ISSN 0016-8521, Geotectonics, 2024. © Pleiades Publishing, Ltd., 2024.

Pre-Existing Structures and Stress Evolution Controlling a Pull-Apart Basin in the Tunisian Atlas Domain (Siliana Area): Geodynamic Implication

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Received August 12, 2023; revised June 11, 2024; accepted June 26, 2024

Abstract—In this paper we use a multidisciplinary approach including field observations, geological mapping and stress analysis to investigate the structural evolution of the NE-trending Sfina Basin, which located in the foreland basin of the Alpine chain (Maghrebides) in Tunisia. The Sfina Basin structure is the Neogene pull-apart basin, forming along the NE-trending Zaghouan fault, it located in Tunisian Atlas domain and formed in a NE–SW-trending dextral strike-slip fault systems. Our result has shown that this NE-trending basin is limited in both northern and southern edges by two NE-trending dextral fault segments. During the Late Cretaceous–Middle Miocene, under NE–SW extensional regime, the NE-trending transtensional fault segments constituted the boundaries of the Sfina Basin that developed as a dextral releasing stepover. During the Late Miocene–Early Quaternary, Sfina Basin was inverted under a regional NW–SE-to-NNW–SSE compressional event in response to the Africa–Eurasia convergence with continental collision process. The inversion occurred mainly along Sfina Basin sidewalls by reactivation of the pre-existing NE–SW-trending weaknesses as right-lateral transpressional shears and led to formation of the NE–SW-trending major folds structures in the Sfina area.

Keywords: Tunisian Atlas domain, Miocene, transtensional regime, transpressional regime, releasing stepover, Africa–Eurasia convergence

DOI: 10.1134/S0016852124700249

INTRODUCTION

The geotectonic irregularities and the kinematics of strike-slip faults play a primordial role in intracontinental tectonics and earthquake process [22, 23, 55]. Even if strike-slip faults may appear as continuous, linear structures at some scales of observation, they are almost always discontinuous, often consisting of stepped fault segments separated by stepovers, and their surface traces commonly shows bends. The discontinuous propagation and the modes of these intracontinental strike-slip faults are focused by pre-existing inherited structures and stress concentration [18].

On the other hand and depending on the trend of the fault network relative to the sense of strike-slip motion or bending relative to the general sense of displacement along the principal displacement zone (PDZ), stepovers can be releasing (transtensional) or restraining (transpressional) [40, 48, 55]. These stepovers (restraining and releasing) bends produce in the sedimentary cover, respectively, localized domains of push-ups and pull apart basins [22, 40, 55].

At North African scale, the Tunisian Atlas domain is a principal intracontinental domain, resulted to far-field effects of Africa–Eurasia continental collision since the Late Cenozoic. This continental collision leads to the development of the main Atlas structures in strike-slip faults, basin opening, halokinetic and tectonic inversion of pre-existing extensional structures [13, 27, 45].

Indeed, several studies carried out in the Tunisian Atlas domain highlighted the role of pre-existing structures in the growth of the Neogene basins, folds and thrust belts during the Late Cenozoic tectonic inversion [15, 16, 30, 38, 59, 60].

Located in the Tunisian Atlas domain, the zone of interest shows a structural architecture containing the NE- trending Sfina Basin associated with NE-trending folds axis (e.g. the Bellouta and Jebel Makthar anticlines) along the Zaghouan major fault (Figs. 1b, 2).

The Siliana area, were the Study area as a part, has been the subject of several structural and geophysical works [26, 30, 37, 38, 44].

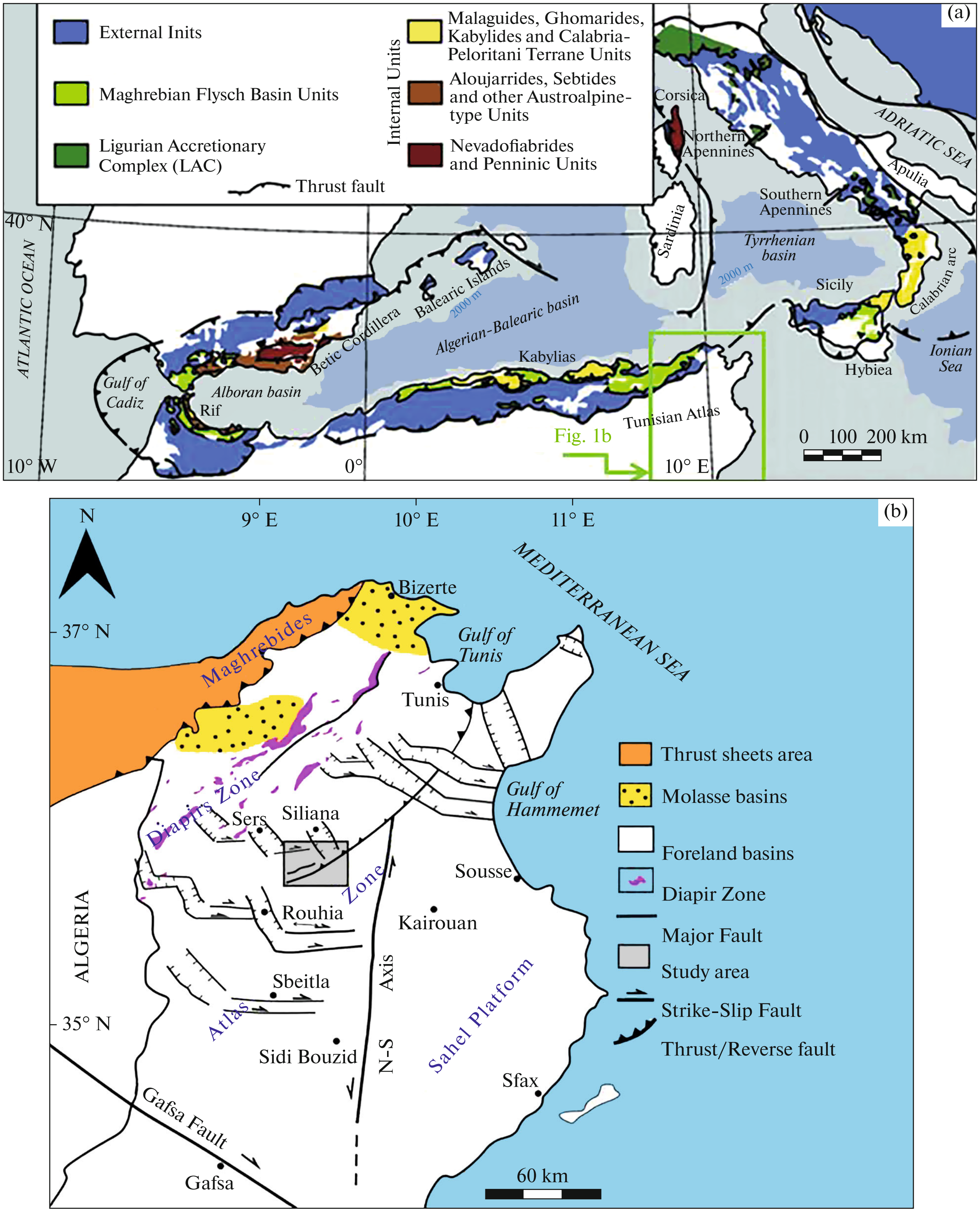

Fig. 1. Regional tectonic setting of the Tunisian Atlas domain: (a) Schematic tectonic map of the Mediterranean orogenic belts; (b) map showing the location of the Sfina Basin in the Tunisian Atlas foreland (after [57], modified).

