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Source Rock Potential of the Eastern Drava Depression and Some Other Source Rock Localities in Croatia as Evaluated From Well Log Data

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Key words: Source rock, Wireline logging, Geochemical analysis, Source rock identification and maturation, Sava and Drava depression, Middle Adriatic ridge, Croatia

Abstract

The eastern part of the Drava depression is an area with extensive source rock distribution in the Miocene formation. Source rock maturity has been determined from the formation resistivity. The formation resistivity of 32 Ohm*m is typical of the area and it represents the threshold value between immature and mature source rocks. The data has been correlated with existing geochemical analyses.

Additional research has been undertaken at other localities (parts of the Drava and Sava depression and Middle Adriatic ridge). Various cross plots which have been obtained are useful for source rock determination from well logs, in very different p/T conditions and the lithologies which are characteristic for source rocks in Croatia.

1. INTRODUCTION

In view of their importance in the generation of hydrocarbons, source rocks have recently aroused quite considerable interest. In Croatia source rocks are determined only from geochemical analysis, which provides data on the quality of the source rocks, but fails to give a full picture of source rock distribution, volume and continuity. This shortcoming could be overcome by well logging measurements, used to determine the quantity and quality of source rocks. The method has not been applied in Croatia as yet. This study also deals with source rocks in the area of the Middle Adriatic ridge, Sava and other parts of Drava depression, on sediments from the Triassic to the Pliocene. The method has been applied and improved at known source rock localities in Croatia, while at the same time some new sites have been discovered. The eastern part of the Drava depression was highlighted and evaluated from well logging data which are calibrated with geochemical analysis data.

The known localities include:

• Miocene deposits of the eastern part of the Drava depression;

• Miocene deposits of the NW part of the Drava depression;

• Miocene deposits of the SW part of the Drava depression;

• Miocene deposits of the Sava depression.

The newly discovered localities include:

• Pliocene deposits of the Middle Adriatic ridge;

• additional Miocene deposits of the SW part of the Drava depression;

• Mid-Triassic deposits of the SW part of the Drava depression (Fig. 1).

The existence and maturation characteristics of source rocks at known localities have been determined by geochemical analysis. The applied method has been confirmed and supplemented at these locations by different crossplots. At new locations already in the phase of drilling and after the completion of well logging, the presented method has established the existence of source rocks, as confirmed by additional geochemical analyses.

Because of the low density contrast between highly water saturated rocks (i.e. low compaction) and source rocks, care should be exercised during interpretation. The source rock volume, yield and state of maturity must be defined in order to estimate the total hydrocar-

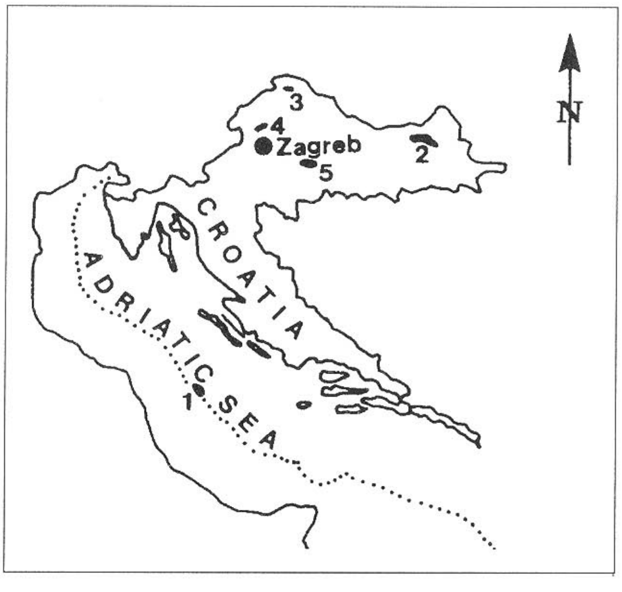

Fig. 1. Location map of wells in the study area: 1) Middle Adriatic Ridge; 2) Eastern part of the Drava depression; 3) NW part of the Drava depression; 4) SW part of the Drava depression; 5) Middle part of the Sava depression.

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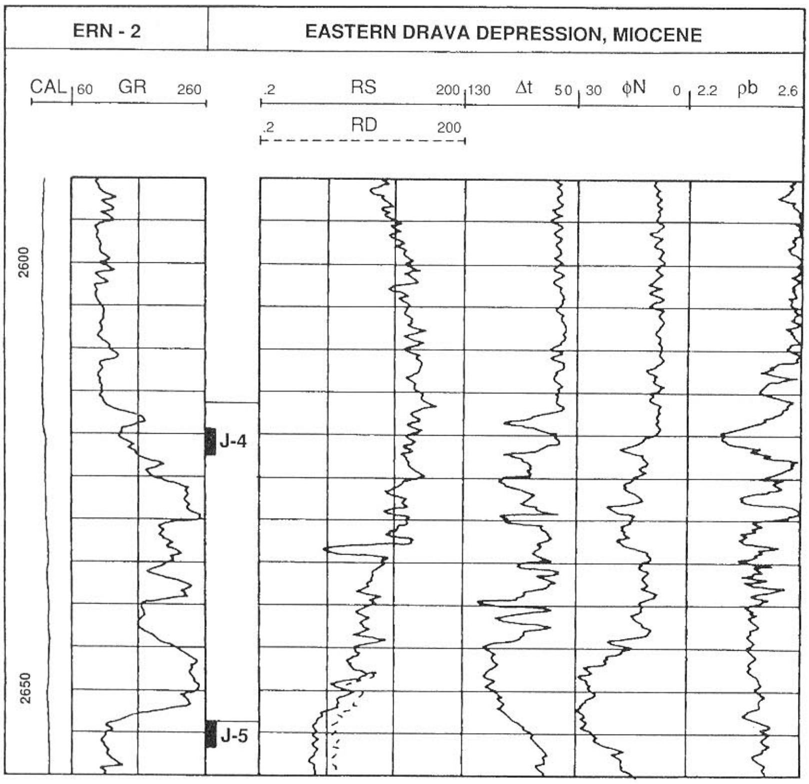

