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# Optimizing Exploration Procedure Using Oceanic Anoxic Events as New Tools for Hydrocarbon Strategy in Tunisia

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**Mohamed Soua[1], Hayet Chihi[2]**

[1]Entreprise Tunisienne d'Activités Pétrolières, 26 Rue Mohamed Badra, Immeuble Zouila, Montplaisir, Tunis, Tunisia. Email: elmohology@yahoo.fr

[2]Georesources Laboratory, Centre for Water Researches and Technologies, University of Carthage, Borj Cedria Ecopark, P.O. Box 273, Soliman, Tunisia.
Email : hayet_chihi@yahoo.fr

## *Summary*

In this paper, we describe a new method for exploration procedure based on the knowledge of the Oceanic Anoxic Events (OAE's) distribution maps in order to delineate the main source rocks existence and thus contribute to improve new petroleum systems. We describe especially the main Mesozoic OAE's which have occurred during short times through the Toarcian-Turonian interval (Jurassic to Mid-Cretaceous), their main thickness/facies distribution, geochemical characteristics (Total Organic Carbon and Maturity) and chemostratigraphic characters (mainly carbon isotopic signatures). The case study concerns the Gulf of Tunis basin which exposes the panoply of complex geological structures (thrusting, grabens, salt tectonics, etc.) in which exploration has ended since the 1990's after drilling six failed wells during more than twenty years. In order to improve and optimize exploration procedure within this basin (offshore) and in addition to the OAE's concept (source rocks distribution), we describe a basin modeling study based on the calibration, burial histories (of drilled wells), generation and expulsion of hydrocarbon from a chosen OAE (Faraoni event of the late Hauterivian level) and hydrocarbon pathway migration (migration line hydrocarbon volumes) from the chosen source rock. The basin modeling generated new prospects which seem to be

near or off-structures from the positions of the past drilled wells. However, it is assumed that the basin modeling does not take into account the rapid change of facies and geological complexity such the case of the Gulf of Tunis. This is the reason why a Multiple-Point Geostatistics (MPS) method is recommended for the integration of the basin modeling study in order to improve more the model. This method is applied in basin modeling to improve the efficiency of the regional exploration procedure in addition to the use of OAE's concept.

## 2.1 Introduction

### 2.1.1 General Summary

Black shales deposition had been recorded over large domains of the ocean floor frequently through Phanerozoic times (Figure 1). They are identified as fine-grained organic-rich carbon deposited during severe paleoecological conditions and displaying oxygen-free or oxygen-deficient bottom waters. Sedimentological and geochemical characteristics indicate that they were deposited under suboxic to anoxic or even strongly euxinic conditions.

Several authors working on such sediments have surveyed the following general and typical characterization: (1) often laminated; (2) sometimes enriched with pyrite; (3) characterized by Type II-marine organic matter generally associated with high organically bound sulphure (TOCs range from 1-20% and HI's range between 350-850 mg Hc/gTOC); and (4) generally enriched in trace metals (Schlanger and Jenkyns, 1976; Jenkyns, 1988; Wignall and Myers, 1988; Schlanger et al., 1987; Arthur et al., 1990; Cecca et al., 1994; Wignall, 1994; Kuhnt et al., 1997; Barrett, 1998; Sageman et al., 1998; Leckie et al., 2002; Kuypers et al., 2002; Luning and Kolonic, 2003; Luning et al., 2004; Algeo, 2004; Tsikos et al., 2004; Kolonic et al., 2005 ; Baudin, 2005; Algeo and Lyons, 2006;

Bodin et al., 2006; Scopelliti et al., 2006; Turgeon and Brumsack, 2006 ; McArthur et al, 2008; Soua, 2010; Soua et al., 2011a; Tribovillard et al., 2012; Soua, 2013).

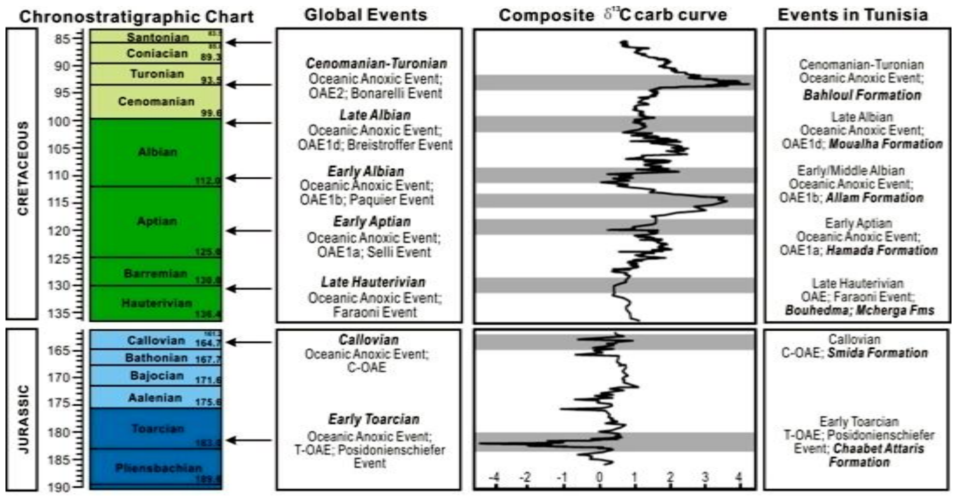
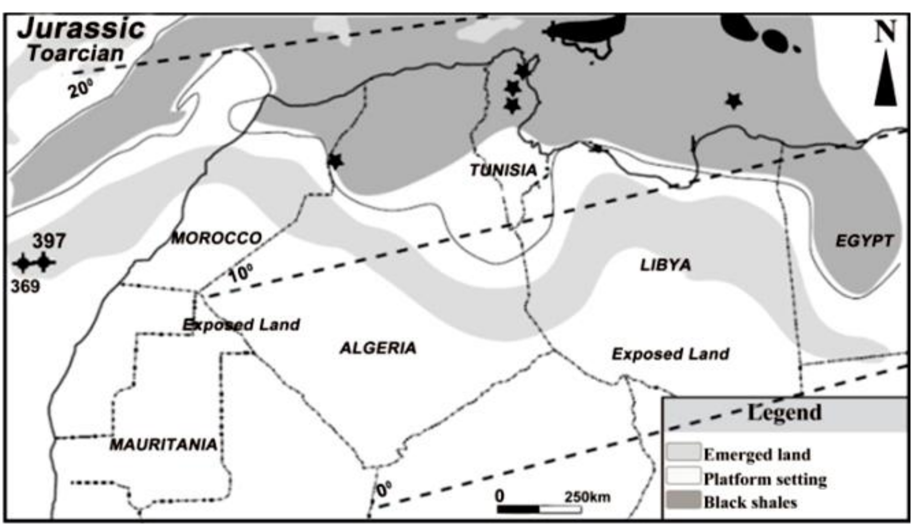
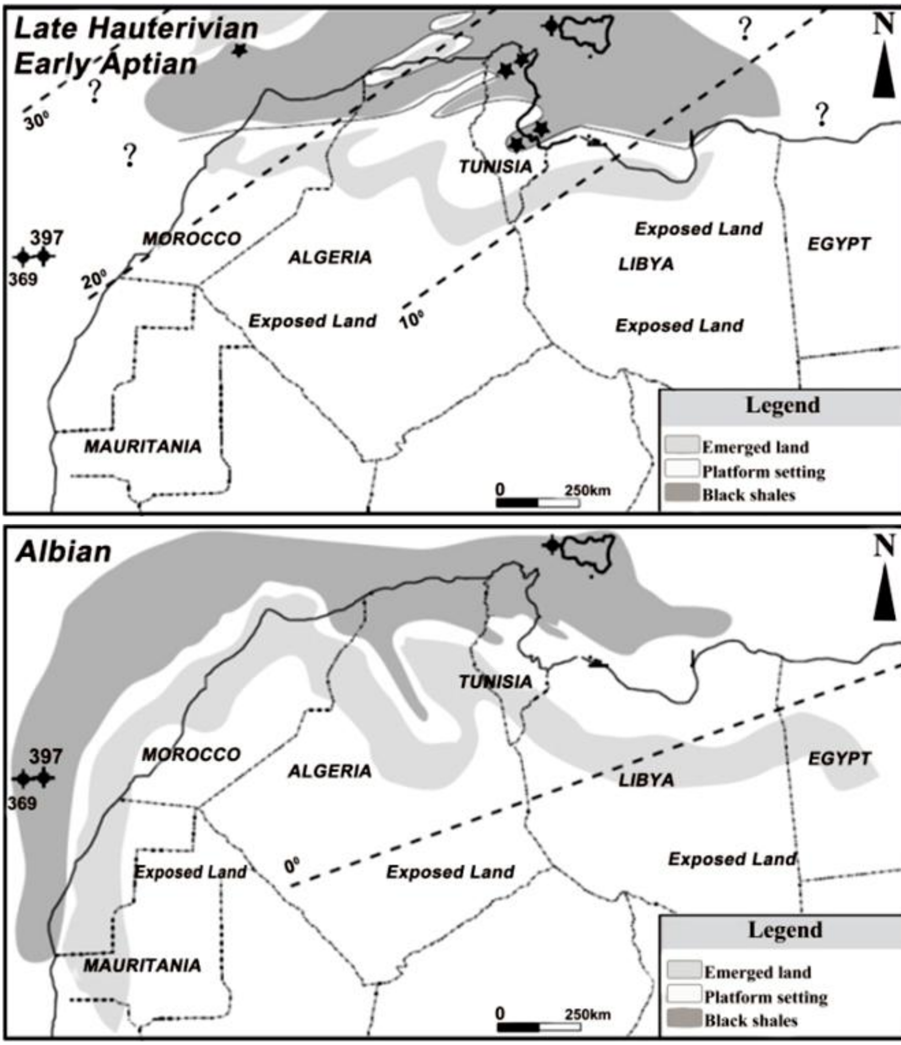



***Figure 1.*** *The main Oceanic Anoxic Events (OAE's) discussed in the text and identified worldwide as well as in Tunisia, a tentative correlation with the events which occurred in Tunisia during the Mezosoic (Jurassic - mid-Cretaceous). Timescale, global events and carbon isotopic data are compiled from Jenkyns (2010).*




Late Hauterivian
Early Áptian
N
?
30°
20°
10°
397
369
MOROCCO
ALGERIA
TUNISIA
LIBYA
EGYPT
MAURITANIA
Exposed Land
Legend
Emerged land
Platform setting
Black shales
0
250km
Albian
0°

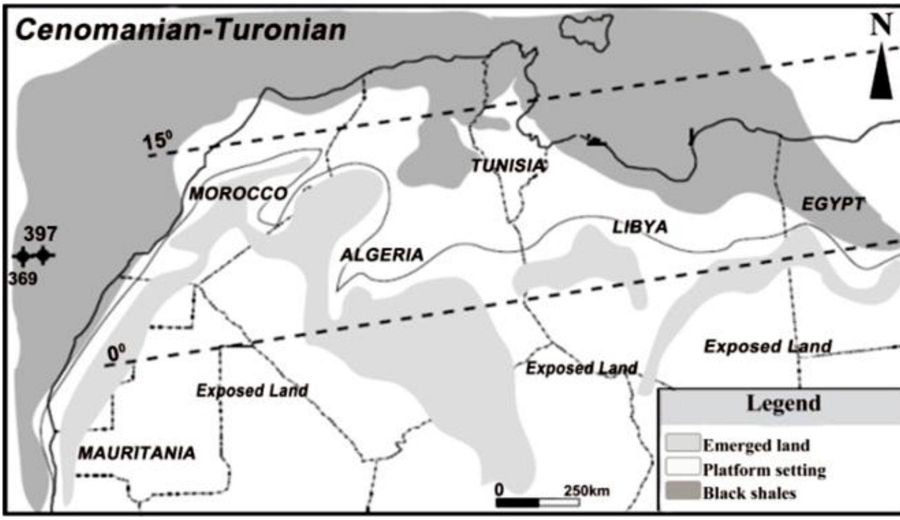



***Figure 2.*** *Organic rich black shales distribution during Toarican, late Hauterivian-early Aptian, Albian and late Cenomanian - early Turonian in North Africa. Data have been compiled from Bassoullet et al. (1993), Luning et al. (2004); Zghal and Arnaud-Vanneau (2005) ; Baudin (2005), Reichelt (2005); Bodin et al. (2006), Chihaoui (2009 ; Jenkyns (2010); Soua et al. (2011a) ; Ben Fadhel et al. (2011); Tribovillard et al. (2012).*

It has been admitted that these organic-rich sediments display large economic significance as they include more than 90% of global recoverable hydrocarbon reserves (oil and gas) in the world (Figure 2). In fact, during the phanerozoic more than six stratigraphic organic-rich intervals have been recorded (Figure 3): (1) the Silurian, ca. 430 Ma ago (this interval generated 9% of the world's reserves); (2) the Upper Devonian, ca.370 Ma ago (8% of reserves); (3) the Carboniferous/Permian transition, ca. 295 Ma ago (8% of reserves); (4) the Jurassic, ca. 145 Ma ago (25% of reserves); (5) the late Hauterivian ca. 133 Ma (Neocomian, 2.5% of reserves); (6) the mid-Cretaceous, ca. 94 Ma ago (29% of reserves); and (7) the Oligocene/Miocene transition, ca. 23 Ma ago (12.5% of reserves) including other oscillating potentials through the tethyan domain such as the Cambrian-Ordovician ca. 465 Ma ago (1% of reserves), the Permian ca. 255 Ma (1% of reserves), Carnian (ca. 229 Ma), the Coniacian-Eocene ca. 86 - ca.

50 Ma (2.8% of reserves) and some diffracted levels within the Cenozoic (Figure 3). All these periods are reported as times of Oceanic Anoxic Events (e.g. Kolonic, 2004; Sorkhabi, 2009).

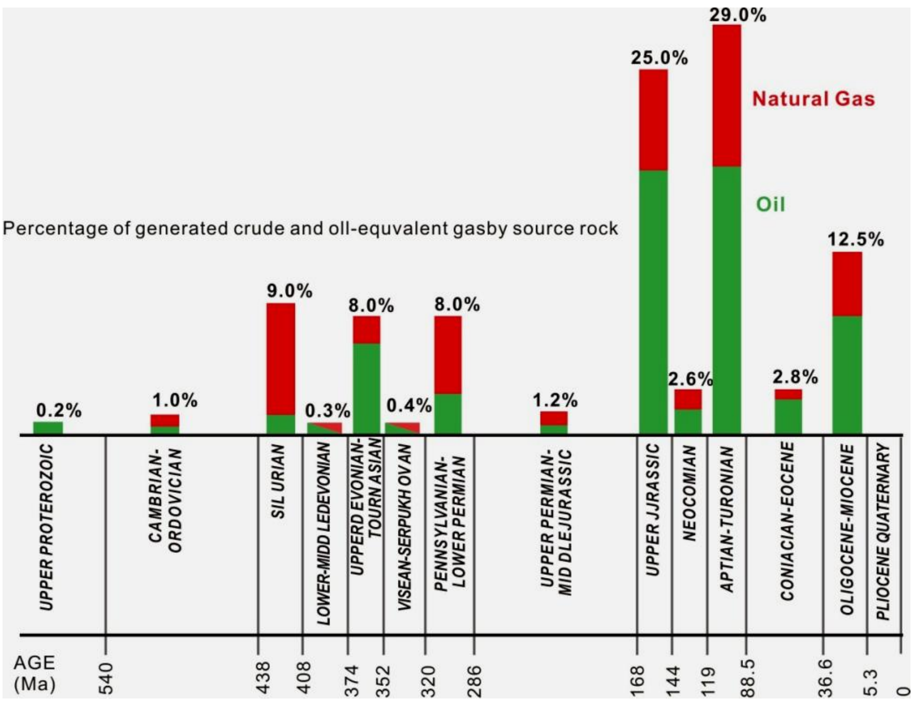



***Figure 3.*** *Main distribution of the world's oil and gas source rocks through time (stratigraphic record), Stratigraphic Distribution of Oil and Gas by Source Rock (Kolonic, 2004; Sorkhabi, 2009 and references therein).*

Several authors have searched adequate and scientific mechanisms leading to the formation of such organic-rich sedimentation (Pedersen and Calvert, 1990; Wignall, 1991; Calvert et al., 1996; Nijenhuis et al., 1999; Luning et al., 2004; Brumsack, 2006; Soua and Tribovillard, 2007; Jenkyns, 2010; Soua, 2011a). Although several attempts have been established on the mechanisms of black shale deposition by a number of authors during these two decades, sometimes antonym ideas are provided regarding the condition of deposition which differs from a geological domain to another. They have been identified as having irregular distribution through time and space and the geochemical character appears different within each level throughout the Phanerozoic time span. Through these efforts many factors have been set up as controlling the genesis of black shales. The main factors could include (1) the opening and/or closure of marine seaways considering stagnation of marine setting; (2) tectonic and eustatic sea level changes; (3) basin structures; and (4) climate change. This may lead to the fact that favorable cases such as tectonic, climatic, oceanographic, and biologic factors could have outcome in the worldwide black shale deposition during these intervals. However, mechanism of black shales deposition is still understood within sedimentary process.

Both the petroleum industry and academic institutions are interested in deciphering the different mechanisms which may lead to black shale deposition since (1) oil and gas production evolved during these two decades via oil shale and gas shale exploration (hydrocarbon production set up directly from the black shale source rock) and (2) the academicians have become conscious that black shales are the most important sedimentary rocks which could provide important information about past climates including periods of rapid climate change and eustatic sea level rises in order to challenge the present perturbations which are controlling the earth. From a petroleum point of view, detailed geochemical analysis of the black shale source rock could lead to savings in time and money during exploration/production programs.

In this paper, our focus sheds the light on Jurassic and mid-Cretaceous (late Hauterivian-Turonian) periods (Figure 2). For several reasons, these periods, and especially in several parts of Northern Tunisia, could express promising time span in order to decipher main mechanisms of black shale formation. In addition, this time span is supported by (1) mapping of North African paleogeographical reconstructions, (2) the existence of geochemical analysis including chemostratigraphy and carbon isotopic data and biostratigraphic (foraminifera and radiolatians) data and (3) the existence of complete sedimentary record displaying laminated lithology which could express Milankovitch cyclic character providing good time control on sedimentation.

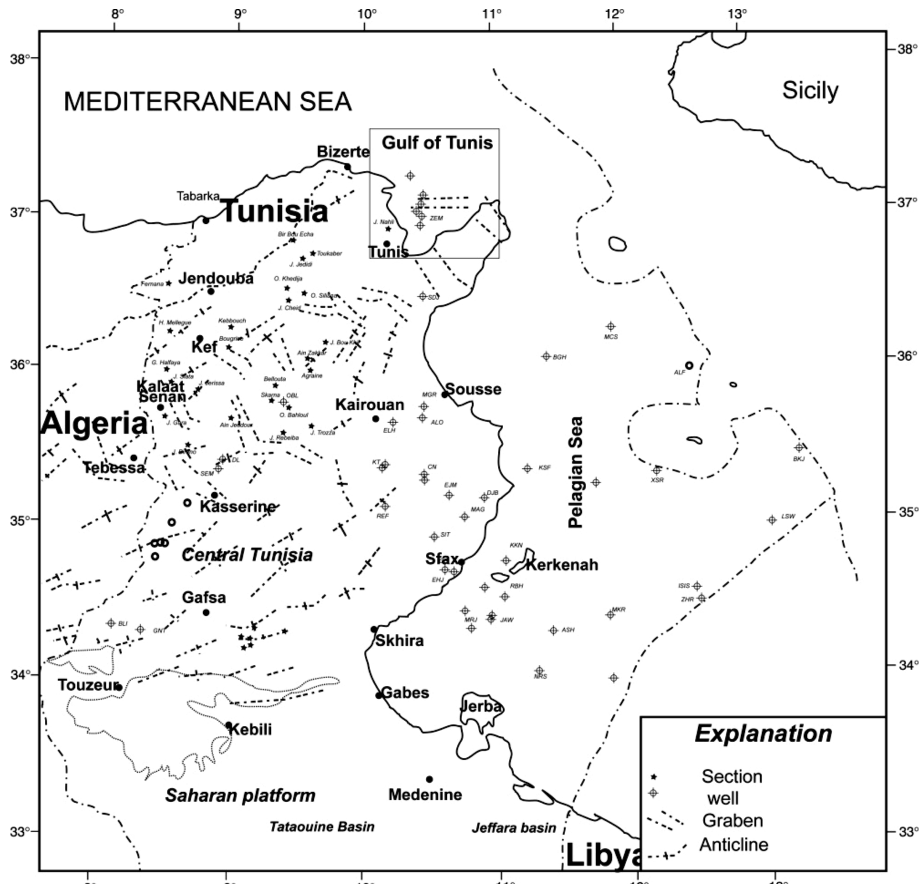



***Figure 4.*** *Main structural features of Tunisia, Data compiled from Ben Ferjani et al. (1990); Burollet (1991); Luning et al. (2004); Soua et al. (2009).*

Thick mid-Cretaceous black shales sections in the Atlantic and Pacific Ocean domains had been discovered within the seventies through the Deep Sea Drilling Project (DSDP) (Schlanger and Jenkyns, 1976) and recently through the Ocean

Drilling Program (ODP) (e.g. Baudin, 2005; Scopelliti et al., 2006; Tribovillard et al., 2012). These discoveries open new exploration challenges regarding the deposition of these black shales and evolved the knowledge of their mechanisms and deposition within the oil industry and the academic institutions that this time-interval was a promising period in earth history. Therefore, black shales which deposited within the short time interval between the late Hauterivian and Turonian (ca.130-90 Ma) are distributed within separated levels and are inventoried as type black shale systems.

