|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| GEOL. CROAT. | 50/1 | 89 - 103 | 19 Figs. | 2 Tabs. |  | ZAGREB 1997 |

# Pliocene Source Rocks, Miocene Reservoir Rocks and Origin of the Gas Accumulation of the Irma Field (Northern Adriatic, Croatia) Based on Wireline-Logging

Ivica **VULAMA**

**Key words:** Pliocene source rocks, Miocene reservoir rocks, Messinian unconformity, Wireline logging, Geochemical analysis, Discriminant function, Overpressure zone, Biogene gas, Middle Adriatic ridge, Croatia.

**Ključne riječi:** pliocenske matične stijene, miocenske kolektorske stijene, mesinijanska diskordancija, geofizička mjerenja, geokemijske analize, diskriminantna funkcija, nadpritisnute zone, biogeni plin, srednjojadranski prag, Hrvatska.

### Abstract

The Pliocene source rocks of the Middle Adriatic ridge appeared to be thermally immature, according to the geophysical and the geochemical analyses, but they may have produced biogene gas. Wireline logging confirmed their broad extent. Correlation between geophysical and geochemical data indicated their distinguishing parameters: GR = 55 - 125 API, $U^{238}$ = 5 - 25 ppm, Rt = 1.5 - 4 Ohmm, $\Delta_t$ = 75 - 170 µs/ft (x 0.306 µs/m), $\rho_{sr}$ = 1.6 - 1.9 g/cm$^3$, $\phi_N$ = 33 - 39%, SP = -44 (-) -56 mV, Corg. = 0.43 - 3.23%, $V_{ot}$(%) = 0.47 - 0.66, K/Th = Illite. These organic matter have been classified as a kerogene type III-II. Characteristic geophysical parameters of the Miocene reservoir rocks are: $\phi$ = 22%, $R_w$ = 0.18, m = 1.8, Fr = 15.3, $R_o$ = 2.75 Ohmm, K avg. = 21.4 x $10^{-3}$ µm$^2$. Favorable lithologic-tectonic conditions (overpressure zones, normal faulting) led to gas accumulation in Miocene calcarenites and sandstones. The Pliocene source rocks discordantly overlie Miocene reservoir rocks, separated by the Messinian unconformity. Statistical analyses show that, although the Pliocene shales are thermally immature, they fit into the model of source rock recognition.

### Sažetak

Pliocenske matične stijene srednjojadranskog praga pokazale su se prema geokemijskim analizama termalno nezrelim, ali imaju mogućnost proizvodnje biogenog plina. Primjenom geofizičkih mjerenja u bušotinama utvrđena je njihova šira rasprostranjenost, te su korelacijom geofizičkih i geokemijskih mjerenja utvrdeni sljedeći parametri za njihovo prepoznavanje: GR = 55 - 125 API, $U^{238}$ = 5 - 25 ppm, Rt = 1.5 - 4 Ohmm, $\Delta_t$ = 75 - 170 µs/ft (x 0.306 µs/m), $\rho_{sr}$ = 1.6 - 1.9 g/cm$^3$, $\phi_N$ = 33 - 39%, SP = -44 (-) -56 mV, Corg. = 0.43 - 3.23%, $V_{ot}$(%) = 0.47 - 0.66, K/Th = Illite. Klasificirane su kao tip III i II kerogena. Karakteristični geofizički parametri miocenskih rezervoarskih stijena plinskog polja Irma dobiveni iz geofizičkih mjerenja u bušotinama su: $\phi$ = 22%, Rw = 0.18, m = 1.8, Fr = 15.3, $R_o$ = 2.75 Ohmm, K avg. = 21.4 x $10^{-3}$ µm$^2$. Povoljni litološki i tektonski uvjeti (nadpritisnute zone, normalno protusmjerno rasjedanje) uzrokovali su nakupljanje plina u miocenskim kalkarenitima i pješčenjacima na koje naliježu Pliocenske matične stijene čiju granicu čini mesinijanska diskordancija. Statistička je analiza pokazala da se pliocenski šejlovi, iako su termalno nezreli, mogu opisanim metodama prepoznati kao matične stijene.

## 1. INTRODUCTION

The Irma Oil field is located in the south-west part of the Middle Adriatic ridge along the border line between Croatia and Italy (Fig. 1). The structural-contour map for the Messinian reservoir (seismic marker "A") shows position where Irma-1 well was drilled, and more to the northwest where Irma-2 well was drilled. The whole area is represented by an anticlinal closure spreading southward over the international boundary line, onto the Barbara field in Italy. To the north, the structure is closed by a normal fault with 26 m throw (Figs. 1 and 2).

Pliocene sediments discordantly overlie the Miocene deposits beneath the Messinian unconformity. In the lower part of the transgressive sequence, these Pliocene sediments have source rocks characteristics recognized by wireline log interpretation, and confirmed by geochemical analyses. The seismic marker "A" also represents an excellent wireline logging marker in the base of the source rocks recognized on the wells Irma-1, 2, 2$\alpha$, 3, 4, Suz-1, Ines-1, Inga-1, Iln-1, J-7, J-22/1 and J 23/1 (Figs. 2 and 3). The source rocks probably also extend southward across the border with Italy (Barbara field) but the Italian well data are not available for study.

Previous work in these area emphasize the existence of source rocks in the region of Middle Adriatic ridge (VULAMA, 1991, 1994). The geological setting of this area was documented by KADIJA et al. (1991), KADIJA (1992), TARI KOVAČIĆ (1995) and MILETIĆ & LUGOVIĆ (1996). Geochemical data were provided by INA-Naftaplin laboratory.

The input data base comprised resistivity, acoustic, density, apparent neutron porosity, spontaneous potential, microlog and spectralog (K, Th and U) logging responses with a secondary geochemical data base:

---

INA-Naftaplin, Šubićeva 29, HR-10000 Zagreb, Croatia.

Fig. 1 Location map of the Middle Adriatic ridge source rocks in the study area.

Corg. content, Tmax. from pyrolysis, Hydrogen index, vitrinite reflectance (Ro), and genetic potential $S_1$ and $S_2$.

The possibility of the recognition and qualification of immature Pliocene source rocks, which possibly produce biogenic gas is discussed together with the origin of gas accumulation in gas field Irma based on wireline logging. The applied methods include classical logging data computed and interpreted through various resistivity, acoustic, density, neutron etc. combinations of crossplots and statistical analysis (discriminant function) correlated with geochemical analyses.

## 2. STRATIGRAPHY

The lowermost Cretaceous, Palaeocene, Eocene, Oligocene, Miocene, Pliocene and Quaternary sediments were drilled across the exploration area. Only those Miocene, Pliocene and Quaternary sediments which are related to the described source and reservoir rocks are discussed briefly.

The Miocene sediments are represented by light gray limestones and gray to light gray fossiliferous marls. The quantity of clay in the limestones varies from 10-80%, while sandy limestones (calcarenites) often occur, which represent good collectors. The average depth of the top of the Miocene sediments is approximately 1500 m (KADIJA, 1992).

Pliocene sediments are mostly represented by less fossiliferous gray to dark gray organic-rich shales, with interbedded sand and silt (MILETIĆ & LUGOVIĆ, 1996). The average depth of the top of the shales is approximately 1420 m (KADIJA, 1992).

Quaternary sediments are represented by marls, clays and poorly to non consolidated sands and silts, and in the shallower parts by coal interbeds. In the deeper part (below approximately 1200 m) marls are more frequent, where the overpressure zone begins. In the deepest parts above the Pliocene sediments, lower concentrations of organic matter were observed.

## 3. TECTONICS

The withdrawal of the African plate beneath the Euro-Asian plate formed the Adriatic Depression situated between the uplifted Outer Dinarides and the Apennines (PRELOGOVIĆ & KRANJEC, 1983). Eocene

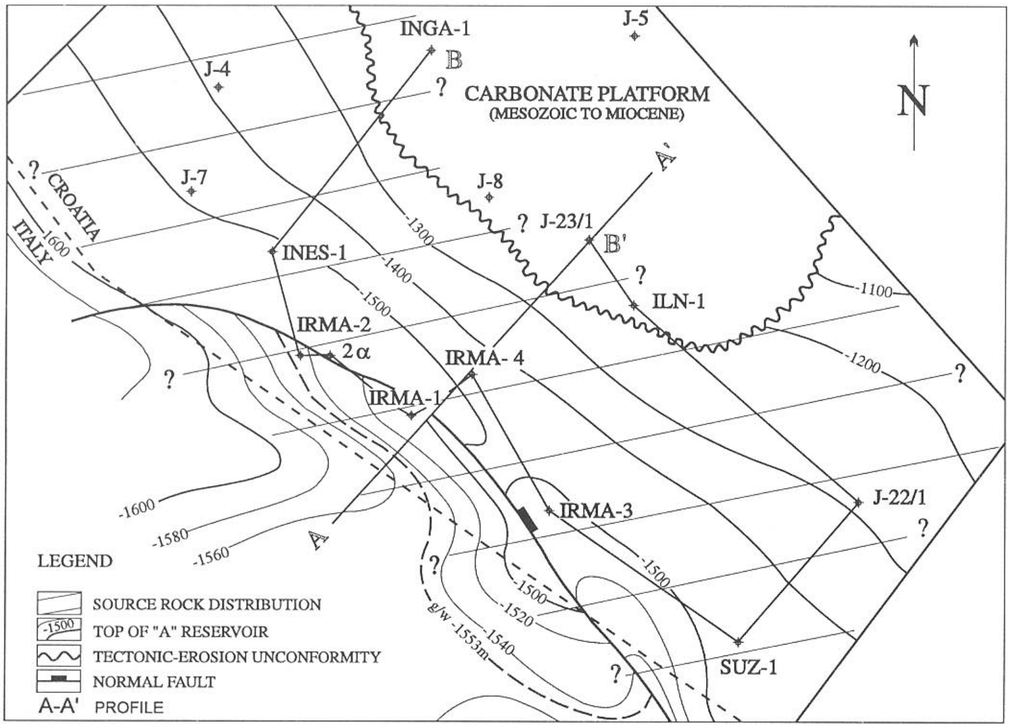

Fig. 2 Structural contour map of the top of the "A" reservoir (after KADIJA et al., 1991) of the Irma gas field with distribution of the source rocks overlying the top of the reservoir (profile B-B').