Fig. 2. Composite log of a Miocene source rock sequence, eastern part of the Drava depression. Note high Gamma-ray, higher formation resistivity, higher interval sonic transit time, higher neutron apparent porosity and lower density. J-4 and J-5 are core samples.

bon charge of a given basin or well. Today, the source rocks are believed to be associated with shales, clays, carbonates and parts of the evaporitic series enriched by organic matter, which may be derived from aquatic organisms and bacteria, or from land plants. Various mixtures of source material may occur to generate kerogen and humus in a later phase. Source rocks containing kerogenus organic matter are usually laminated and humic matter is commonly dispersed through the sediment (with the exception of coal). When exposed to higher temperatures, usually as the result of deep burial, the source rocks will release oil and/or gas. In that case they are considered to be mature.

2. BASIC HYPOTHESIS

Sediments contain solid heavier mineral matter and rocks particles and lighter fluids in the pore space.

In source rocks, the contained organic matter is also part of the light fraction. During compaction, water is expelled from source rocks and consequently the density of the rock (ρ_b) increases and the sonic transit time (Δt) and apparent porosity (ϕ_N) decreases. Because of the presence of organic material, source rocks retain a higher quantity of the light fraction (fluid + organic matter) than organic-poor sediments. In this way source rocks affect the sonic transit time and density measurements and behave as less compacted rocks. Organic matter is not electrically conductive and therefore organic-rich sediments have higher resistivity (R, Ohm∗m) than organic-poor sediments and higher natural radioactivity. These principles are illustrated in Figs. 2 and 3.

Source rocks are characterized by:
- elevated values of natural radioactivity;
- reduced interval sonic velocity values;
- higher formation resistivity;
- higher apparent neutron porosity;
- reduced bulk density;
- increased radioactive uranium content;
- properties of impermeable rocks;
- higher organic carbon content (geochemical data).

By using such a method of source rock presentation their characteristic and recognizable shape is obtained (in this case it represents a four-pointed spiderweb shape - see fig. 4). It can also be defined as a litho-logging unit (JANČIKOVIĆ et al., 1988). A common presentation of all wireline log parameters characteristic for the identification of source rocks, can also be shown on the composite log (Fig. 3). One anomaly on the resistivity curve (R) is clearly visible. There is a reduction of formation resistivity in the 2,599-2,580 m interval, although other measurements, core and cuttings analysis confirm the presence of source rocks in that interval. The situation can probably be explained by a higher water content in the pore-fracture space of the rock, which reduces resistivity. The existence of more permeable parts of the rock in this interval is indicated by the spontaneous potential curve deflection from the base line, which indicates impermeability, i.e. shale.

3. STATISTICAL ANALYSIS

The purpose of using statistical analysis as an aid in the interpretation of source rocks is to established simple rules of classification. This facilitates the separation

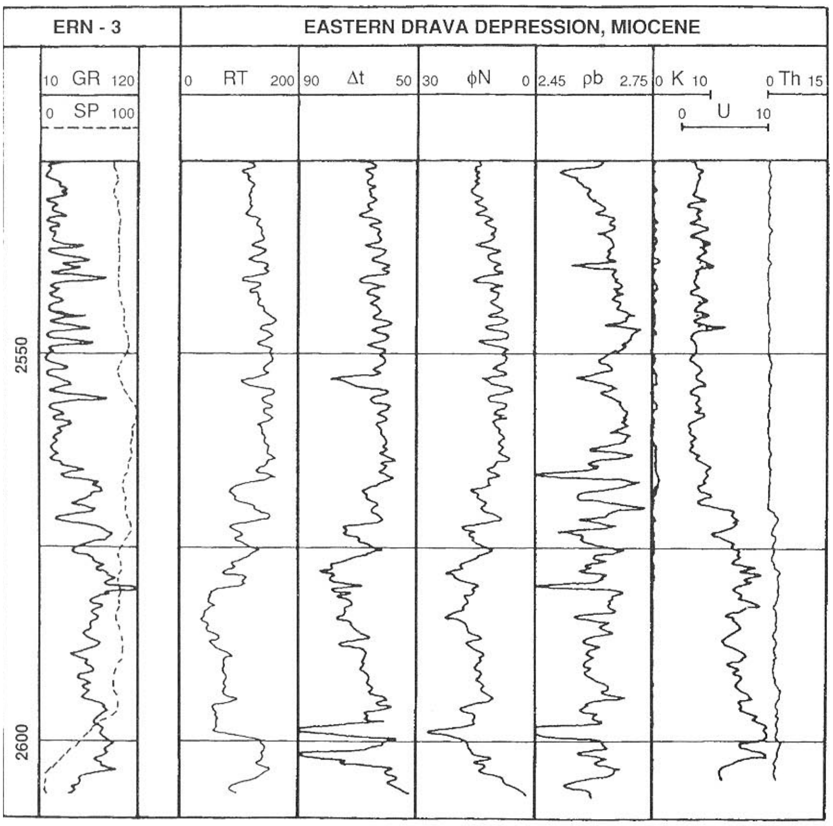

Fig. 3. Composite log presenting numerous geophysical parameters characteristic for source rocks: high natural radioactivity (GR), impermeability (SP), higher formation resistivity (RT), lower acoustic transit time, high U^{238}, low K and Th.