Throughout these two decades research on mid-Cretaceous black shales have therefore carried on with intense energy and has particularly been deciphered by new scientific advances such as chemostratigraphy, cyclostratigraphy, sequence stratigraphy and diversified planktonic organisms (nannofossils, radiolarians, etc.). Nevertheless, these new aspects led to conflicting models and theories regarding black shale deposition. Alternatively the North African Maghrebian domain is mainly appreciated for the analysis of organic-rich sedimentation during the mid-Cretaceous time span, because they could be traced along Cretaceous outcrops well mapped within this domain (Soua et al., 2011a; Soua, 2011b; Ben Fadhel et al., 2012; Soua, 2013).

### 2.1.2 Oceanic Anoxic Events during the Mesozoic and Organic-Rich Deposits in Tunisia

Several rifting pulses occurred on the northern margin of Africa, separated in time and space mainly from Triassic through Cretaceous period. During Oxygen Minimum Zone (OMZ) development periods of black shale accumulation has been recorded through the Mesozoic and notably through the northern margin of Africa (Figure 2). In contrast, paralic to shallow-marine sedimentation occurred along the southern Tunisian margin (e.g. Jeffara basin, Saharian platform, Tataouine basin, etc.). Oil-prone organic-rich strata were deposited in the initial marine sediments of narrow rifts and in parts of the subsiding margin.

Therefore, tectonics played an important role in controlling the physiographic pattern and the accumulation of organic matter occurred on an irregular outer shelf segmented by horsts and grabens which modelled the Central Tunisian domain during these times (Figure 4).

Notably, nine main anoxic events occurred in Tunisia throughout the Mesozoic time (Figure 1) which were delineated by black shale layer accumulations expressing generally eccentricity and precession Milankovitch-like cyclicity and formed during third order transgressive systems tracts. These OAE's occurred in: (1) the Carnian, (2) the Toarcian, (3) the Callovian, (4) the Valanginian, (5) the late Hauterivian, (6) the Bedoulian, (7) the Albian, (8) the Cenomanian-Turonian transition and (9) the Coniacian-Santonian transition (Soussi et al., 1992; 1998; Arfaoui et al., 2004; Soua, 2010; Ben Fadhel et al., 2011; Soua et al., 2011a; 2011b; Elkhazri et al., 2013; Soua, 2013). However, some levels seem to be not interesting or forsaken by the researchers using some geochemical tools or lack of work on this subject which concerns the OAE's.

## 2.2 Geological Setting

The Triassic-Quaternary section covers generally the main Atlas outcropping series establishing important lateral changes constrained by paleogeographic differentiations during the Cretaceous period. Alternatively and in a general point of view, three main paleogeographic domains could be illustrated and mainly expressed during the Cretaceous (e.g. Burollet, 1956; Jauzein, 1967; Rouvier, 1977; Perthuisot, 1981; Burollet, 1991): (1) the Tellian trough, (2) the Tunisian trough, which is defined by continuous and active subsidence as well as with deposition of high amount of organic-rich shales proven as source rocks (e.g. Allam, Bahloul), and (3) the central Tunisian platform series which seemed to be deposited in proximal basin setting. One of the most obvious differences is observed within the early Cretaceous series which are typical shaly basinal section with rare turbidite levels covering up to 4000 m thick in northern Tunisia. However, in central Tunisia, the coeval time span section could show a high content of detritic sandstones typical of deltaic environment displaying more than 500 m thick.

Generally speaking, Tunisia constitutes the so-called eastern part of the Tellian and Atlas domains which are situated geographically in the eastern North African margin. It can be divided into five domains: (1) The Tell domain which is usually interpreted as an alpine chain constituted by several thrust-sheets displaced from the northwest towards the southeast (Rouvier, 1977; Perthuisot, 1981; Luning et al., 2004; Soua et al., 2009), (2) The Mejerda valley domain (Figure 4) corresponding to the so-called imbrication zone exhibiting Triassic evaporate extrusions. Jauzein (1967) and Rouvier (1977) argued that this area may represent during the Paleogene times an important paleogeographic feature as playing the role of a shoal zone separating thus the Tunisian trough to the north from the Eastern Tunisian platform, (3) The Atlas belt which corresponds to NE-SW fold-thrust belt (Turki, 1985; Haller, 1983; Burollet and Ellouz, 1986). It is limited respectively in its Eastern and Southern sides by the Eastern Tunisia Foreland and by the Sahara platform respectively. The boundary between the Atlas and its foreland is the South Atlas Front (SAF), which is an important emergent or buried thrust fault (Coiffait, 1974; Bracene et al., 2003; Frizon de Lamotte et al., 2011) ensuring the thrusting of the Atlas on its foreland basins (e.g. Ainsworth et al., 2002 and references therein). (4) The Eastern Tunisian Foreland is constituted by the Gulf of Hammamet (Messaoudi and Hammouda, 1994), the Sahel and the Gulf of Gabes to the south (Touati and Rodgers, 1998) (Figure 4). This foreland domain represents, in fact, an important deformation zone with thrusting and folding (Haller, 1983; Burollet and Ellouz, 1986; Gabtni, 2006; Zouaghi et al. 2009). It has been demonstrated that this foreland records in fact the main Atlas geological events and illustrated coeval structures buried beneath a thick Quaternary cover and finally (5) the Sahara platform which is usually defined as slightly folded except in its Northern part that suffered locally Cenozoic movements but most researchers have not taken into consideration Paleozoic orogenic phases that modeled and eroded most of Paleozoic section. This domain corresponds to Paleozoic-Mezosoic basins.

## 2.3 Material and Methods

The review of the selected Mesozoic OAE's occurrences in Tunisia is based mainly on: An analysis of more than 30 Tunisian sections and Wireline logs from several petroleum exploration wells penetrating the black shale levels. Gamma-ray amplitudes, INPEFA logs (Soua, 2013), resistivity logs have been analyzed in different anterior studies which will be cited within the text. Isopach/facies maps have been compiled for each OAE level on the basis of this dataset and available data. In addition, paleogeographical maps of the petroleum source rocks have been constructed in order to evaluate the controlling mechanisms on the deposition of the black shale levels. Additionally, field work was carried out in different Tunisian basins where Mesozoic black shales are distributed in order to collect more information. Trace elemental inorganic geochemistry have been used by Soua (2011a and 2011b) in order to give emphasis on the primary productivity, redox and oxygen-deficit conditions. Other geochemical exploration tools are represented by total organic carbon (TOC) and pyrolysis. Carbon isotopic data have been reproduced for the Aptian and Albian strata of Tunisia from Elkhazri et al. (2013) regarding the Aptian and from Chihaoui (2009) regarding the Albian. These data were compiled with biostratigraphy and have been correlated to the C1-C15 carbon isotopic divisions of Menegatti et al. (1998) and Bralower et al. (1999). Four paleogeographical OAE's black shale distribution have been generated in this study.

## 2.4 A Review of the Main Mesozoic Oceanic Anoxic Events (OAE's) in Tunisia

In this paper, we study the characters of well-known and unknown (in Tunisia) organic-rich levels (anoxic events) ranging in age from the Early Jurassic (Toarcian) to the Late Cretaceous (Cenomanian-Turonian) from Tunisia which belongs to the southern Tethyan margin (Figure 1). Only their main features are summarized in order to be provided and utilized within basin modeling section. These organic-rich black shales have been deposited under suboxic to anoxic through euxinic conditions; identified using trace elemental exploration tools (Soua et al., 2011a).

### 2.4.1 Early Toarcian Anoxic Event (T-OAE)

During the Early Toarcian, Tunisia has received panoply of facies transect ranging from lagoonal, evaporitic and locally detrital (Abreghs in southern Tunisia), evaporitic (Mestaoua in the Jeffara basin) over shelfal (Chotts, Tebaga and central Tunisia) to bathyal (northern Tunisia) (Figure 5).

Organic-rich Toarcian strata occur in many places in northeastern and central Tunisia (e.g. N-S axis) and are grouped into the Chaâbet Attaris Formation that was defined by Soussi (2003) and grouped earlier in upper Stah Formation (Fauré and Peybernès, 1986) or in the "Marno-calcaires de Bou Kornine" (Bonnefous, 1972) and even in the lower Guemgouma Formation (Neri et al., 1991). The Chaabet Attaris Formation was deposited during the early Toarcian Anoxic Event (*Polymorphum* to *Serpentinum* Zones), but these black limestone facies could in some regions continue up to the late Toarcian. The thickness distribution of the Chaâbet Attaris Formation in Tunisia is illustrated in Figure 5 (compiled after Soussi et al., 1990; Kamoun et al., 1999; Soussi 2003 and our field measurements).

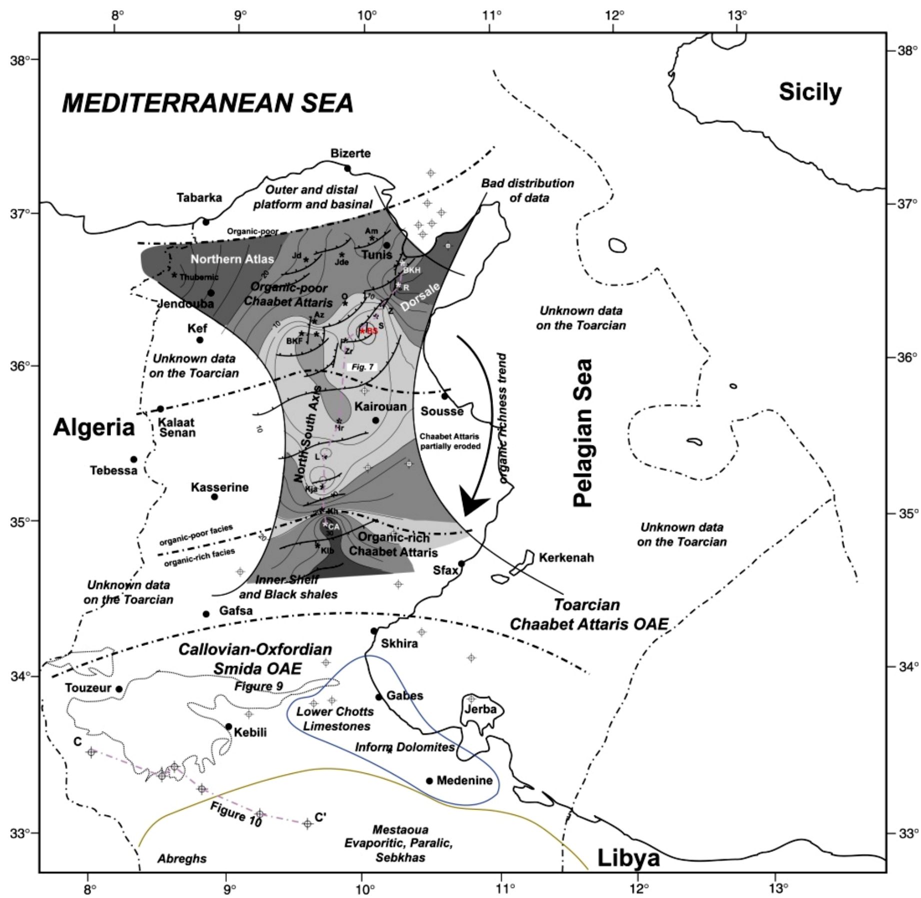



***Figure 5.*** *Thickness and facies distribution of the Toarcian anoxic event in Tunisia, data compiled from Soussi et al. (1990; 1992); Kamoun et al. (1999); Soussi (2000; 2003).*

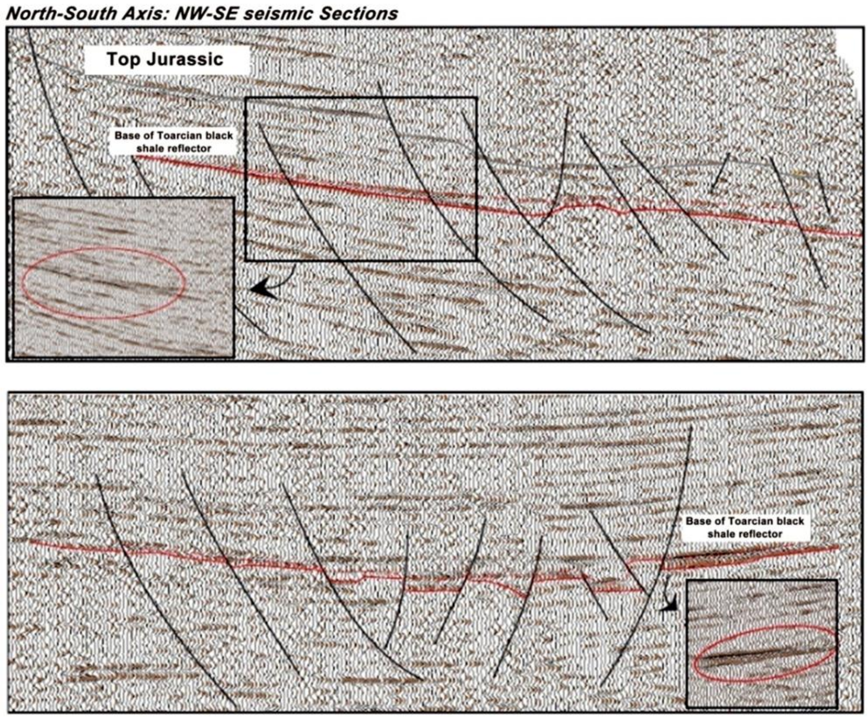



***Figure 6.*** *Interpreted Seismic sections located to the west of the North South Axis (NOSA) confirming the existence of the anoxic facies of the Toarcian strata.*

The organic-rich early Toarcian chaabet Attaris exists in three areas, namely in the North and NW onshore Tunisia (Thubernic), in the NE (the Dorsale) and in the Central Tunisia (the N-S axis). According to Beall et al. (2002) euxinic conditions in the Gantass/Ali Ben Khlifa area (see Figure 5 for location) are clearly diachronous at both the base and the top. They distinguished a typical facies of black shale and shaley limestone within the Toarcian, representing an organic-rich, condensed section of euxinic sedimentation and suggesting development of restricted circulation with "mini-basins" (Soussi, 2000). This is confirmed by our seismic line analysis in the same basin (Figure 6).

A comparison with the palaeogeographic map (Figure 5) suggests that the distribution of the organic-rich Chaabet Attaris is restricted to intermediate to medium water depth and may represent the impingement of an OMZ onto the northern margin of Africa (Figure 7). The Chaabet Attaris Formation constitutes generally few tens of meters thick (2 to 30m) in the Dorsale and the North-South Axis areas with a maximum thickness of about 40 m in the NW Tunisian Trough (Figure 5) (Soussi, 2003, p.765). Generally, the Chaabet Attaris consists of a regular alternation of dark coloured shales and laminated carbonates and nodular black and greyish limestones and marls with TOC values of up to 4% (Saidi et al., 1992; Soussi et al. 1992; Kamoun et al., 1999; Soussi et al. 2004) (Figure 7). A single 11% TOC value was reported by Soussi et al. (2004) from the Ali Ben Khelifa area.

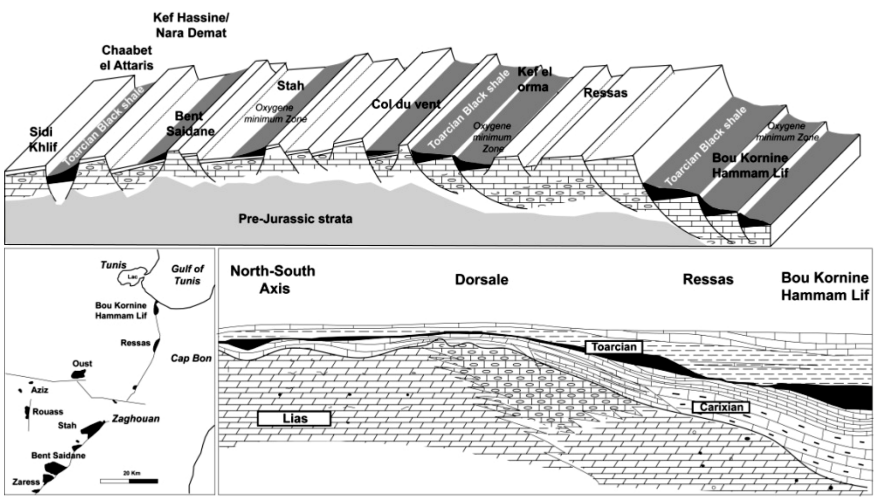
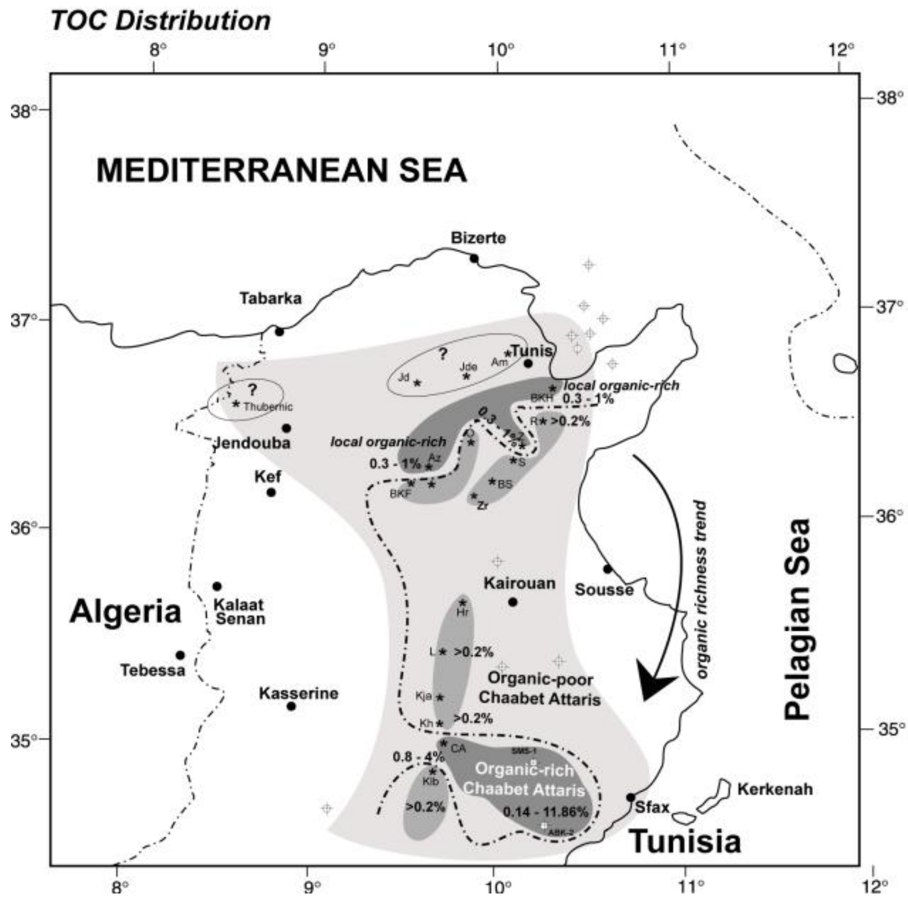



***Figure 7.*** *Organic rich black shales distribution through an Oxygen Minimum Zone Model (OMZ) and Horst & graben structuration which controlled the anoxic deposition during the Toarcian. (After Soussi et al., 1992).*

The TOC ranges vary significantly in different localities. Typical observed ranges include (1) pattern with a sine shape-like gradual increase and decrease of values within the early Toarcian interval in the type section of Chaabet Attaris, (2) interval between 0.3 and 1% (e.g., Bou Kornine Hammam Lif; Jebel Aziz and Zaghouane area), (3) significantly higher range of TOC (e.g., Chaabet Attaris and

Ali Ben Khlifa well) and (4) very poor TOC content lower than 0.2% (Khechem el Kelb; Kef Hassine; Jebel Ressas) (Figure 8).



