Evaluation of organic carbon content and source rock maturity using petrophysical logs and geochemical data: Case study of Horn Valley Siltstone source rock, Amadeus Basin, Central Australia

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Abstract:

In this study, 30 samples from the Horn Valley Siltstone Formation from Amadeus Basin in Central Australia have been analyzed using geochemical method Rock-Eval (RE) pyrolysis. The analysis shows Total Organic Carbon between 0.21 to 2.74%wt . It also shows that kerogen type II, and a mixture of type II and III are the dominant kerogen. This type of kerogens are prone to oil and oil/gas production. The geochemical diagrams show that all samples are in the oil window, and they have good thermal maturation. The Horn Valley siltstone formation has been divided into 4 zones; Hv1, Hv2, Hv3 and Hv4. Although all zones are mature (i.e., have Tmax over 435 °C), Hv2 has a high organic carbon content and is located at the end of the oil window (Tmax between 450-470 °C). Also, to compare the results, petrophysical logs (Resistivity and Sonic) and ΔlogR method were used to determine the organic carbon content of source rock, and investigate zones with high pontentials to produce hydrocarbons. Zones have the potential to produce hydrocarbons was determined. And there was a close adaptation between the results of petrophysical method (ΔlogR) and Rock-Eval pyrolysis technique. The results show that Petrophysical method (ΔlogR) and the Rock-Eval pyrolysis technique have produced close results.

Keywords: Organic matter, Rock-Eval pyrolysis, ΔlogR, Horn Valley Siltstone, Australia.

1. Introduction

In today's world, petroleum geochemistry is used as the fundamental science for understanding the properties of source rocks, productive and non-productive zones, oil migration (all of which result in more efficient exploration), development of oil fields and sustainable production. The term of source rock refers to an organic-rich fine-grained sedimentary rock which can produce hydrocarbons due to thermal maturation (Rezaee, 2002). Source rock is one of the main elements of a Hydrocarbon system. Therefore, to identify a region of hydrocarbon, it is necessary to investigate the source rock and its characteristics first. Thermal maturity is the primary factor that determines whether a source rock can produce oil, gas, or condensate (Lecompte et al, 2010). In order to evaluate the source rocks various laboratory methods and/or burial history are used. Among these techniques, Rock-Eval pyrolysis has been widely used in the industry as a standard method in petroleum exploration (Lafargue et al, 1998). From laboratory methods, the Rock-Eval pyrolysis method has been extensively used, worldwide, for oil and gas exploration in sedimentary basins (Behar et al, 2001). This method is used in determining the thermal maturation of kerogen. Peters (1986), defined the thermal parameters based on which maximum temperature (Tmax) can be used to determine the dimensions of the oil window. According to that definition, the Tmax value for the beginning of the oil window is usually 445 to 435 ºC, for the peak is 450 to 445 ºC, and for the end is 470 to 450 ºC (Peters and Cassa, 1994). Thermal maturity of the samples can be determined with plotting Tmax values versus HI. Besides these methods, Wireline logs is used today as a cheap and available method for most wells to determine Lithofacies, depositional environment, burial history and calculating organic richness (Walaa et al, 2009).

It is standard practice in North American shale play evaluation to use the ΔlogR technique published by Passey et al. (1990) to quantify total organic carbon (TOC) from porosity and resistivity logs (Lecompte et al, 2010). That technique requires an important assumption about the level of maturity of the source rock. In prospective shale plays, such as the emerging plays of Europe, Asia, and elsewhere, accurate maps of maturity might be unavailable. Therefore, it has become desireable for resource play evaluation to invert Passey's ΔlogR equation and solve for the level of organic metamorphism, LOM.

Hood et al. (1975) define LOM as the level of organic metamorphism which is based on coal rank. They developed a single scale which synthesizes several existing indices of organic maturity. The scale relates LOM to vitrinite reflectance among other indicators. Hood (1975) wanted a scale that would cover the entire range from generation to destruction of petroleum. LOM is unitless. LOM is obtained from Various methods of samples analysis (eg. Vitrinaite reflectance, thermal alteration index and Tmax), or estimated using burial and thermal history of the basin (Rezaee and Chehrazi, 2005). As Passey et al. (1990) have shown, there are several methods that can be used to determine the organic content by interpretation of various electric logs. One such method, referred to as the ΔlogR technique, is used for identifying and calculating total organic carbon in organic-rich rocks can be quickly estimated by the improvement of cross-plotting sonic logs (DT) and log of resistivity data and determining the shale line that can then be used to calculate a pseudo-sonic log that is then displayed over the existing sonic logs to determine the organic shale potential for a zone in an individual well. In water-saturated, organic-lean rocks, the two curves parallel each other and allow the shale calculation line to be determined. However, in either hydrocarbon reservoir rocks or organic-rich shale sections a separation between the curves occur. Using the gamma-ray curve, reservoir intervals can be identified and eliminated from the analysis (Bowman, 2010). The separation in organic-rich intervals results from two effects: the porosity curve responds to the presence of low-density, low-velocity kerogen, and the resistivity curve responds to the formation fluid. In mature source rocks the magnitude of the resistivity increases because of the presence of generated hydrocarbons. This technique by cross-plotting multiple wells