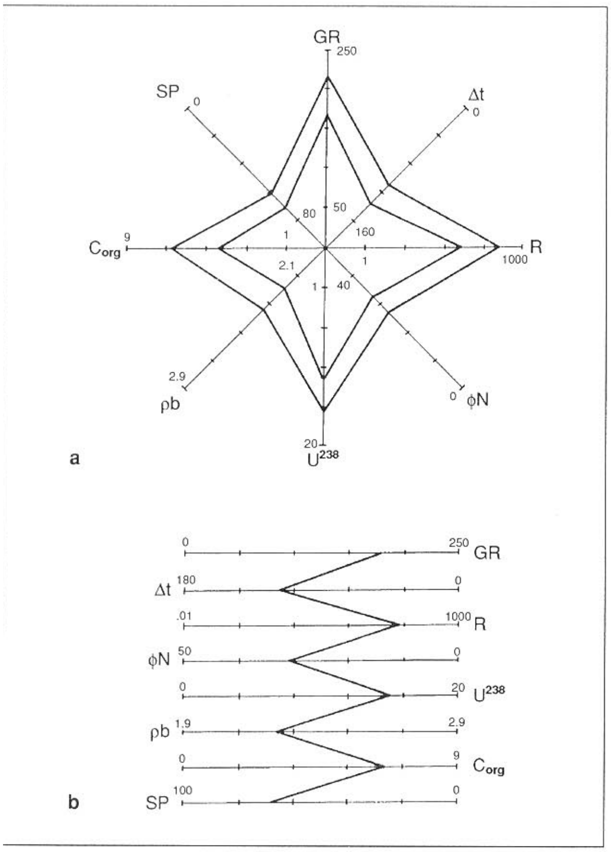

Fig. 4. Measured presentation of source rock curve shape on Spiderweb (a) and steeped (b) diagrams of Miocene source rocks of the eastern part of the Drava depression. Note high gamma ray (GR), higher interval transit time (Δt), higher resistivity (R), higher neutron porosity (ϕN), lower bulk density (ρb), higher content of uranium (U^{238}), higher content of organic carbon (C_{org}) and SP curve shoving unpermeable (shale) zone.

of source from non-source rocks on the basis of quantitative petrophysical parameters obtained from well logging measurements. The source rock control parameters were measured at all locations. Non-source rock control parameters were measured from overlying and underlying strata. The measured parameters were subdivided into two classes on the basis of geochemical sample analysis (Table 1): Class 1 - source rocks (samples 92 through 241), and Class 2 - non-source rocks (samples 60 through 140). The geochemical analysis were based on the results of pyrolysis, vitrinite reflectance and degree of carbonization of palynomorphs. The statistical analysis include a discriminant analysis performed using the scheme of pseudoregression (DAVIS, 1973; MEYER & NEDERLOF, 1984). Wireline log parameters (resistivity, density, sonic, neutron porosity, natural radioactivity with uranium part of the spectrum) were used to produce crossplots (Figs. 6, 7 and 8) which clearly differentiate the subdivision of strata into source and non-source rocks. To test for source rock potential the above mentioned wireline log parameters have to be entered into the equation to calculate "D". If "D" is positive, the rock is a probably source rock; if "D" is negative, the rock is probably barren; if "D" is 0, case remains undecided (figs. 6, 7 and 8). A set of geochemical analyses used for correlation purposes with well logging data will be presented in further text. The eastern part of the Drava depression, where geochemical analyses have confirmed the existence of source rocks in Miocene limestones and shaly (marly) limestones has proved to be interesting for correlation of geochemical measurements, with well-logging data.

DESCRIPTION	SHALES ONLY			ALL LITHOLOGIES		CARBONATE PHYLLITE
	M/N	A/R	D/R	A/R	D/R	D/R
Sample size	217	178	178	177	177	381
Source rock	100	109	118	92	92	241
Non-source rock	117	69	60	84	84	140
Misclassification	6.6	9.1	10.3	8.9	10.4	11.2
Separation of class means in terms of pooled standard deviation	1.22	1.08	1.13	1.33	1.17	1.08
Class 1 mean	0.64	0.35	0.74	0.79	0.69	0.55
Class 1 St. Dev.	1.44	1.25	0.21	1.09	0.71	0.59
Class 2 mean	0.76	-0.55	0.38	0.98	0.57	0.32
Class 2 St. Dev.	0.26	0.33	1.22	0.87	1.18	1.19
Coefficients[1]:						
Beta 0[2]	2.24	-9.52	-13.9	-17.86	-5.33	-29.03
Beta ("M")	3.71	-	-	-	-	-
Beta ("N")	6.31	-	-	-	-	-
Beta sonic (A)	-	0.07	-	1.21	-	-
Beta density (D)	-	-	7.02	-	19.36	9.52
Beta resistivity (R)	-	0.25	-0.09	8.33	-1.46	0.004

Table 1. Results of discriminant analysis. Results are tabulated for different well log combinations:
- M = Sonic transit time versus bulk-density;
- N = Apparent neutron porosity versus bulk-density;
- A = Sonic (in $\log_{10}$ μsec/ft);
- D = Bulk-density (in $\log_{10}$ g/cm^3);
- R = Resistivity at 24°C (in $\log_{10}$ Ohm∗m).

4. FORMATION RESISTIVITY AS AN INDICATOR OF SOURCE ROCK MATURITY

Formation resistivity can be used as an indicator of source rock thermal maturity. Generation of non-conductive hydrocarbons in organic-rich, low-porosity rocks begins to displace conductive pore water (in such cases the noneffective porosity can be considerable, e.g. in shales, where it exceeds 30%). As this process continues, the formation resistivity increases from the 3-4 Ohm∗m (Fig. 5, Irma-1), typical of water-saturated source rocks, to > 100 Ohm∗m (in some wells of the eastern part of the Drava depression it reaches 350-380 Ohm∗m - Bokšić and Klokočevci). If sufficient quantities of hydrocarbons are generated, the resistivity can reach significantly higher levels if the source rock is in the gas generating stage. Factors such as mineral composition, porosity, pore-tortuosity and salinity also affect the formation resistivity, but not to such an extent as to mask the source rock and generation of hydrocarbons, provided the formation is in the mature stage. Temperature correction of formation resistivity to standard conditions is necessary to obtain their true values. In addition, such investigation should be limited to areas of identical or similar lithology, in view of the fact that carbonates and shales, for instance, are not characterized by the same formation resistivity, if viewed as nonporous rocks, i.e. their formation factor is not the same. Pure carbonates are distinguished by resistivity several times higher than that for shales, which makes misclassification possible. Therefore this part of the paper refers only to the eastern part of the Drava depression characterized by source rock units in Miocene limestone and shaly (marly) limestones (Figs. 2, 3 and 14).

