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Depositional Environment and Source Potential of Devonian Source Rock, Ghadames Basin, Southern Tunisia

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***Abstract*—**Depositional environment and source potential of the different organic-rich levels of Devonian age (up to 990m thick) from the onshore EC-1 well (Southern Tunisia) were investigated based on the analysis of more than 130 cutting samples by different geochemical techniques (Rock-Eval pyrolysis, GC-MS). The obtained results including Rock Eval Pyrolysis data and biomarker distribution (terpanes, steranes and aromatics) have been used to describe the depositional environment and to assess the thermal maturity of the Devonian organic matter. These results show that the Emsian deposits exhibit poor to fair TOC contents. The associated organic matter is composed of mixed kerogen (type II/III), as indicated by the predominance of C29 steranes over C27 and C28 homologous, that was deposited in a slightly reduced environment favoring organic matter preservation. Thermal maturity assessed from Tmax, TNR and MPI-1 values shows a mature stage of organic matter. The Middle Devonian (Eifelian) shales are rich in type II organic matter that was deposited in an open marine depositional environment. The TOC values are high and vary between 2 and 7% indicating good to excellent source rock. The relatively high HI values (reaching 547 mg HC/g TOC) and the low values of t19/t23 tricyclic terpane ratio (< 0.2) confirm the marine origin of the organic matter (type II). During the Upper Devonian, the organic matter was deposited under variable redox conditions, oxic to suboxic which is clearly indicated by the low C35/C34 hopanes ratio, immature to marginally mature with the vitrinite reflectance ranging from 0.5 to 0.7 Ro and Tmax value of 426°C-436 °C and the TOC values range between 0.8% to 4%.

***Keywords*—**Depositional environment, Devonian, Source rock.

I. Introduction

SUBSURFACE exploration of the Palaeozoic hydrocarbon systems of the Sahara Desert province of Libya, Algeria, Tunisia and Morocco began in the early 1950s [1].

Located in Northern Africa, Ghadames basin is considered as the major proven petroleum province with several producing petroleum systems, among them Ordovician, Silurian, Devonian, and Triassic petroleum systems. This sedimentary basin (Fig. 1) is thought to be a large intracratonic sag basin on the Northern Africa Platform and is formed during the early Paleozoic. It covers an area of 350000 km^2 and. It contains up to 6000 m of Paleozoic and Mesozoic sediment. The main source rocks correspond to the Ordovician (Jeffara Formation), the Silurian (Tannezuft Formation), and Devonian (Aouinet Aouinine Formation).

In this paper, we apply the concepts of organic geochemistry on Devonian succession strata in order to identify the richest organic matter interval, to characterized source quality, to identify their inferred depositional environment and to estimate their maturity. Correlation along Ghadames basin across Libya, Tunisia and Algeria would be possible using, where available, geochemistry characteristics of these Devonian deposits. Samples gathered from EC well (Fig. 1) have been analysed ETAP's Laboratories (Entreprise Tunisienne d'Activités Pétrolières).

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II. Stratigraphic Succession of Devonian Strata

Borehole EC (Fig. 1) penetrated Devonian succession strata near the northern margin of Ghadames Basin. This succession (around 1000 m thick) is composed of black shale interbedding with shaly greenish marl. Devonian deposits above the Caledonian unconformity include continental and shallow-marine sandstones and shales of the Tadrart and Ouan Kasa formations. Continued transgression led to deposition of argillaceous marine sediments of the Aouinet Ouenine Group, also an important source rock interval in the Ghadames basin. The overlying Late Devonian–Carboniferous shallow marine and deltaic sediments reflect regression associated with the early and main stages of collision between Gondwana and Laurasia [2].

III. Samples and Methods

A total of 130 cutting samples were collected from the EC well (Ghadames basin-Tunisa) representing the Devonian section ((2730m to 3744m).These samples were cleaned with water to remove mud, dried and then crushed. After an initial screen using Rock Eval-Eval pyrolysis and Total Organic Carbon, Ten samples were selected for further detailed studies (GC and GC/MS). Approximately 20 g of pulverized samples were extracted with MeOH/DCM mixture (1/3, v/v) for 24 hours. After extraction the solvent is removed by means of rotary evaporator. Extracts were separated into their saturate, aromatic and polar fractions using the standards method developed by the IFP and called mini-column chromatography. Saturated and aromatic fractions were analyzed by gas chromatography-mass spectrometry (GC-MS). A gas chromatograph Agilent 7890A (DB-1MS capillary column 60m*0.25mm ID, 0.25µm in film thickness He carrier gas) coupled to Agilent mass selective detector (70eV) was used.