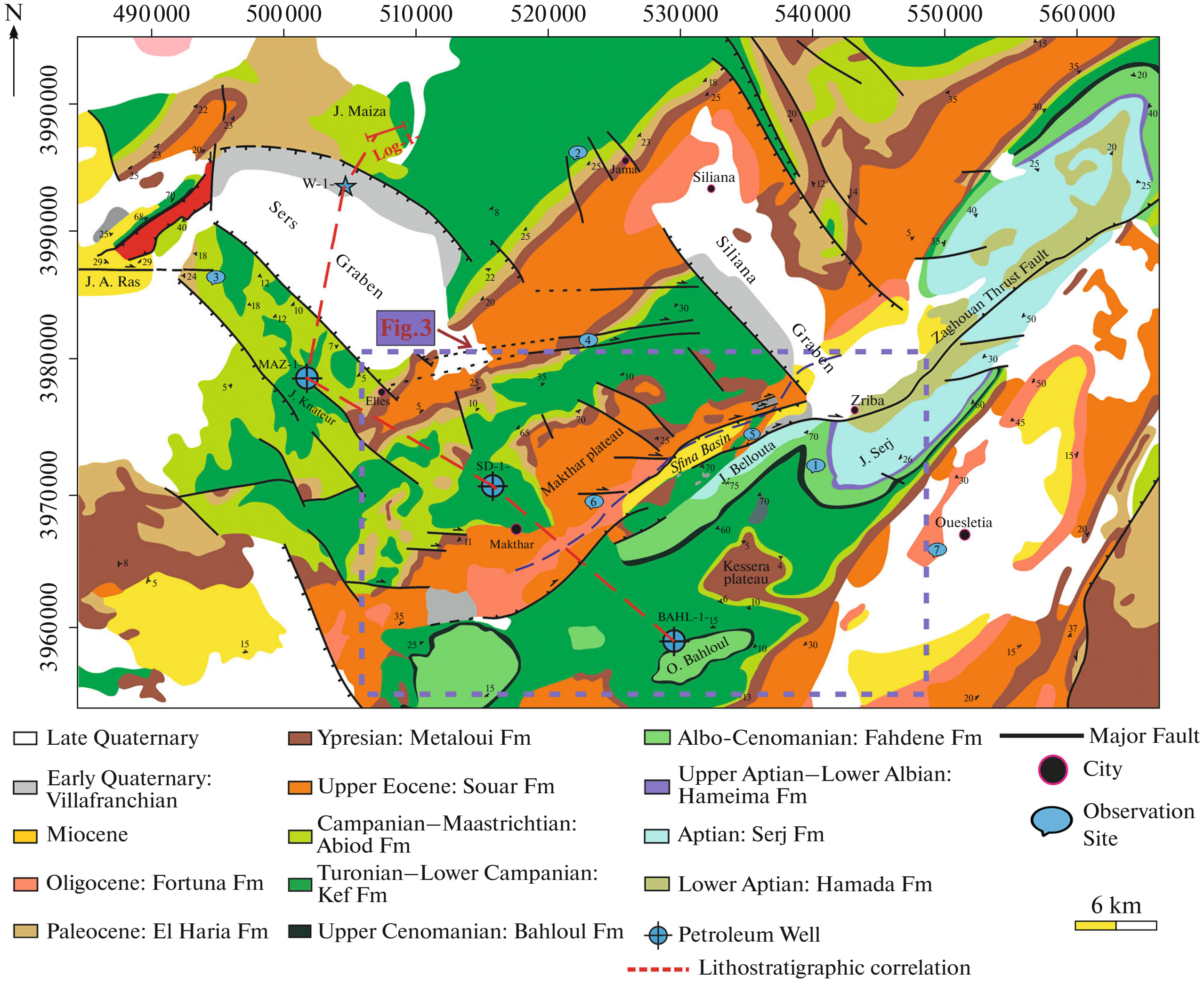

Fig. 2. Geological map showing a simplified sketch of the principal units in the Siliana and surrounding area.

The geophysical data, published by Ezzine et al. [26] showed that the NE–SW-trending segments faults in the Jebel Bellouta and Jebel Serj structures are deep reaching 2000–3000 m of depth. Mahmoudi et al. [37] discussed the structural evolution of the Sers and Siliana grabens during the Neogene-Quaternary times. They further proposed that these two graben structures are Lower-Middle Miocene in age and are mechanically linked by E–W-trending dextral strike-slip faults.

In this research paper, we focus on deformation pattern along the NE–SW major fault segments of the regional Zaghouan fault, in the Siliana area and investigate their relationships with fold structures. Herein, we used numerous data including field observations, detailed geological maps and paleo-stress analysis to study the structural evolution of the Neogene Sfina Basin, during the Mesozoic–Cenozoic, in relation to the Africa–Eurasia convergence.

GEOLOGICAL SETTING

The Tunisian Atlas domain, situated in the African foreland of the Maghrebides (Alpine chain), resulted from the Late Cenozoic convergence between Africa and Eurasia plates [9, 16, 29, 47, 53, 54, 56, 60] (Fig. 1).

This belt domain is dominated by E–W, NW–SE and NE–SW-trending features where the most of theme inherited from Tethyan rifting stages. Indeed, since the Triassic to Lower Cretaceous time, the Tunisian Atlas domain was underlined by NE–SW to N–S-trending extensional phases with NW–SE, E–W and NE–SW-trending synsedimentary normal oblique faulting [2, 12, 38, 53].

However, during the Oligocene until Middle Miocene the subduction between the AlKAPeCa microplate and the African plate lead to the opening of graben structures and Neogene basins in the Tunisian Atlas foreland after a lithospheric rebound [11, 17, 25].

These extensional structures have been progressively folded and inverted as a consequence of the African and Eurasian plate collision. Indeed, during the Cenozoic and after the Tethyan closure, a minor shortening event was started during the Lower Eocene resulted in rejuvenation of the NE-trending diapiric structures and inverted the pre-extensional structures [24, 28, 34, 38].

