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Structural styles of the Tellian fold-and-thrust belt of Tunisia based on structural transects: Insights on the subsurface oil and gas pre-salt plays

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Abstract

We present several structural transects throughout the internal part of the Tunisian Tell focusing on some representative structures and domains. We used also an interpreted seismic cross-section and a 3-D structural view to highlight the styles within the Tellian units in the Fernana-Adissa allochthon domain. The structural style is mainly represented by active roof-thrust and duplex structures affecting the Mesozoic-Cenozoic sequences belonging respectively to the infra-Kasseb and Kasseb units. The main decollement thrusting layer is located in the Triassic evaporites, while the roof thrust corresponds to the Upper Cretaceous or to the Paleocene shaly levels. The structural transects allow viewing that the Numidian Flysch unit presents different structural configurations and relationships with its subsurface supporting units; (1) it rests on an apparent stratigraphic contact above the underlying Kasseb nappe or even over pre-existing Triassic salt structures while elsewhere (2) it is detached above these infra-Numidian units reworking an originally downlap contact. The area is also characterized by important halokinetic movements controlling the overall architecture of the Tell fold-and-thrust belt that allows the thrusting of the whole Tellian wedge. In addition, originally apical parts of former diapiric structures were remobilized subsequently as sole thrust allowing the displacement of the Numidian Flysch. The Upper Miocene syn-folding sequences sourced by the erosion of the precedent uplifted reliefs are folded and tectonically transported along some active thrusts by the Tell tectonic units suggesting a recent reactivation and rejuvenation of thrust during the Upper Miocene to Quaternary Alpine events. Since the Late Miocene, shortening is still active today, allowing the refolding of older nappes contacts as well as rejuvenation of inherited faults.

Keywords Maghrebides · Tell · Thrust · Duplexes · Numidian · Kasseb · Triassic evaporites · Paleozoic plays

Introduction and problematics

The Tellian fold-and-thrust belt (Fig. 1) is a collisional belt resulting from the Lower Miocene docking of the Kabylian block against the African north-western plate margin (Durand–Delga and Fontboté, 1980; Wildi 1983; Bouillin 1986; among others). Its internal part is essentially constituted by thick turbiditic series of Oligocene-Lower Miocene age (Carr and Miller 1979; Rouvier 1985; Khomsi et al. 2009b, 2021). The relation between the Numidian series, widely outcropping (Fig. 1) and broadly studied (Rouvier 1985; Yaich et al. 2000; Talbi et al. 2008; Riahi et al. 2010, 2015, 2021; Thomas et al. 2010; Guerrera et al. 2012; Belayouni et al. 2013; among others), and its Meso-Cenozoic substratum led since a long-time to strong discussions, ending in various and often opposite interpretations.

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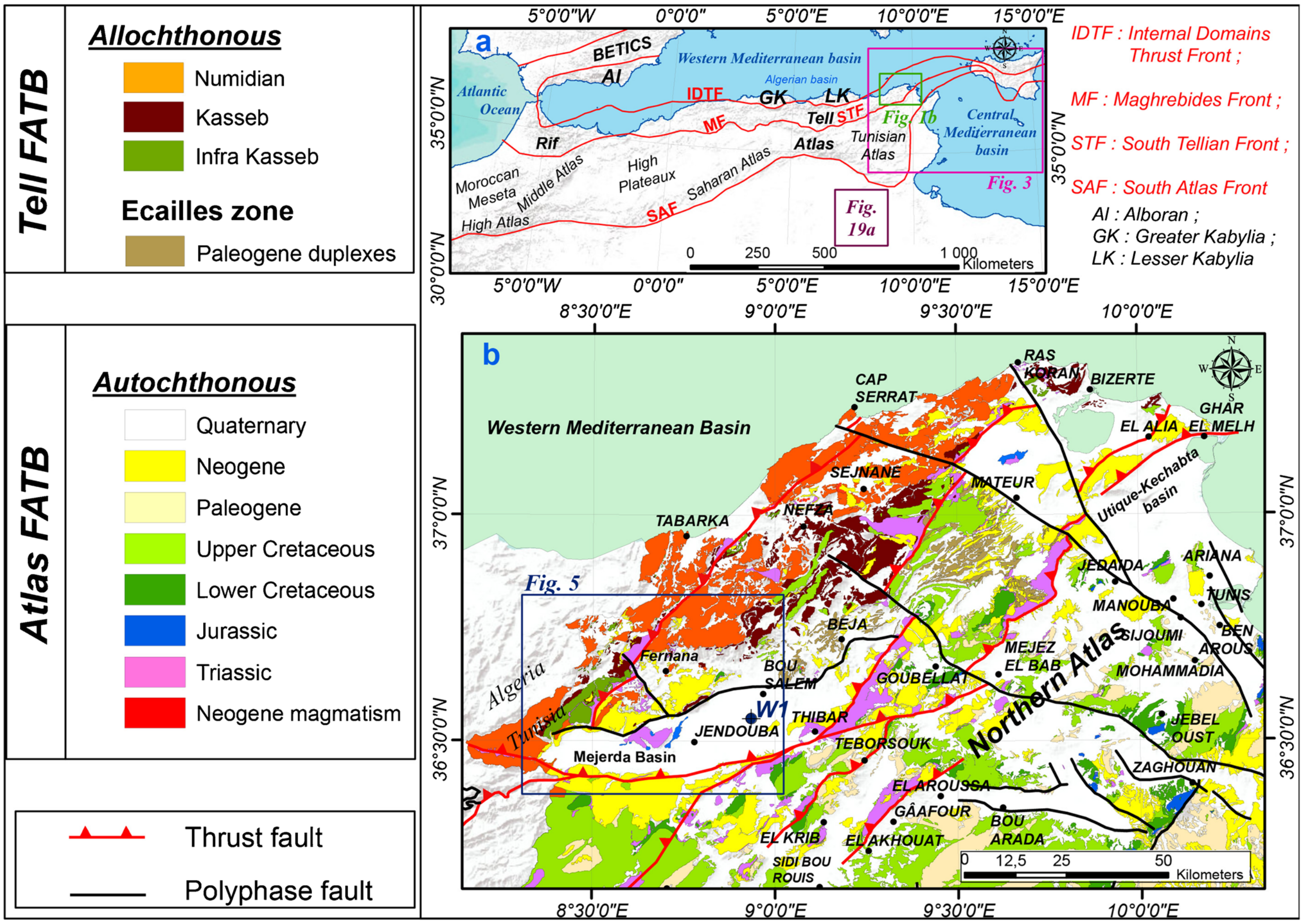


Fig. 1 Structural scheme of North Africa (after Frizon de Lamotte et al. 2000) highlighting the main structural domains: Atlas and Tell-Rif systems (a); geological map of Northern Tunisia (b) with the location of the studied area (Fig. 5)

Many authors, i.e., Gottis (1953), Gottis and Fallot (1962), Kujawski (1964), Crampon (1973), and De Jong (1975), concluded that both the Tellian Mesozoic to Eocene sedimentary units and overlying Numidian Complex represent a conformable sequence of deposits and considered that the Numidian is transgressive over the underlying deformed Tellian series, with a sedimentary hiatus occurring between them during the Priabonian. By contrast, Jauzein (1967) had proposed that only the Numidian is allochthonous. Otherwise, Carr and Miller (1979), Rouvier (1985), El Euchi et al. (2004), and Khomsi et al. (2009b) emphasized the existence of a set of "thrust sheets" characterized by the pile of various allochthonous units where the Numidian series are thrusted over the infra-Numidian units represented by Upper Cretaceous as well as Eocene pelagic limestones of the Kasseb units. It was shown that the Numidian nappe was defined as an "out-of-sequence thrust" (Morley 1988). Since then, several authors did not admit the existence of nappes in the Tell (Tlig et al. 1991; Alouani et al. 1996; Jaafari 1997; Melki 1997; Melki et al. 1999; Talbi et al. 2008). Although the structural styles of the Tellian fold-and-thrust belt are still widely debated, many interpretations from previous work and literature remain controversial. More recently, Khomsi et al. (2021) emphasized the structural relationships between the Numidian Flysch and the underneath structures of Kasseb, showing strong evidences of an onlapping and stratigraphic contact of the Oligo-Miocene Numidian Flysch over the Kasseb units in a piggy-back configuration.

In this paper, we aim to present the configuration of the structural units in the inner part of the Tellian fold-and-thrust belt along the Tunisia-Algeria borders, deciphering their structural relations and allowing proposing a revised deformational model. The timing and tectonic evolution of this part of the Maghrebides belt are also discussed below. In addition, the Mejerda basin and the overall structural evolution of the Northern Tunisian Atlas will be also presented, discussed, and integrated into the regional tectonic evolution. This study is based on the interpretation and integration of all the available surface and subsurface geological and geophysical data by the use of regional structural surface-subsurface transects.

The structural transects in the Tell FABT presented in this work and others (El Euchi et al. 2004; Aissaoui et al. 2016; Khomsi et al. 2019, 2021) emphasize the interest to undertake oil/gas exploration in the Maghrebides. In fact, two major petroleum systems are potentially productive in the Tell: the Pre-salt Paleozoic system and the Meso-Cenozoic system (Khomsi et al. 2019, 2021). In a precedent paper, Khomsi et al. (2021) discussed the interest of the Cenozoic-Mesozoic petroleum system underneath the Tellian allochthon units, emphasizing its importance and high potentialities (see Khomsi et al. 2021). Thus, in this paper, we will focus only on the Paleozoic system and the pre-salt traps.

Tectonostratigraphy and geology of the Tunisian Tell

The Tunisian Tell (Fig. 1) occupies the eastern part of the Tell-Rif orogenic system (Caire 1971; Gélard 1979; Rouvier 1985; Khomsi et al. 2009b, 2016) and results from the progressive closure of the Maghrebian Tethys during the Miocene (Frizon de Lamotte et al. 2009; Khomsi et al. 2016). The compressional deformational pulses reached their climax in the Late Miocene period, resulting in the development of a south-verging accretionary prism in front of the AlKaPeCa (for Alboran, Kabylies, Peloritan, and Calabria; Bouillin 1986) domain until its collision/docking against northern Africa (Catalano et al. 1996; Doglioni et al. 1999; Vergés and Sàbat 1999; Jolivet and Faccenna 2000; Benaouali-Mebarek et al. 2006; Roure et al. 2012; Van Hinsbergen et al. 2014; Khomsi et al. 2016, 2019).

The Tell of Northern Tunisia (Fig. 1) is characterized by several structural units detached and transported towards the southeast. Previous works refer to a geographically variable nomenclature, leading to confusions (see Khomsi et al. 2021), with the definition of more than 7 structural units in Northern Tunisia, based only on typology, lateral facies variations, paleoenvironment records, and biostratigraphic contents. However, and in line with Khomsi et al. (2021), we emphasize that the Tell series of Tunisia can be better subdivided into three major tectonostratigraphic packages (Khomsi et al. 2019, 2021), which account for the overall stratigraphic and structural evolution of the Tell domain of Tunisia and its tectonic history: (i) the allochthonous units represented by the Kasseb units and their lateral equivalents supporting the Numidian Flysch deposits. The Kasseb units rest tectonically on the Langhian Miocene deposits pertaining to the foreland domain of the Tell, (ii) the foreland structures of the Tell represented by the Meso-Cenozoic deposits ending with the major angular/erosional unconformity at the base of the Langhian deposits setup during the post-Eocene compressions, (iii) the foredeep synkinematic layers of the Late Miocene-Quaternary deposits issued from the recent erosion of the rejuvenated structures within many transported minibasins of more than 1000 m of continental deposits.

The following part deals with the description of the lateral facies changes observed between the various structural units, resulting in our subdivision which is therefore based on field observations, geological mapping, and key cross-sections. They are described from the external to internal part of the Alpine chain of Northern Tunisia.

Décollement levels

We have used field data supported by seismic and well data, to localize and identify individual detachment levels (Fig. 2). Obviously, salt is constituting mechanically weak detachment horizon. Therefore, the Upper Triassic series, which are made up of thick salt layers of hundred meters, acted as the main décollement level at the sole and within the Tellian fold-and-thrust system. Thick Cretaceous and Paleogene marl series constitute secondary potential décollement levels. Examining the lithostratigraphic column, we have identified numerous weak horizons within the Lower Cretaceous, Coniacian-Santonian, Paleocene, Middle to Upper Eocene, and infra-Numidian series (Fig. 2).

Importance of the Triassic salt

Both in the onshore as well as in the offshore of the Tellian domain in Tunisia, seismic interpretations (El Euchi et al. 2004; Khomsi et al. 2009b, 2019) show a structural style characterized by Numidian thrust sheets detached over the Triassic salt, whereas the underlying para-autochthonous series were affected by inherited faults and tilted blocks which were subsequently inverted during Eocene and Late Miocene compressional events. The Numidian thrust faults are deeply rooted within the major décollement level represented by the interface between allochthonous Triassic salt and the underlying Mesozoic-Cenozoic para-autochthonous cover. Vila (1980), and more recently, Amri et al. (2020) and Khelil et al. (2021) recognized the occurrence of salt canopies in the foreland domain of the Tell in Algeria and Tunisia, respectively, that might correspond to the long Morocco-Algeria-Tunisia diapiric province that was active since the Early Jurassic as described in Moragas et al. (2018).

On the other hand, it is worth noting that the evaporitic facies of the Upper Triassic series change laterally from SW to NE into dolomites/carbonates when approaching the coastline and in the northern part of the Gulf of Tunis. In fact, in the northern part of the Tell, the Triassic series become more dolomitic with a decrease in the evaporite proportion leading possibly to pure dolomitic series in the Gulf of Tunis (Fig. 3).