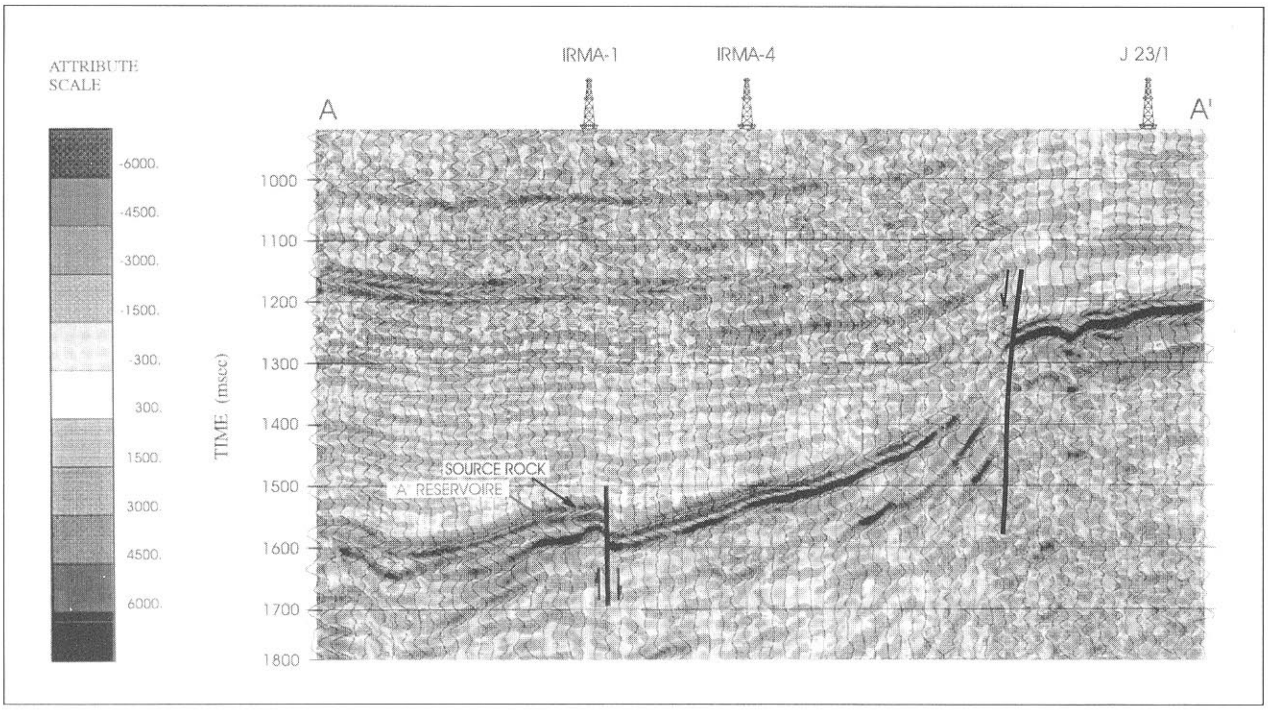

Fig. 3 Seismic section profile A-A' with position of the source rocks and "A" gas reservoir.

tectonic movements caused normal faulting (Figs. 2 and 3) and the uplifting of the "Middle Adriatic ridge" area. The Eocene fault zone remained active during the Miocene when fault related traps were formed. Erosion of the uplifted sediments infilled the Adriatic Depression. The depositional surface of the Pliocene sediments was dominated by multiphase tectonic activity, as well as Quaternary sediment deposition. These tectonic movements caused faster subsidence of the African plate which exceeded deposition rate, and resulted in deposition of transgressive sediments in a North-East direction. This explains the increased sediment thickness of the South-West and reduced sequence to the North-East.

## 4. GEOPHYSICAL WIRELINE-LOG RESPONSES CHARACTERISTIC FOR SOURCE ROCKS IN BASE OF THE PLIOCENE SHALES

All the available logging surveys: natural radioactivity, sonic transit time, bulk density, apparent neutron porosity, formation resistivity, spectralog, crossplots and statistic analysis were applied to determine the recognition and classification of the source rocks.

### 4.1. NATURAL GAMMA-RAY LOGGING

The increased natural radioactivity in the clastic and carbonate sediments is the first indication of a possible source rock, if the sediments are of marine origin. Fresh water source rocks do not show high natural radioactivity because fresh water does not contain uranium ions. In the Pliocene basal shale natural radioactivity as high as 130-150 API units has been observed, while the basal and uppermost sediments can be characterized by 40-110 API units (Figs. 4, 5 and 16).

### 4.2. SONIC TRANSIT TIME LOGGING

Sonic transit time logging ($\Delta_t$), as well as bulk density logging, indicate differential compaction between sediments poor in organic matter and the source rocks. Sonic transit time indicates the organic rich layer within the impermeable sediments (Figs. 4 and 5). The sonic transit time wireline logging is more useful than bulk density logging in the cases where the hole is rugose or if heavy minerals (e.g. pyrite) occur. As the sonic transit time is a function of several factors (water - organic matter relation, mineral content, carbonate and clay content and pressure), it is always useful to apply combinations of the various types of logs. The various crossplot combination of sonic transit time and resistivity proved very effective. The most often used crossplots include the following combinations: sonic transit time, formation resistivity, bulk density, natural radioactivity, apparent neutron porosity or cores correlation's (calibration), as presented on Figs. 4 and 5. Sonic logging can also be applied to calculate the total sonic transit time (ms) and the interval velocities (m/s), which can distinguish the source rocks (Fig. 6). The interval velocity curve (ITVI) shows the clear decline of the sonic transit time in the source rock zones.

### 4.3. BULK DENSITY LOGGING

Bulk density ($\rho_b$) is a function of matrix density ($\rho_{ma}$) and fluid density ($\rho_f$). The greater the fluid content

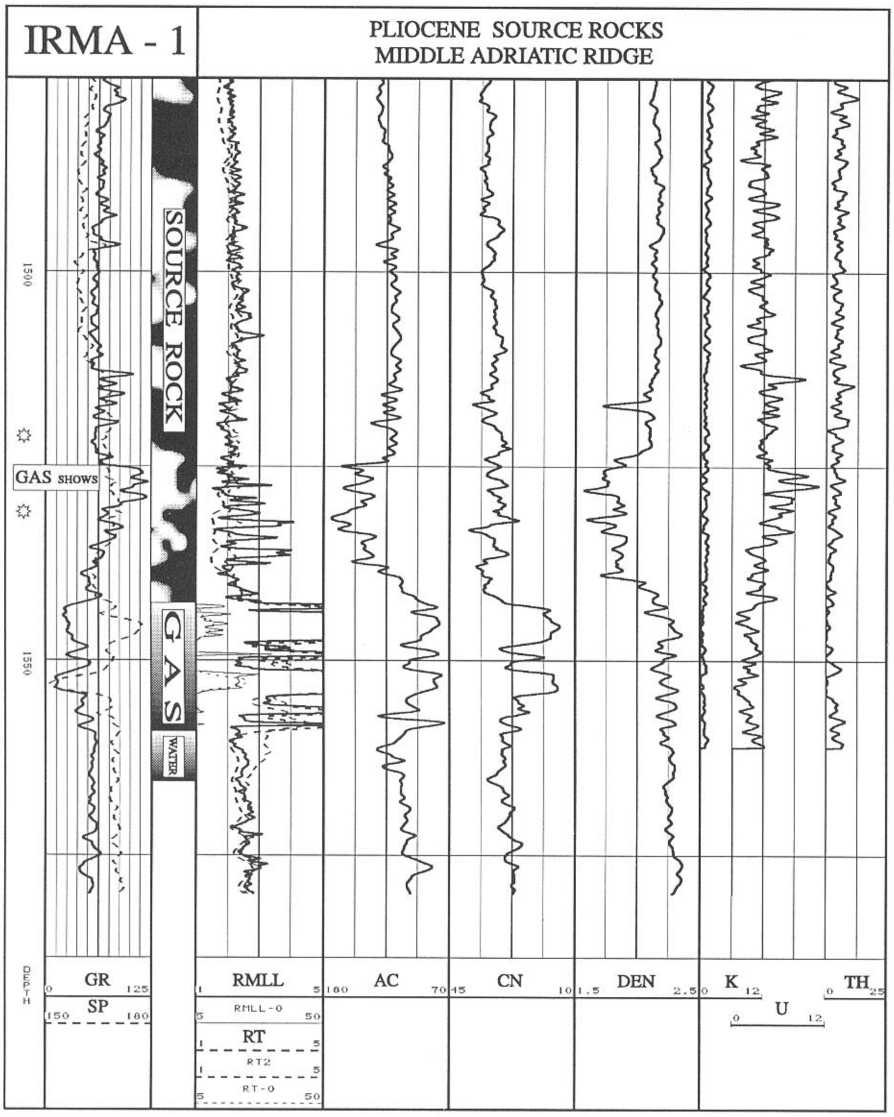

Fig. 4 Composite log responses characteristic for Pliocene source rocks, Irma-1.

of the formation, the greater the rock porosity. The equation for calculating rock porosity ($\phi$) is as follows:

$$\phi=(\rho_{ma}-\rho b)/(\rho_{ma}-\rho_f).$$

In marls (shales) with almost identical degrees of compaction, all the physical parameters, even the water saturation ($S_w$) are equal. If the source rock density ($\rho_{sr}$) is lower than the shale-marl density ($\rho_{sh}$), then organic matter ($\rho_{om}$) is present, and this implies that these marls (shales) are impermeable and indicates that the rock density decline is not the result of the hydrocarbon (fluid) presence in the rock.

