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A Review of Jurassic Oceanic Anoxic Events as Recorded in the Northern Margin of Africa, Tunisia

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Abstract During these last years, considerable attention has been given to Jurassic oil and gas shale in the middle and high latitudes of the northern hemisphere such as the west Europe and Russian platform where the most attractive Jurassic basins are located (e.g. Cleaveland basin, UK; Boulonnais, northern France; Pechora Basin, Moscow Basin, etc). In most petroleum systems which characterize these basins, the Jurassic (mainly the early Toarcian) played the major role in hydrocarbon generation which constitutes 25% of the global reserve of hydrocarbon. Tunisian basins represented by the northern Tunisian trough, the Dorsale and the North South Axis (NOSA) belong to the southern Tethyan margin where northern and central area have recorded the early Toarcian oceanic anoxic event (T-OAE). This short lived (c. 2 Ma) period of anoxia ranges within the whole *Harpoceras serpentinum* Zone which corresponds to deep water environments marked by black shale accumulation. Interestingly, towards the south, the dysaerobic conditions in the Chott basin appear to have begun largely later where the oxygen depletion is assumed to have prevailed during the Callovian, whereas it was limited to the early Toarcian in the Central and Northern Tunisia only a few hundreds of kilometers away. In addition, biostratigraphic and complete geochemical review has been undertaken from published papers and unpublished internal reports to better assess these important source intervals.

Keywords: *Early Toarcian Anoxic Event (T-OAE), Callovian OAE, black shale, Jurassic events, Tunisia*

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1. Introduction

1.1. General Background

The deposition of black shales had been recorded several times through the Phanerozoic over large domains of the ocean floor ([1-29]). During the phanerozoic more than six stratigraphic organic-rich intervals have been recorded: (1) the Silurian, ~430 Ma ago (this interval generated 9% of the world's reserves); (2) the Upper Devonian, ~370 Ma ago (8% of reserves); (3) the Carboniferous/Permian transition, ~295 Ma ago (8% of reserves); (4) the Jurassic, ~145 Ma ago (25% of reserves); (5) the late Hauterivian ~133 Ma (Neocomian, 2.5% of reserves); (6) the mid-Cretaceous, ~95 Ma ago (29% of reserves); and (7) the Oligocene/Miocene transition, ~23 Ma ago (12.5% of reserves) (e.g. [30,31]).

Thick Toarcian black shales sections in the northern tethyan and boreal domains had been described (Figure 1) (e.g. [2,27,32-38]). These discoveries opened new exploration challenges regarding the deposition of these black shales, and evolved the knowledge of their depositional mechanisms within the oil industry and the academic institutions since this time-interval was a promising period in the earth history.

Hence, in the West European platform and the Northern Tethyan margin (e.g. Cleveland Basin, UK), the Toarcian organic-rich black shale accumulation (Figure 1) was controlled by semi-restricted basins surrounded by shallow shelf seas [27] with variable water restriction degrees [39]. These black shales experienced in general short-lived period with a total duration evaluated between 200 and 900 kyrs ([27,39,40]).

Late Jurassic is also known as a period of major black shale accumulation in middle and high latitudes (e.g. Cleveland Basin, UK; Boulonnais, northern France; Pechora Basin, Moscow Basin, Russian platform) ([41-45]).

The worldwide reported data suppose that the early Toarcian is generally a period of global warming which recorded both mass extinction events and enhanced organic carbon burial ([27,34,35,36,38,46]). The described enhanced organic carbon burial through the early Toarcian OAE includes generally a negative and carbon isotopic excursion (Figure 2) analyzed on both carbonate and organic matter [37]. Measured carbon isotopic values of organic matter are found generally under -30‰ [37], whereas, background values are generally placed within the -26 to -27‰ interval [47]. Reported Late Jurassic black shale accumulation (e.g. [27] and reference therein) in middle and high latitudes (e.g. Kimmeridge clay, Boulonnais and Kashpir oil shales) seems to be occurred within the Kimmeridgian through Tithonian time interval.

However, recorded total organic carbon values (TOC) from T-OAE black shales range globally from 0.60 wt%; to 19 wt% [47] indicating variation in redox conditions, eustatic level and primary productivity.