Otherwise, and despite the fact that few petroleum wells have been drilled in the Tell, either onshore or offshore, the Triassic series encountered in the wells of the Gulf of Tunis are rather thick with dolomitic facies in their upper part (Melki et al. 2010). By contrast, the Mejerda well shows a predominance of the evaporitic component (Troudi et al. 2017) (Fig. 2). These changes are important in terms of structural control

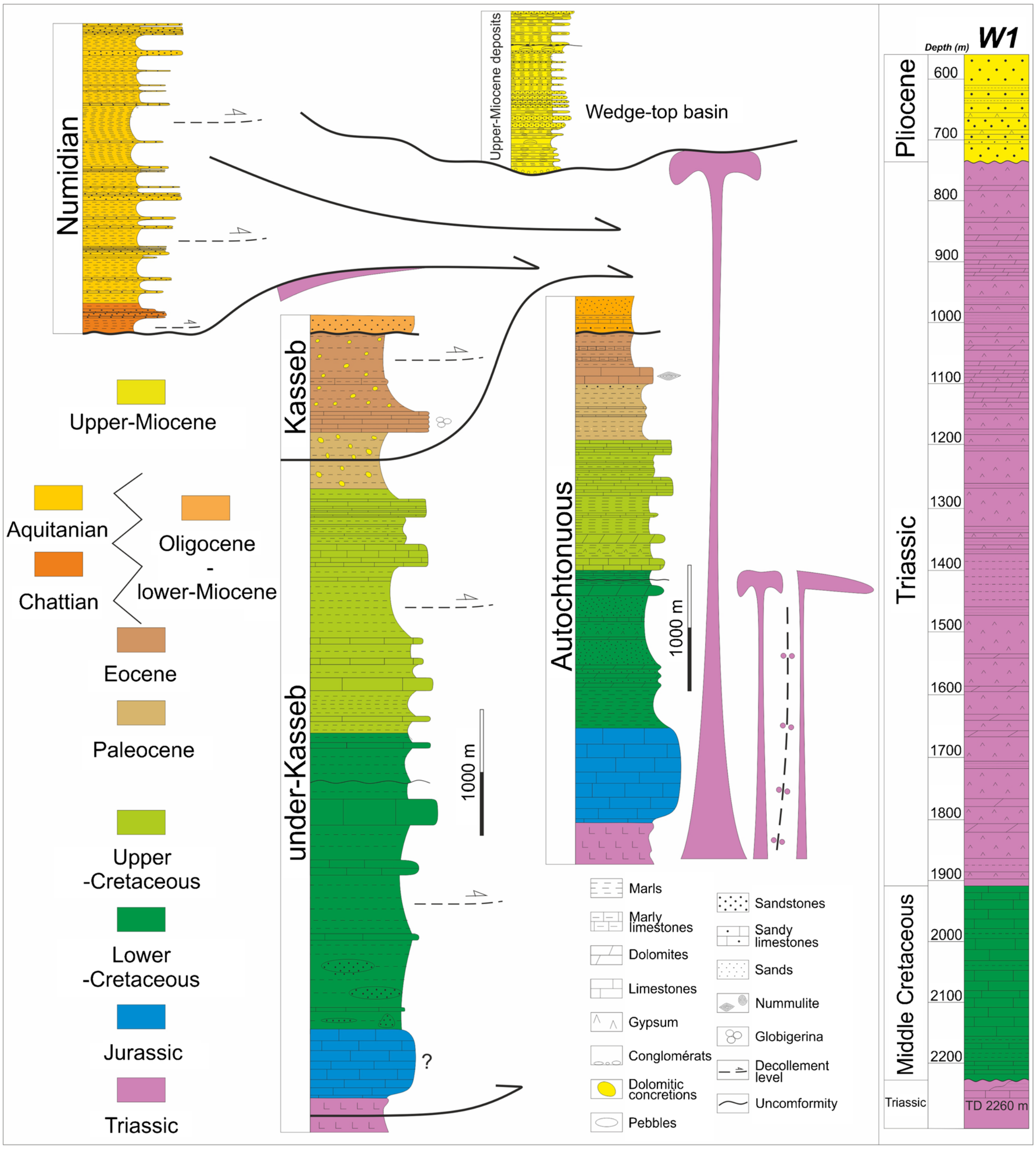


Fig. 2 Lithostratigraphic columns of the different units of the Tunisian Tell and well data (W1) from the Mejerda basin. The well characterizes a thick possibly allochthonous Triassic evaporite body which is overlying Cretaceous series and capped directly with Upper Miocene rocks. The different discontinuities, décollements, and major unit thrusts are presented. Notice that the contact of the Numidian Flysch over the Kasseb units is a stratigraphic contact which was later on reactivated as a tectonic contact during the Alpine compressions

of the deformations and the occurrence of alternative detachment layers, which do not involve here the Triassic-Jurassic interface as in the onshore, but rather involve shallower detachment layers situated within Upper Cretaceous and Paleogene in the offshore.

The southeastern edge of the Tell corresponds to a complicated foredeep (Khomsi et al. 2019; Khelil et al. 2019, 2021) tectonic domain in front of the Tell, in the footwall of the South Tellian thrust front. This area comprises Triassic salt plugs associated with thrusting that occurred during strong Late Miocene-Quaternary Alpine compressions (Khomsi et al. 2019; Khelil et al. 2021). The South Tellian Front is also located in this important deformation zone, along which the Tell domain overthrusts the Neogene foredeep deposits. In fact, this foredeep basin, parallel to the Tellian fold-and-thrust belt, presents locally more than 1300-m-thick Miocene sedimentary sequences, mainly constituted by continental molasse and evaporitic-lacustrine Late Miocene deposits. It constitutes the uppermost part of the sedimentary infill of the Mejerda Valley, reworking some allochthonous

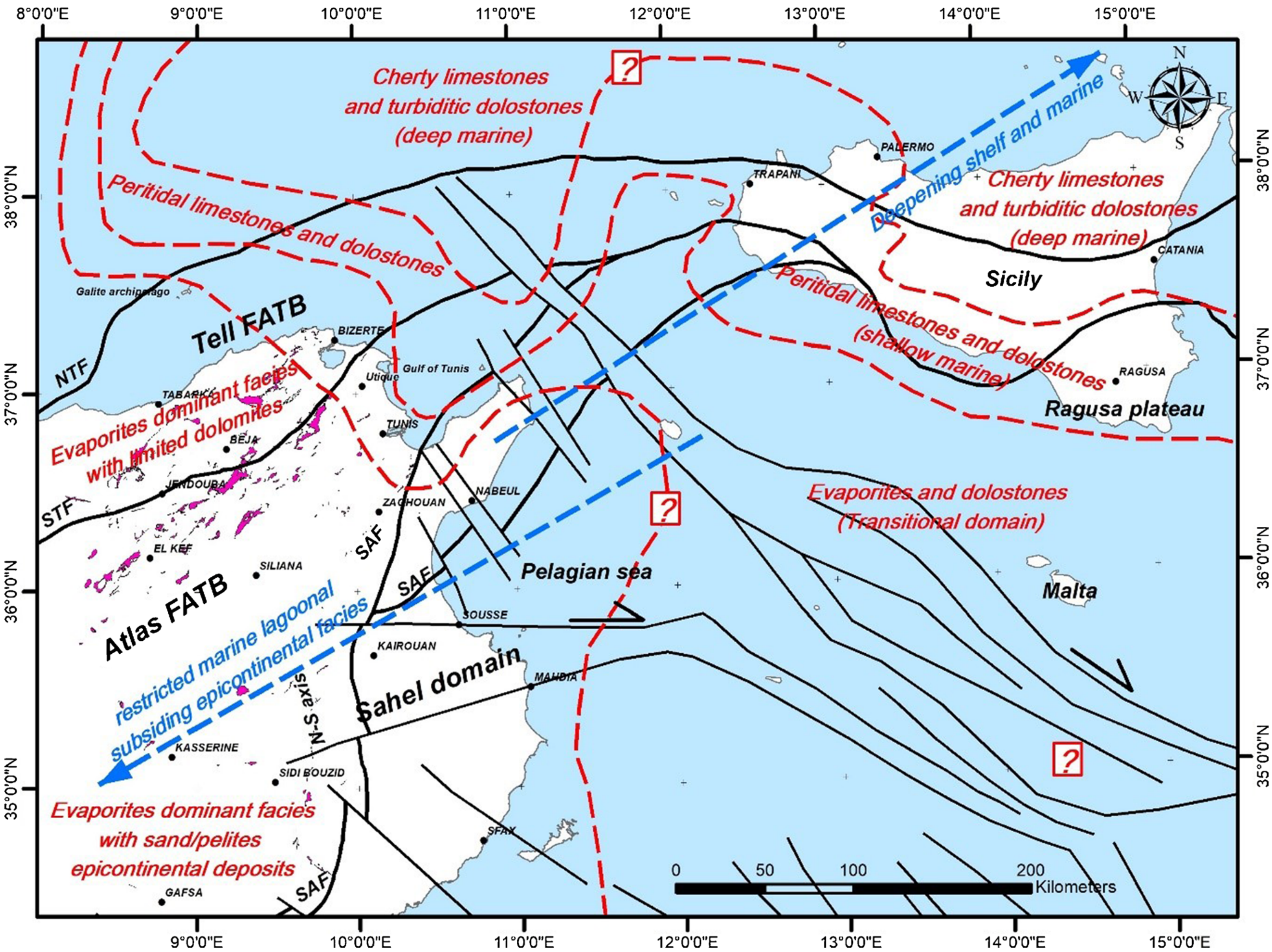


Fig. 3 Present distribution of the Late Triassic facies in Tunisia, Sicily channel, and Sicily (Casero and Roure 1994; Catalano et al. 1996; Di Stefano and Gullo 1997; Kamoun et al. 2001; Soto et al. 2017; in Khelil et al. 2021)

Tellian tectonic units and lying directly on top of the underlying Triassic halokinetic series (Khomsi et al. 2009b, 2016). The Mejerda well (Fig. 2), drilled in the central part of the basin, shows a highly complicated setting with Late Miocene-Pliocene continental deposits overlying unconformably the Triassic evaporites. The latter are locally thrusted on top of the tectonic pile, but elsewhere the Triassic salt remains buried beneath the Upper Cretaceous-Cenomanian strata (Fig. 2).

The tectonostratigraphic units

The infra-Kasseb unit

The infra-Kasseb tectonic unit (Figs. 2 and 4) comprises the entire Mesozoic succession with an average thickness of 2500 m. Its lower part is made up of Triassic salt and breccia which pass to Jurassic carbonates upwards. The Early Cretaceous is characterized essentially by thick clay strata, sandstone at the bottom, and carbonate turbidites at the top of the sequence. The upper part of the Cretaceous succession is made up of interbedded shales and carbonates recording deep-water paleo-depositional environments (Khomsi et al. 2021). The top of this tectonic unit exhibits shales of Paleocene age, which also form the lower part of the Kasseb unit ensuring also the decoupling of the Kasseb units from the underlying Cretaceous structures.

The Kasseb unit

The Kasseb unit (Figs. 2 and 4) is cropping out mainly at the front of the Numidian structures. It comprises Paleocene marls and predominantly Lower Eocene limestones (Globigerina facies), Upper Eocene marls, and Oligocene glauconitic sandstones. Worth noting that these Oligocene sandstones rest unconformably on top of the Paleogene succession and form a lateral equivalent of the Numidian succession with a shallower water paleo-depositional environment. The Kasseb unit of few hundred meters is thrusted mostly on top of Miocene strata.