From the Late Miocene and Early Quaternary the Tunisian Atlas domain recorded two distinct successive compressional phases with NW–SE-trending shortening direction, respectively. These compressional events were responsible for the formation of the NE-trending fold axes, the reactivation of NE-trending faults to thrust ones, NW-trending faults to normal ones and E–W-trending faults to dextral strike-slip faults [7, 37, 38, 46].

As a part of the Tunisian Atlas domain, the Sfina Basin is an NE–SW-trending Neogene basin located along the NE-trending Zaghouan major fault (Fig. 1b). It is limited to the north by the Sers and Siliana graben structures and toward the south by the Kessera Plateau structure (Figs. 2, 3b).

LITHOSTRATIGRAPHIC UNITS

The sedimentary series outcropping in the Sfina area are Aptian to Quaternary in age (Fig. 3a). The Aptian outcrops are composed by shallow-marine carbonates [8]. The Albo-Cenomanian series are composed of clays, marls and grey limestone intercalations, acknowledged as the Fahdene Formation. These sequences are topped by laminated darcks limestones with a bituminous odor and imprints of ammonites defined as Bahloul Formation (Upper Cenomanian). Above this later, the Kef Formation (Turonian–Lower Campanian) consists of clays and marls series with calcareous intercalations.

The Kef Formation is overlain by the Abiod Formation (Campanian–Maastrichtian) and formed by two limestone sequences, which are separated by an intermediate marl level of layers.

The Cretaceous–Tertiary passage is materialized by a sequence of gray clays, with sometimes interaction of some limestone layers, that defined the El Haria Formation (Paleocene) [33]. This formation is overcoming by the Metlaoui (Lower Eocene) and Souar (Upper Eocene) formations. This later is formed by blackish clays and marls.

The Miocene–Quaternary succession is represented by Saouaf and Segui formations. The Saouaf Formation (Serravalian–Lower Tortonian) is formed by yellow sands, with oblique stratification. Next above, the Segui Formation (Messinian–Lower Quaternary) is represented by torrential conglomerates deposits in the basal part, a thick unit of sandstones and sands in the Upper part. It covers, with an angular unconformity, the Saouaf Formation (Serravalian–Lower Tortonian) dating the first Neogene shortening in the Siliana area [37].

On the other hand, the Early Quaternary deposits, are represented by conglomerates and alluvial terraces, cover unconformably the old series with an angular unconformity and dating the Post-Villafranchian compressional event [38] (Fig. 4).

DATASET AND METHODS

Detailed mapping, field observations, structural analysis, and subsurface data (petroleum wells) allows for the structural framework of the NE-trending Sfina Basin (Siliana area) (Fig. 3a). We used lithostratigraphic correlation carried out using Well data acquired by Tunisian Oil Company (ETAP) which is a state-owned industrial and commercial company in Tunisia directly in charge of the petroleum sector as well as the state's partnerships with foreign exploration and production operators and oil company SEREPT specializing in oil sector in Tunisia (Figs. 2, 5).

From a kinematic point of view and to understand the stress evolution since Upper Cretaceous until Quaternary we have determined numerous synsedimentary faults in the Upper Cretaceous, the Paleogene, and in the Oligocene–Middle Miocene series (Figs. 6, 7).

We have used the graphical method [31], in the case where we cannot observe striations along the planes of the syn-depositional faults, which observed in Oligocene–Middle Miocene deposits.

In addition, to know the stress field near the major structures of our study area, we have used the TENSOR program for the fault inversion analysis, following the method described in Delvaux and Sperner [20].

The stress regime is further classified by R': the tensor type index R' [19]. For R' varied:

— 0–0.25 (radial extension);

— 0.25–0.75 (pure extensional);

— 0.75–1.25 (transtensif);

— 1.25–1.75 (pure strike-slip);

— 1.75–2.25 (transpressional);

— 2.25–2.75 (pure compression);

— 2.75–3.00 (radial compression).

In addition, in case of syn-sedimentary faults with striations we used the restoration method, which gives the primitive stress position before deformations by applying the inversion of the back-tilted faults orientations (rotation around the bedding axis: S_0) (Fig. 2, site observation 5).