Correlation of well logging data has confirmed the existence of source rocks in the eastern part of the Drava depression within the regional well logging markers Rs7 and Rs5 respectively, i.e. as numerous authors have established - within the Valpovo Formation (ŠIMON, 1973; HERNITZ, 1983), the basal boundary of which has been defined by the H (Rs7) marker and the top boundary by the G (Rs5) marker (Fig. 14). The basal marker H, or by its operational name Rs7, represents the boundary between the Vukovar and Valpovo Formations. The lithological composition of Valpovo Formation is predominantly uniform and mostly characterized by compact homogeneous marls grey or yellow-grey in colour, which in the source rock zone become dark grey and black. Considerable quantities of lime components appear in the lower part of the unit, and the marls are pure limestones in places (Ern 2, Ern 3). Occurrences of sandstones and coarse-grained clastic rocks are rare.

It has been established that Valpovo Formation source rocks can be correlated, traced and classified as containing kerogen of the same type (II) (Fig. 10), and they show a regular trend of increasing vitrinite reflectance with depth (Fig. 11). The investigation of formation resistivity versus maturity has been conducted to date on shales, mostly by authors in the United States (e.g. MEJER & NEDERLOF, 1984; SCHMOKER & HESTER, 1990; FERTL & CHILINGARIAN, 1990; PASEY et al., 1990) who studied the exceptionally organic-rich source rocks of the Bakken Formation, Woodford Shale and Appalachian-Devonian Shales. This investigation has confirmed the applicability of the method to other source rocks (e.g. limestones and shaly

[1] All beta coefficients of discriminant functions are statistically significant.

[2] Beta 0 is the intercept. A typical equation based A/R is:

$D = -17.87 + 8.33\log_{10}\Delta t + 1.21\log_{10}R(24°C)$;

$D > 0$: source rock;

$D = 0$: indeterminate;

$D < 0$: non-source rock.

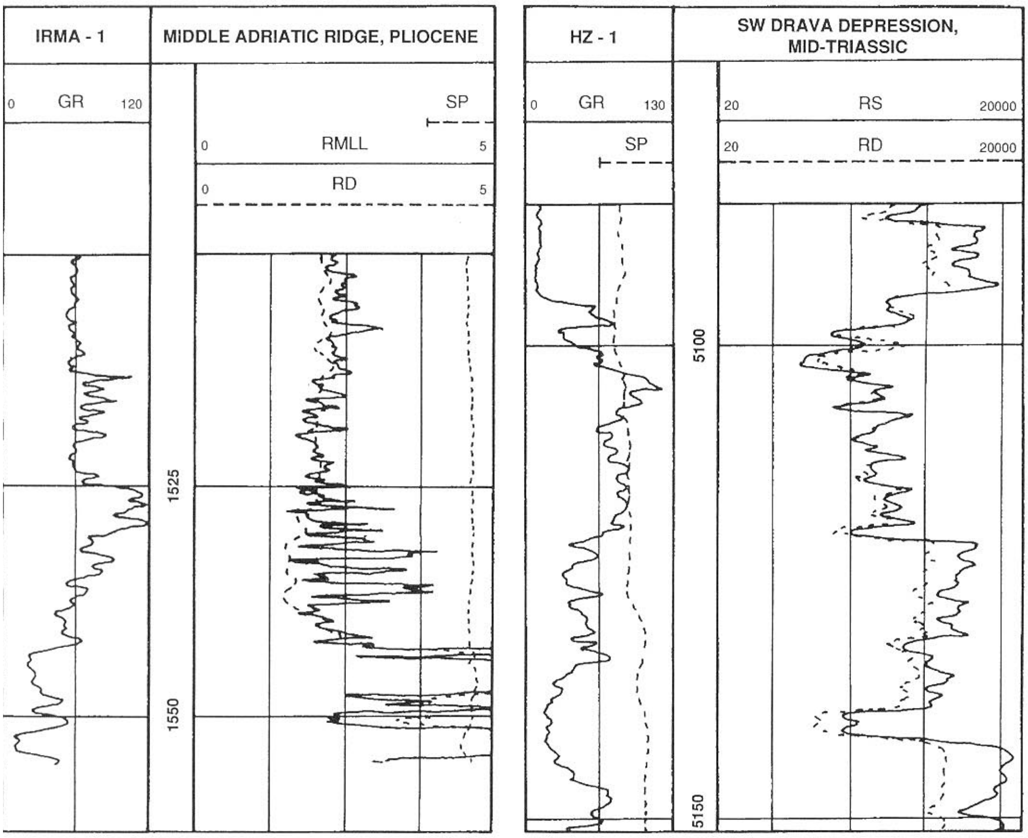

Fig. 5. Resistivity range Ohm∗m in the source rock zone. On well Irma-1 note laminated source rock and electrical anisotrophy.

limestones, etc.; Table 1), provided the appropriate correlation with geochemical analysis has been made. Crossplots of formation resistivity versus one of the geochemical indicators of thermal maturity - the best being vitrinite reflectance (R_o), genetic potential (S1), T.A.I. spore colour index and T_{max} from "Rock-Eval" analysis offer the possibility of calculating a direct empirical link between geochemical and well-logging methods for evaluating source rock maturity. In this way it becomes possible to establish the existence of source rocks in a given area, define their stage of maturity and classify them as oil, and in some cases, gas generating source rocks.

