# Sedimentation of deep-water turbidites in the SW part of the Pannonian Basin

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**Abstract:** The Sava Depression and the Bjelovar Subdepression belong to the SW margin of the Pannonian Basin System, which was part of the Central Paratethys during the Pannonian period. Upper Pannonian deposits of the Ivanic-Grad Formation in the Sava Depression include several lithostratigraphic members such as Iva and Okoli Sandstone Member or their lateral equivalents, the Zagreb Member and Lipovac Marlstone Member. Their total thickness in the deepest part of the Sava Depression reaches up to 800 meters, while it is 100–200 meters in the margins of the depression. Deposits in the depression are composed of 4 facies. In the period of turbiditic activities these facies are primarily sedimented as different sandstone bodies. In the Bjelovar Subdepression, two lithostratigraphic members (lateral equivalent) were analysed, the Zagreb Member and Okoli Sandstone Member. The thickness of the Bjelovar Subdepression ranges from 50 meters along the S and SE margins to more than 350 meters along the E margin. Generally, detritus in the north-west part of the analysed area originated from a single source, the Eastern Alps, as demonstrated by sedimentological and physical properties, the geometry of the sandstone body and the fossil content. This clastic material was found to be dispersed throughout the elongated and relatively narrow Sava Depression and in the smaller Bjelovar Subdepression. Sedimentation primarily occurred in up to 200 meters water depth and was strongly influenced by the sub-aqueous paleorelief, which determined the direction of the flow of turbidity currents and sandstone body geometries. The main stream with medium- and fine-grained material was separated by two independent turbiditic flows from N-NW to the SE-E. Variability in the thickness of sandstone bodies is the result of differences in subsidence and cycles of progradation and retrogradation of turbidite fans.

**Key words:** Upper Pannonian, Croatia, Sava Depression, Bjelovar Subdepression, deep-water environment, turbidites.

## Introduction

The western part of the Sava Depression and the Bjelovar Subdepression evaluated in the present study are both located at the southwestern margin of the Pannonian Basin (Figs. 1 and 2). The primary difference in these depressions is their scale. The Sava Depression is an independent regional geotectonic unit, while the smaller Bjelovar Subdepression represents only the southern part of the Drava Depression (Fig. 1). Both basins were formed contemporaneously by Neogene extension (Velić 1980, 1983; Prelogović et al. 1995, 1998; Vrbanac 1996; Malvić 2003; Saftić et al. 2003; Kovačić & Grizelj 2006; Grizelj et al. 2007), but subsidence in the Bjelovar Subdepression occurred later than in the Sava Depression. The source area of detrital material for both depressions was the Eastern Alps; however, paleotectonic movements created two different depressions with different total amounts of subsidence and thicknesses of deposits. Additionally, paleorelief, which was created by tectonic movements, directed turbidity currents in the Drava and the Sava Depressions. Paleorelief exerted similar effects in the Bjelovar Subdepression.

Besides the geological analysis of the well logs available from wells drilled in the deep basinal areas, Upper Pannonian sediments are also found in numerous outcrops on the basin margins and were analysed for the present study. These outcrops are located along the Zrinska gora Mountain, as well as along the Papuk and Psunj Mountains to the east, Medvednica Mountain to the west, Kalnik Mountain to the northwest, and Moslavačka gora Mountain. The latter is located between the Sava Depression and the Bjelovar Subdepression.

The lithostratigraphic units' subdivision for the Sava Depression and the Bjelovar Subdepression are different (Fig. 3).

The entire Upper Pannonian sequence is lithologically represented by alterations of marls, siltstones and sandstones (Fig. 3). The total thickness of these sediments in the deepest part of the study area reaches up to 800 meters, while it ranges from 100 to 200 meters along the margins of the depression (Fig. 4).

Pure sandstones are deposited only in the central parts of the (sub)depressions. Sandstone members are completely substituted by marls in marginal areas as a result of the usual basin plain sedimentation. There are two main sandstone members in these depressions:

- **Okoli Sandstones,** which can be found in both regions;
- **Iva Sandstones,** which are found only in the Sava Depression.

Evaluation of the sedimentological characteristics of the cored deposits (lithology, bedding, structures and sandstone/

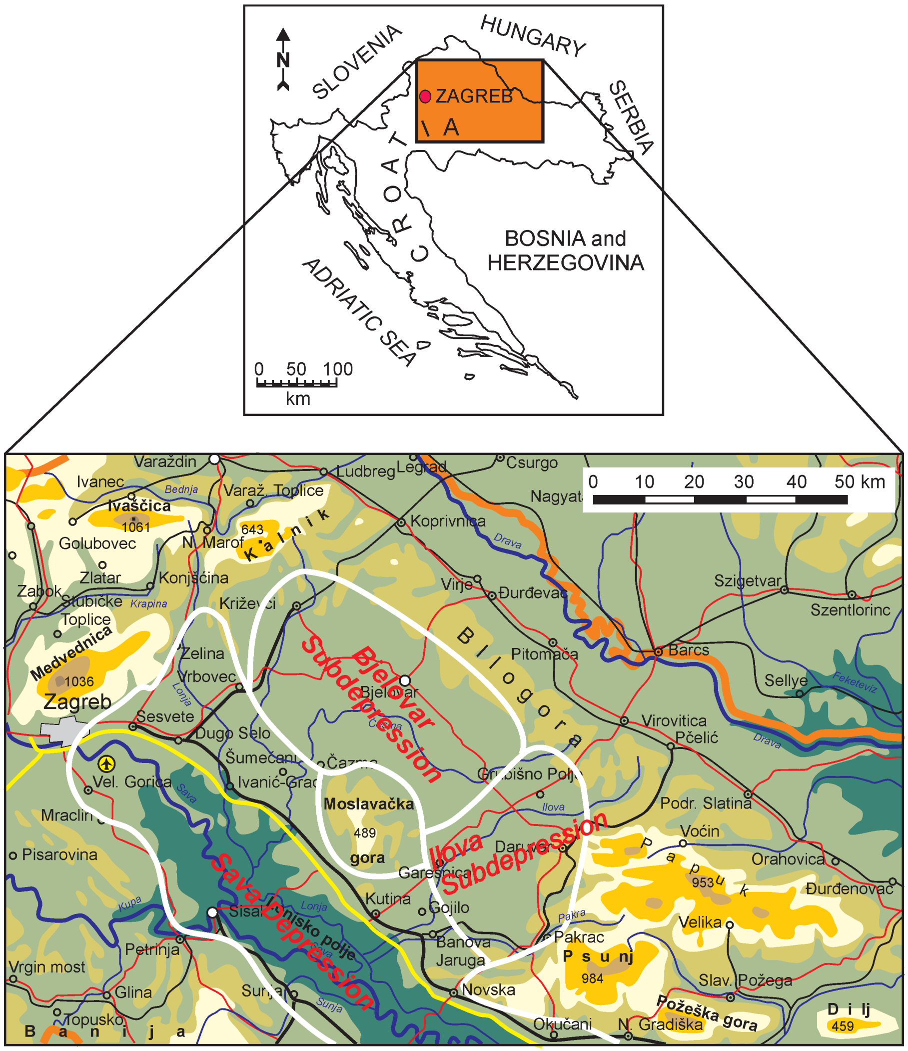




**Fig. 1.** Geographical positions (location map) of the Sava Depression and the Bjelovar Subdepression.

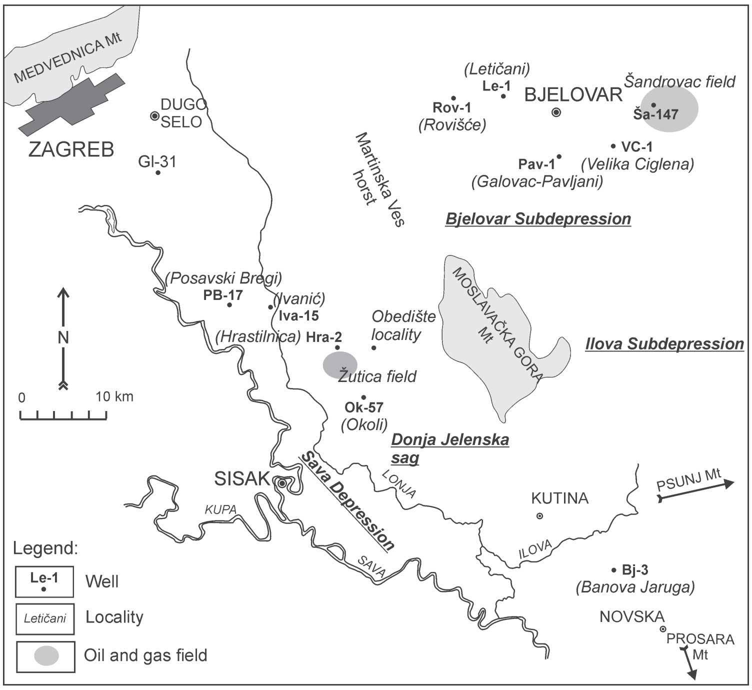



**Fig. 2.** Location map of wells and oil fields, as well as other used localities.

marl ratio) enables identification of four different facies: facies of thick-layered to massive sandstones ($F_1$), facies of thin sandstone layers ($F_2$), facies of laminated sandstones, siltstones and marls ($F_3$), and facies of massive marls ($F_4$).