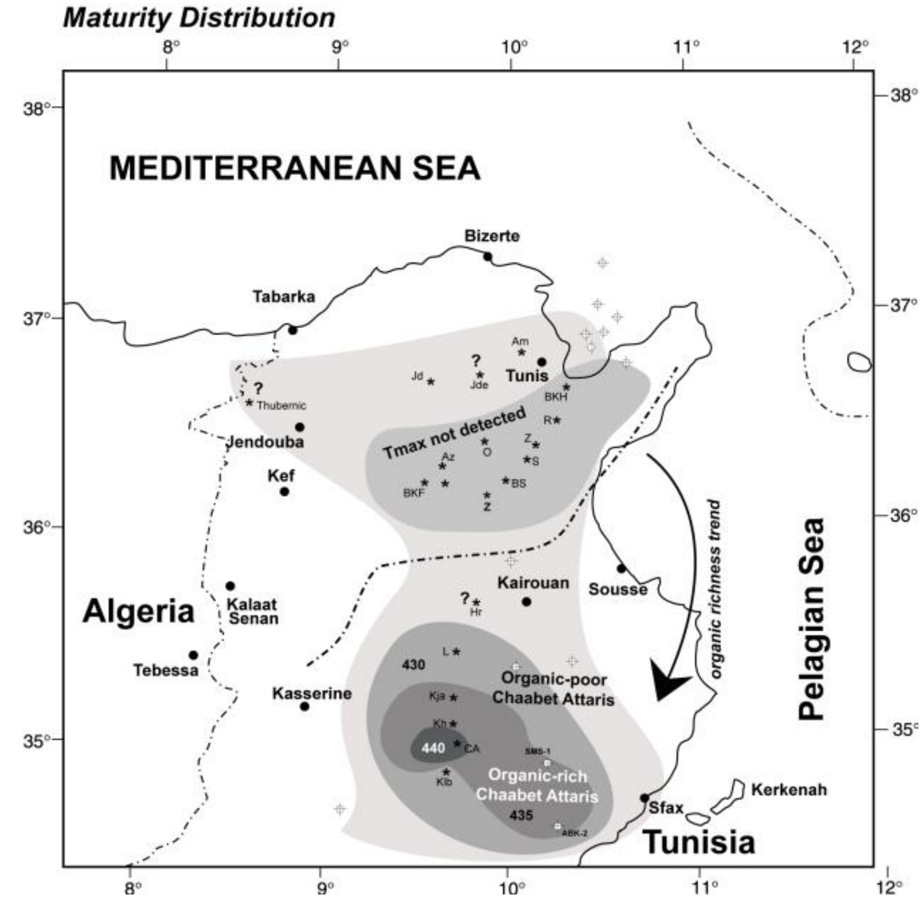



***Figure 8.*** *Total Organic Carbon (TOC) and Maturity distribution maps of the Toarcian anoxic facies (T-OAE). Data are provided from Soussi et al. (1992; 2004).*

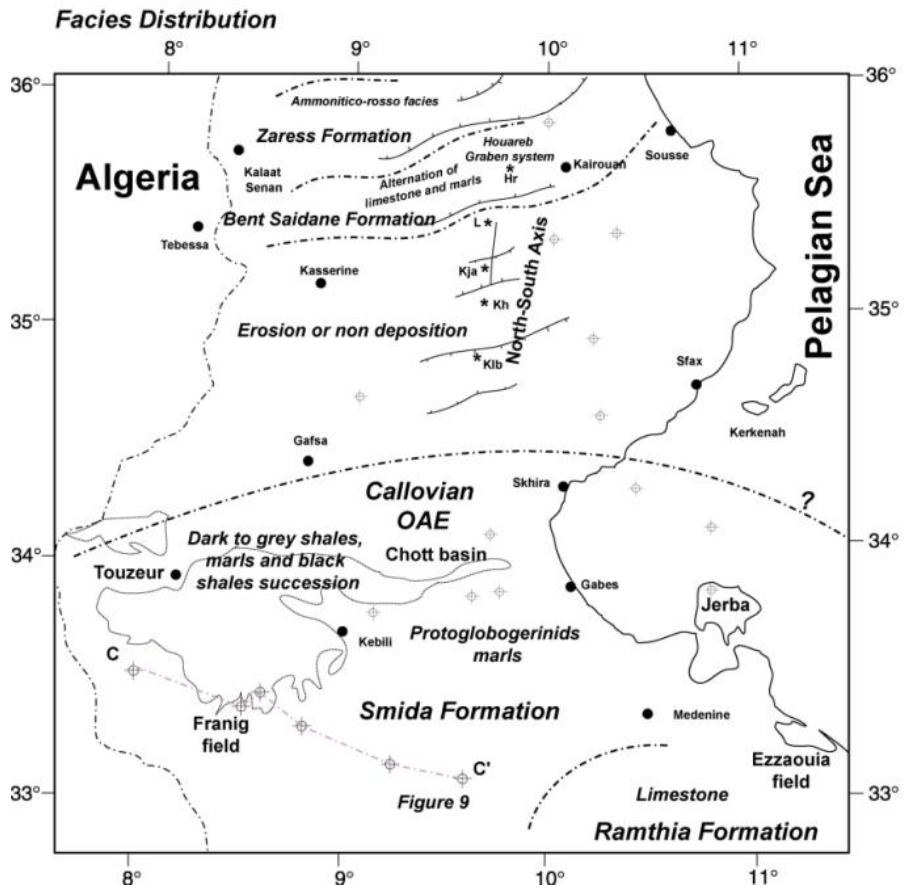
A close inspection of the Chabet Attaris (CA) spiky TOC pattern in combination with typical alternations of dark coloured shales, organic-rich marls with light beds highlights the significance of anoxic and dysaerobic environments cycles during deposition of the early Toarcian.

The low TOC values characterizing some early Toarcian sections could be explained by the absence of the basal part of the Toarcian interval (typically organic-rich in the CA type section) probably capped by the generalized erosion phase (D1 of Soussi, 2003). The values of TOC of less than 1% could be linked to organically leaner location of the logged section or probably they were deposited underneath the Oxygen Minimum Zone (OMZ) (Barrett, 1998; Soua and Tribovillard, 2007). The organic-rich Chaabet Attaris black shales Formation is characterised by mixed type II/III kerogene, i.e. planktonic marine type II and ligneous and hemicellulosic continental type III kerogen (HI ranging between 100 and 650 mg HC/g TOC; OI between 31 and 110g$CO_2$/gTOC) with TOC concentrations of up to 11%, indicating excellent source rock qualities for oil and gas. A sufficient maturity level of these laminated black shales is confirmed by $T_{max}$ values nearly constant between 430 and 440 ℃ (Figure 8).

### 2.4.2 Callovian Anoxic Event (C-OAE)

Organic-rich Callovian strata occur in large part of the southern Chotts domain of Tunisia and are grouped into the Smida Formation that was defined by Marathon Oil Company (Figure 9) and is considered as the equivalent of both the Protoglobigerinids marls and Ramthia limestone Formations (Kamoun et al., 1999; Soussi, 2003).

The thickness distribution of the Smida Formation in Southern Chotts domain of Tunisia is illustrated in Figure 9. The regional distribution of the main Callovian facies types, compiled after Kamoun et al. (1999) Soussi (2003) is shown in the same Figure, which also includes the distinction of an organic-rich and an organic-poor Smida facies trends.


Facies Distribution
8°
9°
10°
11°
36°
35°
34°
33°
Algeria
Pelagian Sea
Ammonitico-rosso facies
Zaress Formation
Houareb
Graben system
Kalaat
Senan
Kairouan
Sousse
Alternation of
limestone and marls
Hr
Bent Saidane Formation
L
Tebessa
Kasserine
Kja
Kh
North-South Axis
Erosion or non deposition
Klb
Sfax
Kerkenah
Gafsa
Skhira
Callovian
OAE
?
Dark to grey shales,
marls and black
shales succession
Chott basin
Touzeur
Gabes
Jerba
Kebili
Protoglobogerinids
marls
C
Smida Formation
Medenine
Franig
field
C'
Ezzaouia
field
Figure 9
Limestone
Ramthia Formation

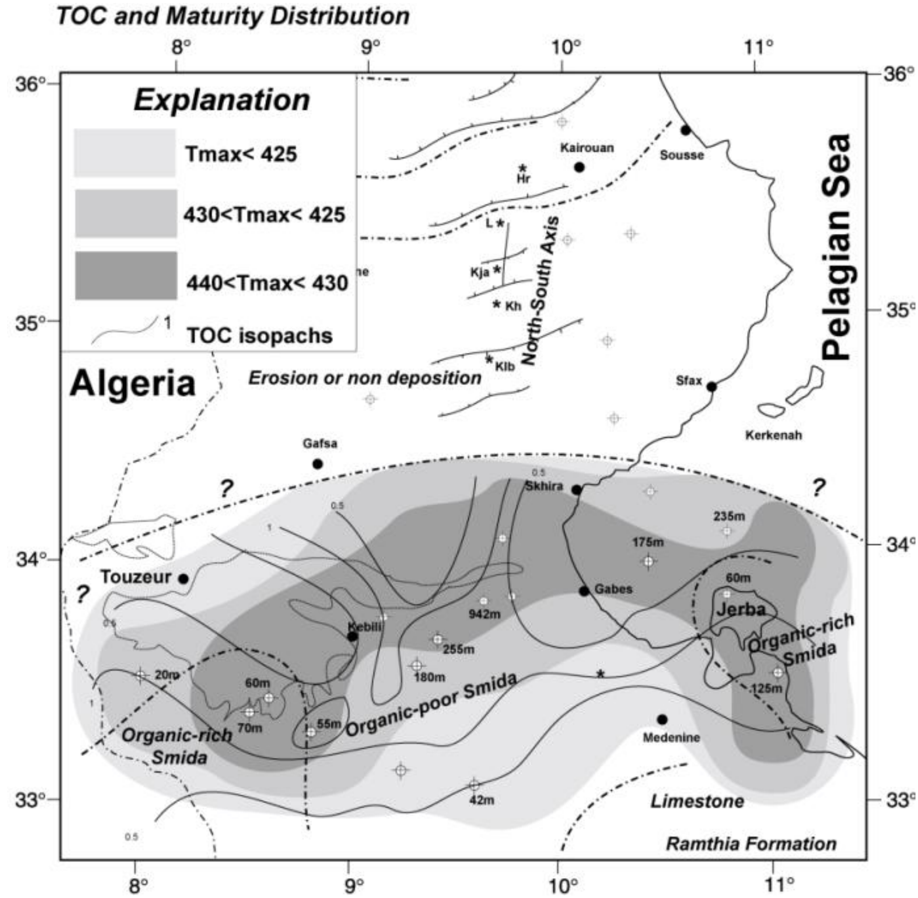



***Figure 9.*** *Facies, TOC and Maturity distribution maps of the Callovian anoxic level recorded within the utilized petroleum wells in this study (see Figure 10).*

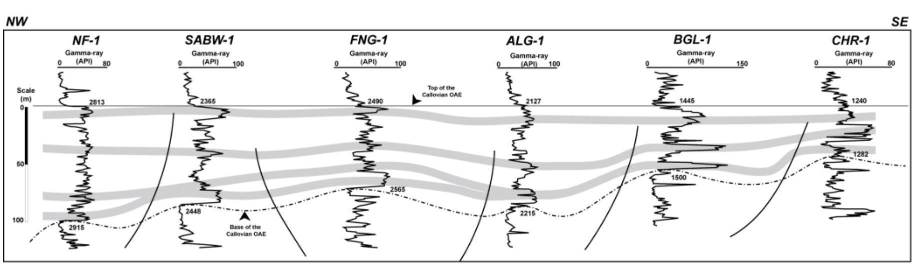
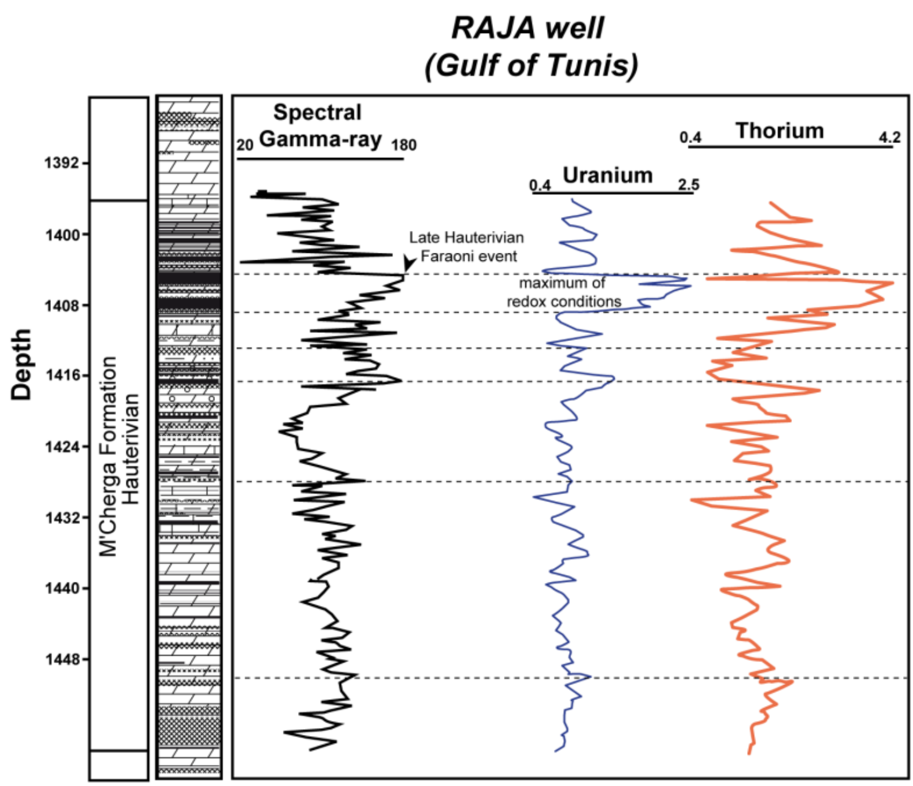


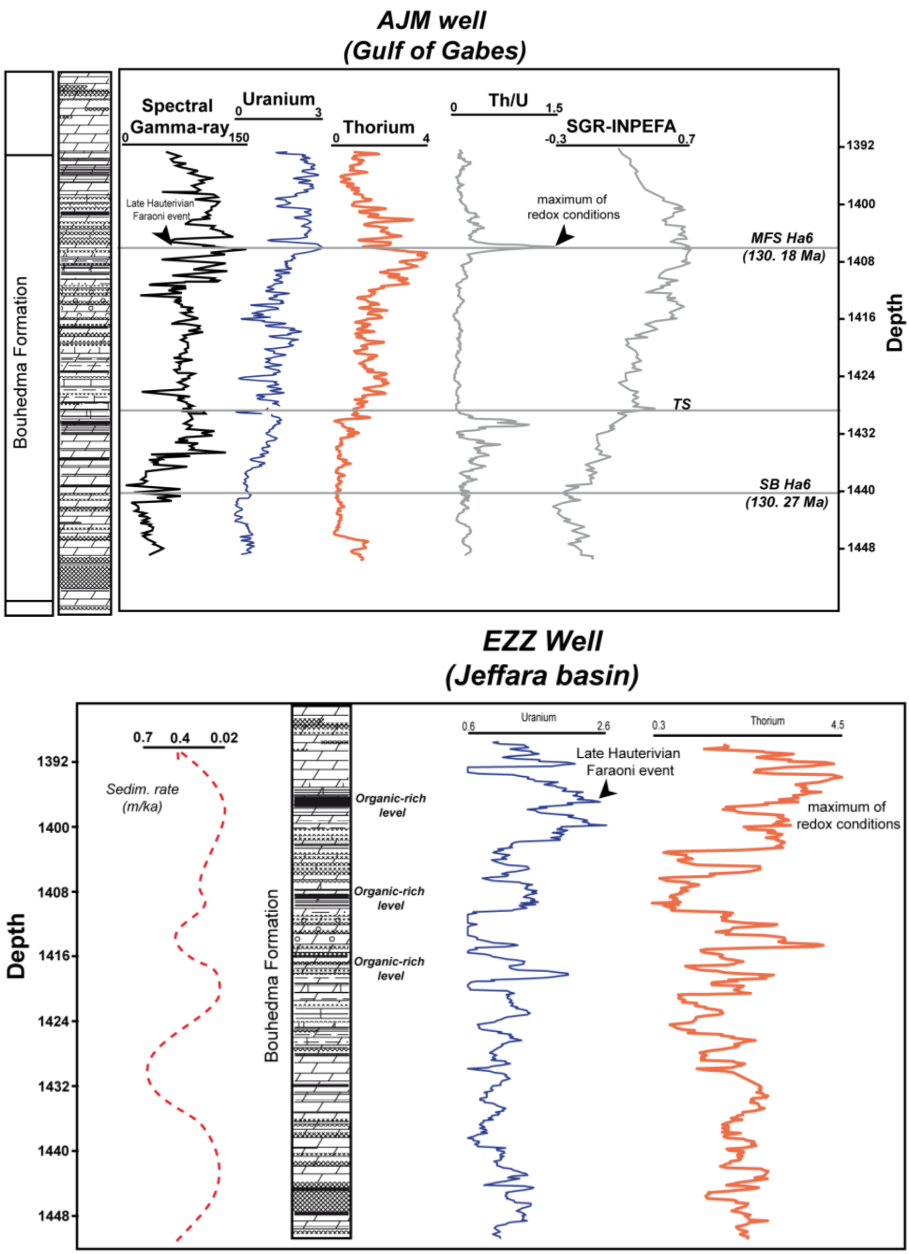

***Figure 10.*** *Gamma ray anomaly recorded through the Callovian anoxic level recording the Callovian anoxic event (C-OAE). Tentative correlation within the south chott basin.*

The organic-rich Callovian Smida is penetrated by several wells in the area (Figure 10). The Figure 10 illustrates the distribution of the organic facies through a NW-SE cross section (C-C') displayed by the Gamma-ray events. The Smida Formation generally constitutes tens to hundreds of meters thick (20 to 255m), with a maximum thickness in Limagess area in the southern Chotts domain. In the Gulf of Gabes (including Jerba Island and Zaouia area) the upper Jurassic section is also represented by grey to dark shales, interbedded with fine alternations of marls, and argillaceous laminated limestones and constitutes a good local source rock. Generally, the Smida consists of a regular alternation of dark coloured shales and marls and laminated carbonates with greyish limestones with TOC values of up to 1% (Saidi and Inoubli, 2001) (Figure 9). The TOC ranges vary significantly in different wells (Figure 9). Typical observed ranges include intervals situated between 0.22 and 1% (e.g., KFG-1 and NF-1) and significantly higher range of TOC are displayed only in two regions which are Franig and Zaouia areas and finally very poor TOC content lower than 0.2% in the center of the Chott basin (Figure 9). The organic-rich smida Formation is characterised by mixed type I/II and III kerogene, i.e. algal type I/planktonic marine type II and ligneous and hemicellulosic continental type III kerogen (HI ranging between 100 and 900 mg HC/g TOC) with TOC concentrations of up to 1%, indicating a good local source rock qualities for oil in Franig and Ezzaouia/El Bibane areas. An early to marginal maturity level of these laminated shales is confirmed by $T_{max}$ values nearly constant between 425 and 440 ℃ (Figure 9).

### 2.4.3 The Late Hauterivian Faraoni Anoxic Event

Late Hauterivian black shales are not estimated to represent a source of hydrocarbons in Tunisia, the reason why it was never studied before. However, our own investigation and analysis of the Uranium and thorium content (Figure 11) of the late Hauterivian organic-rich shales in Tunisia show high gamma-radiation of up to 170 API, originating almost entirely from uranium (ranging between 1.2 and 2.3 ppm) and thorium (ranging between 2 and 4.2 ppm) (Figure 11). This event lies within the *Pseudothurmannia catulloi* ammonite subzone, coincides with the extinction of the calcareous nannofossil species *Lithraphidites bollii*, and records an increase in a globular planktonic foraminifer. High quantities of marine organic matter were and probably elsewhere in the Mediterranean Tethys and Atlantic Ocean. Carbon-isotope stratigraphy from Tethyan and Atlantic sections shows a minor positive excursion in the uppermost part of the Hauterivian and Lowermost Barremian, suggesting accelerated extraction of organic carbon from the ocean reservoir just after the Faraoni Event.