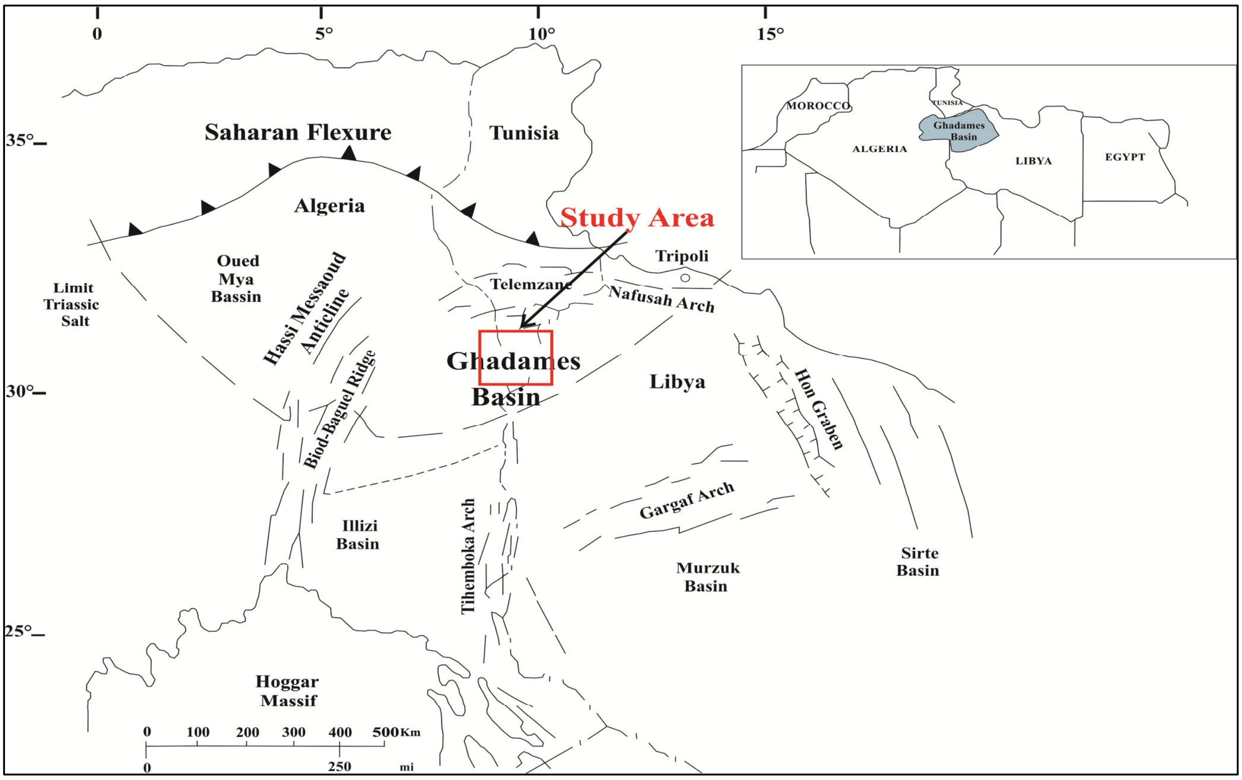

Fig. 1 Geographical map of the Ghadames basin, North Africa [2]