Separated facies are recognized on the diagrams of well logs based on the curve describing spontaneous potential and resistivity. Comparison of the various spontaneous potential curves and the characteristics of well logs revealed four different facies associations: turbidite channel fill facies association ($F_A$), turbidite overbank-levee facies association ($F_B$), lateral or distal turbidite facies association ($F_C$), and massive marls facies association ($F_D$).

The aim of this study was to reveal the main sedimentological characteristics of the facies associations and to settle their areal distribution in the study area. All conclusions regarding the spa-

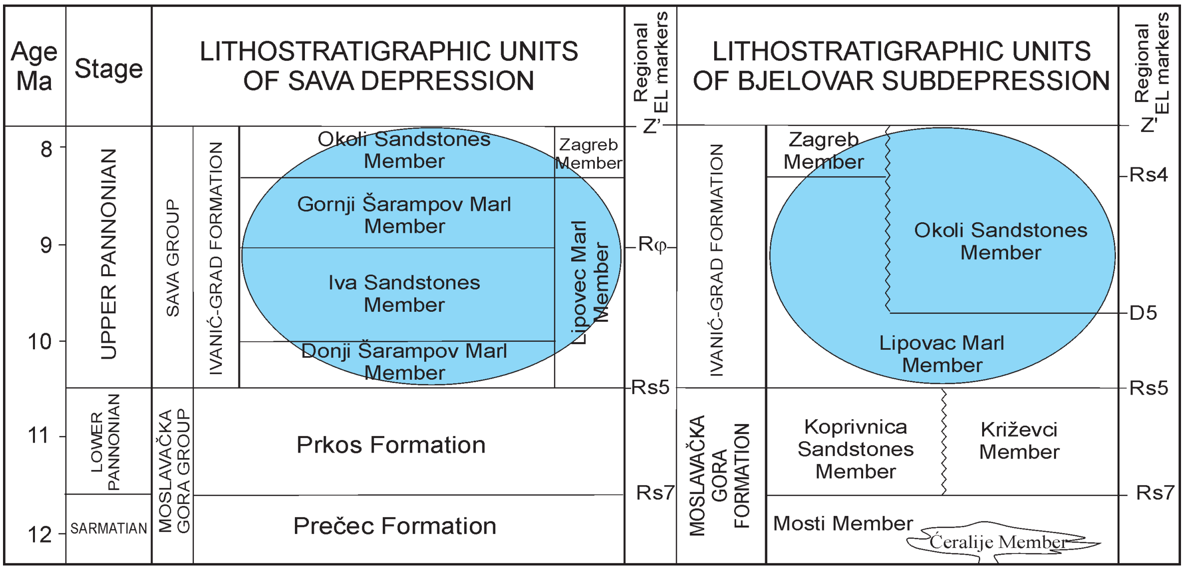



**Fig. 3.** Correlation table of the chronostratigraphic and lithostratigraphic units and positions of EL-markers.

*Note to Fig. 3*: Both the above mentioned units — the Moslavacka gora Group and Moslavacka gora Formation are accepted in formal Croatian lithostratigraphic nomenclature. One (group) is a formal unit in the Sava Depression and another (formation) in the Drava Depression. The name comes from the "Moslavacka gora" Mountain that divided the Sava and Drava Depressions and was the field trip area with outcrops in both depressions. **Sava Depression:** The Moslavacka gora Group is the unit of the highest rank and comprises two formations — Precec Formation (of Sarmatian and older ages) and Prkos Formation (of Early Pannonian age). **Drava Depression:** The Moslavacka gora Formation is the oldest formal lithostratigraphic unit with the rank of formation and it is divided in two lithostratigraphic members — Mosti Member (of Sarmatian and older ages) and Koprivnica Sandstone Member (or Krizevci Member) (of Early Pannonian age).

tial distribution of the separated facies associations in this study are based on data obtained from approximately 2000 wells in the study area.

Generally, the explored sediments are very rarely characterized by fossils. Consequently, the content of macrofossils in well cores can be only found in wells drilled in marginal depression parts. This fossil assemblage indicates fresh to brackish water, relatively shallow environment. Cores collected from deeper depression parts are sometimes characterized only by fragments of *Ostracodes*. More detailed conclusions are obtained mostly based on palinological analyses, which are described and interpreted in subchapter 'Depositional environments — basin plain and/or near-shore mechanisms'.

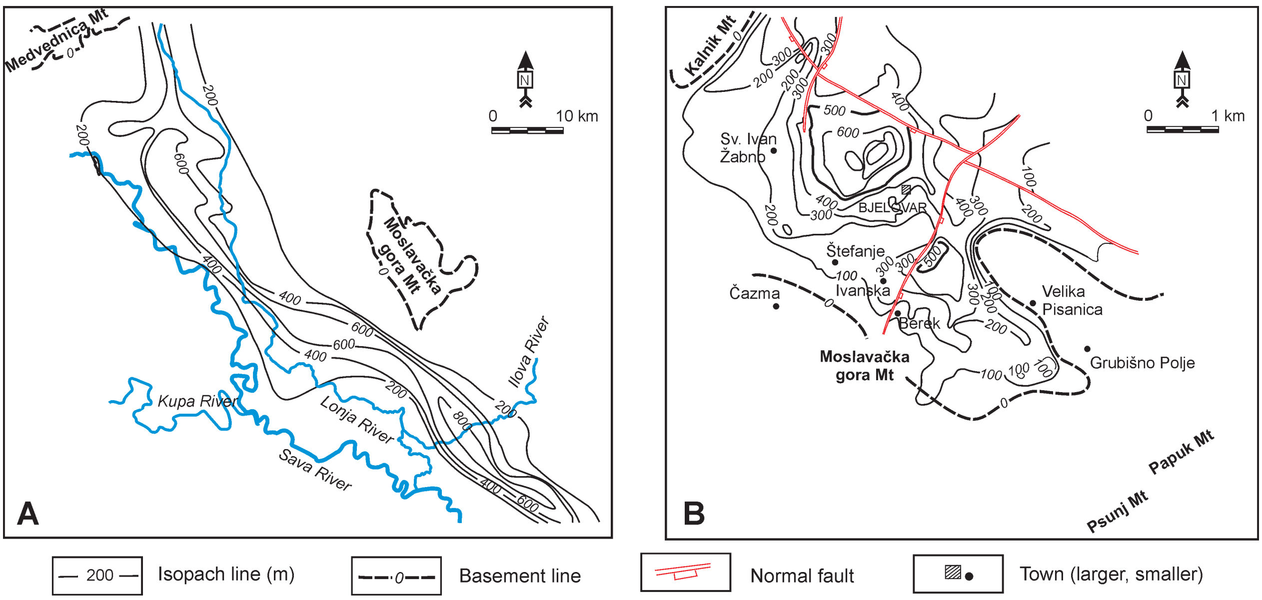



**Fig. 4.** Isopach maps of the Rs5-Z' interval (Ivanić-Grad Formation of the Late Pannonian period) in the Sava Depression (A) and Bjelovar Subdepression (B).

## Thickness and description of facies

As previously mentioned, depositions from the Late Pannonian period are lithologically represented by alterations of marls, siltstones and sandstones.

The Upper Pannonian members include the Iva (older) and Okoli Sandstones (younger) Member. In the western part of the Bjelovar Subdepression, the Okoli Sandstones grade into the Zagreb Member and partially in the Lipovac Marls Member (the lateral equivalent of the Zagreb Member; Fig. 3). However, sedimentation of the Upper Pannonian deposits did not occur in the south-eastern part of the subdepression.

**Sandstones** in the study area are fine-grained, rarely medium-grained (diameter up to 0.5 mm), have a porosity ranging from 10 to 33 % and it decreases from NW to SE (in the direction of paleotransport). The petrographic composition of the sandstones in the study area is very homogeneous. Specifically, the composition is primarily quartz (>60 %) and rock fragments including carbonates, cherts, schists, gneisses and granites (18–35 %). The source area was determined to be the Alps based on the presence of accessory minerals indicating metamorphic rocks (from epi- and mesozones), limestones and cherts (Šćavničar 1979).

**Siltstones** in the study area have a mineral composition identical to those of sandstones, but the mica content is increased.

**Marls** in the study area are characterized by a matrix consisting of clay and cryptocrystalline carbonate. The $CaCO_3$ content of the marls is approximately 60 %.

Four clearly distinguishable facies were observed in the studied Upper Pannonian sediments, based on outcrop and core studies (Vrbanac 1996, 2002a, 2002b). The different facies range from pure, medium-grained sandstones (**$F_1$**), through laminated sandstones, siltstones and marls (**$F_{2-3}$**) to pure marls (**$F_4$**). The description of these main facies is presented below.

