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Role of the NE-SW Hercynian Master Fault Systems and Associated Lineaments on the Structuring and Evolution of the Mesozoic and Cenozoic Basins of the Alpine Margin, Northern Tunisia

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1. Introduction

The Mesozoic and Cenozoic evolution of the northern edge of the African margin (Fig. 1), and particularly the northern Tunisia, fossilized successive paleogeographic and tectonic episodes. In fact, after rifting and extensional periods, which started at the end of the Paleozoic and continued during the Mesozoic [1-6], was settled the Alpine orogeny that results from the convergence movements between the African and Eurasian plates; it is induced by compressive tectonic stresses, beginning at least since the Tertiary intervals and probably the Late Cretaceous [7-24]. This orogeny has induced, on the Mediterranean edges, many mountains chains extend from the Apennines at the East to the Betic Cordilleras at the West.

The various geological works established in northern Tunisia [25-42,18,43-47], north-eastern Algeria [48-50,23] and in the Siculo-Tunisian strait [51-57], demonstrated that the NE-SW inherited fault networks have controlled sedimentation during the Tethyan rifting and have also controlled the structuring of the central and northern Atlas during the successive tectonic events.

This margin of northern Tunisia, including the Tell and the Tunisian furrow domains (Fig. 2), is limited to the East by the Zaghuan master fault, which appears to have effect on the sedimentation since the Jurassic [58,59,33]. It is inherited from NE-SW trending Hercynian master fault networks (Fig. 2) and their conjugate faults [60,61]. These lineaments correspond, from SE to NE, to the Zaghuan fault (ZF), the Tunis-Elles fault (TEF), the

Figure 1. Geological sketch of the Maghreb (modified from Piqué et al. [4] and Frizon de Lamotte et al. [23]).

El Alia-Teboursouk fault (ETF), the Ras El Korane-Thibar fault (RKTF) and the Cap Serrat-Ghardimaou fault (CSGF). Movements of these master faults have effects on the sedimentary deposition and distribution since the Triassic rifting phase up to now.

Our study is mainly focused on northern Atlas (Fig. 2) where the structures tend to be well exposed and on the Tunisian Tell marked by sealed structures. These interpretations will be supported by seismic sections calibrated by petroleum well.

Indeed, based on the structural and paleogeographic zonations, developed during various geological phases in the Tunisian margin, we propose in this paper (i) to demonstrate the implication of the Hercynian deep structures, in the deformation of the Atlas. They have a role in the distribution of the sedimentary basins along the southern Tethyan margin during the Mesozoic and the Cenozoic times; (ii) attempt to clarify the kinematics and chronological relationship between the Tell and the northern Atlas, by proposing a coherent geodynamic model since the Tethyan rifting until the Cenozoic contractional periods, pointing out the role of the NE-SW tectonic lineaments; (iii) to trace a tectonic pattern of the northern Tunisia that contributes to a better comprehension of deformations affecting the Tellian and Atlasic domains in relation with the global geotectonic framework.

2. Stratigraphy

2.1. Triassic

The Triassic outcrops have often abnormal contact with Jurassic, Cretaceous, Paleogene and Neogene series in several localities of northern Tunisia (e.g. Ras El Korane, Jebel Ichkeul,

Jebel Lansarine-Sakkak, Jebel Chehid and Thibar). It is presented either as a diapiric structures [62, 31, 63, 64], or as sole of overthrust folds [32], or also as salt glacier structures [65-69]. The Triassic deposits are characterized by a chaotic aspect; it is consisted of Gypsiferous, argillaceous, carbonated and locally sandy facies, of varied color (Fig. 3).

In the Bizerte area (e.g. Bechateur), the Triassic appears rather stratiform. It is represented by black dolomitic limestones in metric layers becoming centimetric at the top of the succession [18]. The abundant fauna of lamellibranches indicates Carnian-Norian [70, 71]. The subsurface data show carbonated Triassic as well in Utique (W8 well), the Cap Bon (W9 well) and in the Gulf of Tunis (W5 well). The Late Triassic is predominantly evaporitic; its thickness is about 2500m.

2.2. Jurassic

The Jurassic outcrops largely in northern Tunisia [72, 33, 73-78]. Its thickness changes from 700m [76] to 900m [79]. It shows a Tethyan deep sea facies different from the Nara platform Formation defined by Burollet [26] in the Nara outcrop in central Tunisia. It is dominantly calcareous series with some marly intercalations (Fig. 3). In the Ichkeul and Ammar outcrops, the Jurassic shows a thickness series varied from 260m [73] to 480m [80].

At the level of the "Tunisian Dorsale", the lower limit of the Jurassic is not well defined due to the Late Triassic-Lias transition which still not paleontologically characterized [76].

2.3. Early Cretaceous

The Early Cretaceous largely outcrops at the Tunisian furrow [81]. The Jebel Oust lithostratigraphic section is considered as the most complete and richest of microfauna and macrofauna of the Tethyan area [82]. This section consists of fossiliferous marls and clays with micritic limestone intercalations and sandy and quartzitic recurrences (Fig. 3). This succession is approximately 2500m thick and its sedimentation has occurred in a subsiding marine environment [83, 82].

In subsurface, in the Gulf of Tunis, the north-eastern extension of the Tunisian through show Early Cretaceous deposits composed of clays, marls and limestones with some sandy layers [24].

2.4. Late Cretaceous

The Late Cretaceous outcropping in the Tunis area [103] is composed from the base to the top by two lithostratigraphic Formations (Fig. 3); the Aleg Formation (Turonian-Coniacian) composed of alternating limestones and marls rich in faunas (100m), marls and clays (50 to 180m). The Abiod Formation (Campanian-Early Maastrichtian), composed by marls and limestones; an argillaceous limestone bar of the zone with *Globotruncana arca rugosa*; limestone and marl alternations; a limestone bar (80m), marls locally gypsiferous and alternations of marl and limestone.

Figure 2. Study area location map of Geologic outcrops, cross section, seismic lines and petroleum wells (geologic outcrops are modified from 1/500.000 geological map of Tunisia; Castany, 1951).