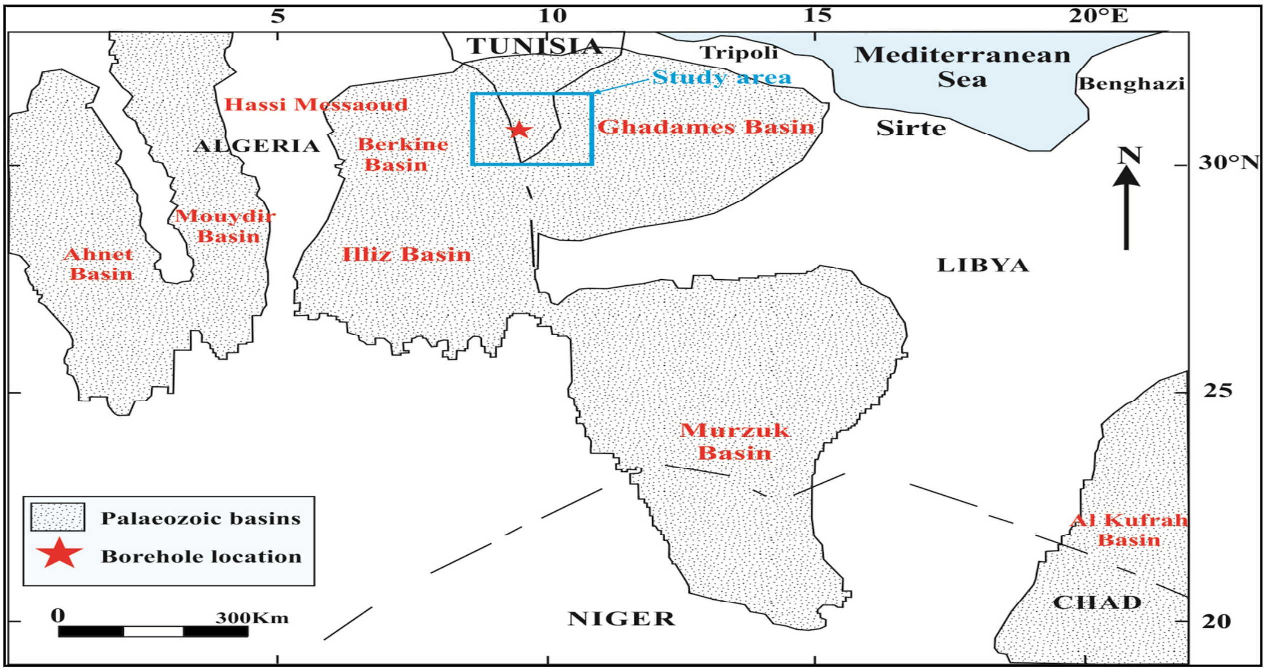

Fig. 2 Geographic location of EC well in the context of main geological features of the Sahara Platform [3]

IV. Results of Rock-Eval Pyrolysis

The Rock-Eval pyrolysis is employed to characterize the source rock richness and quality.

Total organic carbon contents were used to estimate organic matter richness. The TOC values range between 0.8 to 4%. The vertical distributions of TOC values exhibit a unimodal distribution with one single maximum at the depth 2920m.

The Upper Devonian series display low free hydrocarbon contents (S1) ranging between 0,06 and 1 mg HC/g rock and fair to high petroleum potential (up to 12 mg of HC/g rock) (Fig. 4). The variation of S2 in respect to TOC (Fig. 4) shows that the Upper.

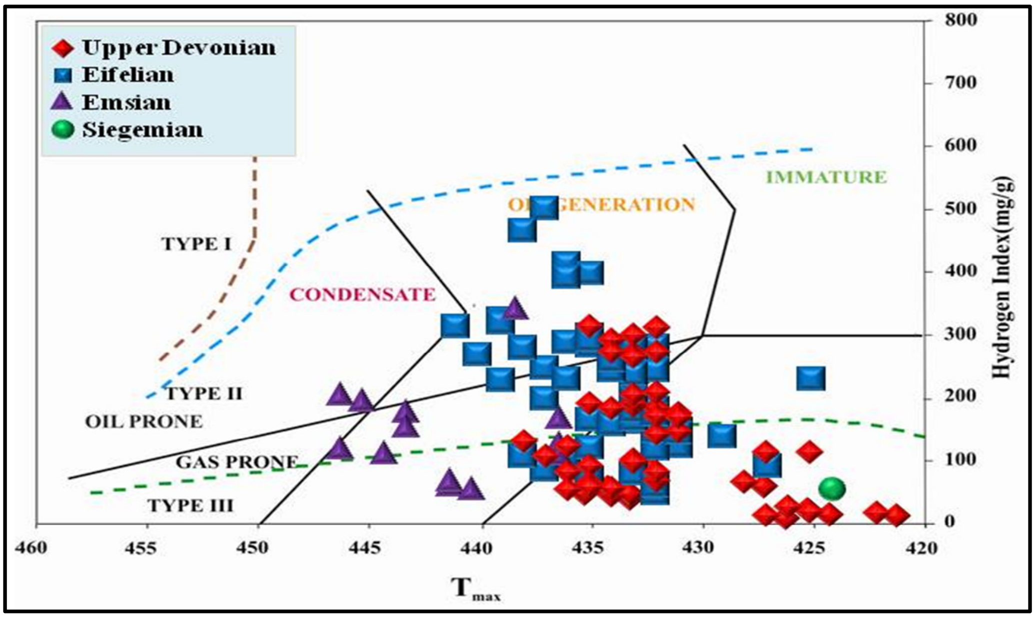

Fig. 3 HI/Tmax diagrams showing the type of organic matter and the maturity level of Devonian

