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Source rock generative potential and volumetric characteristics of the Kurrachine Dolomite Formation, Hayan Block, central Syrian Palmyrides

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ABSTRACT

Source rocks from the lower part of the Triassic Kurrachine Dolomite Formation were investigated in order to establish their role in the Petroleum System of the Hayan Block. Recent deep well discoveries accentuate the Triassic Kurrachine Dolomite Formation as a major play for hydrocarbon accumulations. The characteristic play definition is shown for the Hayan Block based on three defined elements: petroleum charge system, the source-reservoir formation characteristics and the trap-seal type. According to geochemical analyses, Triassic source rocks are of good generative potential, but they are not abundant (only thin layers were estimated). It was presumed that hydrocarbon generation and migration occurred from deeper Middle-Lower Palaeozoic Formations. Exploration results show that the generative potential of the Triassic source rocks in the Hayan Block was underestimated. Correlation and calibration of the petrophysical parameters from well logs and geochemical analyses show a much larger volume of mature source rocks than that predicted purely from geochemical analyses. The Kurrachine Dolomite Formation resistivity of 20 Ωm is typical of the area, and it represents the threshold value (Net Pay cutoff criteria) between immature and mature source rocks. Net Pay thickness (effective thickness), of mature and generative source rock intervals, exceeds more than 150 m in some wells. A calculated volumetric characteristic of source rocks indicates their high hydrocarbon generating capability. Intensive tectonic activity formed fractured zones as favourable reservoir rocks, so in some areas, practically no or very short migration pathways exist. Expelled hydrocarbons (within explored area) have not been accumulated into discrete reservoirs, thus the system is generating oil *in situ*.

The results accentuate the existence of a key Triassic Petroleum System in the area of the Hayan Block. This Petroleum System incorporates the Triassic Kurrachine Dolomite, Amanus Shale Formations and the Permian Amanus Sand Formation.

Keywords: Source rock, Triassic, Kurrachine Dolomite Formation, Amanus Shale Formation, Amanus Sand Formation, Volumetric characteristics, Hydrocarbons generated, Petroleum System, Palmyrides, Syria

1. INTRODUCTION

The characteristics of the Triassic source rocks of the Hayan Block (INA Oil Company exploration Concession) are illustrated. Recent discoveries at the Hayan Block area indicate that the Kurrachine Dolomite Formation is the most important source and reservoir rock formation. Geochemical analyses estimated only thin layers and a small volume of source rocks, which is not commensurate with the amount of hydrocarbons discovered. Calculated Net Pay value and volumetric characteristics of the explored source rocks suggest results different to those known previously. Earlier work on this and the surrounding areas offer some interesting, but to some extent opposing conclusions about the potentiality of the source rocks. LEŠKO et al. (2005) studied the source rocks of the Hayan Block in the central Palmyrides. They concluded that the Triassic sediments have good quality but a low quantity of source material, (only thin streaks of source rocks were estimated). ABBOUD et al. (2005) correlated crude oils and source rocks from the Mesopotamian foredeep, NE Syria and the NE Palmyrides. They defined the presence of two oil families generated by separate source rock types of different ages and concluded that the major source rocks for oils were the Amanus Shale and/or the Kurrachine Dolomite Formations. VULAMA & ŠPILJAK VULAMA (2007) evaluated and correlated well-log data with geochemical analyses and seismic data. They found that the generative potential of the Kurrachine Dolomite Formation of the Hayan Block was underestimated. According to well log data, mature generative intervals (Net Pay) of the lower part of the Kurrachine Dolomite Formation exceeded 150 m. MICHELS & MALARTRE (2007) defined the existence of active source rocks in the Triassic, with two oil types in the Kurrachine Dolomite Formation. They recognized similarities in the content of biomarkers and maturity between the Triassic rocks and oils. BARIĆ & SMOLJANOVIĆ (2007) presumed that hydrocarbons within the reservoir rocks of the Hayan block migrated from clastic rocks of Carboniferous (Markada) and Silurian (Tanf) ages. They supposed that Middle Triassic source rocks were of low volume, (thin strata of shale within the reservoir rocks of the Kurrachine Dolomite Formation), with limited generative potential. HIPS & ARGYELAN (2007) showed that the dark grey dolomite and mudstone of the Kurrachine Dolomite Formation in a nearby area, contained an average C_{org} of 2 %. The expelled hydrocarbons migrated within the Kurrachine Dolomite, or in some cases, to Permian sandstone sequences. Selective leaching, combined with tectonic activity (fractures), improved the reservoir potential of the Kurrachine Dolomite Formation. VULAMA (2009), completed the volumetric calculation of hydrocarbons generated from the lower part of the Kurrachine Dolomite Formation. Intensive tectonic activity, together with good generative potential, and the maturity of these rocks resulted in fracture zones acting as a favourable, *in situ* Reservoir/Source Rock system. Similar petrophysical characteristics were determined between the Kurrachine Dolomite and the Amanus Shale Formation source rocks, and some geochemical correlations of source rock samples and crude oils indicate that the Triassic Petroleum System is a major play in the area of the Hayan Block.

The main aim of this work is to show that source rocks of the Triassic Petroleum System have been underestimated in the sense of their generating capability, volume and areal extent. It is recognized that mature source rocks extend over a 220 m interval (VULAMA, 2009). Estimated volumetric values show the high hydrocarbon generating capability of the source rocks. Synthesis of all the evaluated data (well logging, geochemical analyses and 3D seismic), provides a new image and perspective on source rock distribution and hydrocarbon potential of the Kurrachine Dolomite Formation. Finally, the results presented here, suggest that this Formation generates oil *in situ,* and represents favourable Petroleum System in the area of the Hayan Block.

2. GEOLOGIC SETTING

The exploration area of the Hayan Block is situated in the central part of the Syrian Palmyrides, which represents a typical intracontinental convergent mountain belt. The Palmyrides extend from the Anti-Lebanon Mountain and Dead Sea Fault System, in the southwest, towards the Euphrates Depression in the northeast, a distance of about 400 km over which they sink and disappear. They extend to about 100 km in width reaching heights of approximately 1400 m. To the north, the mountain belt borders the Aleppo Plateau, and the Rutbah Uplift to the south (Fig. 1).

Structurally, the Palmyride Trough is composed of the alternation of highs where sediments of Jurassic to Neogene age outcrop, and depressions in which the sediments of Neogene to Recent age occur. Two structural provinces exist. The Southwest province includes the central Palmyride ridge and folded zone of the southeastern Palmyrides between which, the Al-Daww Depression strikes NE–SW (Fig. 1). The Northeast province was separated by the Jihar fault system, also striking in a NE–SW direction (McBRIDE et al., 1990; CHAIMOV et al., 1990).

Exploration wells of the Hayan Block were drilled through deposits of mostly Carboniferous to Miocene age. An intensive tectonic history created complex and fractured structures (Fig. 2). The sequence of sediments (source rocks) described (VULAMA, 2009) is most typical for the “B”, “J” and “M” fields (Fig. 1). The most frequently drilled sequence starts with Miocene sediments continuing with Oligocene, Eocene, Palaeocene, Upper and Lower Cretaceous sediments. Next are Lower-Middle Jurassic and Upper Triassic sediments, followed by the Middle Triassic (Kurrachine Dolomite Formation), Lower Triassic (Amanus Shale Formation), Permian (Amanus Sand Formation) and finally Carboniferous (Markada Formation) sediments.

The Kurrachine Dolomite Formation is mainly composed of various carbonates. There is a rhythmic alternation of dolomite, limestone, evaporite and shale. The Syrian General Petroleum Establishment divided this Formation informally into several reservoirs: C2, D1, D2-1 and D2-2. Of these, the C2 reservoir represents a series of rhythmically intercalated dolomite, limestone, claystone/shale, dolomitic shale and limy dolomite. The D1 reservoir is uniformly developed over the wider area. It comprises microcrystalline limestone, grading to dolomitic limestone and shale, while the D2-1 reservoir consists of limestone, dolomitic limestone, and dolomite intercalated with shale. A salt interval (D2) separates the D2-1 and D2-2 reservoirs, which have different hydrodynamic properties. The D2-2 reservoir consists of intercalations of silty shale and variations of limestone and dolomite sediments. The Lower Triassic (Scythian) – Amanus Shale Formation is composed of argillaceous shale, claystone, sandstone, siltstone, limestone and dolomite. Sandstones/siltstones with intercalations of shale/claystone and dolomite, predominate in the Permian – Amanus Sand Formation. The Carboniferous Markada Formation is a clastic sequence consisting mostly of shale interbedded with claystone. There are also sandstone, limestone, and dolomite beds which are up to several meters in thickness (Fig. 3).