Within the above mentioned assumptions it is possible to calculate the volume percentage of the organic matter - $V_{ot}(\%)$:

$$V_{ot}(\%) = (\rho_{sh} - \rho_{sr})/(\rho_{sh} - \rho_{om})$$

The density of organic matter ($\rho_{om}$) is almost equal to the water density ($\rho_w$) = 1g/cm$^3$.

The average $V_{ot}(\%)$ value for Middle Adriatic ridge source rocks is 0.47-0.66 %.

Figures 3, 4 and 8 show the decline in bulk density in the source rock zone compared to the overlying and underlying layers. Bulk density logging in the layer above the source rock interval (Irma-1 well; Pliocene deposits - silt-shale) suggested 2.15 g/cm$^3$ as the average bulk density while in the source interval this value was 1.6 g/cm$^3$. The average vertical resolution of the wire logging tools - FDC (Schlumberger) and CDL (Dresser Atlas) for rock density survey is around 60 cm.

In recognizing source rocks by bulk density logging, special attention should be paid to the higher concentration of heavy minerals, especially pyrite indicating reducing conditions (as well as the presence of organic matter). Radioactive thorium Th$^{232}$ is very often bonded to pyrite, as in the case of the Irma gas field (Figs. 4 and 5). Hole rugosity is also important due to the presence of fluid in the increased hole diameter. This applies similarly to strata containing fluid in pore/fracture space.

## 4.4. APPARENT NEUTRON POROSITY LOGGING

Apparent neutron porosity logging ($\phi_N$) is primarily performed in the evaluation of the porosity and lithology. The measurement is primarily the response of

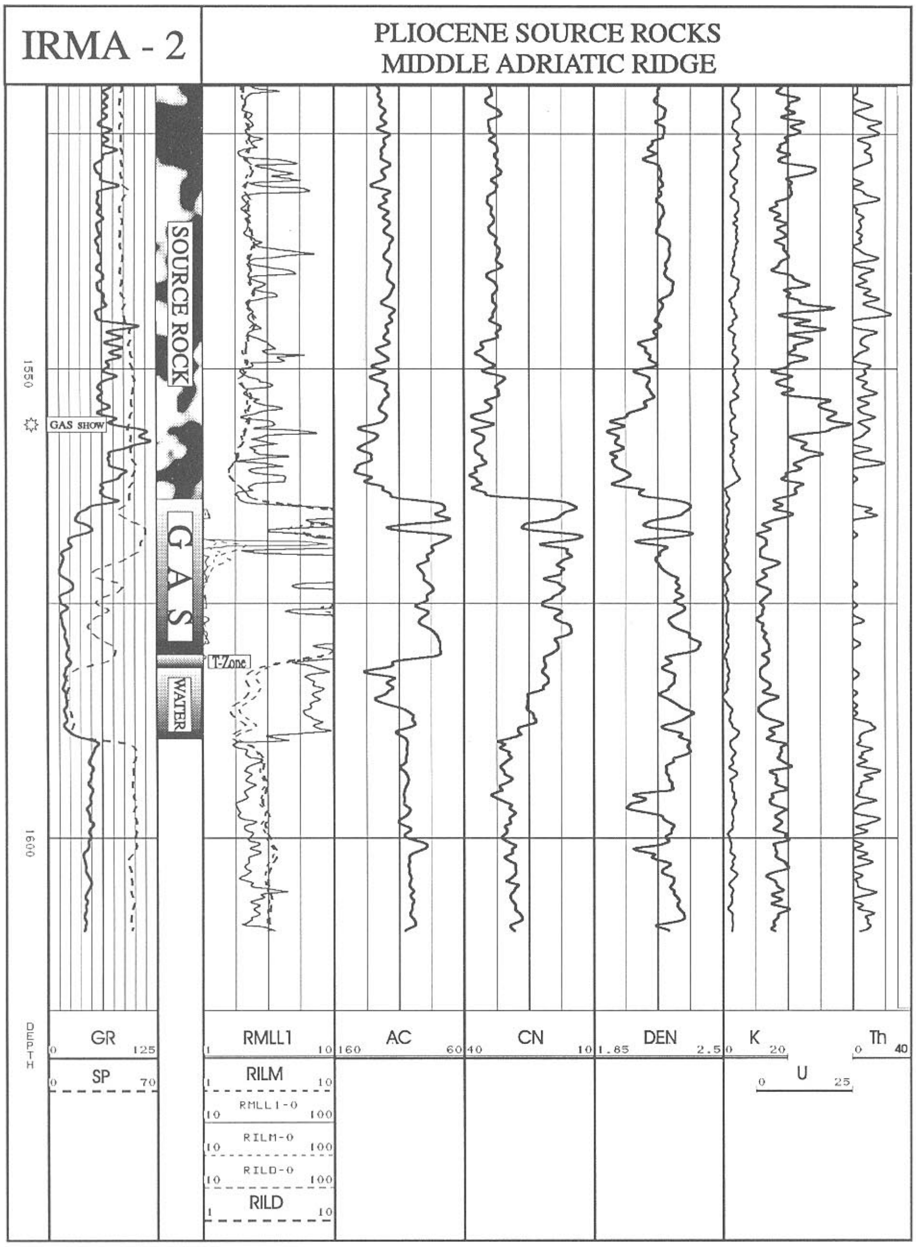

Fig. 5 Composite log responses characteristic for Pliocene source rocks, Irma-2.

hydrogen atoms present in the rock (they are mostly bonded to fluids or organic matter - hydrocarbons). When the hydrogen atom concentration is high, the high-energy neutrons slow down and are captured in the nuclei at a short distance from the logging tool. Accordingly, any increase in the concentration of hydrogen atoms will cause an apparent increase in neutron porosity, registered by logging tool counting. It can be interpreted as the presence of fluids, free hydrocarbons and/or organic matter in the pore space. The shales and silty shales are impermeable rocks, so it is expected that the apparent porosity increase is caused by the higher concentration of hydrogen atoms of organic matter (Figs. 4, 5 and 8).

## 4.5. FORMATION RESISTIVITY LOGGING

Any formation resistivity logging can be used to recognize source rocks. For impermeable rocks, both shallow and deep surveys should give same or similar conductivity values (formation resistivity; Figs. 4 and 5). It is necessary to use microresistivity measurements in the cases of thin intercalations of organic matter in shales, marls etc. These appliances are characterized by considerably better vertical resolution. An example is presented on Figs. 4 and 5 (Irma-1 and 2). In the source rock zone the deep induction log (RT, RILD) does not show increased resistivity, although, according to the other surveys and geochemical analysis the high TOC of that interval has been recognized (VULAMA, 1991, 1994). However, the microlatherolog measurement (RMLL) indicated higher resistivity in the same interval.

Source rocks are often laminated and therefore electrically anisotropic. This anisotropy increases the resistivity of the interbedded organic-rich layers, especially when the source rock is mature. Resistivity can indicate source rock maturity (VULAMA, 1991, 1993, 1994).

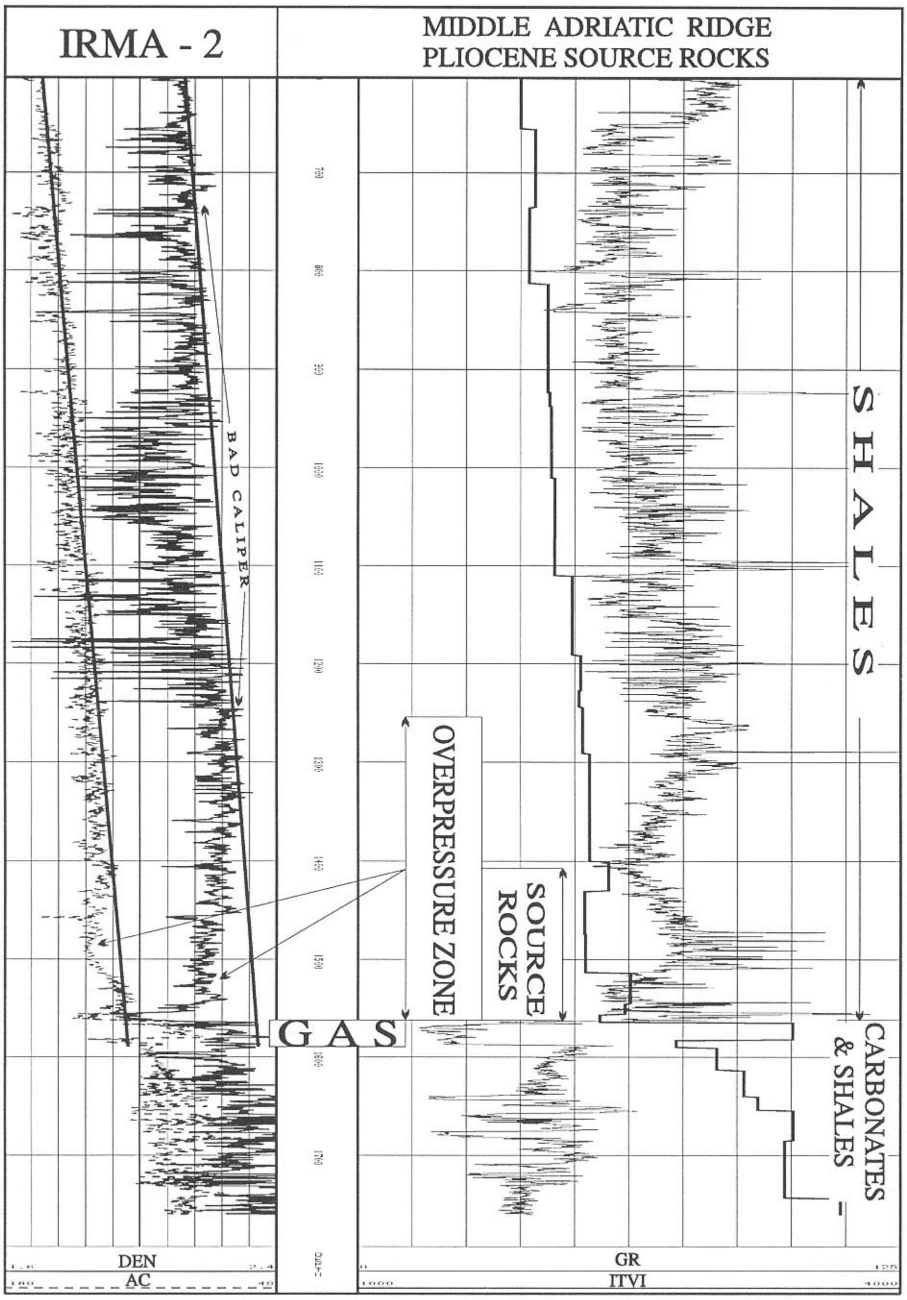

Fig. 6 Composite log responses of the Pliocene source rocks on sonic (AC), bulk density (DEN), gamma ray (GR) and sonic interval transit time (ITVI). Note the characteristic sonic and density log response (increase of sonic transit time, decrease of bulk density) of the Overpressure zone beginning approximately at 1260 m depth.

