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Comparison of the Middle Miocene and the Upper Miocene source rock formations in the Sava Depression (Pannonian Basin, Croatia)

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ABSTRACT

The Sava Depression lies at the very south-western margin of the Pannonian Basin. There are 20 hydrocarbon fields altogether and 17 are still in production. The organic geochemistry data and their statistical analysis from the 25 exploration wells, indicate source rock formations in two stratigraphic levels, an older one of Middle Miocene age (Badenian and Sarmatian) and a younger one of Upper Miocene age (Lower Pannonian). Both source rock formations are composed of marls, calcitic marls, clayey limestones and shales. Source rock intervals lay at depths from 1200 to 3362 m. The Total Organic Carbon (TOC) of analyzed samples varies from 0.39 to 4.94%, while their total generative hydrocarbon potential is from 2.40 to 37.40 mg HC/g rock. The mean thickness of the intervals is 100–150 m. There is a regular linear increase of the maturity level with depth. Source rocks are mature, in the catagenetic phase of transformation that enables hydrocarbon generation.

A favourable organic facies, mostly kerogen type II, (organic facies AB and B), with good hydrocarbon potential, dominates the north-western and central part of the depression. It can be connected with the deeper parts of the depression and/or protected, anoxic to dysoxic stagnant environments with a gradual transition from marine (Badenian/Sarmatian) to brackish depositional environments (Lower Pannonian). In the south-eastern part of the depression, the dominant kerogen type is II–III, (organic facies BC), which indicates a stronger influx of terrestrial material from the uplifted parts that are generally closer to the margins of the depositional basin. The Fisher test (F-test) of the variance similarity (homogeneity), clearly indicates that the Badenian/Sarmatian samples belong to a statistically different population from the Lower Pannonian ones, due to their different depositional environments.

Keywords: Sava Depression, Pannonian Basin, Croatia, source rock, kerogen type II, Middle Miocene, Upper Miocene, Fisher test (F-test), depositional environment

1. INTRODUCTION

The Pannonian Basin is mostly a lowland region between the mountain chains of the Alps, Carpathians and Dinarides. Its south-western part is in Croatian territory, a region that is approximately bordered by the Kupa and Sava rivers to the south, by the river Danube in the east, and by the Drava and Mura rivers to the north. The Sava Depression lies at the very south-western margin of the Pannonian Basin (Fig. 1A). Two large stratigraphic units are distinguished within the basin. The older (Pre-Tertiary) complex consists mainly of the Palaeozoic igneous and metamorphic rocks, with a subordinate presence of Palaeozoic and Mesozoic sediments

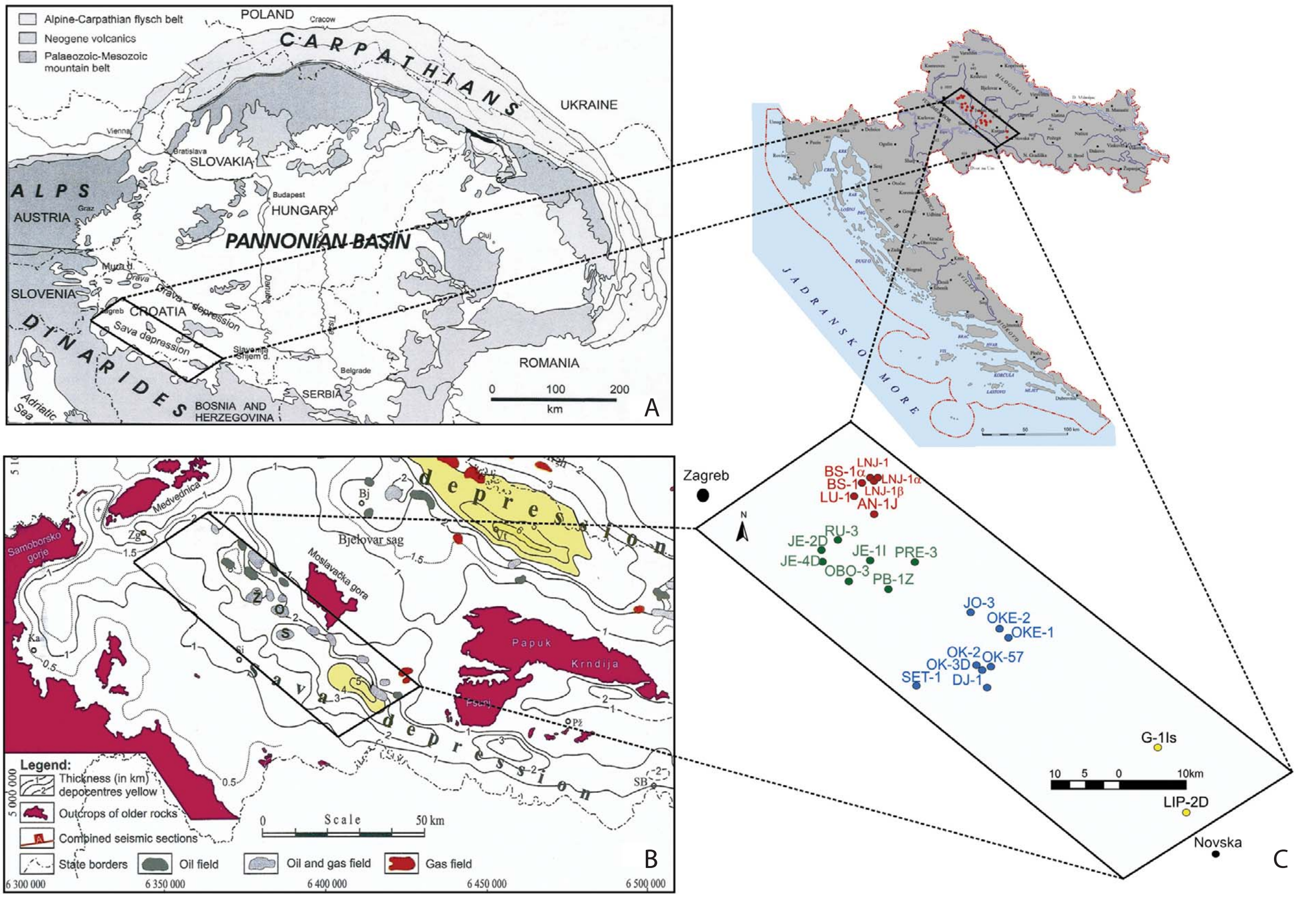

Figure 1: A) Pannonian Basin; B) Isopach map of the entire Neogene to Quaternary sequence with HC accumulations, after SAFTIĆ et al. (2003); C) Index map of the studied wells in the area of the Sava Depression, Croatia.

with markedly complex structure – folds, faults and metamorphism, together with a pronounced lithologic heterogeneity. A younger complex includes Tertiary (mostly Neogene) and Quaternary rock formations.