In the Bizerte area, the Abiod Formation outcrop is composed by the first limestones bar attributed to Campanian, the intermediate marl and limestone alternations, the second limestones bar and the upper marl and limestone of Maastrichtian. This Formation makes more than 200m of thickness [18,81].

2.5. Late Maastrichtian-Paleocene

This serie is represented by a monotonous brown argillaceous package, which outcrops at several localities of northern Tunisia. This argillaceous deposits, corresponding to the El

Haria Formation, presents a lithological succession which starts with marl and limestone alternations, then brown to grey clays and finally of marl and grey limestone alternations (Fig. 3).

Compared to the Tunisian furrow, in the Bizerte area, the Telliian Paleocene is characterized by the presence of the “yellow balls”. Its thickness is about 250m [18,84]. More to the South, in the Messeftine basin, the Paleocene was recognized at the W9 well, with a thickness of 800m [84]. Towards the West and the North-West, these deposits exhibit more significant thickness.

2.6. Eocene

It rests on the black marls and argillaceous limestones of the El Haria Formation; the Eocene is represented by two different series in northern Tunisia (Fig. 3): (i) a carbonated series of Early Eocene (Ypresian) known by two facies: the Bou Dabbous Formation with Globigerines and the El Garia Formation with Nummulites. In the transition zone, we have a mixed facies; (ii) an argillaceous to marly series of the Souar Formation (Middle Eocene).

In the Bizerte area, the Bou Dabbous Formation includes limestones containing Globigerines and schistous marls with glauconies and phosphates at the base. These marls are followed by relatively massive and bituminous limestones with Globigerines. This Formation is 100m thick [84].

To the West, in the Teboursouk area, the Djebba cross-section, to the West of the Gorraâ outcrop, shows a carbonated series of 70m thickness. It is composed, at the base by a carbonated term (10m) with Globigerines, then an upper carbonated term containing Nummulites.

To the South and the South-west of the Globigerines province, the Nummulites province appears represented, in its typical locality in Kef El Garia, by yellow bio-micritic limestones with Nummulites and other great Foraminifera. It makes 50m of thickness.

In the Bizerte area, the Souar Formation is composed by yellow marls and clays containing some limestones layers and yellow balls, typical of the Telliian series. Its thickness is about 300m [18].

Thickness of the Souar Formation, at Jebel Jebbas is about 500m [43] and becomes 800m thick at the Cap Bon peninsula [85,86].

2.7. Oligocene - Early Miocene

During this period, the Northern Tunisia is marked by two large basins including: a depocenter to the SE filled by the Fortuna Formation (600-800m) and a depocenter to the NW corresponding to the deposition of the Béjoua series [87] and the Oligo-Miocene Numidian Flysch succession (2500m; [88]). These two basins are separated by a “bald” zone [89, 24, 87] lengthened according a NE-SW direction, which seem coincides to the domes and diapirs

zone of the Tunisian northern Atlas. The non depositional or erosional zone is inherited from the Eocene period where we have low deep depositional area separating the two basins (Figs. 2 and 3).

Figure 3. Synthetic column of geological series in northern Tunisia (AG- Ain Ghrab fm; H- Hakima fm; OM- Oued Melah fm; K- Kechabta fm; OBK- Oued Bel Khedim fm; RR- Raf-Raf fm; PF- Porto-Farina fm; OH- Oued El Hammam fm; Ma: Mahmoud fm)

At the West of the domes and diapirs zone (Bejaoua group), the Oligocene and Miocene successions show a stratigraphic continuity with the Eocene series. It contains a clayey and sandy lower part, a sandy intermediate part and a carbonated sandy upper part. Its thickness is approximately 100m [87].

The Oligo-Miocene Numidian Flysch succession, occupies the northwestern part of northern Tunisia. It is a thick allochthonous unit of turbidites including clays at the base and sandstones and shales at the top [32,90,89,46]. This succession consists of five turbiditic units filling the channel complexes with silexites at the top [89,88].

The Fortuna Formation occupies all southeastern basin of northern Tunisia. This Formation includes sandy, clayey and carbonated facies indicating a shallow marine environment [89]. This Formation is 600m thick in the Gulf of Tunis [24] and 800m in the Cap Bon [85,89].

2.8. Middle to Late Miocene

The Middle to Late Miocene series are well developed in the Gulf of Tunis [91,24]. The Middle Miocene starts with the Langhian Ain Grab lumachellic limestone bars of 19m thick. This unit is marked by conglomerates at the base indicating the beginning of a major transgression, known on the scale of the country [26,85,92-94].

The following strata are marked by an important change facies and geographical distribution. In the Gulf of Tunis offshore area, the Saouaf Formation (Serravallian-Tortonian) and the Oued Bel Khedim Formation (Messinian) present facies and thickness variations [24]. They are composed of clays, silts and occasionally of sandy limestones at the base and marls and salts at the top. The thickness of these two Formations is about 1300m (Figs. 2 and 3).

In eastern Tunisia, the series are represented by the deep marine green clays of the Mahmoud Formation, rich with microfauna. Above, are deposited regressive continental series, resulting from the erosional strata [95] corresponding to the Segui Formation [58]. Whereas, to the coastline and offshore areas, the Beglia and Saouaf Formations (Serravallian) constitute the lateral equivalent of the Segui Formation. It is a thick series that reach 1700m and composed of clays, sandstones and lignite alternations characterizing an internal shelf depositional environment [95].

In the Bizerte and Mateur areas, the upper Miocene deposits occupy the foreland basins of the Tellian domain. They fossilized marine, lagunal and detrital environment [26,71,96,18,94] and they are concentrating in five different depocenters corresponding to the Douimis, Jalta, Messeftine, Kechabta and El Alia basins [47], which are insulated either by morpho-structural ridges and emerged high zones. Due to the lack of stratigraphic markers, these deposits were subdivided in lithostratigraphic Formations [26]: Hakima, Oued El Melah, Kechabta and Oued Bel Khedim (Figs. 2 and 3). In Jalta, the Miocene deposits are completely continental.