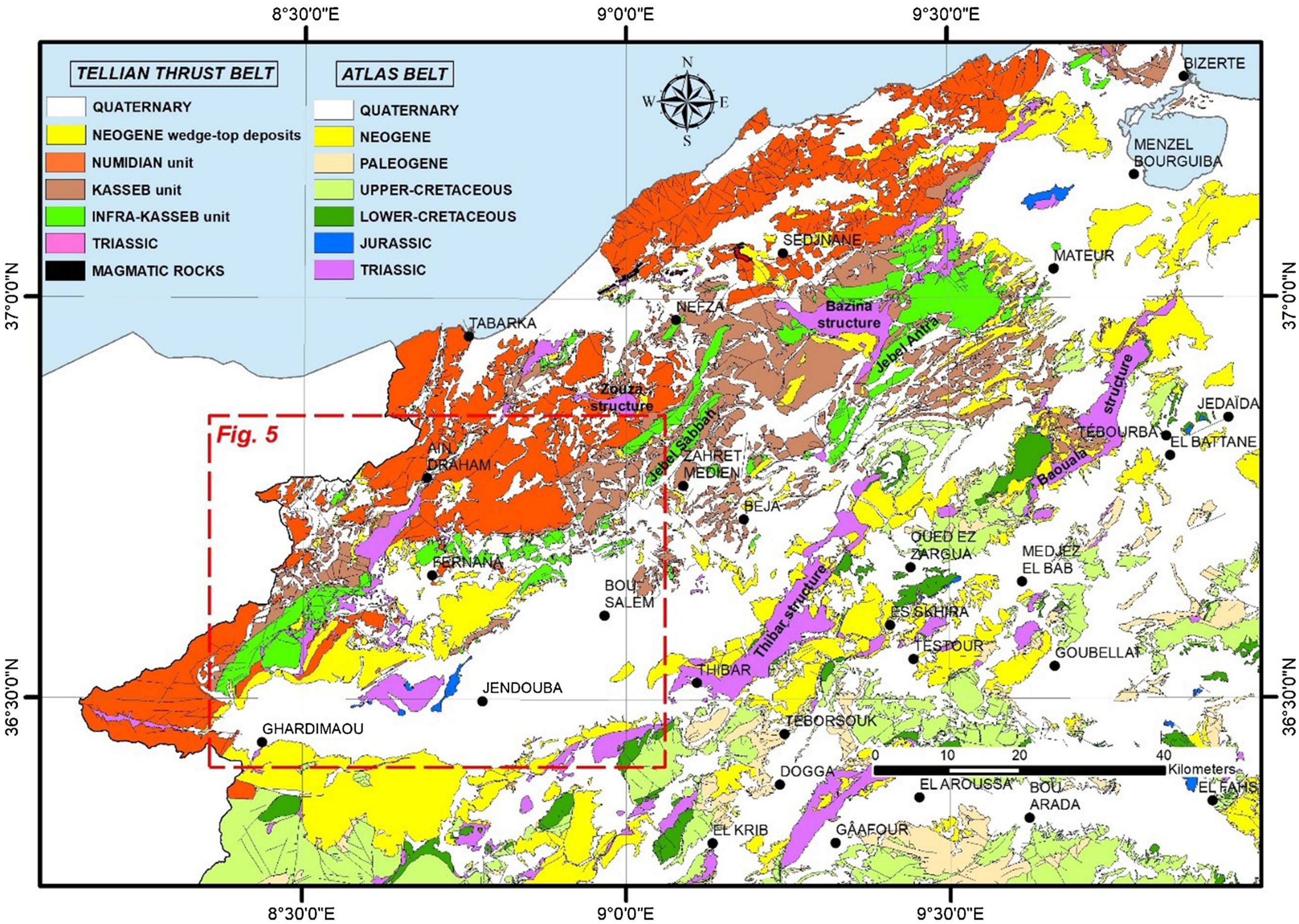


Fig. 4 Northern Tunisia tectono-lithostratigraphic unit mapping (based and compiled from the existing 1/50.000 geologic maps, published by ONM). Notice that the Numidian Flysch occupies the NW corner of the map and is dipping towards the NW with an onlapping lateral configuration above the Meso-Cenozoic structures

The Numidian unit

The Numidian (Figs. 2 and 4) is an important structural unit of the Tellian fold-and-thrust belt. It consists of an alternation of mudstones and quartzarenites with rhythmic character, up to 2500 m thick. The authors agree on the deep-water paleo-depositional environment of the Numidian domain and the turbiditic character of the sedimentation (e.g., Riahi et al. 2010, 2015, 2021). In Northern Tunisia, it is a clay-sandstone formation that crops out over wide areas. It is considered as the shallowest structural unit, resting at the top of the tectonic pile over underlying infra-Numidian units, Triassic breccia, and younger Upper Miocene deposits.

It is worth noting that the Numidian unit crops out along more than 2000 km, from Spain to Italy, across the northernmost parts of Morocco, Algeria, and Tunisia.

Structural styles derived from regional transects and seismic interpretations

Several tectonic phases have impacted the geological history of the Tell, leading to a complex structural configuration. The presented structural cross-sections and transects (Fig. 5) will be discussed to document the structural styles observed within the Tell and Northern Atlas, as well as the geological processes responsible for their setup, and finally the tectonic agenda. These interpretative structural transects were compiled as including a set of data field observations collected through several field-work campaigns in the Tell of Tunisia. The Jebel Rebia, Fernana, the Jebels Adissa and Bessouagui, and ultimately the Kasseb region constitute key outcrops structures for documenting the overall structural style in the Tell. The foreland of the latter (Mejerda basin-Northern Atlas; Figs. 2 and 5) is mostly constrained by seismic interpretations in addition to field observations.

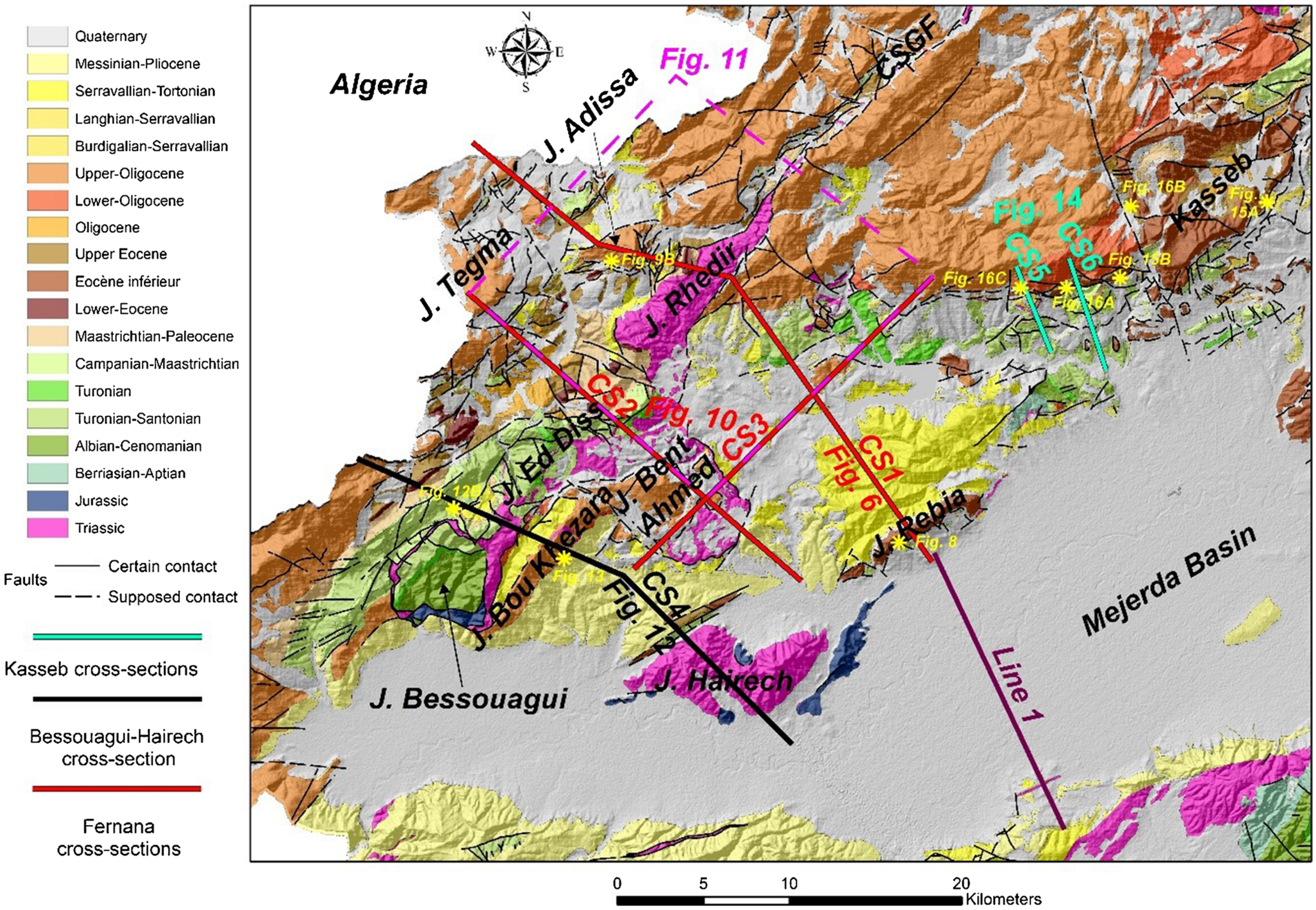


Fig. 5 Geological map of the studied area indicating the emplacement of the different observations, cross-sections, and seismic cross-section (line 1)

Tell fold-and-thrust belt

Fernana cross-sections

The Fernana area is documented here by a set of cross-sections cutting the structures in two orthogonal directions (two NW-SE cross-sections as well as one NE-SW cross-section; positions given in Fig. 5).

Fernana cross-section (CS1) Along the first cross-section, two key outcrops have been investigated in detail in order to better understand the tectonic position of the Kasseb unit (in Jebel Rebia; Figs. 5 and 6) and of the Numidian unit (in Jebel Adissa; Figs. 5 and 6).

The Jebel Rebia corresponds to a thrust anticline structure (Fig. 7) trending N035, limited to the south by the Mejerda Valley (Fig. 5), which is considered as a wedge-top basin (Khelil et al. 2019, 2020, 2021). Locally to the south, blue Jurassic dolomites crop out, forming a part of the Hairech inherited paleo-high (see Martinez and Truillet 1987).

The Rebia anticline northern limb (Figs. 7 and 8A) shows poorly glauconitic sandstones and shales representing the Tellian facies attributed to the Oligocene. The series continue with tabular Lower Miocene conglomerates and breccia (Fig. 8D), which are mostly Ypresian in age. In the Jebel Rebia, the Kasseb unit overlies tectonically the Oligo-Miocene series (Fig. 7 and Fig. 8A, B, and C) and the underlying Campanian carbonates which form the northern limb of the para-autochthonous anticline (Figs. 7 and 8C). This structural unit is affected by a normal fault delimiting to the north of the Fernana wedge-top basin (Figs. 6 and 7), which is filled by Late Miocene deposits derived from the erosion of different units. The infra-Kasseb and Kasseb structural units, covered by the Fernana wedge-top basin, show different structural styles (Fig. 6). The first one is characterized by a duplex geometry with a set of sub-parallel ramps (Fig. 6). The sole thrust corresponds to the Upper Triassic salt representing the main regional décollement. The ramps are merged upward into the upper roof thrust, which is located in the Paleocene marls. The stacked imbricated horses form an antiformal stack (Fig. 6). Then, the Kasseb unit, derived from the unroofing of the underlying duplexes, has been detached from its initial substratum and moved forelandward to the south, defining thereby an active roof duplex. The forward propagation of the roof thrust induced the formation of ramps (Fig. 6). The roof thrust is emerging at Jebel Rebia (Figs. 6 and 7) while

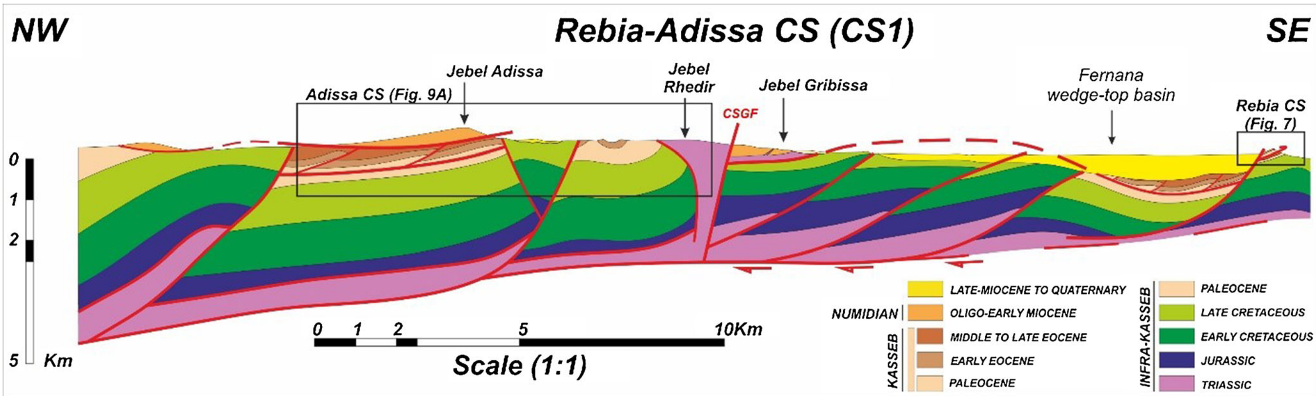


Fig. 6 NW-SE cross-section (CS1) through Jebels Rebia, Rhedir and Adissa, showing the main structures and structural styles; the location is given in Fig. 5. Notice on CS1 transect the Late Miocene-Quaternary synkinematic thrusting/folding deposits

individual ramps were covered later by post-orogenic molasse deposits, after the setup of the Fernana wedge-top basin.

Because they are located beneath the thick and widely distributed Numidian Flysch unit, infra-Numidian units are poorly exposed at the surface in Northern Tunisia, except in the Nefza and Jebel Ben Amara tectonic windows (Khomsi et al. 2021). Casually, these sparsely exposed series crop out around the Jebel Adissa which forms a Numidian klippe. Therefore, we considered the Jebel Adissa as an important sector to study the relations and styles of these various structural units.