The most important feature of the Sava Depression is the sequence of Neogene–Quaternary sediments, estimated locally at more than 5000 m thickness (VELIĆ et al., 2002), in particular in the western part of the depression, south of the Moslavačka gora Mt. (Fig. 1B). This sedimentary sequence is divided into six lithostratigraphic units – formations, with hydrocarbon accumulations documented in five of them. As all of these formations have characteristic lithologic compositions, their superposition is well documented and they are all several hundreds of metres thick. Three megacycles were discerned within the sequence (MATHUR, 1981; VELIĆ et al., 2002). Each lasted for an approximately equal time span (6.8 Ma, 5.9 Ma and 5.6 Ma) enabling them all to be put into the 3rd order (Fig. 2).

Altogether, there are 20 hydrocarbon fields in the Sava Depression and 17 of them are still in production. They are all concentrated in the north-western part of the depression. The prevailing reservoir rock formations are the Pannonian and Pontian sandstones, but significant hydrocarbon accumulations have also been discovered in the weathered and fractured Palaeozoic igneous and metamorphic rocks. The three most important hydrocarbon fields are Stružec, Žutica and Okoli ("Ž", "O" and "S" in Fig. 1B). The cumulative production from the Stružec and Žutica fields amounts approximately to 35 x 10^6 m^3 of oil, while from the Okoli field around 4.5 x 10^9 m^3 of gas have been produced.

The first attempt to scientifically analyse the geological age and facies of the source rock formations in Croatia was undertaken more than 60 years ago (OŽEGOVIĆ, 1944). In that paper the Sarmatian thin-layered brown bituminous schists found in the Gojlo and Janja Lipa fields were identified as "the real source rocks for the Earth oil". The mentioned locations are in the eastern corner of the investigation area delineated in Fig. 1B. Conclusions in PUTNIKOVIĆ et al. (1989) and RADIĆ et al. (1989) refer to the entire Croatian part of the Pannonian Basin. The most important problem treated therein is the correlations between the source rocks and hydrocarbons. Based on the $^{13}C/^{12}C$ isotope ratio, a high source rock-oil correlation has been established. In parallel, results published in ALAJBEG et al. (1990) stressed the fact that all oils were generated from similar Miocene source rocks that comprise one larger group. They originate from the bacterially altered algal material that was to various extents mixed with terrestrial sediments and deposited in the suboxic environment. In the review paper of BARIĆ (1996), the summary of results of the geochemical investigations in the Croatian part of the Pannonian Basin concluded that most of the source rocks identified are in the Lower to Middle Miocene formations. In later papers; BARIĆ et al. (2000) and

BARIĆ et al. (2003), the Miocene petroleum systems are defined, wherein the source rocks are Badenian to Lower Pannonian clayey limestones and calcitic marls, lying deeper than 1600 m, and with the prevailing content of kerogen type II. According to bulk and specific parameters, all oils found in the north-western part of the Sava Depression have a genetic similarity. Short migration distances are proposed and the variation in oil characteristics are attributed to post-generative processes, biodegradation, water washing and evaporate fractionation.

The purpose here is to illustrate in detail the characteristics of source rocks in the Sava Depression, based on the most recent laboratory analyses, their geological interpretation and statistical analysis. Two source rock formations are identified: Badenian with extension into the overlying Sarmatian sediments, (older zone – First megacycle) and Lower Pannonian (younger zone – Second megacycle) (Fig. 2). It is particularly interesting to investigate the similarities and explain the differences between certain characteristics of these source rocks, e.g. their kerogen and organic facies. They are significant for the changes that took place during the gradual transition from the first, marine megacycle into the second, brackish-freshwater one. The results of geochemical analyses – identification of the source rock formations and estimation of their generative potential have therefore been interpreted in relation to the Neogene megacycles.

2. GEOLOGICAL SETTING

A more recent reconstruction of the three-phase Neogene–Quaternary evolution of the Pannonian Basin was published in LUČIĆ et al. (2001) and SAFTIĆ et al. (2003). The first phase includes the initial structural changes during the Oligocene and Early Miocene with the occurrence of andesite volcanism north of Zagreb. The main depositional area was then formed between Zagreb, Varaždin and Ljubljana. In this early extension stage, the sedimentation rate was able to keep pace with basin subsidence, so that all of the depocentres (depressions and sags) were infilled with syntectonic