can provide relative information for an area or entire shale section. This method requires little data and log calculation mathematics to provide a geoscientist sufficient data to easily and quickly determine potential organic shale sections. Across an area, these log cross-plot displays support the correlation and mapping of organic-rich shale sections and allow the geoscientist to quickly determine high graded areas of focus for further study (Bowman, 2010). This method allows organic richness to be assessed in a wide variety of lithologies and maturities using common well logs.

In this study, the compatibility of petrophysical and geochemical methods is investigated by studying the thermal maturation and Zonation of Horn Valley siltstone, using the integration geochemical data (Rock-Eval pyrolysis) and petrophysical logs (porosity and resistivity) with the ΔlogR method.

2. Regional Geology

The Amadeus Basin is an asymmetric, east–west trend, intracratonic depression covering approximately 170000 Km2 (65500 square miles) of central Australia (Fig.1) (Gorter, 1984; Marshall et al, 2007). It contains a Neoproterozoic to Late Devonian sedimentary section that reaches a maximum thickness of approximately 17 km (Fig.2), which lies across the Northern Territory south of latitude 23°30'S and extends into Western Australia. It also contains Proterozoic, Ordovician, possibly Silurian, and Devono-Carboniferous, and minor Permian and Tertiary freshwater deposits.

Tectonic movements in the Proterozoic established the shape of the basin, and formed the structural framework within which subsequent movement took place.

Horn Valley siltstone deposits are known as the source of many hydrocarbons discovered in the Amadeus Basin (Jackson et al, 1984; Marshall, 2003, 2004; Marshall et al, 2007), belonging to the Larapinta Group in central Australia. The Larapinta Group consists of five formations of predominantly siliciclastic sediment deposited in a shallow intracratonic sea (Fig.3). During accumulation of the Larapinta Group from Late Cambrian to mid-Late Ordovician, the Amadeus Basin was covered by a shallow fluctuating sea. Two major transgressions occurred during the Larapinta episode of sedimentation. The first of these sea level maxima corresponds to the deposition of the Horn Valley Siltstone, and the second to the Stokes Siltstone (Elphinstone, 1989).

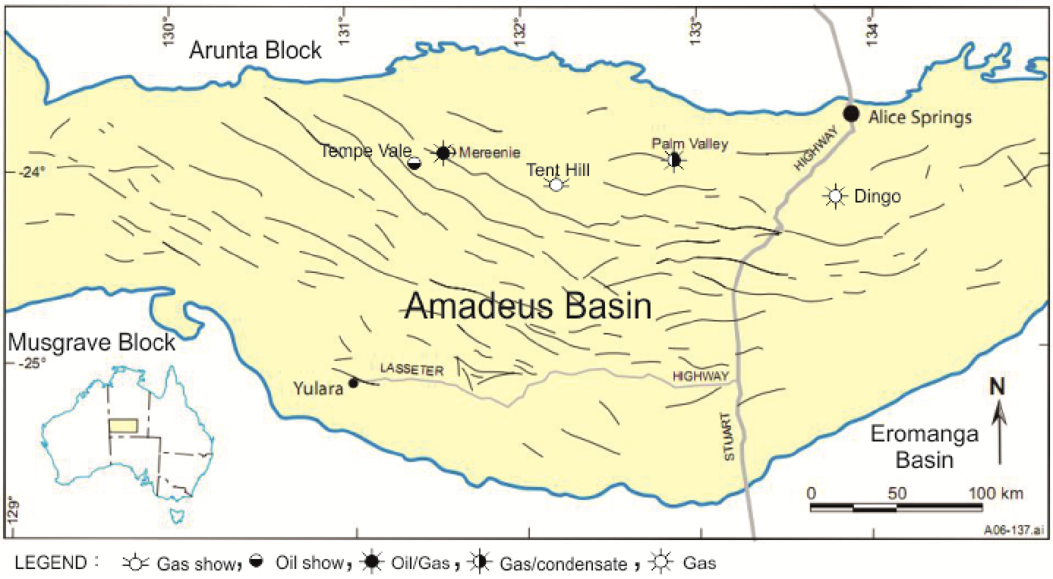

Fig.(1) Location map showing the Amadeus Basin in central Australia. Black lines represent axial traces of anticlines defined by outcrop, seismic and airborne magnetic data (modified after Marshall et al, 2007).

The formations underlying and overlying the Horn Valley Siltstone (i.e., the Pacoota and Stairway Sandstones) were deposited in intertidal to mainly subtidal environments. Both of these formations were intensively bioturbated and contained an evidence of a high energy depositional environment in the form of current bedding, scouring and phosphorite development (Wells et al, 1970).