4.1. CROSSPLOTS OF VITRINITE REFLECTANCE (R_o) VERSUS FORMATION RESISTIVITY (R)

The value of vitrinite reflectance increases as time-temperature exposure increases and vitrinite reflectance represents the current level of thermal maturity of the studied source rock and its hydrocarbon generating potential. Figure 9 indicates grouping of data points on the plot into two rectangles. Low values of vitrinite reflectance and formation resistivity in the lower-left rectangle are interpreted as representing thermally immature source rocks, while higher values in the upper-right rectangle represent thermally mature source rocks. The vertical separation of these two groups of data points represents the value of formation resistivity of 32 Ohm∗m. The horizontal boundaries that separate the rectangles correspond to the level of thermal maturity at vitrinite reflectance values of R_o = 0.50-0.51%. The obtained values of vitrinite reflectance and formation resistivity of Miocene limestones in the eastern part of the Drava depression are boundary values that mark the onset of hydrocarbon generation, i.e. they are an indication of source rock maturity. TISSOT & WELTE (1984) correlated the onset of hydrocarbon generation - oil (oil window in type II kerogen; Fig. 10)

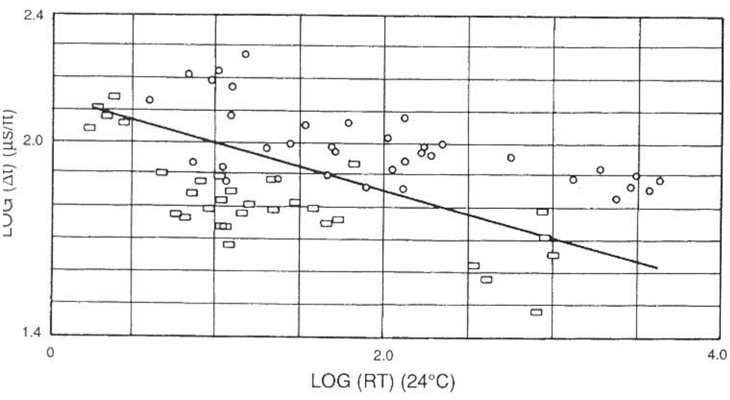

Fig. 6. Sonic transit time and resistivity crossplot, plotted on a logarithmic scale. The oblique line is the position of D=0 (discriminant analysis). Points above this line (D = positive: circle) = source rocks; points below this line (D = negative: rectangle) = non source rock. The analyses are from an area of the Middle Adriatic ridge, Sava and Drava depressions. D = 17.866+8.338∗log(AC)+1.213∗log(RT).

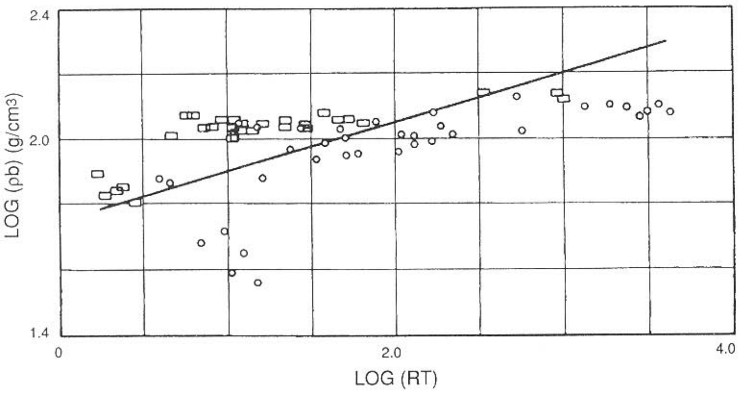

Fig. 7. Bulk density and resistivity crossplot, plotted on a logarithmic scale. Oblique line is the position of D=0 (discriminant analyses). Points below this line (D = positive: circle) = source rocks; points above this line (D = negative: rectangle) = non source rock. Analyses is done in area of the Middle Adriatic ridge, Sava and Drava depressions. D= -5.326+19.366*log(DEN)-1.461*(RT).

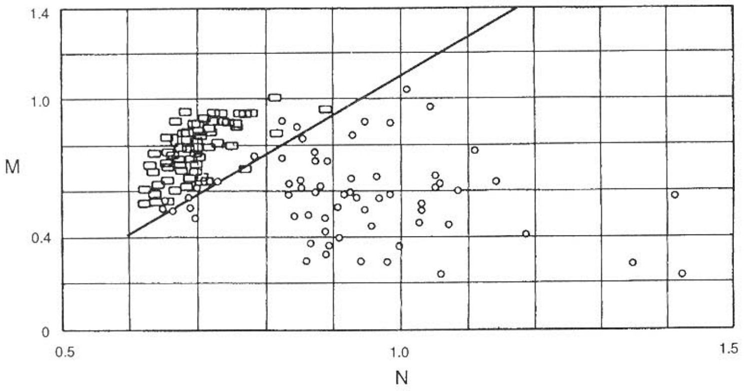

Fig. 8. M/N three component crossplot consist combination of Bulk Density, Sonic transit time and apparent Neutron porosity. Points below this line (D = positive: circle) = source rocks; points above this line (D = negative: rectangle) = non source rock. Analyses are from an area of the Middle Adriatic ridge. D=2.24-6.309*N+3.706*M.