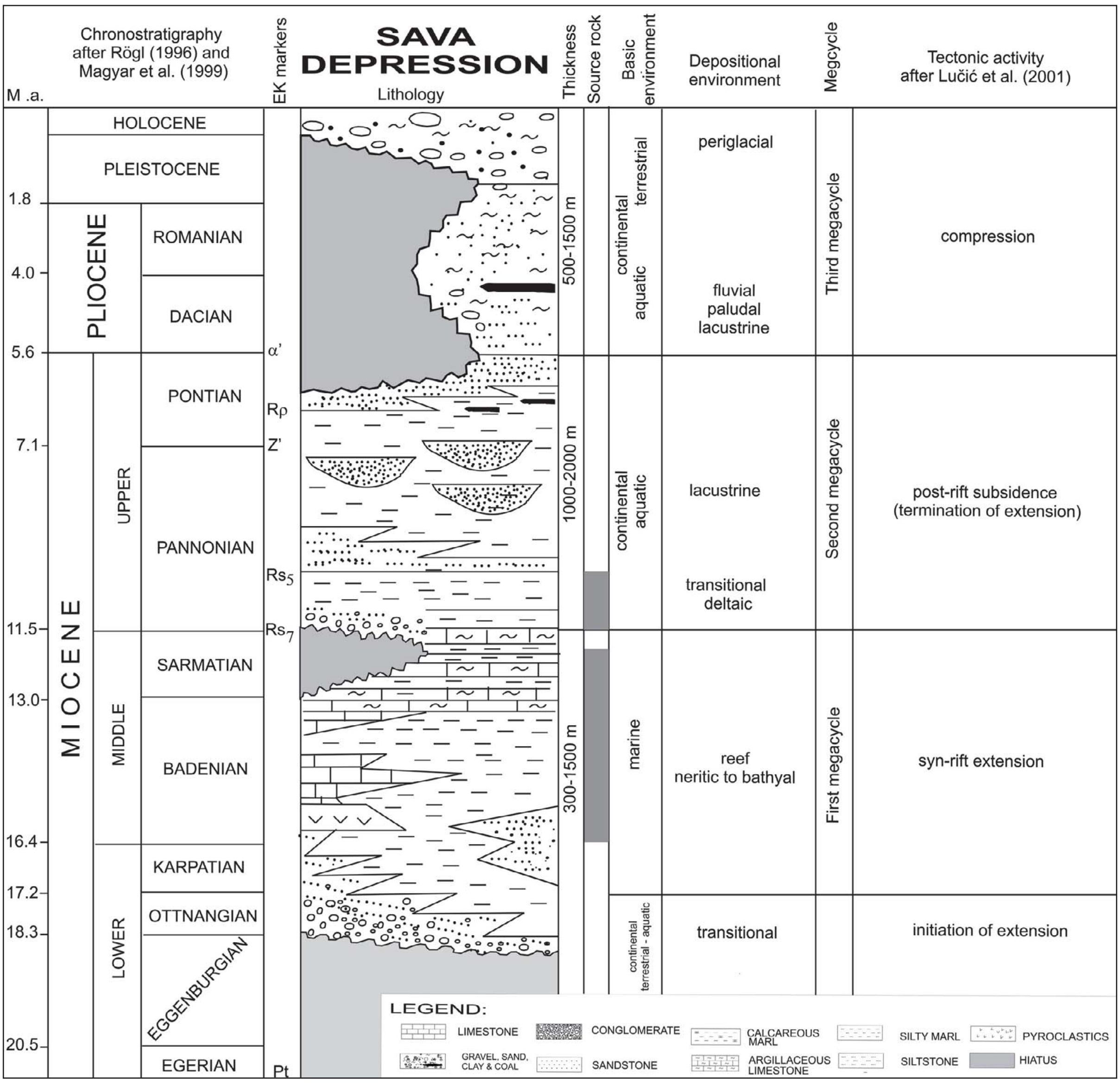

Figure 2: Schematic composite stratigraphic column of the north-western part of the Sava Depression, modified after SAFTIĆ et al. (2003).

coarse- to medium-grained clastics of terrestrial, mostly aquatic origin, with marked lateral facies changes (Fig. 2). The third phase is characterised by the main extensional synrift processes that lasted throughout the Early and Middle Miocene (Eggenburgian–Badenian). It was followed by marine sedimentation and post-rift subsidence during the Late Miocene when again the influence of the sea was diminished and a continental-lacustrine environment was formed.

Sediment transport into the basin only started to lose pace with the growth of accommodation in the depositional area in the Badenian. Large deep-sea basins were then formed with deposition of marls and calcitic marls rich in organic matter. Subsequently, the Sarmatian is characterised by basin starvation, followed by deposition of the condensed sections. Sediments that were accumulated in this phase (Ottnangian–Sarmatian) together make up the 1st megacycle.

During the Sarmatian–Pontian time span, the main extension in the south-western part of the Pannonian Basin came close to an end, explaining why all Upper Miocene sediments exhibit common post-rift characteristics. Large masses of Pannonian and Pontian sediments, mostly marls and sandstones were deposited over an extensive area, also covering the former basin margins. This was especially pronounced during Pontian times. There was an equilibrium between the rate of basin subsidence and sedimentary influx that lasted through the entire Pannonian and Pontian, resulting in periodic reinstatement of similar depositional environments and formation of a thick sandstone-marl sequence (2nd megacycle) (Fig. 2). In the third phase, during the Pliocene and Quaternary, neotectonic structures were gradually formed under the influence of the north-south oriented regional compressional stress, together with activation of the dextral transcurrent faults and pronounced transpression between the major strike-slip faults. There was also a transition from the continental-aquatic environments to purely terrestrial ones (3rd megacycle). The main structures and hydrocarbon traps were shaped in this late phase (Fig. 2).

3. SAMPLES AND METHODS

Organic geochemistry investigations were performed on the samples from cores, side-cores and bit cuttings taken from the 25 exploration wells in the Sava Depression (Fig. 1C). Analyses of both the rocks and hydrocarbons, included standard geochemical methods and determination techniques. Initially, the petrographic composition of rock samples was determined, together with their sedimentological features, and biostratigraphic allocation of their geological age.

The principal parameter in source rock identification is the total organic matter content (% TOC). Only samples with more than 0.5% TOC were taken for further analyses. Organic carbon contents were determined by combustion of acid insoluble matter in a Leco IR–212 carbon analyser, after treatment with hot 1:1 diluted 36.5% HCl.

The powdered rock samples were later subjected to pyrolysis in Rock-Eval II+TOC and/or Rock-Eval 6 systems (ESPITALIE et al., 1985). Various diagrams to illustrate the obtained parameters (TOC, S_1, S_2, S_3, T_{max}, HI, OI, PI= S_1/(S_1+S_2) are presented in Figs. 3, 4, 6 and 7. Instead of the respective source rock intervals their mean depth is used (Figs. 3 & 6), and the results are shown with a span between the minimum and maximum values.

Isolation of organic matter for optical analyses as well as sulphur and stable carbon isotope analyses were undertaken using the conventional HCl/HF/$ZnCl_2$ procedure. Organic matter was examined in transmitted, reflected and blue fluorescent light, using an Olympus BH–2 and Olympus BX–51 microscope and Leitz MPV–3microscope photometer. The mean value of the vitrinite reflectance was measured. The maceral composition determined is: amorphous organic matter (fluorescent and non-fluorescent), liptinite macerals (alginite, sporinite, and liptodetrinite), vitrinite and inertinite. The sulphur content of both the kerogen and bitumen was determined by a Leco SC 132 sulphur analyser. Analyses of the stable carbon isotopes were carried out in a Finnigan MAT delta E mass spectrometer according to the procedure outlined in SOFER (1980).