2.9. Pliocene

The Pliocene is dominantly marine deposits outcropping at the East of the Mateur-Bizerte basins and on the southern edge of the Cap Bon Peninsula (Fig. 2). These series settle with unconformity on the various Miocene and ante-Miocene substratum. They are subdivided by Burollet [26] in two Formations: the Raf-Raf at the base and the Porto Farina at the top (Fig. 3). These two Formations outcrop at the south-east of the Douimis basin, with a first primarily argillaceous series (50m) and second predominantly sandy deposits rich in fossils (50m). In the El Alia-Ghar El Melah basin, Pliocene shows more significant thicknesses.

Towards the East, in the Gulf of Tunis, the Lower Pliocene deposits are represented by clays, sands and sandstones. They exhibit 300m of thickness with notable variations related to the structuring of the inherited substratum and Triassic salt movements. Late Pliocene is essentially made up of sandy series of the Porto-Farina Formation. Its thickness is about 670m and it is sealed by the villafranchian series. From the current coastline, all along the master faults and at piedmont of the reliefs, Pliocene deposits becomes completely continental. These latter are integrated in a detrital sequence of the Ségui Formation, which is attributed to Late Miocene-Pliocene.

2.10. Quaternary

At the level of the depocenters and slopes of the reliefs, the Quaternary deposits are represented by continental facies; the marine ones are spread out over the entire eastern and northern coasts of northern Tunisia. The Early Pleistocene of the north of the Kechabta is composed of silts, continental sands and clays. This series locally made 200m (Fig. 2). The upper Quaternary (Late Pleistocene / Tyrrhenian) marine and eolian deposits are well developed all along the northern and north-eastern littoral of Tunisia [97].

3. Structural framework

The current tectonic framework of central and northern Tunisia [28,54,24] was guided at least by five NE-SW trending master faults (Figs. 4 and 5) that are associated with Triassic saliferous outcrops forming quite exposed ridges [71,98,63,33,18,99,43]. From the SE to the NW, we distinguish:

3.1. Zaghouan fault

It is marked by a relatively irregular layout (Fig. 4) and shows a constant tendency with overlapping towards the SE [100,28,101]. To the North, this master fault is associated to the Triassic and Jurassic outcrops [33]. Towards the south-east, this fault disappears before the Rouhia-Kalaâ Jerda graben. During the Mesozoic, this N40 master fault has bordered the "Tunisian trough" to the SE side, then it evolved to SE overlapping fault during the Cenozoic compressive phases [59,102]. It corresponds to the T2 transversal identified by Jauzein [28].

Figure 4. A- Atlasic and Alpin domains of Tunisia [101]. B- Tectonic map of northern Tunisia.

3.2. Tunis-Elles fault

This lineament of rectilinear layout (Figs. 4 and 5) shows a reverse movement with local overlapping and imbrications of the series [28]. This master fault has controlled distribution and evolution of the associated structures since the Triassic rifting phase [103, 43]. During the extensional periods, this fault has contributed in the individualization of the large subsiding basins and the delimitation of the Tunisian trough since the Aptian. During the end of Cretaceous and Cenozoic contractional periods, this fault has modeled the Tunisian Atlas following its sinistral overlapping movement. It induced the individualization of NE-SW poured south-eastern Atlasic folds and other transverse NW-SE folds strongly involved with sigmoid forms [104]. It corresponds to the T3 transversal [28].

3.3. El Alia-Téboursouk fault

It begins with the El Alia and Kechabta faults to the NE and continues with the fault delimiting the Sakkak-Lansarine diapir then the Teboursouk overlapping (Fig. 4) [31, 63, 105-106].

107]. It corresponds to a sinistral left relay fault system. Towards the SW, it separates the Oulad Bou Rhanem graben from the Kalaâ Jerda graben [28] and bounds the Tebessa graben in Algeria [108]. It corresponds to the T4 transversal cited by Jauzein [28].

3.4. Ras El Korane-Thibar fault

It extends from the Kef Triassic o alignments to the SW to the Ras El Korane in the NE (Fig. 4), crossing the Thibar, Beja and Bazina structures [18]. The Ras El Korane-Thibar segment constitutes the NNE extension of the T5 transversal [28]. This fault, which borders the Bazina Triassic outcrops on the Eastern side [109] extends to the North and delimits the Ras El Korane Numidian deposits [71, 110, 111, 18, 112, 47].

This master fault corresponds to the paleogeographic limit between the Kroumirie and Mogods mountains and that of Hedil and Bizerte [71]. It bounds the Numidian Flysch in Ras El Korane and the Tellian units in Beja. It is a discontinuous and sinistral left relay fault system which is sometimes shifted by other later NW-SE faults. Dubourdieu [113] evokes a recent horizontal displacement towards the SW of about fifteen km on this lineament.

3.5. Cap Serrat-Ghardimaou fault

It is located in the Cap Serrat area [32] and continues in Algeria crossing Souk Ahras and Batna [113,28]. It appears to have an important role in separating the Tunisian and Algerian blocks that have evolved with some independence. [114]. As the other master faults, it is associated to the Triassic outcrops (Fig. 4). Moreover, it shows some Neogene volcanic extrusions [32, 45]. This fault corresponds to T6 transversal of Jauzein [28].

We can follow the extension of the majority of these faults in offshore. They affect the northern Tunisian plate such is the case of the Ras El Korane-Thibar and Cap Serrat-Ghardimaou faults (Fig. 2). Another lineament has the same direction being extended in offshore and could be attached to that, which delimits the Calabro-Peloritano-Kabyle zone (CPK) [29,35] to the SE (Fig. 2). The other faults affecting the North of Tunisia have NW-SE, E-W and N-S directions and they have played a significant role, beside the NE-SW master faults, on the distribution and evolution of the Mesozoic and Cenozoic basins.

These lineaments have subdivided the northern Tunisian margin into six compartments (Figs. 5 and 6) corresponding to the Enfidha-Cap Bon, Jebel Oust, Mejez El Bab, Mateur, Nefza and Tabarka. Within each compartment, the sedimentary floor is organized into several domains corresponding to grabens, half-grabens and horsts delimited by NW-SE, E-W and N-S faults related to the regional deformations.