AJM well
(Gulf of Gabes)
Bouhedma Formation
Spectral Gamma-ray
0
150
Uranium
0
3
Thorium
0
4
Th/U
0
1.5
SGR-INPEFA
-0.3
0.7
Late Hauterivian Faraoni event
maximum of redox conditions
MFS Ha6 (130. 18 Ma)
TS
SB Ha6 (130. 27 Ma)
Depth
1392
1400
1408
1416
1424
1432
1440
1448
EZZ Well
(Jeffara basin)
0.7
0.4
0.02
Sedim. rate (m/ka)
Depth
Bouhedma Formation
Organic-rich level
Organic-rich level
Organic-rich level
Uranium
0.6
2.6
Thorium
0.3
4.5
Late Hauterivian Faraoni event
maximum of redox conditions

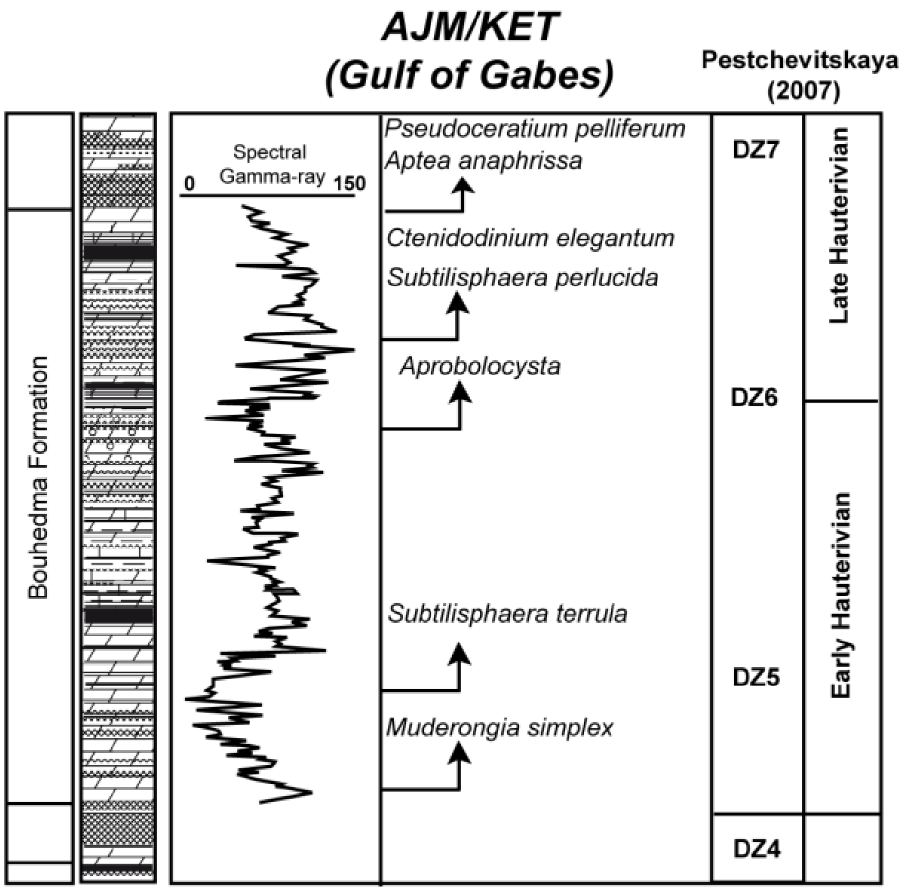



***Figure 11.*** *Analysis of the spectral gamma ray (SGR), uranium, thorium and Th/U ratio in three different domains (Soua, 2013), A. RAJA well is located in the Gulf of Tunis, B. AJM well is located in the Gulf of Gabes, C. EZZ well is located in the Jeffara basin, and D. Biostratigraphic framework is based on the dinocyst vertical distribution in KET and AJM wells after (Brehm and Trichelli, 1991).*

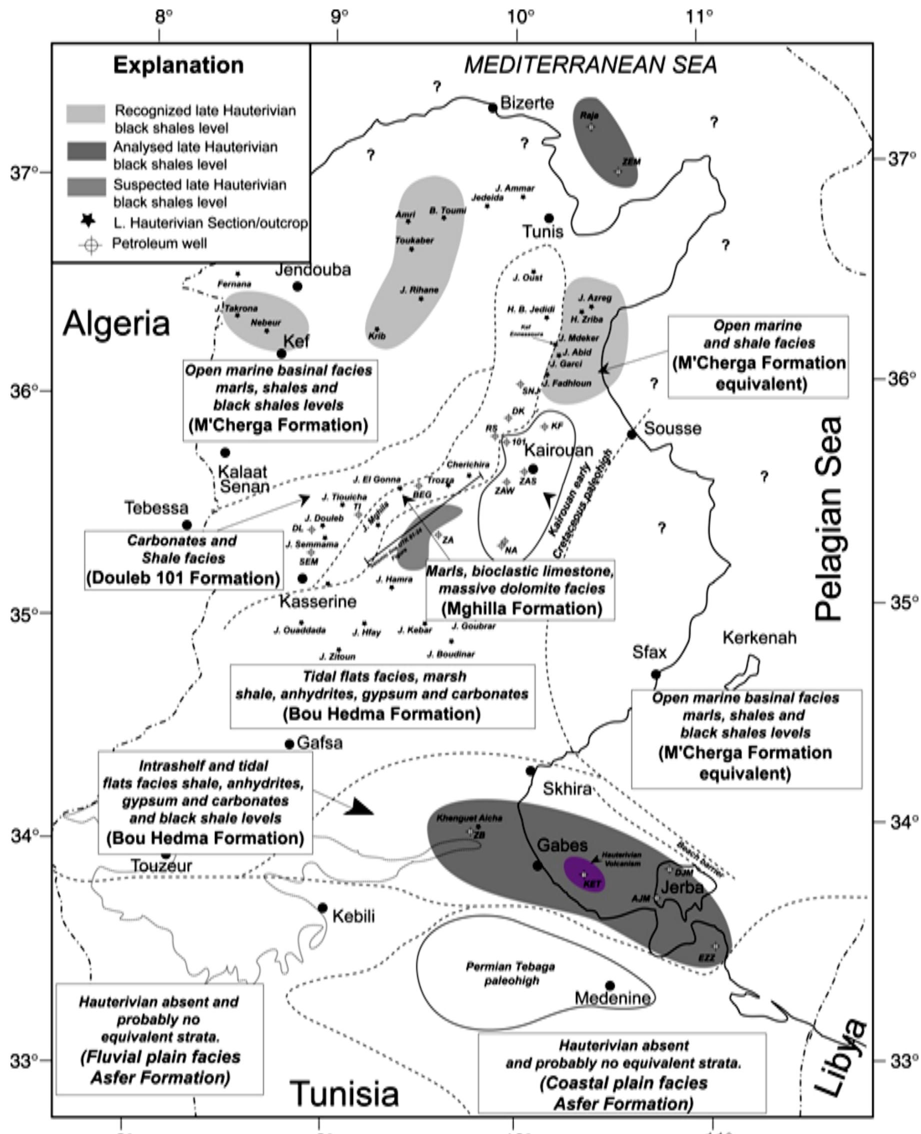
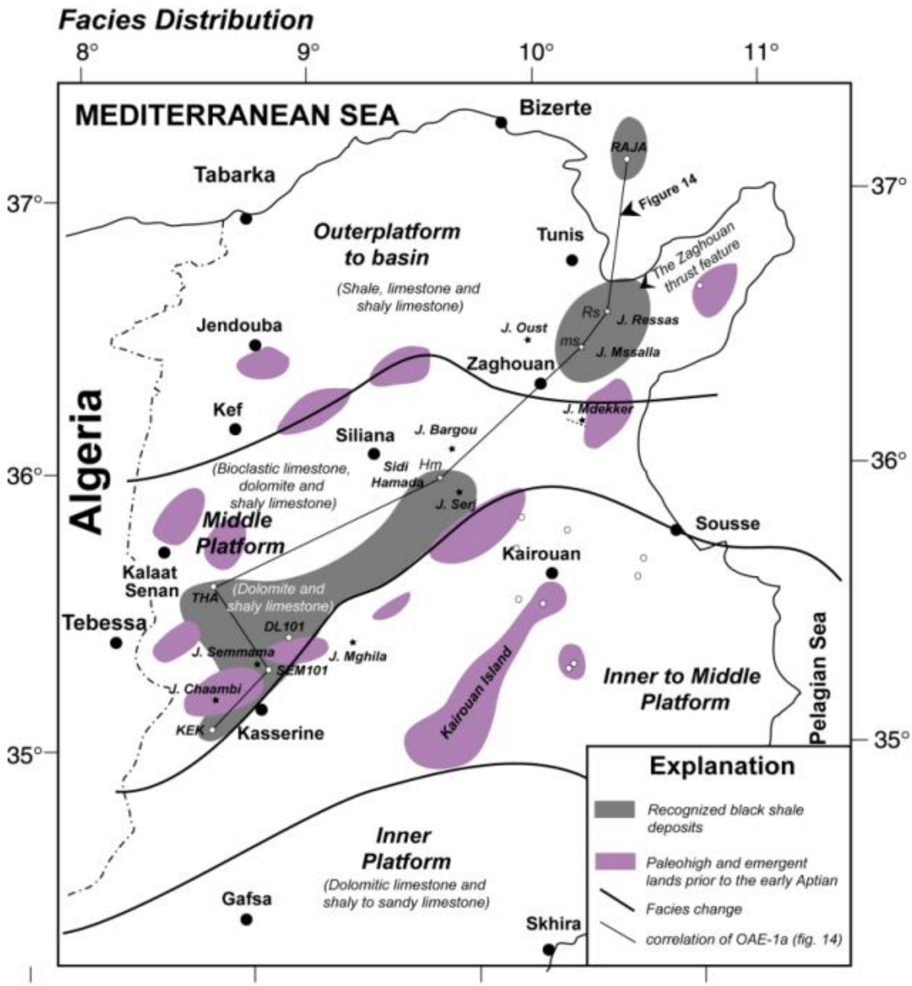



***Figure 12.*** *Paleogeographic map at the late Hauterivian time in Tunisia showing different deposited facies and volcanic activity associated with that period of time and which has been denoted in Baudin (2005). Data compiled after (M'Rabet, 1981; Burollet et al., 1983; Ben Ferjani et al., 1990; Brehm and Trichelli, 1991; Zghal, 1994; Soua et al., 2011b; Soua, 2013).*

As suggested by Adams and Weaver (1958), Jones and Manning (1994), Dypvik and Eriksen, 1983), Doveton and Merriam (2003) and Soua (2011a) the Th/U ratio is taken as proxy of redox potential. It is assumed that this ratio is a useful practical measure of redox conditions (Doveton and Merriam, 2003). However, spectral gamma-ray log provides the Th/U ratio which is a useful indicator of redox conditions. In Ajim well, in upper Bouhedma Formation, it shows a peak at 1.5 suggesting a maximum of redox conditions (Figure 11).

The SGR, U and Th curves of the M'Cherga formation (Gulf of Tunis) and Bouhedma formation (Gulf of Gabes) (Figures 4 and 11) are readily interpretable in terms of transgressive-regressive events that show comparable features with the eustatic sea-level fluctuation curve given by the integrated predictive error filter (INPEFA) log of the SGR (Nio et al., 2005; Soua, 2012). This is confirmed earlier for the Bouhedma in the Gulf of Gabes by Soua et al. (2011a) from well studies. The higher values (more radioactive) have generally been interpreted as deposited in deeper water and tend to be placed at the maximum flooding surface (MFS) (Figure 11).

By contrast, the less radioactive units may have been formed in intrashelf setting. This is in agreement with Hoffman et al. (1998) who suggested that these patterns probably reflect secular and regional differences in the redox conditions at maximum transgression. The upper Bouhedma black shales are characterized by low carbonate content (0.7-13% in Khanguet Aicha section, see Figure 12 for location). Generally, the gamma-ray intensity in these shales can be used as a proxy for the vertical organic richness distribution. In Ajim well, the 170 API could correspond to approximately to 1.8% TOC (Brehm and Trichelli, 1991) of the Faraoni level. Only a few samples from this unit have significant TOC contents with up to 1.8%. These samples from Ajim both have high Hydrogen Indices (HI ranging between 650 and 900 mg HC/g TOC) indicating Type I organic matter. A sufficient maturity level of these laminated black shales is confirmed by $T_{max}$ values nearly constant between 430 and 435 ℃.



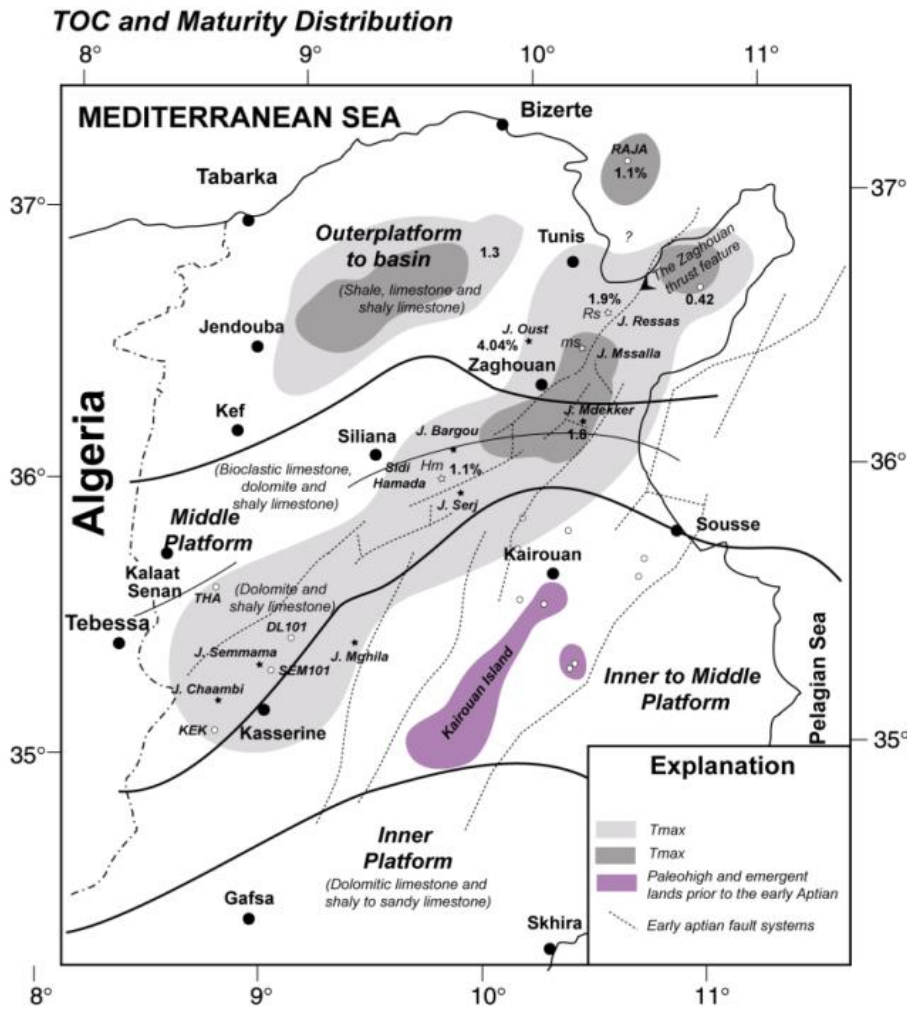
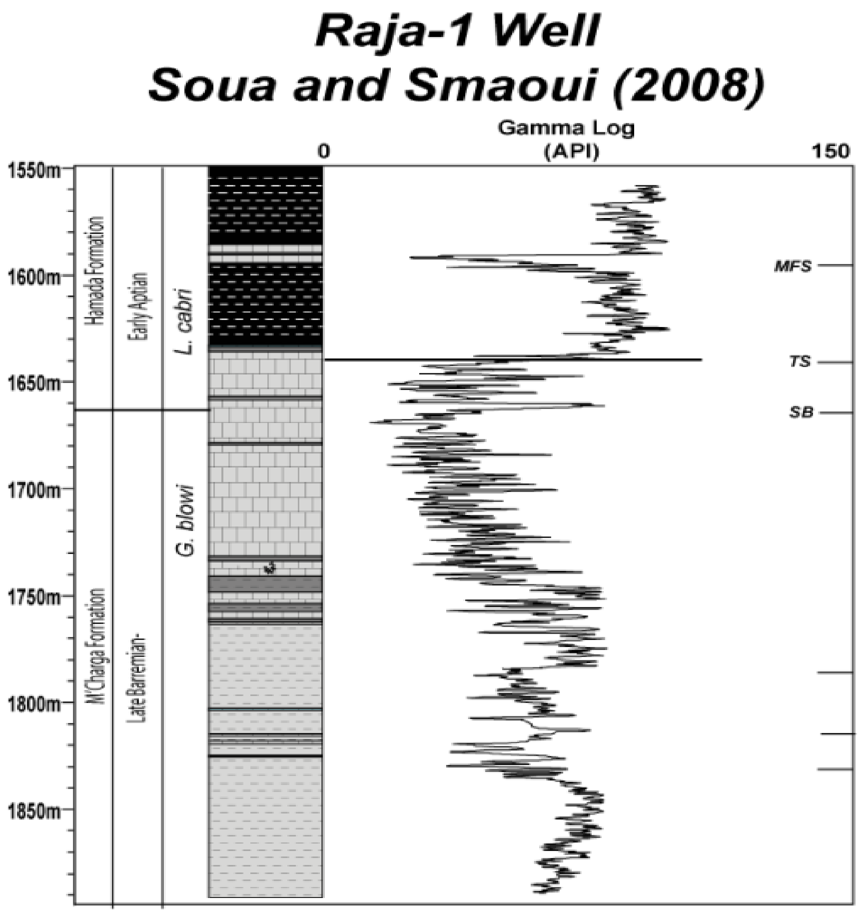


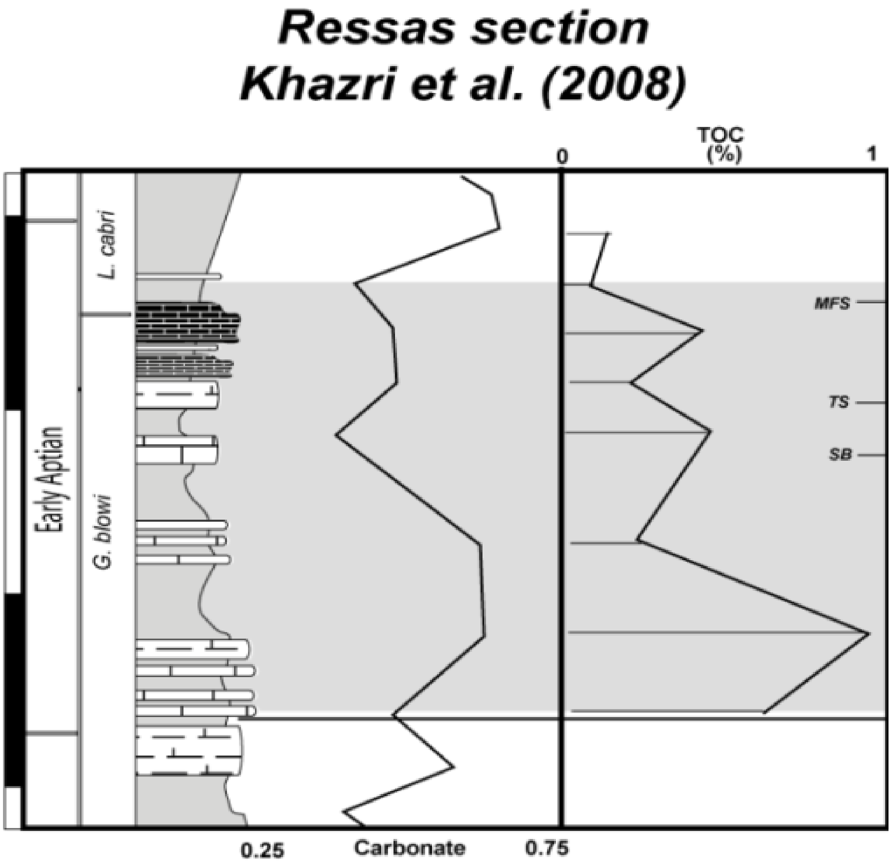

***Figure 13.*** *Facies, TOC and Maturity distribution maps of the early Aptian OAE-1a (selli event) in Tunisia, Data are compiled from M'Rabet (1981); Burollet et al. (1983); Heldt et al. (2008); Zouaghi et al. (2011) ; Elkhazri et al. (2013).*

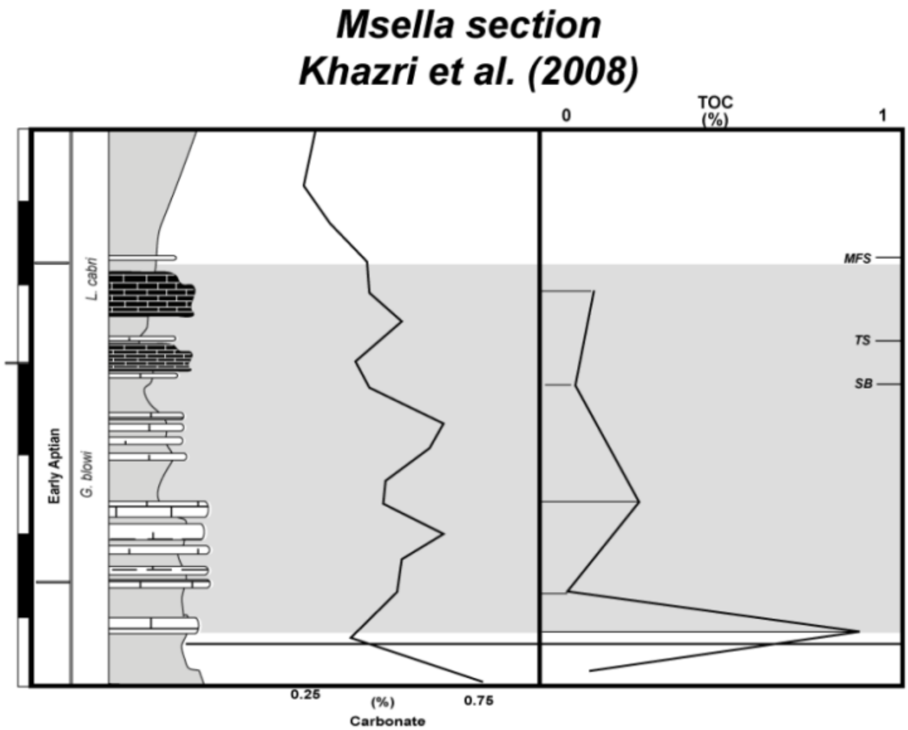
### 2.4.4 Early Aptian Selli Event

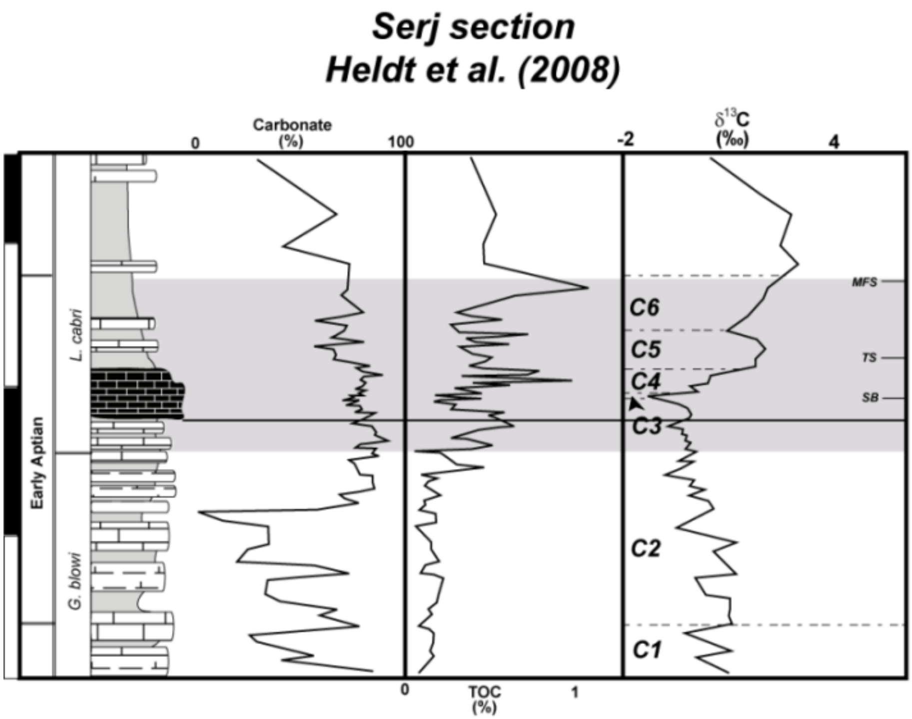
Organic-rich early Aptian strata occur in many places in northern and central Tunisia and are grouped into the Hamada Formation that was defined by Tlatli