Extractable organic mater (EOM) of the powdered rock samples was determined by 36-hr Soxhlet extraction with chloroform. Extracts were separated by column liquid chromatography into four fractions: saturated hydrocarbons (alkanes), aromatic hydrocarbons, NSO-compounds and asphalthenes. Gas chromatography analysis of bitumens and of their alkane fractions was performed on a Perkin Elmer Sigma 300 and Varian 3900 GC.

4. RESULTS AND DISCUSSION

Source rock characteristics were discovered at several intervals composed of marls, calcitic marls, clayey limestones, mudstones and shales of Middle Miocene (Badenian and Sarmatian) and late Miocene (Early Pannonian) age. The geological age was determined by combining several criteria – superposition, biostratigraphic analyses and their position in relation to the regional E-log marker Rs_7 which is attributed to have characteristics of a chronohorizon (VRBANAC, 2002) (Fig. 2).

4.1. Source rock

Based on the results of organic geochemical analyses and organic petrography, source rock intervals were singled out in the drilled columns of 25 exploration wells in the Sava Depression area. The thickness of these intervals, summarized results of the Rock-Eval pyrolysis, maceral composition and composition of EOM are illustrated in the diagrams for the entire source rock intervals (Figs. 3 & 6).

Middle Miocene source rocks (Badenian and Sarmatian age) are dark, grey to black marls, calcitic marls to laminated clayey limestones, with subordinate intervals of silty marls. Source rock intervals were determined at a depth range of 1300–3362 m. Total content of organic carbon (TOC) in the samples taken from these intervals is between 0.46 and 4.94% TOC, with an average of 1.37% (*n*=234) (Fig. 3). In most of the drilled sections, large vertical variations in the total organic content occur, indicating that these

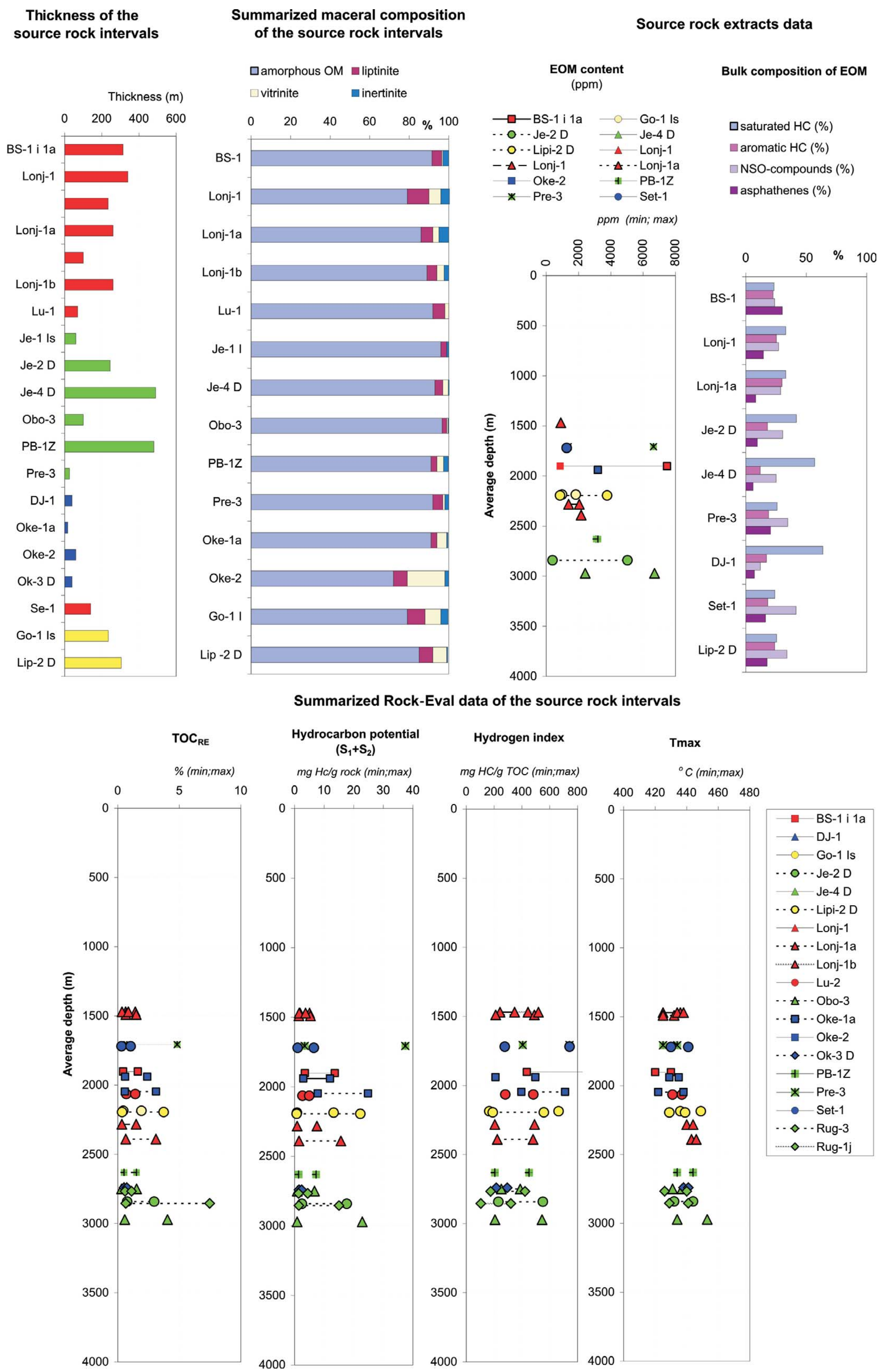

Figure 3: Summarized data of the Middle Miocene source rock intervals – Thickness of the intervals; Summarized Rock-Eval pyrolysis data (*min and max data for the interval*); Average maceral composition; EOM content and bulk composition *(NNW wells of the Sava Depression marked with red colour; NW wells with green, central group with blue and SE wells with yellow).*

source rock intervals actually do not represent homogeneous units. It is therefore also natural that the thickness of source rock intervals is highly variable – from 16 to 485 m (242 m on average), but it is most frequently in the 100–200 m range (Fig. 3). Although it is possible that this apparent inhomogeneity may be caused by results obtained from the bit cuttings (*n*=205) being non-representative in respect of the results obtained from the cored intervals (*n*=29), it is predominantly a reflection of the lithological inhomogeneity. It is noted that the most pronounced variation originates from the increased silty component that correlates well with the reduced content of organic matter and reduced hydrocarbon potential. As a rule, intervals with weak, fair and excellent source rock characteristics are vertically stacked (Fig. 3). The total generative hydrocarbon potential determined by the Rock-Eval pyrolysis (S_1+S_2) varies from 2.40 to 37.40 mg HC/g rock (Fig.3). On average, it is 7.00 mg HC/g rock.