The Numidian sandstones of Jebel Adissa are truncated at a north-vergent contact and overlie tectonically the Kasseb unit. The basal thrust of the Numidian allochthon is well exposed and cuts down-section in the transport direction (Figs. 6 and 9). According to Morley (1988), an out-of-sequence thrusting model could explain such thrust geometry, which is mostly characterized by simple relationships, younger rocks over older ones, in contrast to a low-angle normal fault model proposed in former publications (De Jong 1975; Rouvier 1985). Nevertheless, we agree that this fault is not a thrust but instead corresponds to the frontal part of a low-angle listric fault (spoon-shaped) which resulted from slope instabilities and then to topographic readjustments. Originally, the contact is a sedimentary contact marked by downlaps/lateral onlapping (Fig. 9). The Upper Paleogene unit shows a duplex configuration with the Paleocene marls from the basal décollement (Figs. 6 and 9A). Most of the outcropping series are dipping towards the north, forming duplicated slices. However, we have noticed at Jebel El Tebaga the occurrence of numerous folds (Fig. 9A). This is related to the impediment of thrust

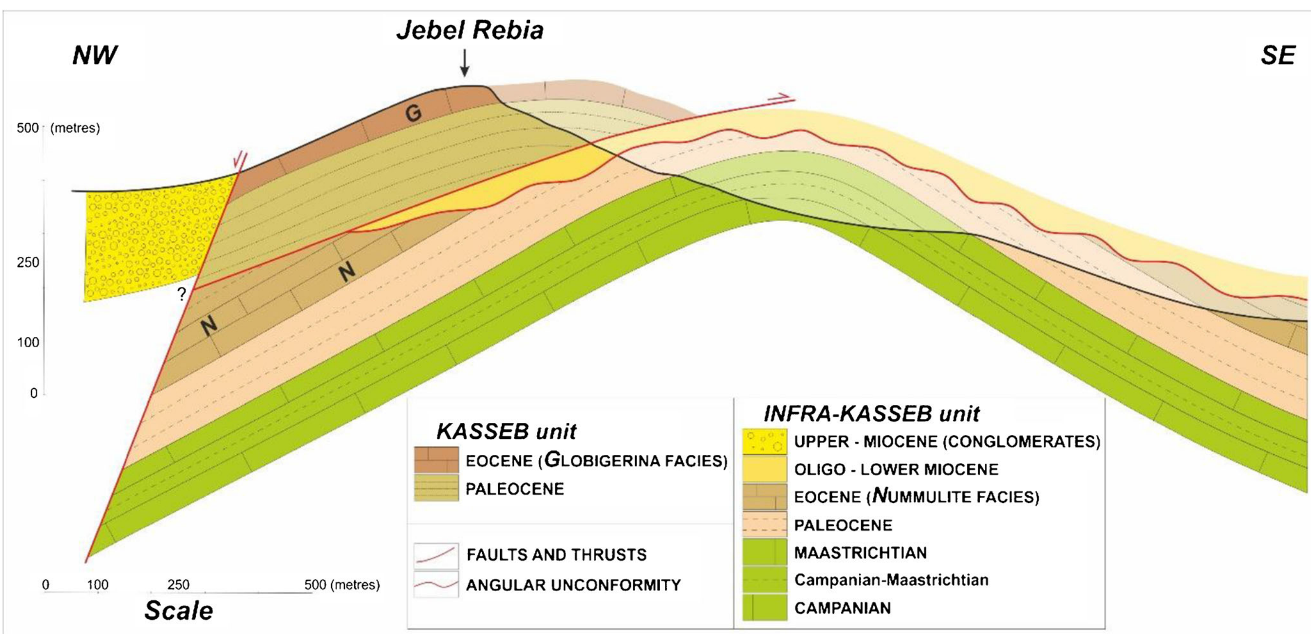


Fig. 7 NW-SE Jebel Rebia cross-section showing mainly the tectonic superposition of the Ypresian limestones (Globigerina facies) over the folded Meso-Cenozoic autochthon (nummulitic facies); the location is given in Fig. 6

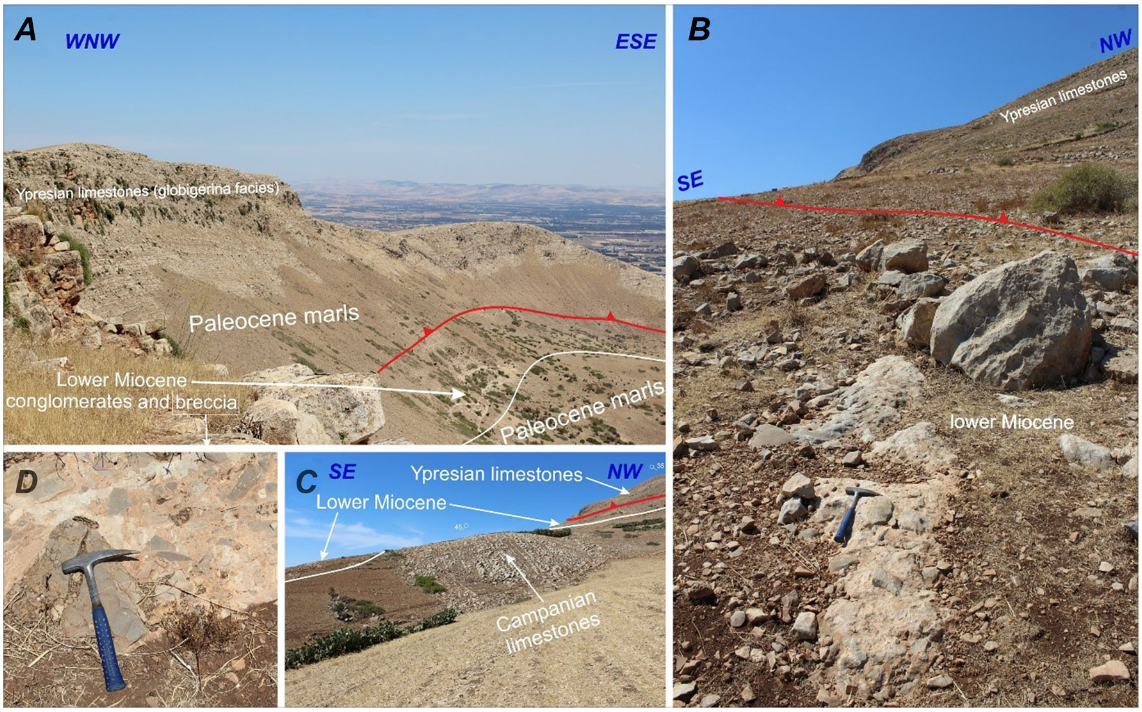


Fig. 8 Interpreted field photos from Jebel Rebia outlining (A+B) the thrusting of Kasseb unit over the Lower Miocene series and (C) over the folded Campanian limestones and (D) tectonic breccia from the Lower Miocene deposits; the location of the photos is shown in Fig. 5

propagation caused by the Cap Serrat-Ghardimaou master fault. This is confirmed by the development of back-thrusting at Kef Ach El Agab (Figs. 6 and 9A).

Fernana cross-section (CS2) The second cross-section (CS2; position given in Fig. 5) goes from Jebel Tegma in the NW to Jebel Halloufa in the SE (Fig. 10). From NW to SE, it shows the Jebel Tegma and Kef Kribissa duplex structures, with repeated sections of the Kasseb unit supporting the detached Numidian unit above (Fig. 10). The major detachment level is situated within the Paleocene shales. The Jebel Tegma anticline and the Jebel Kribissa NW-dipping monocline are separated by a vertical NW-trending transcurrent fault cutting through the entire subsurface structures and presumably related to inherited deep faulting rejuvenated during the Late Miocene-Quaternary compressions.

In the middle part of the transect, the Triassic evaporite of the Jebel Debagh crops out (Fig. 10). It corresponds to a salt-

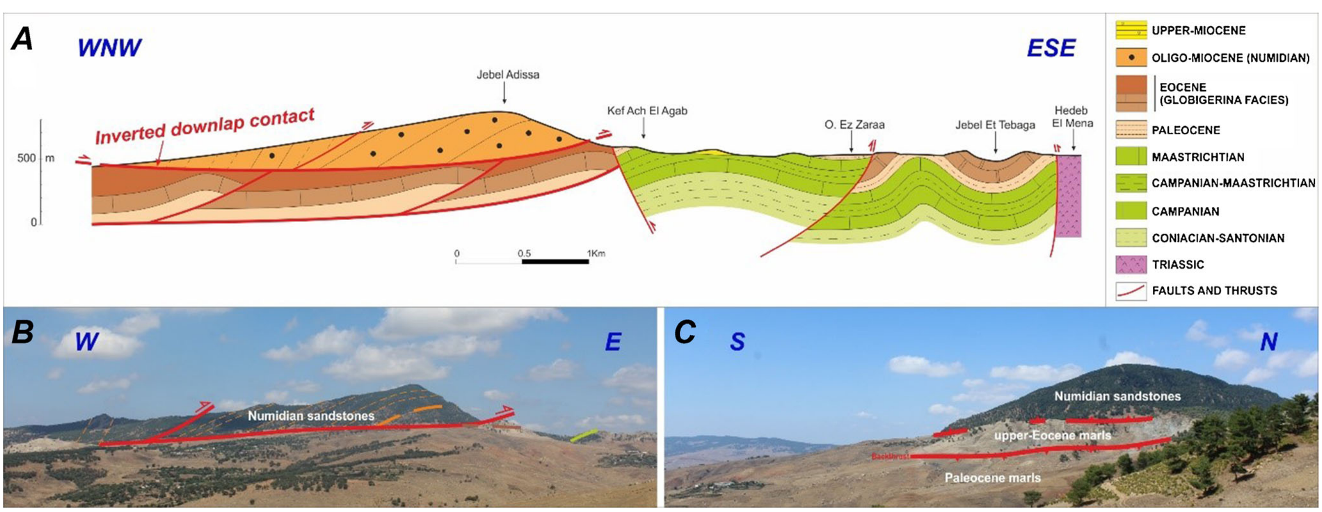


Fig. 9 (A) WNW-ESE Jebel Adissa cross-section (CS1) showing the structures below and around Jebel Adissa Numidian klippe, (B+C) respectively looking N and W interpreted photos of the outcrop; the location of A is given in Fig. 6 and of B in A. Notice that the basal contact separating the Numidian from the underlying units corresponds chiefly to a downlap erosional surface which was reactivated later on during the Alpine Late Miocene-Quaternary thrusting events

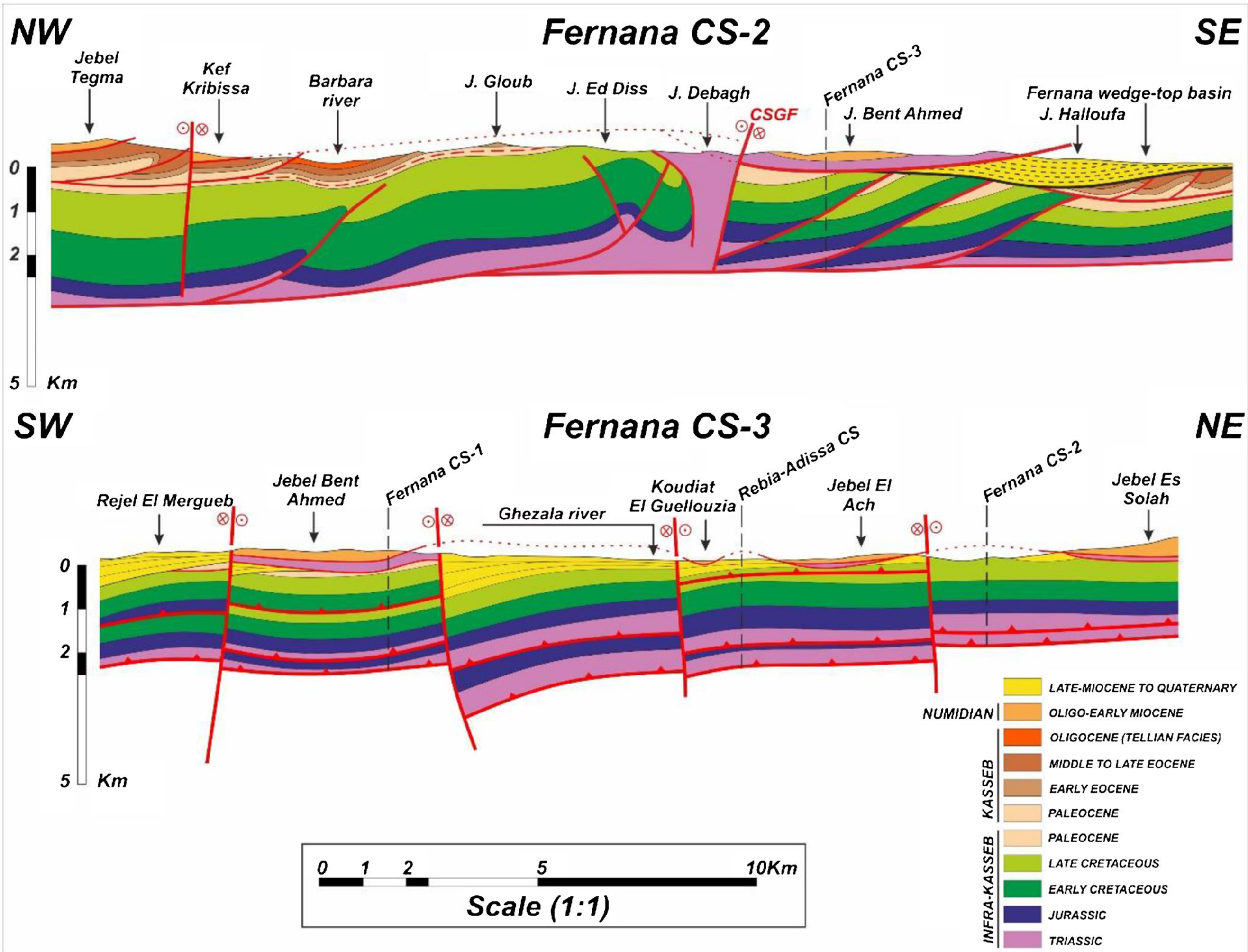


Fig. 10 Structural transects CS2 to CS3 in the Fernana area. Notice the importance of vertical Triassic salt movements. The structural styles presented on the dip section CS2 is predominantly thin skinned with an episode of thick-skinned tectonic materialized by NW-SE transcurrent strike-slip subvertical faults occurring during Late Miocene-Recent

cored structure, probably an ancient Cretaceous diapiric structure. This diapiric structure is limited by two faults: the western fault on the western limb and the eastern fault on the eastern limb. This diapir seems to be controlled by a major and well-known tectonic lineament of the Tunisian Tell, i.e., the Cap Serrat-Ghardimaou Fault (CSGF; Fig. 5). On its western edge, the diapir of Jebel Debagh overhangs the eastern limb of the Jebel Ed Diss anticline, thus corresponding to a major pop-up structure controlled by two opposite dipping thrust faults. The Triassic salt overhangs eroded Late Cretaceous strata (Fig. 10). To the east of the CSGF and Jebel Debagh, the transect crosses the Jebel Bent Ahmed structure, which corresponds to an outcropping syncline structure. There, a low-angle out-of-the-syncline thrust has unrooted and transported horizontally the Triassic salt, overhanging a deeper duplex anticlinorium (Fig. 10). The latter is made by duplications of Jurassic-Cretaceous strata, admitting the Triassic salt as the lower décollement level and the Late Cretaceous-Paleocene shales as roof décollement. To the east, the Triassic salt of the Jebel Bent Ahmed overhangs tectonically, at its most eastern edge, the Late Miocene Fernana wedge-top basin, which is filled by more than 1200 m of Late Miocene to Quaternary continental sands, shales, and conglomerates. These wedge-top basin deposits overlap unconformably the underlying duplex structure made up of the duplicated Kasseb unit

Fernana cross-section (CS3) This transect has a strike direction (CS3; position given in Fig. 5), being parallel to the dip of strata. It was compiled to show a three-dimensional view of the structure and better characterize two distinct sets of faults, i.e., NE-trending thrust faults and orthogonal NW-trending transcurrent polyphased faults. In fact, we can distinguish 4 major subvertical and transcurrent faults separating 5 structural compartments, i.e., from SW to NE: Rejel El Mergeb, Jebel Bent Ahmed, Ghezala River, Jebel El Ach, and Jebel Es Solah (Fig. 10).