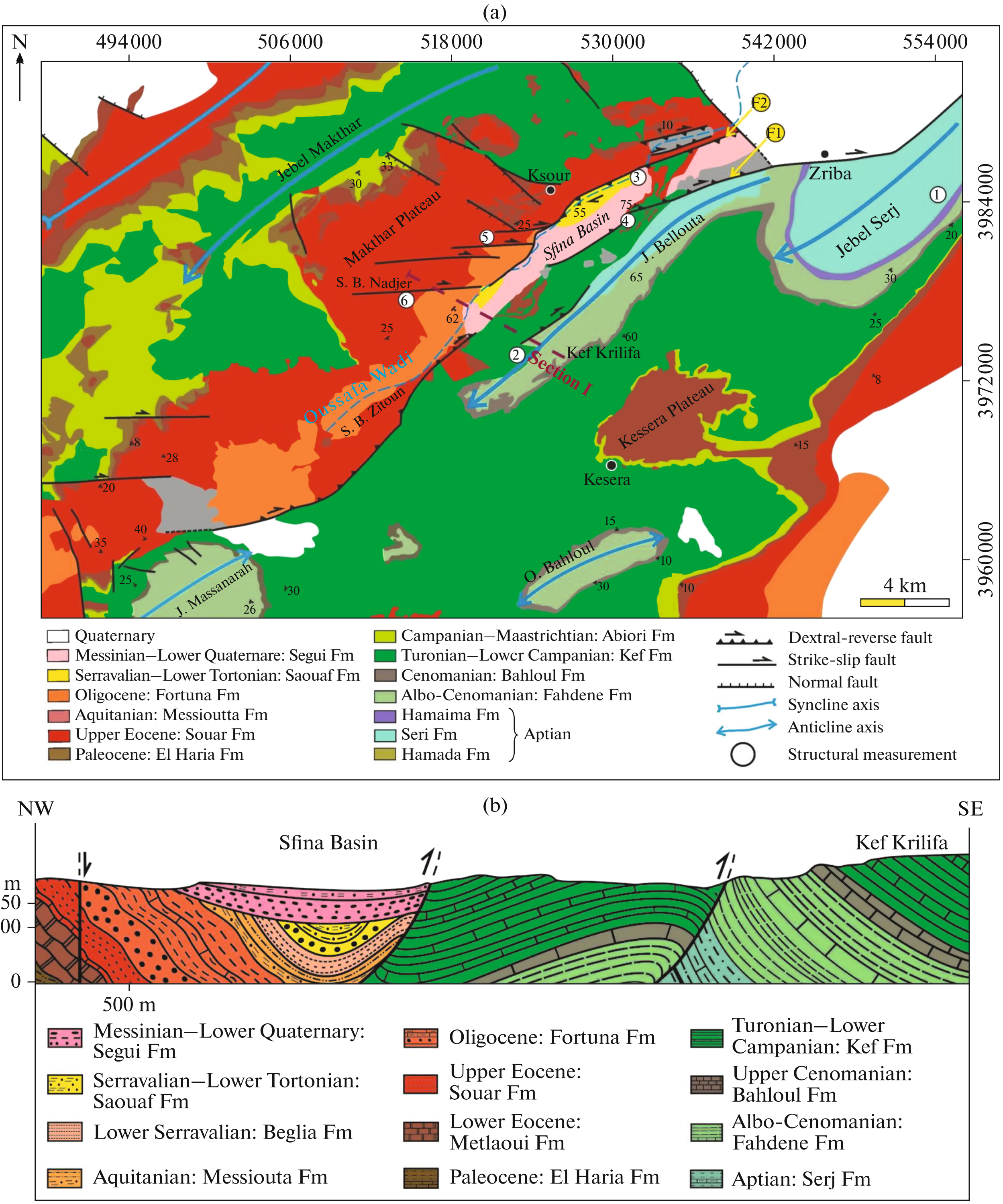

Fig. 3. (a) Geological map of the Sfina structure; (b) geological cross-section in Sfina region.

STRUCTURAL FRAMEWORK

Upper Cretaceous–Middle Miocene Tectono-Sedimentary Analysis

The Siliana area includes the NE-trending Sfina Basin and their associated structural features, represented in several folded and faulted structures. The folded structures include the main anticline and syncline structures (e.g. Jebels Serj and Bellouta anticlines) striking NE-SW. The geological map shows numerous fault networks, especially dense, near the NW-trending Sers and Siliana graben structures and the NE-trending Neogene Sfina Basin (Figs. 2, 3a).

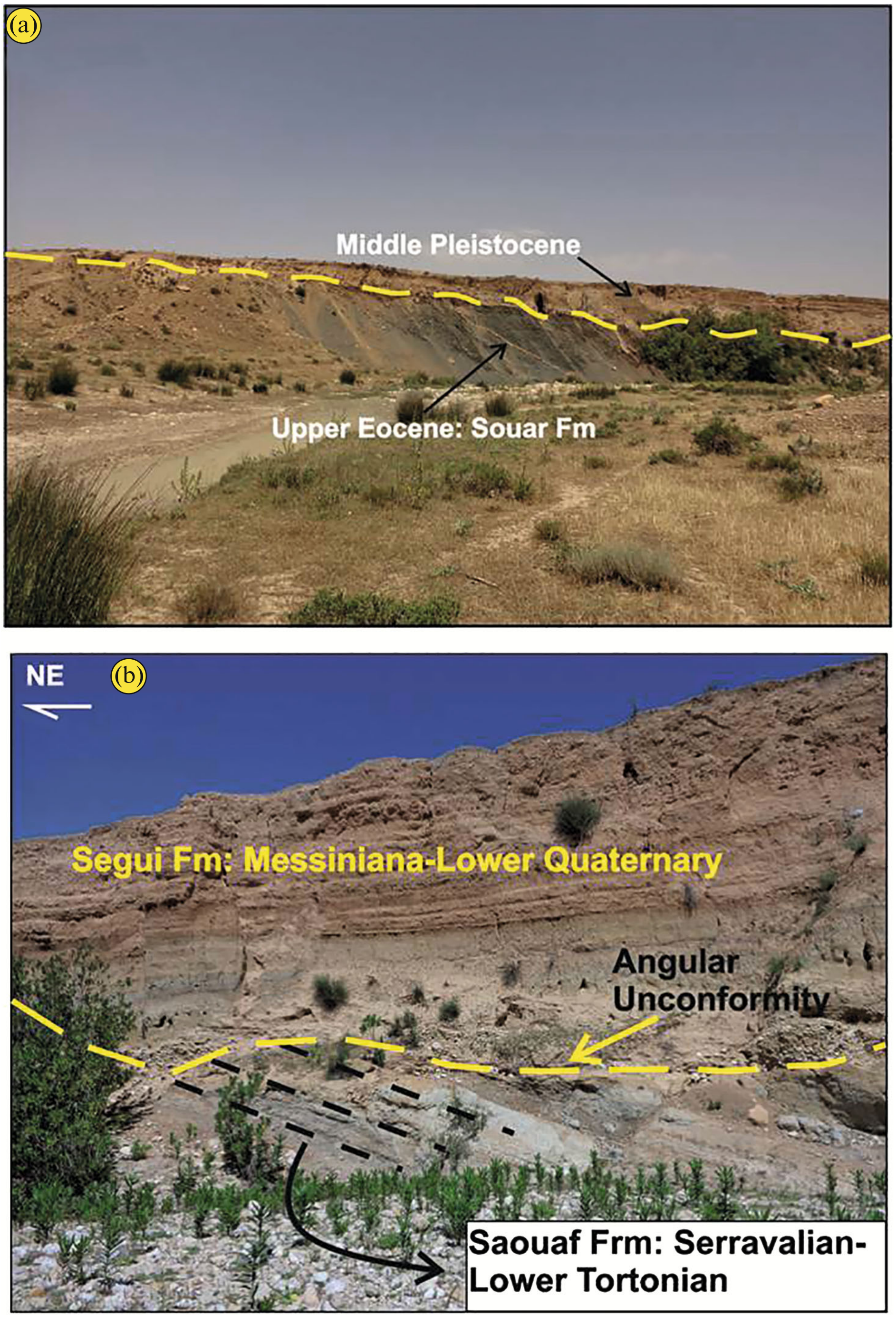

Fig. 4. Angular unconformities: (a) between the Saouaf (Serravalian–Lower Tortonian) and Segui (Messinian–Lower Quaternary) Formations; (b) between the Early Quaternary deposits and the Eocene rocks.

There are three main sets of faults: NW–SE, E–W, and NE–SW, dissect the Siliana area into various tectonic blocks. These faults are similar to the faults recorded in Tunisian Atlas domain (Fig. 1b). The NW-trending faults have also been underlined at both edges of the Sers and Siliana grabens with their traces on the Upper Cretaceous, Paleogene, Neogene, and Quaternary deposits (Fig. 2).

These NW–SE-trending normal faults are considered as pre-existing faults with an activity since the Upper Cretaceous time [37]. In the southern limb of the Jebel Makthar anticline, we observe two main NW-trending normal faults that juxtaposed the Lower Eocene and the Upper Eocene deposits. These faults, dip to the southwest and limit the Makthar plateau structure (Fig. 3a).