The organic facies of source rocks was determined from the obtained values of pyrolytic indices (HI–OI), and is supported by optical investigation of the maceral composition of kerogen. Hydrogen index is between 195 and 743, with an average of 398 mg HC/g TOC. These hydrogen indices suggest that the most frequent kerogen is Type II (organic facies B (JONES, 1987), with a sporadic occurrence of a mixed Type I–II (organic facies AB) (Fig. 4). The dominant component of organic matter is fluorescent amorphous kerogen, (its fluorescent properties are observable down to the depth of around 3000 m), with a variable proportion of aquatic (alginite, dinoflagellata) and terrestrial lipids (sporinite, liptodetrinite) (Fig. 3) (TYSON, 1995; TAYLOR et al., 1998), giving this stratigraphic interval attributes of a good oil-prone source rock (HUNT, 1995). In most of the specimens an increased quantity of pyrite framboids was observed, indicating the anoxic depositional environment. It was also observed that kerogen has an increased, occasionally very high concentration of total sulphur (up to 11.4%). These parameters connect such types of organic matter with the anoxic and dioxic environments favourable for high preservation of their precursors (DEMAISON & MOORE, 1980; DEMAISON, 1991). Facies of this type dominate in the north-western and central part of the depression.

An increased concentration of bitumens also occurs in these source rock intervals (EOM from 904 to 7482 ppm, Fig. 3). In the samples where the hydrocarbon content is over the limit for the source rocks, secondary migration processes were determined. This migration was controlled by the physical properties of the sediments, i.e. by the fracture systems. The EOM content increases in the depth interval from 1800 m to 3000 m. Analytical results confirmed that the bitumens reflect the characteristics of the determined source rocks and also of their maturity levels. Notably, they contain increased amounts of NSO-compounds and asphaltene (22.54 to 58.90%, Fig. 3) and in the molecular distribution dominate the lighter hydrocarbons.

The stable carbon isotope ratios of the analysed kerogens and bitumens vary in a relatively broad range of –21‰ to –28‰ $\delta^{13}C$, which is interpreted as resulting from the facies differences between the source rock intervals (PUTNIKOVIĆ et al., 1989; ALAJBEG et al., 1990) (Fig. 5). In the western part of the depression, these values are up to –25‰

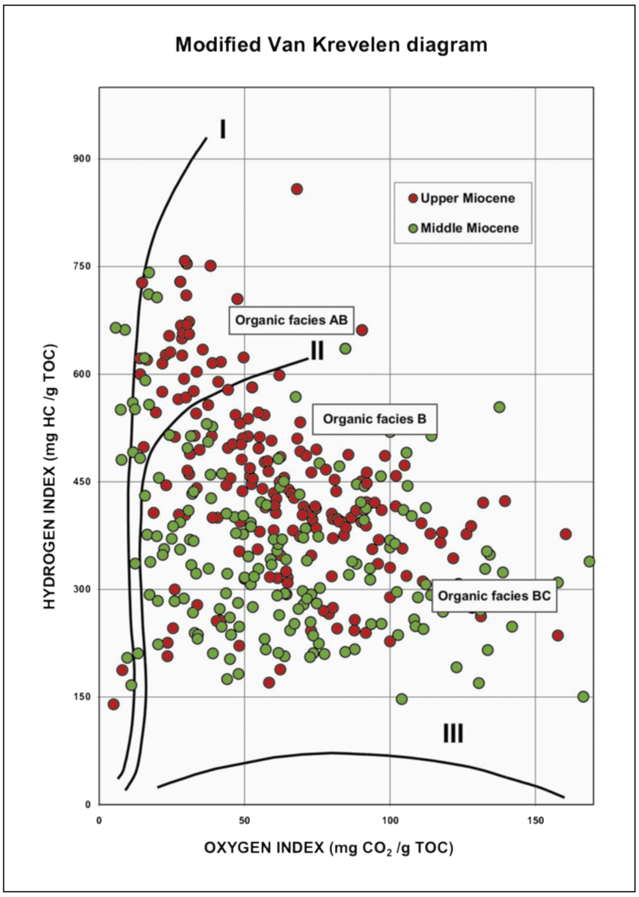

Figure 4: Modified Van Krevelen diagram showing kerogen type of the Middle and Upper Miocene source rocks.

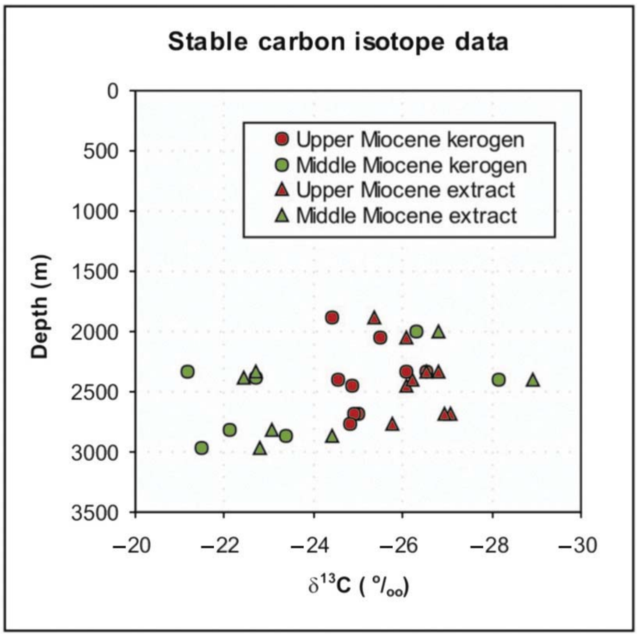

Figure 5: Stable carbon isotope data of the Middle and Upper Miocene kerogen and bitumen.