Tertiary contractions on the northern Tunisian margin have also induced folds that have NE-SW Atlasic direction within the compartments. Some folds affecting the Neogene strata rather show near E-W directions.

Figure 5. NW-SE geological cross-section crossing orthogonally structures of the Atlasic and Tellian northern Tunisian. The master faults subdivide this region into six compartments. (ZF: Zaghuan Fault; TEF: Tunis Ellès Fault; ETF: El Alia-Teboursouk Fault; RKTF: Ras El Korane-Thibar Fault; SGF: Cap Serrat-Gardimaou Fault. Location in Fig. 2.

Figure 6. Structuring of the northern Tunisian margin into six compartments lengthened along NE-SW direction.

4. Geodynamic evolution

4.1. Introduction

Structuring and deformation of the substratum is one of the most significant parameters which induced the distribution and extension of Mesozoic and Cenozoic latter deposits.

Substratum of the Atlasic and Tello-Rifaine chain is well identified in Morocco, where it consists of Paleozoic strata deformed by the Hercynian orogenesis [4]. These strata are affected by N45°E to N70°E strike slip faults with high dip. In northern Algeria, the

substratum seldom outcrops; it extends from eastern Morocco according to W-E direction parallel to the current South-Atlasic lineament (Fig. 7). In Tunisia, the Paleozoic substratum is little known, due to the outcrop missing, except the Permian of Jebel Tebaga in southern Tunisia and those encountered in petroleum wells on the Saharan platform in southern Tunisian.

In northern Tunisia, the ancient fracturing is distributed according the NE-SW master zone of faults, limited to the South by the Zaghouan master fault and to the North by the Cap Serrat-Ghardimaou master fault [100,32,33]. These old fractures are marked by Triassic and Jurassic intrusions and magmatic extrusions (Figs. 2 and 4). The NW-SE direction appeared especially in offshore Pelagian block of eastern Tunisia [4,93]. The current sedimentary and tectonic distribution results from the superposition of tectonic phenomena affecting Tunisia during Mesozoic and Cenozoic periods.

We present in the following sections the geodynamic evolution of sedimentary basins in the northern Tunisian margin, since Triassic times. We insist for each period on the role of the inherited Hercynian structures on basin evolution related to the nature and change of the regional tectonic constraints.

Figure 7. Atlasic domain of the Maghreb during Early Mesozoic [4].

We note the NE-SW orientation of the Hercynian deep faults in the Tunisian trough.

4.2. Triassic

At the Triassic period the paleogeography of Tunisia was dominated by an extended platform between the Saharan continent to the South and the Tethys to the North (Fig. 7). The Triassic series start with a continental detrital sedimentation, then evolves to marine carbonates and capped by evaporates characterizing a littoral environment. The paleogeographic changes were related to an unequally subsidence, which is particularly active in the central and the northern of Tunisia [45]. The Triassic rifting conducts to the paleo-Téthys [63,2]. Magmatic green rocks often accompanied the Triassic deposits of northern Tunisia.

Detrital deposits at the base of the Triassic indicate the beginning of a major transgression on the Hercynian unconformity. In the North of Tunisia, Triassic thickness exceeds 2500m. Due to the absence of well data reaching the base of the Triassic facies, we can't identify an appropriate underlying structure to this interval and thus there is no information on tectono-sedimentary control. The diapirs and domes zone, currently located between the Tellian domain and the "Tunisian Dorsale", have a NE-SW direction (Fig. 8). During the Triassic, this zone occupied an inherited horst of the Hercynian substratum and was delimited by two normal faults, which could correspond to the two known master faults of the northern Tunisian margin: the El Alia-Teboursouk and the Ras El Korane-Thibar faults. This high zone separates two subsiding domains; the north-western domain corresponding to the future Tellian-Numidian basin and the south-eastern domain corresponding to future "Tunisian trough". The bordering faults facilitated the migration of saliferous facies upwards. This can be explained by the particular frequency of the evaporate sediments in the zone located between these two major faults. Rises of the Triassic evaporates begin with Late Jurassic [6,13,116]; some authors believed Late Jurassic and Early Cretaceous [70,58].

4.3. Jurassic - Early Cretaceous

During the extensional Jurassic period, the southern Tethyan margin was structured into horsts, grabens, half-grabens and tilted blocks [117,118]. Since the Late Liassic, this active kinematics had amplified differential subsidence fossilized by thick series in depocenters and thin ones even condensed and/or with gaps on the highs [33,119,76].

Through the Atlasic domain, could exist a deep feature that controlled by the substratum structuring. The most obvious feature is that of the N-S Axis, which limits the deformed Atlasic platform to the West and the stable Sahel platform to the East. This master Axis extends to the North towards the Zaghouan master fault (Fig. 8) and has a continuous paleogeographic role from the Jurassic to Quaternary series [62,120,54].

In northern Tunisia, these old faults affecting the ante-Triassic substratum are not well expressed. However, from Jurassic and especially during Early Cretaceous, the N-S to NNW-SSE extension of the Tunisian margin induced genesis of subsiding basin (Tunisian furrow) delimited by the Zaghouan fault to the SE and that of Tunis-Elles to the NW [33,121,4,103,75,122,123,43]. This basin will receive an enormous accumulation of deposits, which exceeds locally 2000m for Barremian ([82]; Fig. 8). Nevertheless, near the Tunis-Elles fault, this stage is represented only by a few tens meters of limestone, marl and massive limestone.

These ancient listric faults will be reactivated and caused the collapse of the NW compartments. They generate a structuring into half grabens slightly tilted to the SE. At the same time, these NE-SW oriented structures are associated at the level of the sedimentary cover by N-S, NE-SW and NW-SE trending other fractures, which are guided by ascension of Triassic salt in extensional regime.

The Bou Kornine outcrop of Hammam-Lif is placed in a paleogeographic and intermediate structural position between two distinct paleostructural domains, belonging both to the

Figure 8. NW-SE and NE-SW Lithostratigraphic correlations of geological series outcropping in the different identified compartments.