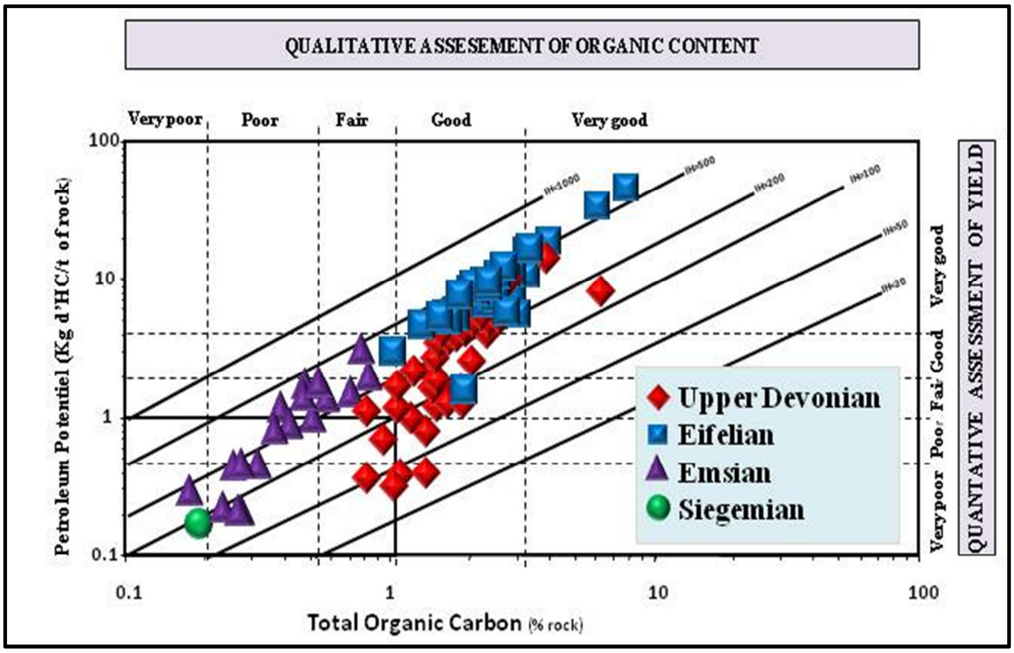

Fig. 4 S2/TOC (%) diagrams showing qualitative the assessment of Devonian

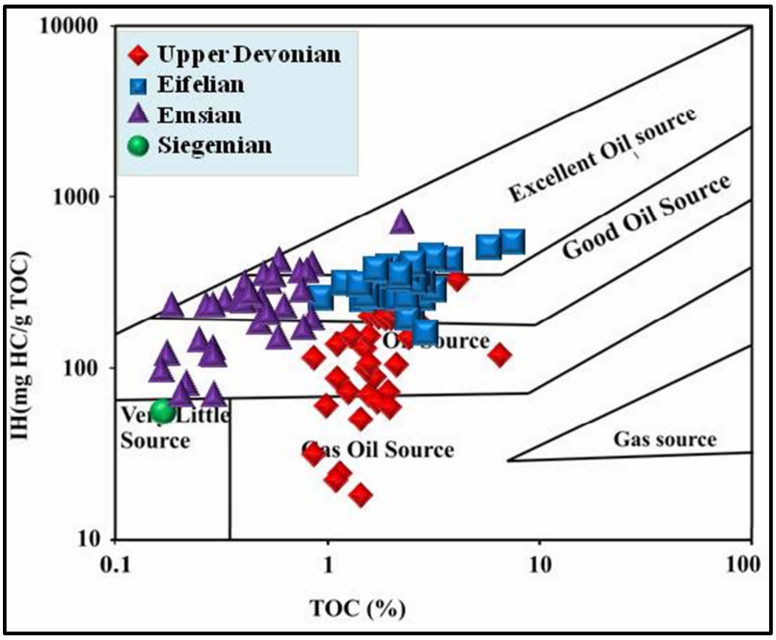

Fig. 5 Quantitative and qualitative assessment of Devonian in Southern Tunisia

Devonian can be rated as fair to good source rock. An assessment of the maturity degree of the samples is provided by Tmax values determined by Rock- Eval pyrolysis. Tmax values vary between 422 and 436°C. As it is illustrated in the HI-T_{max} diagram (Fig. 2), the studied Upper Devonian strata are immature without excluding a possible oil generation.

The values of HI corresponding to Middle Devonian (Eifelian) deposits rise from 70 to 547 mg HC/g TOC. Owing to that, Eifelian deposit may be considered as an excellent oil /gas prone source rock (Fig. 5).

Thermal maturity of Middle Devonian organic matter was also evaluated based on T_{max} which vary between 429°C and 440°C indicating immature to marginally mature (Early oil window).