The structures evident in the Amadeus Basin are the direct result of north-south compressing forces (Marshall, 2003). Fold structures are characterised by broad flat synclines and tight, commonly asymmetric anticlines. Cross-faulting appears minimal, and is generally related to thrust adjustment. Two major episodes of tectonic deformation have largely controlled the development of the structures suitable for petroleum entrapment and preservation: the Late Proterozoic Petermann Ranges Orogeny and the Late Devonian to Early Carboniferous Alice Springs Orogeny.

Petroleum accumulations in the Amadeus Basin occupy structural/ stratigraphic traps in rocks of Cambro-Ordovician and Proterozoic ages. The principal Cambro-Ordovician traps are aligned along a northwest or east-west trend (Figure 1) (Marshall et al, 2007). The petroleum in the Amadeus Basin mainly occupies the structural, fold-related traps within the Upper Proterozoic to Upper Ordovician marine to marginal marine clastic and evaporitic sequences. It is believed to be of algal/bacterial origin (Ozimic et al, 1986).

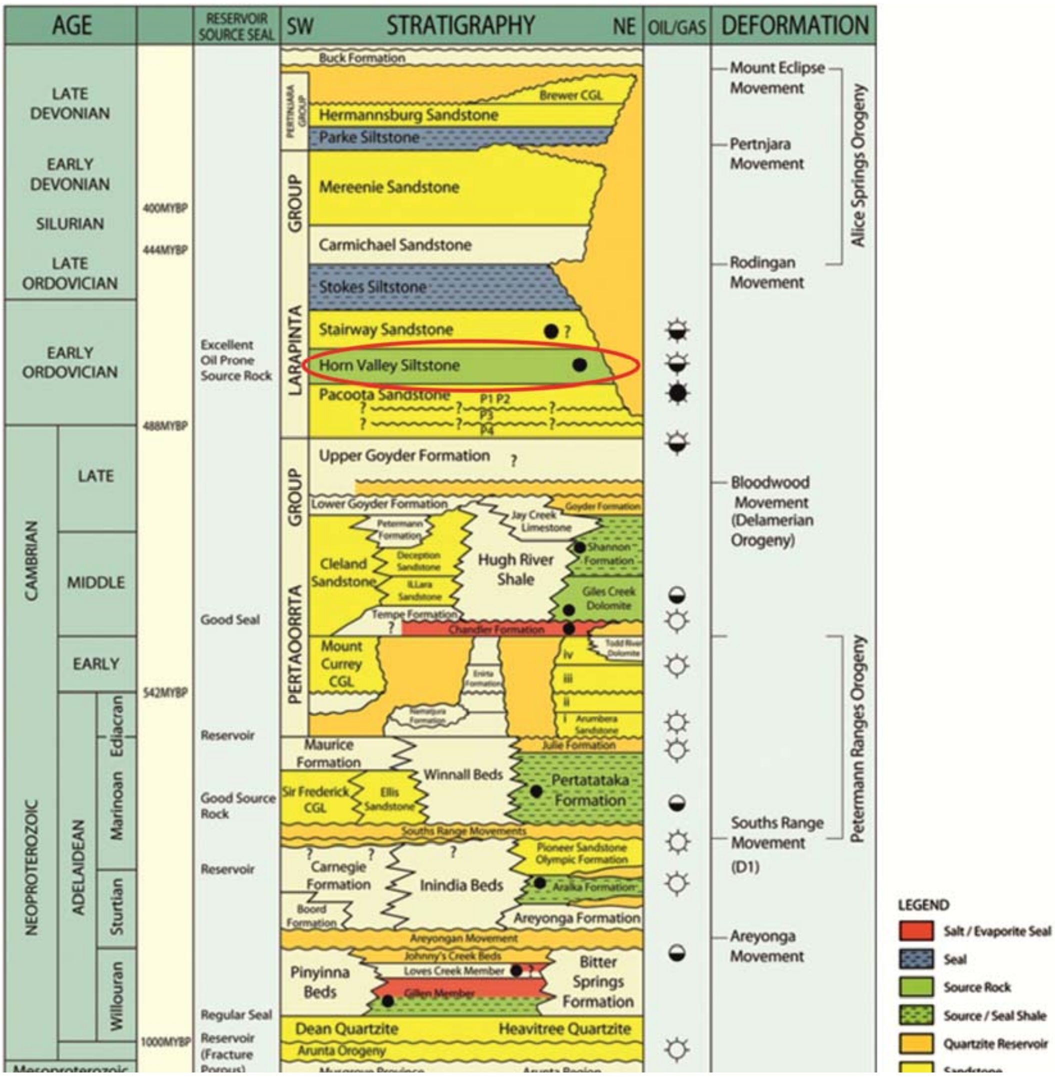

Fig.(2) Generalised stratigraphic column for the Amadeus Basin (after Dunmore, 2010).