### *Facies of thick-layered to massive sandstones*

**Facies of thick-layered to massive sandstones ($F_1$)** — This facies includes thick-layered to massive, homogeneous sandstones, rarely with thin beds or *laminae* of siltstones and marls (Fig. 5). The thickness of the sandstone intervals varies from 0.5

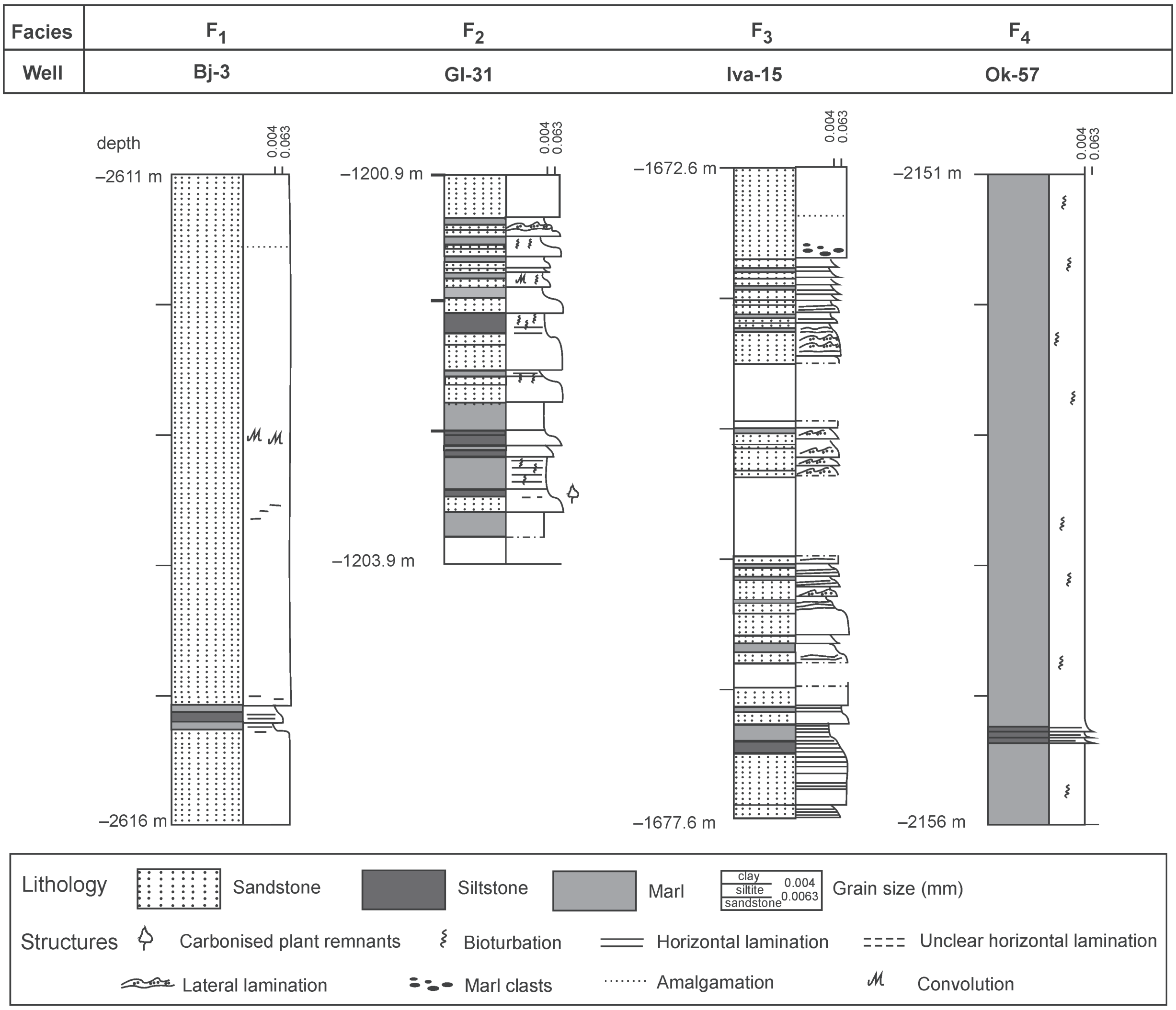



**Fig. 5.** Facies $F_1$, $F_2$, $F_3$ and $F_4$, based on core samples.

to 6 m, with thicker beds most likely formed by amalgamation. Gradation and cross-bedding are hardly visible. Convolution is more often recognizable. Lower bedding surfaces are characterized by erosional marks. Sedimentation is the result of directed, fast and massive deposition from suspension.

The internal structure and texture of the particular bed is the result of the final stage of detritus transport and its depositional epoch. These strata characteristics are especially important for interpretation of depositional environments and conditions. Thick sandstone strata are mostly massive, and only some strata show upwardly decreasing grain size and transition to thin, horizontal laminated or cross-laminated sandstones or siltstones covered by marl. These sequences, which resulted from flows of decreased energy, can be compared by Bouma sequence type A–D. The large amount of sandstones (thick strata) indicates high energy and a capacity for deep-water flow, which was also turbulent (based on the marl clasts and erosional base). All of these characteristics describe gravitationally dense currents (turbidites) including detritus from different populations (Lowe 1982) supported by an upward component of turbulent flow (Middleton 1967; Lowe 1979, 1982). The flows also left marks in flow the base, due to the large shearing that likely occurred in response to dispersive pressure (Middleton 1967; Lowe 1976, 1982).

Thick beds without groove mark structures that were completely massive and deposited in sequence by previously interpreted strata were likely created in a fashion similar to that of interval Ta. Their massive character is probably the result of erosion of the upper parts of a complete deposited turbidites interval. This is confirmed by the characteristics of the lower erosional planes and frequent amalgamation of thick sandstone units (up to 6 m).

The horizontal lamination observed in some parts of the thick amalgamated units also supports the suggestion that the characteristics of the thick beds are the result of erosion. Some of these strata were also created by liquefaction deformation.

Additionally, these facies include thick strata without groove mark structures that are completely massive and overlain by marls (without transitional siltstones). These strata were likely created by the same processes as the previously described massive beds. The sharp transition from sandstones to marls can be explained by a rapid decrease in flow velocity, which led to instantaneous deposition of the remaining coarser detritus. There was not time for grain separation based on their size; therefore, the silt detritus was incorporated into the sand particles.

Inversed gradation can rarely be observed. Such features indicate increasing coarser grains close to the base. It is result of the grain collision as the dominant factor that supported transport (Bagnold 1954). This mechanism leads to the formation of a basal bed of grains supported by strong dispersive pressure and sedimentation of grains on the base, which can be named as a "carpet bed" (Dzulynski & Sanders 1962). According to the decreasing flow energy, such carpet strata will be collapsed and "frozen", and inverse graduate sands of proximal turbidites will be created (Hiscott & Middleton 1979). The thickness of the carpet strata is proportional to the diameter of the grain (Bagnold 1954; Lowe 1976). Similar deposits can be interpreted as "sandy debris flows" as they were described in Shanmugan (2000, 2002).

### *Facies of thin sandstone layers*

**Facies of thin sandstone layers ($F_2$)** are represented by sandstone layers up to 0.5 m thick (Fig. 5). Horizontal and

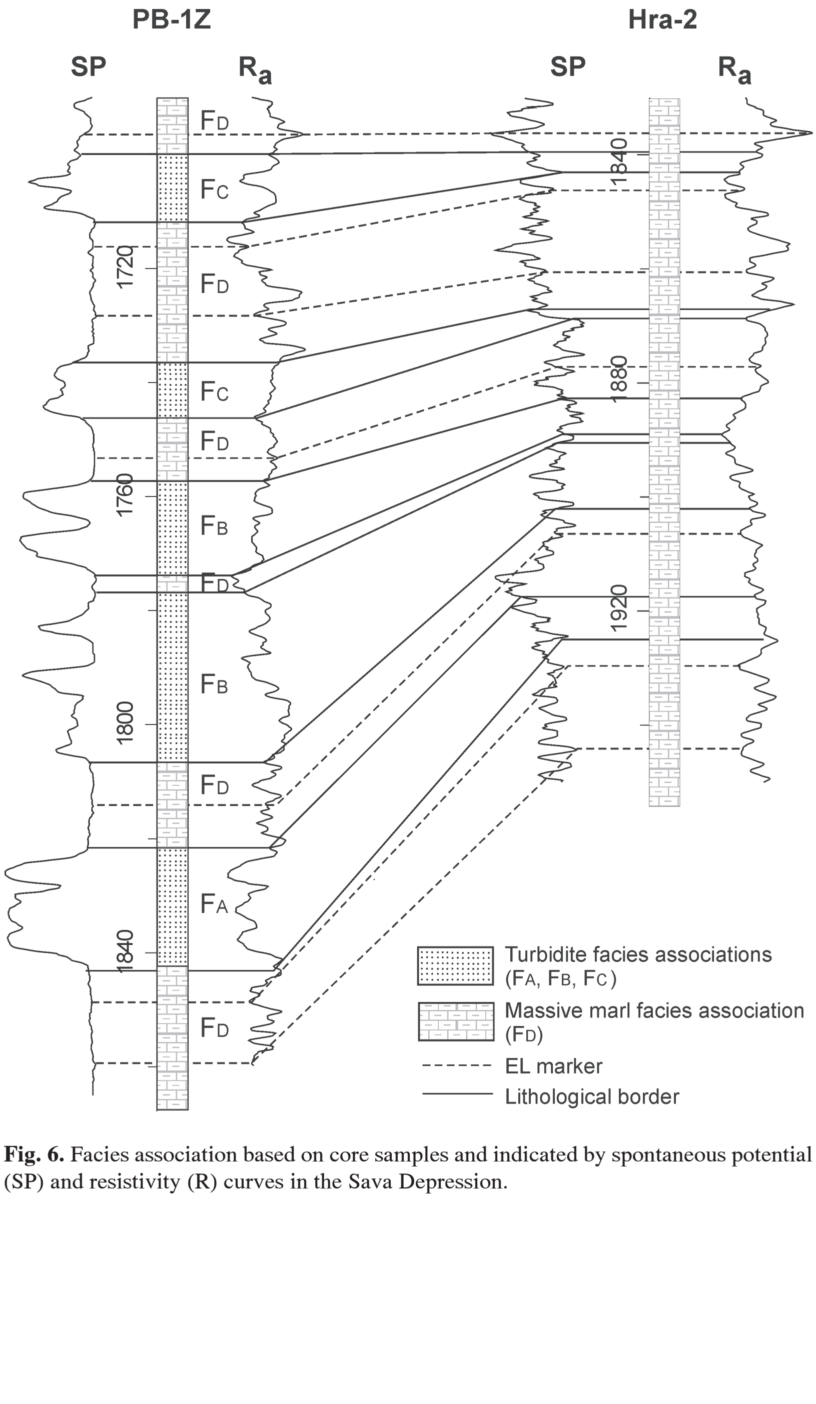



**Fig. 6.** Facies association based on core samples and indicated by spontaneous potential (SP) and resistivity (R) curves in the Sava Depression.

cross-bedded lamination can be easily observed in sandstones and siltstones. Erosional marks are frequently observed on the upper bedding planes.