Example of anisotropy (laminae) and low maturity (low resistivity values) can be seen on Figs. 4 and 5 (RMLL).

The irregular hole diameter (rugosity) can influence the formation resistivity. This is more obvious in case of shallow investigation tools. Further more, resistivity values can be influenced by rock anisotropy (different vertical and horizontal resistivity), temperature and wire logging tool characteristics (investigation depth, invasion diameter, vertical resolution and the geometrical factor).

## 4.6. NATURAL GAMMA RAY SPECTROMETRY (SPECTRALOG)

Spectralog proved to be the most reliable method in recognizing the presence of organic matter. Numerous explorationists (SCHMOKER, 1981; MEYER, 1984, etc.) recognized that the higher radioactivity of the source rock zone is related to the uranium ($U^{238}$) content of the sediments (Figs. 4 and 5). It is assumed that plankton and various organisms absorb the uranium salts (ions) from the sea water together with other rare elements and in this way uranium is concentrated in source rocks.

It is also necessary to pay attention to the concentration of heavy minerals, especially pyrite, as its origin is connected to reducing conditions as well as organic matter. Radioactive thorium $Th^{232}$ is very often bonded to pyrite as is the case in the wells of the Irma gas field (Figs. 4 and 5).

Recognition of high uranium radioactivity in marine sediments is almost certainly indicative of the organic richness of those rocks, as it was confirmed by numer-

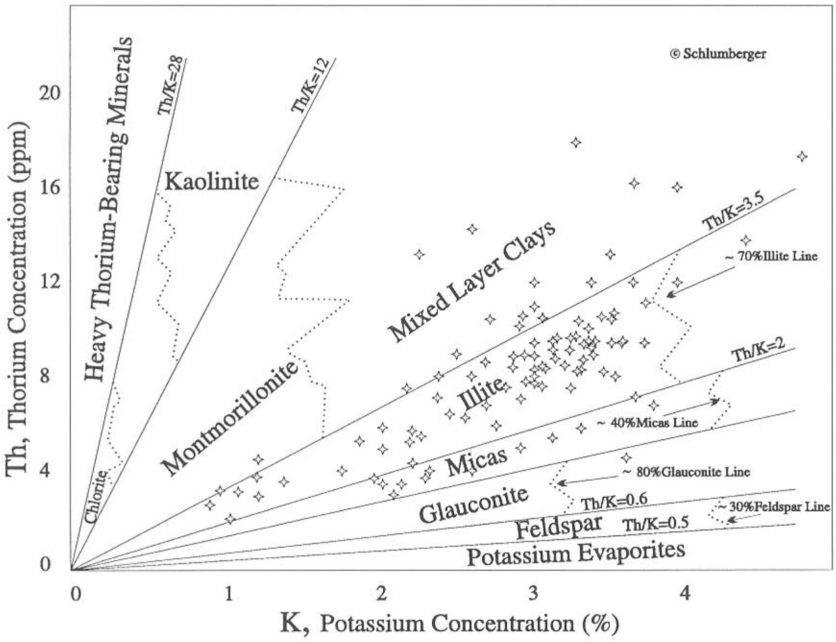

Fig. 7 Thorium vs. potassium crossplot of the Pliocene source rocks.

ous studies for the Croatian exploration area (VULAMA, 1991, 1993, 1994). There are published case studies where uranium is concentrated in fracture systems through which connate water flows (uranium is not transported by migration processes because it remains bonded to the heaviest hydrocarbons in the organic matter). However, the existence of such fractures in our wells has not been confirmed.

## 4.7. SOURCE ROCK IDENTIFICATION BY CROSSPLOTS

Numerous authors (MEYER & NEDERLOF, 1984; FERTL & CHILINGARIAN, 1980, 1990; SCHMOKER & HESTER, 1990, etc.) used various combinations of crossplots to identify source rocks. The most common combinations were: bulk density and true (formation) resistivity or sonic transit time and true resistivity. These combinations of two-component diagrams proved to be useful for qualitative rock evaluation.

Four types of measurement are included in the four component M/N/(Z) and A/K/(Z) diagrams: bulk density ($\rho_b$), apparent neutron porosity ($\phi_N$), sonic transit time ($\Delta_t$) and as the fourth component - a measurement representing the third dimension - Z (natural radioactivity GR - or certain part of the spectrum - K, U or Th, or spontaneous potential - SP, as a rock permeability indicator).

M,N and A,K are practically related to rock porosity. Organic matter is less dense and compact than the rock matrix and gives the reflection of apparent porosity. M, N, A and K are reached by survey combination calculation as follows:

$$M = (\Delta_{tf} - \Delta_t) / (\rho_b - \rho_f),$$

where $\Delta_t$ = sonic transit time; $\Delta_{tf}$ = sonic transit time in

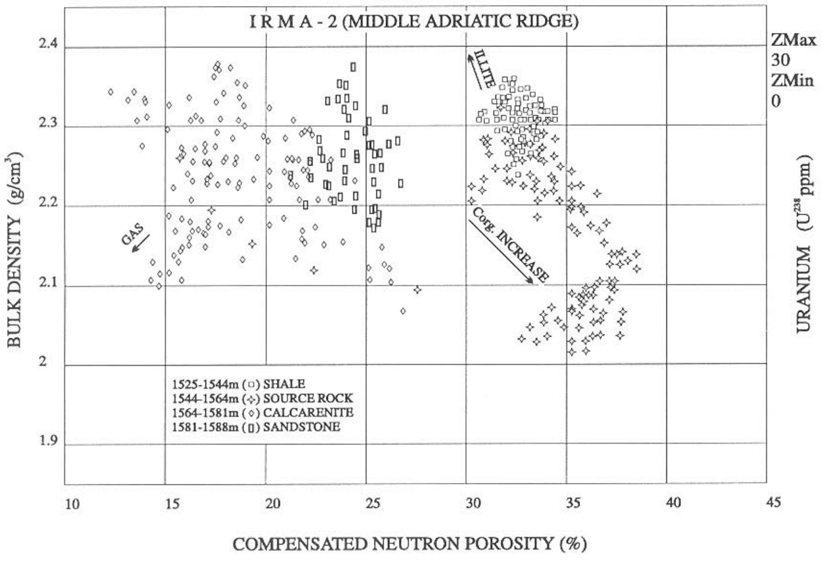

Fig. 8 Bulk density vs. compensated neutron porosity vs. Z (uranium) crossplot of the Pliocene source rocks.

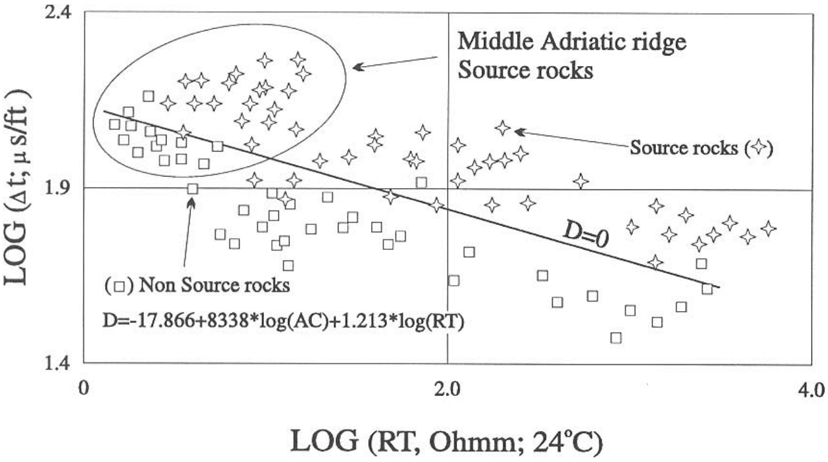

Fig. 9 Sonic transit time vs. resistivity crossplot plotted on logarithmic scale. The oblique line is the position of D=0 (Discriminant analysis). Points above this line (D=positive: star) = source rocks; points below this line (D=negative: rectangle) = non source rock. The analyses are from an area of the Middle Adriatic ridge, Sava and Drava depression (after VULAMA, 1994).