These different panels are resulting from the tectonic activity of the inferred strike-slip faults which seem to control block tilting and differential infilling for the Late Miocene-Quaternary wedge-top deposits. The recent reactivation of this transcurrent fault system seems post-date the emplacement of the nappes duplexes, because the nappe contacts are crosscut by the system orthogonally.

A 3-D view with a map allows visualizing the junction of the different units spatially (Fig. 11).

In fact, this 3-D view plunging towards the N depicts clearly the local morphotectonic configuration, with transcurrent NW-trending strike-slip faults cross-cutting all the tectonic units and structures (Fig. 11).

It is worth noticing that the Triassic salt diapir south of Jebel Ed Diss is crosscut by the southernmost strike-slip fault, with a left-lateral horizontal offset of more than 2 km (Fig. 11).

Jebels Bessouagui-Hairech cross-section (CS4) North of Jebel Bessouagui (Fig. 12A), the Numidian, Kasseb, and the infra-Kasseb units are involved in the same overall structure, which is best described as an antiformal stack of duplexes (Fig. 12A).

This entire structure is thrusted forelandward over the infra-Kasseb series; the sole thrust corresponds to the Upper Triassic evaporites, which represents the main regional décollement. In Jebel Bessouagui, the Kasseb unit issued from the unroofing of the underlying unit is detached and moved forward farther to the south (Fig. 12A). The Santonian shale forms an intermediate décollement layer with the development of duplex or horse structures made up of Campanian-Maastrichtian limestones and Upper Miocene deposits (Fig. 12A and B). Viewing towards the north, a field photo (Fig. 12B) shows a syncline formed by the same series, lying over the Triassic salt. This syncline is interpreted as resulting from an out-of-the-syncline thrust detached and transported towards the south over the salt. On the other hand, south of CSGF, the Jebel Bou Khezara is essentially formed by the Numidian Flysch. The latter overlies tectonically the Upper Miocene to Quaternary deposits which are essentially made up of shales, gypsum, and conglomerates (Figs. 12A and 13). The Triassic salt and tectonic breccia constitute the tectonic contact supporting the Numidian Flysch (Figs. 12A and 13). These evaporites are likely to correspond to a former salt glacier or salt canopy developed along the Cap Serrat-Ghardimaou Fault (CSGF) during the Cretaceous.

The Jebel Chouichia (Fig. 12) corresponds to a monocline structure trending N035, limited to the north by the Fernana wedge-top basin and to the south by the Triassic and Jurassic rocks belonging to Jebel Hairech. In the same area, the Kasseb unit series are cropping out at Jebel Chouichia. We have adopted here the same structural interpretation as for the Jebel Rebia cross-section, with the infra-Kasseb and Kasseb structural units covered by the Fernana wedge-top basin (Fig. 12A), thus characterizing again an antiformal stack. The thrust faults join together upward into an upper roof thrust made up of Paleocene marls. In a similar way as in the previous cross-section, the Kasseb unit issued from the unroofing of the underlying duplexes is detached and moved forward towards the south, thereby accounting for an active roof duplex.

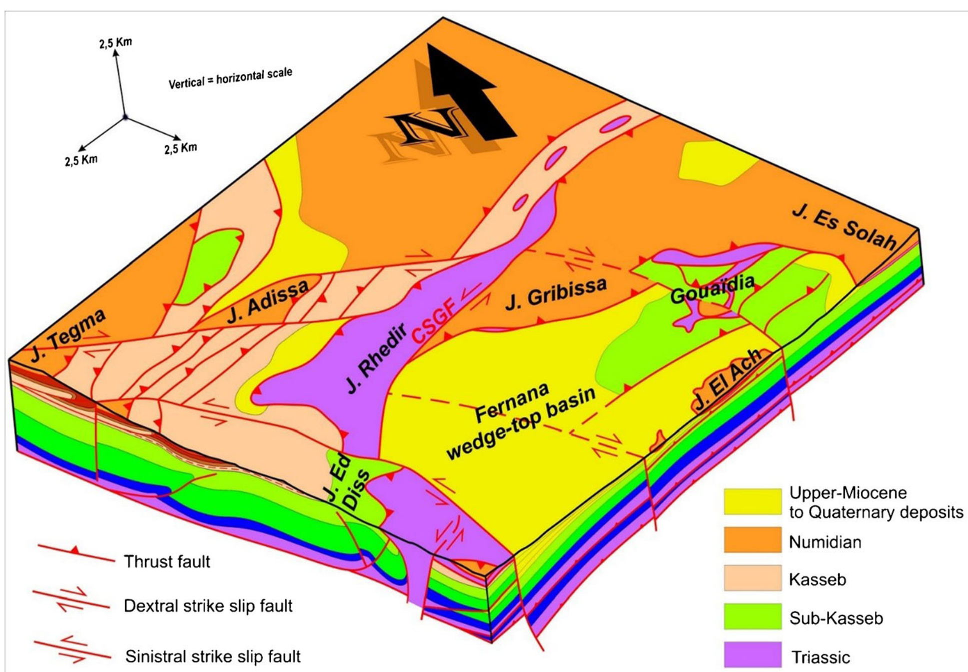


Fig. 11 Structural 3-D view looking North showing the major structures and structural styles. Notice that the transcurrent NW-SE fault crosscut the structures as Jebel Rhedir Diapir and rooting deeper underneath the allochthon cover. Location is given in Fig. 5

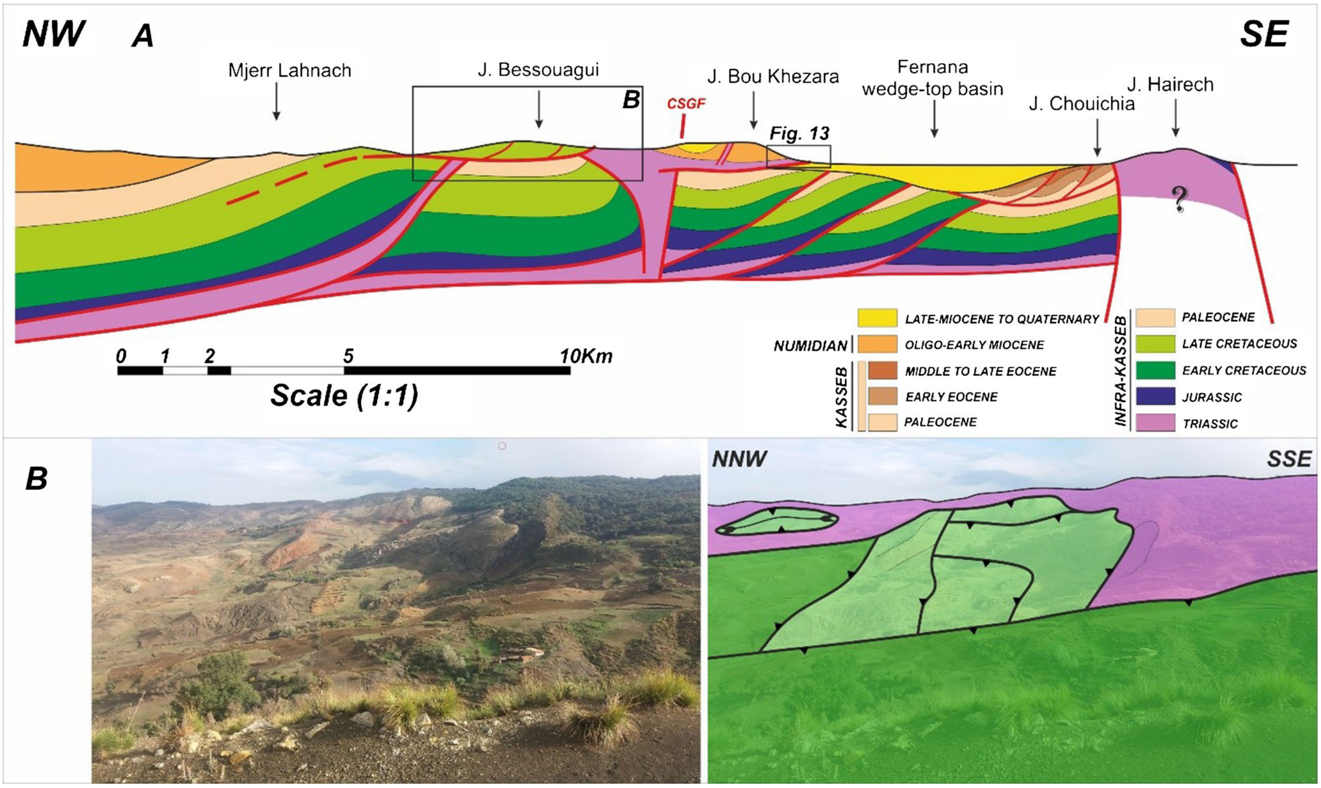


Fig. 12 NW-SE cross-section through Jebels Hairech, Bou Khezara, and Bessouagui (A), showing the main structures and structural styles (the location is given in Fig. 5) and looking E interpreted field photo (B), showing a duplex structure affecting Upper Cretaceous series at Jebel Bessouagui (the location of the photo is located in A)

Kasseb cross-sections

The Kasseb area (Fig. 5), where the Kasseb unit was first described by Rouvier (1985), contains important outcrops outlining the different structural relations between the Kasseb unit, the Numidian unit, and overlying Miocene series, characterized by the Bejaoua facies (cross-sections, Fig. 14). Along their southern and eastern limits, the Ypresian limestones, made up of pelagic and organic-rich Globigerina facies (Khomsi et al. 2018, 2021), overhang tectonically the Aquitanian-Langhian marine sandstones of the Bejaoua Group (Fig. 15A). These Miocene deposits are unconformable over the Mesozoic to Paleogene series, including the Ypresian nummulitic limestones which belong to the para-autochthonous sedimentary package equivalent in time of the Kasseb deep marine sequence.

The para-autochthonous series were presumably folded during the Middle to Late Eocene (the so-called “Atlas Event” (e.g., Frizon de Lamotte et al. 2000, 2009; Khomsi et al. 2004, 2009a; Frizon de Lamotte 2005)) while the overthrusting of the Kasseb unit over underlying Miocene deposits occurred during the Neogene Alpine orogeny.

In the Kasseb area, to the northeast of Jebel Bou Khezara (Figs. 12 and 13), the Numidian Flysch unit occupies different structural positions. In fact, the Numidian sandstone bars show an apparent continuous stratigraphic contact (Khomsi et al. 2021) with underlying deep marine deposits of the Kasseb unit (i.e., Kef Es Salah; CS6 of Fig. 14 and Fig. 16A and B). Alternatively, some contacts between the two units correspond to a synsedimentary normal fault (i.e., Kef Sidi Youssef; CS5 of Figs. 14 and 16C) which can be attributed to the Oligocene quiescence period (Khomsi et al. 2009b, 2016). Because the Numidian Flysch in this region presents locally an apparent stratigraphic continuity with the Kasseb unit, it was thus transported and thrusted towards the south jointly with the Kasseb unit, this unique Kasseb-Numidian assemblage overhanging the already structured para-autochthonous Mesozoic to Paleogene series (Fig. 14).

At Kef Es Salah (CS6 of Fig. 14), the duplicated Eocene limestones belonging to the Kasseb unit form a duplex (Figs. 14 and 15B) with a sole thrust located in the Paleocene shales.

On the one hand, the Mesozoic series (namely Zaflana section, Rouvier 1985) in front of the Kasseb unit pertains to the para-autochthonous series. It is affected by a set of thrust faults duplicating the Upper Cretaceous series which crop out around Kef Guaria and to the north of Kef Rhezal (Fig. 14).