Convolution and marl clasts are frequently found. These deposits were also deposited from turbidites, but in areas distal from the main currents.

This facies is composed of alternating sandstones and marls. Lower bed planes of sandstones are sharp, but upward there is a gradual transition to the top marl. These characteristics confirm the activity of dense currents, which gradually weakened in strength. The current that supported this facies was weaker than the flow that was responsible for the deposition of the previous facies, $F_1$. Internal structures and uninterrupted sequences can be compared by Bouma sequences and interpreted as turbidites. The index of proximity is lower in facies $F_2$ than in facies $F_1$ due to the significantly lesser portion of detritus from the Ta interval (Bouma 1962, 1972).

### *Facies of laminated sandstones, siltstones and marls*

**Facies of laminated sandstones, siltstones and marls ($F_3$)** is composed of a monotonous alternation of thin sandstone layers, which are gradually substituted by siltstones and marls in the upper portion of the facies (Fig. 5). Textures encompass horizontal and cross-lamination, convolution and sandstone veins and dykes. These rocks were deposited from low-density turbidites; however, some of these strata are likely the result of redeposition caused by normal submarine currents along the sea bottom.

Thin alternating beds of laminated fine-grained sandstones and siltstones are often represented as intervals of Tc–Te of the Bouma sequence. This suggests that at least part of these beds were deposited from low-concentrated turbidity currents, which indicates that deposits of this facies can be compared to thin-stratified sediments from low energy deposits of channel banks (Mutti & Ricci-Lucchi 1975; Walker 1978) including intervals Tc, Td, Te or distal turbidites. This interpretation can also be supported by the presence of sandy veins and dykes as result of instability on levee surface. However, there are several other possible depositional models. For example, some thin sandstone and siltstone strata may have formed in response to re-deposition of turbidites on the basin bottom as a result of normal bottom currents. Such processes are known to occur in deep marine environments where sandy contourites are formed as a result of a combination of sedimentation and re-sedimentation of bottom sediments in response to deep currents (Stow & Lovell 1979; Stow 1982). Similar processes of sediment reworking could have occurred in sandy contourites.

### *Facies of massive marls*

**The facies of massive marls ($F_4$)** includes homogeneous, massive, mostly unstratified marls with clearly visible bioturbations. Occasionally, stratification can be recognized based on relics of lamination, colour changes and thin siltstone films. Marls were formed by continuous sedimentation of pelitic detritus (Fig. 5).

These marls differ from marls that represent a gradual transition from the sandstone layers and resulted from the deposition of pelitic detritus from the tail of the dense currents. Such massive marls are the result of sedimentation of the finest detritus that is part of the continuous activity of turbiditic current in the paleo-basin. Massive marl sedimentation can be connected to transport and deposition from inner and shallow currents (Orton & Reading 1993) that also carry suspended detritus. These continuously active currents in the Upper Pannonian are composed of permanent material transported by rivers to the subbasins of the Pannonian Basin. The transport energy of these permanent currents can be expressed by the flow velocity and maximal size of the transported detritus. The area of the river mouth and deposition of material brought by paleo-rivers was located outside the analysed area. The uniform petrographic composition of detritus indicates that there is a single source area for all the turbidite currents, but that the depositional mechanism of particular facies was different. The thicknesses of the massive marls are higher in proximal areas of the depression and lower in the distal (far away from the source) or morphologically uplifted areas. This indicates that bottom (inner) currents were the primary mechanism by which the detritus was carried, while surface currents were the secondary mode of transport. Of course, the flow directions and depositional areas were determined by the paleo-morphology, water depth and temperature gradient.

## Facies associations

In the course of the analysis of the study area four facies associations were recognized (based mainly on well-logs and/or core samples) ($F_A$, $F_B$, $F_C$, $F_D$), which are shown in Fig. 6 (definition of the association in the Sava Depression) and Fig. 7 (definition of the association in the Bjelovar Subdepression).

### *Turbidite channel fill facies association*

**Turbidite channel fill facies association ($F_A$)** — This facies association (Figs. 6 and 7) consists of thick-bedded sandstone facies ($F_1$) and thin-bedded sandstone facies ($F_2$). The channel axis is characterized by thick sandstone beds with rare marl layers. The number of marl layers is greater in the channel margins, while the basin plain sandstones are thinner and contain more fine-grained sediments. Channel sedimentation is described by a spontaneous potential log (SP log), which has a bell shaped curve for channels with continuous decrease of energy (meandering channels) or box shape for rapidly filling sandy, perhaps braided, channels (Pirson 1970). This is because the facies in the lower part of the study area is composed of thick-bedded sandstones ($F_1$), while it is composed of thin-bedded sandstones ($F_2$) in the upper parts (when the channel began to be inactive). If the channel is abandoned rapidly, which means that there is no observed upward fining and thinning, the SP log is characterized by a cylindrical shape (Pirson 1970). The thickness of particular depositional sequences is 10–20 m, and several sequences are often amalgamated in a single sandstone body in which sequences are also divided by marls.

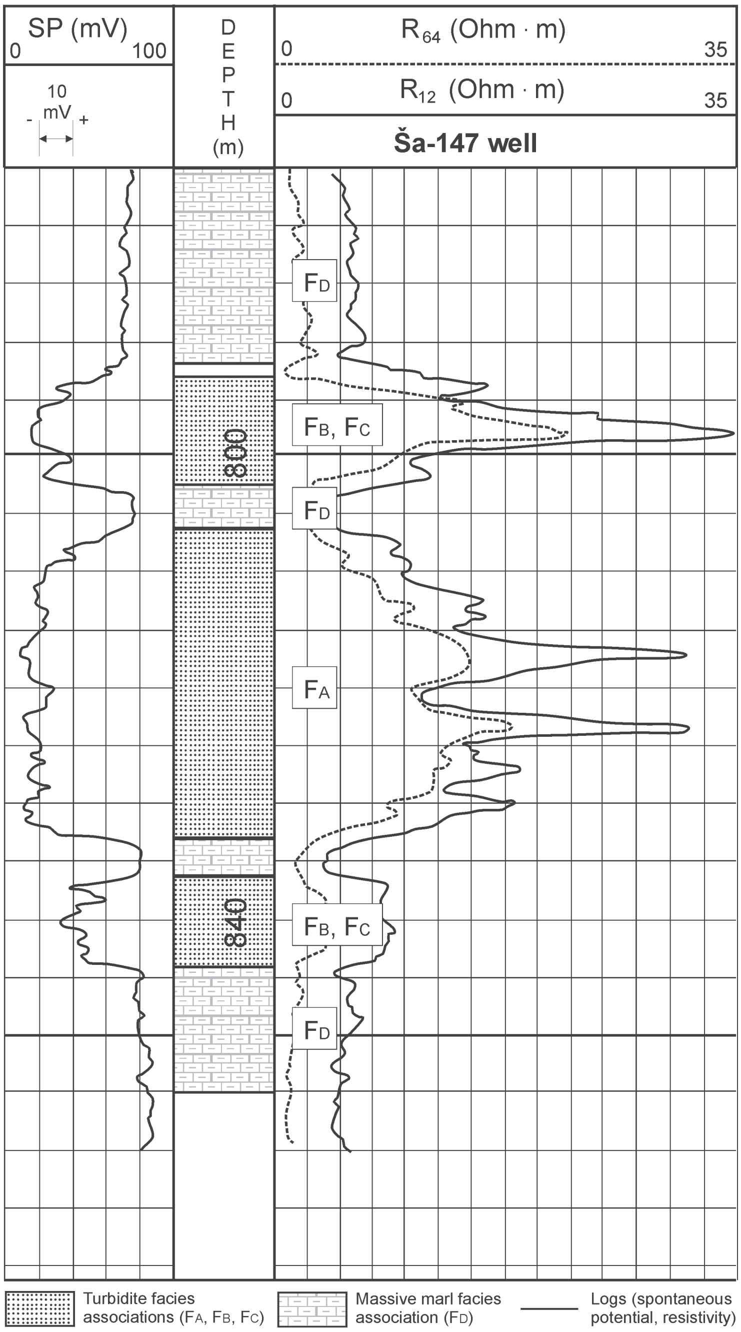



**Fig. 7.** Facies associations found within core samples and indicated by spontaneous potential and resistivity curves in the Bjelovar Subdepression.

Erosion was strongest in the central parts of the channels and weaker in the margins, which indicates that the positions of the channel can be determined based on the marl layers. Specifically, the positions can be deduced based on the direction of the main current during different periods. The energy of currents was strongest inside the channel, which resulted in strong bottom erosion. Therefore, the missing marl that could be deposited by the previous current due to erosion and amalgamations later was probably eroded, which is the result of location along the channel axis where the current was the strongest. Such features describe channels as depositional (Hamilton 1967) and erosional (Laughton 1968) environments in which the main current mass was transported. In the lower parts of the current the particle concentration was highest, while the majority of suspended detritus was deposited in distal areas due to the decreasing current. This resulted in the maximum sandstone thicknesses being developed in channels that were formed according to basin morphology and sedimentary tectonics.