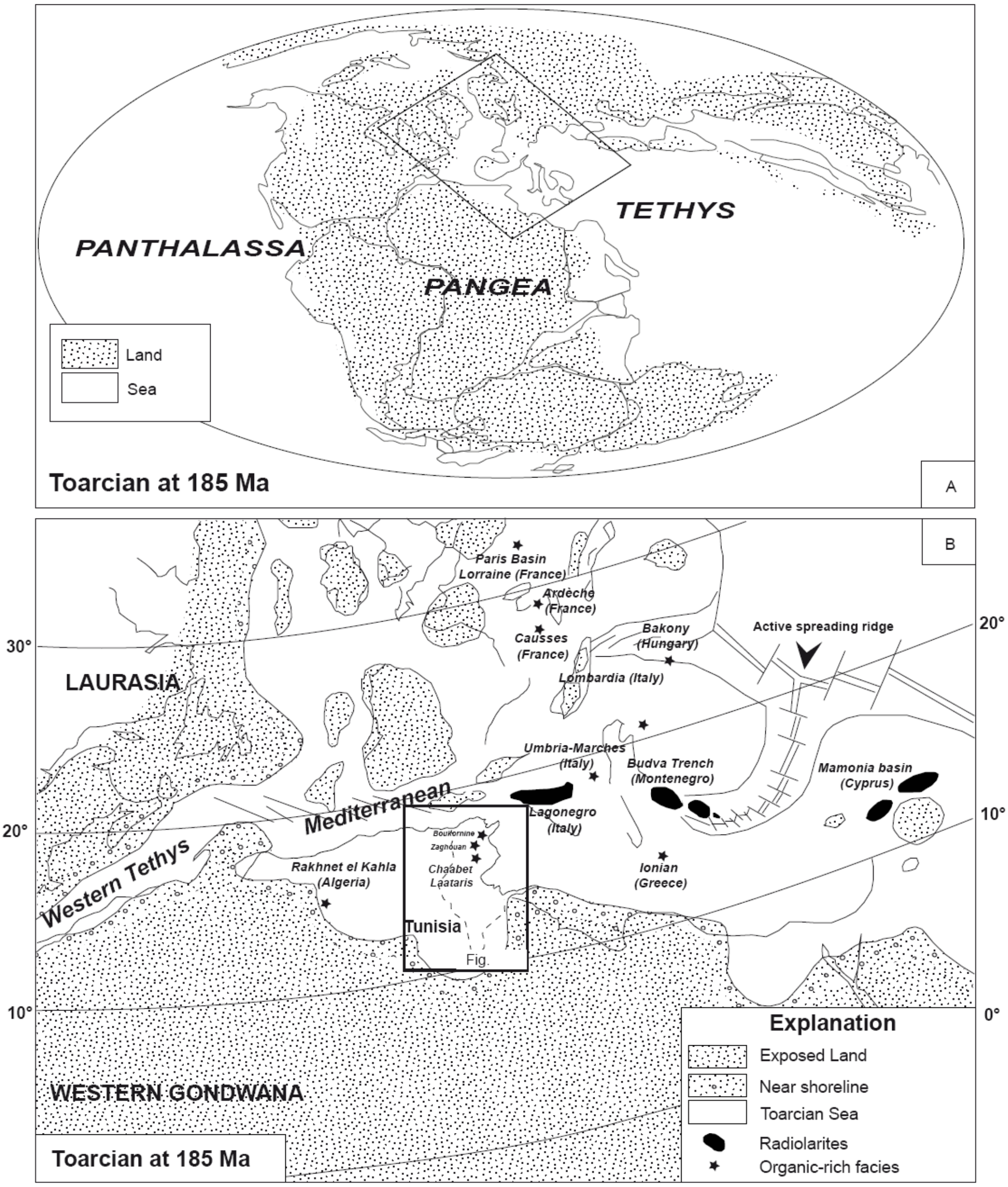

Figure 1. Paleogeographical reconstruction during the Toarcian (ca. 185 Ma), A. position of the southern Tethyan margin among the Tethys and Panthalassa oceans, B. Organic rich black shale accumulation during the early Toarcian in the Tethyan margins. The box outlines Tunisia in which are marked three organic-rich Toarcian sections (Bou Kornine, Zaghouan and Chaabet El Attaris). Paleogeographical reconstructions adapted from ([27,32,37])

1.2. Oceanic Anoxic Events during the Jurassic and Organic-rich Deposits in Tunisia

This global event which occurred in the early Toarcian had been also noted in Tunisia [48] but no massive work on the nature and mechanism leading to such accumulation of organic matter had been undertaken. Interesting is that the southern Tunisia (southern Chott basin through Gulf of Gabes) is characterized by Callovian organic-rich black shale accumulation, Smida Formation, which constitute an excellent source rock in the area.

2. Regional Geological Background

The Triassic-Quaternary section covers generally the main Atlas outcropping series establishing important lateral changes constrained by paleogeographic differentiations during the Jurassic-Cretaceous period. Alternatively, three main paleogeographic domains could be illustrated: (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 and (3) the central Tunisian platform series which seemed to be deposited in proximal basin setting. The Figure 3 shows that Jurassic strata encompassing the organic rich Toarcian black shale accumulation are cropping out in the northern area from Jebel Ammar through Thuburnic, along the Dorsale from Jebel Boukornine of Hammam Lif, near Gulf of Tunis through Jebel Bou Kornine of Fahs, and along the North South Axis from Loridga through Khechem El Kalb. These black shales are labeled Chaabet El Attaris Formation [49]. This sedimentation pass laterally towards the Saharan platform domain into neritic carbonates, evaporates and clastics ([50,51,52]).

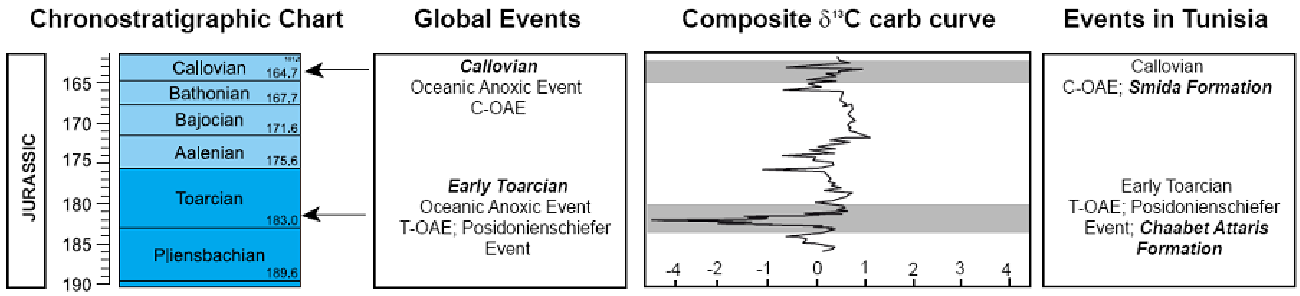

Figure 2. The main Oceanic Anoxic Events (OAE's) discussed in the text and identified worldwide as well as in Tunisia, a tentative correlation with the events which occurred in Tunisia during the Mezosoic (Jurassic – mid-Cretaceous). Timescale, global events and carbon isotopic data are compiled from [37]

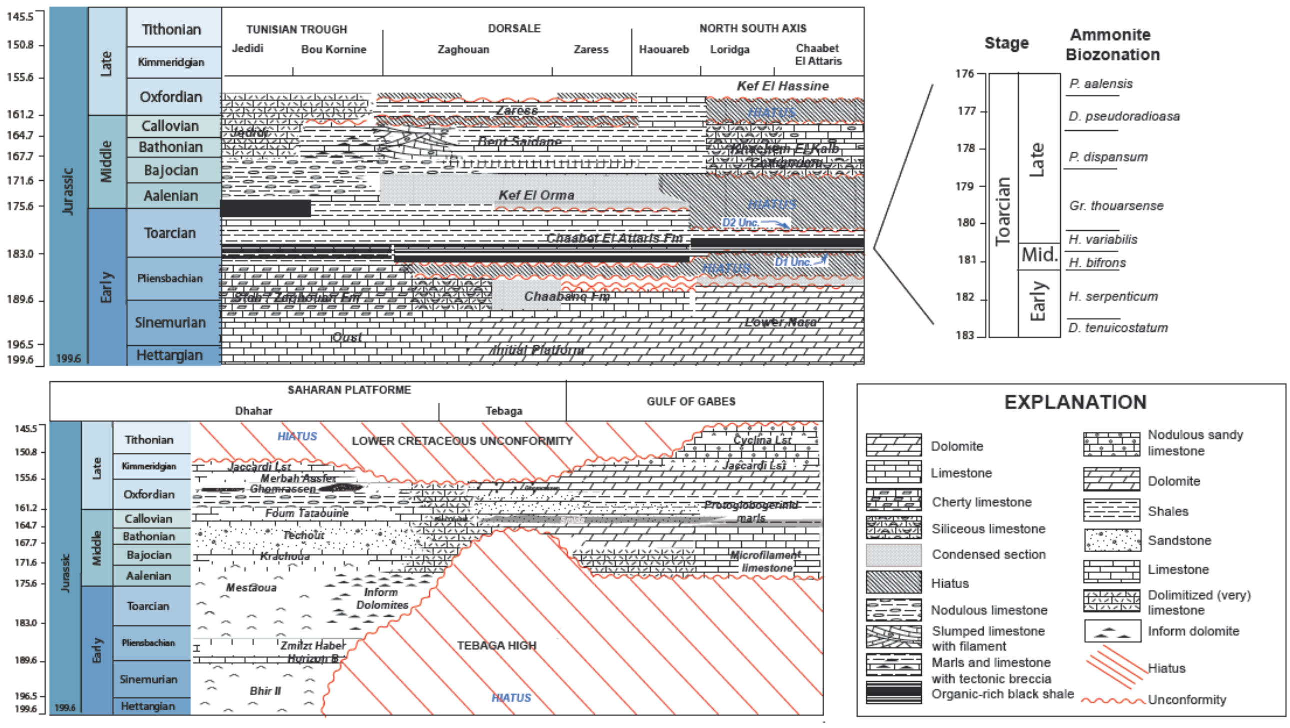

Figure 3. Lithostratigraphic reconstruction of the Jurassic system in different basins of Tunisia discussed in the text (Tunisian trough, Dorsale, North South Axis and the Chott basin) and biostratigraphic bioszonation (ammonites) of the Toarcian. The upper box (Tunisian trough, Dorsale, North South Axis) is adapted from [49] and the lower box is adapted from [51]