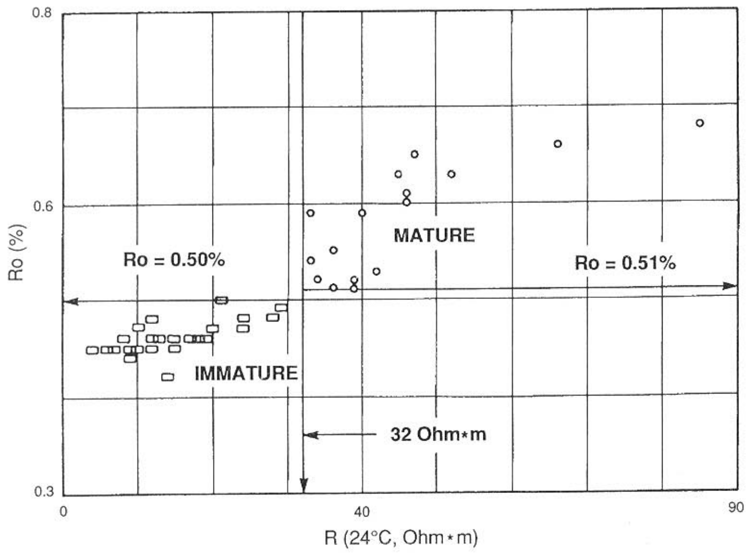

Fig. 9. Vitrinite reflectance (Ro) versus formation resistivity (R) for Miocene source rocks of the eastern part of the Drava depression. Evaluated values of Ro = 0.50-0.51 % and R = 32 Ohm*m divide data between mature and immature source rocks. Data are divided into an upper right rectangle representing thermally mature carbonates that have generated oil and lower left rectangle representing thermally immature carbonates.

to a vitrinite reflectance value of $R_o = 0.50\%$. WAPLES (1985) established that the value of vitrinite reflectance which marks the onset of the oil-window varies with kerogen type. The crossplot of hydrogen index (HI) versus T_{max} clearly shows the kerogen of Miocene limestones in the eastern part of the Drava depression to be of type II (Fig. 10), giving rise to the conclusion that the obtained value of vitrinite reflectance R_o=0.50-0.51% marks the onset of oil generation (i.e. thermal maturity of source rock), and consequently represents a formation resistivity of R = 32 Ohm*m. The cross-section of vitrinite maturity of Miocene limestones in the eastern part of the Drava depression reveals the regular rising trend of reflectance with depth, which points to the identical origin of those rocks. Projection of the obtained "straight-line" to the surface (0.0 m) gives the surface intercept of 0.2% R_o (Fig. 11). The obtained value of vitrinite reflectance of R_o = 0.50-0.51% and formation resistivity of R = 32 Ohm*m from the crossplot also indicates the onset of hydrocarbon generation in the eastern part of Drava depression at an approximate depth of 2,050 m (Fig. 11). According to geochemical analysis, Miocene source rocks are immature to the depth of 2,000 m and a recent temperature of 90°C, with boundary values of vitrinite reflectance R_o = 0.6% for all types of source rocks (the author gratefully acknowledge dr. Gertrud Barić for use of this data from her study performed for "INA-Naftaplin" Zagreb in 1990). The position of the "straight line" which reveals a regular rising trend of vitrinite reflectance with depth

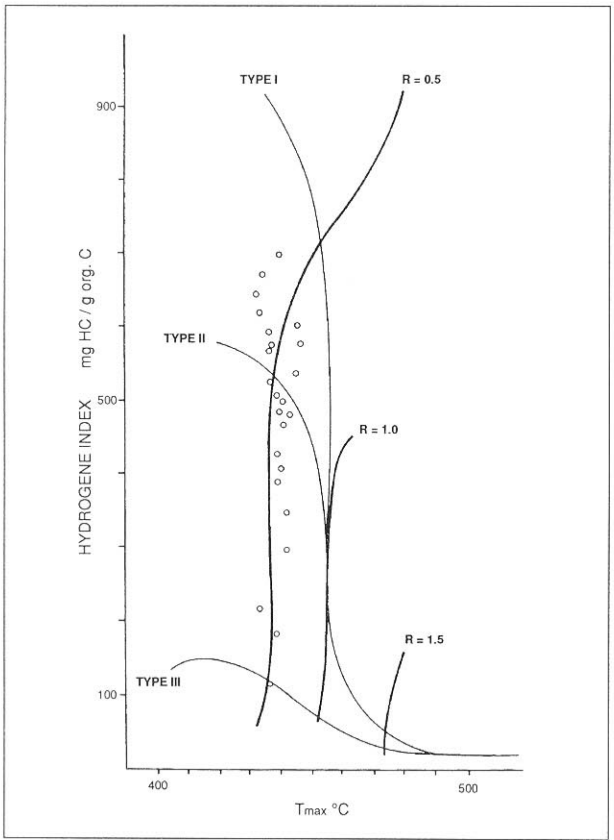

Fig. 10. Kerogen type and mature definition of Miocene source rocks of eastern part of the Drava depression.

has been obtained statistically and it represents a regression (Fig. 11).

4.2. CROSSPLOT OF T_{max} FROM "ROCK-EVAL" ANALYSIS VERSUS FORMATION RESISTIVITY (R)

The evaluation of the maturation stages from "Rock-Eval" analysis in combination with formation resistivity defines formation resistivity as 32 Ohm∗m and that value separates mature from immature source rocks. At this point T_{max} = 435.5 to 436°C. This value represents the beginning of the oil window (onset of oil generation). The maximum measured value of T_{max}= 448°C, and shows Miocene source rocks of the eastern part of the Drava depression to be of source potential with T_{max} in the interval ranging from 435-464°C. Data points grouped in the upper-right rectangle of the cross-plot represent thermally mature source rocks with the above mentioned critical values, while the values in the lower-left rectangle are typical of immature source rocks (Fig. 12).