### *Turbidite overbank-levee facies association*

**Turbidite overbank-levee facies association ($F_B$)** — This facies association is composed of $F_3$ facies in the lower part and $F_2$ facies in the upper part (Figs. 6 and 7). Sediments of this facies association were deposited outside the distributary channels, where the turbidity currents were significantly weaker, which created overbank-levee, fringe and channel bank deposits. These characteristics resulted in the erosional effects being smaller than in the channel facies. As a result, amalgamations are very rare and the thickness of eroded marls is probably not higher than several to several dozen centimeters. In addition, the total thickness of the sandstone body in this association can be more than 30 m and shows upward thickening.

This association is characteristic of the marginal parts of channels and the channel's banks. The characteristics of this association indicate that the distribution was not restricted to the channels, but also occurred in the wider channel area, which resulted in thick sandstones occasionally being deposited in bank (levee) areas.

### *Lateral or distal turbidite facies association*

**$F_C$ or lateral or distal turbidite facies association** — This facies association consists of a monotonous alternation of very thin, thin and medium-thick sandstone beds passing into siltstones and marls (Figs. 6 and 7). The association is represented by facies $F_3$ and $F_2$. In this association, erosion on the upper bedding plane is almost completely absent. In addition, the sub-layers of marls and sandstones are so thin that they are beyond the resolution of well-log curves. This also indicates that the SP curve gives a larger scale representation of the sedimentary succession. Sediments of this association are recognized in distal areas, such as those in which the maximal range of turbidites occurred. Moreover, such sediments are discovered on morphologically uplifted parts between channels and can probably be found on the banks of flume channels (Walker 1978). These sediments can be found further away from the channels for great distances (i.e. from the area of sub-channel and *fringe* sandstones), consequently, the portion of siltstones and marls in the facies is increased and the portion of marly sandstones and sandstones is decreased.

The total thickness of this association can reach several dozens of meters, and can cover several hundreds of meters laterally. Moreover, these distal turbidites can be compared with classical turbidites that are deposited (Walker 1978) at the end of the distal part of a lower fan in the basin plain, which is the area in which the maximal extensions of the turbidity current exist. Distal turbidites can also be found on the banks of the upper fan (Walker 1978). Generally, such turbidites are the result of the deposition of sandy and fine-grained detritus in the marginal, transitional parts of the basin, between the main current flow and morphologically uplifted areas. These results indicate that deposition was active in areas where turbidity current is still active, but only from a thin portion of the current cloud. This activity occurred due to the low energy in the area, which resulted in only small quantities of sandy detritus being transported.

### *Massive marls facies association*

**$F_D$ or massive marls facies association** — This association is primarily represented by massive marl facies $F_4$ with rare intercalations of thin siltstone or sandstone laminae or beds (Figs. 6 and 7). Sediments in this association are continuously deposited in marginal areas of the contemporary Sava Depression or areas outside the range of turbidites. However, deposition of these marls was also active in the central parts of the depression during calm periods in which there were no turbidite activities.

This association can be compared to hemipelagic sediments of open seas deposited on the continental shelf; however, in the case of the Sava Depression and the Bjelovar Subdepression, such hemipelagic deposits can be found in entire basins.

### *Lateral and vertical facies alteration*

Facies recognition of spontaneous potential (SP) and resistivity (R) curves is especially reliable in the oil and/or gas fields, where there is a relatively high number of wells located in a small area. As a result, the lateral and vertical sedimentary facies associations can be easily followed on the section drawn for the Ivanić-Grad Formation of the Žutica oil and gas field (Figs. 8, 9). There was clearly expressed channel migration through time in this area. In addition, vertical and lateral facies transitions are sometimes gradual and sometimes very sharp in this region. Such transitions were particularly evident in areas of rapid transition of channel sediments into massive marl associations (Figs. 8 and 10). These characteristics reflect the rapid changes in the location of the channel.

The size of single channel depends on the width of the channel bottom and the slope dip of the channel margins. For example, in the Žutica field, sediments of association $F_A$ are extended laterally in a thickness of several dozen meters, but laterally they grade into a narrow zone of association $F_C$ (up to 10 m) and later to association $F_D$ (thickness 2–5 m).

The results of this study revealed the general characteristic of the distribution of facies associations in the study area. Evi-