Alternatively, 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, black shale accumulation has been recorded through the Mesozoic and notably through the Toarcian in the northern margin of Africa (Figure 4). In contrast, paralic to shallow-marine sedimentation occurred along the southern Tunisian margin (e.g. Jeffara basin, Saharan platform, Tataouine basin, etc.., Figure 4). 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 5).

General geological background allowing the distribution of such black shale accumulation will be given in the text.

3. Material and Methods

The review of the Jurassic OAE's occurrences in Tunisia is based mainly on: an analysis of more than 20 Tunisian Jurassic sections and Wireline logs from several petroleum exploration wells penetrating the black shale levels. Gamma-ray amplitudes, Spontaneous Potential, resistivity logs have been analyzed in different anterior studies which will be cited within the text. Isopach maps have been compiled for each OAE level (Toarcian and Callovian) 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 Central Tunisian basins where Jurassic black shales crop out in order to collect more information. Geochemical exploration tools are represented by total organic carbon (TOC) and pyrolysis and have been achieved earlier by [53] and [54]. These data were compiled with biostratigraphy achieved earlier where references will be cited within the text.

4. Jurassic Anoxic Events in Tunisia

4.1. Early Toarcian Anoxic Event (T-OAE)

4.1.1. Distribution and Characteristics of the Organic-Rich Toarcian Strata

During the Early Toarcian, Tunisia was characterised by North-South (N-S) normal faults and N70° to East-West (E-W) senestral strike-slip to normal faults (Figure 4; Figure 6) displaying the general structural scheme as being formed by a northward dipping slope at the southern Tethyan margin, including 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 4).

In central Tunisia, [55] reported that the Jurassic sedimentation in Majoura area, limited to the east by the NS Axis (Figure 5), is controlled by N120 strike slip corridor of Gafsa. The general facies trend was complicated by a complex tectonic palaeorelief configuration which resulted in dislocation into tilted blocks towards the south, individualizing deep half-graben systems towards the North, the NW and the West since the late Sinumerian-Carixian ([49,51,55-61]). This configuration results in strong lateral thickness and facies variations of the early Toarcian strata (Figure 7).

Figure 4. Thickness and facies distribution of the Toarcian anoxic event in Tunisia, data compiled after ([48,49,51,57,66]). Note the position on the map of the A-A', B-B' and C-C' sections (Figs. 6, 9 and 12 respectively)

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 recently defined by [49] and grouped earlier in upper Stah Formation [62] or in the "Marno-calcaires de Bou Kornine" [63] and even in the lower Guemgouma Formation [64] (Figure 3). The thickness distribution of the Chaâbet Attaris Formation in Tunisia is illustrated in Figure 4 (compiled after [48,49,51] and our field measurements, see Table 1). The regional distribution of the four main Toarcian facies types, modified after [49] and [51], is shown in the same Figure 4, which also includes the distinction of an organic-rich and an organic-poor Chaâbet Attaris facies trends. The organic-rich early Toarcian chaabet Attaris exists in three areas, namely in the N (Am, Jde and Jd sections) and NW onshore Tunisia (Thubernic), in the NE (the Dorsale: BKH, R, Z, BS, Zr, Az and BKF sections) and in the Central Tunisia (the N-S axis: Hr, L, Kja, CA and Klb sections). Unfortunately several neighboring drilled wells did not reach the Liassic strata, thus, much information about the Toarcian anoxic event dwell unknown. Rare available well and outcrop data confirm the organic-rich provinces of [48] and [57] (Figure 8), however, the exact boundaries still remain unclear, especially the Gulf of Tunis (Figure 9), Central Tunisia (and Eastern Algeria), Gulf of Hammamet (Pelagian Sea) and neighboring Chaâbet Attaris area, due to the non-penetration of wells to Jurassic section [65]. However, geophysical evidence of the early Toarcian black shale extension are mentioned in Figure 7 which exhibit probable black shale reflectors within half-Graben systems and bordering normal faults. These seismic lines are located westwards the southern part of the NS Axis (see Figure 4 for location of seismic lines and generated cross sections A-A' and B-B').

A comparison with the palaeogeographic map (Figure 4) suggests that the distribution of the organic-rich Chaabet Attaris is restricted to intermediate to medium water depth and may represents the impingement of an OMZ onto the northern margin of Africa (Figure 6) 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 4; Table 1) ([49], p.765). In Jebel Ressas (Figure 5), the upper part of the Stah Formation is also represented by hemipelagic black shales interbedded with finely laminated limestones (10m to 27m). 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% ([51,53,57,66]) (Figure 4). A single 11% TOC value was reported by [53] from the Ali Ben Khelifa well (ABK-1). The vertical distribution of limestone vs. marl in the different localities depends on the position on the palaeoshelf/slope (Figure 6). Generally it acquires more carbonaceous deposition in proximal settings and contrary it becomes marls-dominated in distal settings. Particularly, in Zaghouan (Z), Ressas (R) sections and the surrounding area, [57] noted that the TOC values in calcareous and laminated beds rich in fish skeletons (exhibiting 1 to 2m thick) are locally higher than in surrounding marl/carbonate alternations and varying between 0.3 to 1% (Figure 4).

