosion of poorly consolidated sediments of the channel flanks and bottom, started by turbidity flows.

The estimated proportion of marl and siltite in this facies does not exceed 10%.

The internal bed constitution and textural properties are mostly the result of the final stage of transport and

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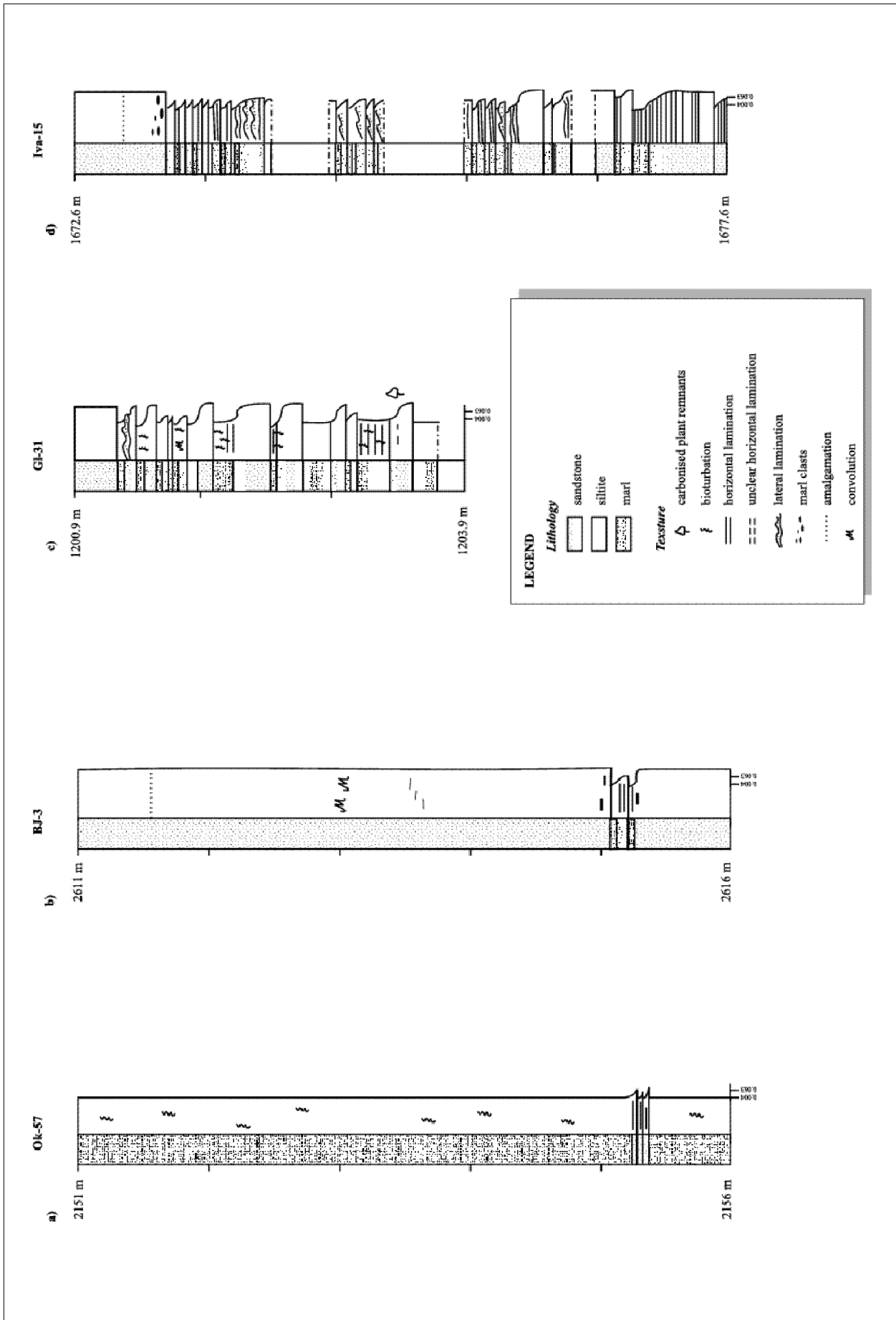[2] Physical and petrographic data - Department of Central laboratory INA-Naftaplin.

Fig. 5 Lithologic columns.

deposition (POSTMA, 1986), and are of special importance for the interpretation of environment and deposition conditions. Thick sandstone beds which are massive in their major part, and show a decrease in grain size (gradation) in their top part, grading into thin, horizontally laminated, and cross-laminated sandstone or siltite covered by thin marl, could be compared to Bouma sequence of Ta-e type (BOUMA, 1962). The high quantity of sand (thick beds) indicates the extremely high energy and capacity of these flows. The presence of marl clasts in different parts of the bed and the erosional base of the bed also suggests turbulent flow. According to the above characteristics, they can be compared with turbidites deposited from mud flows of high concentration, where the detritus population I and II (LOWE, 1982) was supported by upward turbulence (MIDDLETON, 1970; LOWE, 1979, 1982). In the flow base where slipping was the most intensive, it was probably supported by dispersive pressure (MIDDLETON, 1967; LOWE, 1976, 1982). Namely, sediments deposited from liquid flows have flat bases due to their laminar character and high density of flows (LOWE, 1982), so these type of flows are not taken into account. Sedimentation occurred by direct, rapid and massive suspension sedimentation (WALKER, 1978), until the bedding plane did not reach the top of the turbidite current cloud. The energy of such flows was 5 Wm^{-2} (ALLEN, 1984). Deposits formed by direct suspension sedimentation belong to poorly packed sediments (KOLBUSZEWSKI, 1950). These deposits are poorly cohesive and strongly subject to liquefaction and forming of secondary water escape pipes (LOWE & LoPICCOLO, 1974; LOWE, 1975). It is considered (LOWE, 1982) that at this development stage of mud flows, a suspension mass of high density can almost momentarily form an Ta interval Bouma sequence several metres thick without any traction sedimentation textures.

2.2.3. Thin-bedded sandstone facies (F_3)

This facies is represented by sandstone beds several centimeters to 0.5m thick (Fig. 5c). The proportion of marl and siltite in this facies is 30-40%. Regarding internal structure and gradation, the interval with horizontal and lateral sandstone and siltite lamination, and horizontal lamination in fine grained material is the most frequent. Bouma sequences of type Ta-e, Tb-e and Tc-e are all common. Some of these beds are parallel laminated throughout their entire thickness, while in their upper part they pass relatively suddenly into siltite and marl. This facies can be found as the final beds in the sediment sequence deposited in distribution channels, but are more characteristic as marginal channel sediments.

The basal boundary is sharp, and very often strong or weak erosion traces can be noticed on the upper bedding plane of the underlying marl. Amalgamation was not noticed or at least is not characteristic for sandstones of this facies. Convolution is very often present in all parts of the bed, as well as dish structures. Small marl clasts (<5 cm) are quite frequent, and are also found in all parts of the sandstone bed. The thickness of marl which appears among the sandstones varies from several to tens centimetres. Marl bioturbation is well expressed, especially in thicker intercalations.

The marl/siltite ratio is significantly higher in this facies, and the estimated value is 30-40%.

This facies consists of repeated sandstone and marl beds. Sharp lower bedding planes of the overlying sandstone and the gradual upward passage into marl, confirm spasmodic turbidite currents which, compared with flows of the previous facies, are more diluted. On the basis of their internal textures and their constant succession, or similarity of these beds to a Bouma sequence, they can be interpreted as turbidites, with a lower proximity index than the previous facies, due to a significantly lower proportion of the Ta interval.

2.2.4. Thin bedded sandstone, siltite and marl facies (F_4)

Facies four consists of very thin, thin-medium thick sandstone beds in monotonous alternation, passing upwards into siltite and marl, or there are thin siltite intercalations that grade upward into marl (Fig. 5d) They are mostly several centimetre thick beds that start with a sharp bedding plane. On the upper bedding plane of the marl, traces of weak erosion of the subsequently developed mud flow are sometimes visible. Internal textures are represented by horizontal and cross lamination, convolution, and structures developed by water displacement - sand dykes. There is a rare occurrence of uplifted beds, and deformed beds. Ta-e and Tb-e type sequences occur being less numerous than Tc-e and Td-e sequences. Beds of this facies are characteristic for the marginal parts of the channel or prominent parts of the bottom relief where the energy and influence of turbidity currents in the depositional processes were distinctly weaker.