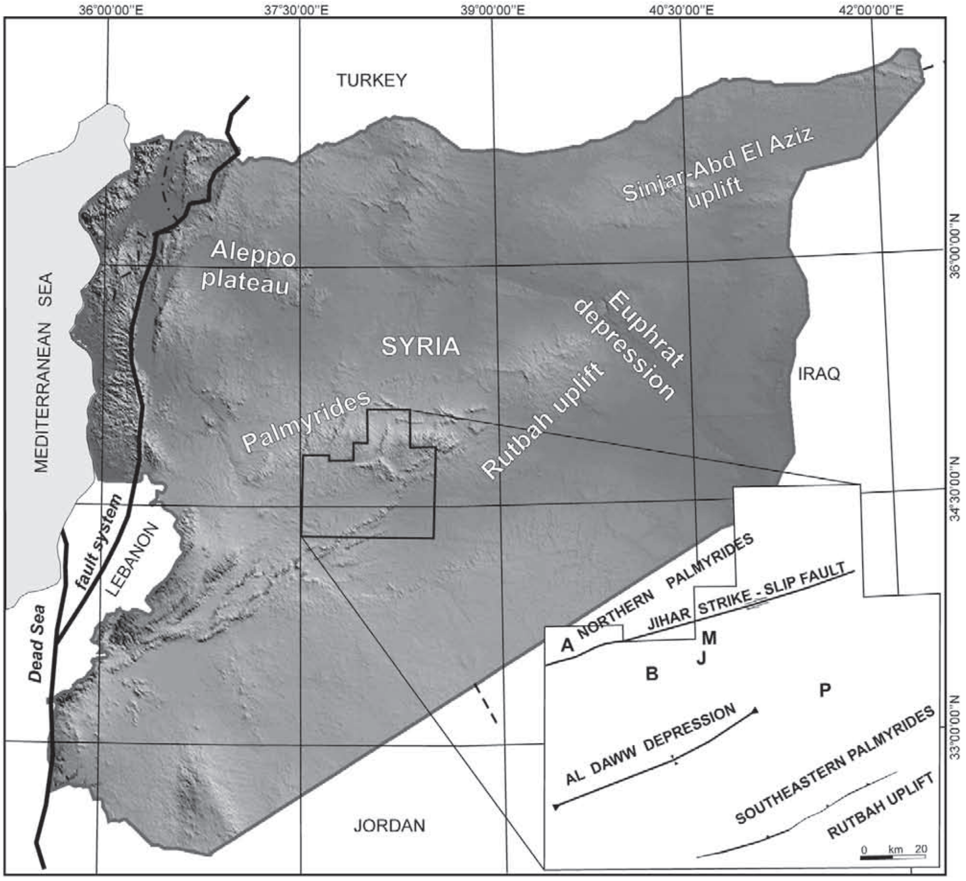

Figure 1: Index map of Syria with the main tectonic units, Dead Sea fault system (modified after BREW et al., 2001) and position of the Hayan Block in the Palmyrides (with tectonic units and position of oil/gas fields: "A", "B", "J", "M" & "P"; modified after VULAMA, 2009).

2.1. Source rocks

Source rocks of the Palmyride Trough were classified as proven and potential (METWALLI et al., 1974; WEBB & THOMPSON, 1994). Proven source rocks occur at three levels in Triassic strata and at two levels in rocks of Cretaceous age. The Amanus Shale represents proven source rocks of Triassic age. It is composed of black, calcareous marine mudstone and shale with a C_{org} content of up to 20 % (average 8–9 %). The younger, Kurrachine Dolomite Formation (Figs. 2 & 3) is composed of interbedded dark grey dolomite, mudstone and limestone with a C_{org} content averaging 2 %. The basal part of the Butmah Formation contains beds of anhydritic mudstone, several meters in thickness, with a C_{org} content of up to 2 %. There are two proven Cretaceous source rocks. In the Euphrates Trough, the Soukhne Formation (Rmah Chert and Arak Marl), is composed of black, bituminous, calcareous, cherty marine mudstones, with a C_{org} content of up to 8.6 % and the Shiranish Formation with up to 14.3 % C_{org} (METWALLI et al., 1974; WEBB & THOMPSON, 1994; HIPS & ARGYELAN, 2007).

The Carboniferous source rocks of the Markada Formation were considered as having the most potential in the Palmyride Trough and they were proven in the Euphrates Trough. Gas prone shales which passed through phases of the oil window and wet gas/condensate window in the Early Cretaceous occur in the Markada Formation. The source rocks of the Markada Formation (in the Hayan Block) contain shale and clayey shale of terrestrial/sapropelic origin (BARIĆ & SMOLJANOVIĆ, 2007).

The Early Silurian Tanf Formation is composed of dark partly silicified marine mudstone. It can be correlated with known source rocks of similar age in Oman, Saudi Arabia and South Iran. By analogy, BARIĆ & SMOLJANOVIĆ (2007) presumed that the Tanf Formation could also be the potential source rock in the Hayan Block area. The Tanf Formation is assumed to be overmaturing for oil throughout Syria, except for the shallow parts beneath the Aleppo platform (WEBB & THOMPSON, 1994; MICHELS & MALARTRE, 2007).

Hydrocarbon occurrences in Syria were proven in two Petroleum Systems – the Triassic and Cretaceous. The Triassic Oil System comprises source rocks of the Amanus Shale, Kurrachine Dolomite, Mulussa and Sergelu Formations. Triassic and Cretaceous carbonates form the reservoirs. These systems actively generated oil in the Late Cretaceous, and wet gas and condensate during the Neogene (WEBB & THOMPSON, 1994). The authors together with MICHELS & MALARTRE (2007) considered the Silurian Oil System of the Tanf Formation and the Carboniferous Markada Formation speculative, unproved systems. ALSHARHAN & KENDALL (1986) pointed out that the small Butmah oil field in northern Iraq, produces light oil from Kurrachine limestone. This Formation has both reservoir and source rock characteristics and it is composed of limestone with intercalations of thick-bedded dolomite and silty shale.

Source rocks of Carboniferous, Triassic, Cretaceous and Palaeogene age were determined on the Hayan Block (BARIĆ & SMOLJANOVIĆ, 2007). Palaeogene marl and limestone of the Kermav Formation were immature. Cretaceous deposits of the Shiranish and Soukhne Formations were rich in organic matter, but mostly immature. Occasionally they reached a maturity level of the early catagenetic phase. Middle to late Triassic source rocks of the Kurrachine Dolomite Formation are rich in organic matter. They represent significant source rock in a regional sense (ALSHARHAN & KENDALL, 1986). Carboniferous shales and clayey shales of the Markada Formation also indicate increased levels of organic matter of terrestrial/sapropelic origin. Dark shales were classified as medium to good gas prone and condensate source rocks (BARIĆ & SMOLJANOVIĆ, 2007).

Table 1: Geochemical parameters of Kurrachine Dolomite Formation source rocks from "B", "A" and "P2 oil/gas fields (see location on Fig. 1).

	B	A	P
Triassic	C_{org} (%)= 0.48–5.32	C_{org} = 0.46–1.80	C_{org} = 0.32–4.72
	S_2 (mgHC/gC_{org})= 0.63–12.11	S_2 = 0.49–2.96	S_2 = 1.09–30.86
	TAI = 3–3$^+$	TAI = 3	TAI = 2–3

(C_{org} – total organic carbon content; S_2 = pyrolisis content of hydrocarbons in kerogen; TAI= thermal alternation index)

3. METHODS AND SAMPLES

Hydrocarbon source rock parameters (geochemical analyses), including the type and amount of kerogene, and thermal maturity data, were assessed by the INA-Naftaplin laboratory. Net Pay of source rock, volumetric characteristics, maturity and other source rocks characteristics have been determined through the correlation of well logs, 3D seismic and geochemical analyses.

Petrophysical (well log) characteristics of reservoir and source rock parameters have been interpreted on the basis of a broad-spectrum of well logs, which include: GR (natural gamma ray log), NGS (natural gamma ray spectrometry log), AC (acoustic-sonic transit time log), DEN (density log), CN (compensated neutron log), R_t (true formation resistivity) & FMI (Formation MicroScanner Imager) logs. These well log data were used for various cross plots in statistical analysis and for correlation with geochemical and 3D seismic data. Through statistical analyses Discriminant function (D=0) was evaluated to divide source from non-source rocks.

3.1. Geochemical characteristics of source rocks

Geochemical analyses of the Triassic succession of "B", "A" and "P" oil/gas fields of the Hayan Block show good generative potential and they are in a thermal oil generating phase. Kerogene is of Type II and III (Tab. 1).

3.2. Petrophysical characteristics of Source and Reservoir Rocks

Petrophysical characteristics of source/reservoir rocks from the Kurrachine Dolomite Formation (Hayan Block; D2-2 reservoir, respectively) were interpreted on the basis of numerous well-log derived parameters which include: GR, NGS, R_t, AC, DEN, CN and FMI. (Figs. 4–10). Various crossplots (Figs. 6–9) of AC/CN/DEN/R_t/(NGS) logs were made to evaluate characteristic petrophysical parameters (Figs. 4–6).