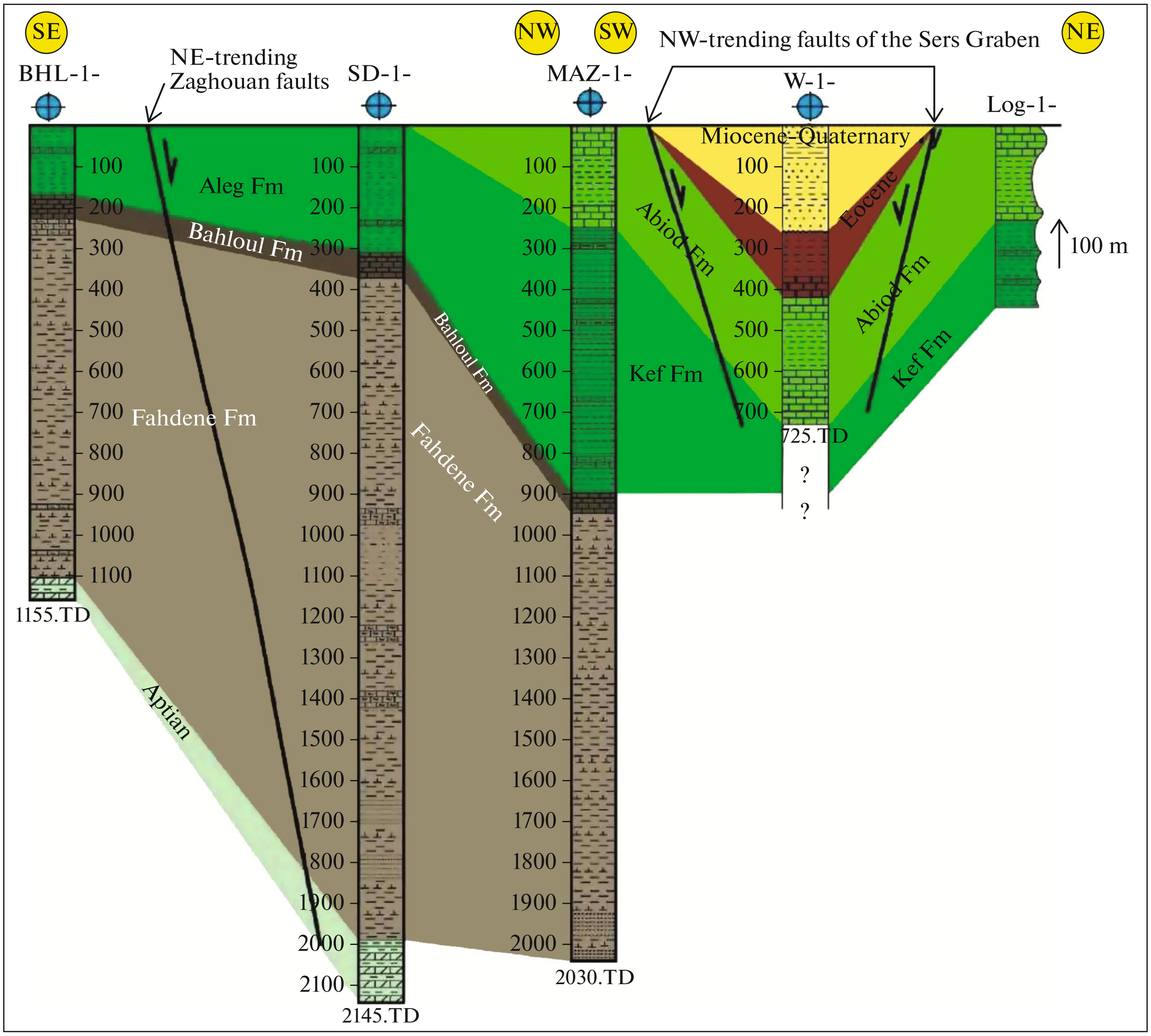

Fig. 5. Lithostratigraphic correlation of Late Cretaceous outcrops in the Siliana area.

In the Neogene Sfina Basin the main rock structural anisotropy have controlled the accommodation space and its structural evolution over times. Indeed, this basin is cut by a set of dextral-reverse faults trending roughly NE–SW and they seem to be the most important ones and exhibit strike-oblique displacement (Fig. 3a).

Figure 3a represents a structural map diagram and the location of the main structural features in the Sfina region. This map shows the existence of numerous fault sets, which affect Upper Cretaceous–Early Quaternary deposits. The main faults that affect at under Paleogene and Neogene series bound the structure of the Sfina region according the NE–SW direction such as these showing in section I (Fig. 3b).

Both edges of this basin are bordered by the F1 and F2 faults with NE–SW-trend, which dip toward northwest and southeast, respectively (Fig. 3a). These faults (F1 and F2) form the most expressive NE–SW-trending faults, with an overall NE–SW path and constitutes the principal displacement zone (PDZ) that here controlled the sedimentary and the deformational history of Sfina Basin. They seem to be the most important ones and exhibit dextral-reverse displacement.

Fault F1. This fault, which dips toward northwest, juxtaposes the Miocene-Early Quaternary and the Upper Cretaceous–Paleogene deposits. The direction of this fault seems changing from NE–SW at Sfina Basin, to nearly E–W near the Zriba City (northern limb of the Jebel Serj anticline) (Fig. 3a).

At this locality, we observe dense fault sets, with E–W-and NE–SW-trend. Locally, we observe an E–W-trending fault (prolongation of fault F1) that juxtaposed the Aptian outcrops in structural contact