Marl clasts of 2 cm size are also present, as well as carbonised plant remnants. In smaller sediment fractions ichnofossils occur regularly, and are sporadically visible in the coarser fractions. The traces of digging, drilling and moving of organisms in the sediment are occasionally so abundant that they disturb primary textures.

The proportion of marl and siltite in this facies is estimated as between 50-60%.

Thin beds of well laminated fine-grained sandstone and siltite in alternation with marl, frequently organised in Bouma sequence Tc-e, suggest that at least a part of these beds were formed by deposition from turbidity currents of low concentration. In this regard, this facies corresponds to thin bedded low energy levee deposits (MUTTI & RICCI-LUCCI, 1975; WALKER, 1978) or distal turbidite deposits.
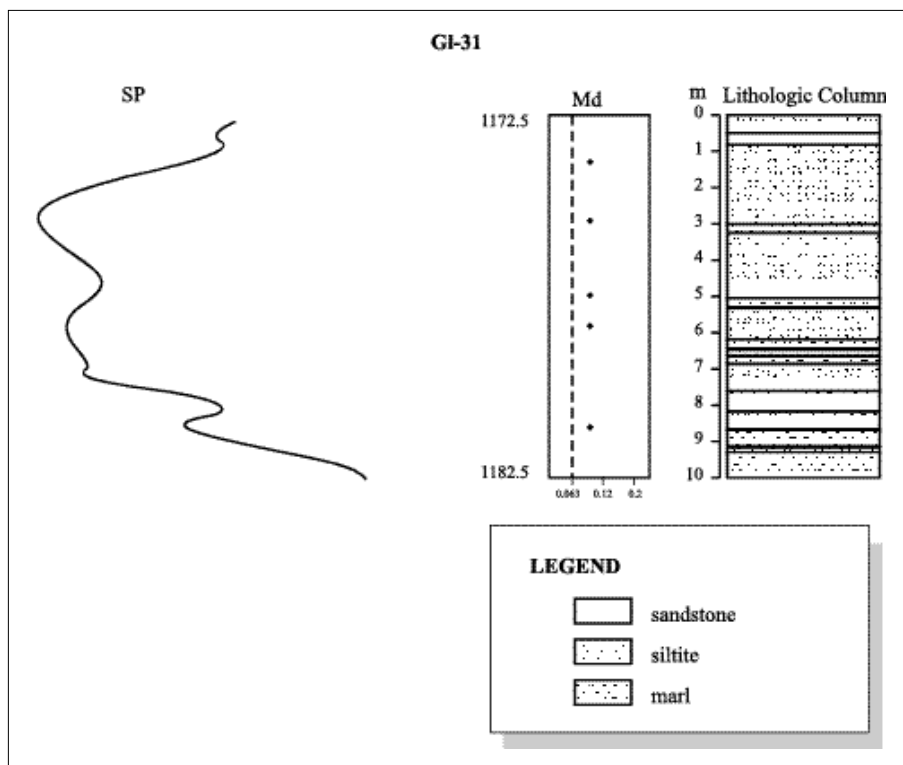
Fig. 6   Comparison between lithologic column and corresponding interval on the SP curve.

3. ORIGIN OF DETRITAL MATERIAL

The deposits are interpreted as sediments of moderate water depth. Detrital material was brought into the basin by turbidity flows or as normal basin deposit. The constant sandstone type, uniform detrital content, consistent structural characteristics and composition of heavy minerals suggest Alpine metamorphics as the source rocks. However, a significant part of the carbonate detritus in the content of sandstone, as well as the carbonate-clay content of siltite and marl and plant remnants in marls, indicate more local sources of detrital material. It can be assumed that the detrital material has been reworked several times, the basis of which is formed from an association of metamorphic minerals and fragments of metamorphites of Alpine origin, enriched with carbonate and clay material from local sources.

The concept of the depositional environment of the study area suggests that the present Sava depression was part of the southern marginal part of the Pannonian basin (lake) which extended southwards probably significantly further from the presently determined boundaries. Prior to deposition in the Sava depression, the detrital material was, after other probable multiple episodes of deposition, deposited into the area of todays Mura depresion, which represented a slope area - area of material accumulation, from where it was occasionally carried into the Sava depression. Coarse material was brought by turbidity flows while pelitic material was continuously brought and deposited by aggradation in the basin regardless of its morphology. Since turbidi-

ty flows moved through the deepest parts of the basin, a substantial mass of sand detritus was deposited in the deepest parts of the basin.

4. FACIES ASSOCIATION ACCORDING TO SP AND R$_A$ CURVES

SP and Gamma-ray curves reflect the change in grain size in clastic sediments. This is why they are used for the identification of lithologic structure/composition and boundaries between formations, as well as for the identification of depositional environments (e.g. GALLOWAY, 1968, 1998; FISHER, 1969; PIRSON, 1970; SELLEY, 1976, 1985).

The SP curve is the basic curve which defines facies associations of the studied layers containing sandstones (turbidite facies associations), while R$_a$ curve determines the massive marl facies association. The SP curve has values that are a function of the grain size of sand detritus, and the relationship can be established between the funnel or bell shape of these curves and the tendency to coarsen or fine upward. With regard to the sedimentological analyses which showed the structural complexity of sedimentary bodies built of thin intercalations of sandstone and marl, it can be determined that the **thickness ratio** in sandstone and marl intercalations in alternation have a crucial influence on the final shape of SP curve. A comparison of the SP curve and a lithologic column of the same interval in Gl-31 well (Fig. 6), shows that SP values depend on the relationship between thicknesses of sandstone and marl intercala-

tions. Granulometric analyses performed on sandstone intercalations indicate approximately identical values of average grain diameter (Md). A tendency of upward coarsening of sandstone beds on the SP curve is expressed by a funnel curve shape. This symmetry/regularity was established in numerous examples of upward coarsening of sandstone beds. A tendency of upward fining of sandstone beds, noticed in cores, results in a bell shape SP curve.

Taking into consideration the facies that were determined by sedimentological analyses (F_1-F_4), and the defined depositional environment (ŠIMON, 1980; VRBANAC, 1989, 1996), as well as the SP and R_a curve shapes, four associations of facies were singled out: channel filling facies association (F_A), depositional lobe facies association (F_B), lateral or distal turbidites facies association (F_C), and massive marls facies association (F_D). Facies associations were recognized and defined on well log diagrams (SP and R_a curves), which enabled the reconstruction of their structure in space, and mutual relationship. Since that relationship can be best observed in oil fields - owing to a great number of wells on a relatively small area, the Žutica oil field was selected, where relationships of facies associations were shown in detail, as an illustration of relationships in the depression.

4.1. Channel filling facies association (F_A)

This facies association consists of thick-bedded sandstone facies (F_2) and thin-bedded sandstone facies (F_3). The channel axis is characterised by thick sandstone beds with sporadic marl intercalations. Sandstone beds become thinner towards the channel edges, while marl intercalations become thicker. It is important to emphasise that the expression "channel" does not imply the type of channel which is forming within a classic fan that occurred in the continental slope towards the open sea.

The depositional sequence of channel sediments is represented on the SP curve by a bell shaped or cylindrical curve (PIRSON, 1970; SYED, 1979; GALLOWAY, 1998). The thickness of some depositional sequences is 10-20 m; most frequently, several sequences are joined into one sandstone body (Fig. 7). A depositional sequence is formed of sandstone beds which are characterised by a certain shape on the SP curve - bell, funnel or cylindrical shape. These shapes reflect the tendency of the changing thickness of sandstone and marl beds in alternation. One depositional sequence can be formed by one sandstone bed or there can be several depositional sequences separated by rather thick marl intercalations. Trends of particular sequences may or may not correspond.

Bed erosion is strongest in the middle parts of the channel, and weaker in the marginal parts, so that the absence of marl intercalations, and numerous amalgamations undoubtedly suggest the position of the chan-

nel axis, or direction of the main flow of the turbidity current in some phases of detrital deposition. So, channels were both depositional (HAMILTON, 1967) and erosional (LAUGHTON, 1968). The main mass of turbidity current passed through these channels. As turbidity current energy weakened, particles carried in suspension were deposited. Therefore, the thickest sandstone beds are related to the channels whose position, in the deepest parts of the basin, depended on basin morphology which was controlled by synsedimentary tectonics.