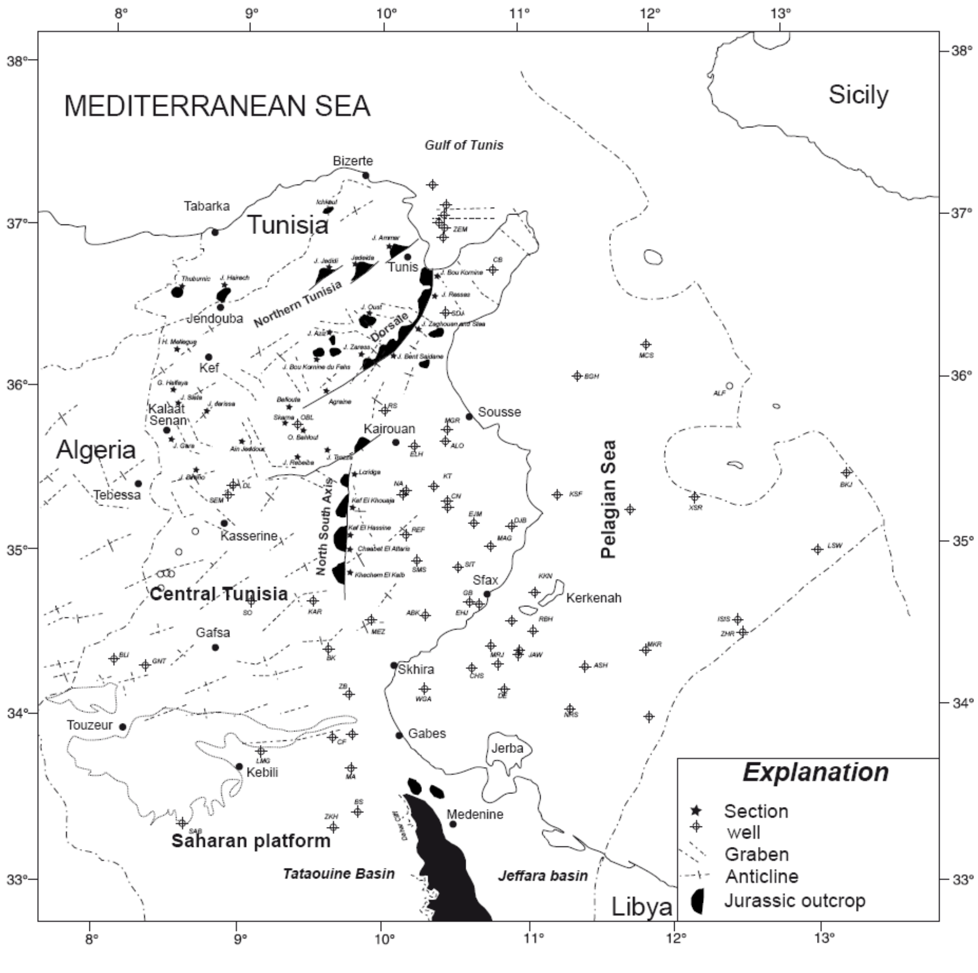

Figure 5. Jurassic outcrop showing early Toarcian black shale accumulation pertaining to the Chaabet El Attaris Formation and main sections discussed in the text. Note the structural control of the Jurassic trend. On the map is also shown the position of wells and half-graben systems

The TOC ranges vary significantly in different localities. Typical ranges observed 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 (Figure 8), (2) interval between 0.3 and 1% (e.g., Bou Kornine Hammam Lif/BKH section; Jebel Aziz/Az section; and Zaghouane area), (3) significantly higher range of TOC (e.g., Chaabet Attaris/CA section and Ali Ben Khlifa well/ABK well) and (4) very poor TOC content lower than 0.2% (Khechem el Kelb/ klb; Kef Hassine/kh; Ressas/R sections) (Figure 4). A close inspection of the Chabet Attaris spiky TOC pattern (Figure 8) 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 (Figure 4) 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 [49]; see Figure 3). 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 Oxygene Minimum Zone (OMZ) ([9,14,23,29]).

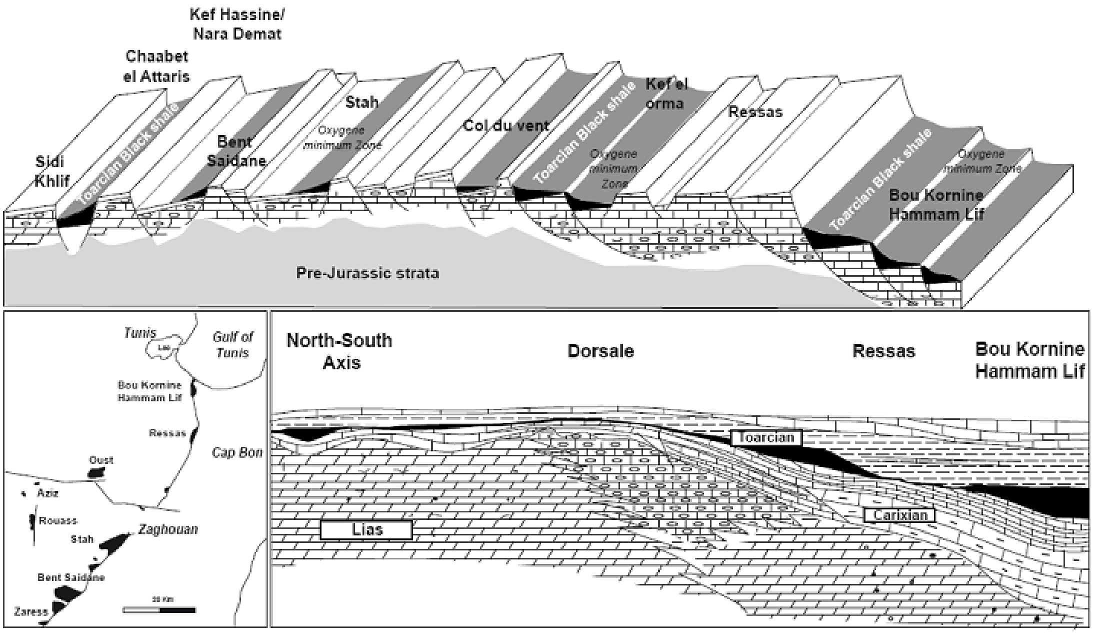

Figure 6. A-A' section of the Figure 4: **o**rganic rich black shales distribution through an Oxygen Minimum Zone Model (OMZ) and Horst & graben structuration which controlled the anoxic deposition during the Toarcian. (modified After [57])

4.1.2. Biostratigraphy and Sequence stratigraphy

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 [66] (Figure 3). This reflects probably the significant input of local upwelling conditions during black shales deposition (e.g., sections CA and BKH; [14,49,57]). Originally, the Toarcian black shales in the Jebel Chaabet Attaris area (section CA) is assumed by [48] and [57] to be included in the *Falciferum* Zone only (reported also in [55]), however, this stratigraphic interpretation was later reevaluated in [53] who by means of biostratigraphy and geochemistry demonstrated that the Chaabet Attaris in this section spans the *Polymorphum* to *Serpentinum* Zones (Figure 3).

Generally speaking, the early Toarcian of the Dorsale area is marked by alternating marls, limestones and laminated black shales containing some phosphate and echinoderm debris, radiolarians, ostracoda and scarce benthic foraminifera ([57]). Hence, several unconformities and erosions levels within the Toarcian had been described by [67] and [62] (Figure 3).