Hydrogen Index vs Tmax crossplot reveals that the Lower Devonian deposits (Emsian member) corresponding to Ouan Kasa formation contains type II organic matter. PI and Tmax can be used together to evaluate maturity levels. PI value are between 0,1 and 0,6. Tmax values range between 437°C and 446°C. These maturity parameters show that the Emsien member is early mature to mature. According to the plot of HI vs TOC plot, these Lower Devonian deposits probably may generate low to fair hydrocarbon quantities. The top of Emsian seems to be contaminated by hydrocarbon compounds as indicated by high PI values (>0.6) and low Tmax values which are lower (380-420 °C). Gas chromatograms (GC) of representative samples of saturated hydrocarbons extracted from Devonian are shown in Fig. 7. They show a unimodal n-alkane distribution ranging from nC14 to nC29+ and maximizing at nC16-nC18 with no odd/oven predominance (<nC22) and with small "Hump" typical of marine origin. It should be noted that light hydrocarbon are missing and seem to be loosed during sample preparation. Pristane (Pr) and Phytane (Ph) are the predominant isoprenoides and their ratio (Pr/Ph) ratios are used biomarker parameter for assessing redox conditions during sediment accumulation. The Pr/Ph ratios of the Upper Devonian are significantly upper than 1 indicating deposition under suboxic conditions. This ratio is also greater than 1 for the lower part of Aouinet Aouinine but less than 1in its upper part. The Pr/Ph ratios of the Ouan Kasa are significantly lower than 1 which reflects reducing depositional environment conditions (Fig. 7).

Ratio varying from 0.5 to 1 indicates that source have been deposited within alternated conditions between swamps and open waters [4].

V. MATURITY

The analysis of saturated fraction and aromatic fraction indicates an early mature stage for the most samples. Isiomerization at C-20 in the C29 C29 5α, 14α, 17α(H)-steranes causes 20S/(20S+20R) to rise from 0 to ~0.5 50.52-0.55 equilibrium) with increasing thermal maturity [5]. The other isomerization at C-14 and C-17 in the C29 20S and 20R regular stérane causes an increase in ββ/(ββ+αα) from 0 to ~0.7 (0.67-0.71= equilibrium) with increasing maturity [5]. Maturity study was improved through the evaluation of C29 S/(S +R) steranes ratio correlated with TNR and Rock-Eval Tmax.