The channel width for the member of Iva sandstones on the Žutica oil field is about 250 m, possibly up to 1000 m. Some channels have a constant width; others split into two arms or two channels merge into one. The channel was probably not very deep, except where the association of facies F_A is laterally equivalent to the association of facies F_C or even F_D, it probably concerned a deeper channel of steep flanks which had a narrow or non depositional area for facies associations F_B or even F_C. Turbidity currents ran mostly through the channel itself. Outside the channel only the marginal parts of the turbidite cloud carried detritus depositing associations of facies F_B and F_C.

On the SP curve diagram of the Iva-15 well (Fig. 7), the channel filling facies association F_A is expressed as a succession of depositional sequences with a tendency of upward fining of sandstone beds, composed of F_2 and F_3 facies sandstones. They were amalgamated by stronger or weaker erosion into some 80 m thick sandstone bodies. On the SP curve, the association of channel sandstone facies is shown as a funnel shape, as the result of the abrupt formation of a channel and deposition of thick sandstone beds. In the final phase, upward fining sandstones and marls were deposited, depending on the migration speed of the channel. If the migration was abrupt, SP curve is of cylindric shape.

Although there was no statistical research of the relationship between sandstone and marl within this facies association, sandstone probably forms 90% of the total.

4.2. Depositional lobe facies association (F_B)

This association is composed of F_3 facies in the lower part and facies F_2 in its upper part. They were deposited outside and parallel to the distributary channels where the power of turbidite currents is significantly weaker so that erosional occurences, if any, are less expressed than within the channel. As a consequence, amalgamation is very rare. The total thickness of sandstone bodies that belong to this facies association can exceed 30 m. Sandstone beds of this association show a tendency to coarsen upward, while marl intercalations are usually ten centimetres thick and more.

On the SP curve diagram of the Iva-15 well (Fig. 7), the F_B association of facies is expressed as a depositional sequence of upward coarsening sandstone beds, and
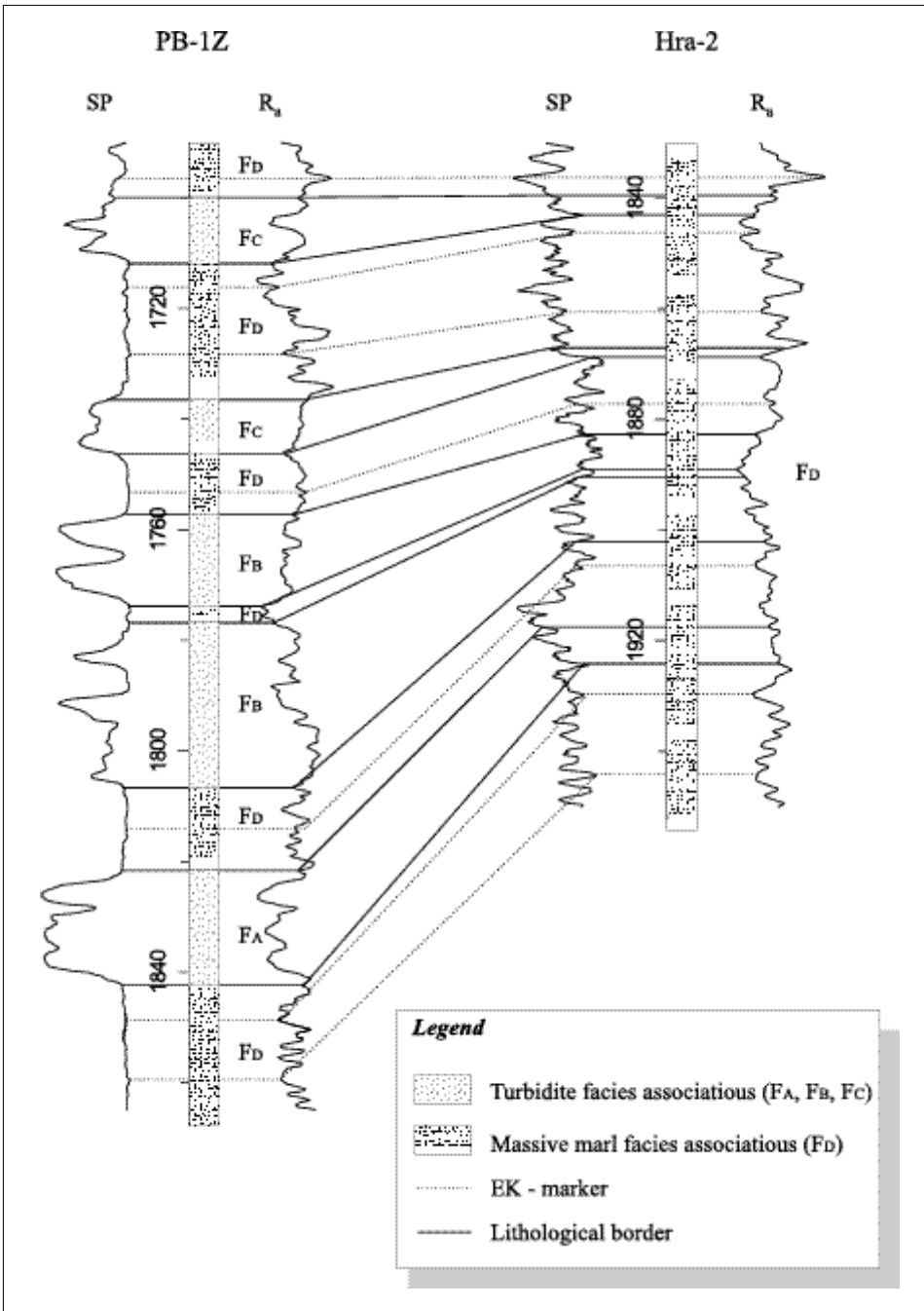
Fig. 7 Vertical succession of the facies associations.

by a funnel shaped curve. The depositional environment of this association of facies is parallel to channel extension, it directly continues on channels and extends for several to tens of kilometres in length and several hundred metres to 1-2 km in width. In its narrowest part this zone is less than several tens of meters wide. This facies association is characteristic for a near channel zone, or marginal parts of the channel, since turbidite currents of great capacity did not move only through channels but also in a wider channel zone. In this way, from time to time, thick sandstone beds were deposited outside the channel.

The estimated proportion of sandstone is 70 to 80%.

4.3. Lateral or distal turbidite facies association (F$_c$)

This association consists of a monotonous alternation of very thin, thin and medium thick sandstone beds (according to CAMPBELL, 1967) passing into siltites and marls. They are represented by facies F_3 and F_2. On upper bedding surfaces there is practically no erosion or only very weak traces can be noticed. Alternation of thin marl and sandstone intercalations cannot be registered by the logging tools, making the derived SP curve a result of the relationships between final lithological members (Fig. 7). This association of facies is charac-

teristic for the areas of distal and lateral termination extend of the turbidite currents, as well as the morphologically higher interchannel areas. In a lateral direction further from the channel, namely from the area of deposition of channel sandstones, the share of sandstone decreases with increasing share of siltite and marl. This decrease of turbidite bed thickness continues until they pinch out. The total bed thickness of this facies association may be several tens of metres. In the north west and central part of the depression, areas of turbidite occurrences have a narrow elongated shape several hundred metres wide, roughly following the channel direction. They were formed by deposition of sandstone and fine grained detritus in the lateral, transitional parts of the basin, between the main current area and morphologically higher zones. Therefore, deposition took place in the area where the turbidite current travelled, but were affected only by the upper part of the turbidite cloud which is, in this part, thin and of low energy, and capable of carrying only small quantities of sand. Distal turbidites correspond to classic turbidites being deposited at the end of the basin plain, namely in the area of termination of the turbidite current (WALKER, 1978).

The estimated sandstone ratio in the deposits of this facies association is between 30 and 50%.