Evaluation of FMI logs indicates numerous conductive (open) fractures in the zone of source rocks. FMI logs of the Kurrachine Dolomite Formation (also including the Amanus Shale Formation) on "B" and "J" wells, shows typical frac-

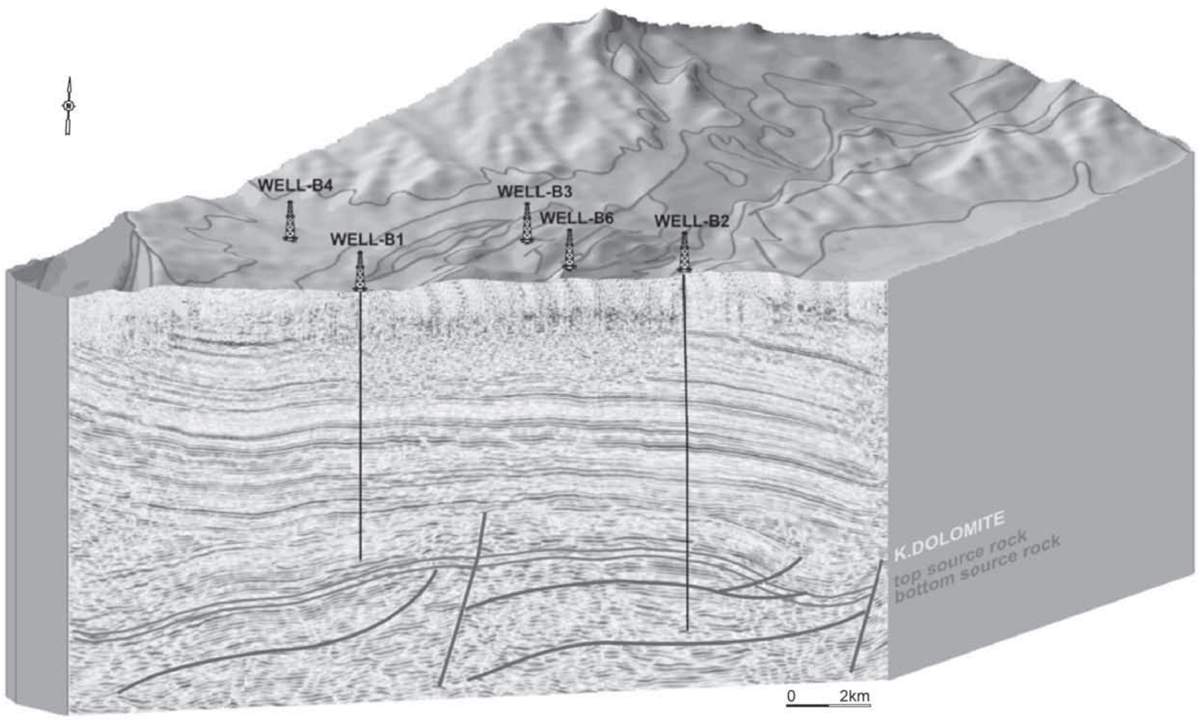

Figure 2: Block diagram of the survey area showing the Kurrachine Dolomite Formation and explored source rocks of "B" oil/gas field area (see position of "B" on Fig. 1).

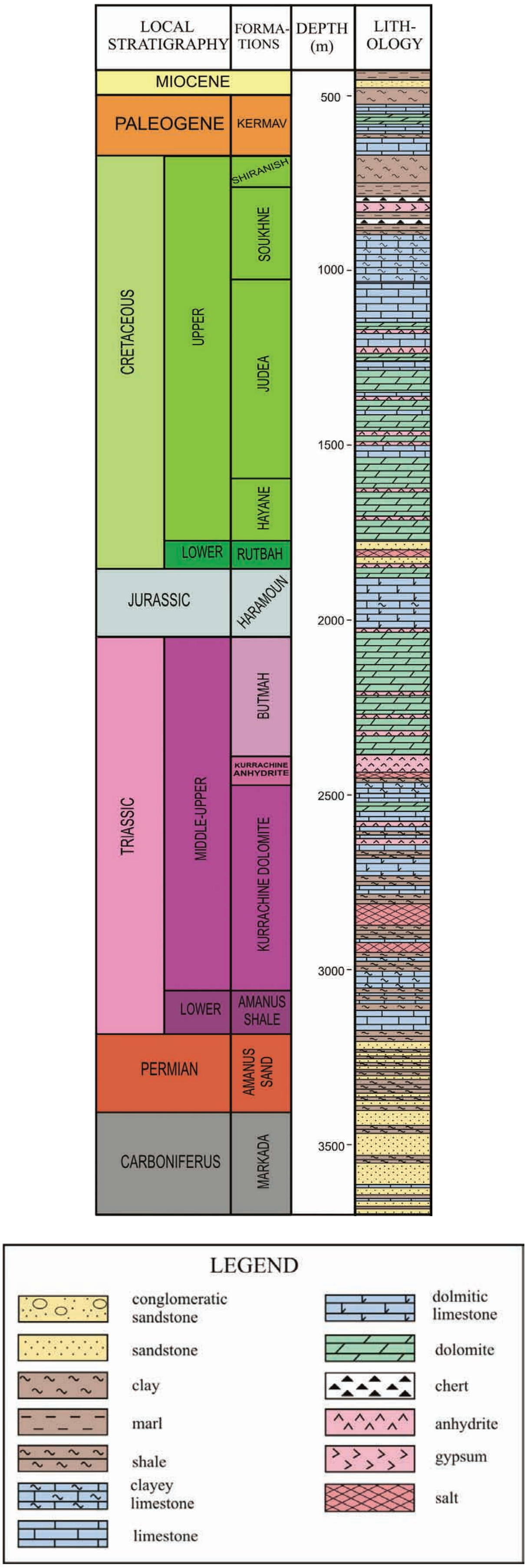

Figure 3: Schematic lithostratigraphic column of the Hayan Block with local lithology (after VULAMA, 2009)

ture development in the carbonate zone and associated organic-rich layers – source rocks (high GR). Additionally, the GR (NGS) of observed D2-2 reservoir shows a high uranium (^{238}U) content ranging from 2–13 ppm (Fig. 4). It is assumed that plankton and various organisms absorb uranium salts (ions) that are present in salt water, together with other rare elements. In this way the uranium is concentrated in the organic matter – source rocks (SERRA, 1979; SCHMOCKER, 1981).

4. RESULTS

Well log interpretation identified the petrophysical properties of the reservoir and source rocks of the Kurrachine Dolomite Formation. Correlation and calibration of these petrophysical parameters and geochemical analyses was focused on the lower part of the Kurrachine Dolomite Formation, which shows characteristics typical of mature source rock (Figs. 2–4).

Maturity data were provided by geochemical analyses of the Kurrachine Dolomite Formation from the Hayan Block area. As mature source rocks throughout the study area they have low to good generative capabilities, but according to geochemical interpretation they are low in quantity.

The characteristic geological development of the Hayan Block area is expressed by thick salt layers (Fig. 3) and significantly fractured reservoirs (Fig. 5). The consequence of these geological conditions was drilling with light oil based mud, blended with numerous organic additives. Geochemical analyses were affected by contamination of cuttings and core samples. The sampling rate of the cuttings taken for geochemical analyses was usually every 20 m, which meant that some samples were not representative and non continuous for the purpose of characterization of source rock quality and quantity. Figure 10 shows that samples taken for geochemical analyses have high variations in C_{org} quantity ranging from 0.56 to 5.32 %, with an average of 1.81 %. Samples taken from low GR readings (assuming low GR = low organic C = poor source rock) shows low C_{org} values and vice versa. Average C_{org} values calculated from well logs show a significantly higher amount (2.22 %). C_{org} was also measured from core samples taken from most favourable (limy, fractured) part of the reservoir, giving low readings of C_{org} (0.08 to 0.30 %). This is also a non-representative, sporadic sample, for the purpose of evaluation of the source rocks. The core was cut from the most favourable zone (lowest GR reading, Figs. 4 & 10) for reservoir parameter characterization (VULAMA, 2009). In addition, typical geophysical parameters were appraised by correlation of well-log (continuous) parameters with geochemical analyses and assorted samples of source rocks.