In Jebel Bent Saidane (BS section), [68] described these black shales and situated them between the Domerian and the Middle Toarcian. So, when referring to these authors, the age of these black shales is now well documented as early Toarcian. Their distribution and extension revealed much important than described earlier by [69] since they have been already characterized in the west of the Dorsale [57] and more recently in the Jedidi (jde section) area [66].

In the North-South Axis, these black shales are very well documented especially in the type section Chaabet Attaris (CA section). They are reported as early Toarcian black shales spanning the *Polymorphum* and *Levisoni* zones (synonym of *Serpentinum*) ([48,55,61,70])

According to [61] euxinic conditions in the Gantass/Ali Ben Khlifa area (see Figure 4; Figure 5 for location) are clearly diachronous at both the base and the top. They distinguished a typical facies of black shale and shaly limestone within the Toarcian, representing an organic-rich, condensed section of euxinic sedimentation and suggesting development of restricted circulation with “mini-basins” [66]. This is confirmed by seismic line analysis in the same basin and in the Gulf of Tunis domain (Figure 7 and Figure 9). Generally speaking, the early Toarcian black shales contain dwarfed and impoverished benthic fauna as well as fish impressions, belemnites and ammonites [61]. However, the dysaerobic conditions in the Chotts area described by the same aurhors appear to have begun largely later (Callovian anoxic event, see later in the text) than in central, northeastern and northern Tunisia. Through the southern Chott basin system (Figure 4), the oxygen depletion is assumed to have prevailed during almost all of the Callovian, whereas it was limited to the early Toarcian in the Central Tunisia only a few hundreds of kilometers away. The minimum duration of the organic-rich facies in the Chaabet Attaris area ranges the whole *Harpoceras serpentinum* Zone which corresponds to *ca*. 2 millions years.

The onset of deposition of the Chaabet Attaris Formation in the Central Tunisia (e.g. North-South Axis) generally coincides with the base of the Early Toarcian Trangressive Systems Tract (TST) ([53] p. 46; [55] p. 22, [71,72,73]) of a major third-order Tethyan eustatic sea-level ([71,72,73]).

A similar sequence stratigraphic interpretation was presented by [53]. Particularly in the Chaabet Attaris section the Sequence boundary (SB) is confused with the transgressive surface (TS) due to the generalized underlying discontinuity D1 of [49].

To correlate the TST we used the Gamma ray (GR) and the Spontaneous potential (SP) patterns of the ABK-2 and SMS-1 wells respectively (Figure 8)

The third-order Highstand Systems Tract (HST) overlying the early Toarcian TST along the North-South Axis is generally represented by shallower deposits, such as the shallow marine, bioclastic carbonates of the Guemgouma Formation and equivalent units (e.g., [49,64,68]). In Zaghouane region limestone with belemnite, zoophycos, filaments of the Kef el Orma Formation belonging to the middle Toarcian HST was deposited on the Dorasale and northern Tunisian trough (e.g. BKH and R sections), implying a pronounced diachroneity of this lithostratigraphic unit. Unfortunately, no data have been given in the offshore Gulf of Tunis or the Pelagian Sea or the Mediterranean. The Figure 9 represents NW-SE seismic line and seismic interpretation of the Gulf of Tunis, nearby the Dorsale and the Northern Tunisian trough and we tried inspection about the presence of the early Toarcian black shales within this basin.

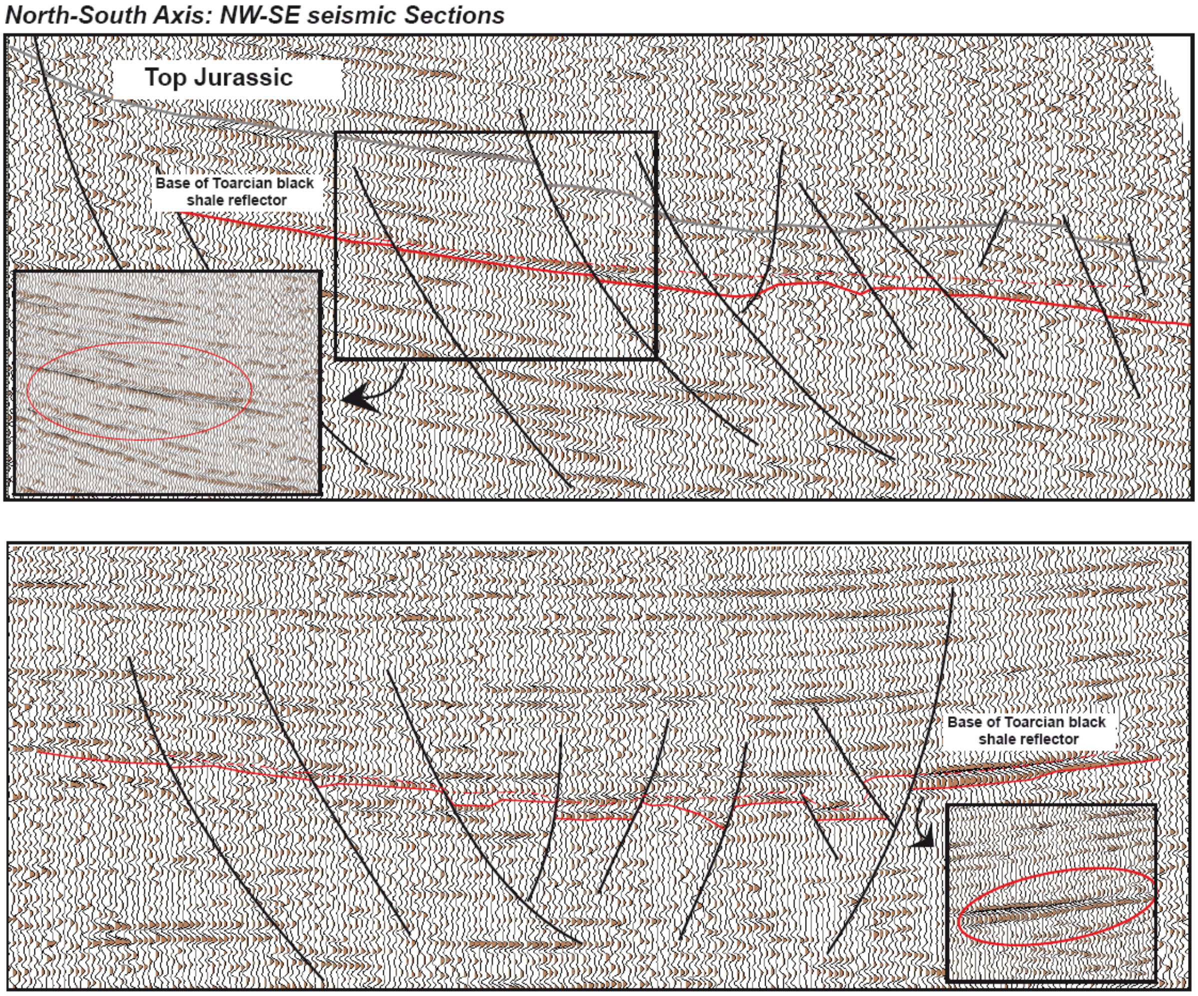

Figure 7. Interpreted Seismic sections located to the west of the North South Axis (NOSA) confirming the existence of the anoxic facies of the Toarcian strata (from [29])