On the other hand, and as a whole, the structural configuration of the Kasseb area is complicated by the N160 Balta sinistral strike-slip fault which affects the whole structure and contributes to its tectonic transport towards the south. In fact,

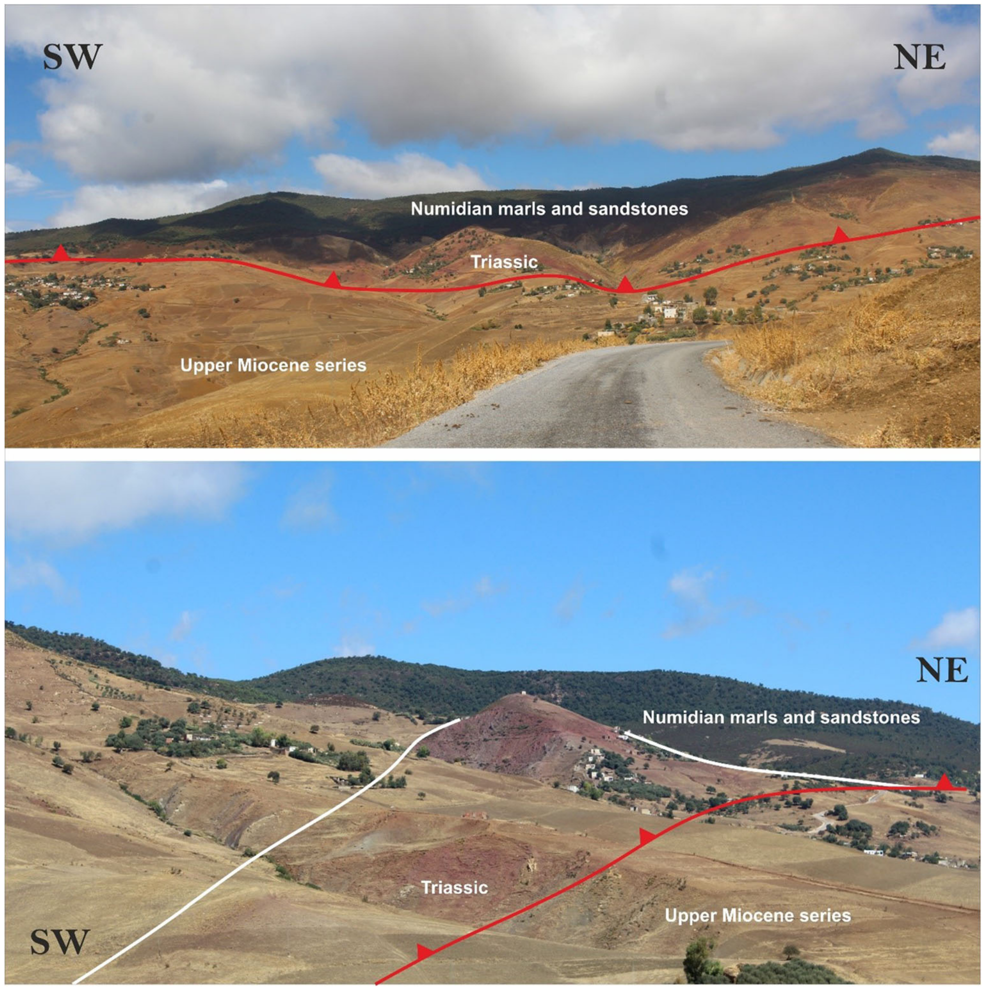


Fig. 13 Interpreted looking NW field photos from Jebel Bou Khezara outlining the thrusting of the Numidian unit over the Upper Miocene wedge-top deposits where the Triassic salt decorates the contact

the horizontal lateral displacement of the Numidian front amounts to 6 km along this transcurrent fault (Fig. 5).

South Tellian Front: the Mejerda basin

The Upper Miocene Mejerda basin is a major graben lying at the boundary between two distinct fold-and-thrust belts: the allochthonous Tell to the north and the inverted foreland domain of the Northern Atlas to the south (Khelil et al. 2019, 2020). It is filled by Upper Miocene to Quaternary deposits. Several diapirs are documented in the Mejerda zone (El Euchi et al. 2004; Khomsi et al. 2009b; Amiri et al. 2011; Ayed-Khaled et al. 2015). Although developed in an overall contractional context with the thrust emplacement of allochthonous nappes and mountain-building processes of the Tell, the Mejerda basin is characterized by dominantly extensional deformation affecting Neogene-Quaternary deposits (Khelil et al. 2019, 2020).

The structural interpretation of the seismic section (line 1; Fig. 17) documents the occurrence of a major extensional tectonic event as outlined by a set of normal and faults (Fig. 17), which controlled local thickness variations within the Miocene to Quaternary series. The innermost normal fault represents the northern tectonic boundary separating the Mejerda basin from the Tell. This extensional fault boundary does not match with the overall regional Miocene to present-day tectonic framework which corresponds to a contractional episode. Therefore, the Mejerda basin build up is a result of special conditions (Khelil et al. 2019) related to salt diapirism that created several deep minibasins (Fig. 17).

The Jebel Hairech (Figs. 5 and 12) is made up of two NE-trending anticlines structures, separated by a syncline showing highly brecciation (Ghorabi and Henry 1992; Martinez and Truillet 1987). It presents two distinct stratigraphic series; the first one is Triassic (Perthuisot 1978; Rouvier 1985) and the second one dates from Liassic times (Rouvier 1985; Alouani 1991). These rocks were affected according to Ghorabi and Henry (1992) by burial metamorphism, which caused the crystallization of strongly oriented phyllosilicates. This metamorphism was developed before the main Alpine folding and after a local tilting episode (Ghorabi and Henry 1992). The exhumation of these metamorphic rocks is related to the local extension characterizing the Mejerda basin in front of the Tellian wedge during the Alpine orogeny.

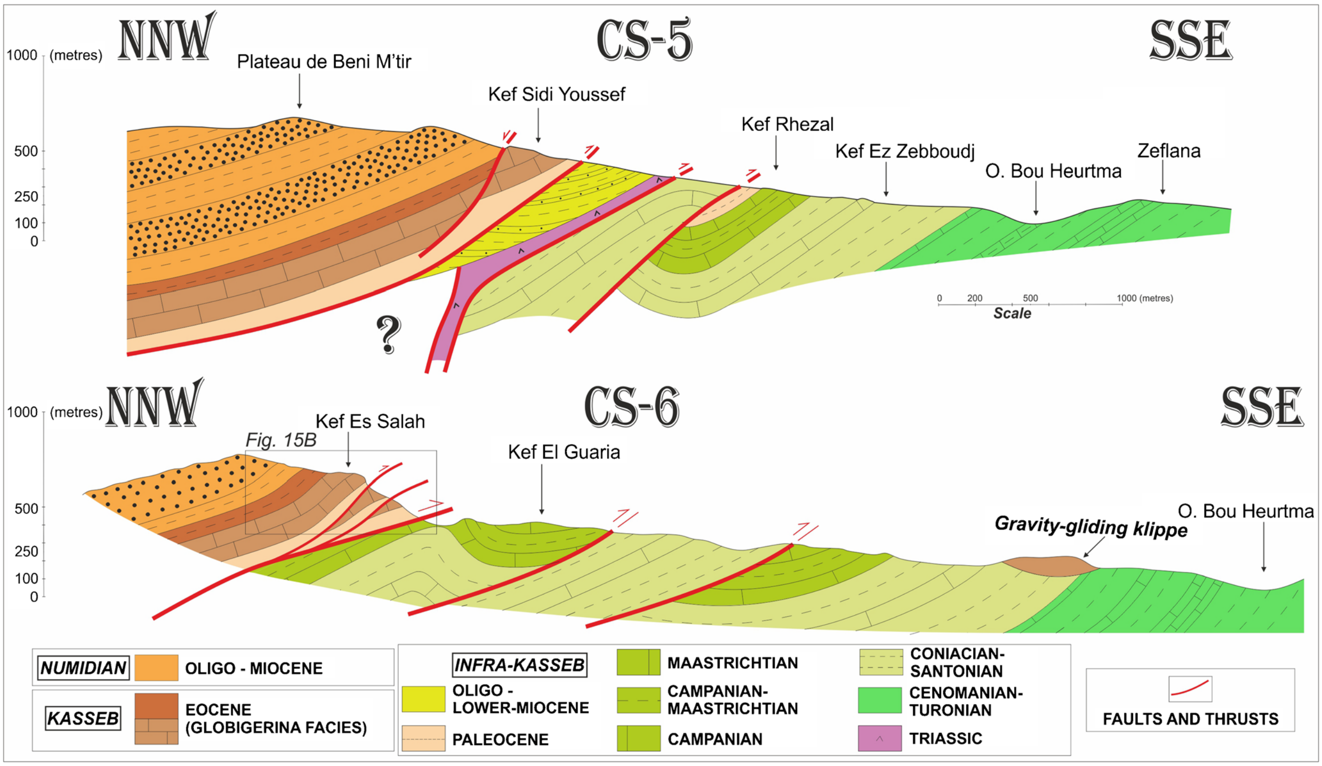
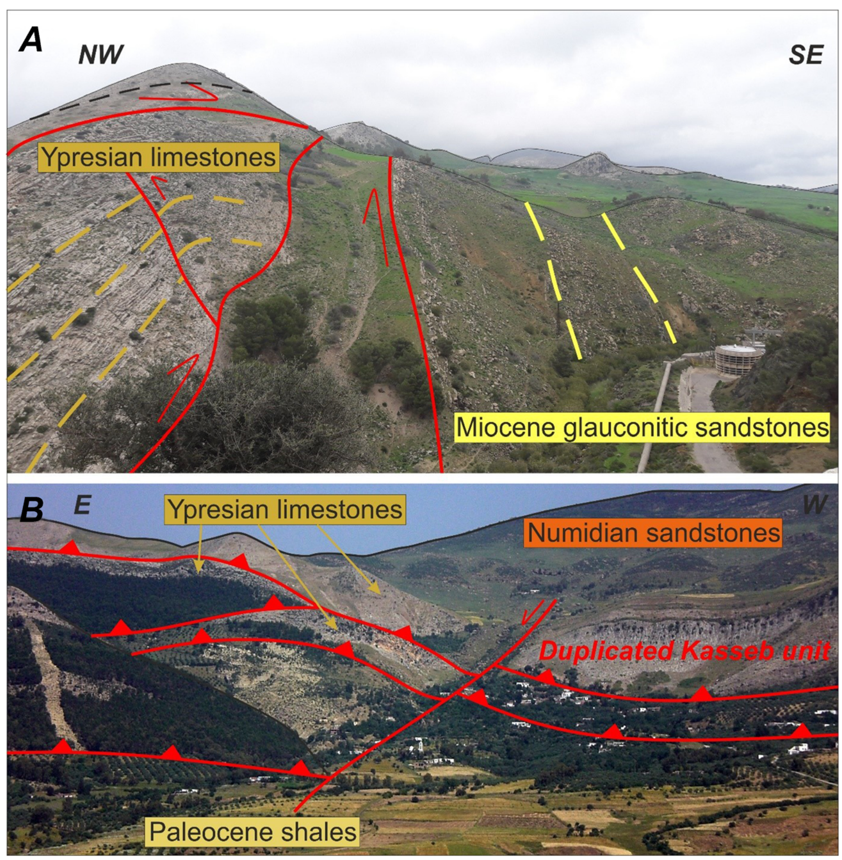


Fig. 14 NNW-SSE cross-sections through Kef Sidi Youssef (CS5) and Kef Es Salah (CS6) showing the structures at the front of the Kasseb unit; location is given in Fig. 5

Fig. 15 Interpreted field photos showing the structural relations between the different units: (A) looking NE photo of the Ypresian limestones thrusts Lower Miocene sandstones and (B) looking to the North panorama showing duplications of the Ypresian limestones belonging to the Kasseb unit. Notice the apparent stratigraphic continuity of the Numidian over the Kasseb unit



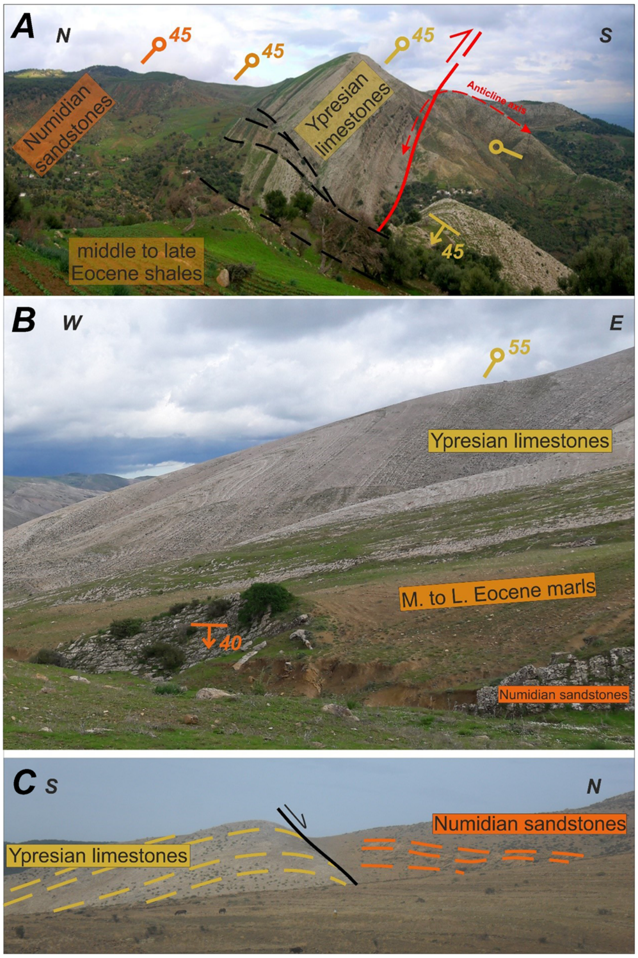


Fig. 16 Different relations between the Kasseb and Numidian units. (A and B) Looking respectively E and N photos showing conformal series formed by Ypresian limestones of Kasseb unit and the Numidian sandstones and (C) looking W photo of a normal fault separating the Kasseb and Numidian units. Location is given in Fig. 5

Discussion

Revised tectonic styles

The analysis of field data allowed us to distinguish several superimposed structural units, resulting from thrust tectonics with horizontal displacements of different styles and magnitudes. For instance, we have differentiated three main structural units, i.e., from bottom to top, the infra-Kasseb, Kasseb, and Numidian units, and the two first units being also known as infra-Numidian units.