4.1. Source rock data derived from crossplots

The most common combinations used in this research were true resistivity (R_t; Ωm) vs. bulk density (DEN, ρb; g/cm^3), and true resistivity vs. sonic transit time (AC, Δt; μs/ft) crossplots (Fig. 6). These combinations of two-component diagrams

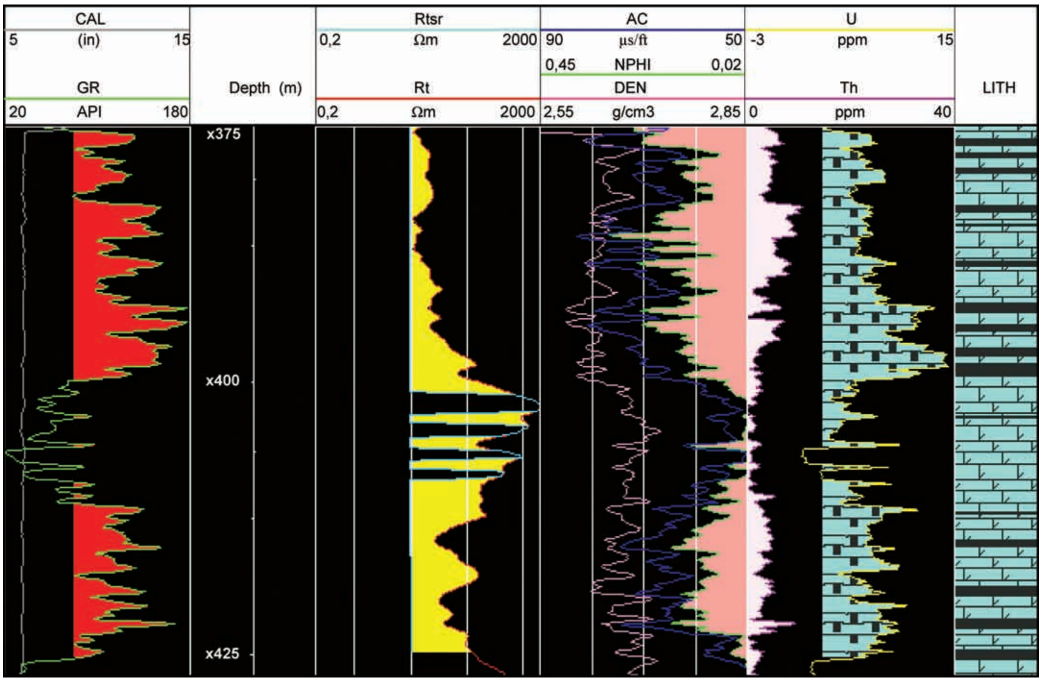

Figure 4: AC/CN/DEN/Rt/^{238}U logs of the Kurrachine Dolomite Formation ("M-1" well). Note ^{238}U curve starting from 2 ppm and scale of neutron (NPHI) curve starting from 0.02 (2 %). Both are min. cut-off values for Source and Reservoir Rock properties.

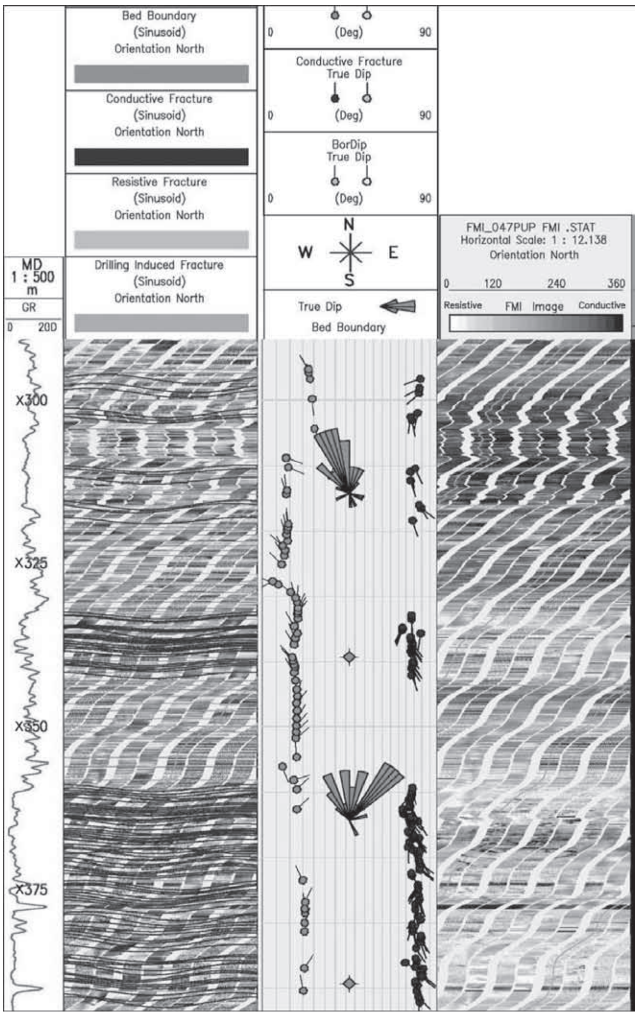

Figure 5: FMI logging of the Kurrachine Dolomite Formation ("B-6" well), showing high fracture porosity of source rocks and adjacent zone. Open-conductive fractures are shown with sinusoids.

proved to be useful for qualitative rock evaluation, especially when statistically estimated (Figs. 6–9). When, crossplots were correlated with geochemical parameters, it was possible to determine the Net Pay of the mature source rocks by defining their typical resistivity values. The most often used crossplots include the following logs: true (formation) resistivity (R_t) combined with volatile (free) hydrocarbons (S_1), vitrinite reflectance (R_o) and T_{max} from "Rock Eval" analysis. Crossplots were used to set the boundary value of formation resistivity at 20 Ωm, thus separating mature from immature source rocks, and setting up the value of volatile hydrocarbons (S_1) to be 0.20 mgHC/g of rock, R_o = 0.7 % and T_{max} = 436 °C (Figs. 7, 8 & 9).

4.2. Source rock data derived from statistical analysis and crossplots

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. These data which determined source rocks were filtered through several combinations of crossplots and then additionally checked through statistical analysis. The source rock well log parameters were recorded through organic rich deposits of the Kurrachine Dolomite Formation. Non-source rock parameters were logged at intervals above and below the source rocks (Figs. 4 & 10). These parameters were divided into two classes, based on the geochemical analyses of rock samples: Class 1 = source rock; Class 2 = non-source rock. Discriminant analysis (pseudoregression scheme, D=0) was performed in the statistical analysis (Fig. 6). Geophysical parameters (true resistivity, bulk density, sonic transit time, neutron porosity and natural radioactivity spectrum – uranium, respectively) were used as coordinates to locate the classified rocks.

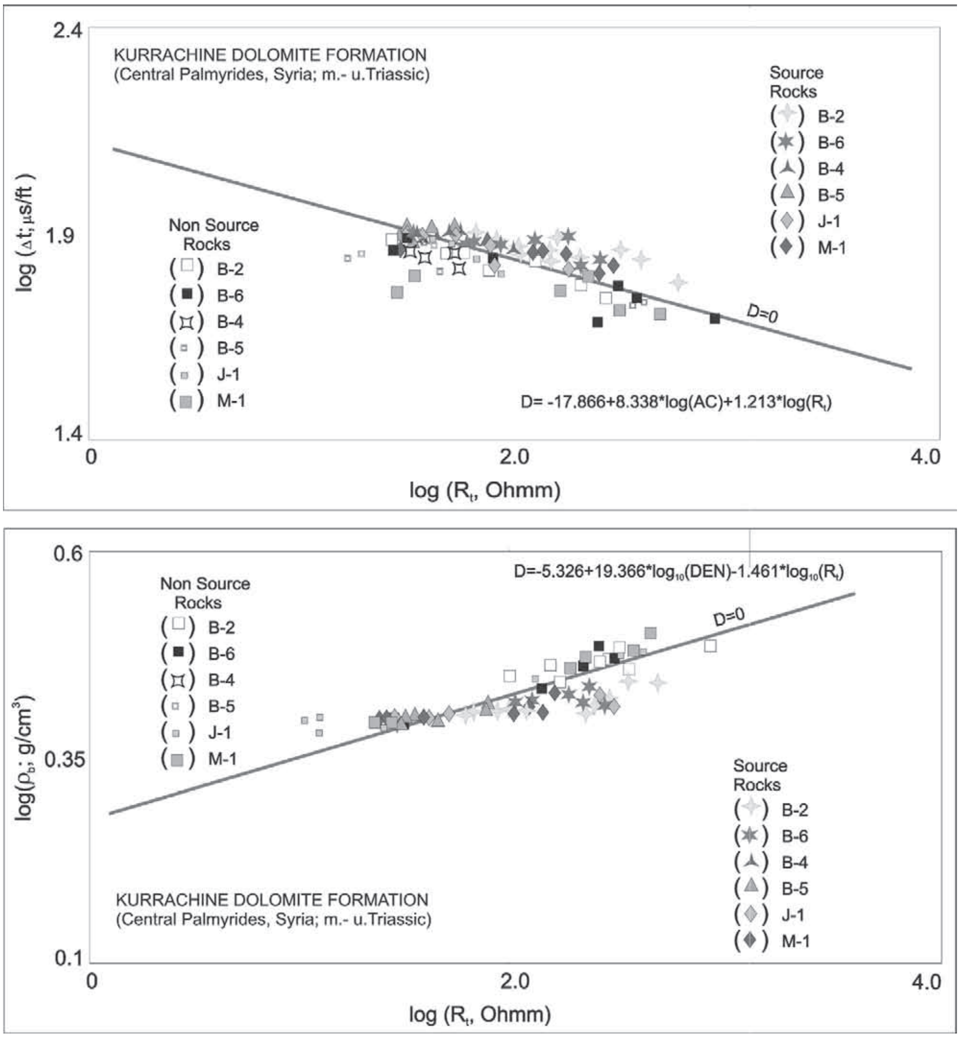

Figure 6: Upper part of the figure shows a crossplot of resistivity (R_t) and sonic interval transit time (AC, Δt). D=0 (discriminant analysis). Points above this line (D=positive) = source rock; points below line (D=negative) = non-source rock. Lower part shows a crossplot of resistivity (R_t) and bulk density (DEN, ρ_b). Points above D=0 line (D=negative) = non-source rock; points below line (D = positive) = source rock.