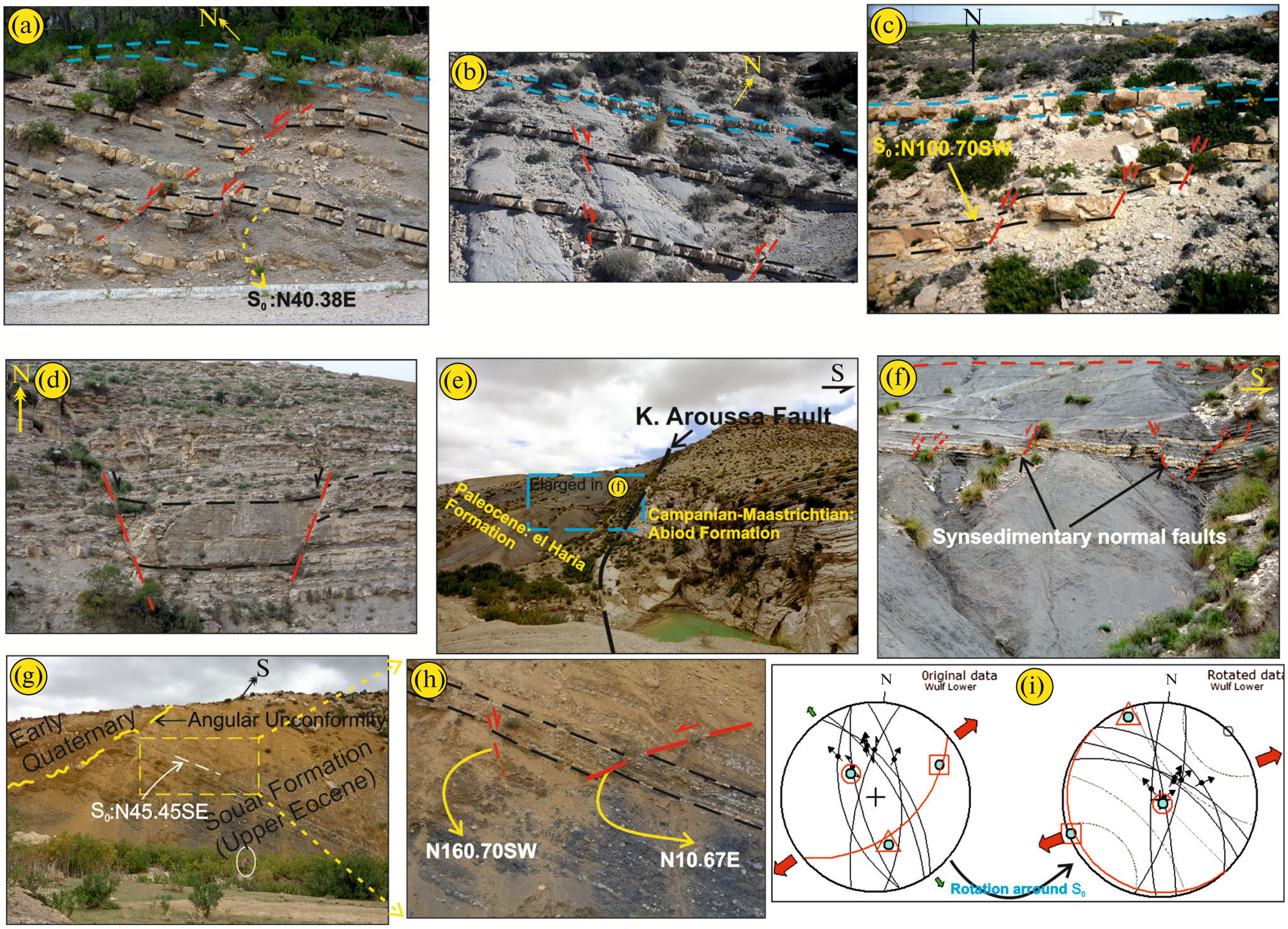

Fig. 6. Field photos showing syn-sedimentary faults affecting. (a)–(g) Formations: (a) Fahdene; (b) Kef; (c) Abiod; (d), (e) and (f) El Haria; (g) and (h) Souar; (i) example of back-titling of the corresponding fault slip-data in Souar Formation.

with the Early Quaternary deposits that filled the NW–SE-trending Siliana graben (Fig. 8a).

The fault plane is usually dipping 75° NW and shows numerous subvertical slickenlines and grooves, which prove an extensional toward the Siliana Basin. The calcite veins at this fault plane prove a dextral strike-slip displacement (Figs. 8b, 8c). The presence of many tensions calcite veins and subvertical slickenlines on the mirror fault, in several places indicate the existence of two distinct tectonic events.

Fault F2. On the other hand, the geological map view of the Sfina Basin shows that the northern edge of this basin is limited by a second NE–SW-trending fault F2 that dipping toward southeast and juxtaposed the Upper Eocene outcrops (Souar Formation) with the Miocene-Quaternary deposits (Fig. 3a).

On the northern side of the Sfina Basin we observe numerous NE–SW-trending sets faults, in a row, that affected the Pleistocene series and associated with some drag folds structures (Fig. 9f).

This fault seems changing direction, to the west and shows a horsetail splays geometry (Fig. 3a).

Late Cretaceous–Middle Miocene Deformation Pattern

To characterize the Upper Cretaceous–Middle Miocene syn-sedimentary deformation and related paleostress regimes, we have provided numerous field examples, together with the stress inversion results computed after back-tilting the corresponding fault-slip data.

In addition, to test the depositional variation on the either side of the main faults, in the Siliana are, we used some lithostratigraphic logs which are deduced after direct measurements from field outcrops or some of well logs (Fig. 5).

The pre-Miocene and Early Miocene deposits show abundant metric to decametric-scale sealed normal faults illustrated in Figs. 6 and 7.

The field data, carried out in our study area, showed the Albo–Cenomanian, Campanian Maastrichtian, Paleocene series (Fahdene, Kef and El Haria formations, respectively) (Fig. 2: observation sites 1, 2, 3 and 4), and metric to decametric-scale sealed synsedimentary