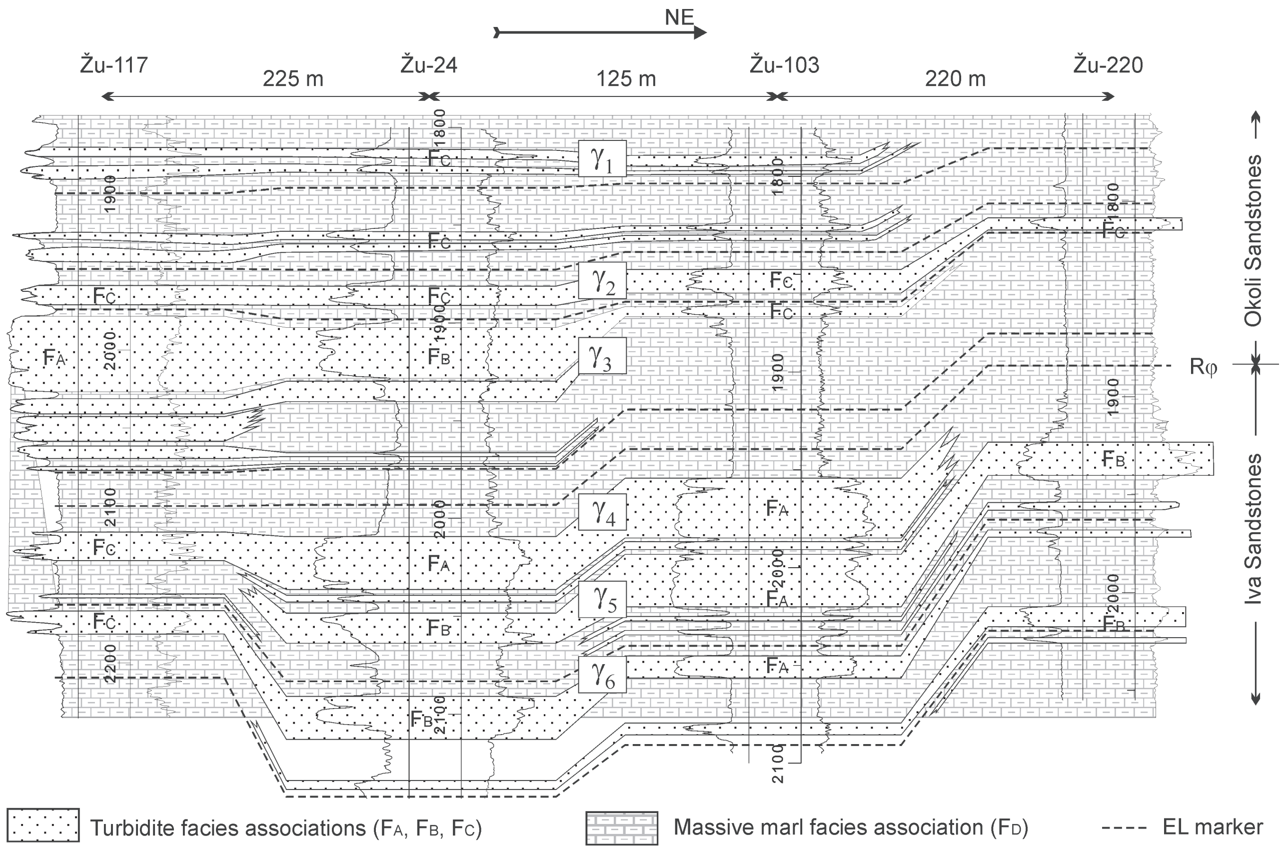



**Fig. 8.** Vertical and lateral facies correlation section over SW part of the Žutica field in the Sava Depression.

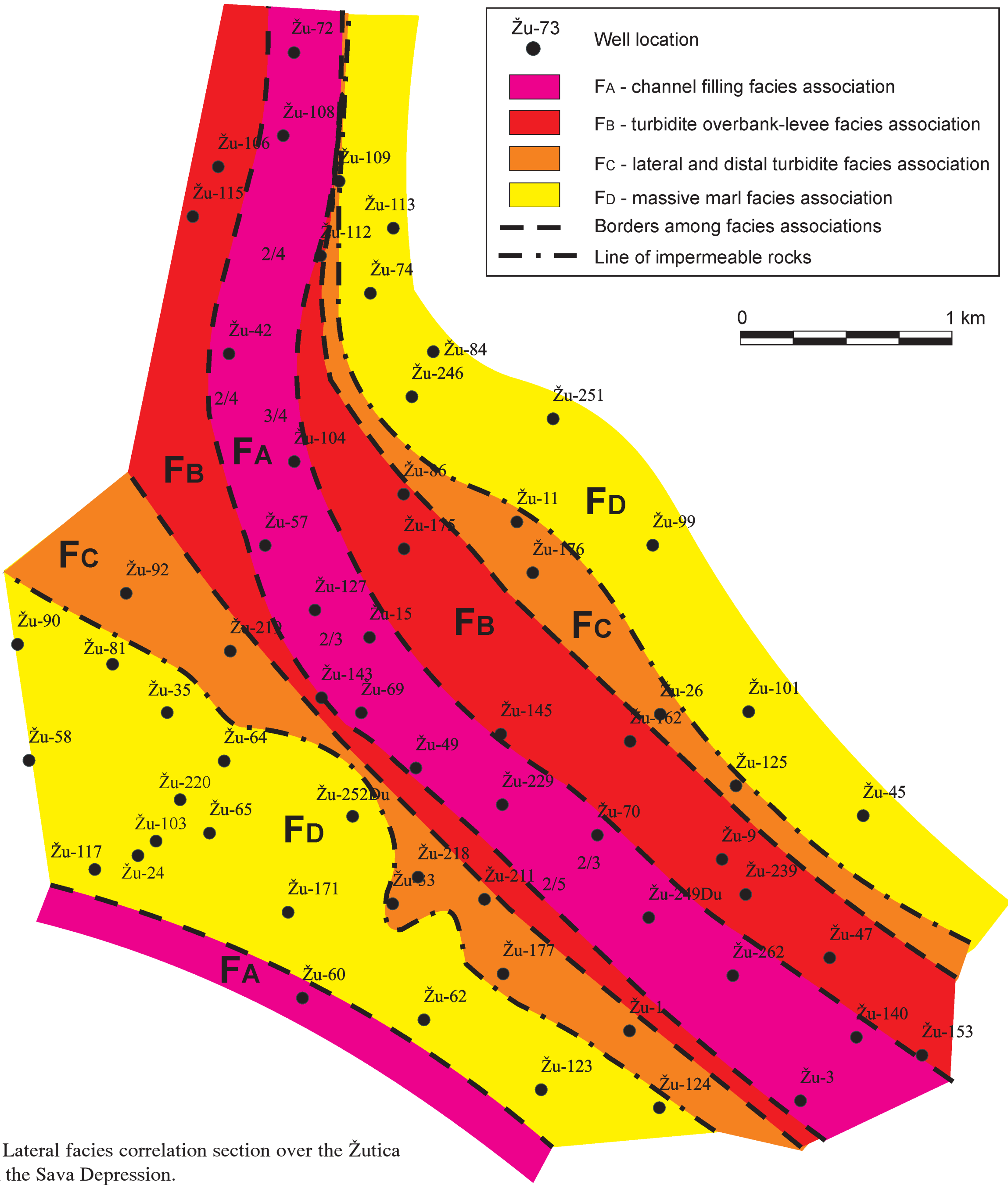



**Fig. 9.** Lateral facies correlation section over the Žutica field in the Sava Depression.

dently, parallel to the channel directions (channel fill facies association) we mostly found the sediments of the turbidite overbank-levee facies association. Laterally it passes into distal turbidite sediments and finally into the massive marl facies association (Figs. 8 and 10).

The distribution of the identified facies associations conforms to the general distribution of facies in an ideal turbiditic fan (Walker 1978). The central depositional area is the channel, which is filled with thick, stratified to massive sandstones. The facies distribution in Fig. 9 suggests that the Žutica field is on the marginal part of a submarine fan and decreasing of sandy facies is a result of deposition on channel-overbank areas. In fringe areas, there are thin and thick stratified sandstones. More distally, in the direction of turbidite flow and in areas far from the channel axis, thin-stratified sandstones and distal and lateral turbidites are present.

Massive marls are deposited in all parts of the depression that were outside the route of the turbidity current, such as geomorphologically uplifted parts of the depression. Such uplifted lake-bottom areas are also occasionally located in the central (sub) areas of the depression. In addition, marl associations can be incorporated into the more abundant channel sandstone association; if they had not been eroded (such mechanism is described earlier).

Inside the Iva Sandstone Member lithostratigraphic unit there are eight sandstone layers saturated with oil and gas that

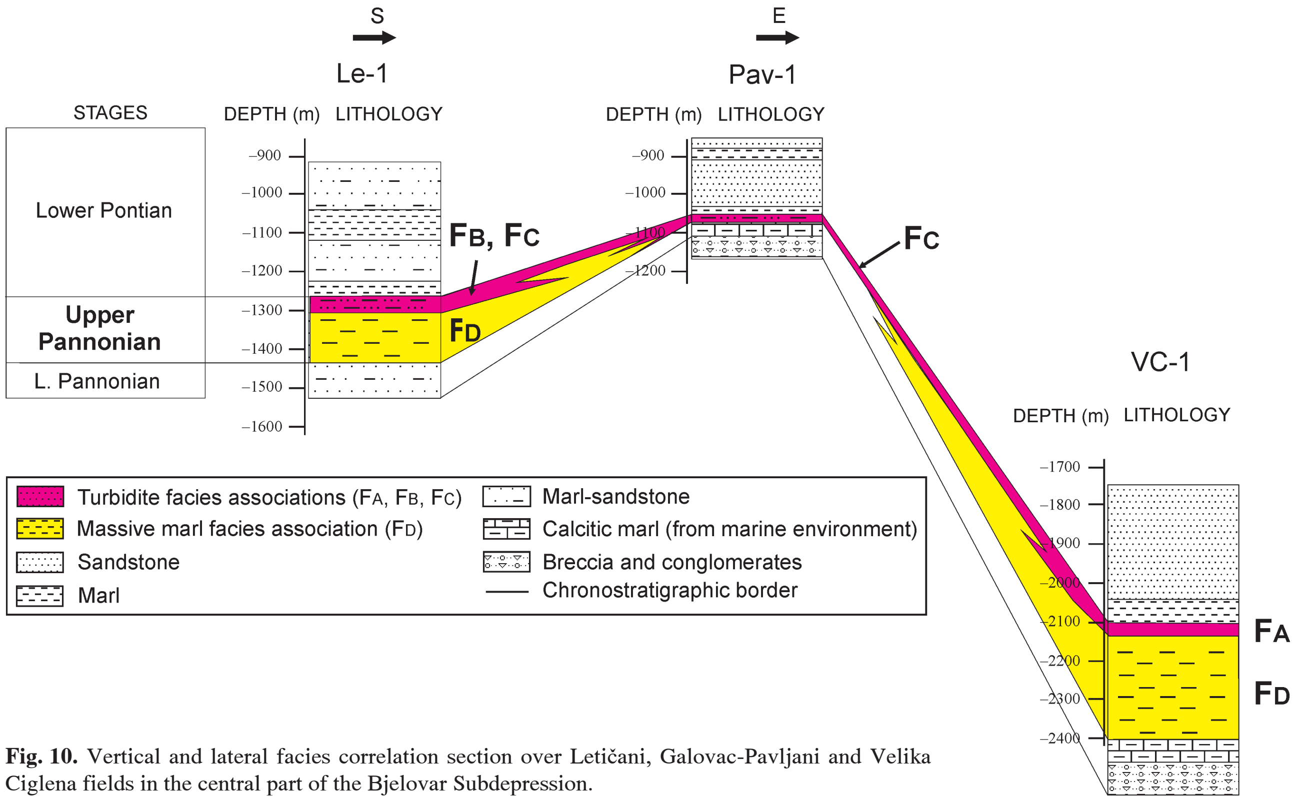
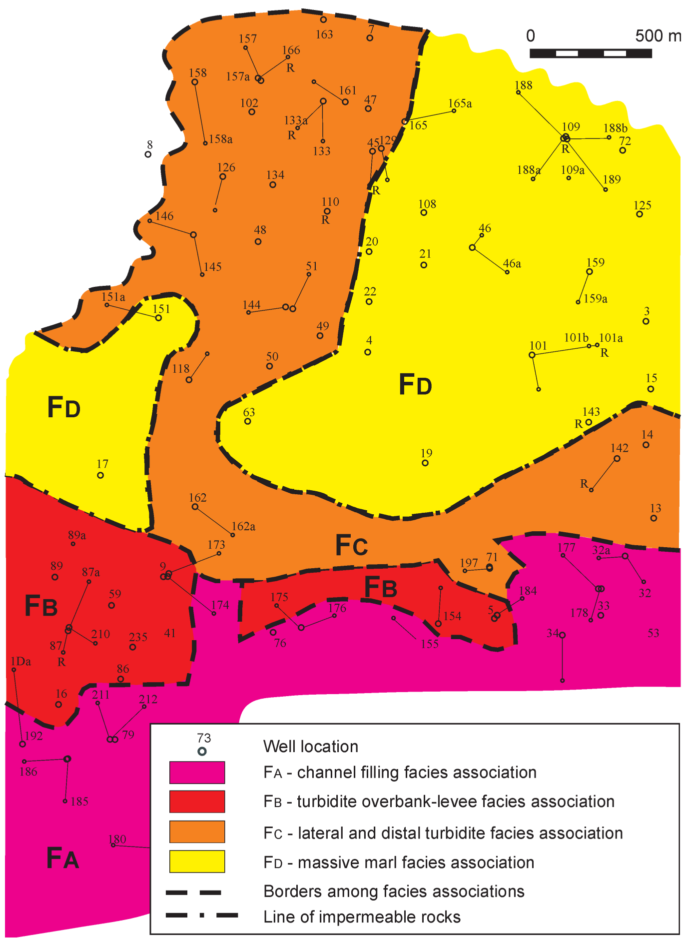



**Fig. 10.** Vertical and lateral facies correlation section over Letičani, Galovac-Pavljani and Velika Ciglena fields in the central part of the Bjelovar Subdepression.




are known as the γ series ($\gamma_1$–$\gamma_8$). Fig. 8 shows the extension of the sandstone body $\gamma_3$ (Žutica field). The facies association transition can be clearly followed in this area. The sandstone body (reservoir), $\gamma_3$, is mapped only in the central part of the field, namely in the channel (Fig. 9). The channel direction in the northern part of the reservoir is N–S, while it eventually transitions to a NW–SE direction. The direction and contact with younger ($\gamma_2$) and older ($\gamma_4$ and $\gamma_5$) sandstones have been mapped in the channel. The contact of these sandstone bodies has occurred in response to (inter-sandstones) marl erosions caused by turbidite activities.