Through the observations made in this paper, several deformation styles (Fig. 18) are described:

(I) Covered by the thick Neogene wedge-top basins and/or the Numidian deposits, the infra-Kasseb unit is characterized by several thrust slices (Fig. 18A and C); the sole décollement is represented by the Triassic salt while the roof thrust is embedded mostly in Santonian or Paleocene marls (as demonstrated to the north of Jebel Bessouagui). This unit forms active antiformal stacks (Figs. 6, 10, and 12).

(II) The roof thrust (Incipient Kasseb décollement, Fig. 18A) was activated to displace shallower but basinal and not yet deformed Paleogene units towards the south (Fig. 18C). The forward propagation of this roof thrust was hampered, inducing the propagation of thrusts affecting the Kasseb unit, thus resulting in local duplex structures (Fig. 18C and D). The Kasseb unit is interpreted as made up of a succession of active roof thrust structures (Figs. 6, 10, and 12; i.e., Jebel Rebia).

(III) The Numidian unit overlies these tectonic duplex/horse units and shows different deformation styles:

(III-1) It is sealing unconformably the underlying structures (see Khomsi et al. 2021) and then constitutes a neo-autochthon series (Fig. 18D), transported jointly towards the south with the Kasseb unit (i.e., in the Kasseb area).

(III-2) The Numidian unit is also locally and slightly displaced towards the South near the morphologic top of the Tell over north-verging low-angle normal faults remobilizing mostly Triassic salt (i.e., Jebel Bou Khezara; Fig. 18C), due to topographic instability induced by the stacking of the underlying infra-Kasseb and Kasseb structural units. The salt was cropping out during pre-inversion times (Fig. 18B; Khelil et al. 2020).

(IV) Localized wedge-top basins (Fig. 18E) are filled with Miocene to Quaternary deposits and developed since the Late Miocene in a similar way as in the model proposed by Platt and Leggett (1986). These minibasins are mostly related to the wedge topographic readjustment or mostly in relation with salt collapse (Fig. 18E and F).

Regional tectonic events

In this final part, we propose a tectonic calendar that encompasses the regional events affecting the Tellian zone. The timing of this tectonic evolution is based on our observations and interpretations, coupled to those of our antecessors (e.g., Carr and Miller 1979; Rouvier 1985; Morley 1988; Khomsi et al. 2004, 2009b, 2009a) as well as on the tectonic scenario documented in Algeria (e.g., Frizon de Lamotte et al. 2000; Bracène and Frizon de Lamotte 2002; Benaouali-Mebarek et al. 2006; Roure et al. 2012) and Morocco (e.g., Frizon de Lamotte et al. 2000; Missenard et al. 2007).

The former Tellian basin, along the African plate margin, registered multiple rifting and inversion episodes:

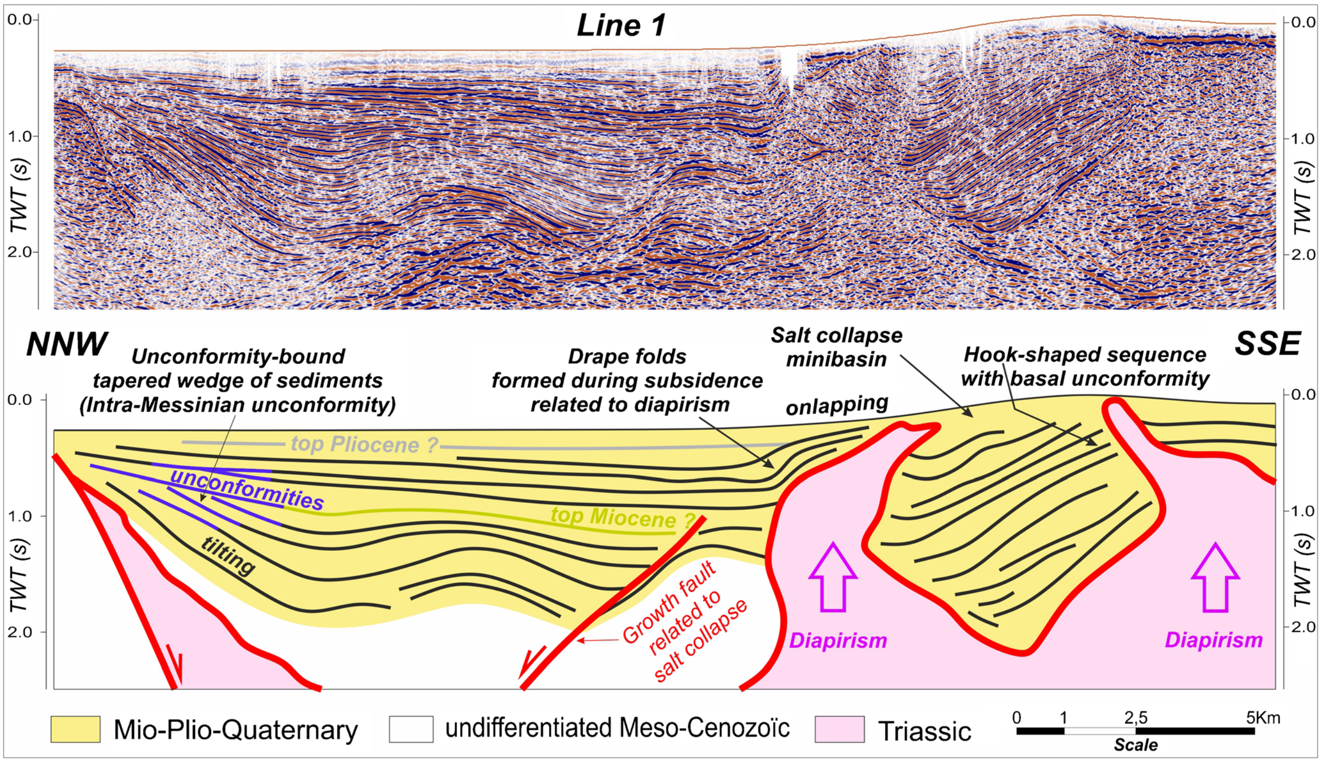


Fig. 17 Seismic line interpretation (line 1) through the Mejerda basin outlining the extensional faults and important salt activities; location is given in Fig. 5

(1) The main rifting stage that highlighted the northern African Tethyan margin started in Late Jurassic and continued during the Early Cretaceous. The NE-trending master faults cropping out in Northern Tunisia (i.e., Cap Serrat-Ghardimaou) are involving the infra-Mesozoic substratum, being, inherited from this rifting episode.

(2) The Mesozoic basins installed along the African margin are inverted repeatedly. The first compressional events are clearly expressed in the Tell which occurred during the Middle to Late Eocene in relation to the onset of active convergence between Africa and Europe. We highlight the existence (i.e., in Jebel Ben Amara (Khomsi et al. 2009b, 2021), Jebel Rebia) of several angular unconformities separating the Oligo-Miocene from the Pre-Oligocene series. The Tellian foreland domain records far-field effects of this tectonic event inducing sedimentary hiatuses and erosion near the forebulge and in the vicinity of active thrusts (Khomsi et al. 2016). The infra-Kasseb unit is characterized by a stack of imbricated slices involving Mesozoic layers, resulting also from this compressional event.

(3) The resumption of shortening was set in Middle Miocene times as a response to the major stage of the Africa-Europe collision. Since then, the Kasseb unit has moved forelandward, inducing the unroofing of its Mesozoic duplexes which overlap the Early Miocene series, as described at Jebel Rebia. This event is characterized also by wedge-top basins development (i.e., Mejerda basin (Khelil et al. 2019, 2020, 2021)) and the reactivation of major inherited faults (i.e., Cap Serrat-Ghardimaou Fault), which are associated with Neogene volcanism and/or Triassic movements. Shortening was still active during the Pliocene and Pleistocene and is still active today. Some authors highlighted recent tectonic activities along active faults from the Tell (i.e., Cap Serrat-Ghardimaou Fault) in relation to North-South compressions (see Roure et al. 2012; Bahrouni et al. 2020; Arab et al. 2020; Gaidi et al. 2020). These activities correspond to the renewal of subduction-related mechanisms with back-thrusting of the Kabylies on the Algerian margin (Roure et al. 2012).

These late contractional events have amplified the south- to southeast-ward translation of structural units and halokinetic rise of Triassic salt bodies. Therefore, we show the structural superposition of the Numidian unit over younger series such as the Upper Miocene deformed molasses as observed at Jebel Bou Khezara and Jebel Tegma.

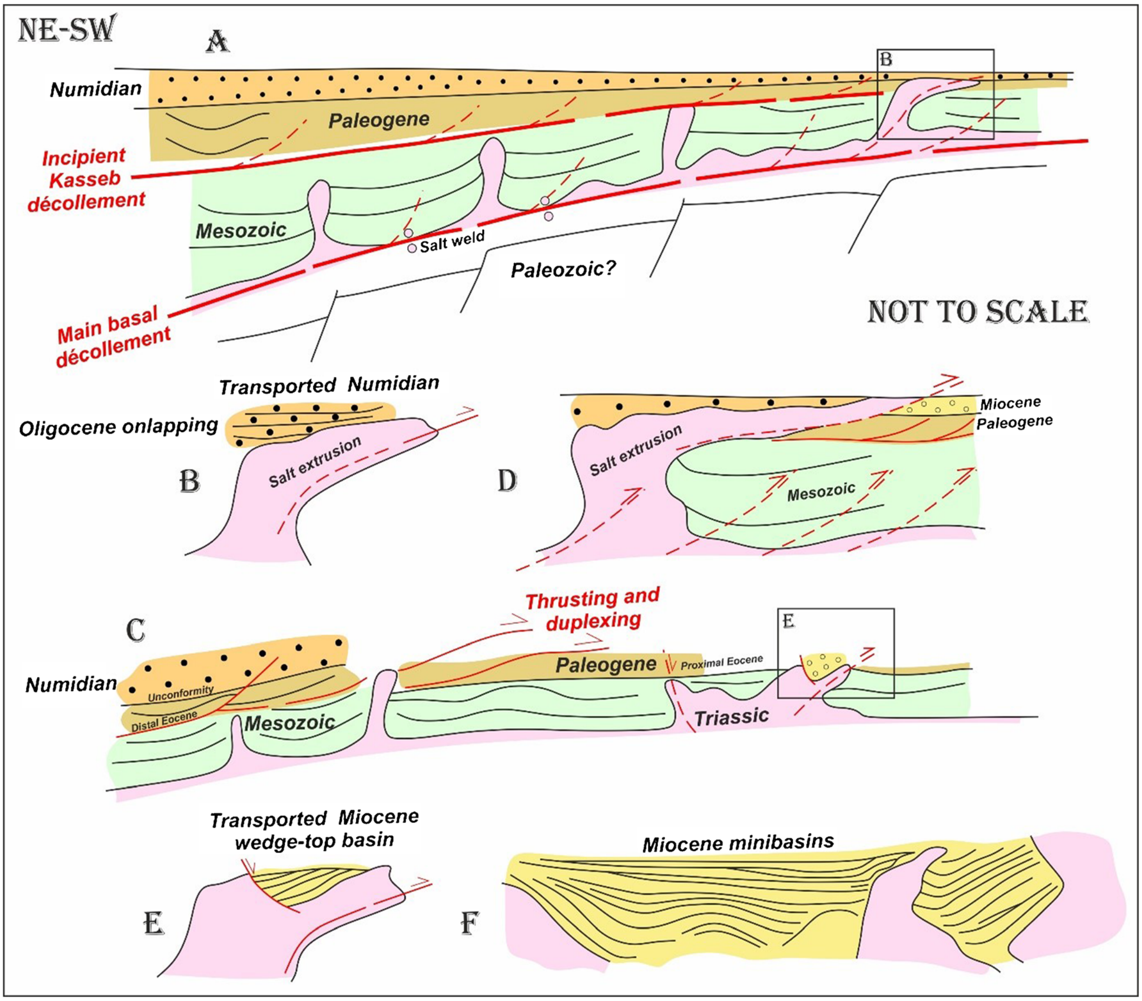
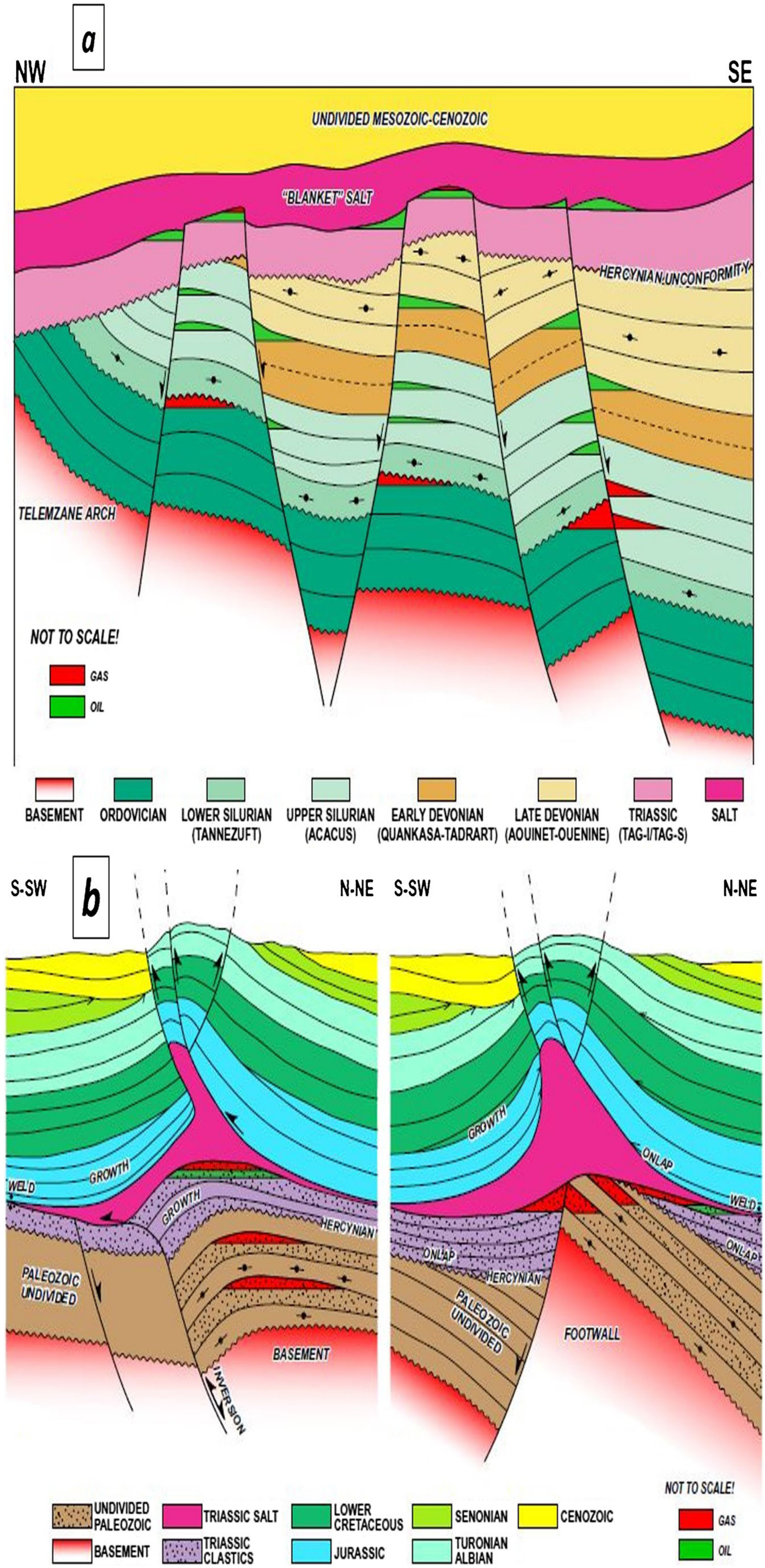