Maghrebin margin of western Tethys. These domains are the "Tunisian Dorsale", corresponding to a carbonated platform and the "Tunisian trough", corresponding to a NE-SW deep graben with sedimentary pelagic filling [124].

Located on an active flexure zone between these two domains, the Jurassic deposits of Jebel Bou Kornine will record different stages of the geodynamic evolution of the margin [125]. Since Late Toarcian-Early Aalenian, synsedimentary tectonics of tilted blocks have a dominating role on the progressive erosion of the near carbonated platform, on the dynamics of the gravitation flow and on the installation of the four conglomeratic levels [125].

However, at the Tunisian trough, where differentiated grabens, sedimentation is thick and turbiditic [36]. The Tunisian furrow, characterized by upper Jurassic radiolarite deposits, has the main structural features of the Tethyan domain [117]. The Zaghouan lineament would have separated the Jebel Oust compartment from that of Enfidha-Cap Bon (Figs. 4, 5 and 6).

The Jurassic deposits remain unknown in the Gulf of Tunis because there are no drilled wells that reach them. The interpretation of seismic lines crossing this area shows structuring and geometry of the Jurassic limestones and marls above the Triassic carbonated strata (Fig. 9). These series are marked by downlap progradational structures on the sides of flanks. The Jurassic is characterized by condensed surfaces of unconformities, marked by high amplitude and good continuity reflections (Fig. 9).

Figure 9. Interpreted seismic line L1 of the Gulf of Tunis, showing distribution of Mesozoic and Cenozoic deposits and its evolution towards the NE-SW and the associated Triassic ascensions [24]. E-Pl: Early Pliocene; L-Pl: Late Pliocene. Location in Fig. 2.

At the level of the northern Tunisian margin, depocenters, half-grabens and high zones lengthen preferentially according NE-SW direction since the Jurassic and especially the Early Cretaceous [63,126]. Triassic salt rising has been clearly emphasized since the Early Cretaceous extensional phase corresponding to an intracontinental rifting [4,3]. This deformation was very active, with formation of tilted blocks related to activity of synsedimentary normal faults. These structures have been induced by regional N-S transtensional event [112,123,24].

In the Gulf of Tunis, the Early Cretaceous is particularly thick in W6 well (2341m). However, it only presents 912m and 477m in W2 and W3 wells indicating structuring into low and raised zones under effects of bordering faults (Fig. 10). Differently to the underlying Jurassic

Figure 10. N-S and WNW-ESE Lithostratigraphic correlations of petroleum wells in the Gulf of Tunis, showing inversion of the subsidence at Top Cretaceous, Top Miocene and Top Early Pliocene [47].

reflectors, the Cretaceous deposits are thicker on the "Gamart" tectonic corridor and are considerably reduced towards the depocenter. This distribution seems to be related to the movements of the Triassic diapir, which caused the structural inversion and the tilting of high edges. Towards the "Raouad" raised structure, the sedimentary sequences are associated with retrogradational on laps and top laps (Fig. 10).

During the Berriasian, the Zaghouan fault delimits a subsiding basin, which occupies all the northwestern part of an uplifted zone of limestones with organic-detrital deposition [33]. This high zone constitutes the northwestern edge of the Enfidha compartment.

Locally, in Jebel Bou Rahal of the Mejez El Bab area, the El Alia-Teboursouk fault delimits the Triassic outcrops to the NW. It separates a NW basin with thick and continuous sedimentation, of a SE basin with reduction and gap of sedimentation (Barremian-Coniacian gap; [127]) in extensional and transtensional context.

The N-S extension induced appearance of other fractures orthogonal to the Hercynian strike slip faults already active since Jurassic [103,43]. Thus, the upper Aptian-Albian period is characterized by the occurrence of grabens directed close to NW-SE following the normal movement of faults that have the same direction [128].

In the Gulf of Tunis, this N-S to NNW-SSE extensional and transtensional direction recorded during this period has mobilized the NE-SW Hercynian faults, generating tilted blocks and opening grabens and horsts along the NW-SE trending faults (Fig. 10).

4.4. Late Cretaceous

A master change of the African plate movement compared to European plate has emphasized in Albian [102], related to beginning of the northern and southern Atlantic Ocean expansion. This displacement has caused movement of Africa to the North and stopped accretion of the oceanic lithosphere at the level of African-European Rift Zone.

During the Albian and Turonian, the Zaghouan master fault has separated a stable eastern platform from a deformed western platform represented by the "Tunisian furrow" [129]. This last, having a geosynclinal form, was structured into several compartments. This paleotectonic zonation had a great influence on the development and distribution of the varied facies during the Senonian.

In the "Grand Tunis" area [103], the tectono-sedimentary analysis of the upper Cretaceous series shows a significant instability of the sedimentary floor inducing a structuring into tilted blocks, which are bounded by NW-SE faults [103].

Differential movements of various faults exhibit the "keys of piano" architecture well express neighboring the Zaghouan fault [33] and that of Tunis-Ellès [43]. This extensional to transtensional period is accompanied by an intense halokinetic and magmatic activity [130-132]. Some E-W contractional pulsations were highlighted in the Tunisian furrow during the Late Albian-Cenomanian [43]. This transtensional event is also evident by the presence of slumped sandstones and synsedimentary N30- 40 trending normal faults, which affect the Cretaceous deposits of the Mejez el Bab area, at the level of El Alia-Teboursouk lineament [105] and in the "Grand Tunis" area (Jeriffet outcrop; [103]).

4.5. Paleocene

In northern Tunisia, several authors [58,129] distinguished two domains; the first where the Danian is present, whereas the other where it is lacking; the limit between these two domains

is roughly located on the Thala-Elles-Tunis line (Fig. 2). Paleogeographically, they correspond to two different basins where the El Haria Formation, of Late Maastrichtian-Paleocene age doesn't have the same stratigraphic significance [58]. The eastern Tunisia basin with less thick and locally condensed sedimentation and northwestern Tunisian furrow basin with very thick sedimentation.