3. Methods

In this study, the pyrolysis data from 30 core samples obtained from Horn Valley siltstone formations of Tent Hill 1 well in Amadeus Basin are used. The samples were pulverized, and about 100mg from each sample was analyzed using a Rock-Eval/TOC 6 version. The Rock-Eval 6 apparatus is the latest version of the Rock-Eval product line, which is the best method to evaluate the source rocks due to the high accuracy of the analysis (Behar et al. 2001). Rock-Eval analysis is a quick and common method for initial evaluation of geochemical characteristics of source rocks. Total organic content (TOC) was determined. Thus, S_1, S_2, S_3 and Tmax values were obtained (Table 1). Parameter S_1 is the amount of free hydrocarbon (mg HC/grock) liberated at 300°C (without cracking the kerogen). Peak S_2 is the amount of hydrocarbon released from cracking of kerogen (mg HC/grock) and heavy hydrocarbons during temperature-programmed pyrolysis (300 - 600°C) and represents the existing potential of a rock to generate petroleum. Peters and Cassa (1994) believed that S_2 is a more realistic measure of source rock potential than TOC because TOC includes "dead carbon" incapable of generating petroleum. S_3 represents the amount of CO_2 from breaking carboxyl groups and other oxygen-containing compounds in kerogen, obtained at 300 to 390 ° C.

TOC is determined by oxidizing the pyrolysis residue in a second oven (600°C in air). The Hydrogen index (HI) is the normalized S_2 value (S_2/TOC), expressed in mg HC/gTOC. The oxygen index (OI) is related to the amount of oxygen in the kerogen and is the normalized S_3 value (S_3/TOC), expressed in mg co_2/gTOC. The production index (PI) shows the level of thermal maturation. The S_2/S_3 values indicate the type of organic matter for low to moderately mature samples (Leckie et al. 1988).

Results of samples Rock-Eval pyrolysis is shown in Fig.3. In this Figure Geochemical diagrams of Horn Valley siltstone formation are drawn and geochemical parameters are compared with each other.

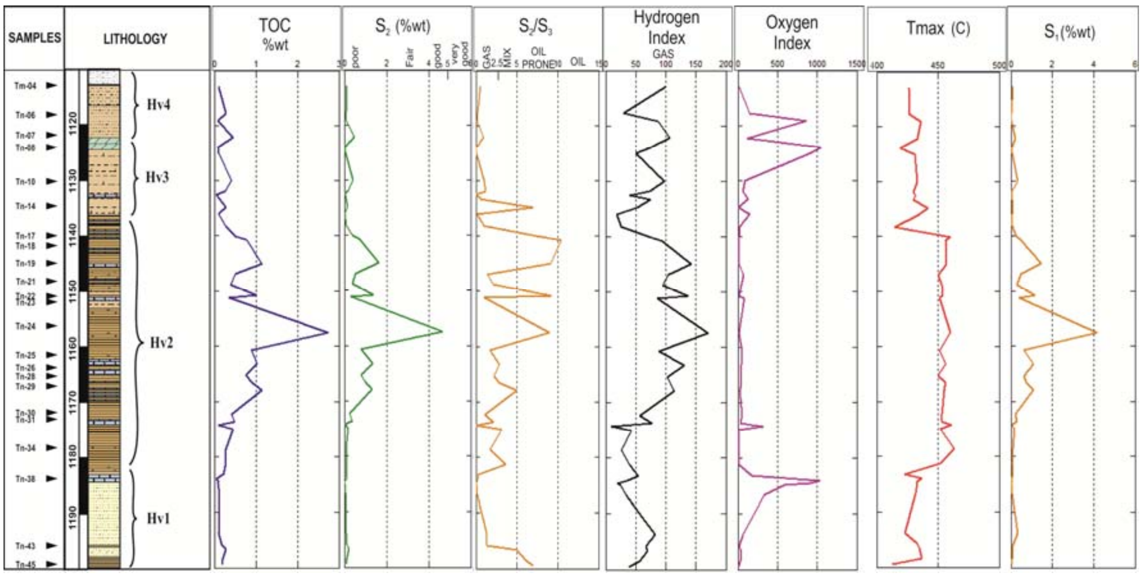

Fig.(3) Stratigraphic log and Geochemical diagrams of the Horn Valley Siltstone sequence at Tent Hill 1 Well with location of the samples of organic matter rich rocks.

Table.1: Result of Rock-Eval analyses of representative samples from Tent Hill 1 Well.