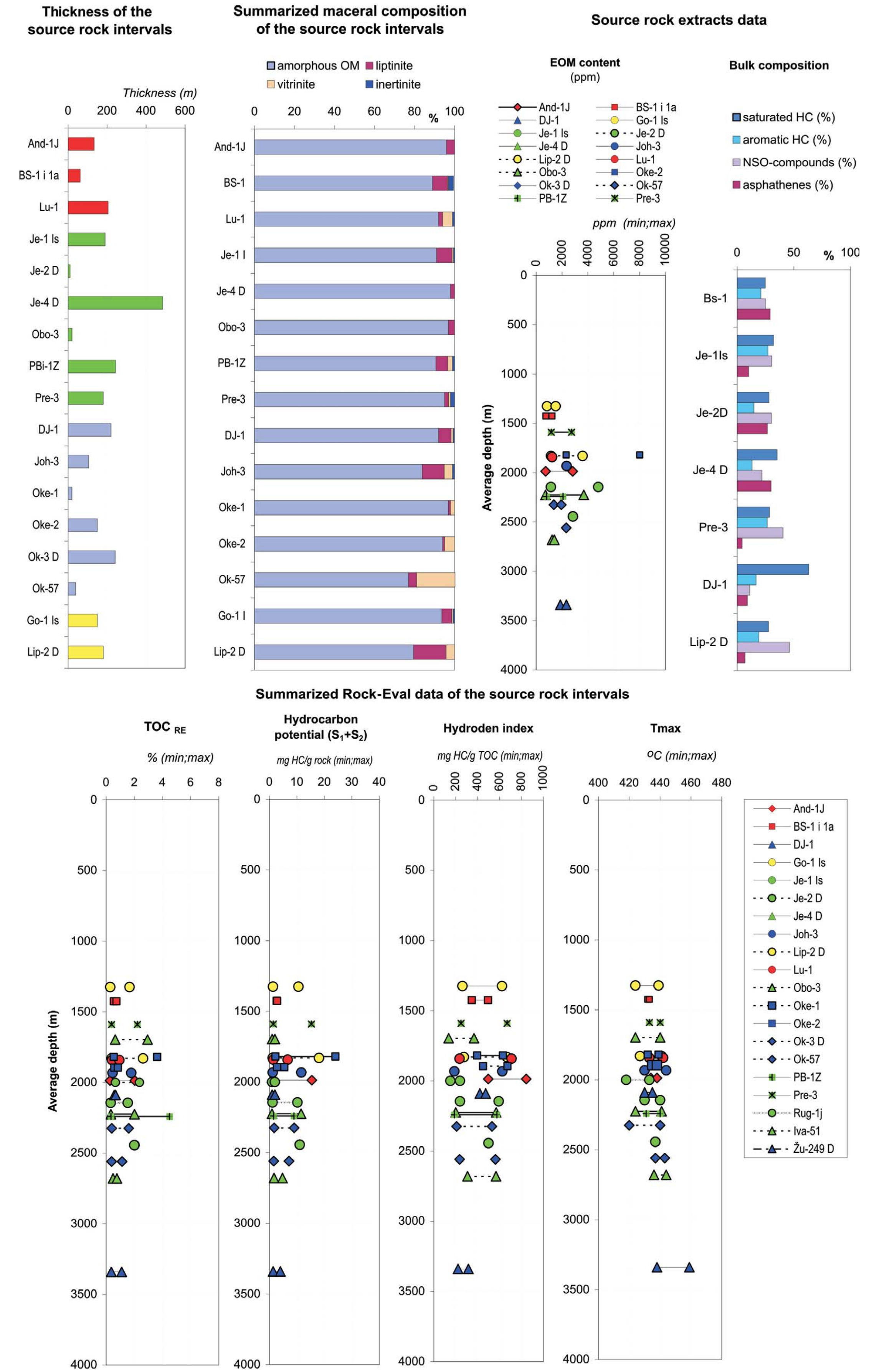

Figure 6: Summarized data of the Upper Miocene source rock intervals – Thickness of the intervals; Summarized Rock-Eval pyrolysis data (*min and max data for the interval*); Average maceral composition; EOM content and bulk composition *(NNW wells of the Sava Depression marked with red colour; NW wells with green, central group with blue and SE wells with yellow).*

$\delta^{13}C$. Alternatively, the deeper intervals in the south-eastern part of the exploration area of the Sava Depression have isotope compositions of –28.14‰ $\delta^{13}C$ (Fig. 5) which indicates their more terrestrial origin as well as more oxic depositional environment.

Lower values of pyrolytic indices (HI) have also been determined in this south-eastern area. Values of HI, especially in relation to depth, are to a certain extent connected with the thermal maturity level, (these rocks are in the oil window, where the lower S_2 values are caused by the separation of hydrocarbons from the effective source rock intervals). However, in these intervals they are mostly caused by the increased content of kerogen type III, in other words the mixed kerogen type II and III is present. A stronger terrestrial influence has also been confirmed by the results of the organic petrology investigations. The maceral composition is dominated by non-fluorescent amorphous kerogen and by the hydrogen-rich liptinite macerals of terrigenous origin (organic facies BC after JONES, 1987; Figs. 3 & 4). Correspondingly, bitumens from these intervals have an increased content of solid paraffin, a long-chained molecular structure, and highly negative values of isotope composition which indicates their generation from these source rocks.

Based on the results obtained, it can be concluded that the determined organic facies reflect the facies differentiation and lateral variations within the Badenian–Sarmatian sediments. Several separate areas with thicker sediments formed within one depositional basin during the Badenian. These areas were not only influenced by the subsidence of depocentres, but were also formed in the marginal parts of the basin, in areas where marked progradation of new sediments took place (LUČIĆ et al., 2001). Organic facies of the more favourable kerogen type II are connected with stagnant, relatively deep-water parts of the basin and anoxic depositional conditions. Kerogen type II–III occurs in the dysoxic environments closer to the basin margins and is related to faster sedimentation rates and transport of phytoclasts from the land (surrounding uplifts, present day Medvednica Mt. and Moslavačka gora Mt.).