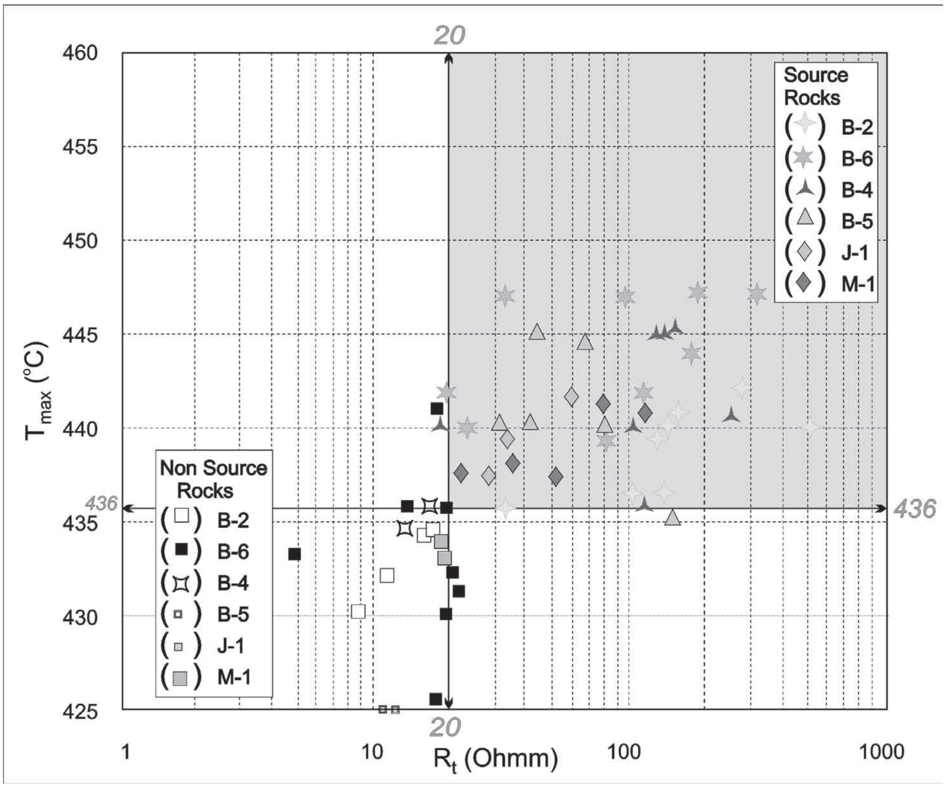

Figure 7: Crossplot of resistivity (R_t) and T_{max} showing 20 Ωm and 436 °C as a min. values of mature oil-prone source rocks.

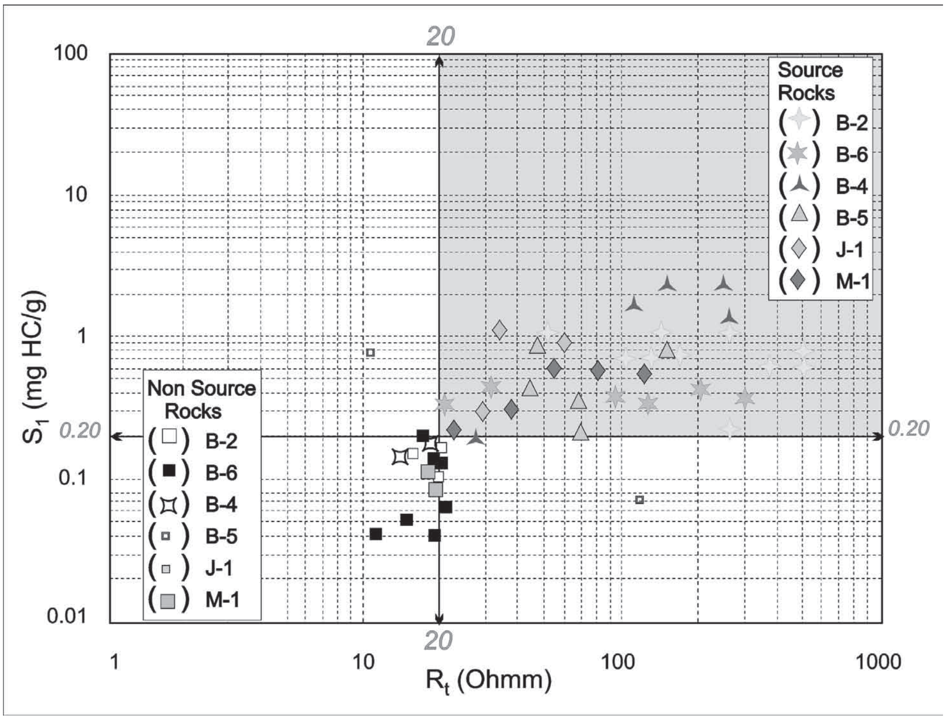

Figure 8: Crossplot of resistivity (R_t) and free (Volatile) hydrocarbons (S_1), showing 20 Ωm and 0,2 mg HC/g as a min. values of mature oil-prone source rocks.

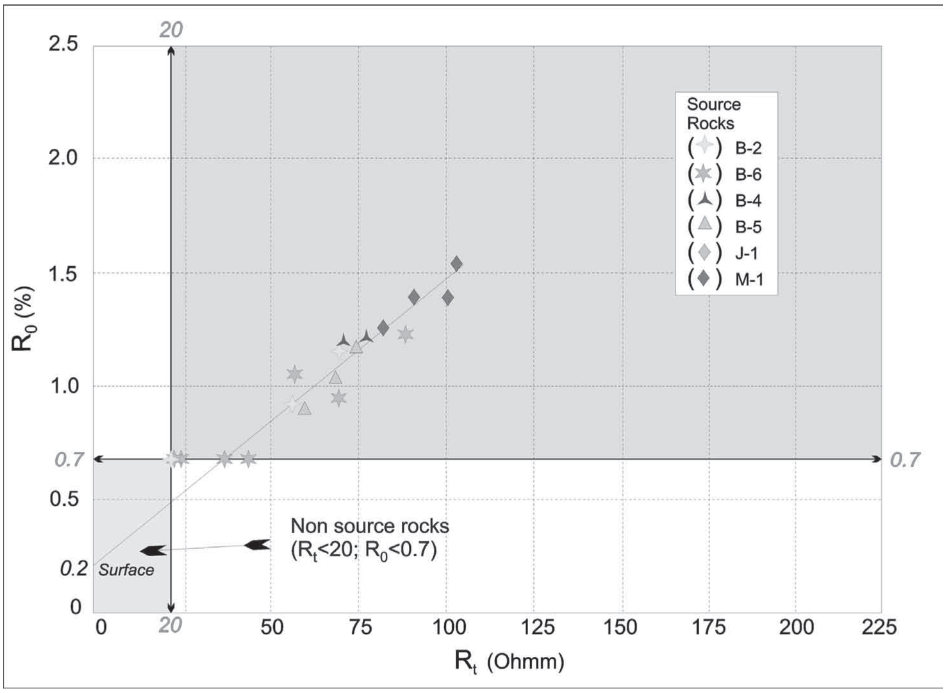

Figure 9: Crossplot of resistivity (R_t) and R_0 showing 20 Ωm and vitrinite reflectance (R_0= 0.7 %) as a min. values of mature oil-prone source rocks.

Finally, according to the petrophysical interpretation, the Kurrachine Dolomite Formation of the Hayan Block area is classified as a significant resource of source and reservoir rocks. Well log analysis of reservoir properties (FMI; Fig. 5) also proved that mature source rocks of the Kurrachine Dolomite and Amanus Shale Formations are fractured, and they represent *in situ* source and reservoir rocks with no or short distance migration pathways. Geochemical maturity parameters of source rocks were calibrated with electrical resistivity logs. A resistivity of 20 Ωm represents the minimum cut-off value separating source rocks from none-source rocks

Table 2: Geophysical and geochemical parameters of the Kurrachine Dolomite Formation of the Hayan Block evaluated from the correlation of well logs and geochemical analyses.