The thickness of $\gamma_3$ sandstones in the channel reaches up to 15 m, and extends up to 12 m laterally. In areas in which several sandstone reservoirs are connected as a result of erosion, the total thickness of such sandstone bodies can reach up to 60 m.

Two presentations of facies lateral extension are shown in Figs. 10 and 11. The slightly different distribution of the facies association has been mapped in the Bjelovar Subdepression (Fig. 11) in sandstone reservoir E of the Late Pannonian age. The direction of the channel in this area is approximately W–E and is characterized by a relatively large channel width. The association of massive marls ($F_D$) is located on the north part of the channel in this area, and the transitional association of

**Fig. 11.** Lateral facies correlation within the Šandrovac field in the Bjelovar Subdepression (modified after Bokor et al. 2000).

$F_B$ and $F_C$ is very irregular in this area. In addition, the transition from $F_A$ to $F_D$ is not complete and regular in some areas of the channel. These characteristics are due to differences in the paleotectonic position of the Bjelovar Subdepression.

## Paleogeography during the Late Pannonian (7.8–10.8 Ma) in the studied subbasins

In the Late Pannonian (7.8–10.8 Ma), the Sava Depression and the Bjelovar Subdepression were parts of the Pannonian Basin System. Investigations of the western part of the Sava Depression revealed a narrow, elongated basin with a width of 25 km and a length of 100 km.

The Bjelovar Subdepression is a branch of the Drava Depression, with an approximately 50×25 km rhomboidal shape. This subdepression is separated from the Sava Depression by the Moslavačka gora Mountain and two uplifted basement highs as two subsurface continuations of the mountain range (Fig. 12).

The Pannonian Basin System in the Late Pannonian was an open lake system, composed of several connected basins with active inflows and outflows (rivers) that have been described in detail by Bérczi et al. (1988). The chemical composition of water was determined by the continuous inflows of fresh water from rivers. The result was the development of a fresh or slightly brackish lake environment.

### *Paleogeographic position of the Sava Depression*

Based on the present-day structural and tectonic relationships and those that are evident in the geological history of the region, it is possible to determine the depositional mechanism of particular lithostratigraphic members. It is also possible to interpret the paleogeography that was present during the studied Late Pannonian period (7.8–10.8 Ma).

The Sava Depression had a very complex paleorelief. There was a tectonic graben in the central part of the depression, located between uplifted parts of sub-aqueous paleorelief. The bottom of the depression was indented and probably dipping slightly towards the SE and E. The present-day sediment thickness indicates that in the centre, the deepest part of the depression was formed by the subsidence of the pre-Neogene basement. The subsidence probably started in the NW, although the strongest tectonic activity later occurred in the NE. The facies distribution, thickness of the particular members and the tectonic activity indicated that the deepest part of the Upper Pannonian (period of Iva Sandstone Member deposition) started in the western part of the Obedište locality. This deep area continued away along the Martinska Ves horst, south from the Žutica field and ended in the Donja Jelenska sag (Vrbanac 1996).

Some shallower, transitional plateau was also located in the NE area of the depression near the Kloštar, Ivanić, Žutica and Okoli fields. Shallowing continued toward the NE in the area of the Križ field and finally, at the Moslavačka gora Mountain the underwater paleorelief controlled the direction of turbidite flows through the (sub)depression. This is the reason why different depositional areas (filling from different currents) had similar lateral characteristics; however, there were two primary channels — northern and southern.

Later, during the time of sedimentation of the Okoli Sandstones Member, deposition in the NW part of the Sava Depression was inclined toward the SW (Hernitz & Jurak 1973). This was likely the result of the uplifting of Moslavačka gora Mountain and stronger subsidence of the Donja Jelenska and Ilova sags in the NE as well as existence of the Martinska Ves horst in the SW. In these uplifted areas, the thickness of massive marls is small. Currently, Upper Pannonian sediments can be found on the surface of the Moslavačka gora Mountain.

In addition, the Sava Depression was closed to the N by Medvednica Mountain, or rather by the paleorelief of the Medvednica and Moslavačka gora Mts (mostly located in shallow water). South of these uplifted areas turbidites transported material and filled the depression (Šimon 1980). North of this buried paleorelief were the source areas from where the clastic material were occasionally transported to the central parts of the Sava Depression.

The E side of the Sava Depression was closed by an underwater paleorelief chain located between the Psunj and Prosara Mountains (Blašković 1982). This is also the pinchout zone of the turbidites, and only a few sandstone bodies are found

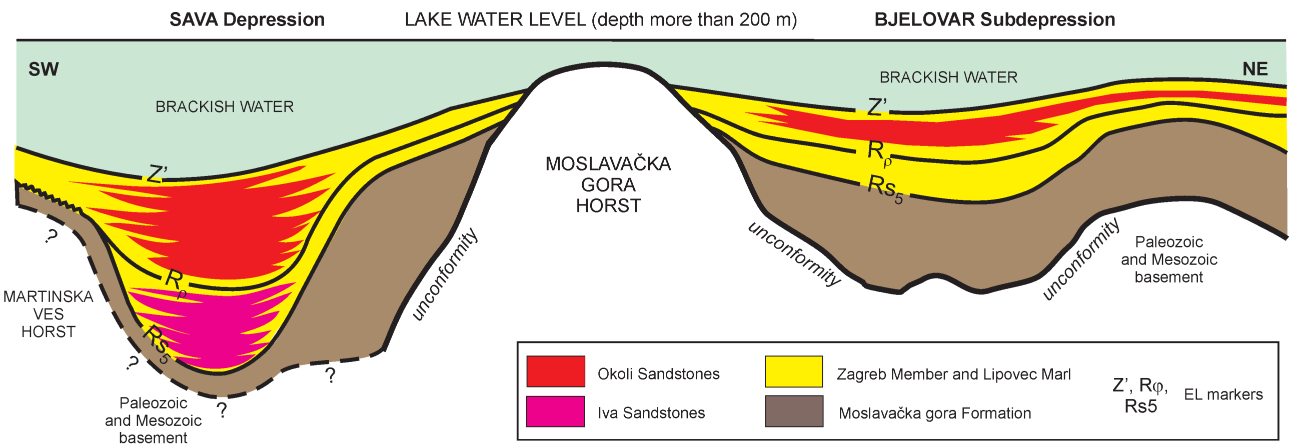



**Fig. 12.** Schematic lateral facies correlation between the Sava Depression and Bjelovar Subdepression.

along the E part of the depression. The paleogeographic situation at the end of the Late Pannonian is shown in Fig. 13.

***Paleogeographic position of the Bjelovar Subdepression***

The Bjelovar Subdepression was a relatively closed basin of moderate paleorelief. At the beginning of the studied period (Late Pannonian, 7.8–10.8 Ma), only hemipelagic marls were deposited (facies of massive marls, $F_A$). Later, this area was opened toward the NE, which resulted in re-direction of a part of the turbidite currents into the Bjelovar Subdepression, and deposition of coarse-grained sediments there (Figs. 12 and 13).

Due to the relatively flat bottom of the sub-depression, was not only active pronounced (Fig. 11); consequently, the depositional area was much larger, and the transition among facies was different and irregular (Figs. 12 and 13).

The deepest parts of the Bjelovar Subdepression are currently known as the Rovišće syncline (northwest of Bjelovar) and the Velika Ciglena syncline, which is the deepest part of the subdepression (southeast of Bjelovar) and contains more than 2500 m of Neogene sediments. These were the routes of the main turbidity current longitudinally along the depression. Conversely, the southern and eastern parts of the subdepression formed the relatively shallow flanks of the trough, without any sedimentary channels. This resulted in current activity occurring only in the northern and north-eastern parts of the subdepression. In other areas, only marls were deposited and sandstones are very rare or completely absent.

The northern margin of the Bjelovar Subdepression, the Bilogora Mountain was uplifted relatively recently, only during the Pliocene and Quaternary. This indicates that a passage between the western part of the Drava Depression and the Bjelovar Subdepression was open until 2–3 Ma ago.