Upper Miocene source rocks (Early Pannonian age) were drilled through at depths between 1250 and 2690 m. The thickness of the source rock intervals is between 19 and 345 m (213 m in average), but most frequently in the range of 100–150 m (Fig. 6). These rocks also have a certain level of lithologic inhomogeneity, but they are generally more homogeneous than the older unit and are mostly represented by marls, calcitic marls and clayey limestones. The organic carbon content in these rocks is in the range of 0.39 to 4.15% TOC, with an average value of 1.30% (n=259; 199 of these samples are from the bit cuttings and 60 are from cores). The total hydrocarbon generative potential (S_1+S_2) is between 2.85 and 24.01 mg HC/g rock (Fig. 6). The average value is 6.34 mg HC/g rock. Measured HI and OI values revealed that the most frequent kerogen is Type II (organic facies B (JONES, 1987), but there are also those of a mixed Type I–II (organic facies AB) (Fig. 4). Hydrogen index values are in the range of 188 to 710, on average 422 mg HC/g TOC. The more favourable facies type is mostly developed in the north-western and central parts of the depression. Organic matter is prevailingly amorphous and of algal and bacterially degraded origin (Fig. 6) (TYSON, 1995; TAYLOR et al., 1998). Principal components of organic matter are hydrogen-rich lipids with good generative capabilities that make typical oil-prone source rocks (HUNT, 1995). There are local occurrences of variable proportions of the liptinite (terrestrial lipids) and vitrinite macerals. Analyses of the carbon isotope composition of kerogen from these intervals indicate $\delta^{13}C_{PDB}$ between –24 and –26‰ (Fig. 5).

Total bitumen yield (EOM) of these rocks is in the range of 726–8018 ppm (Fig. 6). The increased content of EOM, based on analytical results, reflects the characteristics and maturity level of these source rock formations. Increased quantities of the NSO and asphalthene components (Fig. 6) are characteristic for the bitumens generated from the source rocks in the carbonate complex, but also for the maturity level of these intervals. The algal type of organic matter can be observed in the gas chromatographs that are dominated by lighter hydrocarbons.

Deposition of this type of organic facies is connected with the relatively stagnant, anoxic, often relatively deep, parts of the depression where during the 2nd megacycle the marine environments gradually became transitional, brackish and lacustrine. This was also palaeontologically documented.

4.2. Thermal maturity

The maturity of the organic matter has been determined based on the pyrolytical (T_{max}, PI) and optical maturation parameters (TAI=*Thermal Alteration Index*, %R_o=*Vitrinite reflectance*). The maximum temperature of pyrolysis (T_{max}) is 420–453 °C in the Badenian and 420–444 °C in the Lower Pannonian source rock intervals, and there is an increasing trend with depth (Figs. 3 and 6). Another trend observed is the increase of PIs (S_1/S_1+S_2, Fig. 7) starting at a depth of 2400 m (PI over 0.05) and reaching the maximum values (PI=0.5) at approximately 3500 m, which indicates the generation process.

Since the vitrinite macerals are a secondary component in respect to the prevailing amorphous organic matter, the thermal alteration index (TAI) was in most of the wells used as a basis for making estimates of the degree of transformation of organic matter. The relatively smaller number of vitrinite reflectance measurements was used to confirm the maturity levels defined by the thermal alteration index. Vitrinite reflectance values vary from %R_o 0.29 (at 1265 m) to 0.91 (at 3515 m), and are mostly in the oil window range of 0.6–0.8 %R_o. The change of vitrinite reflectance, (logarithmic scale of the measured %R_o values and converted TAI–%R_o values), with depth is shown in Fig. 7. As can be observed, a regular linear increase of maturity with depth has been determined. The thermal alteration of organic matter reached the mature, katagenetic phase that enables hydrocarbon generation (Fig. 7). The estimated early stage of the oil window (approx. 0.5 %R_o) lies between 2100 and 2200 m, and its end (approx. 1.3 %R_o) is at 3600 m (Fig. 7). It is therefore con-

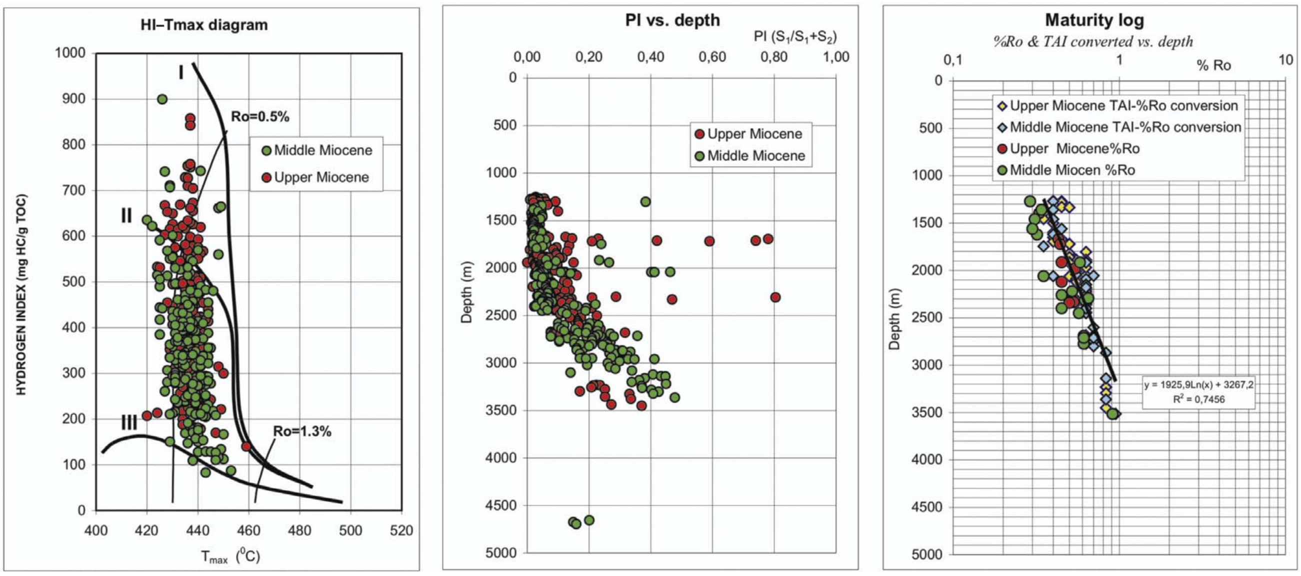

Figure 7: Maturity data – Rock-Eval pyrolysis maturity data (HI–T_{max} and PI vs. depth diagrams) and maturity log (%R_o & TAI converted vs. depth).

cluded that the Badenian–Sarmatian and Lower Pannonian source rocks are mature, i.e. that they have reached the conditions for expulsion of hydrocarbons (Fig. 7). The only difference is in the intervals that are still to shallow.