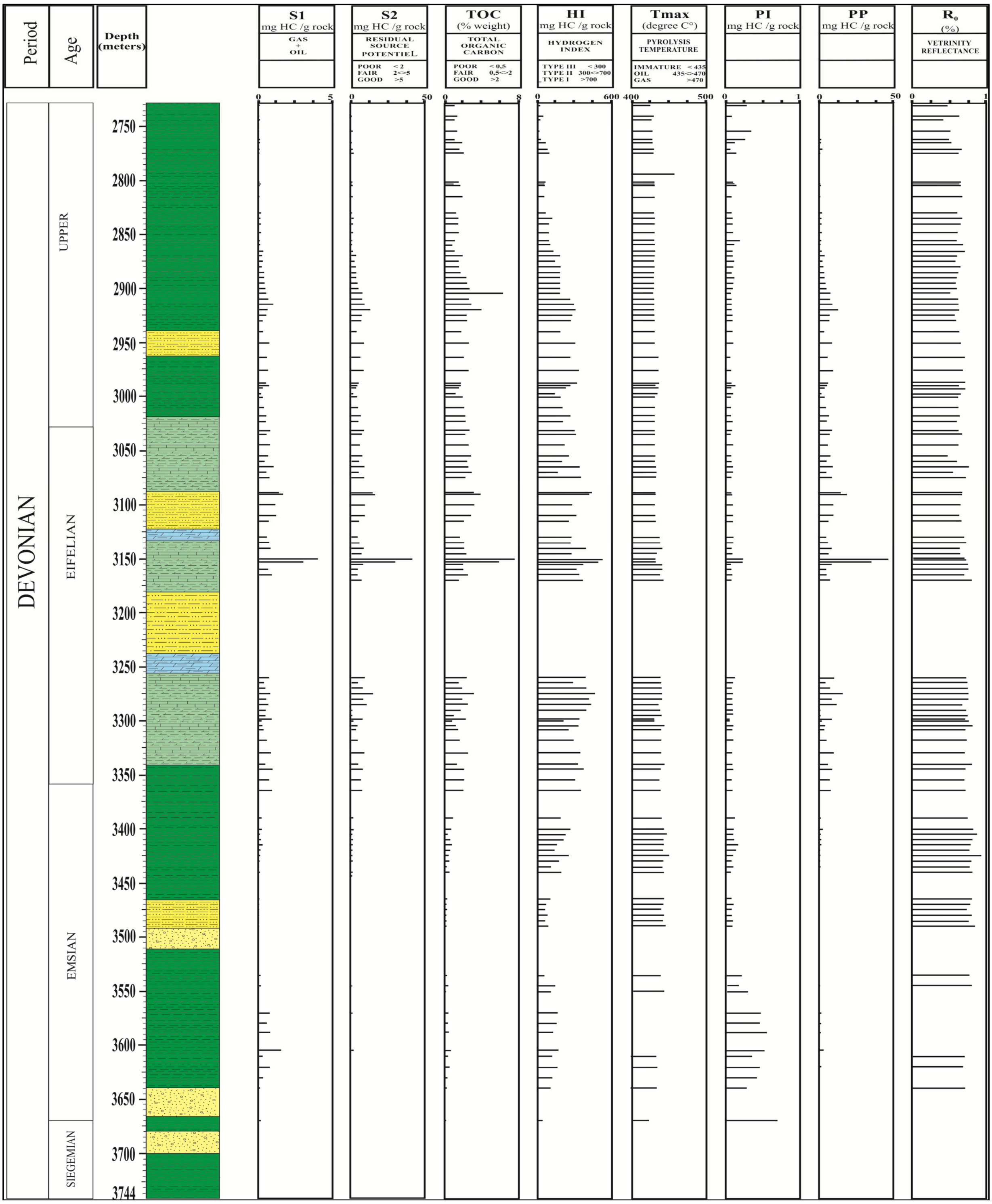

Fig. 6 Geochemical log of EC well, Southern Tunisia. This log shows various geochemical factors including free hydrocarbon (S1), Total Organic matter (TOC), Hydrogen Index (HI), Production Index (PI), Petroleum Potential (PP) and Vitrinite reflectance (R_0)

The Upper Devonian exhibit Tmax values below 434°C and C29 S/(S+R) steranes ratio below the value of 0.32 which indicate immature to early mature source rock. The Eifelian and the Emsian samples have values of C29 S/(S +R) sterane higher than 0.35 indicating early mature to mature source rocks (oil window). This finding is confirmed by the aromatic-based biomarker parameters such as Methylphenanthrene index (MPI) [6] and TNR [7].

VI. Origin and Depositional Environment of Organic Matter

Huang and Meinschein [8] proposed the distributions of C27, C28 and C29 sterol homolog in ternary diagram which can be used to differentiate the origin of organic matter. In fact C27 steranes derived from animals and green algae; steranes C28 are produced from microalgae and C29 steranes are synthesized from plants [9]. Based on the Rock-Eval data, the organic matter in the Emsian deposits has a mixed origin organic matter (type II/III). Also, the samples of Emsian have a similar distribution of C27, C28 and C29 steranes at approximately 35%, 20%, 45% respectively. This distribution is consistent with a mixture of terrestrial and marine infill sediment. Emsien has the higher values of C35/C34 homohopanes than upper Devonian and Eifelian indicating a deposition under more reducing conditions.

The tricyclic terpanes are considered to be the diagenetic products of prokaryote membranes [10]. In addition, tricyclic diterpanes (C19-C20) are originated mainly from diterpenoids, such as acid abietic which is produced by vascular plants. The C19/C23 or C19/(C19 + C23) tricyclic terpanes ratio is usually considered as a parameter for determining the type of organic matter [11]. The Eifelian aged deposits are distinguished through a lower C19 and generally higher C23 tricyclic terpanes compared to the other samples indicating that they are of marine origin organic matter have an open marine depositional environment.

Several source rock extracts show a low C35/C34 hopanes ratio (<0,6) indicating a suboxic marine shaly environment [8].

The hopane ratios of C29/C30 in the Devonian samples are less than 1which indicates that these latter are clastic-origine rocks.

The C27 sterane are relatively more abundant in the Upper Devonian. The higher C27 sterane content relates to algal marine infill [6] based on the previous discussion indicates that the organic matter of Eifelian deposits is likely a marine shale witch have suboxic depositional conditions.