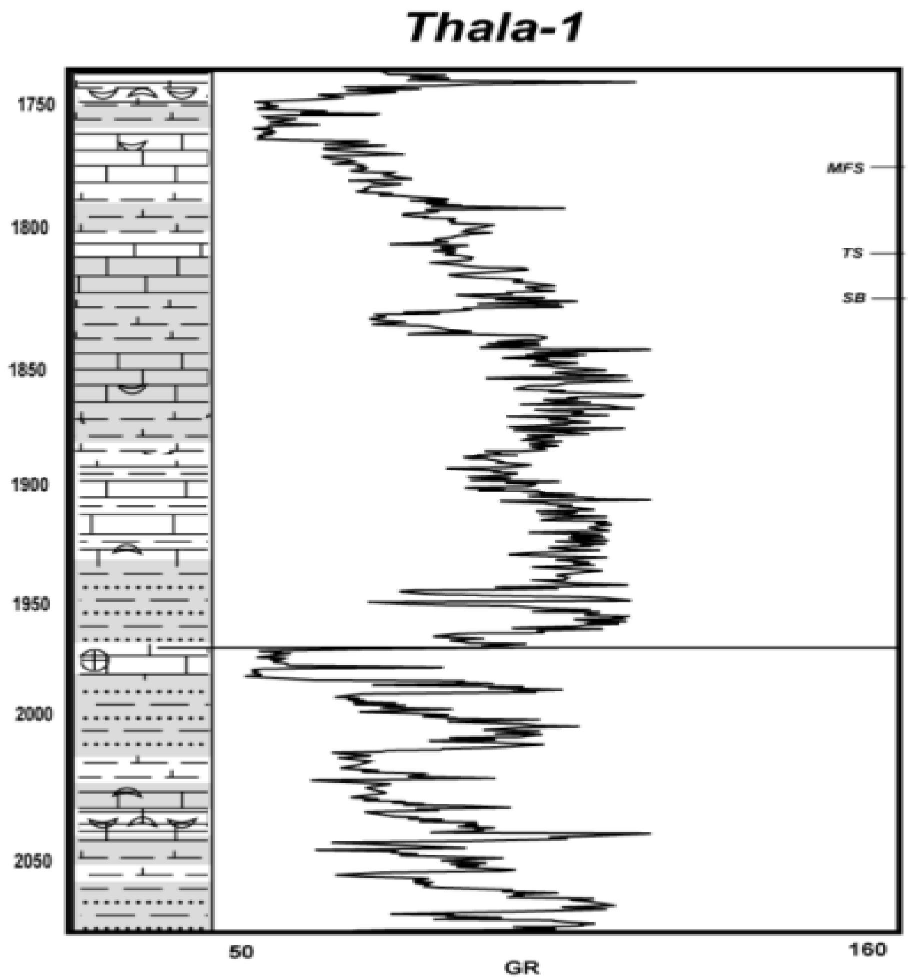
(1980) in the Sidi Hamada area in NW of Jebel Serj and grouped earlier into Serj Formation by many authors (Burollet, 1956; Fournié, 1978) or the lower member of the Serj (Ben Ferjani et al., 1990; Zghal, 1994; M'rabet et al., 1995; Bessaies and Ben Jemia, 1998; Benzarti, 2002; Zouaghi et al., 2011). It may vary laterally to the southwest to the Bou Laaba dolomite defined by Bismuth et al. (1981), and to the Berrani member which constitutes the lower part of the Orbata Formation (Ben Youssef et al., 1985). In general, the Hamada formation is deposited within the transitional interval of the *Blowiella blowi* and *Leupoldina cabri* foraminiferal Zones indicative of the Bedoulian (Elkhazri et al., 2013).

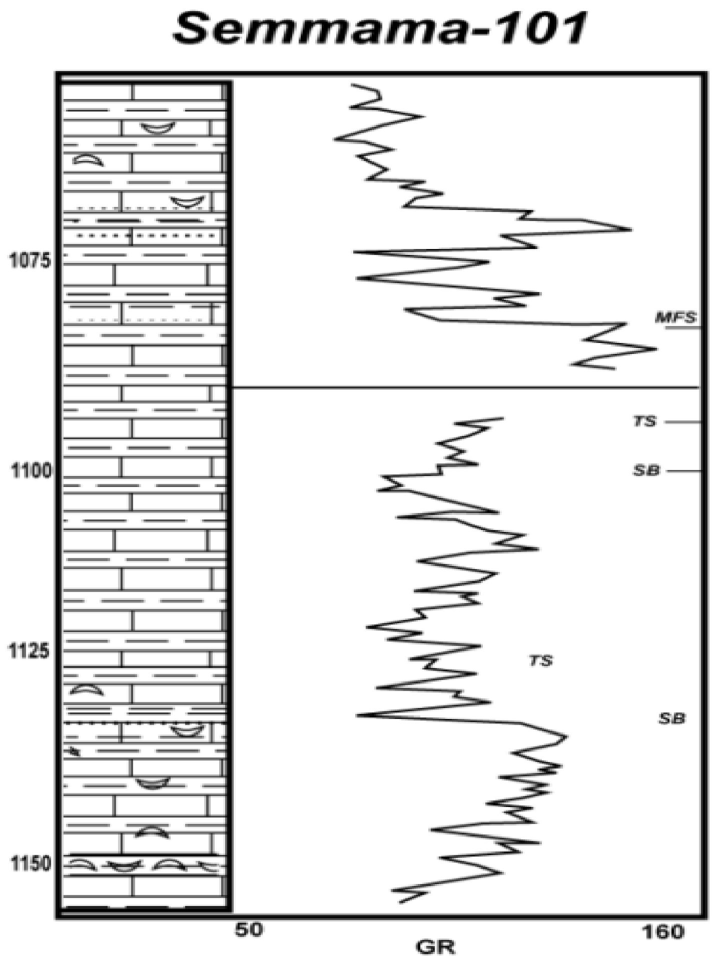



Ressas section
Khazri et al. (2008)
TOC
(%)
0
1
Early Aptian
L. cabri
G. blowi
MFS
TS
SB
0.25
Carbonate
0.75


Msella section
Khazri et al. (2008)
TOC
(%)
0
1
MFS
TS
SB
Early Aptian
L. cabri
G. blowi
0.25
(%)
0.75
Carbonate


Serj section
Heldt et al. (2008)
Carbonate (%)
0
100
δ13C (‰)
-2
4
TOC (%)
0
1
Early Aptian
L. cabri
G. blowi
C6
C5
C4
C3
C2
C1
MFS
TS
SB


Thala-1
1750
1800
1850
1900
1950
2000
2050
MFS
TS
SB
50
160
GR


Semmama-101
1075
1100
1125
1150
MFS
TS
SB
TS
SB
50
GR
160

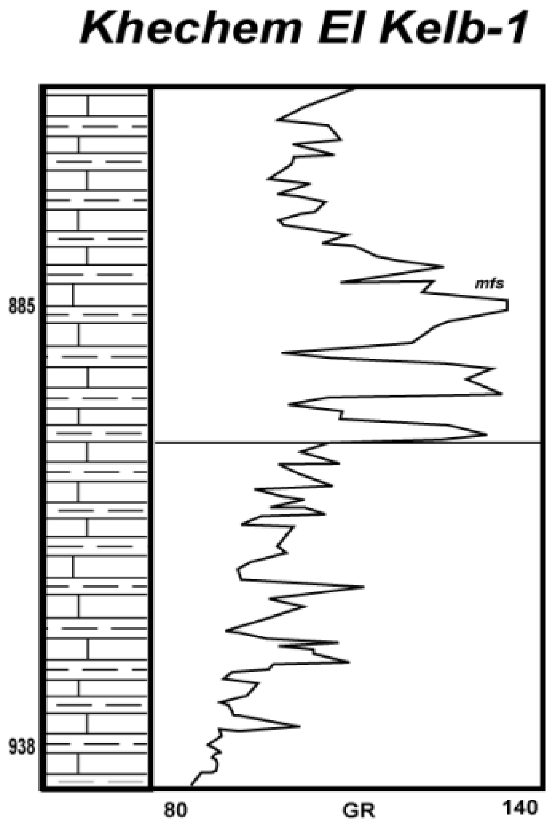



***Figure 14.*** *Tentative correlation between different domain recording the selli event (OAE-1a) in Tunisia, data compiled from Soua and Smaoui (2008); Sandman (2008); Heldt et al. (2008); Elkhazri et al. (2013) and unpublished petroleum reports from ETAP.*

The regional distribution of the two main early Aptian facies types, modified after Bessaies and Ben Jemia (1998), is shown in the same Figure 13. The organic-rich early Aptian exists in three areas, namely in the NE (Rs/Ressas, ms/Mssalla sections) and Central Tunisia (Hm/Serj section), in the offshore NE (the Raja well) and in the Western Central Tunisia (Thala, Khechem El Kelb, Semmama wells, see Figure 13 for location). Several neighboring drilled wells have identified black shale deposition or have confirmed the extension of the lower Cretaceous emerged areas. These data give new insight on the distribution of the organic-rich provinces of Tlatli (1980), however, the exact boundaries still remain unclear, especially in the Pelagian Sea, Central Tunisia and Algeria.

The Hamada Formation generally constitutes few hundreds of meters thick (100 to 350m), with a maximum thickness of about 400 m in the NW Tunisian Trough. However, the early Aptian black shale package which corresponds to the Selli Event does not exceed 15m or 20m. In Jebel Ressas (Rs section) and Msalla (ms section), the upper part of the M'cherga Formation is also represented by hemipelagic black shales interbedded with finely laminated limestones (Souquet et al., 1997; Elkhazri et al., 2013), while Saadi et al. (1994) described condensed section for the Aptian-Albian section in the Jebel Mdeker (Figure 13 for localization).

The first unit is characterized by a regular alternation of dark coloured shales and laminated carbonates and nodular black and greyish limestones and marls with TOC values of up to 1% (Heldt et al., 2008; Lehman et al., 2009; Elkhazri et al., 2013) (Figure 13). A single 1.99% TOC value was reported by Elkhazri et al. (2013) from the Rs section (Jebel Ressas). The vertical distribution of limestone vs. marl in the different localities depends on the position on the palaeoshelf/slope. A general overview of the paleogeography during the early Aptian Hamada black shale levels may explain that generally in proximal settings it acquires more carbonaceous deposition with bioclast richness and, on the contrary, becomes dominated by marls in distal settings. Particularly, in Rs/Resas and ms/Msalla sections (Elkhazri et al., 2013) and the lower 55m of the Hm/Serj section (Heldt et al., 2008), we note that the TOC values in calcareous and laminated beds rich in bioclasts and benthic foraminifera are generally locally organic-lean varying between (0.2 to 0.3%).

In this study, we also used Gamma ray log distribution in some wells (Raja, Thala, Semmama and Khechem el Kelb). A close inspection of the GR profile patterns could display a peak in the radioactivity at the base of the Hamada Formation (Figure 14) probably resulting from the Uranium content as the case for the Late Hauterivian.

The organic-rich Hamada black shales Formation is characterised by mixed type II/III kerogene, i.e. planktonic marine type II and ligneous and hemicellulosic continental type III kerogen (HI ranging between 10 and 260 mg HC/g TOC; OI between 50 and 320g$CO_2$/gTOC) with TOC concentrations of up to 1.99%, indicating good source rock qualities for oil. A sufficient maturity level of these laminated black shales is confirmed by $T_{max}$ values nearly constant between 438 and 459 ℃ (Figure 13). In Raja Well a single value of 1.2% of TOC has been given with a HI is equal to 435 (Sandman, 2008).

### 2.4.5 Albian Anoxic Events

The Fahdene Formation encompasses the remaining Oceanic Anoxic events of the Albian, i.e. the paquier level, the Leenhardt level and Breistroffer level (Figures 15, 16 and 17).

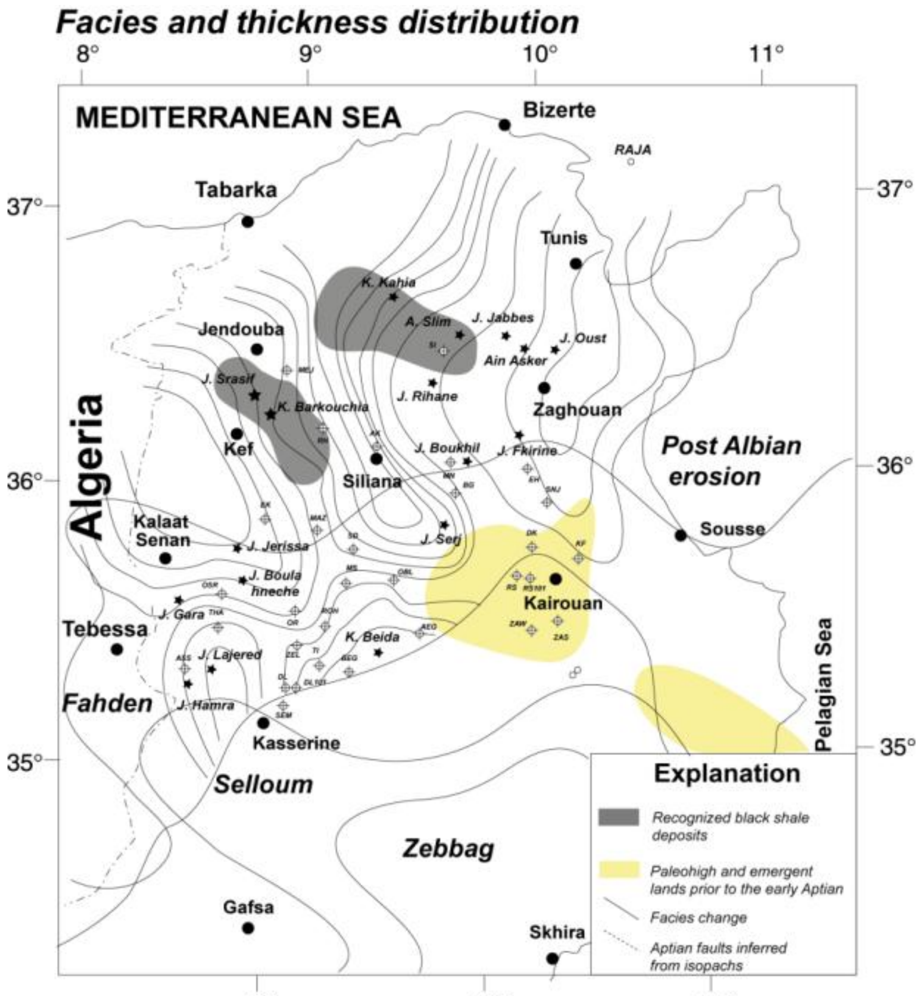
Lithologically, it can be subdivided into five marker members: the lower shale member (early Albian), which is generally lying unconformably on the Hamaima Formation (if present) or the underlying strata of the late Aptian Serj Formation. Generally it consists of green shales interbedded with bioclastic limestones partly dolomitized followed by a conglomeratic bed which is in turn overlain by a thick shale package with thin limestone intercalations displaying pelecypods, crinoids, belemnites, *Ticinella raynaudi* and *Ticinella primula* (Rami, 1998; Chihaoui, 2009; Ben Fadhel et al., 2012). The Allam (source rock, middle Albian), it is composed of alternating dark grey to black coloured marls and decimetric beds of laminated limestones which consist of mudstones and wackestones. The uppermost limestone bed exhibits a burrowed surface. The middle shale member is composed of dark grey to black coloured marls and shales, intercalated with a few decimetric limestone beds, locally containing ammonites. The uppermost part consists of alternating marls and argillaceous limestones locally exhibiting burrows and belemnites. The marls are rich in planktic foraminifera such as *Biticinella breggiensis*, *Ticinella roberti* (Rami, 1998). The Moualha (Source Rock, late Albian), is represented by black shales and limestone unit. At the base of this unit a conglomeratic limestone having an erosive base is generally present. The overlying series are composed of laminated limestone, which consist of mudstone and wackestone beds, admitting decimetric organic rich shales-marls interbeds.

The basal shales consist of *Rotalipora subticinensis* (Rami, 1998; Ben Fadhel et al., 2012). The upper shale member (latest Albian), consist of relatively thick dark shales and marls admitting few argillaceous limestone beds. This unit is overlain by organic rich shales and marls containing ammonites and abundant planktic foraminifera indicating latest Albian (*Ticinella subticinensis*). This unit is in turn overlain by early Cenomanian green shales containing *Rotalipora apenninica*.

The TOC ranges vary significantly in different localities. Typical observed ranges include mainly pattern with a sine shape-like gradual increase and decrease of values within the Albian interval in the Fahdene Formation. A close inspection of the Albian spiky TOC pattern in combination with typical alternations of dark coloured shales, organic-rich marls with light beds highlights the significance of anoxic and dysaerobic environments cycles during the deposition.

The low TOC values characterizing some early Albian sections could be explained by the partially absence of the Lower shaly member of the Fahdene Formation interval (exhibiting significant organic-rich) probably capped by the generalized erosion phase (D8 to D9 of Chihaoui, 2009), where in many places the Allam member is lying unconformably on Triassic or on late Aptian strata

(Chihaoui, 2009; Ben Fadhel et al., 2012). The values of TOC of less than 1% could be linked to organically leaner location of the logged section or probably they were deposited underneath the Oxygen Minimum Zone (OMZ).



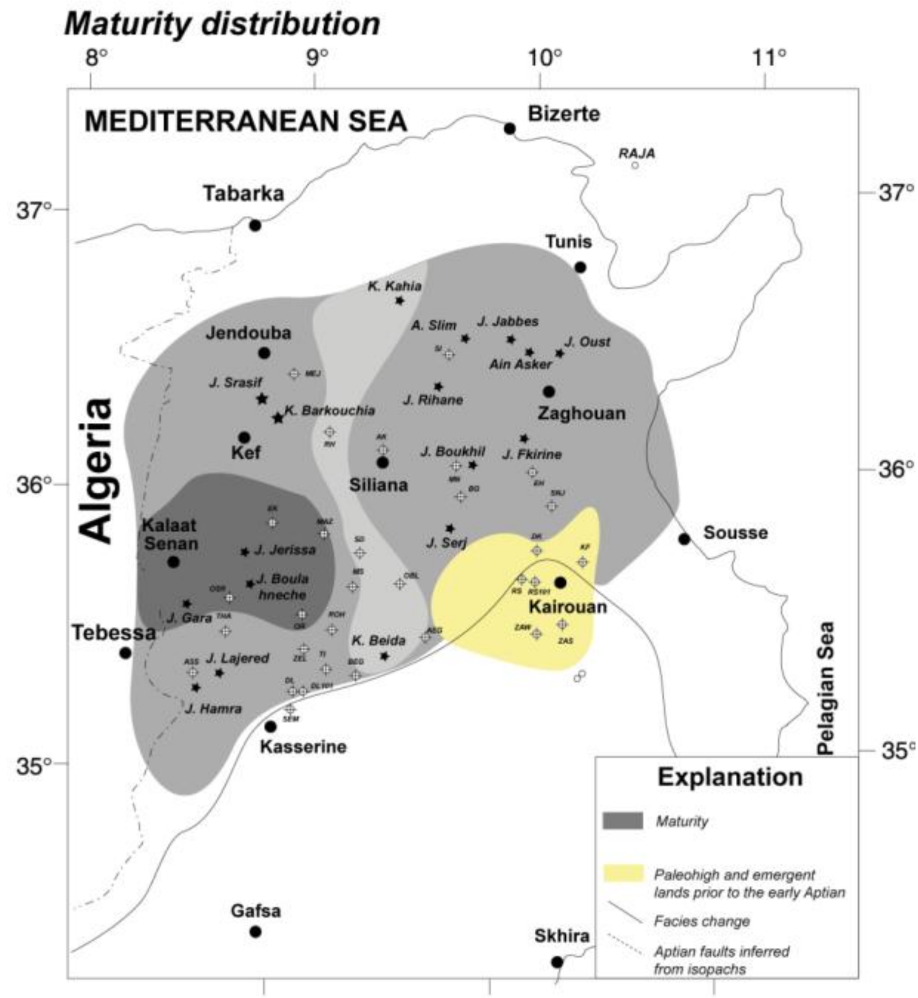



***Figure 15.*** *Facies, thickness and Maturity distribution maps of the Albian anoxic events (OAE-1b-1d), data compiled from Zghal and Arnould-Vanneau (2005); Chihaoui (2009); Ben Fadhel et al. (2011).*

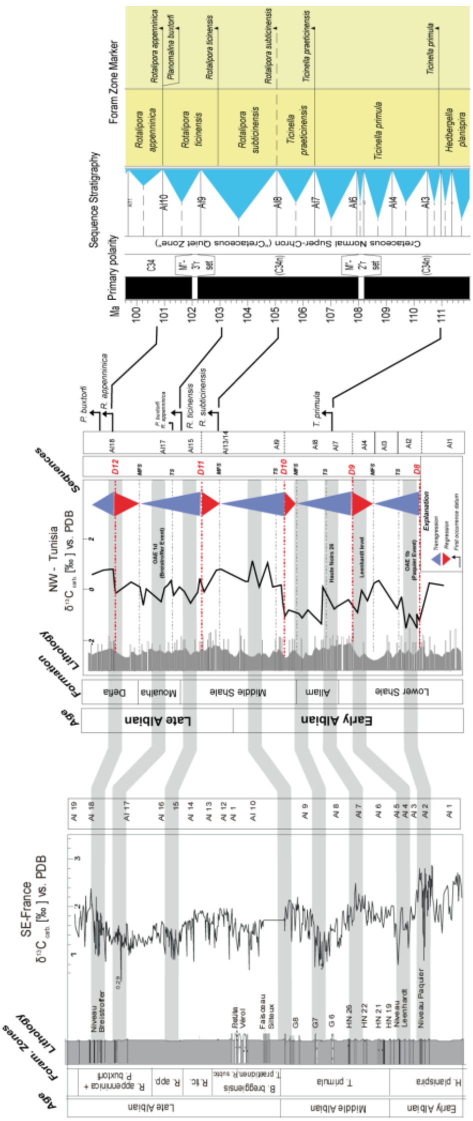


***Figure 16.*** *Tentative correlation of the Albian events (OAE-1b-1d) between the Voccontian basin in France (Reichelt, 2005) and Tajerouine in Tunisia (Chihaoui, 2009) using the carbon-isotopic events and the worldwide time scale. The correlation is mainly made to express the Paquier, Leenhardt, Hautenoir 26 and Breistroffer levels (OAE-1b to OAE-1d of the Albian) within the Fahden Formation.*

NB: Paquier and Leenhardt levels are located in the Lower Shale member of the Fahden Fm.; the Haute Noir 26 is located within the Allam member; and the Breistroffer event (OAE-1d) is located within the Moualha member.