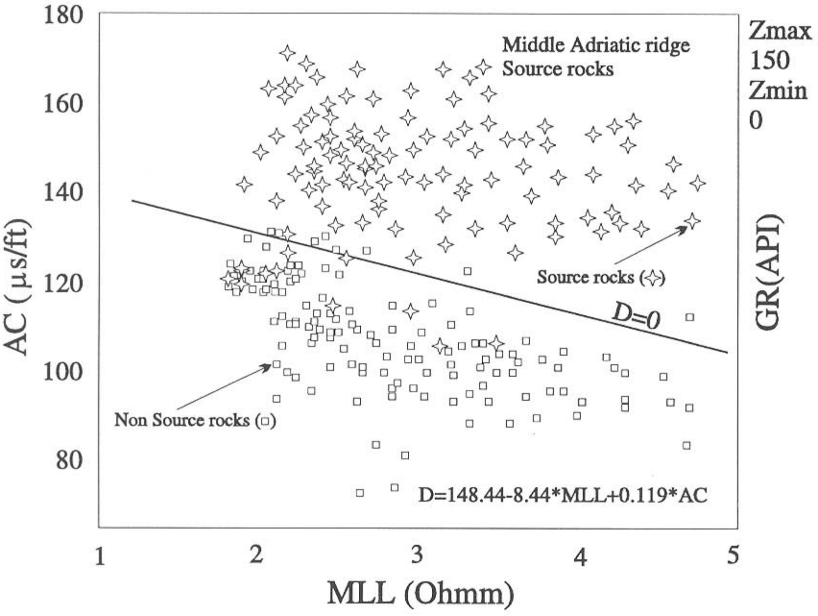

Fig. 10 Sonic transit time vs. resistivity crossplot plotted on linear scale. The oblique line is the position of D=0 (Discriminant analysis). Points above this line (D=positive: star) = source rocks; points below this line (D=negative: rectangle) = non source rock. The analyses are from an area of the Middle Adriatic ridge.

water (for fresh water it is 189 µs/ft, whereas for the salt water is 185 µs/ft∗0.306 µs/m); $\rho_b$ = bulk density (g/cm$^3$); $\rho_f$ = fluid density (for fresh water it is 1.0 g/cm$^3$, whereas for salt water it is 1.1 g/cm$^3$).

$$N = (\phi_{Nf} - \phi_N) / (\rho_b - \rho_f),$$

where $\phi_N$ = apparent neutron porosity (%); $\phi_{Nf}$ = neutron water porosity which is 1, or 100%, so the equation should read:

$$N = (1 - \phi_N) / (\rho_b - \rho_f)$$

$$A = (\rho_b - \rho_f) / (1 - \phi_N)$$

$$K = 0.01\ (\Delta_{tf} - \Delta_t) / (1 - \phi_N)$$

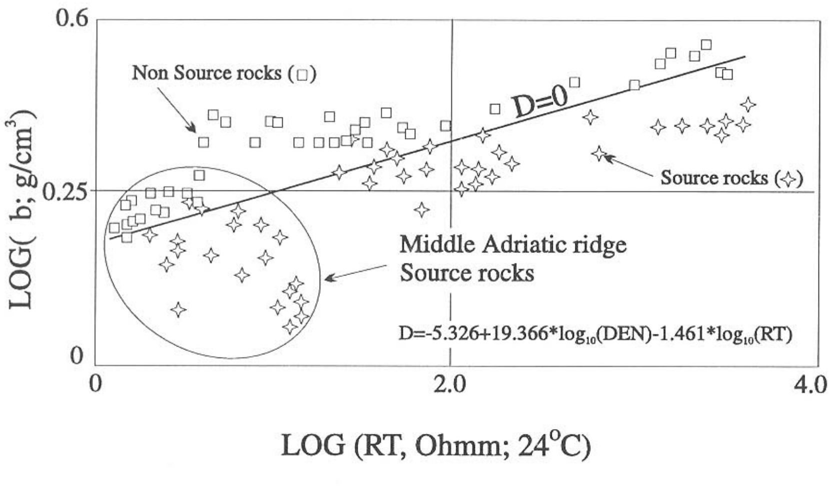

Fig. 11 Bulk density vs. resistivity crossplot plotted on the logarithmic scale. The oblique line is the position of D=0 (Discriminant analysis). Points below this line (D=positive: star) = source rocks; points above this line (D=negative: rectangle) = non source rock. The analyses are from an area of the Middle Adriatic ridge, Sava and Drava depression (after VULAMA, 1994).

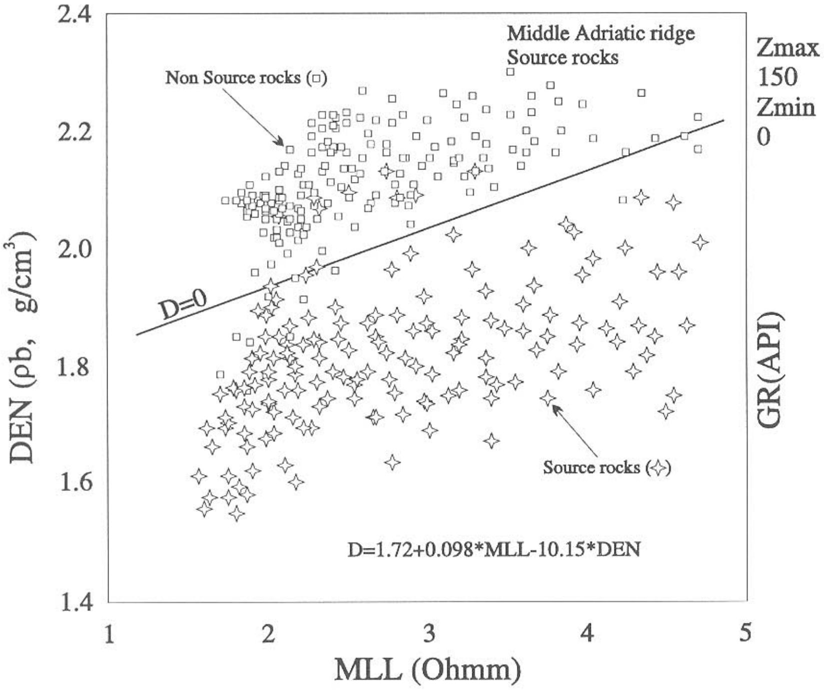

Fig. 12 Bulk density vs. resistivity crossplot plotted on the linear scale. The oblique line is the position of D=0 (Discriminant analysis). Points below this line (D=positive: star) = source rocks; points above this line (D=negative: rectangle) = non source rock. The analysis is from an area of the Middle Adriatic ridge.

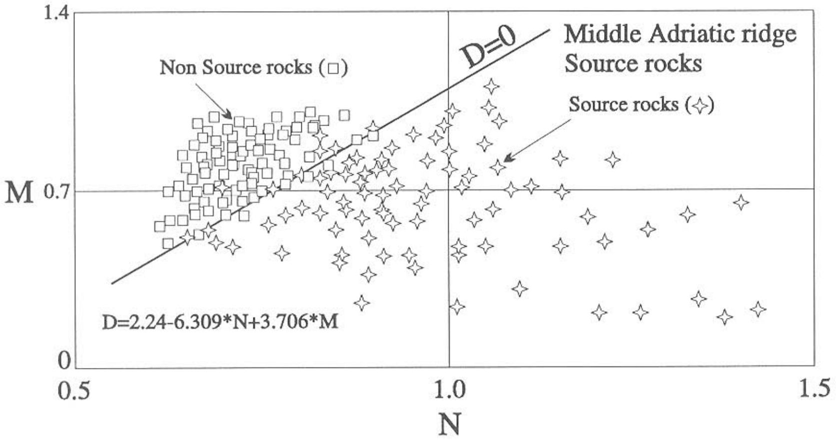

Fig. 13 M/N(Z) four component crossplot consisting of a combination of sonic transit time, bulk density, compensated neutron porosity and $Z=U^{238}$. The oblique line is the position of D=0 (Discriminant analysis). Points below this line (D=positive: star) = source rocks; points above this line (D=negative: rectangle) = non source rock. The analyses are from an area of the Middle Adriatic ridge (after VULAMA, 1994).

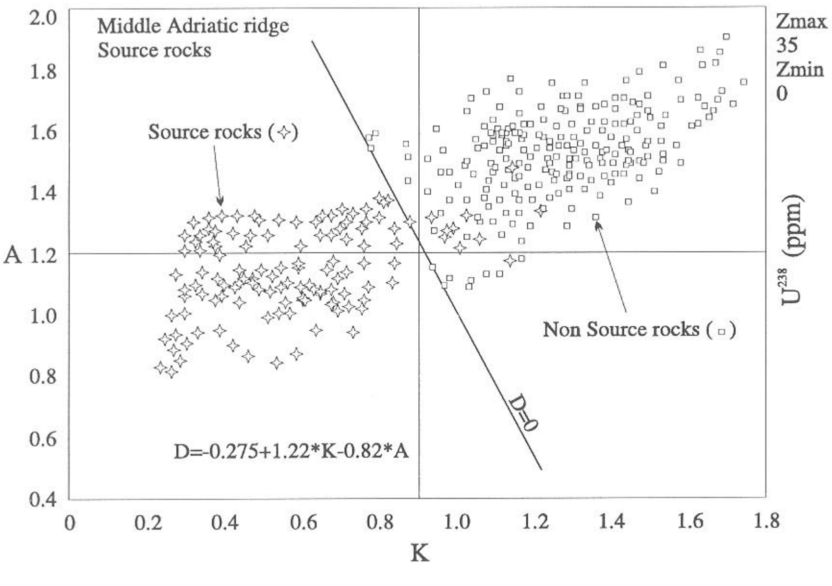

Fig. 14 A/K(Z) four component crossplot comprising combination of sonic transit time, bulk density, compensated neutron porosity and $Z=U^{238}$. The oblique line is the position of D=0 (Discriminant analysis). Points below this line (D=positive: star) = source rocks; points above this line (D=negative: rectangle) = non source rock. The analysis is from an area of the Middle Adriatic ridge.

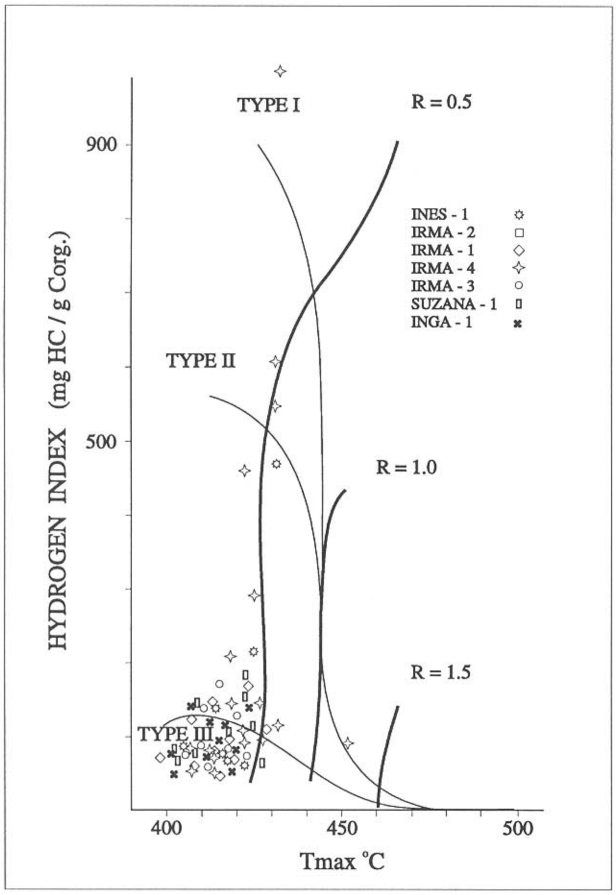

Fig. 15 Kerogen type and maturity of Pliocene source rocks of the Middle Adriatic ridge.