4.4. Massive marls facies association (F_D)

This association is mostly represented by massive marl facies F_1 with rare intercalations of thin siltite or sandstone laminae or beds (Fig. 7). The depositional environment of this facies association is the whole area of the Sava depression; only in its central parts is this association "masked" by turbidite associations. In the lateral, morphologically higher parts of the basin, sediments of this association were exclusively deposited, while in the central, morphologically deepest parts of the basin, they only form a part of the depositional sequence.

5. FACIES ASSOCIATIONS ARCHITECTURE

Depositional architecture in a basin reflects the interaction of processes of sediment supply, relative subsidence or uplifting and eustatic changes of sea level (GALLOWAY, 1998). In addition, an important role in depositional evolution are local factors: water depth in the basin, palaeorelief, palaeoclimate, transport and depositional mechanisms, quantity of transported detritus and current velocity, local synsedimentary movements, etc. The influence of each factor can significantly vary in different parts of the basin, which additionally makes the determination of relationships between lithological members and facies in the basin more difficult.

5.1. Lateral changes of facies associations

Determination of facies associations on well logs, more particulary on SP and R_a curves, is especially reliable in oil fields with many wells in a relatively small area. By following lateral relationships on the favourably positioned profiles, perpendicular to the strike of distributary channels, the facies association of channel filling is most frequently well noticed, as is their lateral transition into the depositional lobe facies association and facies association of lateral turbidites, while beyond the direction of turbidite currents the massive marls facies association was deposited. Lateral spreading of the channel filling facies association depends on the width of the basin bottom and slope of the channel. There are examples in the Žutica oil field where the facies association of a several tens metres thick channel filling is laterally continuous into a narrow zone of thin (10 m) lateral turbidites facies association. This zone is followed by the massive marl facies association (2-5 m thick, Fig. 8). The association of massive marl facies appears in all parts of the depression that were outside the turbidite current direction, or in parts of the depression that are so far above the channel bottom that turbidite currents could not or seldom reached them. The morphologically higher parts of the bottom were also found in the central part of the depression, so that the facies association of massive marl was often surrounded by the association of facies containing sandstones (Figs. 10 and 12). In observing the lateral succession of facies associations, a general rule for their distribution is noticed. Parallel with the spreading of channels in which the channel filling facies association was deposited, the lobe facies association most frequently appears, followed by the association of lateral turbidite facies which pass laterally into the association of massive marl facies (Fig. 8). This distribution of the facies associations follows a general rule of the distribution of facies in a fan (WALKER, 1978). Central deposition occurs in the channels where thick-bedded to massive sandstones were deposited. In near channel zones, thin and thick bedded sandstones were deposited, while in a more distal turbidite current direction, and lateral to the channel axis, thin bedded turbidite sandstones and massive marls were deposited (Fig. 9).

Detailed distributional relationships between the facies associations is shown in the example of a sandstone body member of the Iva sandstones of the Žutica oil field. In this field a member contains ten sandstone bodies. The lowest is $_8$, followed by $_7$, $_6$, $_5$, $_4$, $_3$, $_2$, $_x$, $_1$ and $_0$. Maps are given for $_4$, $_3$, $_2$ and $_1$. On the maps, for each sandstone body, distributional channel areas were marked where the deposited channel filling facies associations (F_A), other facies associations (F_B-F_C), and the massive marl facies association (Figs. 10-13) were deposited. On the maps, the form of the channel system, changes of channel position in space, and changes in the shape and size of deposition surfaces of sandstone detritus are easily observed. Within distribu-
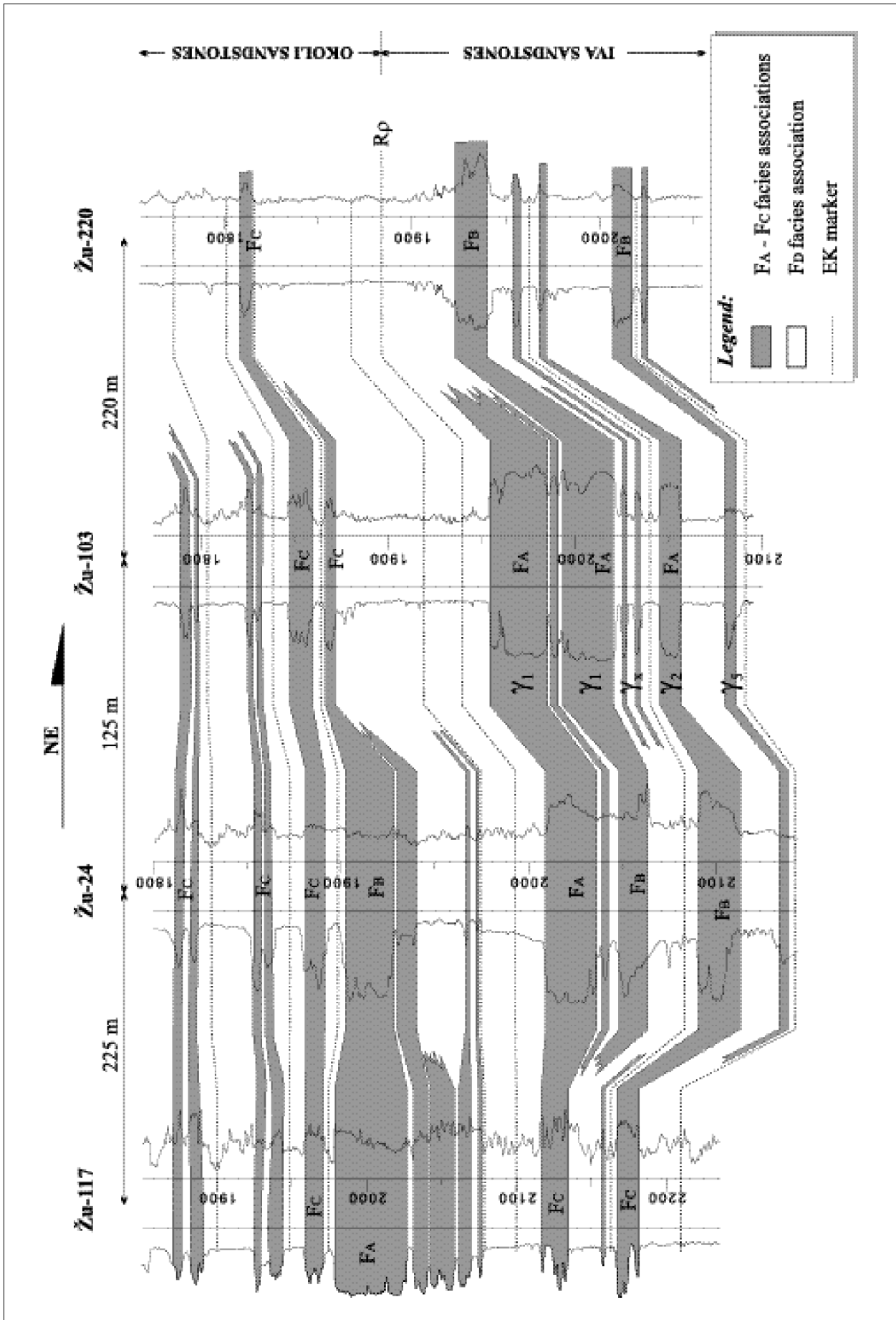
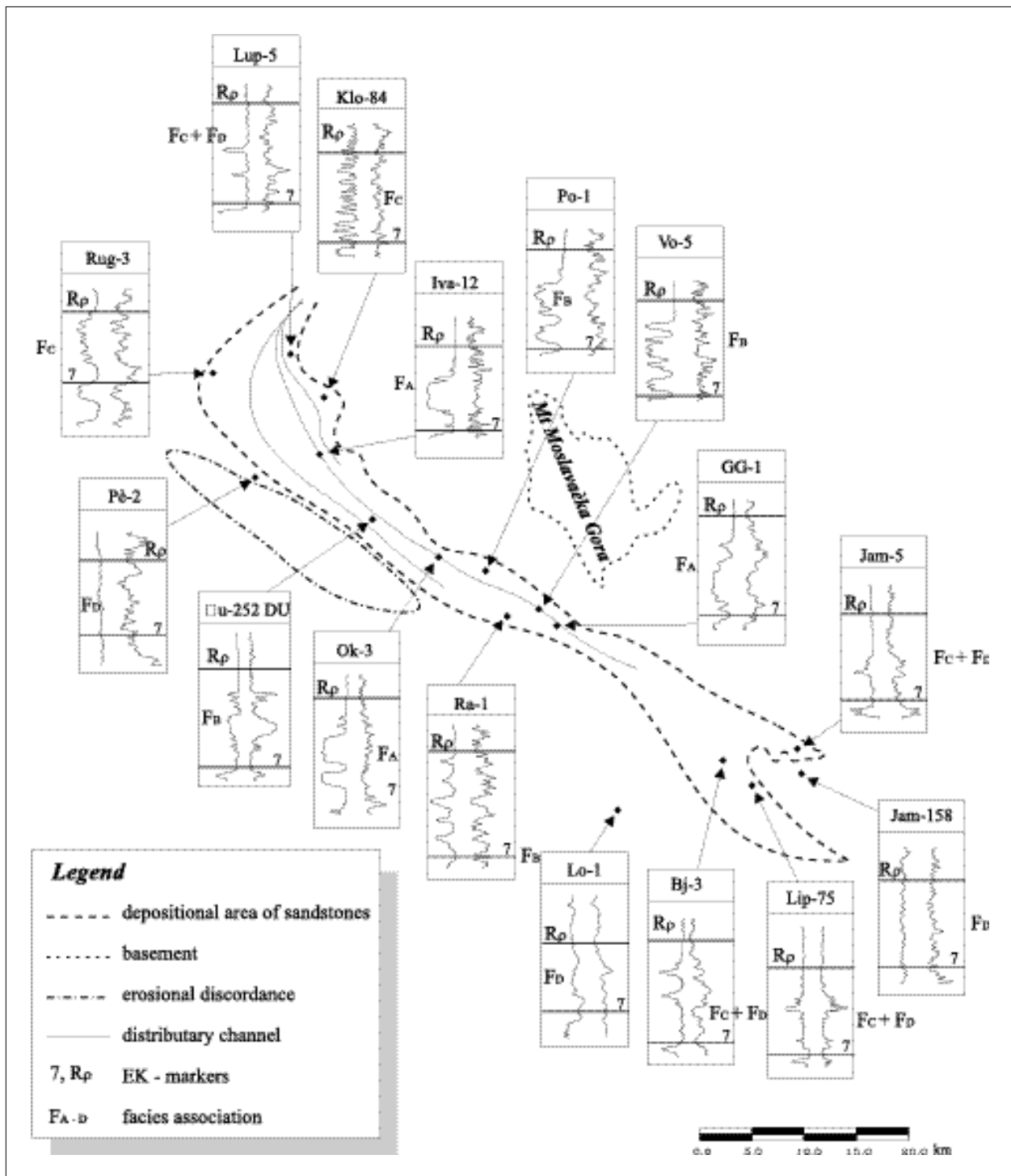Fig. 8 Correlation profile over the SW section of Žutica oil field.