Alternatively, Ben Fadhel et al. (2011) suggested however, that the uppermost Allam black shale unit could possibly correspond to the oceanic anoxic event OAE1b Paquier level, while Chihaoui (2009) using carbon isotopic analysis showed that the latter Paquier level is situated in the Lower Shale Unit of the Fahdene Formation (Figure 16) few meters under the Allam member in the Tajerouine area (see Figure 15 for location). Taking into consideration the position of *P. buxtorfi* first occurrence, Ben Fadhel et al. (2011) correlated also the Mouelha black shales with the Breistroffer level (OAE1d) identified in the Vocontian Basin (Erbacher et al., 1996; Bréhéret, 1997) and with the Pialli level in the Italian Apennines domain (Coccioni, 2001) while the Breistroffer level is dated within the *R. appenninica* Zone situated prior to the FO of *P. buxtorfi*. The Figure 17 shows a summarized composite $\delta^{13}C$ and TOC for the Tunisian Aptian and Albian anoxic events. The Selli, Paquier and Breistroffer levels are underlined by gray bands and correlated to the Section of Mexico (Bralower et al., 1999). The composite $\delta^{13}C$ is divided into 15 segments. Segments C1 to C8 are the division of Menegatti et al. (1998) and the segments C9 to C15 are the division of Bralower et al. (1999) in Sierra Madre (Mexico). The Figure 17 also shows a tentative correlation of the main anoxic events (OAE 1b and OAE 1d) using carobon-isotopic events in Tunisia and worldwide (Bralower et al., 1999). From the figures 16 and 17, we may summarize that (1) the Paquier and the Leenhardt levels are exclusively related to the Lower shale unit of the Fahdene Formation, (2) the Allam member displays the same carbon isotopic signature of the “Haute Noirs 26” black shale level of Reichelt (2005) in the Vocontian basin, (3) the Moualha member is the equivalent of the Breistroffer level and (4) the D9 and D10 sequence boundaries correspond to the Albian major unconformity (El Euchi et al., 2002; Zghal and Arnaud-Vanneau, 2005) since several carbon isotopic segments are absent in Tunisia (Figures 16-17).

The Albian organic-rich sedimentation of Tunisia was deposited during the *Hedbergella planispira* and *Rotalipora ticinensis*. Interesting is the presence of the $\delta^{13}C$ isotopic expression of the Paquier and Leenhardt levels situated within the *H. planispira* Zone and *H. buldti* ammonite zone of Chihaoui (2009) in the Lower Shale unit of the Fahdene Formation (Figure 16). The two source rock levels of the Albian: Allam (*T. primula* Zone) and Moualha (*R. ticinensis* Zone), revealed a good TOC levels and match with the C-isotopic events of the HN 26 and the Breistroffer levels of the Albian of the Vovontian basin (Figure 16). Moderate abundant radiolarians have been described earlier by Ben Fadhel et al. (2012) within the Mouelha black shale which lies generally within the lower part of the *Rotalipora appenninica* zone. This black shale interval is assigned to the early Albian U.A.10 biochronozone of O'Dogherty (1994) which is equivalent to the *Romanus* Zone of O'Dogherty and Guex (2002).

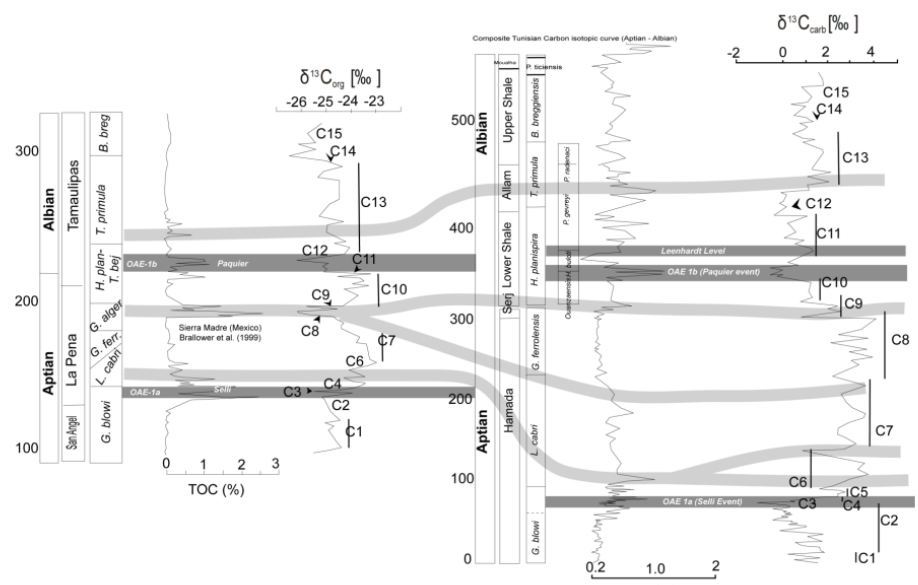



*Figure 17. Tentative correlation of the Selli event and different Albian levels recorded in Mexico (Bralower et al., 1999) and Tunisia (composite Carbon-isotopic curve is compiled from Chihaoui, 2009 and Elkhazri et al., 2013).*

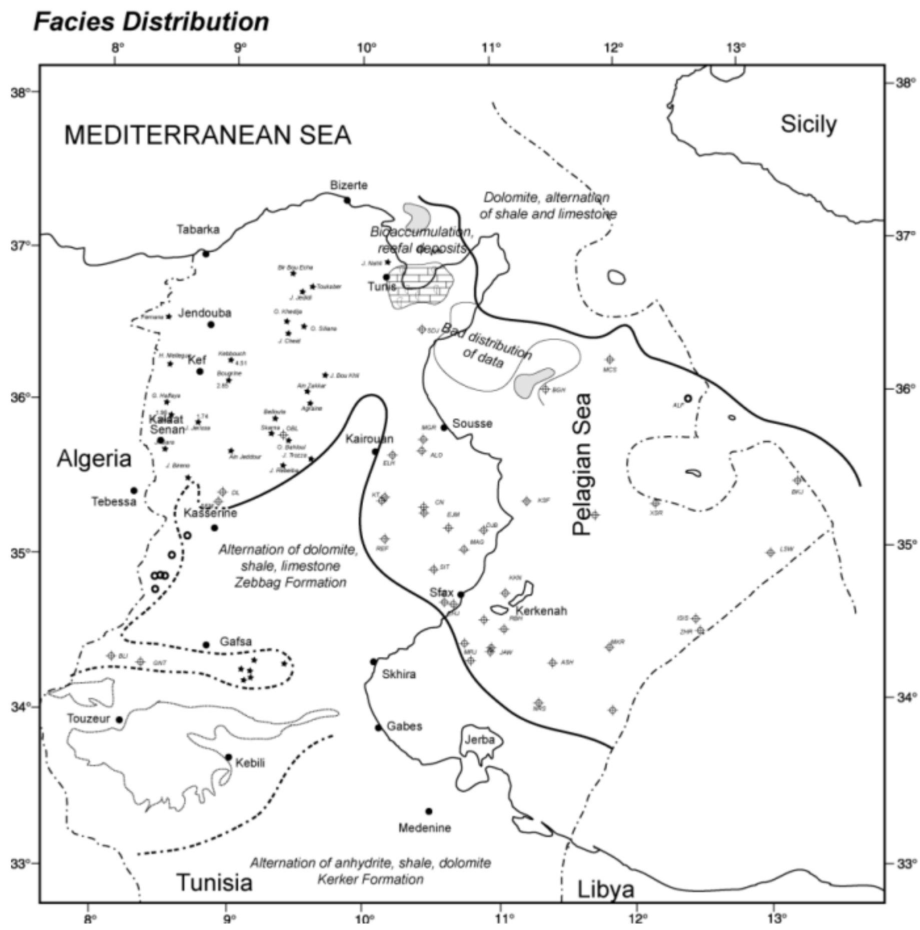
The organic-rich Albian black shales are characterized by mixed Type II/III, i.e. planktonic marine type II and ligneous and hemicellulosic continental type III kerogen (HI ranging between 40 and 700 mg HC/g TOC) with TOC concentrations of up to 4.5%, indicating fair to good source rock qualities for oil and gas. A sufficient maturity level of these laminated black shales is confirmed by $T_{max}$ values which vary along a NE-SW trend (Figure 15), recording two major intervals of about 430-440 ℃ and 440-460 ℃.

### 2.4.6 Cenomanian-Turonian Anoxic Event OAE-2

Organic-rich C/T sediments occur in many places in northern, central and offshore Tunisia and are grouped into the Bahloul Formation (Burollet, 1956). The Figure 18 illustrates the facies distribution of the anoxic C/T facies in Tunisia and Algeria (Bishop, 1988; Luning et al., 2004; Soua et al., 2009; Layeb et al., 2013; Affouri et al., 2013). The regional distribution of the Tunisian C/T facies including the distinction of an organic-rich and an organic-lean anoxic facies, is shown in three main Provinces (Figure 18).

The Bahloul Formation contains generally the biomarker of the *Rotalipora cushmani* Zone and the *Whiteinella archaeocretacea* Zone and/or not the *H. helvetica* Zone (Soua, 2005; Soua et al., 2011a; Zaghbib-Turki and Soua, 2013). The last occurrence (LO) of *R. cushmani* is generally found above the base of the Bahloul Formation.

The spectral analysis applied to the *Heterohelix/Guembelitria* spp. fluctuations points to the presence of a metre-scale periodicity regarding the two species (Soua, 2010). *The good correlation* between *the* spectral peak ratios and those of the orbital components *suggest Milankovitch orbital forcing during deposition of the Bahloul*. Calculated average sedimentary rates, are ranging between 12 and 20cm/kyr. A triple subdivision (referred to as peaks I, II and III) was based on small variations in the C-isotopic profiles that develop in the majority of the isotopic curves ($\delta^{13}C$) of all the studied sections and are pointed out by several authors (Bechtel et al., 1998; Barrett, 1998; Accarie et al., 1999; Nederbragt and Fiorentino, 1999; Luning et al., 2004; Soua and Tribovillard, 2007; Layeb et al., 2013). Soua and Tribovillard (2007) suggested that the $\delta^{13}C_{org}$ seems to be a better correlation tool than $\delta^{13}C_{carb}$ for the C/T boundary.



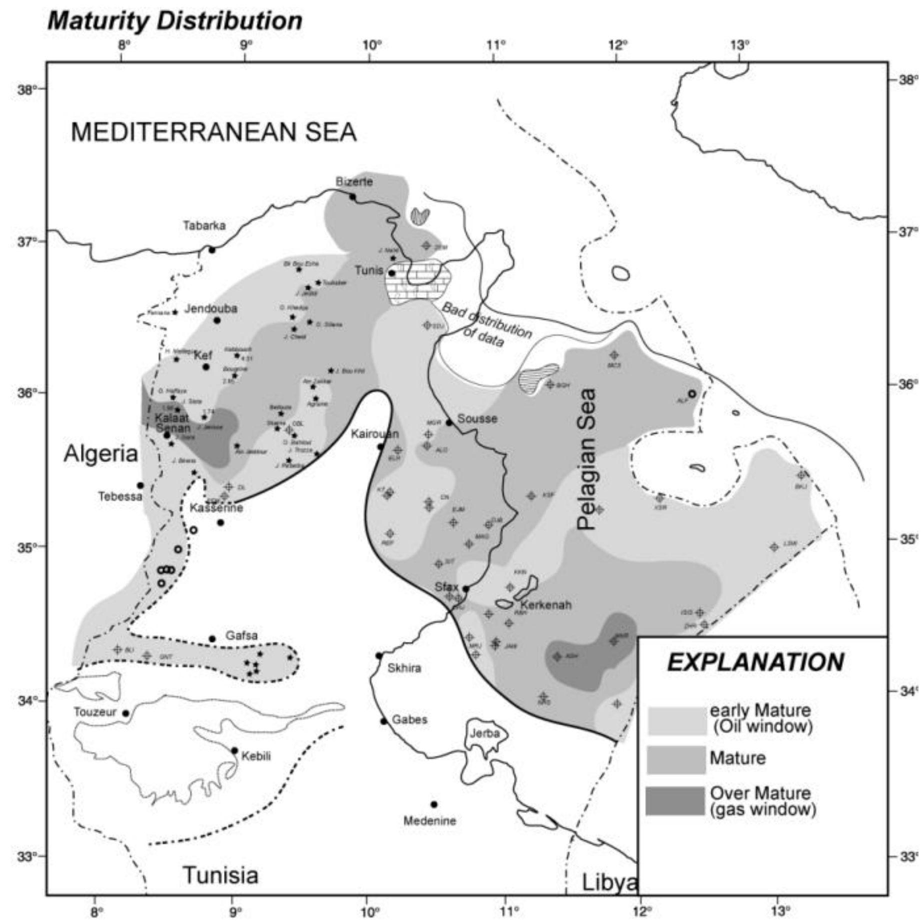



***Figure 18.*** *Facies and Maturity distribution map of the Bahloul Formation (Bonarelli event; OAE-2) in Tunisia, data compiled from Bishop (1988); Luning et al. (2004); Soua and Tribovillard (2007); Soua (2011); Layeb et al. (2013); Affouri et al., (2013).*

Summarized major and trace elements chemostratigraphy have been given by Bechtel et al. (1998); Caron et al. (1999) and recently detailed chemostratigraphic study on the Bahloul has been given by Soua et al. (2011a) who noted (1) a relative enhanced rate of terrigenous supply to the sediment during the Bahloul deposition related to fluvial contributions. This reflects a decrease in eolian supply and probably enhanced fluvial influence during the deposition of the

Bahloul (Soua et al., 2008; 2011), (2) the sediments were likely depleted in $O_2$. The lower part of the Bahloul shows the highest values suggesting that they represent the levels of the most oxygen-poor conditions, (3) increased productivity at the time of the Bahloul deposition inducing severe sulfate-reducing conditions coupled to barite dissolution and Ba remobilization within moderate reducing conditions below the sediment-water interface. This is in agreement with the very low Mn data which suggest an absence of oxidizing conditions close to the sediment-water interface. Also, the increased Si abundance in some Bahloul sections (e.g. Bargou) must be linked to the echo of a local increased biogenic productivity by silica-secreting organisms (mainly radiolarians), consistent with the coeval enrichment in the abundance of the productivity proxies (Ni, Cu and Ba) (Soua, 2011a). The organic-rich Bahloul black shales are characterized by planktonic marine Type II kerogen (IH between 200 and 700 mg HC/g TOC) with TOC concentrations of up to 13.5%, indicating good source rock qualities for oil and gas. A sufficient maturity level of these laminated black shales is confirmed by the OM thermal maturity which presents a rather homogeneous distribution with $T_{max}$ ranging between 430 and 500 ℃.

## 2.5 Basin Modeling and Integration of Dataset

### 2.5.1 Basin Modeling

Since the last Century, geologists within petroleum companies tried to develop new methodologies helping in minimizing investment risks during oil and gas exploration in order to build models for risk assessment during the drilling of the generated prospect which are exclusively seismic-related interpretation (time-structure maps). This concept is admitted as the best way to diminish investment risks in oil and gas exploration by determining volumes of hydrocarbons (reserve calculation) in a prospective structure before drilling. The problem was the use of seismic interpretation which could define closed structures and lay out potential subsurface traps, but never predict what could be the content within a trap. This seismic interpretation is essentially generated through the survey interpretation of the studied area by generating time-structure maps of both target reservoirs and source rocks. Thus, the geophycist can thereafter do his own prospect ranking which could be the best for the company investment. Experience from all over the world as well as from Tunisia shows that drilling structures near a producing oil or gas field, does not promise hydrocarbon found which is the case in Tunisia for example of Sidi Kilani oil field in Central Tunisia and Belli field in the Cap Bon which is near to the Gulf of Tunis subject of this paper (Figure 19).

Since that time, petroleum geologists began building new concepts that display predictive methodology.

The basin modeling concept displays a simple theory which connects several parameters in one sole project. This is illustrated within a connection of the past represented by the:

- history of a basin.
- sediment lithology.
- age (absolute and relative).
- related geochemical analysis.
- geodynamic conditions.

These parameters are joined to the present which is represented by the hydrocarbon discoveries.

This conception is based mainly on quantitative methods which apply mathematical algorithms to seismic, stratigraphic, paleontologic, geochemical, petrophysical, well log geophysical tools and other data in order to rebuild the sedimentary basins evolution.

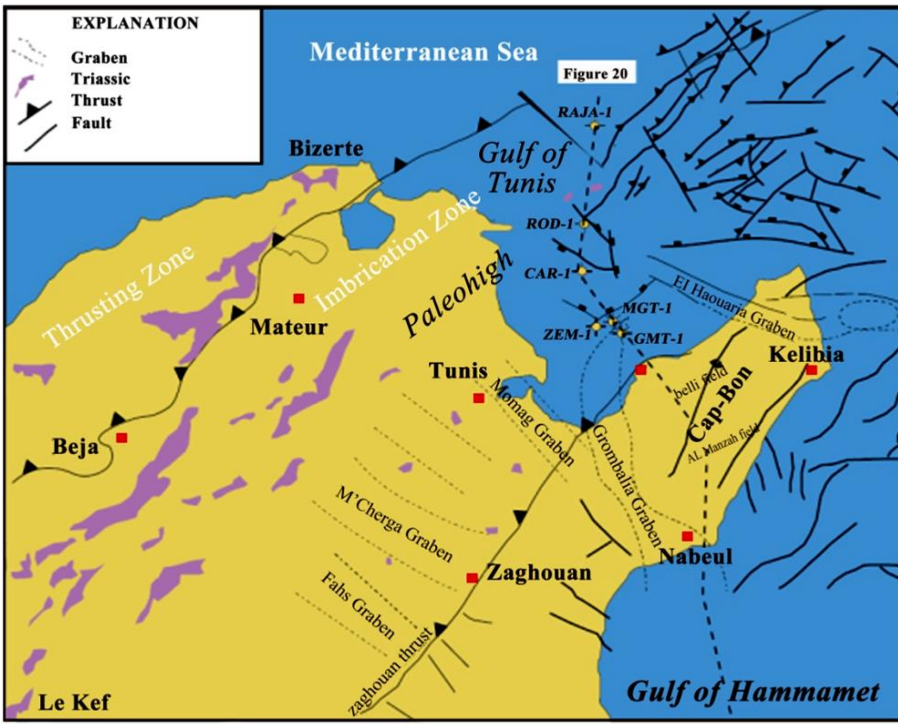



***Figure 19.*** *Location map and structural context of the Gulf of Tunis (after Soua and Smaoui, 2008).*

Our case study will be focused on the Gulf of Tunis area (Figure 19) which had attested the drilling of six wells in different geological sections during more than twenty years (from 1973 to 1996). The prospect generations associated with these petroleum wells had been conducted mainly on seismic survey interpretations through several seismic campaigns. This failure touches also the Central Tunisia which attests that 90% of the drilled wells are negative. This is why we chose in this paper to redirect and recommend a basin modeling concept for petroleum exploration in Tunisia based on a case study which is located in the Gulf of Tunis (Figure 19).

This concept is based essentially on these parameters:

- define new source rock intervals using Oceanic Anoxic Events notion and associated distribution, paleogeographical and thickness maps.
- define new petroleum systems using the OAE's intervals and reservoirs combination.
- integration of interpreted seismic surveys (2D/3D), reservoir time structure maps, monodimensional (1D) basin modeling wells, geochemical analysis (TOC, pyrolysis, etc.) and calibration of required dataset into a basin modeling project.
- generation of the hydrocarbon pathway migration (oil and gas) maps.
- generation of the hydrocarbon (oil and gas) volumes (generated and expelled) maps.
- generation of the report of the cumulative hydrocarbon volume of the source rock (studied OAE interval).

### 2.5.2 Case Study: The Gulf of Tunis

The Gulf of Tunis (GOT) domain is surrounded by proven petroleum provinces where significant discoveries have been made in the past decades (e.g., Bishop, 1988; Bishop and Debono, 1996; Klett, 2001). To reassess the prospectivity of this domain and to review the play concepts that have inspired exploration activity in this area, a regional synthesis and study of the Gulf province have been performed earlier (Soua and Smaoui, 2008).