4.1.3. Molecular geochemistry and environment of deposition

Detailed organic geochemical description of the early Toarcian Chaabet Attaris Formation and available early Toarcian source rock data from wells was given by [53], [57,61,66,74]. The organic-rich Cahaabet 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 110gCO_2/gTOC) with TOC concentrations of up to 11%, indicating excellent source rock qualities for oil and gas since modeling studies indicate its burial to a depth of gas window [75]. A sufficient maturity level of these laminated black shales is confirmed by T_{max} values nearly constant between 430 and 440°C (Figure 10). Organic petrological and palynological studies on these sediments indicate kerogen dominated by dark brown to black colour fluorescing organic matter with stick shape and elongate to round yellow to light-yellow amorphous organic matter (AOM) (hemicellulosic continental origin). The higher molecular weight *n*-alkanes reveal a wide range of normal alkanes extending from nC_{20} to nC_{35}. The moderate molecular weight *n*-alkanes and acyclic isoprenoids such as pristine and phytane occur in low concentrations in the early Toarcian Chaabet Attaris black shales. In addition, they display a smooth homologous series within the higher molecular weight *n*-alkane suggesting a significant input of higher land plant organic matter into these sediments. The presence of pristine and phytane in low amounts within these sediments, inferred from the Pr/Ph ratios (1.27) is indicative of a redox environment (anoxic condition) and reflect significant input from the chlorophyll of higher plants, algae and photosynthetic bacteria and from archaeobacteria [76]. This low Pr/Ph ratio in the early Toarcian black shales suggests also an aquatic depositional environment under reducing bottom conditions [77] and it is concomitant with lower Pr/n-C_{17} and Ph/n-C_{18} ratios (0.28 and 0.34 respectively) reflecting probably the marginal and sufficient maturity degree (T_{max}) since the values of these ratios decrease with increasing thermal maturity (e.g. [78,79]).

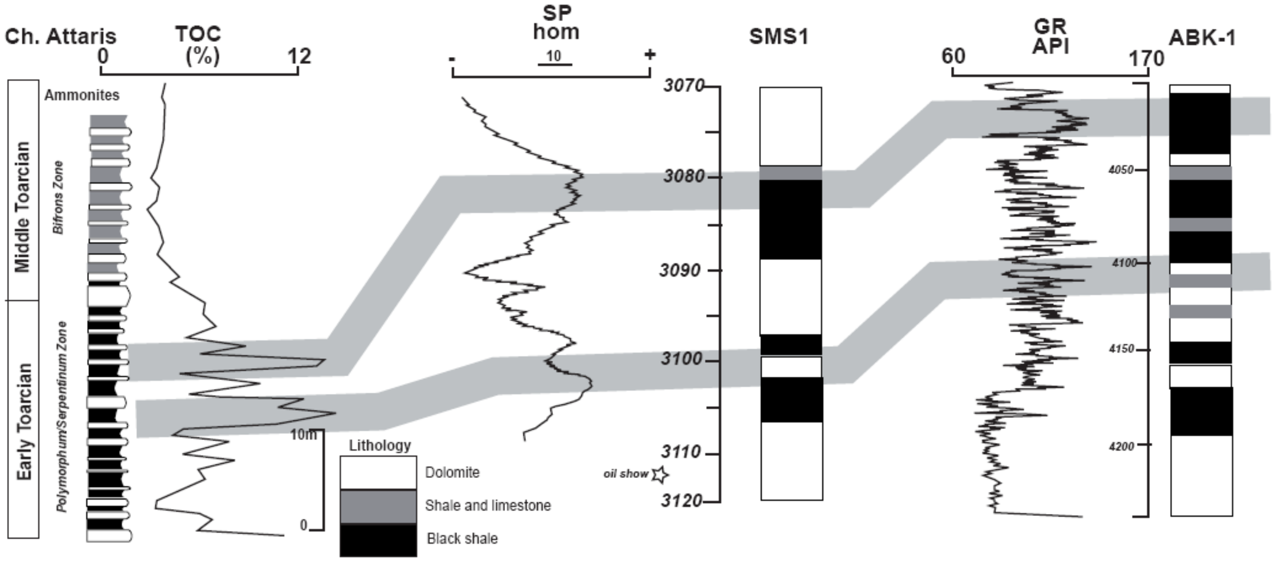

Figure 8. Tentative correlation of the early Toarcian organic-rich strata in Central Tunisia (see Fig. 4 and Fig. 5 for location)