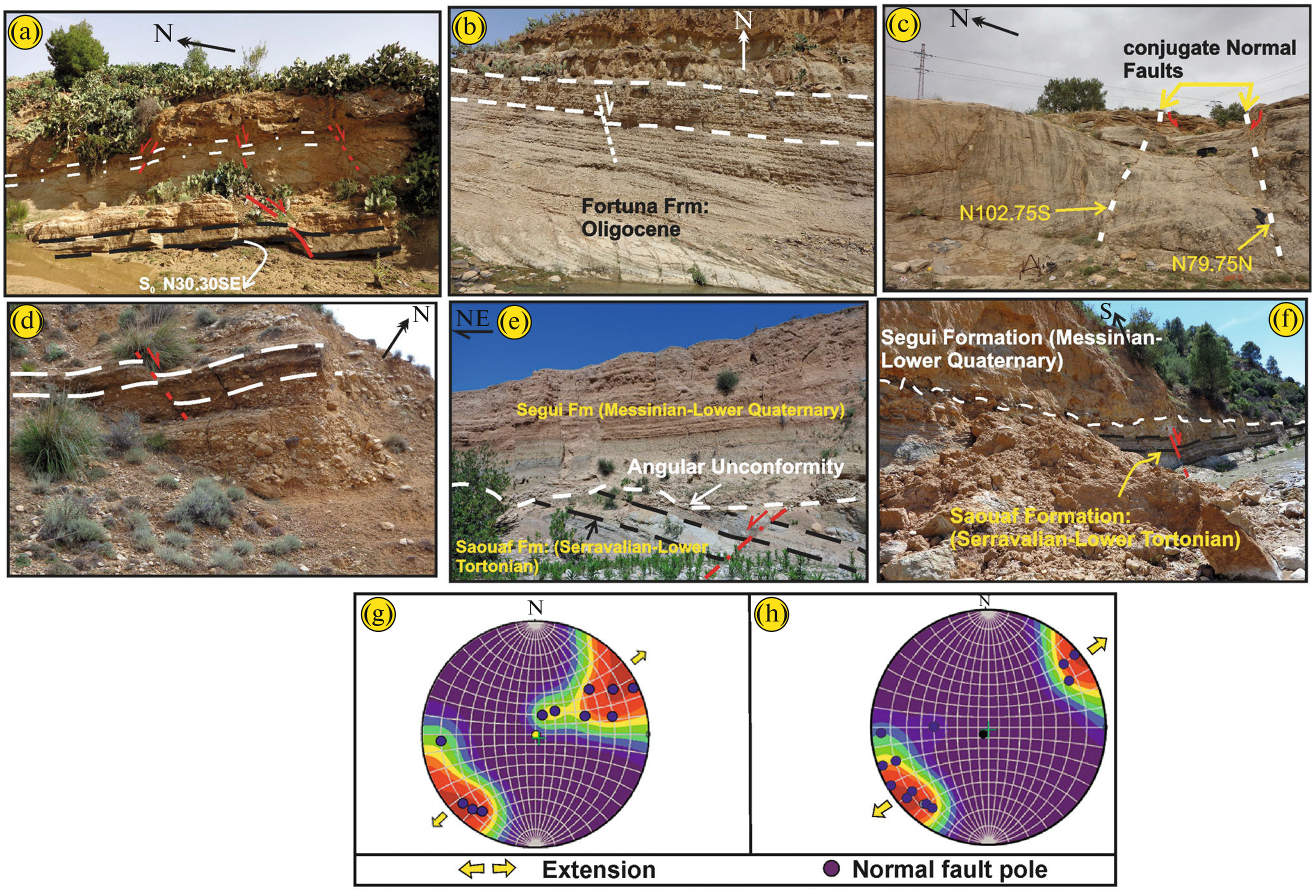

Fig. 7. Photos showing synsedimentary normal faults affecting the Oligocene–Middle Miocene series in our study area. (a)–(f)—(a) and (b)—Fortuna; (c) and (d) Messiouta; (e) and (f) Saouaf; (g)–(h) results of the microtectonic structural measurements with poles and average extension.

normal faults with NW–SE-and-E–W-orientation with lateral changes in the thickness.

Herein and to characterize the Late Mesozoic–Lower Cenozoic syn-sedimentary deformation and stress regimes, we have provided numerous field photos (Figs. 6a–6c) and one example of back-titling of the corresponding fault slip-data that affected the Upper Eocene deposits (Figs. 6f–6h). The inverted slip-data from these exposed normal faults shows an NE–SW-trending extensional stress tensor (subvertical σ1 and horizontal NE–SW-trending σ3).

In addition, in the Oligocene–Lower-Middle Miocene series, we observe numerous syn-sedimentary normal faults population with lateral variations in the thickness (Fig. 2: observation sites 5, 6, and 7).

These normal faults defined in some sites small-scale grabens and half-grabens (Fisg. 7a–7f).

The corresponding calculated stress tensor, by the graphical method, demonstrates an extensional tectonic event with N–S-to-NE–SW orientation (Figs. 7g, 7h).

The kinematic analyses of synsedimentary fault slip geometries and computed stress tensor of the synsedimentary faults (by numerical and graphical method), in numerous localities, proves commonly similar extensional stress regime with N–S-to-NE–SW-trending σ3 (Figs. 2; 6h; 7g, 7h).

This tectonic regime is well correlated at the Tunisian Atlas domain during the Late Cretaceous and Middle Miocene [5, 53, 59, 60].

At the larger scale, outcrops and wellbores show significant thicknesses and facies changes of the Fahdene Formation and Senonian series (Bahloul, Kef, and Abiod formations) from the southeast (BAHL-1-) to the northwest. In the BAHL-1-well data the Fahdene, Bahloul and Aleg formations show a thickness of 500, 20 and 40 m respectively, however, in the SD-1-well, these formations are 800, 50 and 70 m thick, respectively (Fig. 5).

The last two formations (Bahloul and Aleg) become thicker in the MAZ-1-well. In the BAHL-1-well the Fahdene, Bahloul, and Aleg formations are represented by a facies rich in carbonates, however, towards the northwest (SD-1-and-MAZ-1-), the lithology becomes more rich in ammonites and planktonic microfauna. Furthermore, in the BAHL-1- the