Fig. 9 Facies associations distribution - upper part of Iva sandstone.

tary channels there are clearly marked areas where, due to the erosional action of turbidite currents, a direct contact between two or more sandstone bodies occurred. The existence of three hydrodynamic units which were determined during oil and gas exploitation explain the erosional action of turbidity currents. The sandstone bodies $_8$, $_7$ and $_6$ form one hydrodynamic unit, $_5$, $_4$, $_3$ and $_2$ form the second, and $_x$, $_1$ and $_0$ form the third, and it is obvious that the erosional action of turbidite currents, which brought certain sandstone bodies into direct contact, directly influenced the establishment of the hydrodynamic relationships.

5.2. Vertical succession of facies association

Most interpretations of depositional sequences are based on facies sequence, namely on observation of facies of the progradational and retrogradational movements of lobes and channel filling (MUTTI & GHIBAUDO, 1972). Let us consider the vertical rela-
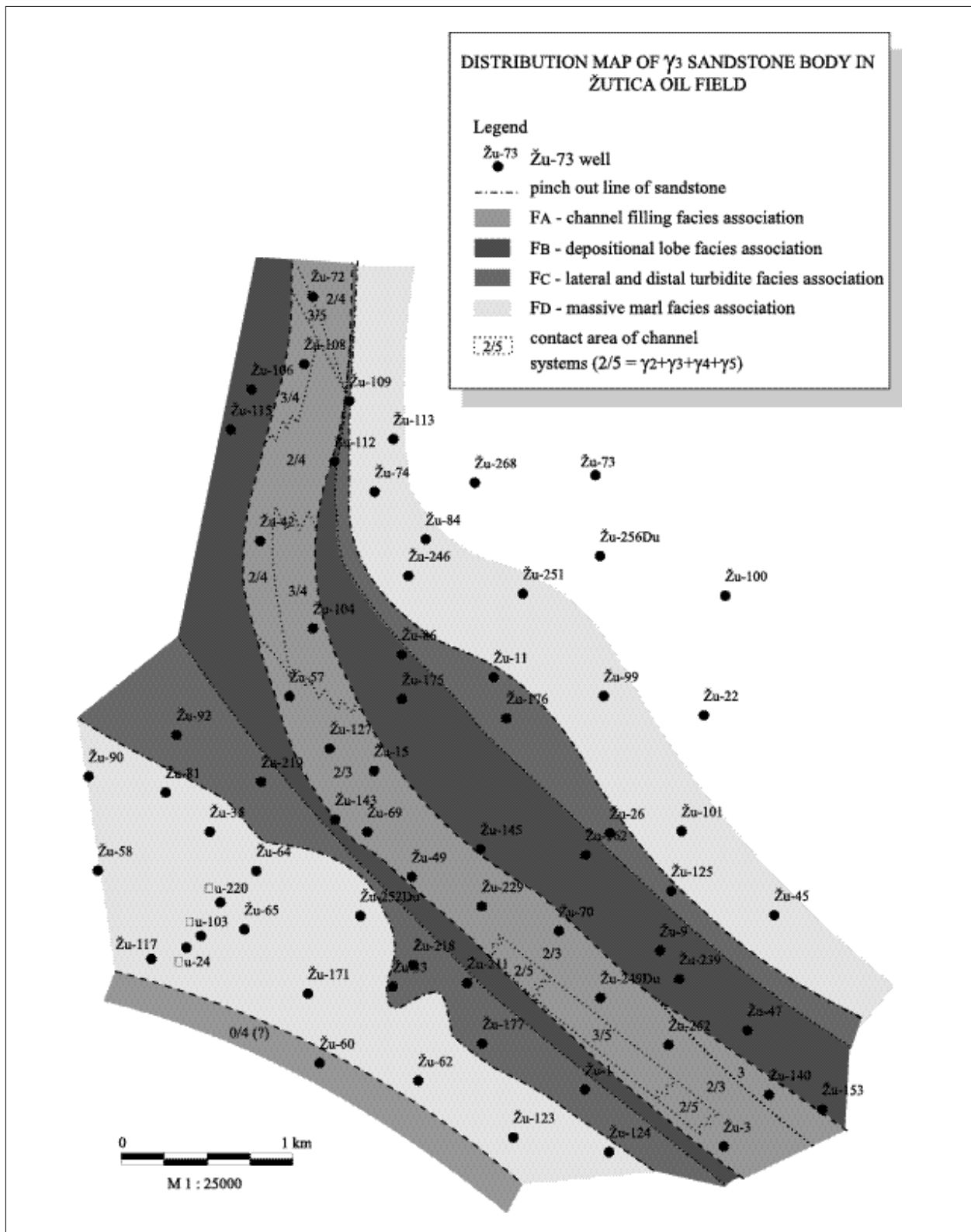
Fig. 10 Distribution map of ₄ sandstone body (Iva sandstone) in Žutica oil field.

tionships of the facies associations of the whole Ivanić Grad Formation. The example of the Iva-15 well (Fig. 7) clearly illustrates the vertical succession of the facies associations of the Iva-sandstone member that appear over the whole area of the depression. The sequence begins with the massive marls facies association as basinal hemipelagics, followed by the facies association of lateral (distal) turbidites represented by a serrated SP curve. It is further followed by the depositional lobe facies association (prograding lobe), which is obvious

Fig. 11 Distribution map of ₃ sandstone body (Iva sandstone) in Žutica oil field.

by the tendency of upward thickening sandstone beds (funnel shape of SP curve), and the channel filling facies association marked by a bell shaped SP curve. The depositional lobe facies association is repeated marking side channel migration, followed by distal turbidity facies association, and massive marl facies association.