Moreover, the limit between the two basins coincides perfectly with the Tunis-Elles fault (Figs. 2 and 8). This confirms the role of this fault on the control of deposition, which is well justified during the Paleocene (El Haria Formation) [42,43].

Furthermore, the Cap Serrat-Ghardimaou fault seems continued its impact on sedimentation by delimiting the Tellian facies to the NW, which is characterized by marl and limestone alternations from marls of northern facies of the Tunisian furrow to the SE [129].

The Tunis-Elles fault has controlled the Paleocene deposition; it clearly separates a low subsiding basin to the South-East from a subsiding basin to the North-West (Fig. 8).

The Ras El Korane-Thibar master fault (RKTF) induces an accumulation of more significant Paleocene series on the Western northern side than on the Eastern southern side. Thus, the thickness of this series reached 1200m in Bazina to the West of Mateur [109] and 800m in the Henchir Haroun (W10) petroleum well to the East of Mateur [47].

The distribution of Paleocene deposits on both sides of the NE-SW master faults indicates that has contributed to the installation of a tilted blocks and half-grabens associated with condensed series and hiatuses near the location of faults and a thick and argillaceous facies in the distal subsiding depocenters.

4.6. Early Eocene

During the Early Eocene (Ypresian), a high zone was individualized, which extends from the Kef area to the SW, towards the Mateur area to the NE. It corresponds to the extension of the Nummulitic limestone facies, which characterizes low subsiding platform. This high zone separates to the NW and SE two relatively deep provinces (Fig. 11A) with pelagic sedimentation corresponding to a limestone facies with Globigerines [133,34,134,102,135,136]. This high zone coincides with the domes zone. It is located, therefore, between two master faults: the El Alia-Teboursouk fault (ETF) to the SE and Ras El Korane-Thibar fault (RKTF) to the NW. The paleogeographic position of this high zone is related to the instability of the Triassic domes whose have rise of and pierced their covers [31,63,43].

This high zone, lengthened according to an NE-SW average direction, has an asymmetrical form with a southeastern margin with weak slope and a northwestern margin with steep slope. This asymmetry, inherited from previous period, was accentuated and reactivated again by Lutetian contraction [31,112,84,137].

In addition, the morphostructural ridges or underwater peaks [138] seem to have controlled the distribution of facies, following the movements of the NE-SW substratum faults, associ-

ated with the Triassic salt rising, which began since the extensional Cretaceous periods. These Triassic bodies length along the Hercynian lineaments, indicate their successive rejuvenations [40]. Moreover, in the Beja area, the Nummulitic limestone outcrops of the Early Eocene show a NE-SW privileged orientation [134].

Figure 11. Paleogeographic and paleotectonic maps of northern Tunisia at the Ypresian (A) [129,133,34,134,135,84] and at the Aquitanian (B) [129,84,89,86]. Interpreted NW-SE cross-sections are based on the present work.

Under effect of the tectonic deformation, the Paleocene-Eocene deposits are unequally distributed in the Gulf of Tunis. Thickness of these Formations changes from 434m in W2 well, to 307m in W3 well. We note the absence of the Bou Dabbous and Souar Formations in W5 and W6 wells (Fig. 10). The seismic reflectors are bordered by an angular unconformity and are associated on the side of the "Gamart" structure by aggradational/retrogradational onlaps above marly and carbonated Maastrichtian seismic horizons. Reflectors are moderately continuous and associated with pinch outs on the "Raouad" uplift (Fig. 9). Deposits are marked, in W2 well by the Eocene breccias. These structures should indicate a slope of the sedimentary floor along the faulted zone (Fig. 9). The Paleocene-Eocene deposits, which are marked by a development in the center of the depression and the "Raouad" uplift, are reduced towards the "Gamart" high zones, where clays of El Haria and limestones of Boudabous are directly deposited on the Triassic evaporites (Fig. 9).

From the end of Cretaceous (Late Maastrichtian) and until the Middle Eocene, the NE-SW preexistent faults continue their effects on sedimentation in a contractional and transpressional regime.

The El Alia-Teboursouk and Ras El Korane-Thibar faults have controlled sedimentation during the Ypresian. Moreover, the NW-SE faults appeared above the Triassic bodies during the previous period, will express and we thus attend notable variations of the facies and thicknesses on both sides of these faults. The extensional movements testified by the NW-SE normal faults are integrated in a NW-SE regional contractional event [139,112,120,21,47,136]. This compressive constraint generated principally reverse displacements along the NE-SW ancient faults.

However, some authors [17,38,42,103,122,140,141] consider that this period constitute the continuation in time of the Mesozoic extension.

4.7. Middle to Late Eocene

During this period, there was the genesis of the Proto-Mediterranean following the movement of microplates towards the North. In the high zone, where underwater peak, identified during the Early Eocene, appear many gaps in the Middle Eocene and especially in the Late Eocene (Souar Formation) with the presence of several glauconitic levels (Fig. 8). Salaj [129] announce the absence of the Late Eocene, in most of this zone. This is related to the high structural position of this zone following rejuvenation of the Ras El Korane-Thibar and El Alia-Téboursouk faults [63,98] (Fig. 11A). Elsewhere, in the Tunisian furrow and at the level of the eastern Tunisian platform, the Middle and Late Eocene is very developed [86].

In addition, the Middle and Late Eocene, represented by marl and limestone alternations in the Mejez El Bab area, is much reduced [127]. These variations of facies accompanied sometimes by gaps and unconformities characterize the Lutetian contractional period [98,48,84,142-144,69,137,24].

At the outcrop scale, the witnesses of contractional tectonics are showed by the presence of (i) unconformity of the Oligocene on the Middle Eocene in the Jebel Sebâa outcrop and at the level of the Bizerte town [84]; (ii) unconformity of the Late Eocene at the level of the Bir Afou structure, which was formed during Late Maastrichtian-Early Eocene and the presence of synsedimentary reverse faults affecting marl and limestone alternations of the El Haria Formation of Late Maastrichtian-Paleocene age. These faults have N20, N40-50 and N70-80 directions [43], (iii) unconformity of the Oligocene on a folded substratum in the Enfidha area [144].