4.3. CROSSPLOT OF VOLATILE HYDROCARBONS (S1) AND FORMATION RESISTIVITY (R)

The S1/R crossplot shows that low values of S1 in source rocks of the eastern part of the Drava depression (Fig. 13) are associated with low resistivity (R). Conversely, elevated values of S1, which are indicative of oil generation (source rock maturity) are associated with higher values of resistivity (R). This crossplot made allows the boundary value of formation resistivity of 32 Ohm∗m to be defined, which separates mature from immature source rocks, and establishes the value of volatile hydrocarbons (S1) to be 0.32-0.36 mgHC/g of rock. In preparation of the crossplot, where a combination of one of the genetic potentials (S1, S2) and formation resistivity (R) has been used, the combination S1/R proved to be better, since the S2 potential often indicates higher values, even in thermally immature rocks (according to T_{max}), resulting in misclassification (Fig. 13). The resistivity level depends upon several factors: porosity, water resistivity, formation temperature, salinity and mineral composition. Since these values can vary considerably from area to area, the obtained formation resistivity value of 32 Ohm∗m in Miocene limestones-shaly limestones of the eastern part of the Drava depression, should be characteristic of that area, i.e. to the same stratigraphic member or unit of equal or similar petrophysical characteristics. The 32 Ohm∗m resistivity contour can be used to map the source rock intervals in the eastern part of the Drava depression and to separate mature and immature regions. Therefore, at the well site (after completion of

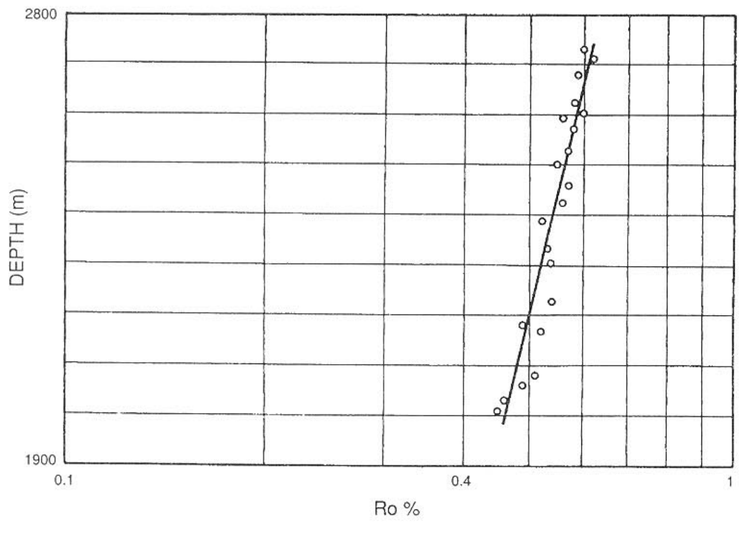

Fig. 11. Vitrinite maturity profile of the eastern part of the Drava depression. Ro=0.0002∗Depth+0.0467.

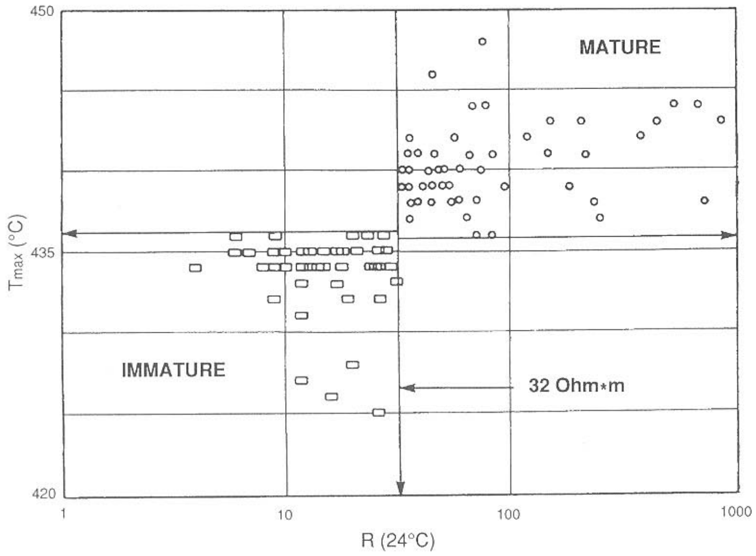

Fig. 12. Tmax from Rock-Eval analysis (Ro) versus formation resistivity (R) for Miocene source rocks of eastern part of the Drava depression. Evaluated values of T_{max} = 435.5-436°C and R=32 Ohm*m are boundary data between mature and immature source rocks. Data are divided into an upper right rectangle representing thermally mature carbonates that generated oil and lower left rectangle representing thermally immature carbonates.

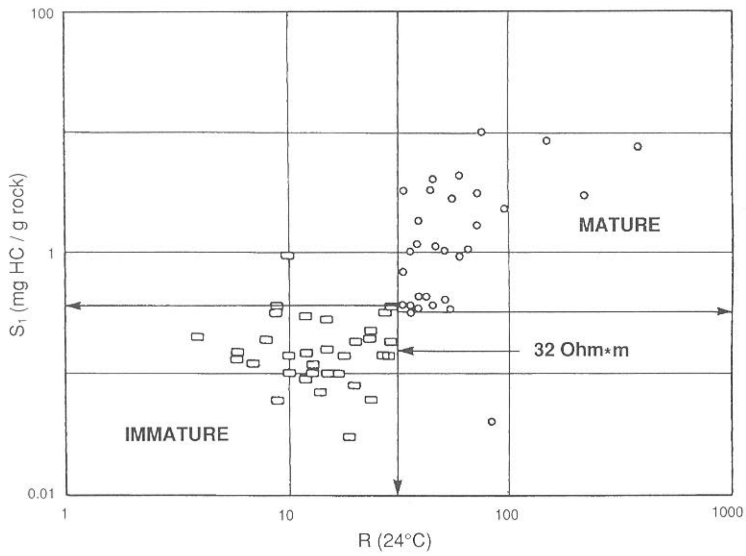

Fig. 13. Volatile hydrocarbons (S1) versus formation resistivity (R) for Miocene source rocks of the eastern part of the Drava depression. Evaluated values of S1 = 0.32-0.36 mgHC/gROCK and R = 32 Ohm*m are boundary data between mature and immature source rocks. Data are divided into an upper right rectangle representing thermally mature carbonates that have generated oil and lower left rectangle representing thermally immature carbonates.

well logging runs) the existence, quantity and quality of source rocks and their areal extent can be established using these crossplots.