Fig. 18 (A) Schematic-idealized cross-section through the Tell in a pre-inversion stage (Pre-Langhian), representing the tectonic units, salt activity, and incipient décollements. (B) A zoom from A showing the onlapping of the Numidian sandstones on the pre-existing salt structure which is used later as décollement. (C) Schematic-idealized cross-section highlighting the inversion structures such as the thrusting and duplexing of the Paleogene unit (Kasseb). (D) Schematic-idealized cross-section showing the duplexing of the Mesozoic unit (infra-Kasseb), active roof thrust duplexes affecting the Kasseb unit, and the overthrusting of the Numidian and Triassic salt over the Late Miocene wedge-top basin deposits. (E, F) Important salt activity and minibasins setup

Oil and gas exploration potentialities: the Paleozoic system/pre-salt traps

As emphasized earlier by Tari et al. (2017) for the Atlas FABT and its foreland basin and by Khomsi et al. (2019) for the Tell and Atlas belt and their respective foreland basins, the Paleozoic system is obviously a very interesting system to explore and drill: in this system, the main source rocks are represented by the Devonian and Silurian hot shales (see Aissaoui et al. 2016; Tari et al. 2017) and Khomsi et al. (2019). The structural transects presented in this work underline that the major regional seal of the Paleozoic system is represented by the Triassic salt levels (Figs. 19 and 20). In the Fernana structures (Fig. 20), the Meso-Cenozoic sequences do not exceed 4500 m in thickness. The Triassic salt level represents a regional seal above the possible Paleozoic traps seated in the subsurface of the Tell. As emphasized by Tari et al. (2017) for the Atlas belt and by Khomsi et al. (2019), the underlying Paleozoic inherited highs and anticlines should be sourced by the Silurian hot shales (Aissaoui et al. 2016; Khomsi et al. 2019). Unfortunately, the lack of deep seismic soundings and investigations still prevents characterizing the sub-salt traps certainly seated in the Paleozoic sequences and subsurface structures. As recently argued by Khomsi et al., (2019) and Roure et al. (2019), a deep seismic sounding project would be very important to unlock the Paleozoic system allowing imaging of the overall crustal architecture and potential traps in −10 S to −15 S TWT (Two-way travel time). From this point of view, it seems clear that the existing industrial seismic sections are limited to the


a
NW
SE
UNDIVIDED MESOZOIC-CENOZOIC
"BLANKET" SALT
HERCYNIAN UNCONFORMITY
TELEMZANE ARCH
NOT TO SCALE!
GAS
OIL
BASEMENT
ORDOVICIAN
LOWER SILURIAN (TANNEZUFT)
UPPER SILURIAN (ACACUS)
EARLY DEVONIAN (QUANKASA-TADRART)
LATE DEVONIAN (AOUINET-OUENINE)
TRIASSIC (TAG-I/TAG-S)
SALT
b
S-SW
N-NE
S-SW
N-NE
GROWTH
WELD
GROWTH
HERCYNIAN
PALEOZOIC UNDIVIDED
BASEMENT
INVERSION
GROWTH
ONLAP
WELD
ONLAP
HERCYNIAN
ONLAP
PALEOZOIC UNDIVIDED
FOOTWALL
NOT TO SCALE!
UNDIVIDED PALEOZOIC
BASEMENT
TRIASSIC SALT
TRIASSIC CLASTICS
LOWER CRETACEOUS
JURASSIC
SENONIAN
TURONIAN ALBIAN
CENOZOIC
GAS
OIL

◀ **Fig. 19** Conceptual models for the play types seated in the Paleozoic subsurface system (Tari et al. 2017). (a) Trap categories in the Paleozoic productive petroleum system of the Sahara Platform. For an approximate location see Fig. 1a. Notice that the main trap types are represented by wrench faults and shorts and deep-seated anticlines underneath the Triassic salt level. (b) Two possible structural configurations underneath the Triassic salt levels and walls. On the left: inversion tectonics affecting the subsurface Paleozoic structures with Alpine rejuvenation and reactivation of deep-seated Paleozoic faults together with thrust tectonics affecting the Meso-Cenozoic Tethyan structures admitting the Triassic salt as decollement level. The Triassic salt ensures also the sealing of the potential Paleozoic traps with possible multiple gas/oil trap in the rejuvenated anticline. Fault traps can form in such configuration. On the right: an inherited salt wall and diapir above inherited normal

shallow Mesozoic cover and of very low to moderate resolution and with a widely spaced grid in the Tell belt. In Fernana structures there is no seismic section yet available. Thus, we hope that in the next years an international oil/gas project with deep seismic sections records will allow visualizing properly the structures underneath the Tellian allochthon and the Triassic seal.

Conclusions

The present structural cross-sections throughout some representative structures and domains of the Tell of Tunisia allow us to better describe the structural style and tectonic events in the Tell of Tunisia. The structural style of the investigated structures corresponds chiefly to thin-skinned tectonic evolution materialized by tectonic duplexing. The infra-Kasseb unit is characterized by a sole décollement level localized within the Triassic evaporites, resulting in the duplex formation. The Kasseb unit is displaced towards the SE above the roof décollement at the top of the underlying infra-Kasseb duplexes. The most dominant style of the Tell is represented by active roof thrust and duplex structures.

In some areas as in Fernana, the Numidian Flysch is detached above the infra-Numidian units reworking an originally downlap contact. In some other areas, no clear detachment is visualized, and the Numidian rests in an apparent stratigraphic contact with underlying units, or is separated from the infra-Numidian units by a north-dipping normal fault, defining a neo-autochthon displaced together with the Kasseb nappe.

Important NW-trending faults controlled the sedimentation during the Tethyan rifting, contributed then to the morpho-structural configuration of the Tell and have been reactivated as strike-slip faults during the recent Upper Miocene-Quaternary events.

The Fernana structures underline the importance of the Triassic salt in the overall architecture of the belt and indicate high halokinetic movements in accordance with a Triassic salt-rich province. The Triassic salt has played a primordial role in the thrusting events forming the main décollement level. It is also implicated in the recent thrust rejuvenation with

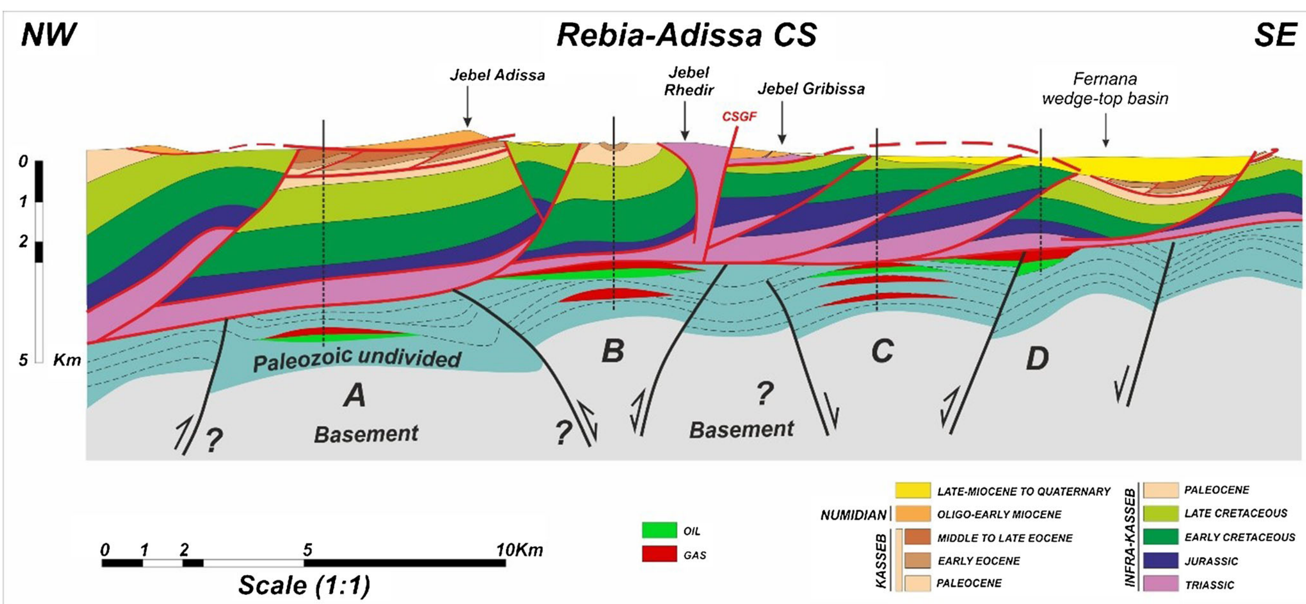


Fig. 20 Conceptual models for the play types seated in the Paleozoic subsurface system along the Rebia-Adissa transect emphasizing the occurrence of oil and gas traps in the Paleozoic structures. The sealing is ensured by the Triassic salt level. The presented transect allows predicting that the Top Paleozoic is around –3000 m beneath the surface. Structure A: large anticlinorium structure controlled by the Alpine rejuvenation of the Paleozoic inherited faults. B and C: pop-up anticlines affecting the Paleozoic structures with the occurrence of possible multiple oil/gas reservoirs in the axial part of the Paleozoic structures. D: Tilted blocks along inherited normal faults affecting the Paleozoic and possible traps related to fault trapping mechanisms. Notice: red color: potential gas accumulation, green color: potential oil accumulation.

a good example given in Jebel bent Ahmed where the Triassic sole thrusts over the Upper Miocene-Quaternary Fernana wedge-top basin. This sole thrust is interpreted as the apical part of the former diapiric structure.

An important Aquitanian-Langhian angular unconformity occurs in the foreland domain of the Tell throughout the Northern Atlas, materialized by Neogene proximal deposits onlapping already folded and partially eroded structures. The tectonic units of the Tellian wedge thrust above these Aquitanian-Langhian series. After the emplacement of the nappes in post-Langhian times, the area underwent tectonic compression and thrusting, allowing the folding of older nappes contacts as well as the rejuvenation of ancient inherited faults and thrust folds. The major tectonic event seems to be Upper Miocene to Quaternary to Recent because the post-nappes Upper Miocene continental series are folded and tectonically displaced along some thrusts. The base of the post-nappes Upper Miocene-Quaternary syntectonic deposits is lying with an angular and erosional unconformity above former duplex structures as in the Fernana wedge-top basin.

Along the Tunisian external Tell as shown for Fernana structures, inherited Paleozoic highs and anticlines which are sealed by Triassic salt and sourced by the Silurian hot shales characterize an interesting pre-salt trap system.

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Code availability Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interest The authors declare no competing interests.

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