4.8. Oligocene - Early Miocene

In many localities of the Mejez El Bab, the marine Oligocene deposits, represented by clays and bioclastic sandy limestones with Nummulites, unconformably rests on the Triassic. It is surmounted by the Late Oligocene-Aquitania continental deposits [127]. This tendency to emergence since the Kef area towards the Mateur and Bizerte areas is guided by the El Alia-Téboursouk and Ras El Korane-Thibar two master faults (Figs. 8 and 11B). During the Oligocene, we also attend to the appearance of a bald zone, which lengthens from the Kef area to the SW towards the El Alia offshore to the NE, passing by the Lansarine chain [98,89,24,87]. This bald zone separates two different basins, characterized by a clay-sandy deposition; (i) basins of Beja-Ghardimaou and subsiding and deeper Numidian basin to the NW and (ii) the less deep but subsiding Fortuna basin to the SE.

We think that this distribution is the result of the installation, in northern Tunisia, of an extensional event controlling the Oligocene-Early Miocene deposits as was announced by Piqué et al. [4].

At the regional scale, the Oligocene-Aquitania basin is contemporary with reactivation of old lineaments, which appear as normal faults controlling the genesis of the half-grabens. At the local scale post Lutetian extensions are numerous and are fossilized by synsedimentary

normal faults [63,37,127,43]. The end of the Oligocene-Aquitania is marked by a continental deposit characterized by coarse sands with cross-bedding stratifications. These deposits seem to be related to a total emergence of the majority of the study area.

We think that, in spite of the contractional constraints on the northern Tunisian and northern Algerian margin [15,145], induced by rotation of the Corso-Sarde block, we have always an extensional context. This event has induced the siliciclastic deposition in the Numidian basins [146,45] and of the middle Mejerda on the one hand, and the sandy deposits of the Fortuna Formation in central and north-eastern Tunisia on the other hand [147,89].

Moreover, several indices of NW-SE to N-S extensional deformation were announced (i) sedimentation is controlled by the activity of NW-SE and NE-SW faults, which delimited the different blocks, all along the Tunis-Elles zone [43]. The passage from the Eocene to Oligocene is marked by an inversion of subsidence following the reactivation of the NW-SE faults; (ii) several indices of N140 synsedimentary normal faults affecting the Oligocene sandstones of Korbous [147]; (3) the Ras El Korane-Thibar fault has moved in extensional mode and was at the origin of the clayey and sandy deposition on the NW side of the mega half graben; (4) furthermore, in the Téboursouk area, Perthuisot [63] highlighted an extensional event accompanied by N45 diapirism.

4.9. Middle Miocene - Quaternary

The structures recognized in the northern Tunisian margin (Figs. 2 and 4) result from the whole of the Eocene (Lutetian), Miocene (Tortonian) and Quaternary (Villafranchian) contractional phases, which followed the multiple extensional and transtensional episodes. These contractional phases induced tectonic inversions [24,47].

The evidence of major contractions are fossilized in the sedimentary sequences by angular unconformities as it is the case of the Neogene (post-Tortonian) deposits, which settled on the Oligocene-Aquitania folded series at the Rmil outcrop in eastern Gaâfour [43] and on the Campanian-Maastrichtian (Abiod Formation) at the Mejez El Bab [127]. Moreover, an unconformity of the Pliocene marine on the underlying strata has showed in the Bizerte [18], in Messeftine and Kechabta outcrops (Menzel Bourguiba) [26,18,47] in the Cap Bon [37,93], overlappings to the SSE in the Lansarine chain [98], Quaternary deformations on the El Alia-Téboursouk fault near the Sloughia [148] and unconformity of marine Pliocene in the Gulf of Tunis [24].

During the Middle Miocene-Quaternary period, three types of Neogene basins (Fig. 12) in the Bizerte-Mateur area have been developed following their position compared to the raised zones delimited by NE-SW, N-S and NW-SE master faults [47]; they correspond to the (i) narrow, strongly subsiding synclines (Douimis, Kechabta and El Alia basins), (ii) lozenge-shaped basins (Messeftine basin) and (iii) trapezoidal basins (Jalta basin).

The Alpine and Atlasic contractional phases have caused the formation of the Tellian and Atlasic folds trending NE-SW as well as the installation of the overthrust folds at the north-western end of Tunisia [32,38].

Figure 12. 3D Block diagram of the Neogene basins in the Tellian foreland domain [47]. EATM Fault: El Alia-Téboursouk master fault; RKTm Fault: Ras El Korane-Thibar master fault; Pl, Pliocene; M, Miocene; O1, Oligocene-Aquitainian (Numidian unit); O2, Oligocene-Aquitainian; E, Eocene; P, Paleocene; C, Cretaceous; J, Jurassic; T, Triassic.

These phases have also induced the reactivation of the old lineaments into reverse faults on the NE-SW direction and strike slip faults on the other directions. They also caused unconformity of the Miocene-Pliocene series (Ségui Formation) on the Oligocene sandy banks (Goubellat graben, [43]) and unconformity of the Middle Langhian Aïn Grab Formation on the folded limestones of the Ypresian during the Alpine phase [149].

From the end of the Messinian and during Early Pliocene, the transtensional events induced increase of the subsidence in the center of the depocenters, which received clayey sediments of the Raf-Raf Formation (Fig. 2). At the scale of the outcrop, this succession shows syndimentary normal faults.

The contractional event begins again during Late Pliocene and Quaternary [31,150,15] and continues until the Actual [38,18,44,24]. Thus, several structures having participated in the Neogene evolution are reactivated under current tectonics [38]. In the Tellian continental domain, the Neogene basins are also deformed at the level of its levels.

In northern Tunisia, the distribution of epicenters of the earthquakes is oriented NE-SW according to the direction of the master faults [151]. The current movements of the Cap Serrat-Ghardimaou fault, for example, are characterized by a seismicity which expressed principally on the level of its active segment of Ghardimaou [152,153]. It is at the origin of several earthquakes; the last one dates from 17/09/1986. Its focal mechanism is related to sinistral strike-slip movement and the axis of sub horizontal shortening is oriented NW-SE to N-S [151].