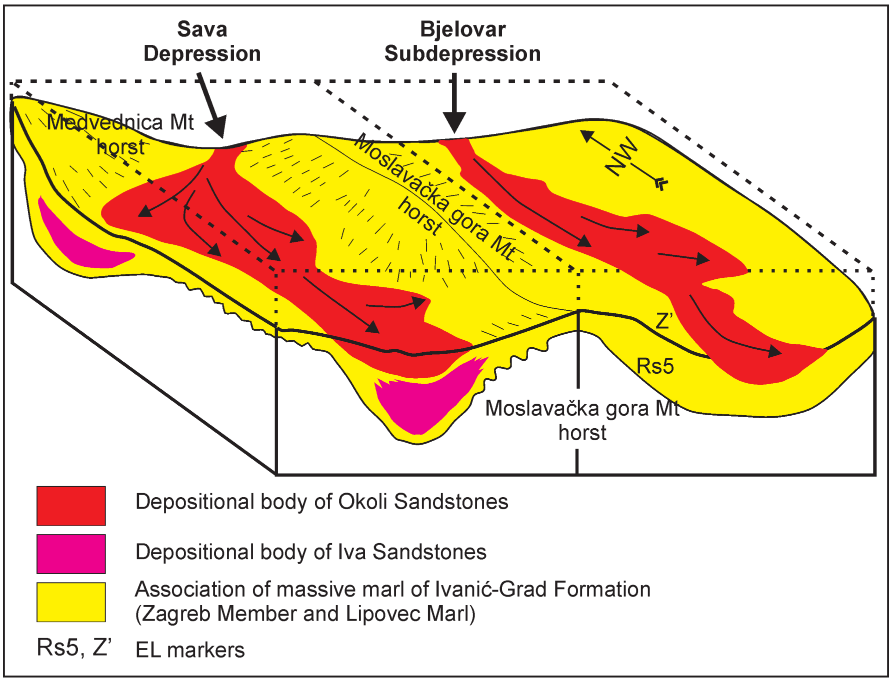



**Fig. 13.** Schematic paleogeographic situation at the end of Late Pannonian.

***Depositional environments — basin plain and/or near-shore mechanisms***

Reconstruction of the approximate paleorelief shape can indicate the paleowater depth of the lake in the study area. The most reliable indicator of water depth and the depositional environment are the remains of animals and plants (biotop) that characterize particular environments. Unfortunately, the Upper Pannonian sediments contain very few fossils. However, some macrofossils occur at the point at which the transition from fresh-water to brackish water occurred, and some others indicate the presence of shallow water (Pletikapić 1965). The majority of microfossils were found in the cores of older wells located on the margins of the depressions. Based on the distribution of microfossils in the study area, Pletikapić (1965) concluded that marginal marls were deposited in marsh and swamp environments. Other authors such as Lučić et al. (1995) came to the same conclusion based on palinological analysis and evaluation of additional core samples from the Ivanić-Grad, Žutica, Okoli and Lipovljani oil and gas fields located in the deep parts of the Sava Depression. They found phytoplankton species common to shallow water, such as *Spiniferites* sp., as well as species associated with deeper water such as *Impagidinium* sp. and *Gonyaulax* sp. In addition, they suggested that deep-water organisms were transported into the littoral zone by bottom currents, which explains why they are currently found together with shallow-water plankton. Based on these results, they concluded that the sediments containing these organisms were from near-shore areas, shoals, beaches, lagoons and tidal channels. Relatively rare samples of sporomorphs would indicate that land was relatively far, but the presence of kerogen type III (terrestrial) supports the authors' (Lučić et al. 1995) conclusion that the shore was close. This explains why sediments of deeper water (turbidite) are only found occasionally. Other possible mechanisms allow that the clastic materials could be derived from a near-shore environment, and then delivered either by turbidity currents to the deeper parts of the basin or they were reworked from the elevated flanks.

Other facts also support the view that the presence of marls indicates shallow water and near shore sediments. The almost perfect correlation of massive marls (using SP logs) in the interval between EL-markers Rs5 and Z' throughout the Sava Depression and the Bjelovar Subdepression indicate that these areas were surrounded by a belt of marshes and lagoons filled with fine mud detritus. Regarding the relatively narrow depositional areas, such as those in the Sava Depression that are only 10 km wide, it is not clear where the beaches and shoals were located and where the transported material was eroded from the land.

Generally, marls defined as sediments of swamps and lagoons do not include any characteristics that indicate the presence of close land areas, but they could be reworked. Moreover, it is difficult to accept the statement that the influx of detritus via subsidence that occurred throughout the Late Pannonian, which was about 3 Ma long and occurred in a tectonically active depression(s), was so ideally synchronized that the water level did not change. Indeed, this would indicate that no parts of the shallow water (marsh, lagoons) were exposed to the air and subjected to erosion throughout this period at all.

The second option by which the shallow-water sediments were deposited may have been through the activity of the delta. Sandstones are distributed throughout the delta, and mud and marls are deposited in marshes, flooded areas of abandoned channels and levees (e.g. the on-shore environment). However, this suggestion is also contradicted by the absence of evidence of erosion and near-shore, land material.

***Deep-water mechanism***

A complete sequence of massive marl has been described and confirmed in SP logs of the marginal and central parts of the Sava Depression (Figs. 6, 8). These marls were deposited under the same conditions and at the same time intervals, which indicates that deep-water deposition occurred in a calm environment via the same depositional mechanism. Only such an environment can explain all of the rapid changes and the nearly identical conditions that were observed over a long geological period. In such deep areas, even changes in depth of several hundred meters would not necessarily lead to drastic changes in the depositional environments and mechanism if the depth was maintained at more than 200 m. Detection of the complete sedimentary sequences of the Late Pannonian in wells located throughout the (sub)depression(s) confirm that the depositional environment was definitely deep water, except in the transitional zones at a depression flanks.

The deep-water mechanism is contradicted by the presence of relicts of palynomorphs that indicated a shallow depositional area. However, they can also be reworked. We accepted the fact that all of the siliciclastic material originate from one source (Eastern Alps). Furthermore, the last slope, which contained detrital material that was accumulated with varying intensity, was probably located into the Mura Depression (north of Varaždin). From this point, due to tectonic events, sediment was relocated and transported to the Drava and Sava Depressions and the Bjelovar Subdepression. The water depth in marginal depression areas (slopes) was (significantly?) lower than in the depression, which resulted in a shallow-water environment characterized by skeletal and plant remains that had been re-deposited in the deeper depression.

Furthermore, distribution of particular lithological members was strongly pre-determined by the paleorelief. The central parts of the depressions were surrounded by basement highs, where water depths could have been lower than 200 m (sometimes these highs could be uplifted above the water level as islands). These areas may have produced biotopes suitable for shallow-water plant and animal associations. Their remains could have then been transported by permanent, slight currents from the N toward the S, SE and E in all of the depressions, independently from the periodical turbidites. Finally, the only traces of erosion, which were observed in cores and well-logs, appear to have been the result of turbidite activity on older sediments at the base of the turbiditic deposits.

***Source and paleotransport of detritus***

Some conclusions about the source areas of the sediments are given in previous chapters. Additional information can be obtained from the petrographic composition, which can enable identification of the source areas of the sediments, or the region from which source material originated. In addition, granulometric parameters, the geometry of sandstone bodies, the areal distribution of facies, and depositional environments and mechanisms can provide additional information regarding the location of a possible source.

The sedimentary, mineralogical and petrographic characteristics of the Upper Pannonian and Pontian of the Sava Depression and the Bjelovar Subdepression are very similar. The majority of the detritus originates from the Alpine mineral association (Šćavničar 1979). Conversely, the influence of local horsts as a source of detritus was limited as they were probably under water at that time. These results indicate that transport took a very long time, and that the material was re-deposited several times. This explains why the sandstones are mostly medium- to fine-grained, with relatively rounded grains.

Clastic material of Late Pannonian age found in the outcrops of the surrounding hills primarily consists of marls that are very rarely interbedded with sandstone laminae.

The distribution of sandstone bodies only in the central parts of the depression, their thickness, shape and location clearly indicate a single source area. Sandy detritus was transported from the NW in the first phase of turbiditic activity, while later on it was transported from the N or N/NE.

The Upper Pannonian sediments are also present on mountains that surround the Sava Depression and the Bjelovar Subdepression. These sediments are composed of calcitic marls and limestones, but contain no evidence or deposits of nearby land, such as surface erosion or deposition characteristic of a near-shore, shallow-water environment.

Regarding paleotransport, the strongest indicator of turbidite direction is the geometry of the sandstone bodies. No surface marks identifying direction were evident in the present study. The sandy detritus was transported into the depression exclusively by turbidites, and the primary flow direction had an arching (curved) shape from the NW, to N, NE and finally toward the SE and E. This material came from a relatively uplifted area north of the Medvednica-Moslavačka Mountain range. During a period of inactivity, permanent inside basin currents resulted in transport and deposition of the finest detritus throughout the entire (sub)depression(s). One branch of the main turbidite flow in the late period of the Late Pannonian was turned into the Bjelovar Subdepression. In both areas, the primary pathways of the paleotransport directions were pre-determined by shallow channels. These channels carried along the main part of the sandy material, while the minor part was deposited in the inter-channel areas. In addition, the channel locations were changed through space and time, continually migrating, thereby defining the inter-channel area pattern.

## Conclusion

Two mechanisms of transport and deposition in the Upper Pannonian were proposed: massive marls are the product of "normal" basin hemipelagic deposition ($F_1$ facies), while periodic turbidity currents transported coarser-grained material, as well as finer grained detritus of silt size as a turbidite facies ($F_2$–$F_4$). These results indicate that the depositional environment was calm and stable due to the sufficient water depth (more than 200 meters) compensating for all water level changes caused by tectonic movements and cyclic climate changes. This low-energy environment was disturbed only by temporary turbidity currents, which deposited most of the detritus in the deepest parts of the depression. Depositions of the Iva Sandstone Members (lower part of the Upper Pannonian) occur only in the Sava Depression. Contemporaneous deposits of the Bjelovar Subdepression are represented only by basin marls. The younger Okoli Sandstone Members are found in both depressions as a result of the deepening and opening of the Bjelovar Subdepression to source areas and transport by turbidity currents.

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