The GOT corresponds to a promontory of the African plate that includes the

SE-Sicily. Towards the East and the Southeast, it includes the Cap Bon peninsula, the Maltese and Pelagian Islands (Figure 20). The present day structural architecture of the GOT domain is characterised by complex sub-basins with prolongation of the North-South Axis (NOSA) and of the structures of the adjacent area, associated with deep Upper Miocene depocenters (e.g., Jongsma et al., 1985; Grasso et al., 1999; Messaoudi and Hammouda, 1994; Burollet, 1991).

The tectonic evolution of the GOT province occurred in three main steps, which were controlled by major plate tectonic processes. This stratigraphic framework is represented in Figure 20 where the main depositional environments along a South West to North East transect are synthesized.

Following the breakup of Gondwana and the opening of the Neo-Tethys Ocean and Liguro-Provencal Ocean in Late Carboniferous-Early Jurassic times (e.g. Guiraud, 1998; Morgan et al., 1998; Stampfli and Borel, 2002), several rift basins and grabens were formed along the northern margin of the African plate, GOT province and in the Pelagian domain.

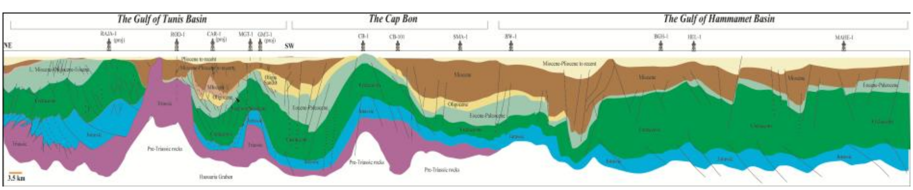



***Figure 20.*** *NW-SE regional seismic section: Gulf of Tunis, Cap Bon peninsula and Gulf of Hammamet domains showing structural styles.*

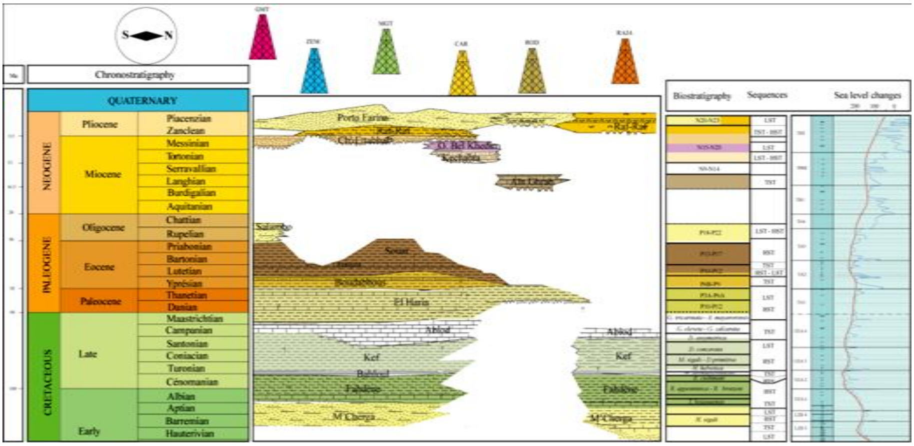



***Figure 21.*** *The different stratigraphic units identified within the Gulf of Tunis.*

Through this time, continental to shallow marine deposits with evaporite intervals characterized the Triassic stratigraphy of the Tunisian margin, while persistent shallow to deep-marine carbonate sedimentation occurs in GOT province (inferred from well data) and Sicily (Bishop, 1975; Patacca et al., 1979; Antonelli et al., 1988; Bishop and Debono, 1996). The main steps are: (1) Middle Jurassic-Early Cretaceous, (2) Late Cretaceous-Miocene and (3) Late Miocene-Recent and they are detailed in Soua and Smaoui (2008).

## Exploration History in the Gulf of Tunis

Oil exploration in the Offshore Gulf of Tunis dates back to the 1970s with the first well drilled in 1973 (MGT-1). Exploration continued in the offshore area from the '70s to the mid-'90s. In this period, exploration was mainly focused on Tertiary limestones as well as sandstones reservoirs (Figure 21). Carbonate rocks, ranging from Triassic to Oligocene, have been penetrated both in the offshore GOT and in the periphery (Cap-Bon peninsula, Utique). The lack of seal, reservoir, together with a poor hydrocarbon charge delineate absence of commercial hydrocarbon accumulations in the GOT where only minor oil shows (oil having been extracted from sample) have been reported in late

Cretaceous rocks in the northern and central GOT (Figure 22). However, interesting oil shows have been encountered in the Eocene section of wells drilled along the GOT (Figure 22).

## Failure of the Classical Exploration Methods

In the GOT province and surrounding regions, several petroleum systems have been recognized. The essential geologic elements (sources, reservoirs, and seals) as well as possible traps of these petroleum systems are shown in Table 1. Two regional Seismic Cross-Scetions were established in this work to show the structural and sedimentary evolution within this province. The main characteristics of these plays are summarized in the following.

***Table 1.*** *Summary of the existing wells, objective source rocks and possible new source rocks inferred from paleogeographical OAE's maps and data provided from drilled wells.*

| Wells | Known Source Rocks | Possible OAE's | Proposed Source Rocks | Petroleum Systems |
|---|---|---|---|---|
| **GMT-1** | Bou Dabbous (Eocene) | C/T (OAE-2)<br>Albian OAE's 1b-d<br>Bedoulian (early Aptian: Selli Event)<br>Late Hauterivian (Faraoni Event)<br>Valanginian (Weissert Event) | Bahloul<br><br><br>LH M'Cherga<br>V M'Cherga | Abiod-SR |
| **MGT-1** | Bou Dabbous<br>Bahloul<br>Fahden | C/T (OAE-2)<br>Albian OAE's 1b-d<br>Bedoulian (early Aptian: Selli Event)<br>Late Hauterivian (Faraoni Event)<br>Valanginian (Weissert Event) | Bahloul<br>Fahden<br>Aptian<br>M'Cherga | Abiod-SR<br>Or Tertiary reservoirs |
| **CAR-1** | Bou Dabbous | - | | |
| **ROD-1** | - | Carnian OAE's | Carnian | Triassic |
| **ZEM-1** | Bou Dabbous<br>Bahloul<br>Fahden | C/T (OAE-2)<br>Albian OAE's 1b-d<br>Bedoulian (early Aptian: Selli Event)<br>Late Hauterivian (Faraoni Event)<br>Valanginian (Weissert Event) | Fahden<br>Aptian<br>M'Cherga<br>M'Cherga | Abiod-SR |
| **Raja-1** | Bahloul<br>Fahden | C/T (OAE-2)<br>Albian OAE's 1b-d<br>Bedoulian (early Aptian: Selli Event)<br>Late Hauterivian (Faraoni Event)<br>Valanginian (Weissert Event) | Bahloul<br>Fahden<br>Aptian<br>M'Cherga<br>M'Cherga | Late Cretaceous Reservoirs-SR |

1. Upper Cretaceous petroleum system characterizes the vast majority of the adjacent Cap-Bon peninsula and Pelagian Domain as well as the eastern and southern Tunisia (e.g., Bishop, 1988; Ben Ferjani et al., 1990; Bédir et al., 1996; Bishop and Debono, 1996; Klett, 2001).

   Cretaceous sandstones (M'Cherga Fm), inner shelf and shelf margin carbonates (Serj equivalent Fm.) and fractured chalky limestones (Abiod Fm) in both stratigraphic and faulted traps, sealed by Maastrichtian-Paleogene shales and marls of the El Haria Fm, do have been charged during the Miocene-Pliocene from Albian and Cenomanian-Turonian, respectively Lower Fahdene (Moualha mb) and Bahloul Fm source rocks.

2. The Tertiary petroleum system may be constituted of deep water micritic carbonates deposits of Bou Dabbous (Marathon discovery in the nearby Belli Field) and sealed by Middle-Upper Eocene shales (Souar Fm) do have been charged also during Miocene-Pliocene from Lower Eocene marls and mudstones (Bou-Dabbous Fm) (e.g., Bédir et al., 1996; Bishop and Debono, 1996; Macgregor and Moody, 1998; Klett, 2001; Caline et al., 2003).

   In the adjacent Gulf of Hammamet, Oligocene to Miocene reservoirs includes the Ketatna limestones, the Aïn Grab limestones, and Birsa sandstones (Figure 20). However, the existence of the Langhian Ain Grab Fm is evident, since its presence in ROD-1 well, within the GOT domain (Figure 22).

   Since Bou Dabbous Fm is already immature, the tertiary petroleum system may be constituted of the Cretaceous Source rocks (Moualha and Bahloul Fms) and of Bou Dabbous, Reineche, Korbous, Fortuna and Ain Grab reservoirs sealed respectively by Souar and Oued Belkhedim Fms. One must understand that this study is due to a classical petroleum system reconstruction.

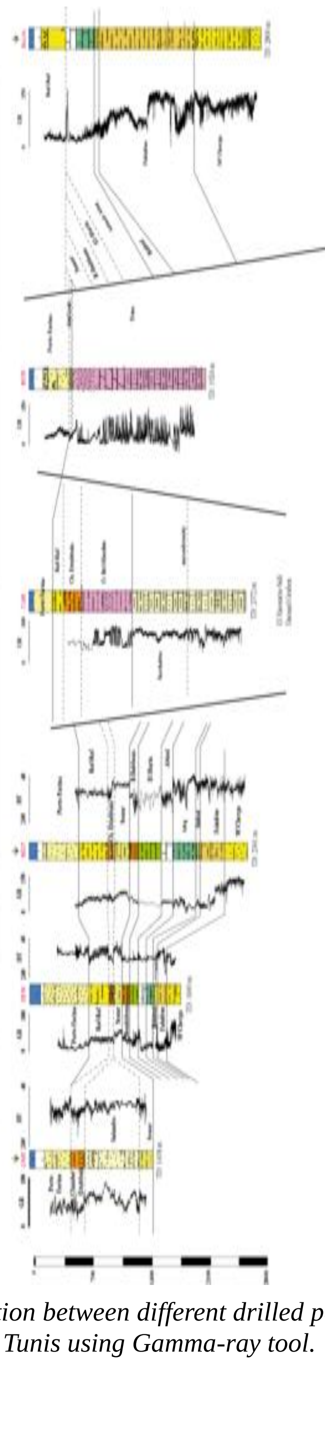
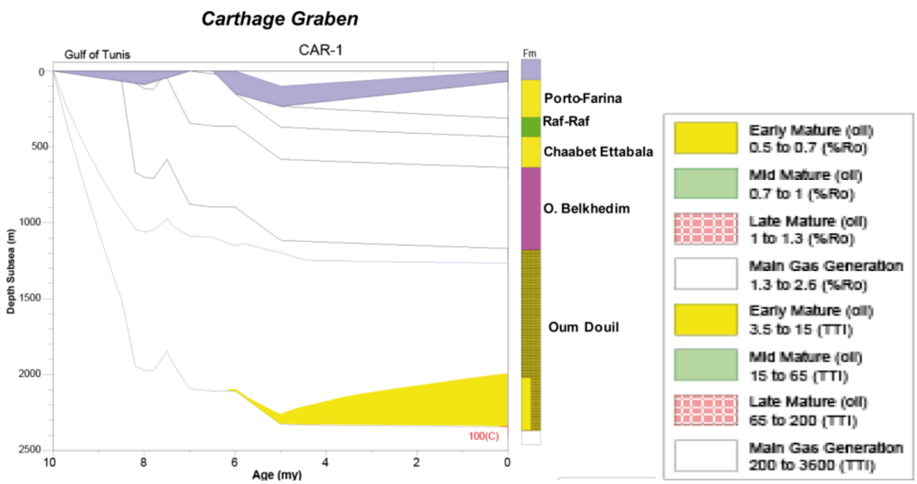


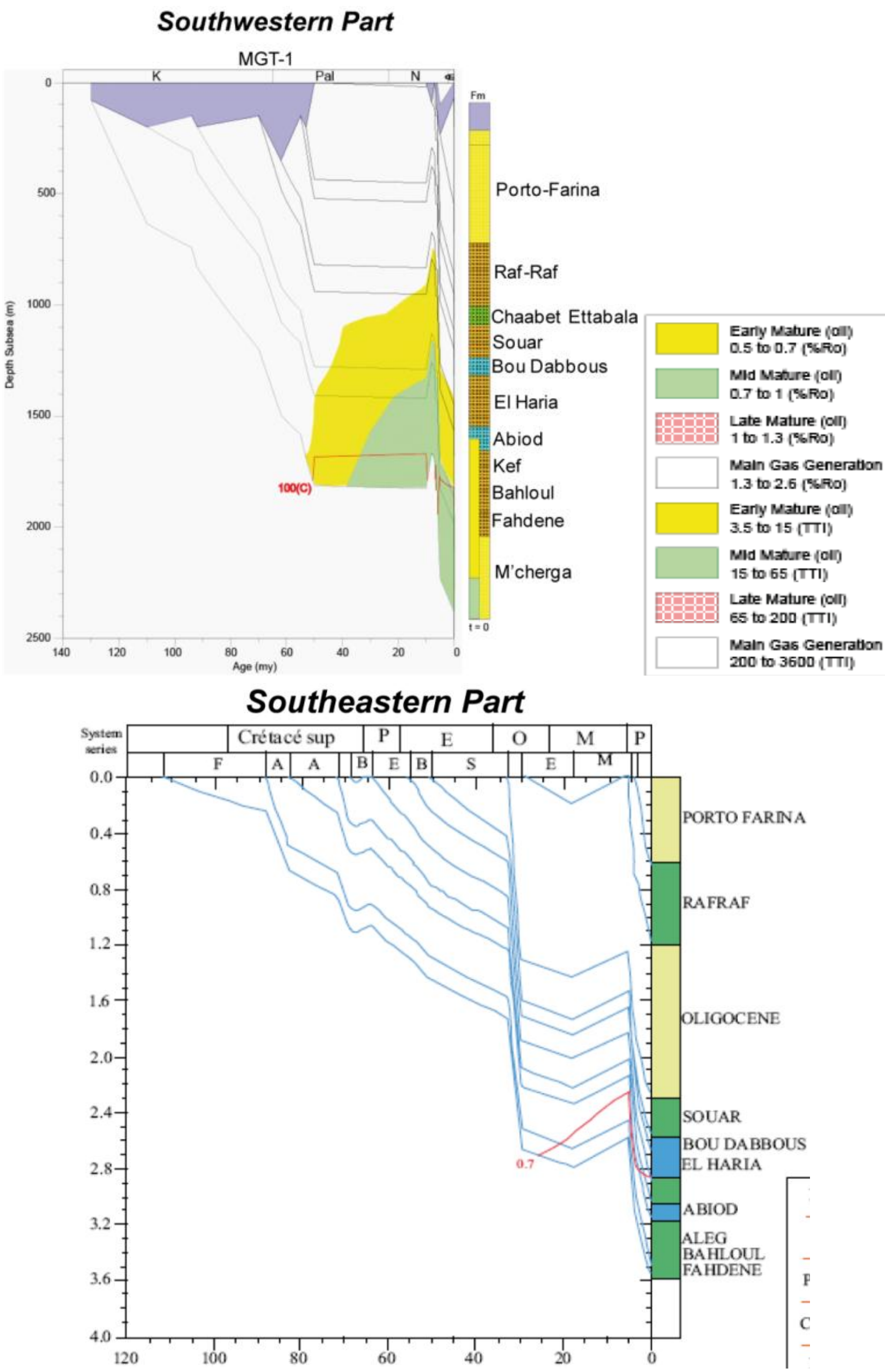

***Figure 22.*** *Tentative correlation between different drilled petroleum wells in the Gulf of Tunis using Gamma-ray tool.*

## 2.5.3 An Application of the New Concept Presented in this Paper in Order to Optimize the Exploration Procedure

### Burial History

The Burial history diagrams (Figure 23) were generated by using the BasinMod 1D software available at ETAP for the six (06) penetrated wells in the Gulf of Tunis (Figure 22). In this section, petroleum systems, burial history and sedimentation rate were calculated using the same software.




Southwestern Part
MGT-1
K
Pal
N
Fm
Depth Subsea (m)
0
500
1000
1500
2000
2500
140
120
100
80
60
40
20
0
Age (my)
t = 0
100(C)
Porto-Farina
Raf-Raf
Chaabet Ettabala
Souar
Bou Dabbous
El Haria
Abiod
Kef
Bahloul
Fahdene
M'cherga
Early Mature (oil) 0.5 to 0.7 (%Ro)
Mid Mature (oil) 0.7 to 1 (%Ro)
Late Mature (oil) 1 to 1.3 (%Ro)
Main Gas Generation 1.3 to 2.6 (%Ro)
Early Mature (oil) 3.5 to 15 (TTI)
Mid Mature (oil) 15 to 65 (TTI)
Late Mature (oil) 65 to 200 (TTI)
Main Gas Generation 200 to 3600 (TTI)
Southeastern Part
System series
Crétacé sup
P
E
O
M
P
F
A
A
B
E
B
S
E
M
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
120
100
80
60
40
20
0
0.7
PORTO FARINA
RAFRAF
OLIGOCENE
SOUAR
BOU DABBOUS
EL HARIA
ABIOD
ALEG
BAHLOUL
FAHDENE

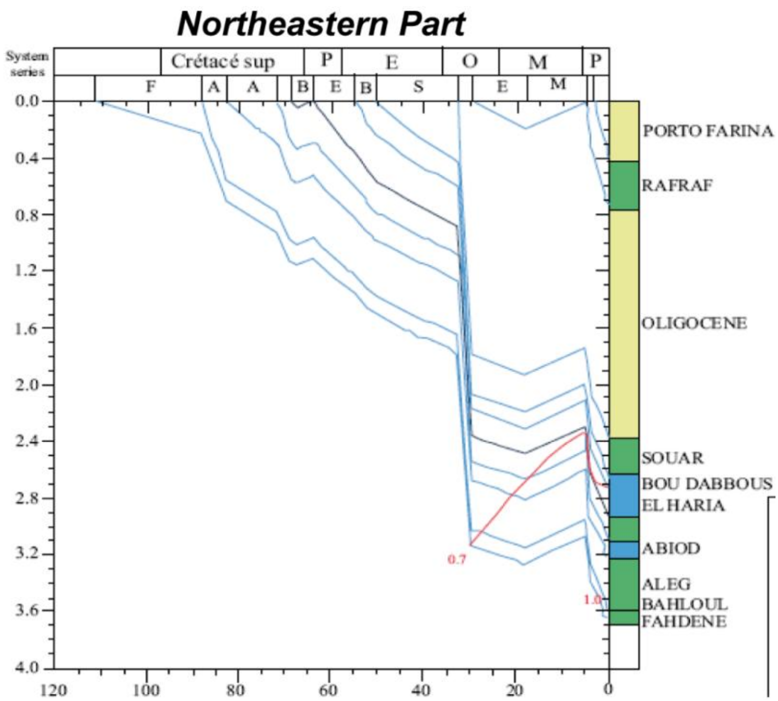



***Figure 23.*** *Burial histories of four drilled wells in the Gulf of Tunis (after Soua and Smaoui, 2008).*

## Main Events

The early Cretaceous to recent burial history of the Gulf of Tunis wells is characterized by several main events as follows:

The south western part of the Gulf of Tunis (Figure 19) well thermal history was constructed by applying a geothermal gradient of 2.5 ℃/100m and 20 ℃ for the surface temperature.

- The Middle to upper M'cherga Formation reached maturity at early Paleocene, at the present time it is still in the early to late stage of oil generation.
- The North eastern part of the basin wells thermal history was constructed

by applying a geothermal gradient of 2.5 ℃/100m and 20 ℃ for the surface temperature.

### Heat Flow

The present heat flow is determined from the temperature measurements (borehole temperature BHT) in the recorded well depth (from each final geological report). The current heat flow obtained for the MGT-1 well is 70 $mW/m^2$.

### The Choice of the Source Rock

In ancient studies, classical source rocks were used. We note the Cenomanian-Turonian Bahloul source rock Fm and the Albian Fahden Fm for Cretaceous section and the early Eocene Boudabbous source rock for tertiary petroleum system. These source rocks are mostly used in hydrocarbons prospection. By using the concept of "Oceanic Anoxic Events" and specially those which occurred during Mid-Cretaceous (Figure 3) three (03) other source rocks are available which are:

- the Late Hauterivian M'Cherga Formation (Faraoni Event).
- the Valanginian M'Cherga Fm (Weissert Event).
- the Bedoulian (early Aptian) M'Cherga (Selli Event).