DEPTH(m)	S1(mg/g rock)	S2(mg/g rock)	TOC(wt %)	TMAX(deg C)	HI(mgHC/g TOC)	OI(mgCO2/g TOC)
1112.9	0.08	0.1	0.22	436	100	162
1117.7	0.09	0.08	0.27	437	29.63	148.15
1122.2	0.21	0.48	0.45	433	106.67	115.56
1130	0.31	0.41	0.42	443	97.62	95.24
1131.9	0.07	0.19	0.26	450	73.08	61.54
1134.8	0.08	014	027	452	51.85	7.41
1138.2	0.06	0.07	0.27	415	25.93	25.93
1140	0.23	0.37	0.51	460	72.55	9.8
1140.7	0.47	0.73	0.78	456	93.59	8.97
1145	1.46	1.64	1.15	463	142.61	15.65
1146.9	0.49	0.52	0.5	450	104	74
1148.8	0.28	0.38	0.4	453	95	45
1150.8	1.14	1.38	1.01	454	136.63	14.85
1151.2	0.41	0.31	0.36	451	86.11	83.33
1157.5	4.14	4.67	2.74	455	170.44	18.98
1160.7	0.61	0.8	0.9	451	88.89	52.22
1163.2	1.08	1.34	1.03	456	130.1	45.63
1165.3	0.63	0.78	0.76	450	102.63	47.37
1166.7	0.73	0.98	0.91	456	107.69	38.46
1167.9	1.09	1.3	1.14	455	114.04	22.81
1172.3	0.22	0.24	0.42	453	57.14	54.76
1173.7	0.29	0.38	0.49	450	77.55	36.73
1175	0.17	0.19	0.45	452	42.22	13.33
1178.6	0.08	0.07	0.27	463	25.93	14.81
1181.6	0.05	0.11	0.27	452	40.74	28.11
1183.2	0.1	0.12	0.22	433	54.55	172.73
1186.7	0.04	0.04	0.21	442	33.33	333.33
1196.6	0.11	0.2	0.28	455	70	43
1198.4	0.05	0.12	0.21	437	57.14	23.21
1199.5	0.02	0.07	0.22	435	38.89	5.56

In order to predict Organic matter content, the petrophysical logs (Resistivity and porosity), and the ΔlogR method were used. For this purpose, the scale of the logs can be changed (where 50 µsec/ft is equal to 1 of log decade Resistivity (ohm-m), the separation between the two curves can be calculated in any depth.

Given that vitrinite is found in post-Silurian terrestrial basins (UCL, 2002), the level of organic metamorphism (LOM) were estimated using the conodont alteration index and the Hood charts 1975 (Figure 4). Based on that, LOM values between 8.5 and 12 usually represent oil window intervals (Hunt, 1996), and LOM value equal to 12 indicates that organic matter has produced hydrocarbons in the past, and can no longer produce hydrocarbons (Rezaee and Chehrazi, 2005).

The following formula was used to ΔlogR calculation:

$$\Delta \text{LogR} = Log_{10}(R/R_{baseline}) + 0.02 \times (\Delta t - \Delta t_{baseline})$$

Where:
ΔlogR = calculated separation between sonic and resistivity logs
$R_{baseline}$ = base line resistivity reading
$\Delta T_{baseline}$= base line time difference reading
R = resistivity reading based on log
ΔT = time difference based on the sonic log
And an experimental formula for calculating TOC in clay rocks (rich of organic matter) issuggested as below:

$$TOC = (\Delta LogR) \times 10^{(2.297 - 0.1688 \times LOM)}$$

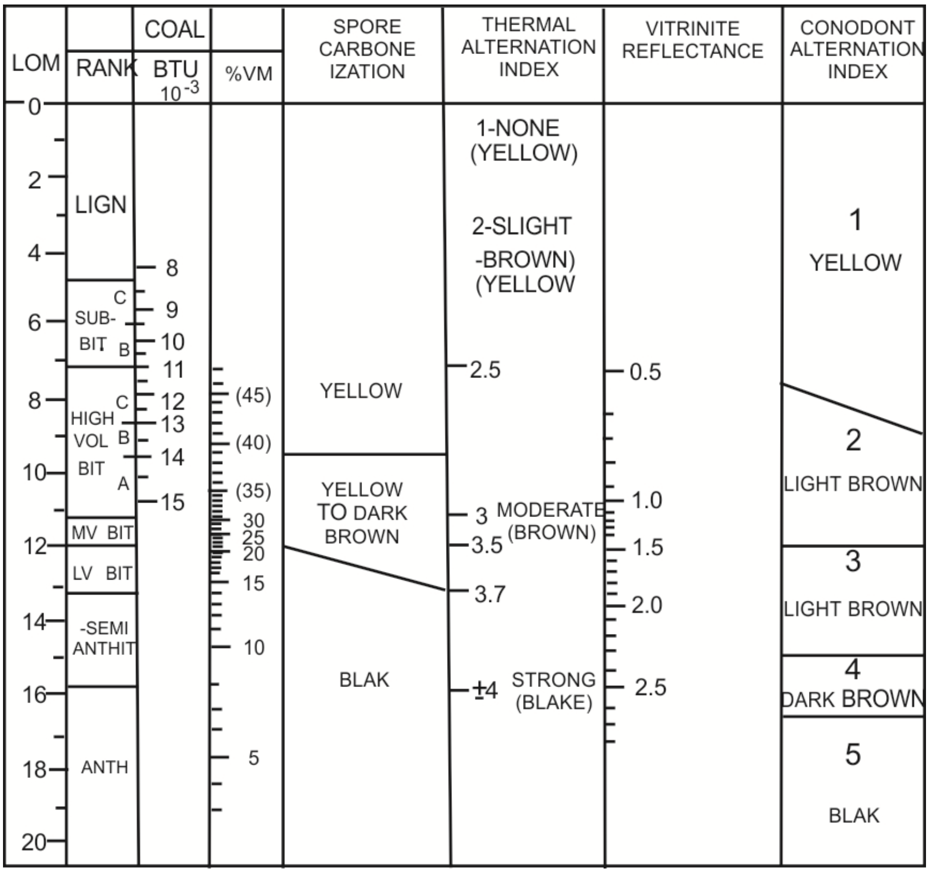

Fig.(4) Relation of %Ro to another thermal maturity indicator known as Level of Organic Metamorphism (LOM) (Modified after Hood, 1975).

4. Results and discussion

Table 1 illustrates the values of total organic carbon, Rock-Eval pyrolysis for the Horn Valley siltstone samples. Total organic carbon values were measured on 30 samples (Table 1). The obtained data show that the total organic carbon values are between 0.22 and 2.74 wt%, with an average of about 0.58 wt%.

In order to determine samples' contamination to hydrocarbon material, the S1/TOC diagram was used (Fig. 5) (Hunt, 1996).

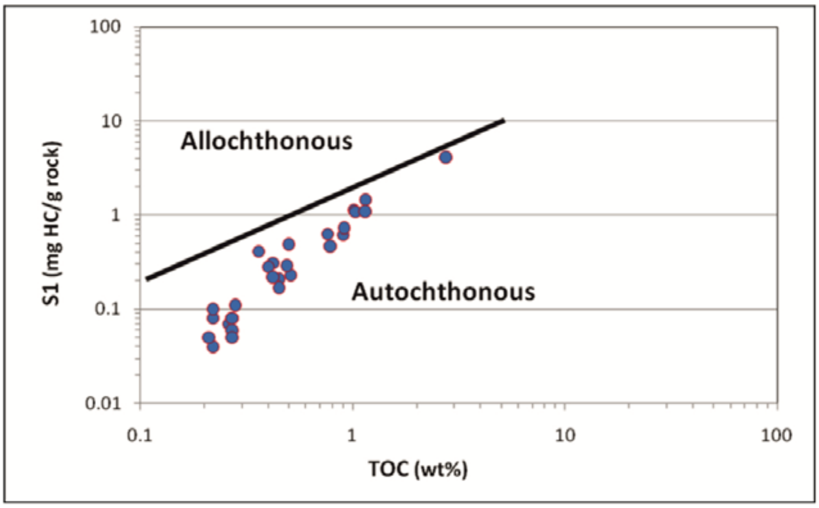

Fig.(5) S1 versus TOC diagram to discriminate non-indigenous and indigenous hydrocarbons

Plot of S_1 versus TOC can be used to discriminate between non-indigenous and indigenous hydrocarbons (Hunt, 1996; Rabbani and Kamali, 2005). The migrated oil in formation can be detected with high S_1 and low TOC. All studied rock samples have relatively high S_1 and high TOC values (Fig.5) indicating the presence of indigenous (expelled) oil. It should be noted that hydrocarbon-contamination of the samples does not mean that oil migrated from the lower layers, but it means that hydrocarbon has been produced in the source rocks prior to the primary migration process. To assess thermal maturity and Kerogen type (Organic-geochemical measurements), the samples were plotted on a HI versus Tmax diagram (Tissot and Welte 1985; Espitalié et al, 1985) (Fig 6). The results indicated that the samples contained type II/III kerogen dominantly. In the Horn Valley sediments, hydrogen index ranges from 53.22 to 170.44 mg HC/gTOC, with an average around 90.55 mg HC/gTOC. PI ranges from 0.14 to 0.86, with an average of 0.44, and Tmax ranges from 415 to 463°C, with an average of 448°C.

Tmax and production index show that the organic matter in the samples is mature (Peak of Oil window) (Figure 7).