The vertical succession of facies associations can be well observed on the profile which shows the section through the Ivanić Grad Formation of the Žutica oil
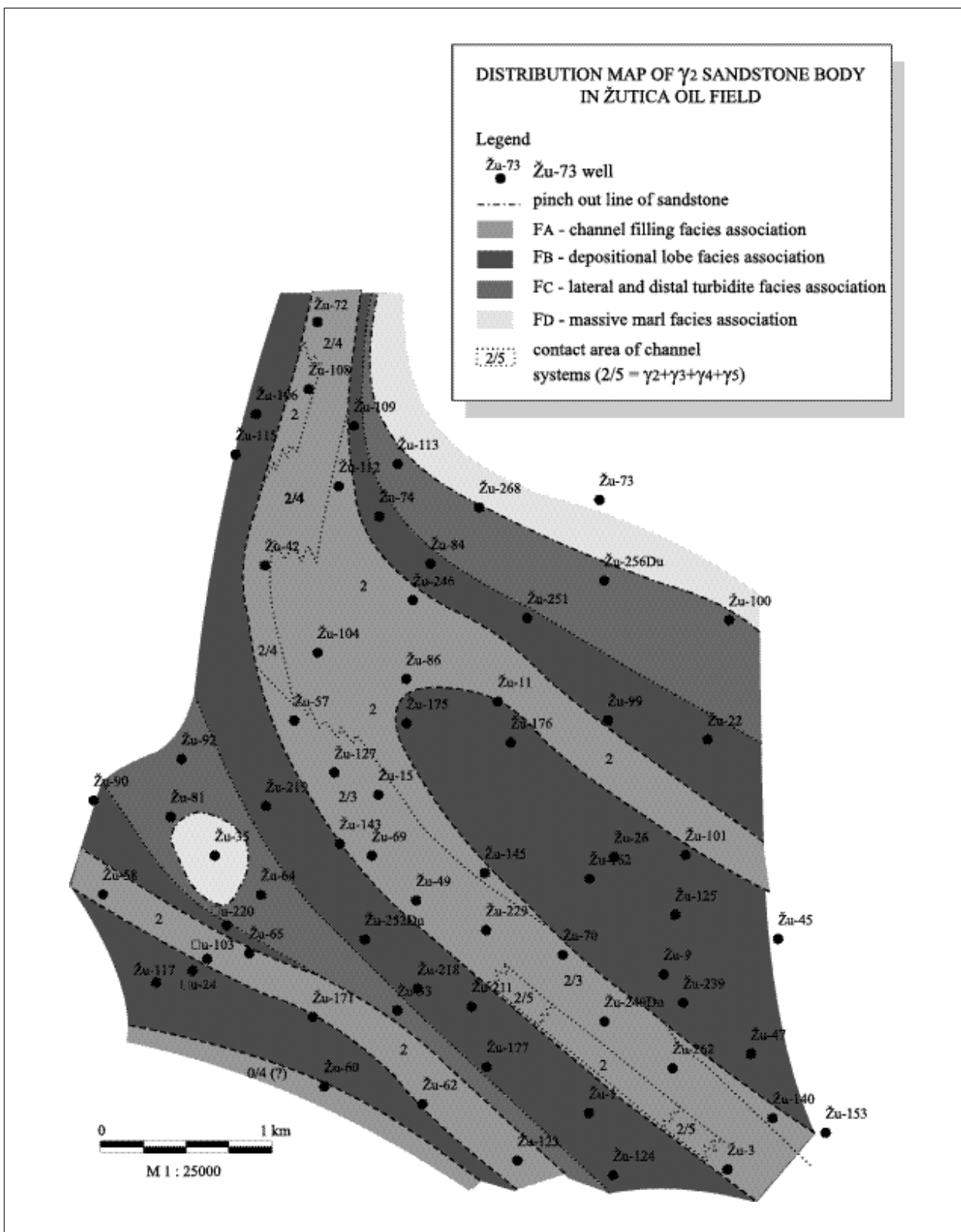
Fig. 12 Distribution map of ₂ sandstone body (Iva sandstone) in Žutica oil field.

field (Fig. 8). Not only is the vertical succession of associations in each well obvious, but also the lateral transitions of one facies association into the other, from the channel filling facies association into the massive marls.

If we summarize the experience obtained by such analyses of SP and R_a curves, not only from the wells on this profile, but from the wells in the depression, in which all or most facies associations are well developed, certain conclusions can be reached. Vertical suc-
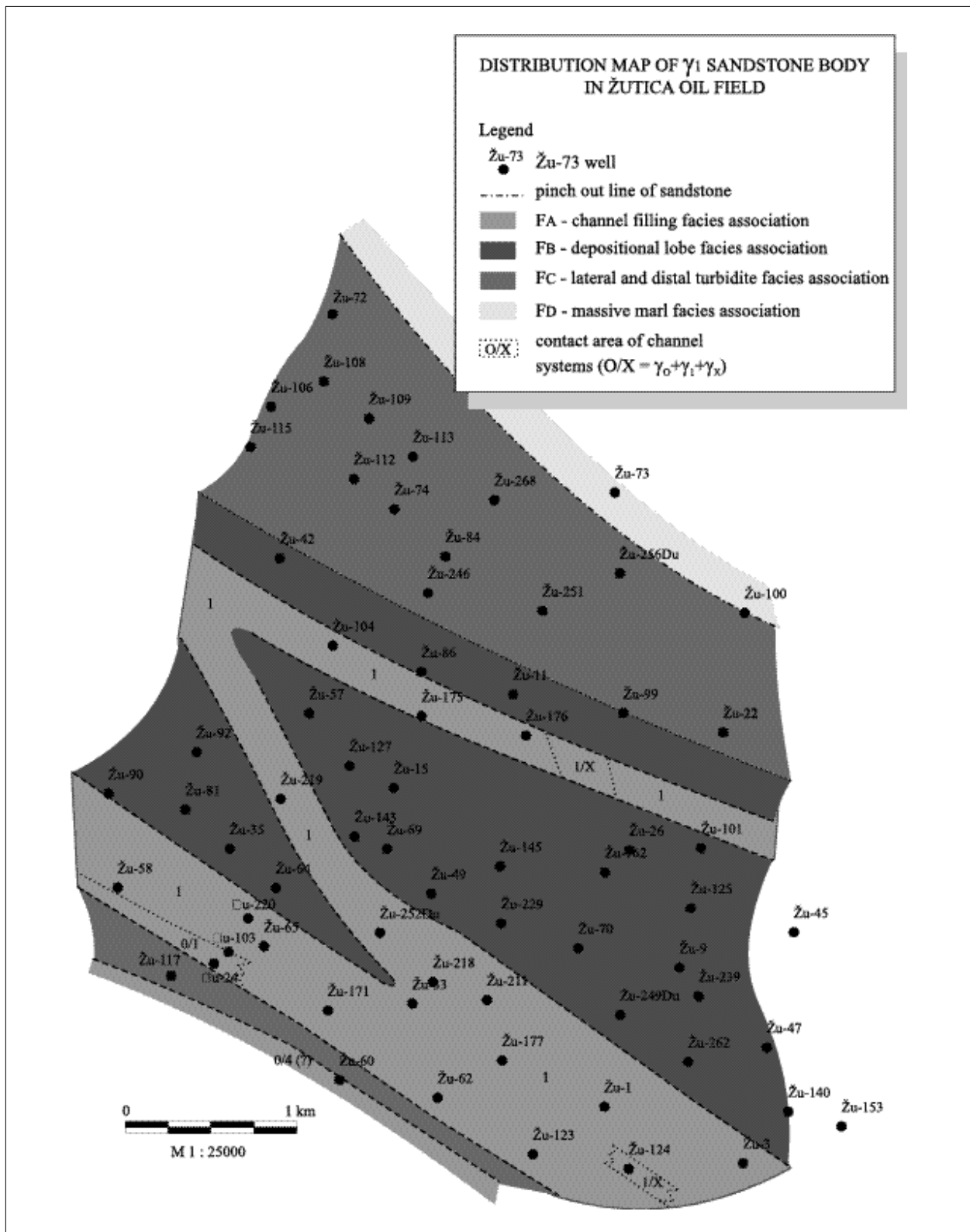
DISTRIBUTION MAP OF γ_1 SANDSTONE BODY
IN ŽUTICA OIL FIELD