4.3. Statistical analysis of the maturity level measurements

Statistical analysis of the maturity level data has been performed on 23 measurements of vitrinite reflectance. Out of this number, 7 samples were taken from the Lower Pannonian strata and 16 from the Badenian and Sarmatian rocks. It should be considered that the normal statistical minimum for reliable analysis is an input set of 30 samples (n=30), and this is therefore why the statistics here are only used as an indicator of the statistical parameters of the input dataset. In this way, it is possible to indicate data behaviour regarding their stratigraphic association. Such results, in themselves, cannot be interpreted if we consider statistics alone, but they are applied here as a supplement to the main analysis based on data about the source potential measured by laboratory equipment.

Based on previous experience in the correlation of various geological data, when some were not shown at the same scales, it was decided to calculate two types of correlation. The first was the classical Pearson's linear coefficient, while the other was the Spearman ranking coefficient wherein the values were substituted with their rank, i.e. with values from 1 on. The obtained correlation coefficient values are very high, the Badenian and Sarmatian samples correlation with depth gie a value of 0.91; variance is 0.0257, and the median value 0.52; while the Lower Pannonian data show a correlation with depth producing a coefficient of 0.89; variance of 0.075, and a median value of 0.40 (Fig. 8). After the Fisher test (F-test) (calculation of variance ratio using F=larger variance/smaller variance), using a null hypothesis that there is

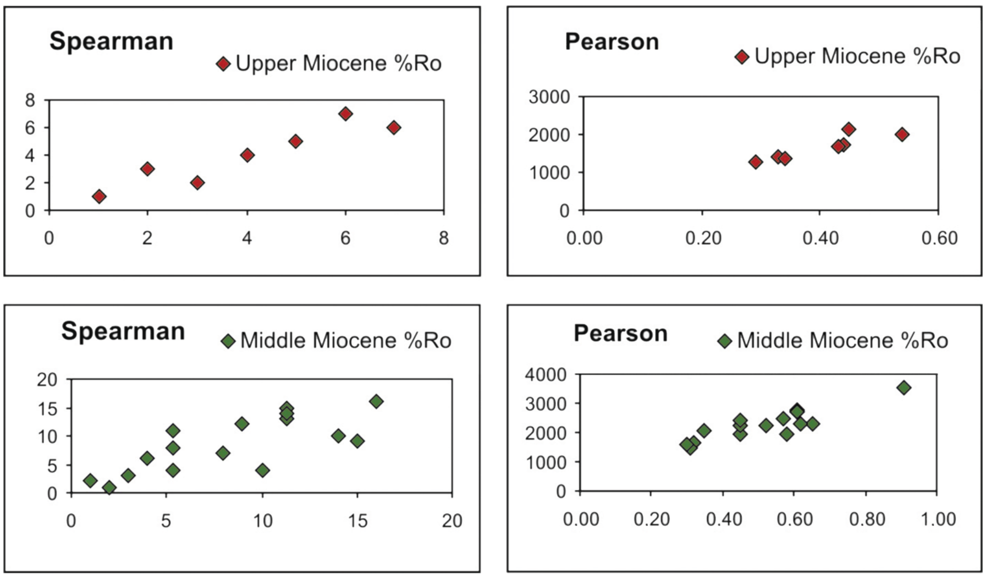

Figure 8: Correlation points for the Middle Miocene and Upper Miocene samples.

no difference in population variances had been performed, it was clearly indicated that the Badenian/Sarmatian samples belong to a population statistically different from the Lower Pannonian ones.

5. CONCLUSION

Geological and geochemical investigations of the sediments from 25 exploration wells in the Sava Depression led to identification and separation of the two source rock intervals and enabled the analysis of their characteristics in terms of the total content of organic matter, its type, quality and maturity level, together with the analysis of their generative potential.

A high content of organic carbon was determined in marls, calcitic marls, clayey limestones and shales of Middle Miocene (Badenian and Sarmatian) and Upper Miocene (Lower Pannonian) age. Average TOC of source rock formations is 1.37 and 1.30%, respectively. Source rock intervals lay at depths of 1200–3362 m. The mean thickness of the intervals is 100–200 m. Most of the investigated sediments are the petroleum source rocks with good generative potential. A regular linear increase of maturity with depth was determined. Organic matter is in the mature, catagenetic stage of thermal alteration that enables hydrocarbon generation. Due to the similarities in organic facies and maturity level, by far the largest influence of the generative capabilities of the source rock intervals comes from the content of organic matter. The most pronounced difference that has been determined is actually lateral and within the Badenian sediments. In the north-western and central parts of the depression, the organic facies of the analysed stratigraphic units are similar. Kerogen type II (to a lesser extent I–II) prevails in both units and has ample hydrocarbon potential. The favourable type of organic facies (B to AB) was deposited in the anoxic marine deepwater parts of the basin that were formed during the 1st megacycle. In the Pannonian (2nd megacycle), the continuation of sedimentation of similar facies types has been preserved in the deeper parts of the depression, and in the protected and undisturbed environments with a gradual transition from the marine basin into the brackish and lacustrine environments. In the south-eastern part of depression a somewhat different situation occurred, where within the deeper intervals of the Badenian source rock formations the mixed kerogen type II and III (organic facies BC) has been determined. It originates from environments with a larger sedimentary influx (of terrigenous lipids and phytoclasts) from the land (Medvednica Mt. and Moslavačka gora Mt.), indicating the presence of dysoxic environments that were generally located closer to the margins of the depositional basin.

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