GEOPHYSICAL PARAMETERS	GEOCHEMICAL PARAMETERS
GR = 48–210 [API]	C_{org} = 0.48–5.32 [%]
^{238}U = **2**–13 [ppm]	T_{max} = 436–448 (455) [oC]
AC = 72–90 [µs/ft]	S_1 = 0.2–2.5 (5.18) [mg HC/g]
DEN = 2.38–2.74 [g/cm^3]	S_2 = 0.63–12.11(30,86) [mg HC/g]
CN = **2**–32 [%]	R_o = 0.7–1.25 [%]
Rt = **20**–>350 [Ωm]	TAI = 3–3$^+$

(Figs. 4, 7–9). A uranium content of 2 ppm (^{238}U) was also statistically determined, together with 2 % neutron porosity (CN, NPHI) as the lower (minimum) values for potentially good and mature source rocks and favourable producible reservoir parameters. These parameters were use for calculation of the Net Pay of mature source rocks (Tab. 2).

4.3. Volume of source rocks and generated hydrocarbons

Calculation of the volumetric characteristics of source rocks and hydrocarbons generated represents a step forward in the understanding and definition of the Petroleum System. Estimation of the amount of hydrocarbons generated from active source rocks, represents a basic element for evaluation of the expulsion, migration and accumulation processes affecting the efficiency of the Petroleum System. Differences between the amount of hydrocarbons generated, compared to the amount in place, can be enormous. It is assumed that only a few percent of oil generated is recoverable oil for most basins, and up to 10 % of recoverable oil is generated in several sedimentary basins. This part of the article will deal with calculation of the mass of hydrocarbons generated in one part of Triassic Kurrachine Dolomite Formation, of the “B” wells field (Fig. 2, 11, 12 & 13). The SCHMOKER (1994) method is the basis of calculations, which is, in this case, statistically controlled and improved in some parts by using 3D seismic data. The method is based on following elements (steps):

1. Source rock identification (WL, GA), definition of mapable boundaries and calculation of the volume of the homogeneous Unit (WL, WL+3D).

2. Calculation of the organic carbon mass in the source rock (WL, GA).

3. Estimation of the mass of hydrocarbons generated per unit mass of organic carbon (WL, GA).

4. Determination of the total mass of hydrocarbons through calculation. (WL=Well Log, GA= Geochemical Analyses, 3D= 3D Seismic Data)

The volume, V (cm^3), of the Unit is calculated using 3D seismics calibrated with well logs in an effort to extract the Unit from one particular part of the “B” wells of the Hayan Block (Figs. 11–13). The calibration and correlation of the 3D seismic and well logs was undertaken after the well logs were correlated with geochemical analyses. Therefore, we were able to calculate the Net Pay of the mature source rock with higher accuracy.

For volumetric calculation of hydrocarbons generated, a potential source rock Unit was bounded by physical fault boundaries to the south and west, but with a fictive ”contact” at –3 000 m to the north (Fig. 11). The thickness of the Unit was set at 70 m. Following this setup parameters, the volume of the Unit was calculated as (V) = 1.4×10^9 m^3 (1.4×10^{15} cm^3; Fig. 12).

The second step (Fig. 12) is to calculate the mass of organic carbon $M(gC_{org})$, formula (1)

$$M(gC_{org}) = [C_{org}(wt\%)/100] \times [\rho b(g/cm^3) \times V(cm^3)] \quad (1)$$

The next step is to determine the mass of hydrocarbons generated per unit mass of organic carbon, $R(mgHC/gC_{org})$ formula (2). The data needed to calculate R are the original hydrogen index HI_0 $(mgHC/gC_{org})$, prior to any hydrocarbon generation, and the present hydrogen index HI_p $(mgHC/gC_{org})$ of the source rock. The difference between these two indexes indices approximates the mass of hydrocarbons generated per gram C_{org}.

$$R(mgHC/gC_{org}) = HI_0\,(mgHC/gC_{org}) - HI_p\,(mgHC/gC_{org}) \quad (2)$$

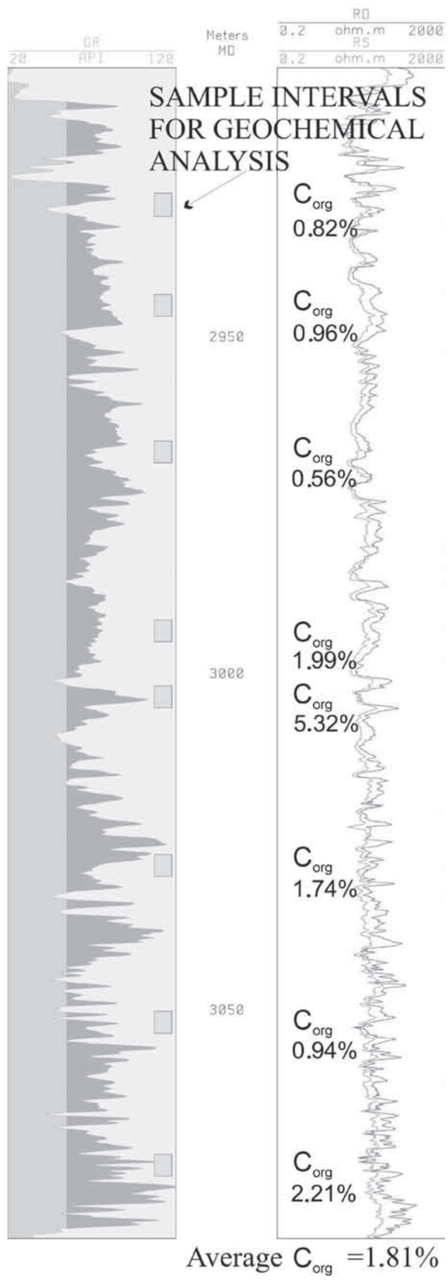

Figure 10: Sampled intervals (rectangles) for geochemical analyses from the B-5 well show high discrepancies in C_{org} concentration. Samples from the high GR zone show high concentration of organic matter and vice versa. The average value of 1.81 % is not a representative value for the lower part of the Triassic Kurrachine Dolomite Formation. Calculated average C_{org} concentration from well logs is 2.22 %.

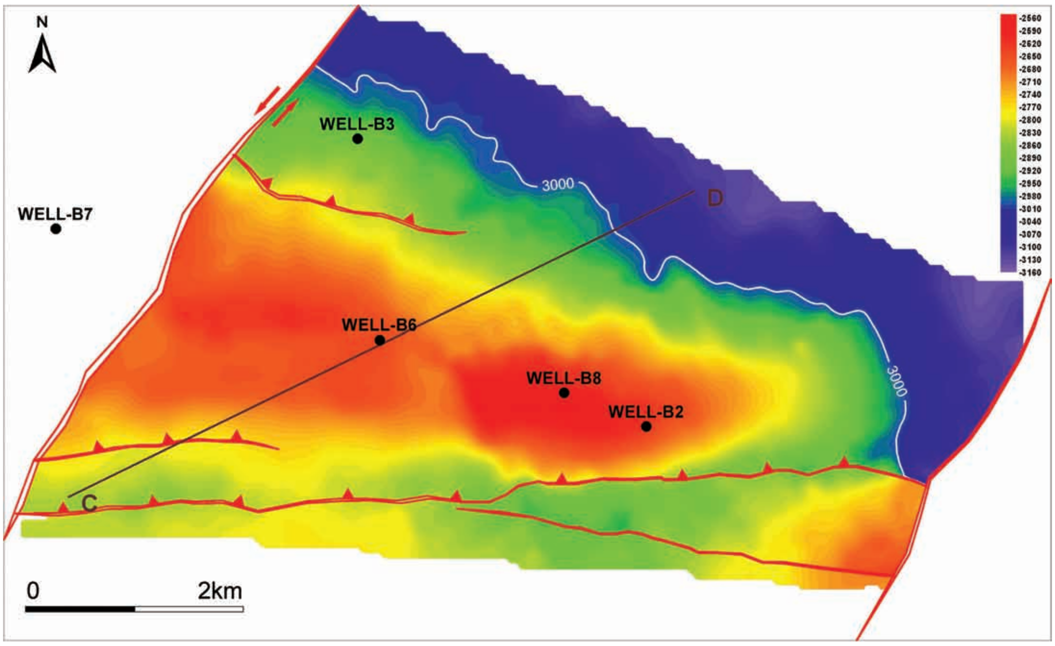

Figure 11: Structure map on the top of the mature source rocks of the Kurrachine Dolomite Formation of "B" oil/gas field (see location on Fig. 1).

The equation equates the decline in generation potential to hydrocarbons actually generated. The explored area of the Hayan Block has an initial index of 650 $mgHC/gC_{org}$ derived from immature source rocks of the Kurrachine Dolomite Formation from "P" wells.