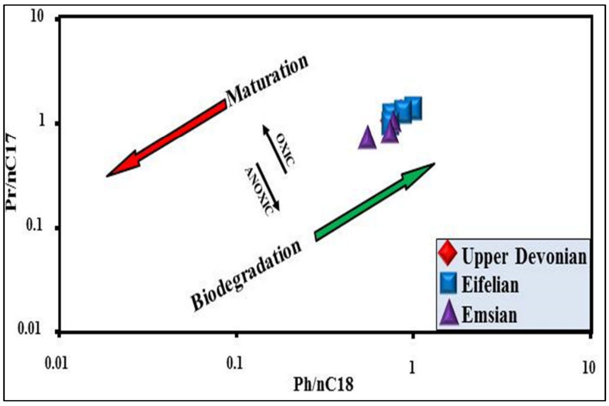

Fig. 7 Ph/nC$_{18}$ vs Pr/nC$_{17}$

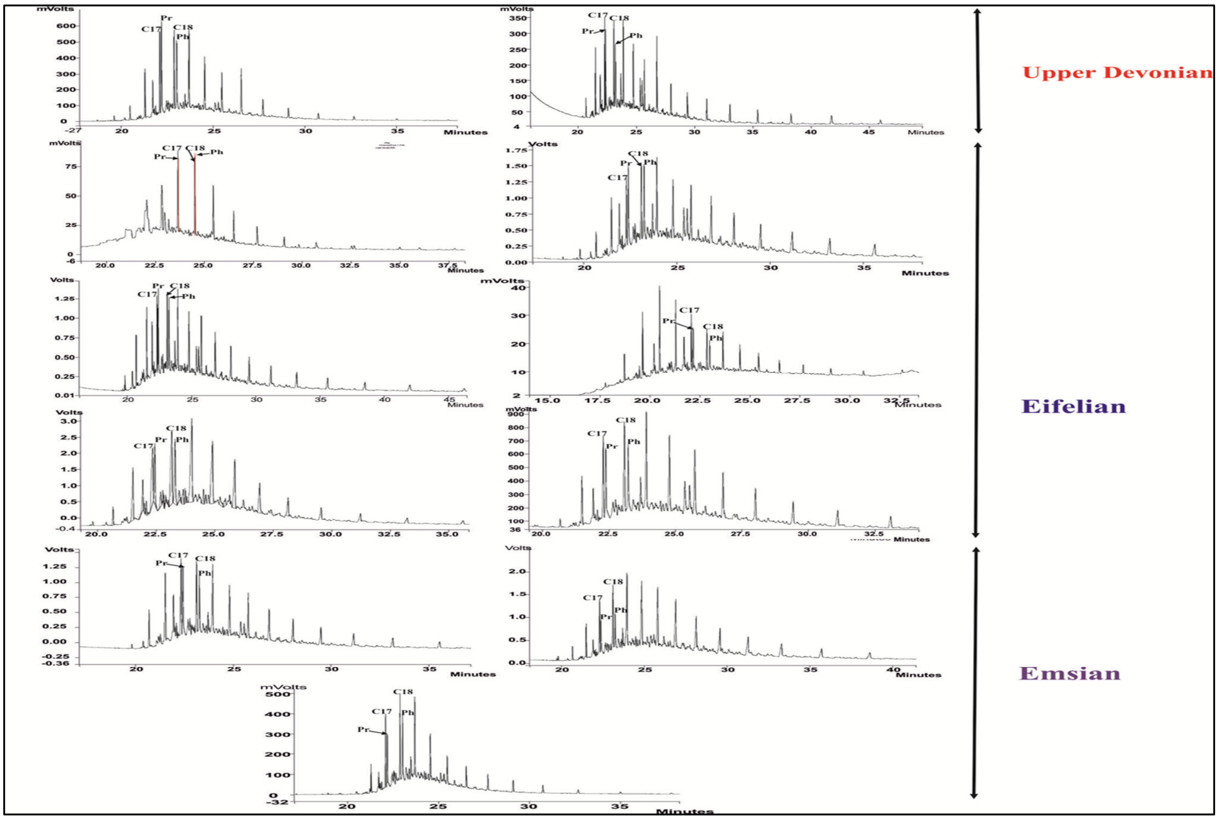

Fig. 8 Gas chromatograms of the saturated fraction

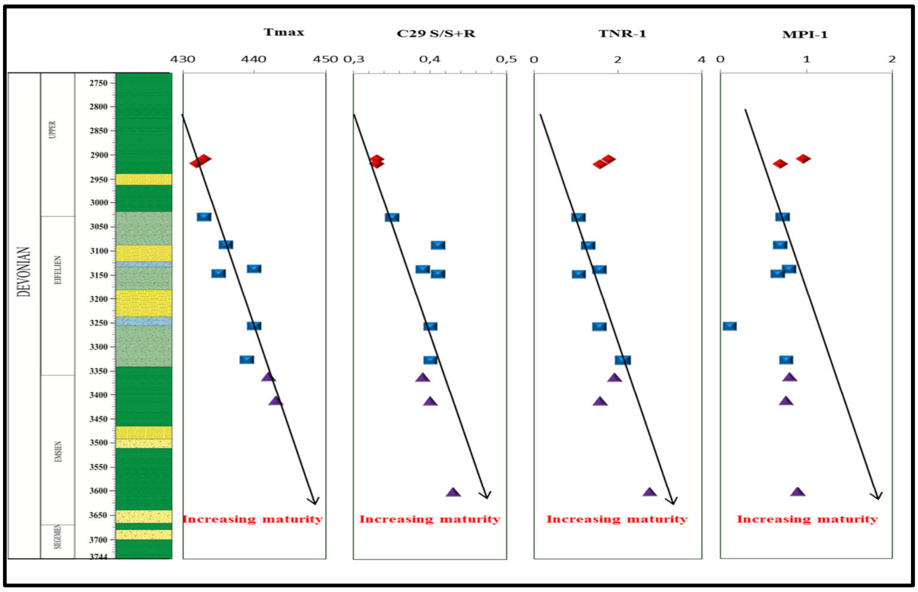

Fig. 9 Parallel changes with depth in maturity of Well EC based Rock-Eval parameters (Tmax) and Biomarker ratios (C29 S/S+R, TNR-1, MPI).

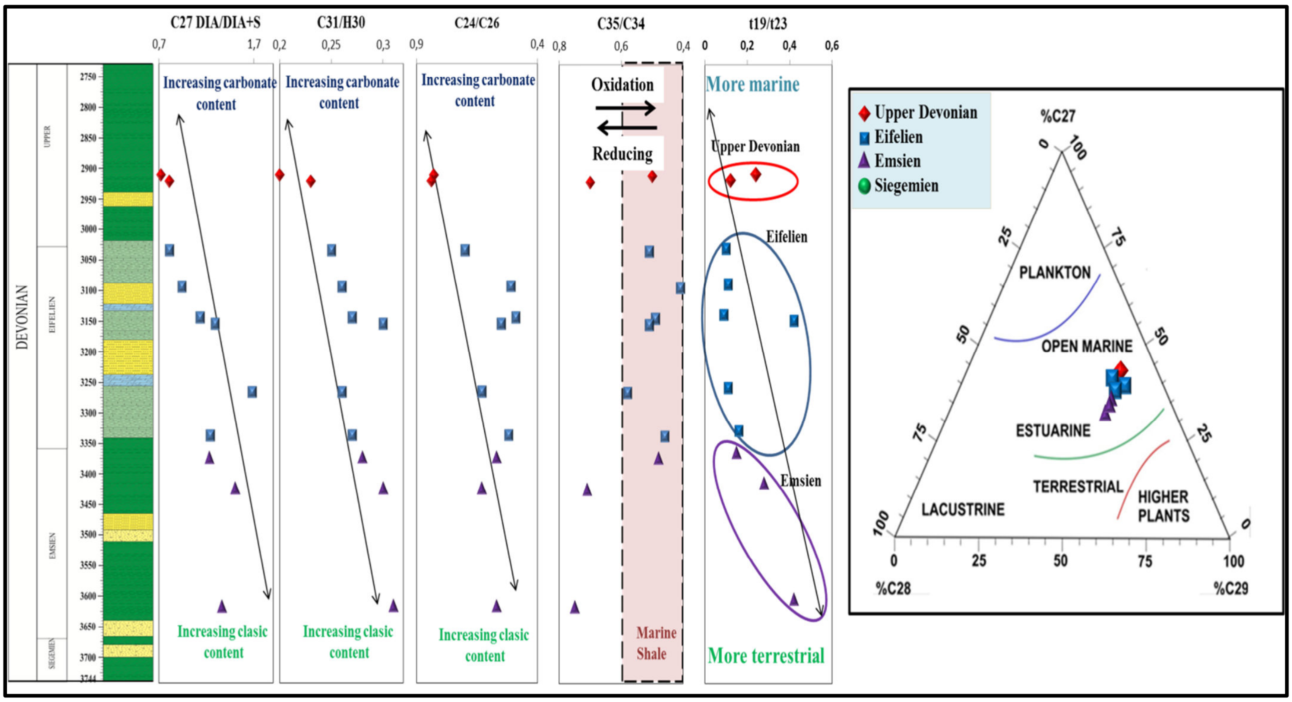

Fig. 10 Geochemical well profiles of EC. This distribution shows Depositional environment based Biomarker ratios (C29 S/S+R, TNR-1, MPI, C27 DIA/DIA+S, C31/H30, T24/C26 and C35/ C34 Homohopanes and t19/t23 tricyclic terpane)

VII. Conclusion

A source rock with an effective potential for generating oil has been identified in the Upper Devonian section. A predominant suboxic marine depositional environment is indicated by biomarker parameters. Source rock facies within the interval between 3000 m and 3350 m shows a maturity range from an early mature to mature level. As this maturity, together with good organic matter content, the Devonian source rock has an effective potential for generating oil.

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