5. CONCLUSION

According to geochemical analysis the Miocene source rocks are immature to the depth of 2000 m, and have a recent temperature of 90°C, with a maturity value of vitrinite reflectance of R_0 = 0.6%. By the correlation well logging measurements with geochemical analysis for Miocene limestones, and marly limestones with source rock potential in the eastern part of the Drava depression, a depth of 2050m is indicative of hydrocarbon generation, at vitrinite reflectance values of R_0 = 0.5-0.51%. This depth, therefore, corresponds to that obtained by geochemical analysis alone, with R_0 values which are slightly lower. The discrepancy is the result of the fact that the R_0 = 0.6% value has been taken as an average for all Miocene source rock types in the Pannonian basin, while this research has been limited to limestones - marly limestones of the eastern part of the Drava depression. The obtained value of R_0 = 0.5% is in correlation with values obtained from geochemical analysis, performed in limy deposits only (WAPLES, 1985). Well logging methods applied here to evaluate source rocks and their maturity in the Pannonian basin, have established the existence of source rocks in sediments older than the Miocene (Middle Triassic). Beyond the Pannonian basin, source rocks have been established in sediments younger than the Miocene, particularly in the Pliocene of the Middle Adriatic ridge. Geochemical analysis conducted on Pliocene deposits in the Middle Adriatic ridge have confirmed them to be in the immature stage, with biogenic gas generating potential. Mid-Triassic source rocks in the SW part of the Drava depression are in the late maturity stage. Further use of well logging measurements aimed at the evaluation of source rock maturity will make a valuable contribution to geological research associated with the production of oil and gas.

Well logging surveys have confirmed the existence of source rocks in the broader area of Croatia, in strata covering a large stratigraphic range from the Triassic to Pliocene), different p/T conditions (5,175-1,450 m),

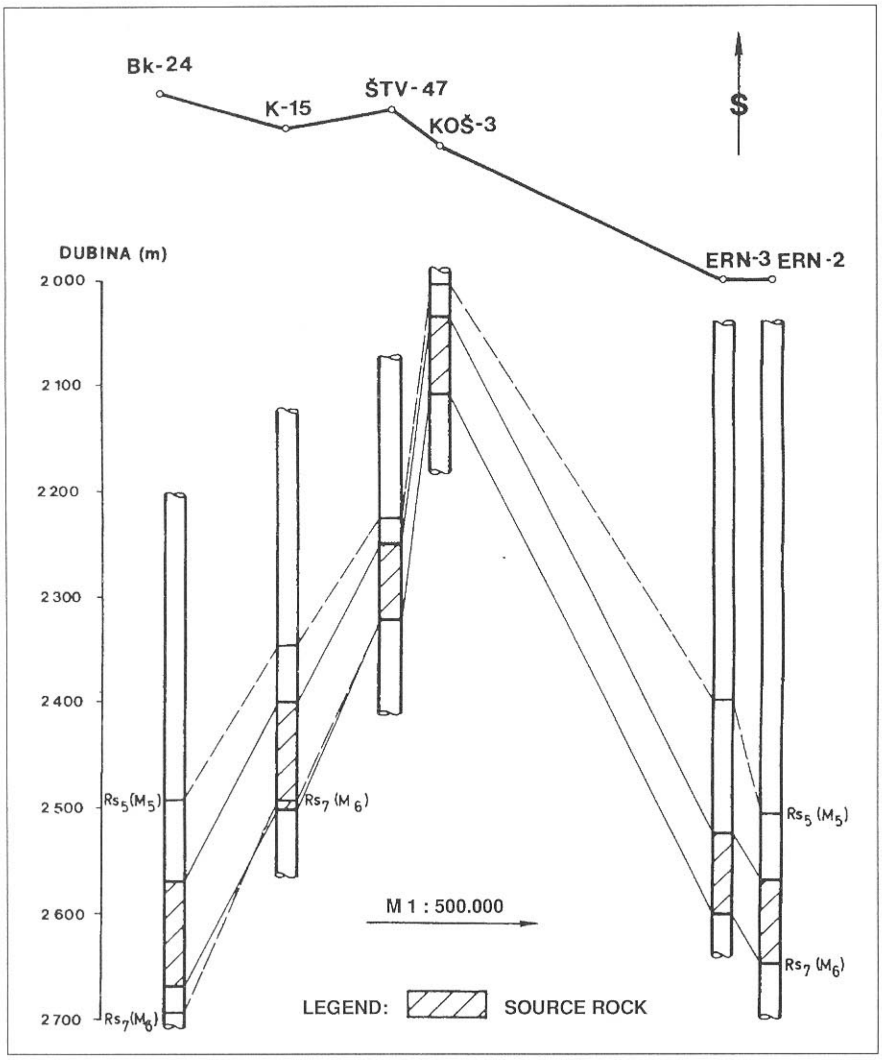

Fig. 14. Schematic profile of studied Miocene source rocks of the eastern part of the Drava depression. Markers Rs5 (M5) and Rs7 (M6) are stratigraphic boundaries of the Valpovo Formation.

varied lithologies (shales, silty marls, limestones, shaly limestones and carbonate phyllite) and different depths of burial (5,175-1,450 m) and a great diversity of petrophysical parameters. Investigation of the Miocene limestones of the eastern part of the Drava depression, where the method has been verified and calibrated, provided the following well-logging and geochemical indicators and parameters, characteristic for the boundary values between mature and immature source rocks:

- Formation resistivity, R = 32 Ohm∗m;
- Vitrinite reflectance, R_o = 0.5-0.51%;
- "Rock-Eval" analysis, T_{max} = 435.5-436°C;
- Volatile hydrocarbons, S1 = 0.32-0.36 mgHC/g rock;
- They were classified as type II kerogen;
- The increase of vitrinite reflectance is directly proportional with depth;
- The onset of hydrocarbon generation in the eastern part of the Drava depression can be linked to a approximate depth of 2050m.

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