The final step is to compute the total mass of hydrocarbons generated HCG (kgHC) computing the data from first two steps:

$$HCG\ (kgHC) = R(mgHC/gC_{org})\ x\ M(gC_{org})\ x\ 10^{-6}(\ kg/mg) \quad (3)$$

Following these equations, the volumetric calculation method was applied to one part (Unit) of the Kurrachine Dolomite Formation (Figs. 10, 11 & 12). These parameters were calculated:

– $V = 1.4\ x\ 10^{15}\ cm^3\ (1.4x10^9\ m^3)$, volume from 3D seismic)

– $C_{org} = 1.84\ mgHC/gC_{org}$ (average data from GA – geochemical analysis),

– $\rho b = 2.45 g/cm^3$ (WL)

According to equation (1) mass equals:

– $M = 6.32x10^{13}\ C_{org}$ (1)

For the second step present Hi_p is 450 $mgHC/gC_{org}$ (GA), and initial Hi_0 is 650 $mgHC/gC_{org}$, according to equation (2):

– $R = 200\ mgHC/gC_{org}$ (2)

Concluding with equation (3):

– $HCG = 1.27x\ 10^{10}\ kgHC$ (3)

Converted to oil equivalent, using SCHMOCKER's, (1994) graph, produces: 0.8 x 10^8 bbl or 12.7 x 10^6 m^3 or 10.7 x 10^6 tons of oil equivalent.

Finally, taking into consideration evaluation of Net Pay of mature source rocks with discriminant factors R_t= 20 Ωm, ^{238}U= 2 ppm and CN= 2 %, (VULAMA & ŠPILJAK VULAMA, 2007), the result must be reduced by approximately 20 % to HCG = 10.16 x 10^6 m^3 or 8.6 x 10^6 (36 API) tons of oil equivalent.

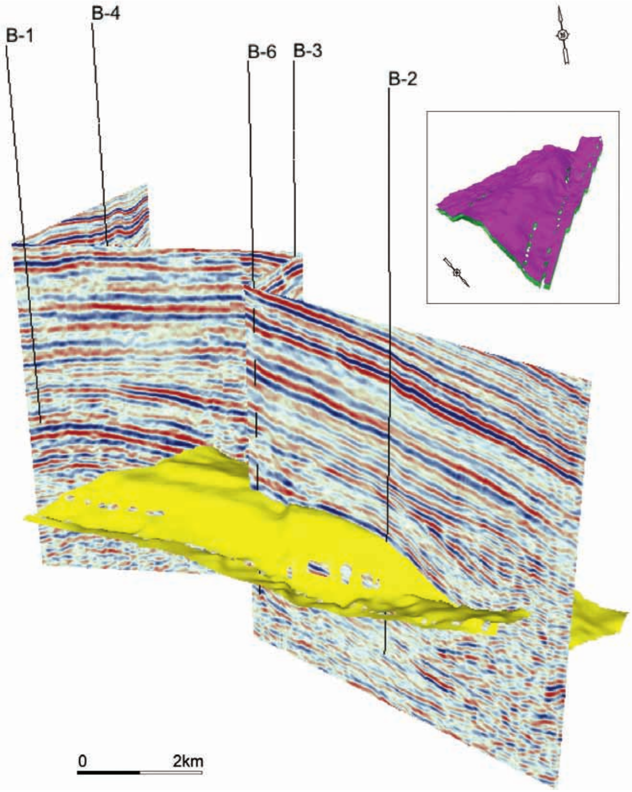

Figure 12: Seismic section through the "B" oil/gas field with extracted source rock Unit (yellow) and 3D shape (magenta) of the source rock body, 70 m thick (see location on Fig. 1).

According to McDOWELL (1975), recoverable oil is in the range of 10 % of the total oil generated, for only a few sedimentary basins, and is only a few percent for most basins. The difference between the amount of hydrocarbons generated, compared to the amount of oil in place can be enormous, due to the inefficiencies associated with the expulsion, migration, and trapping of hydrocarbons are often large.

As SCHMOCKER (1994) pointed out, the parameters necessary to calculate the amount of hydrocarbons generated are poorly constrained, resulting in the calculation error. Although disadvantageous, existing errors do not necessarily negate the value of volumetric hydrocarbon calculations because it is useful to know the range of the oil equivalent e.g. 1–10–100 millions tons of equivalent oil.

5. DISCUSSION

Recent hydrocarbon discoveries ("A", "B", "J", "M" and "P" Oil/Gas fields) in the Hayan Block showed that the Triassic Petroleum System is a major play in that area. The hydrocarbon potential of the Kurrachine Dolomite Formation, (both reservoir and source rock properties as a system *in situ*) in previous explorations was not considered as significant. Herein, results and conclusions from previous work by authors from the INA Oil Company or their consultants are discussed.

BARIĆ & SMOLJANOVIĆ (2007) concluded that hydrocarbons of the Kurrachine Dolomite Formation were probably of secondary origin (Carboniferous and Silurian ages). This secondary, migrated origin of hydrocarbons is not supported by the geochemical ("Rock-Eval") analyzed data. These authors only presumed that the main regional source rocks were marine shale pellet deposits of the Markada and Tanf Formations.

Data from geochemical analyses (with high HI content (450–620 mgHC/g; in P-wells area even 555–650 for immature source rock in that area), and other geochemical parameters (Tab. I) support a high generative potential for the Kurrachine Dolomite Formation.

Following, in their conclusion, authors (BARIĆ & SMOLJANOVIĆ, 2007) pointed out that Middle Triassic source rocks of the Kurrachine Dolomite Formation were thin streaks of shale within the reservoir rocks of that Formation, with limited generative possibility. This conclusion is also not acceptable as VULAMA & ŠPILJAK VULAMA (2007) confirmed that more than 150 m of Net Pay of mature source rocks exists only in the lower part of the reservoir. These source rocks layers are not thin at all (Figs. 4 & 10). BARIĆ & SMOLJANOVIĆ (2007) emphasized that these source rock sequences (thin layers) are thermally mature, and that they reached the main oil window phase. The older sediments of the Amanus Shale and Amanus Sand Formation, have restricted organic matter content (C_{org} < 0.5 %).

The conclusion of the existence of thin layers of source rocks was also addressed by previous work of VULAMA & ŠPILJAK VULAMA (2007) where it was shown that a lot of the geochemical tested samples were from non representative parts of reservoirs. This resulted in a much lower C_{org} content and misleading conclusion about the low C_{org} content, low capacity of source rocks and the conclusion of the existence of thin layers of source rocks throughout the entire Kurrachine Dolomite Formation.

The Markada Formation, in the area of the "B" wells, was only sampled by one deep well and both reservoir and source rock capacity, was low to medium and it has not been sufficiently explored.

MICHELIS & MALALTRE (2007) confirmed the existence of an active Triassic source rock (with some reservations). Strong similarities in geochemical characteristics between the oils from the Kurrachine Dolomite reservoirs and rock extracts from the Triassic were determined. They proposed that oils from the Kurrachine Dolomite reservoirs were sourced from Triassic source rocks. MICHELIS & MALALTRE (2007) pointed out that they identify only oil prone source rock from the "Rock-Eval" data of the Kurrachine Dolomite Formation from the "P" well. Markada "Rock-Eval" data indicate rather gas-prone immature to highly mature source rocks (R_o= 1.31–1.54 %, TAI = 3–3^+, C_{org} = 0.82–1.07 %). Concerning the Tanf Formation, they hypothesize that as it is deeply buried in the area, it must be over mature, (in addition – only one well drilled the Tanf Formation, some 45 km SE from the "B" wells in the Southern Palmyrides). Finally, in their conclusion they pointed out that they didn't have enough good quality samples to analyze. The samples were either very altered by meteoric water input, i.e. water washing and biodegradation or contaminated by drilling fluid.

This conclusion can also be related to the evaluation of results from VULAMA & ŠPILJAK VULAMA (2007), who indicated the problems of contaminated samples which were mostly taken from non-representative parts of the Kurrachine Dolomite Formation (non-source rocks zones) for geochemical analyses.

This problem was solved after drilling the "M" well (Fig. 4), where geochemical analyses were focused to selected zones with good source rock characteristics inter-

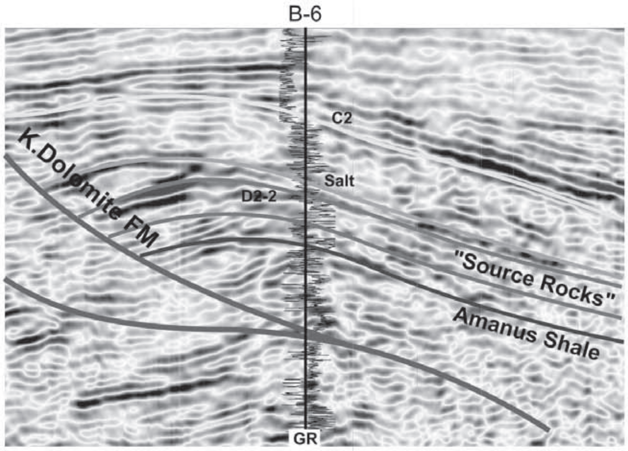

Figure 13: Interpreted detail of seismic profile (see C-D, on Fig. 11) of Kurrachine Dolomite Formation (B-6 well).

preted from well logs (VULAMA, 2009). The samples were selected according to several criteria selected from correlation of well logs and geochemical analyses, in order to represent the most significant parts of the reservoir with a special focus on formations bearing source rock potentiality. This means that the chosen rock samples have "Rock-Eval" characteristics of good to excellent source rocks, over an interval of 220 m, but only in the lower part of reservoir. Selected representative samples helped to avoid the rock samples of equivalent facies but without proven oil potential (rock samples with unfavorable "Rock-Eval" characteristics).