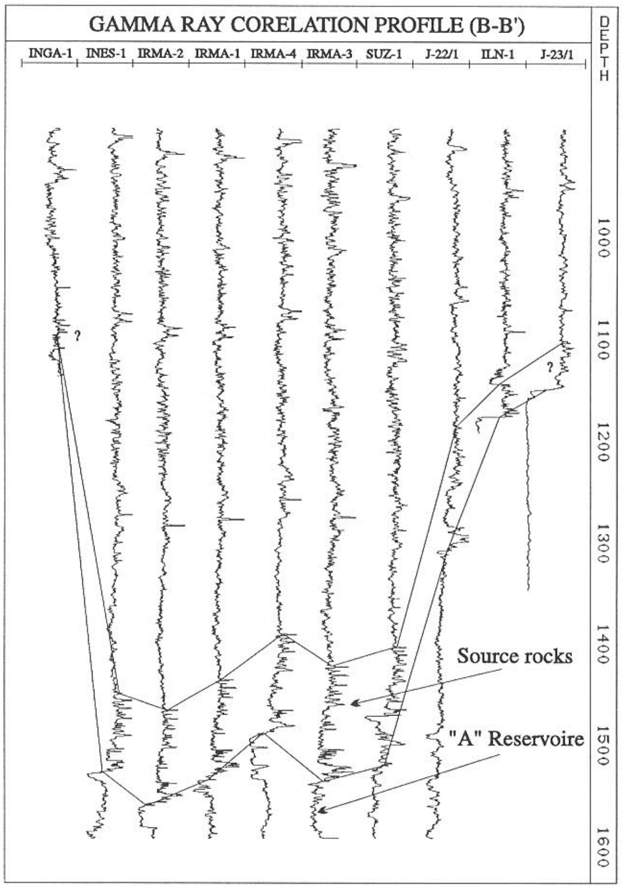

Fig. 16 Gamma ray composite log response of the Middle Adriatic ridge source rocks.

Figures 7-14 and 19 show K/Th, CN/DEN/Z, ($Z=U^{238}$), $\Delta_t$/Rt(RMLL), $\rho_b$/Rt(RMLL), M/N and A/K crossplots.

The diversity of well log parameters produces a characteristic and distinguishable four point star feature on the spiderweb diagram. It is also possible to define this as a litho-logging unit (JANČIKOVIĆ et al., 1988; VULAMA, 1991, 1993, 1994). The specific example related to the source rocks of the Irma gas field is presented on Fig. 17. The typical geophysical parameters for the source rock recognition of Irma gas field are clearly visible on the complex diagrams of Figs. 3, 4 and 17.

The crossplots K/Th showed that the main clay mineral is illite together with some mica (illite and mica are structurally very similar) and mixed components of various clay minerals (Fig. 7). The source rocks of this clay mineral are aluminum and potassium rich rocks which can be found in the hinterland of the Middle Adriatic ridge, as well as volcanic rocks of Pliocene and Pleistocene age (TARI-KOVAČIĆ, 1995; MILETIĆ & LUGOVIĆ, 1996).

## 5. STATISTICAL ANALYSIS

Statistical analysis was applied in order to emphasize the simple classification rules to distinguish source rocks from non-source rocks, based on quantitative well log parameters.

The source rock well log parameters were logged for the Pliocene organic rich deposits of the Irma gas field. Non-source rocks parameters were logged at intervals above and below the source rocks. These parameters were divided into two classes based on the geochemical analyses of rock samples: Class 1 = source rock; Class 2 = non-source rock. Geochemical analyses are based on the results of the pyrolysis, vitrinite reflection values and the carbonization degree of palynomorphs.

Discriminant analysis (pseudoregression scheme) was performed in the statistical analysis (DAVIS, 1973; MEYER & NEDERLOF, 1984; VULAMA, 1991, 1993, 1994) - Figs. 9, 11 and 13, Tables 1 and 2. Geophysical parameters (formation resistivity, bulk density, sonic transit time, neutron apparent porosity and natural radioactivity - uranium) are used as coordinates to locate the classified rocks.

To separate Class 1 from Class 2 it is necessary to establish the Discriminant line. The main characteristic of the Discriminant function is that the distance between the average values of Class 1 and Class 2 projections is maximal when the distance between the points inside a class is reducing.

The pseudoregression method means adding the appropriate value "Y" to each class:

| Description | SHALES ONLY (Middle Adriatic ridge) | ALL LITHOLOGIES (Middle Adriatic ridge, Sava & Drava depression) | |
|---|---|---|---|
| | M/N | A/R | D/R |
| Sample size | 217 | 177 | 177 |
| Source rock | 100 | 92 | 92 |
| Non-source rock | 117 | 84 | 84 |
| Misclassification | 6.6 | 8.9 | 10.4 |
| Separation of class means in pooled standard deviation | 1.2 | 1.33 | 1.17 |
| Class 1 Mean | 0.64 | 0.79 | 0.69 |
| Class 1 Stand. Dev. | 1.44 | 1.09 | 0.71 |
| Class 2 Mean | 0.76 | 0.98 | 0.57 |
| Class 2 Stand. Dev. | 0.26 | 0.87 | 1.18 |
| **Coefficients[1]:** | | | |
| Beta "0"[2] | 2.24 | -17.86 | -5.33 |
| Beta("M") | 3.71 | - | - |
| Beta("N") | 6.31 | - | - |
| Beta sonic ("A") | - | 1.21 | - |
| Beta density ("D") | - | - | 19.36 |
| Beta resistivity | - | 8.33 | -1.46 |

Table 1 Results of Discriminant analysis. Results are tabulated for different well log combinations (after VULAMA, 1994): "M" = sonic transit time vs. bulk-density; "N" = apparent neutron porosity vs. bulk-density; "A" = sonic transit time (in $\log_{10}$ µs/ft); "D" = bulk-density (in $\log_{10}$ g/cm$^3$); "R" = resistivity at 24°C (in $\log_{10}$ Ohmm).

**Legend:**

[1] All Beta coefficients of Discriminant functions are statistically significant;

[2] Beta "0" is the intercept. A typical equation based on:

M/N is: D=2.24-6.309·N+3.706·M. (Middle Adriatic ridge).

A/R is: D=-17.866+8.338·log(AC)+1.213·log(RT) (Middle Adriatic ridge, E, NW and SW part of Drava Depression, Middle part of Sava Depression).

D/R is: D=-5.326+19.366·log(DEN)-1.461·(RT) (Middle Adriatic ridge, E, NW and SW part of Drava Depression, Middle part of Sava Depression).

| | Middle Adriatic ridge source rocks | | | |
|---|---|---|---|---|
| Description | A/K | M/N | A/R | D/R |
| Sample size | 315 | 315 | 315 | 315 |
| Source rock | 200 | 200 | 200 | 200 |
| Non source rock | 115 | 115 | 115 | 115 |
| Misclassification | 3.2 | 6.6 | 7.9 | 8.1 |
| Mean - X | 0.8358 | 0.7167 | 2.5195 | 2.51 |
| Mean - Y | 1.4066 | 0.6012 | 127.1564 | 1.9710 |
| Slope | -2.3156 | 1.2220 | -8.4487 | 0.09829 |
| Intercept (Beta[1]) | 3.3421 | -0.2746 | 148.4436 | 1.7234 |
| R2 | -0.7615 | 0.9663 | - 0.2491 | 0.3409 |
| dX/dY | 0.4264 | -0.8189 | 0.11880 | -10.153 |
| X - intercept | 1.433 | 0.2254 | 17.592 | -17.493 |

Table 2 Results of Discriminant analyses (Middle Adriatic ridge source rocks only).

**Legend:**

[1] All Beta coefficients are statistically significant; "A"= bulk-density vs. apparent neutron porosity; "K"= sonic transit time vs. apparent neutron porosity.

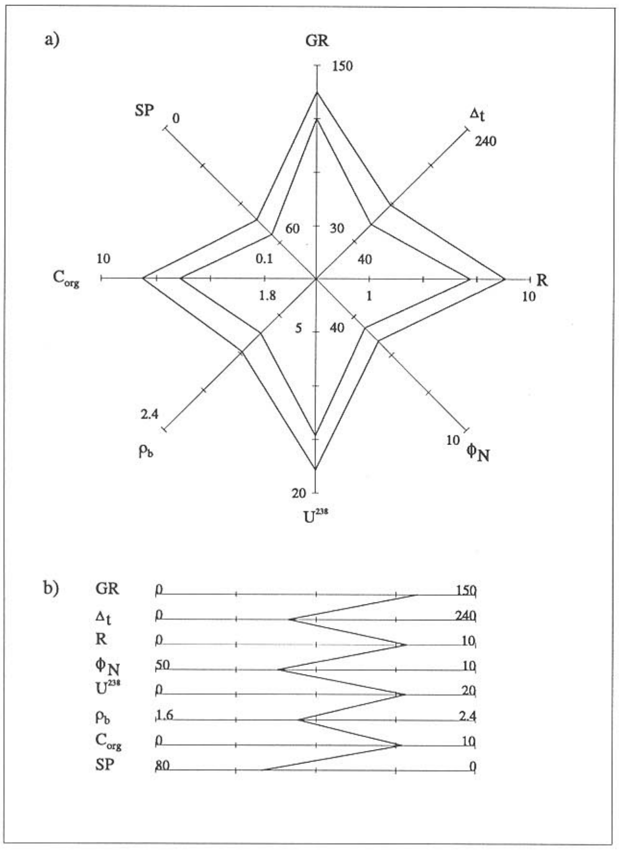

Fig. 17 Spiderweb (min./max.) (a) and average steeped (b) logs responses and C-organic content of the Middle Adriatic ridge source rocks.