The calculation of the composite mechanisms based on the seismic events recorded in the neighboring areas of the Ras El Korane-Thibar fault, to the NW of Garaât Ichkeul, shows sinistral strike slip movements with nodal plans of N45 direction and dip of about 70° towards NW. This plan can correspond to the Ras El Korane-Thibar fault and the axis of shortening is oriented N170 [151].

Other earthquakes are located along the NE-SW Zaghouan fault indicating its recent activity. This locally overlapping master fault seems continued in the gulf of Tunis. The composite mechanisms of the majority of the seismic events allow us to deduce an axis of pressure oriented NW-SE to NNE-SSW [152,154].

5. Synthesis and conclusions

The geodynamic evolution of the northern African margin during the Late Triassic and Jurassic was mainly guided by the reactivation of the first order NE-SW Hercynian faults, associated to a second order conjugate NW-SE, E-W and N-S faults. These lineaments have differentiated either lozenge basins in the Saharan Atlas [155] or high and subsiding zones in northern Algeria with basins lengthened according to a N50 direction [156,48,13] or rather the « pull apart » basins in the high and Middle Moroccan Atlas and in northern Tunisia [157,117,158]. Moreover, in the Apennines, the Alps and the Betic [159], the Triassic basins would have evolved in a strike slip mode, which is controlled by the Hercynian directions (Fig. 13).

The rejuvenation of the southern Tethyan margin faults is related to the movement of the African plate against the Eurasian plate along the E-W sinistral transforming fault [9,160,119]. The explanation of the subsiding NE-SW oblique Tunisian furrow, compared to the global direction of the N70° to W-E Maghrebin furrow is explained by the presence of N-S to NNW-SSE regional transtensional stresses during the Triassic and the Jurassic-Early Cretaceous.

This tectonic framework is explained, at the Mediterranean scale, by dextral to reverse dextral movement of the N70 master faults, separating the African and Eurasian plates [9,160].

The total closing of the Tethys related to the opening of the western Mediterranean in Early Miocene [16] has induced genesis and rising of the Atlasic chains, which constituted thereafter the structural units of Tunisia. Generally, the complexity of the geological structures increases towards the North of Tunisia, at the level of the Tellian domain, where are developed the overthrust folds [32] and where the Tethyan is closing.

The varied and oriented faults and folds affecting the northern Tunisian margin are the result of complex changes in geometry and style of movements of the African and Eurasian plates, which started since Triassic and continued until now.

During the Mesozoic, the northern Tunisian margin is characterized by tectonic instability highlighted by several variations of facies and thickness of series. The NE-SW and N70°E Hercynian lineaments have controlled deposition [4] and caused structuring into tilted

blocks and compartments generally lengthened NE-SW. Each compartment is affected by other NW-SE and E-W conjugated faults.

Figure 13. Table Summarizing the regional and global tectonic event that affected the northern Tunisian margin and western Mediterranean during the Mesozoic and Cenozoic [58,32,63,139,1,16,164,168,33,160,2,169,119,37,165,127,40,18,4,166,84,120,75,103,123,54,21,43,45,125,154,24,47].

These faults have locally controlled the sedimentation and induced horst and graben structures lengthened orthogonally compared to the old structures [127,103,43,24]. This interpretation implies that the Tunisian furrow is an oblique « pull apart » graben, compared to the northern Maghrebian transform margin; that the bordering faults are very deep; that the Eocene inversion of the old bordering faults increase in Middle and Late Miocene, as in old Quaternary, generated reverse movements that controlled the rising of the central and northern Atlas and the Tellian Atlas.

Evolution of the Atlasic and Tellian domains was controlled by the Atlantic opening. Thus, at Late Liassic, the beginning of oceanic accretion in the central Atlantic induced drifting of Africa towards the East compared to North America and Europe [2,4,3] (Fig. 13).

During the Aptian and Albian, the opening of the Tunisian rift is related to the anti-clockwise rotation of Africa compared to Europe and the opening of the South Atlantic [2,4].

During the Cenozoic, the first effect of the Africa-Europe collision is marked by a clear folding phase in Algeria and Morocco at the Middle to Late Eocene [161,157]. In Tunisia, synsedimentary reverse faults are highlighted in the central and southern Atlas [37,120,142] as well as folds sealed by the Oligocene deposits [84,69,144], or by the end Eocene [137] in the northern Atlas (Fig. 13).

An Oligocene-Aquitainian extensional phase was highlighted in Tunisia [63,37,127,147,45,120, 162,24]. This phase was followed by upper Miocene major collision between Europe and Africa, resulting in the Tunisian Atlas and the installation of the overthrust folds poured to the South-East following a NW-SE contractional event [31,32,139,47]. The folding was largely amplified at Late Pliocene-Quaternary following the persistence of the NNW-SSE to N-S contractional regime [163,150,164,37,165-167,154].

These transcurrent movements have been evolved during various tectonic phases according to the geodynamic context. They controlled sedimentation in extensional context and they moved either in reverse or in strike slip of contractional event. Thus, these faults, which have at the beginning, the rather strong dips, tend to lean towards the West and the North-West following the NW-SE contractions. This is seen clearly for the most northern faults due to their proximity to the zone of contact between the African and Eurasian plates.

The NE-SW, NW-SE, E-W and N-S trending faults that have affected the North-African margin have evolved during the tectonic periods and controlled deposition in relation with (i) sinistral displacement of Africa compared to Europe during the Late Jurassic-Early Cretaceous, following the opening of the southern and central Atlantic [160,2,4]; (ii) dextral to convergent displacement of Africa compared to Europe during Campanian-Lutetian [16,168,160]; (iii) collision of Africa against Europe since the Middle Miocene [32,137,168,169,54,47].

All the authors agree on the fact that faulting recognized in outcrop has related the effect of master deep lineaments. Movement of master faults are fossilized in sedimentary series by thickness and facies changes associated with complex structures and accentuated by salt tectonics along various orientations.

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