Finally it can be concluded that geochemical analyses of the Kurrachine Dolomite Formation from wells of the Hayan Block encountered contamination problems because of drilling with oil based mud and added organic additives. Non-representative samples collected according to a program of ~20 m interval sampling were mostly out with the best concentrations of organic matter (source rocks, especially cores; Fig. 4 & 10). This resulted in the conclusion of the existence of only thin layers of source rocks with low hydrocarbon generating capability. By interpreting continuous data from well logs, it was established that the entire Kurrachine Dolomite Formation, especially the lower part, represents mature source rock with an effective Net Pay thickness of more than 150 m.

This research defined marginal geophysical (well logging) parameters for mature source/reservoir rocks, the most important being the value of formation resistivity of 20 % Ωm, and ^{238}U content of 2 ppm and CN porosity of 2 %.

Favourable tectonic and sedimentation conditions (carbonates and shales sealed with thick salt-evaporite layers), significantly affected and shaped this area. Intensive tectonic activity played a double function – it shaped structures and traps, and formed fractured zones – reservoirs for hydrocarbon accumulation (Fig. 13). Mature and fractured source rocks, represent a significant hydrocarbon generative and reservoir system *in situ* (oil in place), with no or minor migration path ways, as was regionally recognized in some surrounding areas.

Reservoir pressure measurements in the "B" field well contributed to these results (Fig. 14). The figure shows that three different, separated hydrodynamic units have various and mixed hydrocarbon saturation. If sources for these hydrocarbons were from Silurian and Carboniferous Formations, deeply buried in this area (1000–1500 m deeper), it would be difficult to explain how the hydrocarbons migrated through these regional barriers in such amounts with such a high pressure difference and mixed composition. Bearing in mind possible migrations through faults, we must take into consideration that deeper rocks are capable to generate only dry gas – as in the Markada Formation, or they can be overmature – as in the Tanf Formation. In the area of the Hayan Block, several major – regional barriers prevent migrations from deeper sediments, and they generate separated hydrodynamic units. The first barrier is the regional shale layer of the Amanus Sand Formation, which is up to 300 m thick. Then there are two very thick salt/evaporite layers which may also exceed several hundred meters in thickness (Figs. 13 & 14).

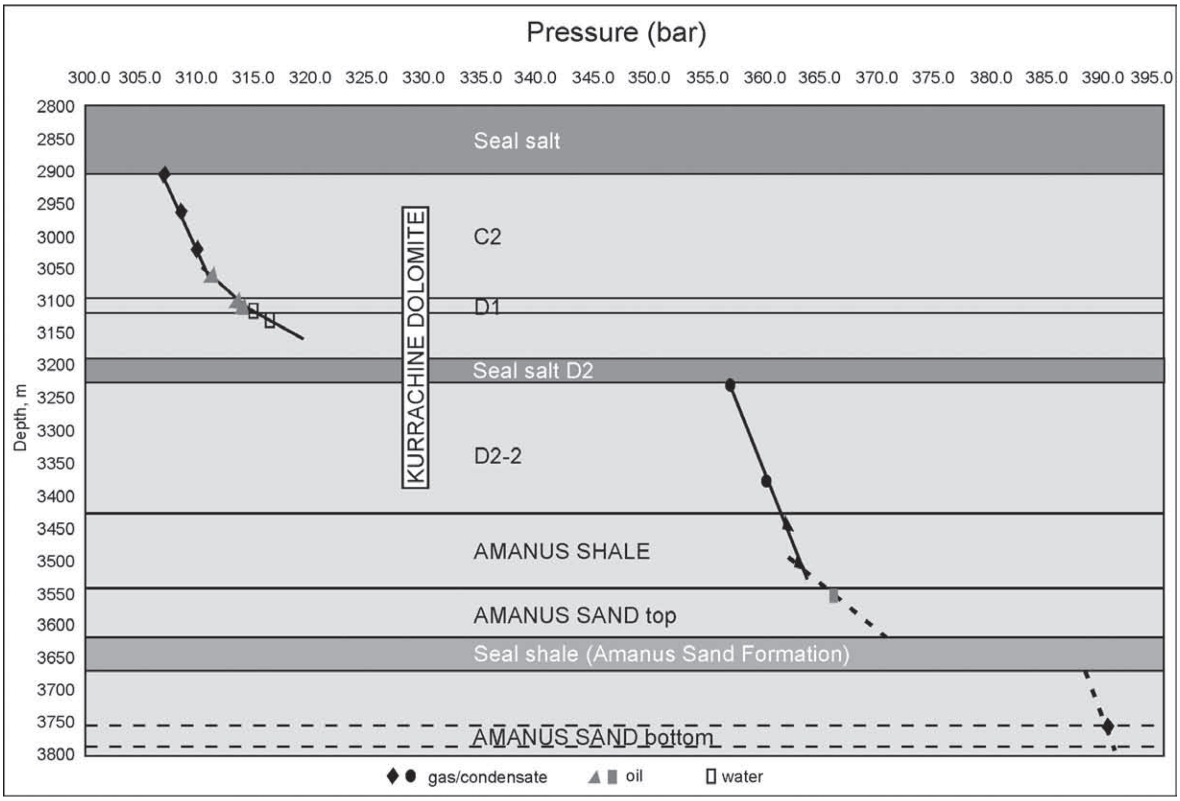

Figure 14: Pressure gradients of Kurrachine Dolomite, Amanus Shale and Amanus Sand Formations ("B" oil/gas field).

Results presented here lead to the conclusion that an active Triassic Petroleum System exists in the area of the Hayan Block. Hydrocarbon accumulations in Syria were already proven in the Triassic Oil System which includes source rocks of the Amanus Shale, Kurrachine Dolomite, Mulussa and Sergelu Formations and Triassic and Cretaceous carbonate reservoirs (METWALLI et al., 1974, WEBB & THOMPSON, 1994; ABBOUD et al., 2005). In order to prove the Triassic Petroleum System as an important source and reservoir rock complex over the whole area, some additional work is necessary (i.e. the upper part of Kurrachine Dolomite Formation also shows strong mature source rock characteristics).

6. CONCLUSION

Investigation of the Triassic Kurrachine Dolomite Formation elements (source, reservoir, seal rock type and trap configuration), was essential for Petroleum System and play definition.

It was found that according to geochemical analyses, the source rock potential was underestimated. Geochemical analyses predicted only thin layers of source rocks which could not generate sufficient amounts of hydrocarbons present in the Triassic/Permian reservoirs. Moreover, it was presumed that hydrocarbons in Triassic reservoirs were generated from deeper Palaeozoic formations (BARIĆ & SMOLJANOVIĆ, 2007).

However, Net Pay of mature source rocks calculated from well logs showed much higher thicknesses of mature source rocks. A Formation resistivity of 20 Ωm is typical of the area and it represents the threshold value for mature source rocks and Net Pay calculating criteria.

Source rocks were also marked on 3D seismic sections. The calculated volume (from 3D seismic) and amount of generated hydrocarbons on the one part of the "B" wells field highly supports the final results and conclusions.

Triassic source rocks of the Kurrachine Dolomite Formation in the area of the Hayan Block have significant Net Pay of mature source rock, exceeding more than 150 m (through 220 m gross interval of source rock, which belongs only to the lower part of the reservoir). It was concluded that mature fractured source rock represents an *in situ* source and reservoir rock, and that either no hydrocarbon migration pathways exist or they were over very short distances.

Evaluated and compared well log petrophysical similarities between the Kurrachine Dolomite and Amanus Shale Formations source rocks, supported with strong geochemical matching of source rock/oil samples, set the Triassic Petroleum System as a mayor play in the area of the Hayan Block.

The Triassic Petroleum System is represented by the fractured source rock and reservoir system *in situ* – Triassic Kurrachine Dolomite and Amanus Shale Formations, respectively, and in some parts conventional Permian Amanus Sand reservoirs. Thick salt-evaporite layers represent the seals: D2 salt and salt on top of the Kurrachine Dolomite Formation – bottom part of the Kurrachine Anhydrite Formation.

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