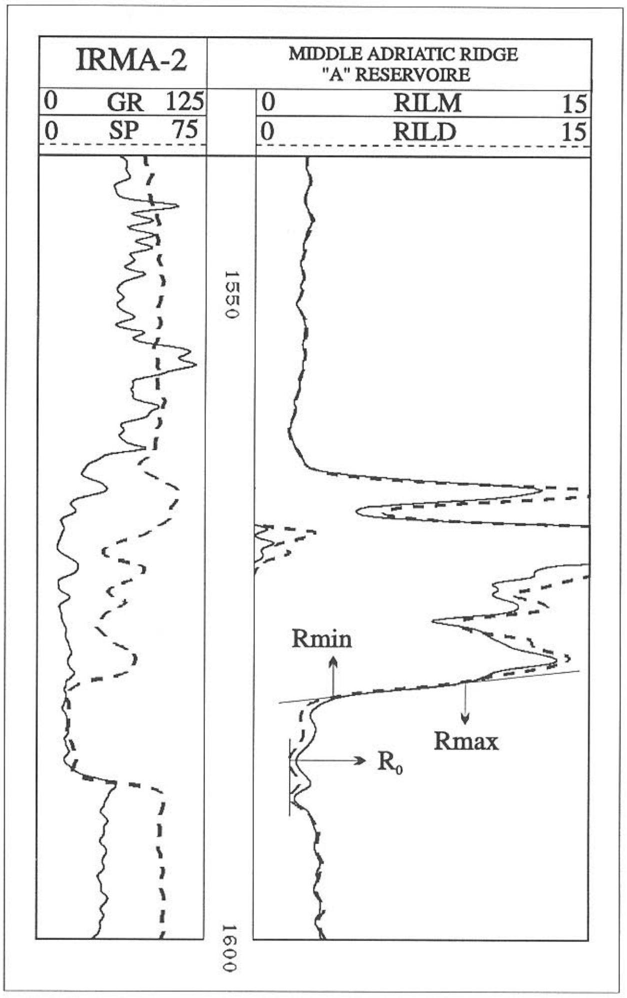

Fig. 18 Permeability estimation from resistivity gradient in Miocene reservoir rocks of the Irma gas field (a consistent result with laboratory analysis).

N2 / (N1 + N2) for Class 1, and
-N1 / (N1 - N2) for Class 2,

where N1 = source rock and N2 = non-source rock.

Next, the regression upon variable "X" is performed, using one of the multiplying regressive programs. The resulting "pseudoregression" is the Discriminant function, where "Z" is replaced by "D".

The analysis results in the linear value of the Discriminant "D", while the parameters can also be expressed in logarithms if the range of their values is wide. The typical calculation of the crossplot Δt/Rt (Fig. 9) is as follows:

$$D = -17.866 + 8.338 * \log_{10} * AC + 1.213 * \log_{10} * RT(24°C),$$

for the crossplot Δt/ρb (Fig. 11):

$$D = -5.326 + 19.366 * \log_{10} * DEN - 1.461 * \log_{10} RT(24°C),$$

and for the crossplot M/N (Fig. 13):

$$D = 2.24 - 6.309 * N + 3.706 * M$$

The well log and geochemical parameters are equations for calculating "D". If "D" is positive then the rock is most probably a source rock; if "D" is negative, then the rock is a non-source rock; and if D = 0, the case is considered to be undefined (Figs. 13, 14 and 19).

Analytical results show that such a qualification has certain statistical errors. The Discriminant analysis method used for source rock classification showed the average error between 3.2 - 10.4% (Tables 1 and 2).

Errors in classification can be caused by:

1. Poor correlation between geochemical and petrophysical data caused by the presence of shallow interbeds. One shallow interbed of the non-source rock, sampled for geochemical analysis can give false data and vice versa (this case occurred during the geochemical analyses of gas field Irma).
2. Heavy minerals in high concentration, e.g. pyrite, can cause low readings of bulk density and diminish the resistivity.
3. In unconsolidated rocks, the physical contrast between organic rich and organic poor layers is minimal, especially in the case of low concentrations of organic matter.
4. In very dense and compact rocks (with high velocity of the sonic wave), the measurements of the bulk density can be inaccurate.

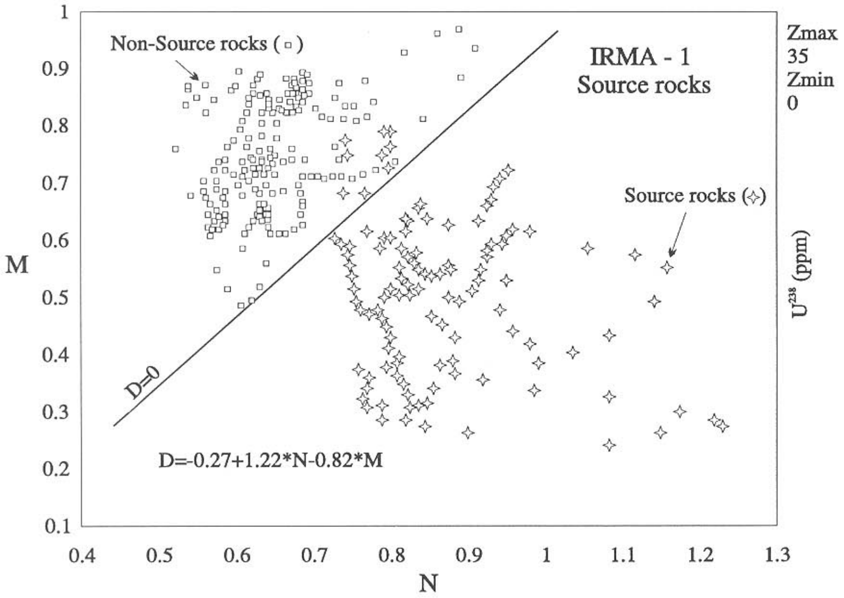

Fig. 19 M/N(Z) four component crossplot consisting of a combination of sonic transit time, bulk density, compensated neutron porosity and $Z=U^{238}$. The oblique line is the position of D=0 (Discriminant analysis). Points below this line (D=positive: star) = source rocks; points above this line (D=negative: rectangle) = non source rock. The analysis is from IRMA-1 well (Middle Adriatic ridge).

## 6. VERTICAL PERMEABILITY FROM THE FORMATION RESISTIVITY GRADIENT

Vertical permeability can be calculated from the difference in the value of the formation resistivity in the transition water/gas zone according to the Schlumberger formula:

$$K = c(a \times 2.3/(\rho_w - \rho_h))^2,$$

where c = Schlumberger constant = 20, a = basic gradient of formation resistivity ($a = \Delta R/\Delta D \times 1/R_o \Delta R$ = difference between max. and min. resistivity in the gradient, where: $\Delta D$ = differential depth (in feet), $R_o$ = 100% water saturated resistivity; $R_o = Fr \times R_w$, where: $R_w$ = formation water resistivity; Fr = formation factor; $\rho_w$ = water density in formation conditions; $\rho_h$ = CH density in formation conditions).

For IRMA - 2 (Fig. 18) this translates as: $\phi = 22\%$, $R_w = 1.8$, $Fr = 15.3$, $R_o = 2.75$ Ohmm, $\Delta D = 1580$ m - 1578.5 m = 1.5 m x 3.28 = 4.9 ft, $\Delta R = 10 - 4 = 6$ Ohmm, $a = 0.44$, $\rho_w - \rho_h = 1.02 - 0.0407 = 0.98$, Kavg. = $21.4 \times 10^{-3}$ $\mu m^2$.

Evaluated vertical permeability should only be considered for the transition zone (T-zone, Fig. 5) and can not be applied to the entire interval. We could calculate permeability by resistivity gradient only when the T-zone is clearly visible on the resistivity logs.

## 7. CORRELATION WITH GEOCHEMICAL ANALYSES

Interpretation of well logging data and crossplots for these source rocks showed good correlation with geochemical analyses. Logging data show very low values of formation resistivity of 1.5-4 Ohmm, that, according to exploration performed elsewhere (VULAMA, 1991, 1993, 1994) indicated the immaturity of these source rocks. Geochemical analyses confirmed this low maturity, but also suggested that these source rocks produced biogenic gas (on Irma-1 well isotope C and H depletion showed $\delta^{13}C$ -73‰ and $\delta D$ -188 (-) -192‰, and chromatogram giving >98.5% of methane).

Based on statistical discriminant analysis crossplots, $\Delta t/R$, $\rho_b/R$, A/K(Z) and M/N(Z) were computed, and the processed geophysical parameters ($\rho_b$, Rt, RMLL, $\Delta_t$, $\phi_N$, GR - $U^{238}$) were used as coordinates for the classification. The measured parameters were divided into two classes according to the geochemical rock sample analysis: Class 1 - source rocks; Class 2 - non-source rocks.

The following methods were used for correlation: pyrolysis, vitrinite reflectance and degree of palynomorph carbonization. If one of these did not meet the source rock criteria, this point was automatically classified as non-source rock, or at least listed as unidentified if the point was on the function (D=0) itself (Figs. 9, 11 and 13).

The correlation of geophysical and geochemical surveys determined the following parameters as being typical for these source rocks: GR = 55-125 API, $U^{238}$ = 5-25 ppm, Rt = 1.5-4 Ohmm, $\Delta_t$ = 75-170 μs/ft (x 0.306 μs/m), $\rho_b$ = 1.6-1.9 g/cm$^3$, $\phi_N$ = 33-39%, SP = -44 (-) -56 mV, Corg. = 0.43-3.23%, K/Th = Illite.