Legend

Žu-73 ● Žu-73 well

---·--- pinch out line of sandstone

▒ FA - channel filling facies association

▓ FB - depositional lobe facies association

▓ FC - lateral and distal turbidite facies association

░ FD - massive marl facies association

O/X ▫ contact area of channel
systems (O/X = $\gamma_o + \gamma_1 + \gamma_x$)

Fig. 13 Distribution map of $_1$ sandstone body (Iva sandstone) in Žutica oil field.

cession of the explored deposits usually starts with the massive marl facies association, followed by sandstone beds of the distal turbidite facies assocciation, depositional lobe facies association and channel filling facies association. This part of the succession would corre- spond to the progradational phase. Then again follows the facies association of depositional lobe, distal tur- bidite facies association, and massive marl facies asso- ciation. This part of the succession corresponds to a ret- rogradational phase. These two phases form a cycle of

SW

NE

MARTINSKA VES HORST

MOSLAVAČKA GORA HORST

Z'

R₂

Rₛₛ

Legend

OKOLI SANDSTONES

IVA SANDSTONES

ZAGREB MEMBER AND LIPOVEC MARL

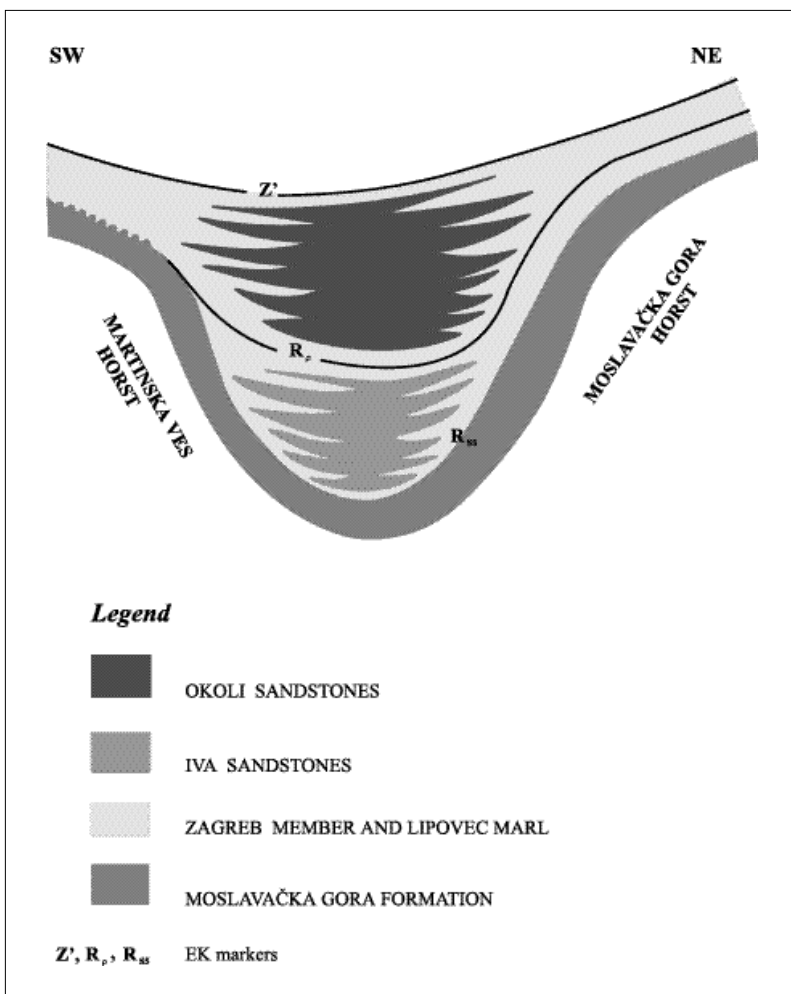MOSLAVAČKA GORA FORMATION

Z', R₂, Rₛₛ   EK markers

Fig. 14 Schematic palaeogeographic section of Sava Basin towards the end of Upper Pannonian.

sandstone material transport in the depression, comprising the lithostratigraphic unit of the Iva sandstones. After a longer period of time in which, over the whole Sava depression, sediments of the massive marl facies association were exclusively deposited, except in the part of the Kloštar Ivanić oil field where the distal turbidite facies association was deposited, another relatively long period of time occurred with numerous turbidite currents that brought large quantities of sandstone detritus in the depression. This cycle of deposition of sandy detritus in the depression also consists of progradational and retrogradational phases, and the sediments of this cycle comprise the Okoli sandstones lithostratigraphic unit. It can be concluded that sandstone material of the Ivanić Grad Formation was brought during two cycles of turbidite current movements. Each cycle had progradational and retrogradational phases, and corresponds to an extending and narrowing of the depositional area of detrital material (Fig. 14). The vertical succession of facies associations in each well is subject to those occurrences of higher order, and to its position in the depositional system. In each member that contains sandstones, the vertical succession of facies associations was dictated mainly by the lateral migration of channel, and afterwards by oth-

er numerous factors such as distance from the channel, channel depth, density and size of turbidite cloud, palaeorelief, etc. Proximity to distributional channels determines thickness and number of sandstone beds within a sandstone body, as well as the facies association. In the channel, the thickness of sandstone beds and bodies is maximal. It decreases with lateral distance from the channel axis and southwards where the action of turbidite currents gradually weakens.

6. CONCLUSION

(1) A double mechanism of transport and deposition of the Ivanić Grad Formation was defined. Massive marls represent "normal" basin hemipelagic deposition (F_1 facies). Periodic turbidity brought coarser sand-size detritus, as well as finer grained detritus of siltite and mud size, lithification of which formed turbidite facies (F_2-F_4 facies).

(2) Marginal parts of the research area were composed exclusively of massive marls deposited in a calm, low energy environment of moderate water depth. However, since these marls are also present in the central parts of the depression, in turbidite beds, it

can be concluded that the depositional environment was calm and stable, owing to sufficient water depth that compensated for all water level changes caused by either tectonic movements or cyclic climate changes. This calm environment was disturbed only by temporary turbidity currents which deposited most detritus in the depression.

(3) Understanding of the lateral and vertical relationships of the four facies associations in the area (oil and gas field) made it possible to understand depositional occurrences in other parts of the explored basin.

(4) Reconstruction of the lateral extent of facies association starts with channel filling facies association which pass laterally into depositional lobe facies association, and further from the channel axis into the lateral turbidites facies association and finally into the massive marl facies association. The same regularity is noticed in the reconstruction of the vertical succesion of facies associations.

(5) Detailed reconstruction of the distribution of sand bodies - potential hydrocarbon reservoirs above all, spatially defining channel position directs future exploration activities to the most prospective parts of the basin significantly diminishing exploration expenses.

(6) Accurate understanding of the relationships of the determined facies associations, which are characterised by specific reservoir properties, contributes to defining the strategy of locating development and injection wells in previously discovered oil and gas fields. This will result in the enhancement of recoverable hydrocarbon reserves.

7. REFERENCES

ALLEN, J.R.L. (1984): Sedimentary structures: their character and physical basis.- Developments in Sedimentology, 30, unabridged one-volume edition, Elsevier, 593+663 p.

BOUMA, A.H. (1962): Sedimentology of some flysch deposits.- Elsevier, Amsterdam, 159 p.

BOKOR, N., DEVALD, M., LUČIN, J. & THALLER, J. (1979): Usporedni prikaz naftnogeoloških odnosa u "Iva-pješčenjacima" polja Ivanić Grad-Žutica-Okoli.- Zbornik radova III god. znan. skupa ZSN Jugosl. akad. znan. umjetn. (Novi Sad), 2, 585-595, Zagreb.

CAMPBELL, C.V. (1967): Lamina, lamina set, bed, and bedset.- Sedimentology, 8, 7-26.