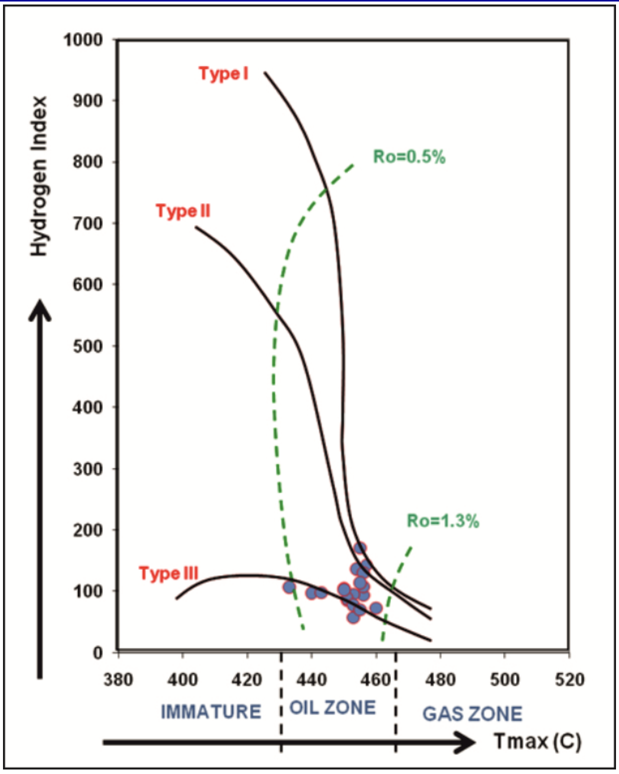

Fig.(6) Organic matter type discrimination diagram of the studied samples from the Amadeus Basin based on crossplot of Tmax and hydrogen index.

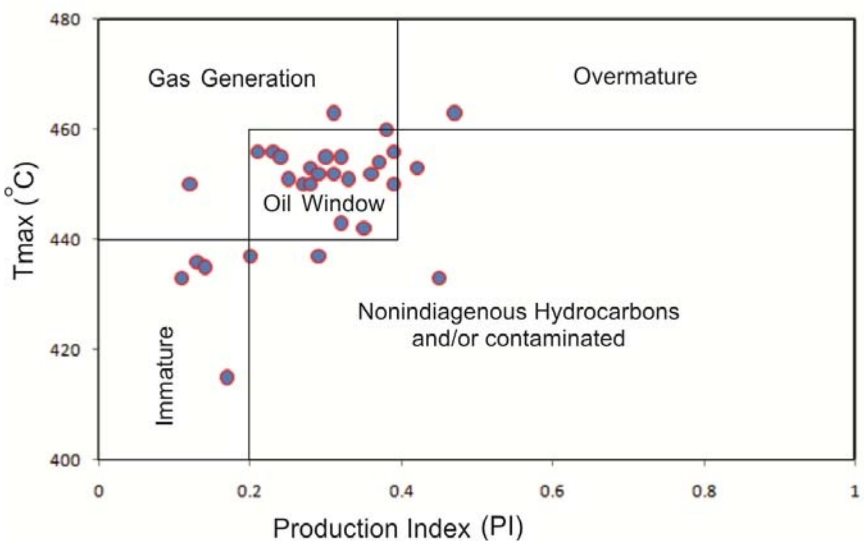

Fig.(7) Tmax (°C)-PI diagram of the investigated samples.

Thus, using the resistivity and Sonic logs, the maximum separation of ΔLogR was at about 0.8, the obtained LOM values were between 9 and 10, and using equations 1 and 2 the TOC values log was calculated (Figure 8). As it is evident in Figure 8, values obtained from the petrophysical logs indicate a very good conformity with values obtained from the pyrolysis of core samples.