They are classified as kerogene type III and II (Figs. 4, 5, 8, 15-17).

Characteristic geophysical parameters of Irma Miocene gas reservoir rocks are: $\phi = 22\%$, $R_w = 0.18$, m = 1.8, Fr = 15.3, $R_o$ = 2.75 Ohmm, K avg. = $21.4 \times 10^{-3}$ $\mu m^2$.

## 8. DISCUSSION AND INTERPRETATION OF THE PROBABLE GAS ACCUMULATION PROCESS IN THE IRMA FIELD

Previous work in this area indicated the Irma gas accumulation originated by migration processes from deeper parts of the basin - from older Miocene and Mesozoic sediments (KADIJA at al., 1991; KADIJA, 1992). The origin and source of this gas was not clearly defined. Vertical migration processes which led to gas accumulation in Miocene reservoirs were also involved. These papers summarized drilling, logging and geochemical analysis data which indicated very short downward migration pathways for biogenic gas produced by low maturity Pliocene source rocks overlying the Miocene reservoirs, which were result of overpressure.

All the geophysical parameters proved that the basal part of the Pliocene shales is rich in organic matter. It is a source rock confirmed by geochemical analysis. At first, the survey of the induction resistivity logging tool (DIFL) was misleading because these curves did not show resistivity increasing in the source rock zone, although resistivity is an important indicator of a source rock. However, using the micro-resistivity curve (MLL) the problem can be resolved (Figs. 3 and 4). The organic matter within the shales occurs as laminae, and could not have been detected by the low resolution (DIFL) wire logging tool. The MLL curve clearly shows the thin lamination of the source rock and electric anisotropy (Figs. 3 and 4). Very low formation resistivity values (1.5 - 4 Ohmm) indicate the immaturity of this source rock (VULAMA, 1991, 1993, 1994).

In the source rock zone, overlying the Messinian calcarenites, during the drilling of Irma-1, a gas show was recognized at depth of 1520 m (7%; 1.7% $C_1$) and at 1530 m (40%; 18% $C_1$), and also in the Irma-2 well at 1588 m. The shales above source rock zone also represent a very good seal. Geochemical analysis proved that this was an immature source rock with the possibility of biogenic gas production (VULAMA, 1991).

In the Irma-1 well the Overpressure zone ($\Sigma$ log) was confirmed in the overlaying Pliocene and Quaternary shales. The basal section of these shales is the source rock (1445 - 1543 m). This zone is also clearly visible on the total transit time curve ($\Delta_t$) and interval velocity curve (ITVI), according to the deviation from the normal compaction trend of the hydrostatic pressure (Fig. 6). The $\Delta_t$ increase is the result of water trapped within the shales. The Overpressure zone is also clearly indicated on the $\rho_b$ curve where the deviation from the normal compaction trend occurs. Curve $\Delta_t$ and $\rho_b$ shows that the Overpressure zone begins at about 1260 m.

The hydrocarbons migrate (and fluids in general) in the Overpressure zone toward the lower pressure zone (MAGARA, 1978). Under hydrostatic conditions migration trends are upward and sidewards. In the Irma field, where overlaying shales were overpressured, the migration trend is downward to the zone of lower pressure - in the calcarenites and sandstones of the Messinian unconformity, where gas accumulated. Consider also that the capillary pressure in the reservoir rocks (especially in sandstone) is lower than in the impermeable - non-reservoir rocks.

Geochemical analyses proved that the gas of the Irma field is methane (up to 99.4%) of biogenic origin, and that it was generated from type III-II kerogene (Fig. 12). MATTAVELLI & NOVELLI (1988) point out that 80% of all gas fields in Italy contain gas of biogenic and/or diagenetic origin (most of these fields are in the Adriatic off-shore), while 20% contain gas generated by thermal degradation of organic matter. The existence of thin laminated source rocks of Plio-Pleistocene age is also documented and it is assumed that the primary migrations of the biogenic gas were short and that migration was connected to the more porous parts of the source rocks (MATTAVELLI & NOVELLI, 1988). It is also suggested by the Sp curve and gas shows on Figs. 4 and 5.

In the Irma field there is direct contact between the source rock producing biogenic gas and the calcarenites and sandstones of Messinian unconformity as the favorable reservoir (Figs. 3-5) and there is an Overpressure zone. The gas from those source rocks probably migrated downward - into the Miocene calcarenites and sandstones. It can also be assumed that partial fracturing of source rocks occurred in the contact zones and gas migrated through these fractures.

In the North-East part of the area gas shows have been observed in shallower sediments (Quaternary) above the carbonate platform (Wells: Inga-1, J-8, J23/1 and Iln-1; Fig. 2). Gas migrations in these locations are vertical (through fault's zones - KADIJA, 1992), but there is no vertical migration in the South-West area (Irma gas field). During drilling and logging overpressured zones were not indicated in North-East area and the Pliocene (source rock) is usually missing (Figs. 2 and 3).

## 9. CONCLUSION

The results of geophysical, geochemical and geological investigations indicate the presence of source rocks of Pliocene age in the area of the Middle Adriatic ridge. These were immature for oil and gas generation by thermal degradation, but they were capable of producing biogenic gas.

The geological conditions (organic rich overpressured shales/silty shales bearing the organic matter) and structural-tectonic setting (sealing normal fault) of the source rocks, indicate a short downward migration gas pathway between the porous - fractured Pliocene source rocks and underlying Miocene calcarenites and sandstones reservoir.

The correlation of gas recovered during drilling from source rocks and from the gas of reservoir Irma ("A") and the laboratory results also indicate the origin of the gas from the overlying Pliocene source rocks.

## Acknowledgments

I would like to thank dr. György POGÁCSÁS for his helpful advises and comments on manuscript. Special thanks goes to dr. Josipa VELIĆ for hers always very precious comments and criticism. Also thank to Vlasta TARI, M.Sc., for her comments on manuscript. For preparing the English manuscript thanks also to Borka VUČINIĆ and to Katica M. KRPINA and Z. BUDANOVIĆ for technical support.

This investigation was approved and supported thanks to INA-Naftaplin oil company.

## 10. REFERENCES

DAVIS, J.C. (1973): Statistics and data analysis in geology.- John Wiley and Sons, New York, 550 p.

FERTL, W.H. & CHILINGARIAN, G.V. (1988): Total organic carbon content determined from well logs.- SPE 1562, 61st Annu.Tech.Conf., 407-419, Houston.

FERTL, W.H. & CHILINGARIAN, G.V. (1990): Hydrocarbon resorce evaluation in the Woodford shale using well logs.- J. Pet. Sci. Eng., 4, 347-357.

HERNITZ, Z., VELIĆ, J. & BARIĆ, G. (1995): Origin of the hydrocarbons in the eastern part of the Drava Depression (Eastern Croatia).- Geol. Croat., 48/1, 87-95.

JANČIKOVIĆ, B., VULAMA, I. & JUNGWIRTH, M. (1988): Nove spoznaje o dubokim naslagama Dravske potoline na temelju karotažnih mjerenja.- DIT, 23, 11-23, Zagreb.

KADIJA, N. (1992): Stratigrafsko-tektonski odnosi plinonosnih sedimenata u jugoistočnom dijelu padske depresije.- Unpublished M.Sc. Thesis, University of Zagreb, 71p.

KADIJA, N., DURN, T., ŽUGEC, N. & TOMIĆ, B. (1991): Possibility of collecting hydrocarbons in carbonate sediments of the Irma-exploration area.- In: VELIĆ, I. & VLAHOVIĆ, I. (eds.): Second International Symposium on the Adriatic carbonate Platform, Zadar, Abstracts, 48, Zagreb.

MATTAVELI, L. & NOVELLI, L. (1988): Geochemistry and habitat of natural gases in Italy.- Org. Geochem., 13, 1-13.

MAGARA, K. (1978): Compaction and fluid migration.- Elsevier Scientific, New York, 392 p.

MEYER, B.L. & NEDERLOF, M.H. (1984): Identification of source rocks on wireline logs by density/ resistivity and sonic transit time / resistivity crossplots.- AAPG Buletin, 68, 121-129.

MILETIĆ, D. & LUGOVIĆ, B. (1996): Pliocene vulcaniclastic sediments in the Croatian Adriatic offshore region (drill-hole Kruna-1).- In: DROBNE, K., GORIČAN, Š. & KOTNIK, B. (eds.): International workshop Postojna 1996: The role of impact processes in the geological and biological evolution of planet Earth. 52-53, Ljubljana.

PRELOGOVIĆ, E. & KRANJEC, V. (1983): Geološki razvitak Jadranskog mora.- Pomorski zbornik, 21, 387-405, Rijeka.

SCHMOKER, J.W. (1981): Determination of organic matter content of Appalachian Devonian shales from gamma-ray logs.- AAPG Buletin, 65, 1285-1298.

SCHMOKER, J.W. & HESTER, T.C. (1990): Formation resistivity as an indicator of oil generation-baken formation of North Dakota and Woodford shale of Oklahoma.- The Log Analyst, 31/3, 1-9.

TARI KOVAČIĆ, V. (1995): Razvoj pliocenskih i pleistocenskih naslaga sjevernog i srednjeg Jadrana - karotažni markeri i korelacija.- In: VLAHOVIĆ, I., VELIĆ, I. & ŠPARICA, M. (eds.): First Croatian Geological Congres, Opatija, Proceedings, 2, 609-612, Zagreb.

VULAMA, I. (1991): Source rock definition on the basis of well logging.- Unpublished M.Sc. Thesis, University of Zagreb, 131p.

VULAMA, I. (1993): Procjena matičnih stijena na temelju karotažnih mjerenja u bušotinama.- Naftaplin, 1/1, 19-39, Zagreb.

VULAMA, I. (1994): Source rock potential of the Eastern Drava Depression and some other source rock localities in Croatia as evaluated from well log data.- Geol. Croat. 47/2, 205-214, Zagreb.

Manuscript received November 4, 1996.
Revised manuscript accepted April 28, 1997.