CLAYTON, J.L. & KONCZ, I. (1994): Petroleum geochemistry of the Zala Basin, Hungary.- Am. Assoc. Petrol. Geol. Bull., 78 /1, 1-22.

DALIĆ, N. (1996): Okoliš taloženja i oblici sedimentnih tijela pješčenjaka Iva naftno-plinskog polja Okoli (gornji panon) (Sedimentary environment and shape of sediment bodies of Iva sandstones of oil and gas field Okoli (Upper Pannonian).- Unpublished MSc Thesis (in Croatian), University of Zagreb, 46 p., Zagreb.

ĐUREKOVIĆ, M. (1995): Taloženje i rezervoarska obilježja Iva pješčenjaka na naftnom polju Ivanić (Deposition and reservoir characteristics of Iva sandstone on oil field Ivanić).- Unpublished MSc Thesis (in Croatian), University of Zagreb, 58 p., Zagreb.

FILJAK, R., PLETIKAPIĆ, Ž., NIKOLIĆ, D. & AKSIN, V. (1969): Geology of petroleum and natural gas from the Neogene Complex and its basement in southern part of the Pannonian Basin - Yugoslavia.- In: HEPPLE, P. (ed.): The exploration of Europe and North Africa. Institute of Petroleum, 113-130, London.

FISHER, W.L. (1969): Facies characterization of Gulf Coast Basin delta systems, with some Holocene analogues.- Gulf Coast Assoc. Geol. Soc. Trans., 19, 105-125.

GALLOWAY, W.E. (1968): Depositional systems of the Lower Wilcox Group, north-central Gulf Coast Basin.- Gulf Coast Assoc. Geol. Soc. Trans., 18, 275-289.

GALLOWAY, W.E. (1998): Siliciclastic slope and base-of-slope depositional systems: component facies, stratigraphic architecture, and classification.- Am. Assoc. Petrol. Geol. Bull., 82/ 4, 569-595.

HAMILTON, E.L. (1967): Marine geology of abyssal plains in the Gulf of Alaska.- Jour. Geophys., 101, 725-728.

HÁMOR, G. & BÉRCZI, I. (1999): Common issuses of Neogene paleogeographic models and petroleum systems.- 2nd. Int. Symp. on Petroleum Geology (Probability approach to Petroleum Exploration), Proceedings, 125-133, Zagreb.

KOLBUSZEWSKI, J. (1950): Notes on the deposition of sands.- Research, 3, 478-483.

LAUGHTON, A .S. (1968): New evidence of erosion on the deep ocean floor.- Deep-Sea Research, 15, 21-29.

LOWE, D.R. (1975): Water escape structure in coarse-grained sediments.- Sedimentology, 22, 157-204.

LOWE, D.R. (1976): Subaqueous liquefied and fluidized sediment flows and their deposits.- Sedimentology, 23, 285-308.

LOWE, D.R. (1979): Sediment gravity flows: their classification and some problems of application to natural flows and deposits.- Soc. Econ. Paleontol. Mineral., Spec. Publ., 27, 75-82.

LOWE, D.R. (1982): Sediment gravity flows II: depositional model with special reference to the deposits of high-den-

sity turbidity currents.- Jour. Sed. Petrol., 52/1, 279-297.

LOWE, D.R. & LoPICCOLO, R.D. (1974): The characteristics and origins of dish and pillar structures.- Jour. Sed. Petrol., 44, 484-501.

LUČIĆ, D. (1994): Regressive and transgressive depositional systems and parasequences in the shallow shelf deposits (Sava Depression, Pannonian Basin, Croatia).- Liverpool Sequence Stratigraphy Conference, Abstracts, 387-388.

MATTICK, R.E., RUMPLER, J. & PHILLIPS, R.L. (1985): Seismic stratigraphy of the Pannonian basin in Southeastern Hungary.- Geophysical Transactions, 31, 13-54.

MIDDLETON, G.V. (1967): Experiments on density and turbidity currents, III: Deposition of sediment.- Canadian Jour. Earth Sci., 4, 475-505.

MIDDLETON, G.V. (1970): Experimental studies related to problems of flysch sedimentation.- In: LAJOIE, J. (ed.): Flysch sedimentology in North America. Geol. Assoc. of Canada, Spec. Paper, 7, 253-272, Toronto.

MILJUŠ, P. & VUGRINEC, J. (1977): Neke osnovne crte geološke građe sjevernog dijela Hrvatske i karakteristike nakupljanja ugljikovodika.- Nafta, 22/7-8, 425-439, Zagreb.

MUTTI, E. & GHIBAUDO, G. (1972): Un esempio di torbiditi di conoide sottomarina esterna: le Arenarie di San Salvatore (Formazione di Bobbio, Miocene) nell' Accademia de Piacenza.- Memorie dell' Accademia delle Scienze di Torino, Classe di Scienze Fisiche, Matematiche e Naturali, 4/16, 40 p.

MUTTI, E. & RICCI LUCCHI, F. (1975): Turbidite facies and facies associations.- In: Examples of turbidite facies and associations from selected formations of the northern Apennines. IX Int. Congress of Sedimentology, Field Trip A-11, 21-36, Nice.

PIRSON, S.J. (1970): Geologic well log analysis.- Gulf Publ. Co., Houston., 370 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).- Unpubl. PhD Thesis, University of Zagreb, 71 p.

POSTMA, G. (1986): Classification for sediment-gravity flow deposits based on flow turbidites: a mechanism for their emplacement.- Sediment. Geol., 58, 47-61.

REINECK, H.E. & SINGH, I.B. (1973): Depositional sedimentary environments.- Springer Verlag, New York, Heidelberg, Berlin, 439 p.

SANDERS, J.E. (1965): Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms.- In: MIDDLETON, G.V. (ed.): Primary sedimentary structures and their hydrodynamic interpretation. Soc. Econ. Paleontol. Mineral., Spec. Publ., 12, 192-219.

SELLEY, R.C. (1976): Subsurface environmental analysis of North Sea sediments.- Am. Assoc. Petrol. Geol. Bull., 60/2, 184-195.

SELLY,R.C. (1985): Ancient sedimentary environments and their sub-surface diagnosis.- III edition, Cornell University Press, Ithaca, New York, 317 p.

SÜTÖ-SZENTAI, M. (1982): Organic microplantonic and sporomorphous remains from the Pannonian from the borehole Tengelic-2.- Ann. Inst. Geol. Publ. Hung., 65, 205-233, Budapest.

SYED, A.A. (1979): Recognition of sandstone depositional environments from well logs.- Gulf Co. Int. Publ., 57 p.

SZENTGYÖRGYI, K. & JUHASZ, Gy.K. (1988): Sedimentological characteristics of the Neogene sequences in SW Transdanubia, Hungary.- Acta Geologica Hungarica, 31/3-4, 209-225.

ŠĆAVNIČAR, B. (1979): Pješčenjaci pliocena i miocena Savske potoline.- III god. znan. skup ZSN Jugosl. akad. znan. umjetn. (Novi Sad, 1977), Zbornik radova, II, 351-382, Zagreb.

ŠIMON, J. (1980): Prilog stratigrafiji i taložnom sustavu pješčanih 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 (in Croatian), University of Zagreb, 66 p.

VRBANAC, B. (1989): Okoli pješčenjaci južnog dijela naftoplinonosne strukture Žutica (Okoli sandstones of southern part of oil and gas structure Žutica).- Unpublished MSc Thesis (in Croatian), University of Zagreb, 105p.

VRBANAC, B. (1990): Neki rezultati istraživanja naslaga litostratigrafske jedinice pješčenjaci Okoli naftoplinonosne strukture Žutica.- Nafta, 41/11, 475-492, Zagreb.

VRBANAC, B. (1996): Paleostrukturna i sedimentološka analiza gornjopanonskih naslaga formacije Ivanić Grad u Savskoj depresiji (Paleostructural and sedimentological analysis of Upper Pannonian deposits of Ivanić Grad Formation in Sava depression).- Unpublished PhD Thesis (in Croatian), University of Zagreb, 125 p.

WALKER, R.G. (1978): Deep-water sandstone facies and ancient submarine fans: model for exploration for stratigraphic traps.- Am. Assoc. Petrol. Geol. Bull., 62/6, 932-966.