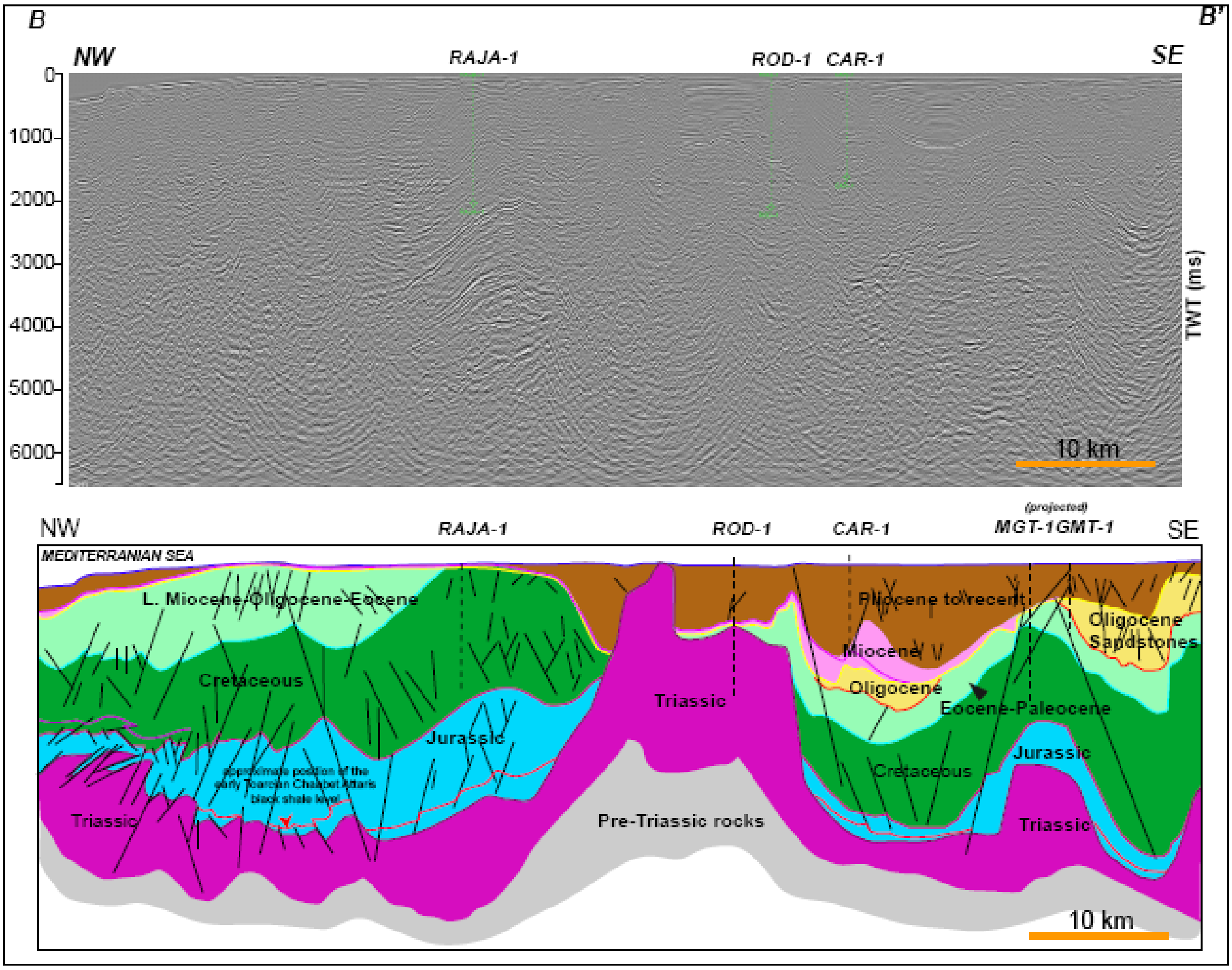

Figure 9. B-B' section: Early Jurassic half graben systems controlling deposition of Toarcian strata on the Tunisian shelf in the Gulf of Tunis. Note the Triassic structural style. Position of early Toarcian strata only approximated. For location, see Figure 4. Interpretation is based mainly on the existing well data and on the NW-SE regional seismic section

4.2. Callovian Anoxic Event (C-OAE)

4.2.1. Distribution and characteristics of the organic-rich Callovian strata

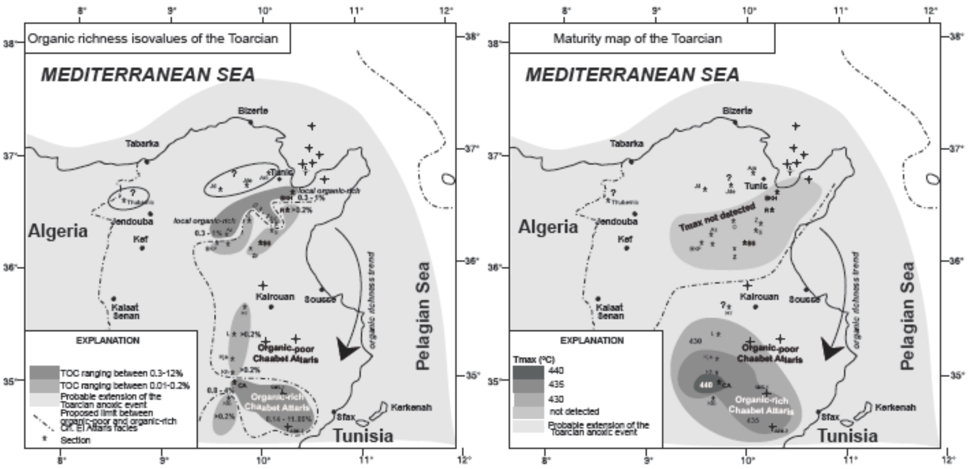

Figure 10. Total Organic Carbon (TOC) and Maturity distribution maps of the Toarcian anoxic facies (T-OAE). Data are provided from [57] and [53]

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 11) and is considered as the equivalent of both the Protoglobigerinids marls and Ramthia limestone Formations ([49,51,54]). The thickness distribution of the Smida Formation in Southern Chotts domain of Tunisia is illustrated in Figure 11. The regional distribution of the main Callovian facies types, compiled after [49,51,54] is shown in the same Figure 11, which also includes the distinction of an organic-rich and an organic-poor Smida facies trends. The organic-rich Callovian Smida is penetrated by several wells in the area. The Figure 12 illustrates the distribution of the organic facies through a NW-SE cross section (C-C') displayed by the Gamma-ray events. However, the exact boundaries still remain unclear, especially the northern Gulf of Gabes and the eastern Algeria.

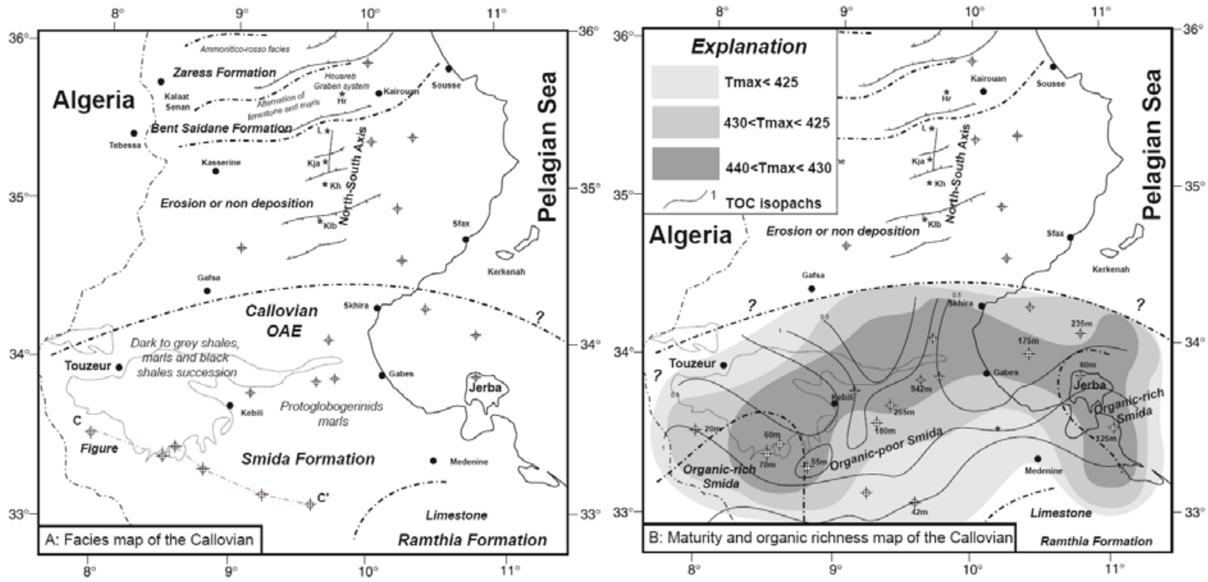

Figure 11. Facies, TOC and Maturity distribution maps of the Callovian anoxic level recorded within the utilized petroleum wells in this study

The Smida Formation constitutes generally tens to hundreds of meters thick (20 to 255m) (see Table 2), with a maximum thickness in Limagess area in the southern Chotts domain (Figure 11). In the Gulf of Gabes (including Jerba Island and Zaouia area), the upper part of the Nara Formation is also represented by grey to dark shales interbedded with fine alternations of marls and argillaceous laminated limestones and constitute 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% ([54,74]) (Figure 11).