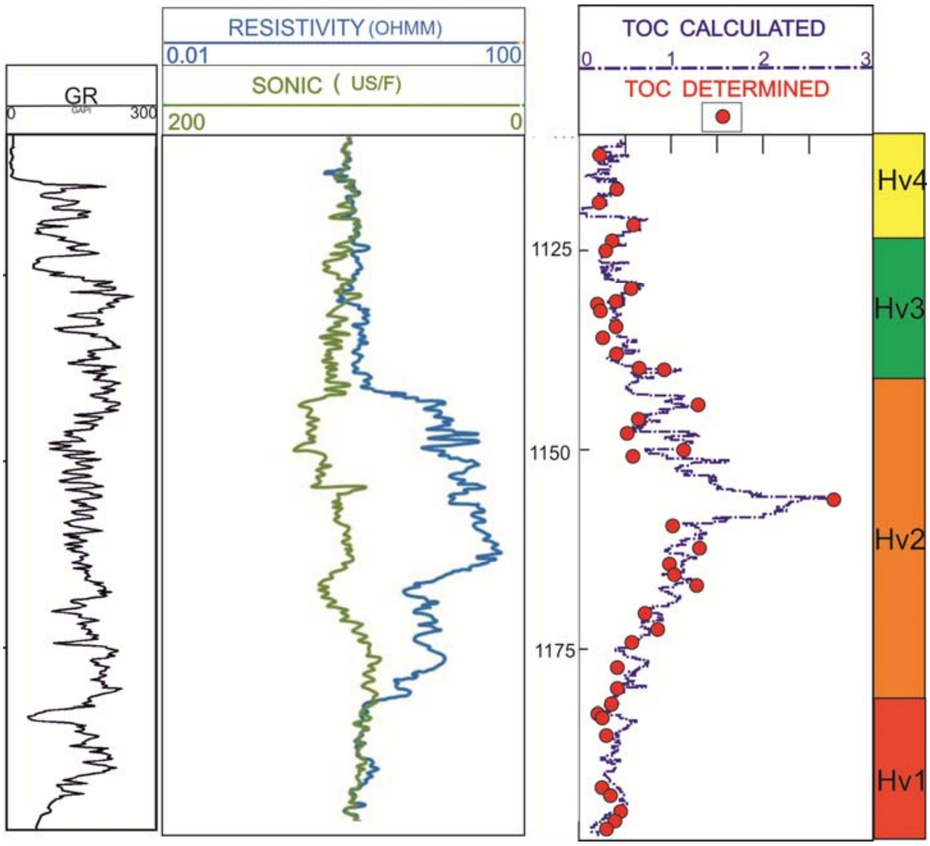

Fig.(8) Sonic versus resistivity (ΔLogR) Crossplot showing non-source rock and source rock cluster of data. Scale Sonic and Resistivity where 50 µsec/ft equal to 1 decade Resistivity (ohm-m), TOC calculated from Passey DlogR Method.

Horn Valley siltstone formation was divided into four zones Hv1, Hv2, Hv3 and Hv4 zone, due to the high TOC and thermal maturity for hydrocarbon, has the greatest potential for hydrocarbon production (Figure 8).

The geochemistry of the Hv1 and Hv4 zones are the same, but the Hv3 zone is in a better condition .

The quality and type of the hydrocarbons produced from source rocks, can be identified by S_2/S_3 versus TOC diagram (Peters and Cassa, 1994). Figure 9 suggests plot of the studied samples.

Samples belonging to each zone is marked in a unique color, i.e., different from other zones. As evident in Figure 9, samples from the Hv2 zone are located in the Good to Very Good, oil and gas/oil generation area. This zone with shale, carbonate shale, lithology and interbeded carbonate siltstone, Abundant fossils, thickness of about 40m, maximum 2.74 TOC and Tmax more than 450 °C, is located in the range of oil generation.

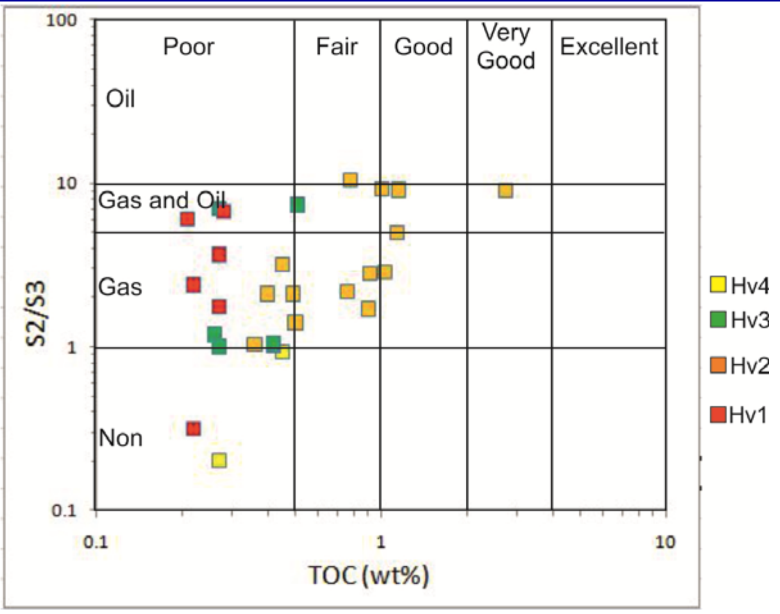

Fig.(9) Cross plots of TOC vs. Rock-Eval S2/S3 values of the investigated samples.

5. Conclusion:

In this study, LOM values in the Horn Valley siltstone formation is obtained between 9 and 10 using the Conodont alteration index. The results of the thermal maturation study of Horn Valley siltstone formation using a combination of geochemical information (Rock-Eval pyrolysis) and petrophysical logs with ΔlogR techniques, shows a close conformity between the results of these two methods. This indicates that using the petrophysical logs, the geochemical data, and the ΔlogR techniques by multiple wells, relevant information for an area or the entire shale section can be provided.

This method requires little more than a simple cross-plot and log calculation mathematics to provide a geoscientist sufficient data to easily and quickly determine potential organic shale sections. Using this technique across an area, supports the correlation and mapping of organic-rich shale sections, and allows the geoscientist to quickly determine high graded areas of focus for further studies. This method allows organic richness to be assessed in a wide variety of lithologies and maturities using common well logs.

Acknowledgements

The authors are grateful to the management of Occam Technology Pty. Ltd and Michael Wiltshiremike, for the provision of Rock-Eval pyrolysis data for this study.

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