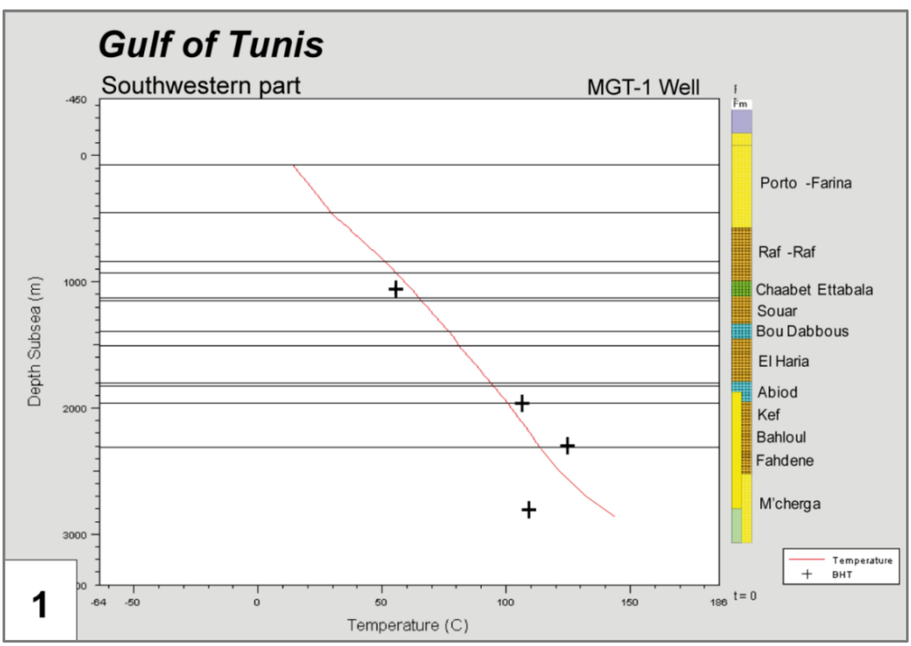
Soua (2013) showed the existence in the Gulf of Tunis of the Faraoni Event (late Hauterivian) using chemostratigtaphic tool the Th/U, U and Th as proxy for recording the event. In this case, we choose the late Hauterivian level as a source rock (M'Cherga) (Figure 11).

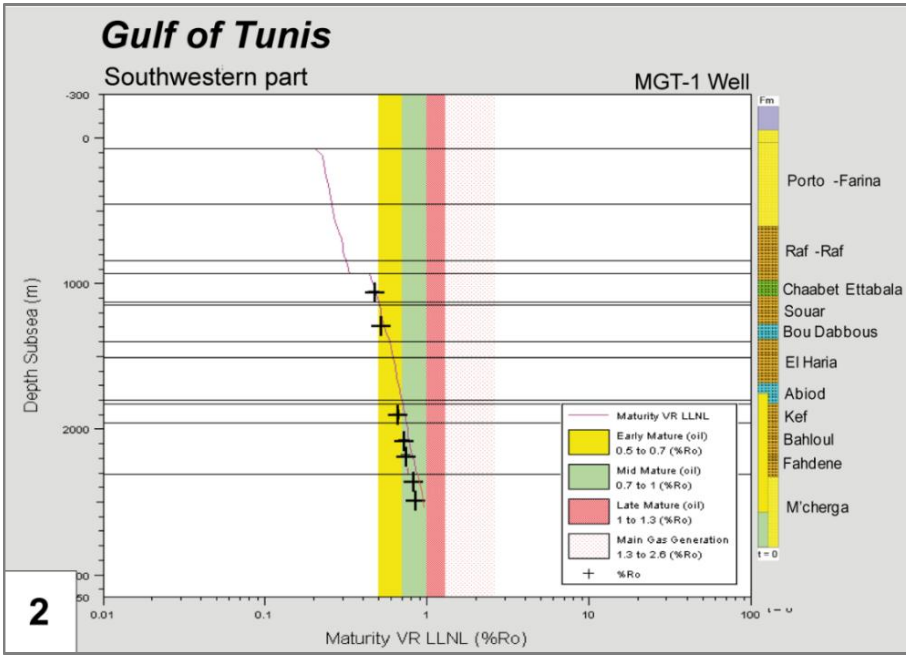
### Maturity Calibration

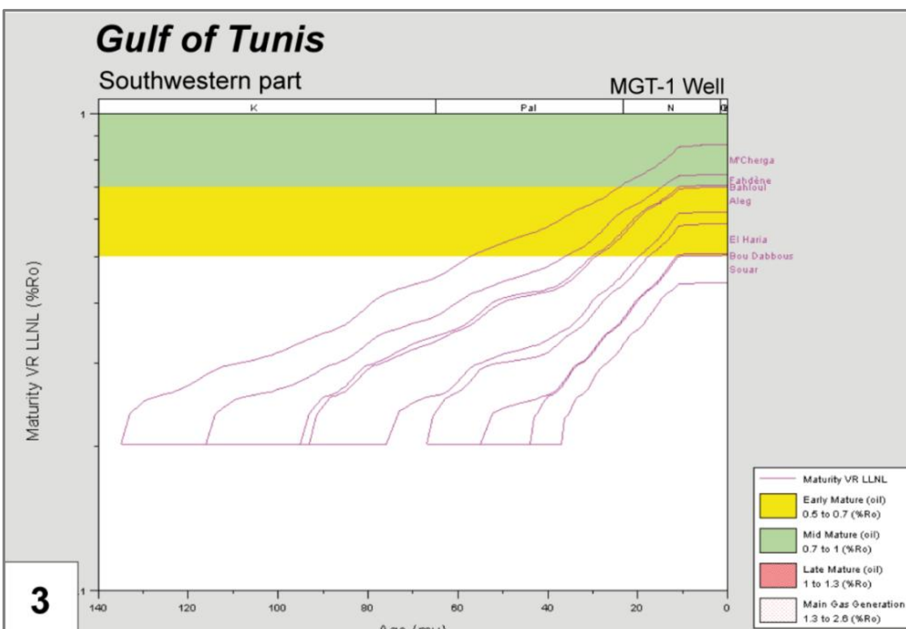
A calibration test of the measured reflectance values of the vitrinite has been calculated on the depth curve versus maturity (Figure 24).

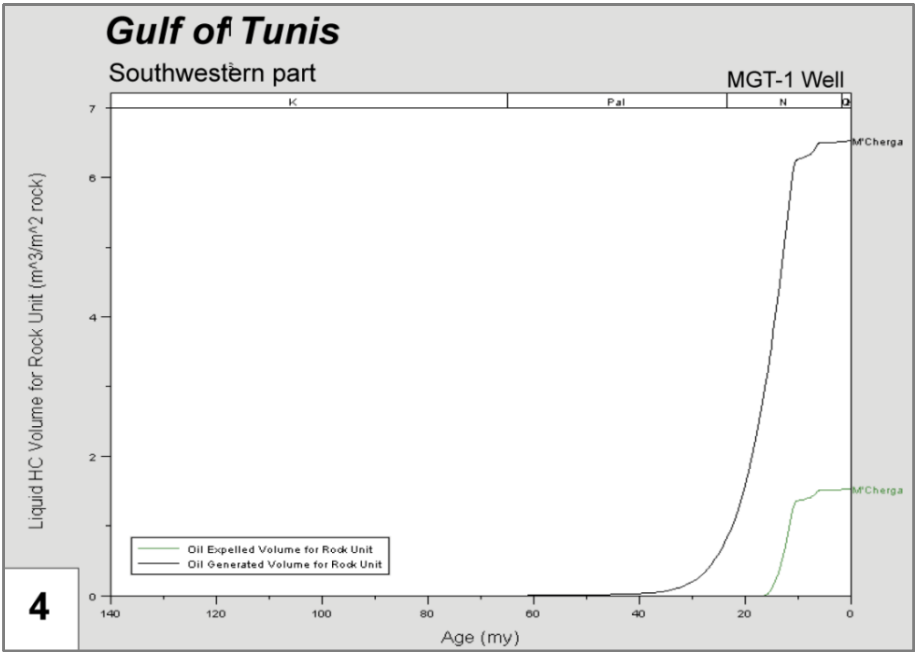
## Generation and Expulsion of Hydrocarbons

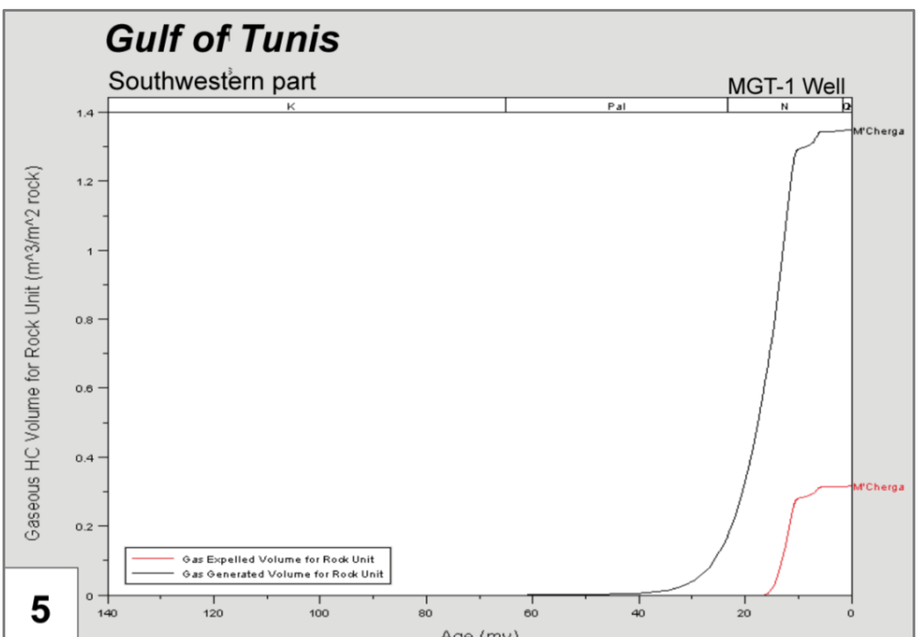
It is assumed from the Figure 24 that M'cherga Formation generated and expelled hydrocarbons (oil and gas). The hydrocarbon generation began at 62 Ma (Danian) and became pronounced since 40 Ma (Bartonian) (MGT-1 well data). The volumes of oil and gas generated per surface unit of rock are 6.5$m^3/m^2$ and 1.35$m^3/m^2$ respectively (Figure 24, see box 6). The expulsion of hydrocarbons began at 17 Ma (Burdigalian). The volume of oil and gas expelled per surface unit of rock are 1.4$m^3/m^2$ and 0.32$m^3/m^2$ respectively (Figure 24). The volume of oil in place, determined from the ratio curve of cumulative volumes of hydrocarbons is 1.4 $10^{-2} m^3/m^3$ (Figure 24). The volume of gas is assumed to be 3 $10^{-3}$ $m^3/m^3$ (Figure 24).




2
Gulf of Tunis
Southwestern part
MGT-1 Well
Depth Subsea (m)
Maturity VR LLNL (%Ro)
Porto -Farina
Raf -Raf
Chaabet Ettabala
Souar
Bou Dabbous
El Haria
Abiod
Kef
Bahloul
Fahdene
M'cherga
Maturity VR LLNL
Early Mature (oil) 0.5 to 0.7 (%Ro)
Mid Mature (oil) 0.7 to 1 (%Ro)
Late Mature (oil) 1 to 1.3 (%Ro)
Main Gas Generation 1.3 to 2.6 (%Ro)
%Ro


3
Gulf of Tunis
Southwestern part
MGT-1 Well
K
Pal
N
Maturity VR LLNL (%Ro)
Age (my)
M'Cherga
Fahdène
Bahloul
Aleg
El Haria
Bou Dabbous
Souar
Maturity VR LLNL
Early Mature (oil) 0.5 to 0.7 (%Ro)
Mid Mature (oil) 0.7 to 1 (%Ro)
Late Mature (oil) 1 to 1.3 (%Ro)
Main Gas Generation 1.3 to 2.6 (%Ro)


Gulf of Tunis
Southwestern part
MGT-1 Well
K
Pal
N
Liquid HC Volume for Rock Unit (m^3/m^2 rock)
M'Cherga
M'Cherga
Oil Expelled Volume for Rock Unit
Oil Generated Volume for Rock Unit
4
Age (my)
140
120
100
80
60
40
20
0


Gulf of Tunis
Southwestern part
MGT-1 Well
K
Pal
N
Gaseous HC Volume for Rock Unit (m^3/m^2 rock)
M'Cherga
M'Cherga
Gas Expelled Volume for Rock Unit
Gas Generated Volume for Rock Unit
5
Age (my)
140
120
100
80
60
40
20
0

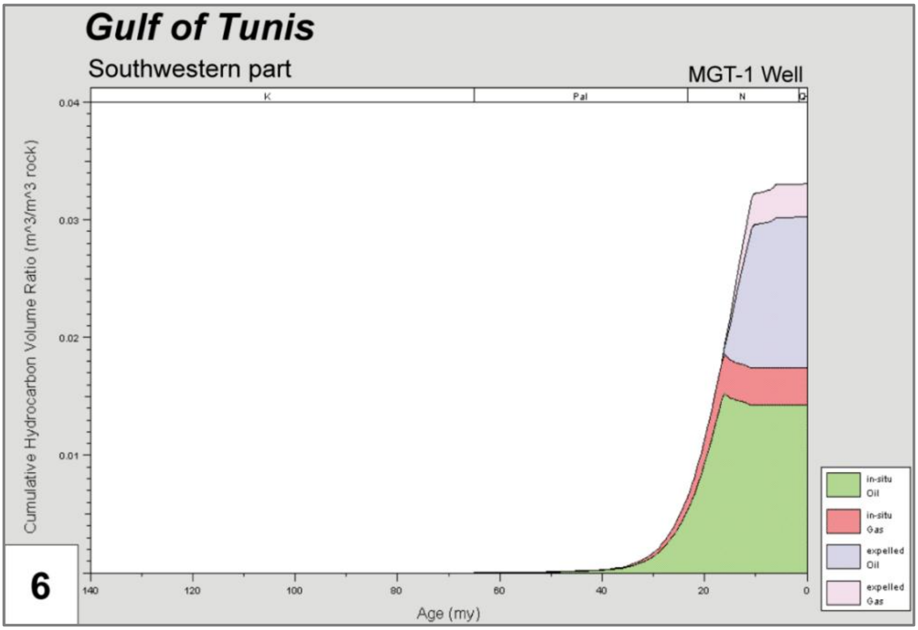



***Figure 24.*** *Basin modeling of the existing wells in the Gulf of Tunis (MGT-1). (1) Thermal calibration, (2) Maturity calibration, (3-6) generation and expulsion model for hydrocarbons from the late Hauterivian anoxic level (Faraoni Event) of the M'cherga Formation.*

## Generation and Expulsion of Hydrocarbons Maps

### *Hydrocarbon Generation*

The oil generation curve shape of the M'cherga source rock shows an increase in oil volume generated by a unit of rock, with a south-north trend. Indeed, the most important values are observed to the north, where volumes generated may exceed $80m^3/m^2$. Poor values are observed near GMT-1, ZEM-1 and MGT-1 well structures.

The gas generation from the late Hauterivian source rock shows values decreasing progressively towards the east (18 to 24 $m^3/m^2$, example: ROD- 1 and CAR- 1) and from the south, it becomes very poor to the west.

### *Hydrocarbons Expulsion*

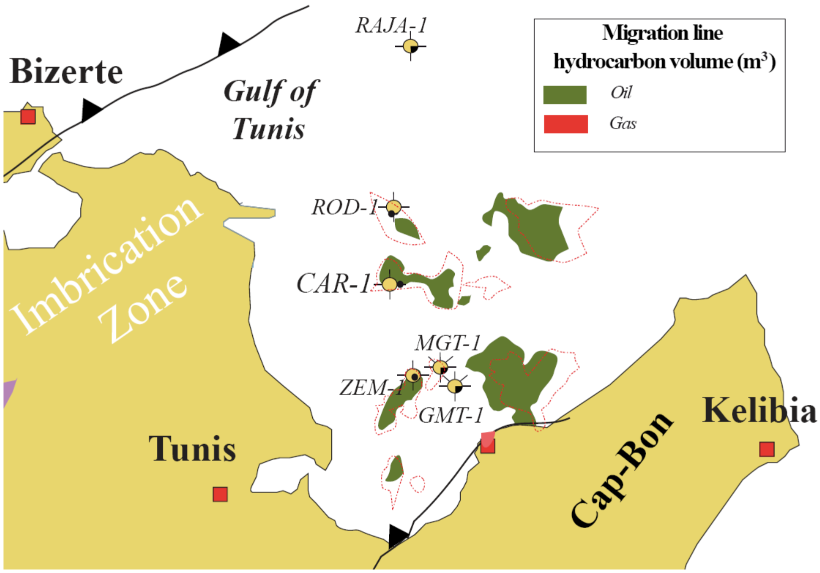



***Figure 25.*** *Oil and Gas pathway migration lines and hydrocarbon volumes generated from the late Hauterivian (Faraoni level) of the M'cherga Formation. Green colour (oil) and red colour (gas). Note that the positions of the drilled wells are located near or off structures explaining the failure to producing hydrocarbons from these boreholes.*

The oil expulsion from M'cherga source rock (late Hauterivian) shows significant values of volumes of expelled oil in the north-western part that reach $66m^3/m^2$ (rock unit). These values decrease going towards the East. Since then, the expulsion edge of hydrocarbons has advanced to the Southeast.

### *Oil and Gas in Place*

Oil volume distribution map generated for the M'cherga source rock shows that the largest volumes are located near CAR-1 well area as they reach the $19m^3/m^2$. They decrease remarkably to the south. The west of the northern part shows values exceeding $15m^3/m^2$ rock. Gas retained volume distribution map generated for the same source rock shows volumes reaching $40m^3/m^2$.

***Secondary Pathway Migration***

Secondary oil pathway migration from the late Hauterivian source rock to the Abiod reservoir where accumulation occurred is shown in the figure 25. The calculated total area of traps is 297.72 $km^2$ and actual oil filled area calculated is 266.8 $km^2$. For the gas pathway migration, we denote an area of about 225.8 $km^2$ which has been filled with gas (Figure 25).

## 2.6 Comparison Between Prospect-Related to Seismic Interpretation and Prospect-Related to Basin Modeling

In comparison between older seismic-related prospect generation (drilled prospects where existing drilled wells failed to produce hydrocarbons) and present basin modeling related prospect generation (Figure 25) we denote that location of drilled wells has been generated in wrong geographical positions. This explains clearly the failure of the six wells (Figure 25) in having generated oil and gas potential. These wrong positions are admitted as the principle cause of the failure. These wrong positions are also due to the seismic interpretation which has generated the drilled prospects. The basin modeling connected slightly to the concept of “OAE’s” which revealed the existence of several anoxic levels playing the role of source rocks with important emphasis in terms of oil world reserves (Figure 3). The integration of this concept with the basin modeling knowledge in order to refine calculations helped, thus, to generate new oil and gas filled traps with different sizes.

## 2.7 Geostatistical Tool and Optimizing the Basin Modeling

The basin modeling concept used solely is not sufficient to optimize exploration procedure due to the rapid facies change and the geological complexity of the majority of the sedimentary basins.

A structure model and a facies distribution are among the most important modeling inputs in basin modeling and have crucial impact on the oil generation, migration and accumulation of petroleum. Many techniques had been developed for structural modeling and facies simulation. The geostatistical methods had been proven to be very efficient in such modeling. It offers the possibilities to (1) integrate geological, seismic and well data, (2) take into account the models of spatial continuity and structures of the different input parameters and (3) integrate geological constraints in the estimation and simulation procedures.

Moreover, geostatistical tools can be used to assess spatial uncertainty. The interest of uncertainty analysis in basin modeling is to evaluate multiple models. Often the interpretations by different geologists are quite different, so it is important to study the impact of different geological interpretations which could be integrated into the constrained model procedure. The evaluation of different geological realizations and the associated spatial uncertainties help efficiently in constructing realistic models (Deutsch et al., 2002) which honor the geological interpretation, and the borehole as well as the seismic data at the same time and thus for drilling decision making.

Several different geostatistical methods are available for modeling categorical data like facies including truncated gaussian approach (Doligez et al., 2007; Chihi et al., 2009), indicator simulation (Carle and Fogg, 1996), Object based simulations (Haldorsen and Chang, 1986), Multiple-Point Geostatistics (MPS) methods (Impala; Straubhaar et al., 2011).

The MPS are generally the best used when geologic heterogeneities are too complex and could not be modeled easily with 2-point variograms, like the case for the Gulf of Tunis. MPS require at the same time both hard constraints (well data: LAS) and soft constraints (probability fields derived from seismic data, rotation and scale fields) and thus to reproduce the facies distribution. Multi-point geostatistical algorithm (Strebelle, 2002) requires 2D or 3D training images that characterize the spatial distribution of geological properties, as input for generating multiple facies maps.

This method could be applied in basin modeling to improve the efficiency of the regional exploration procedure within the Gulf of Tunis due to the geological complexity of the basin.

## 2.8 Conclusion

By applying the concept of the "Oceanic Anoxic Events" as a proxy and good tool for source rocks existence, new petroleum systems can be revealed. This is a part of new challenging in the petroleum prospection procedures. Our new technique was applied for the Gulf of Tunis, a tertiary basin which exposes panoply of complex structures (thrusting, grabens, salt tectonics, etc.) in which exploration has been ended since 1990's by drilling six failed wells during more than twenty years. The ancient prospects were generated using seismic reflection interpretations through many surveys. By knowing the distribution of the Mesozoic black shale events (Toarcian, Early Hauterician, Early Aptian, Albian, Late Cenomanian-early Turonian) new source rocks which have been proved successful worldwide and nearby are identified and selected for a basin modeling exercise.

The Late Hauterivian (Faraoni Event) is chosen as a source rock for the Gulf of Tunis and integrated within the basin modeling project. Data calibration, burial histories, hydrocarbon generation and expulsion have been used to create the hydrocarbon pathway migration map and new prospects have been generated. However, it is assumed that the basin modeling does not take into account the rapid change of facies and geological complexity of the basin. This is the reason why we recommend the integration of Multiple-Point Geostatistics (MPS) method (among other geostatistical methods) in the basin modeling study in order to improve the model, especially when geologic heterogeneities are too complex like the case of the Gulf of Tunis. It is also assumed that the MPS method allows the better use of seismically derived estimations of facies and other geologic property distributions. These methods can be applied in the basin modeling to improve the efficiency of the regional exploration procedure in addition to the use of OAE's concept.

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