The TOC ranges vary significantly in different wells. Typical ranges observed 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 southern Chott basin (Figure 11, Table 2). The low TOC values characterizing some Callovian well sections could be linked to organically leaner location or probably they were deposited underneath the Oxygene Minimum Zone (OMZ) ([9,14,23]).

4.2.2. Sequence stratigraphy

The onset of deposition of the Smida Formation in the Southern Chott and Gulf of Gabes domains generally coincides with the base of the Callovian Trangressive Systems Tract (TST) of a major third-order Tethyan eustatic sea-level ([71,72,73]). Particularly, the transgressive surface (TS) is situated generally underneath the Smida Formation (Figure 3). In order to correlate the TST we used the Gamma ray (GR) patterns of six wells (Figure 12) The third-order Highstand Systems Tract (HST) overlying the Callovian TST along the area is generally represented by shallower deposits, such as the alternations of the dolomites and interbedded anhydrites of the Tlalett Formation and equivalent units (e.g., [51]).

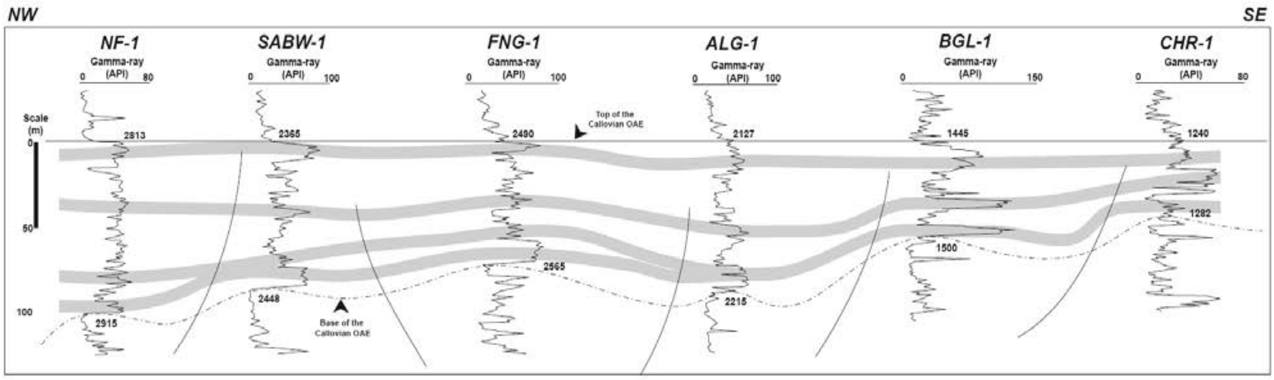

Figure 12. Gamma ray anomaly recorded through the Callovian anoxic level recording the Callovian anoxic event (C-OAE). Tentative correlation within the south chott basin

4.2.3. Molecular geochemistry and environment of deposition

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% ([74,54]), 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°C (Figure 11).

5. Conclusion

The review of the two black shale levels in northern/central (early Toarcian) and southern (Callovian) Tunisia centers on probable highest quality Jurassic source rocks of the country. The deposition of the organic-rich black shales has often been associated with intensification and expansion of an oxygen minimum zone (OMZ) along the southern Tethyan margin. In most cases, the deposition of these organic-rich black shales is accompanied with initial transgression phases resulting from different mechanisms (rifting pulses within distensive regime, tectonic subsidence, tectonics, mixing mechanisms, etc) prior and/or within short-lived severe anoxic events (e.g. T-OAE anoxic and mass-extinction event). Although these anoxic events are recorded within the Chaabet El Attaris and Smida Formations and detected by the mean of geochemistry (total organic carbon) and wireline logs (mainly Gamma ray), unfortunately, no large scale carbon-isotopic investigation or high resolution biostratigraphic analysis have been conducted in order to correlate these worldwide events. Dysoxic to anoxic conditions have been interpreted using molecular geochemical ratios where the presence of pristine and phytane in low amounts, inferred from the Pr/Ph ratios, is indicative of a redox environment and reflect significant input from the chlorophyll of higher plants, algae and photosynthetic bacteria and from archaeobacteria. Although primary productivity also could be interpreted from lithological and faunal content, carbon isotopic investigation has to be undertaken and coupled with chemostratigraphic analysis (major and trace elements) to allow a worldwide correlation between the southern and northern Tethyan margins.

Table 1. Abbreviation codes, thickness and references of Tunisian early Toarcian sections discussed in the text. Th is Thickness

code	Locality	Th.	Coordinates	Reference
Am	Jebel Ammar	8	36°52’28’’N 10°04’59’’E	[49]
Jde	Jedeida	11	36°54’05’’N 9°55’58’’E	[49]
Jd	Jebel Jedidi	17	36°25’10’’N 10°27’26’’E	[49]
BKH	Jebel Bou Kornine	17	36°40’12’’N 10°21’41’’E	[49]
R	Jebel Ressas	10	36°36’23’’N 10°20’12’’E	this work
Z	Zaghouane area	6	36°21’20’’N 10°06’36’’E	[49]
O	Jebel Oust	9	36°31’25’’N 10°03’17’’E	[49]
BS	Jebel Bent Saidane	2	36°14’19’’N 10°00’08’’E	[49]
Zr	Jebel Zerass	8	36°08’31’’N 9°49’01’’E	[49]
Az	Jebel Aziz	12	36°30’26’’N 9°52’43’’E	[49]
BKF	Jebel Bou Kournine of Fahs	1	36°24’44’’N 9°40’58’’E	[49]
Hr	El Houareb	1	35°43’09’’N 9°43’07’’E	[49]
L	Loridga, Jebel Guemgouma	9	35°21’05’’N 9°42’39’’E	[49]
Kja	Kef Lekhouaja	3	35°18’02’’N 9°42’15’’E	[49]
CA	Jebel Chaabet Attaris	32	35°14’20’’N 9°42’21’’E	[48,57] [49]
Klb	Khechem el Kelb	26	35°07’24’’N 9°43’07’’E	[49]
Thub	Jendouba	17		[49]

Table 2. Abbreviation codes, total organic carbon (%) and thickness of the allovian organic rich Smida Formation. TOC values are from [54] and [74]

Well name(ID)	TOC (%wt)	Thickness (m)
NF	1.00	20
SABW	0.97	70
FNG	0.95	60
BGL	0.76	55
KGF	0.22	180
CHR	0.5	42
CF3	0.35	94
LMG2	0.24	255
WGA	0.45	175
CHS	0.42	235
DJM	0.89	60
EZZ8	0.78	125

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