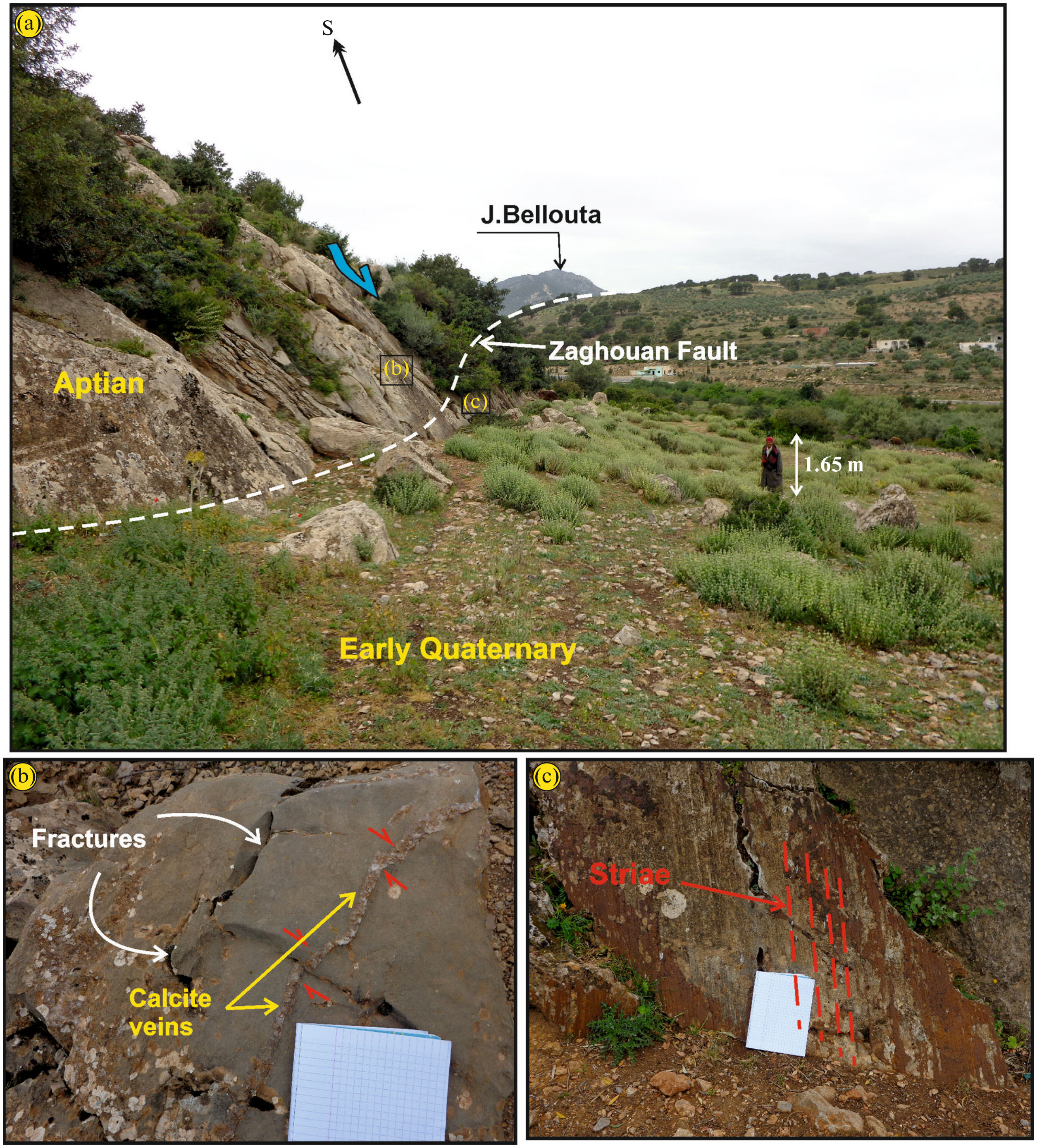

Fig. 8. (a) Photo of the major NE–SW Zaghouan fault in the study area; (b) calcite veins showing dextral strike-slip displacement; (c) oblique slickenlines.

Aleg Formation is represented by clays and marls with intercalations of limestones and gypsums.

Towards the NW, it is constituted of clays and marls with calcareous intercalations rich in ammonites in the eastern edge of the Sers graben which remind us of the Kef Formation (Turonian–Lower Campanian) and which is the lateral equivalent of the Aleg Formation. The facies change and the subsidence increase towards the northwest suggests that the Zaghouan fault is northwestern dipping and constituted by a stepped subsiding area towards the NW during the Albian–Early Campanian.

Based on the lithostratigraphic correlation harvested along the NW-trending Sers structure (MAZ-1-, Well-1-and-Log-1-), thickness variations were observed in the Early Cretaceous series (Kef and

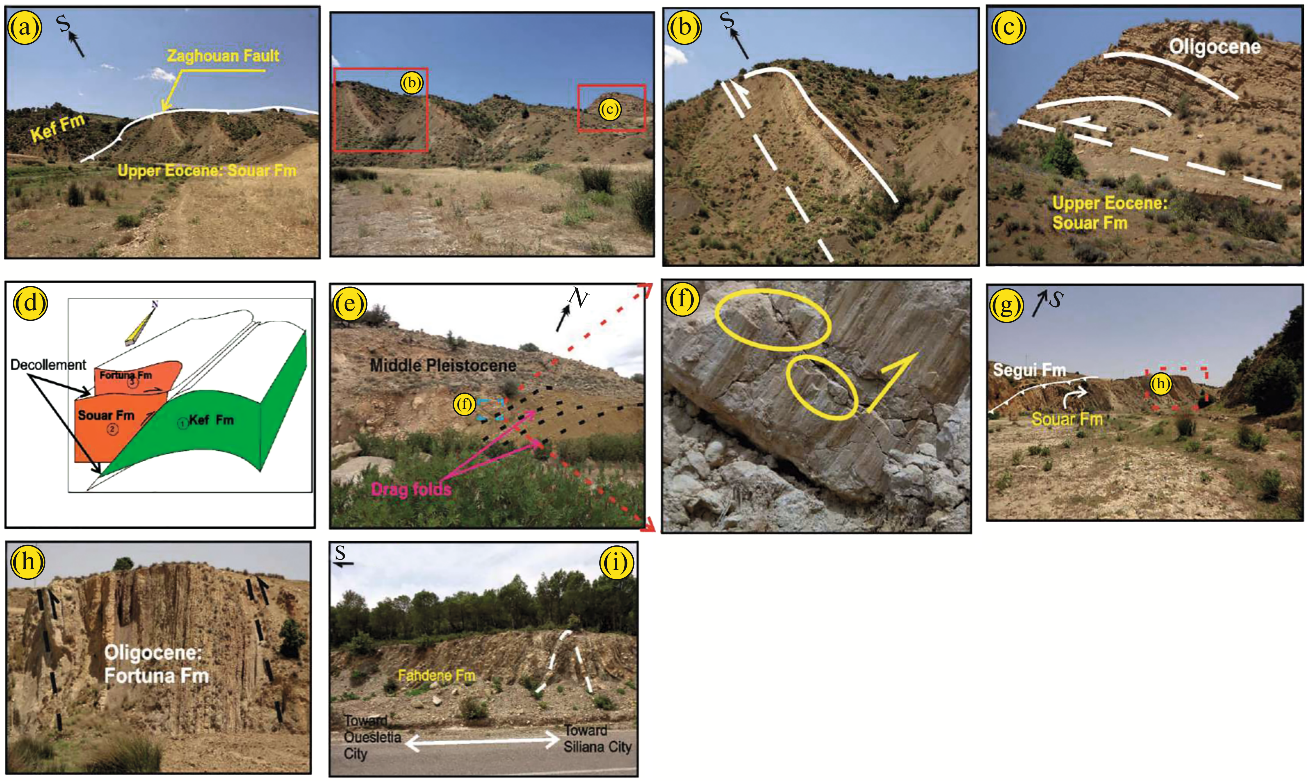

Fig. 9. (a)–(c) Photos showing some example of kinematic indicator of Late Cenozoic compressional phase in our study area and the decollement phenomena; (d) block diagram explaining the el Kef and Souar formations decollement levels; (e) drag fold structure; (f) NE–SW-trending fault plane with groove testifies a dextral-reverse displacement movement; (g)–(h) NE–SW-trending reverse faults in the Sfina region; (i) fold structure related to reactivation of the NE–SW-trending pre-existing faults.

Abiod formations). Indeed, the thickness of these two formations is greater in Well-1- than in MAZ-1-and-Log-1- (Fig. 5).

This lithostratigraphic correlation, along the NE–SW-and-NW–SE-trending faults gives evidence that the sedimentation during the Upper Cretaceous episode is controlled by these major normal faults.

Late Miocene–Early Quaternary Kinematic Analysis

In order to determine the deformation pattern related to Late Miocene–Quaternary compressional events, we investigate the relationship between the Late Miocene–Quaternary series and the Pre-Miocene deposits, as well as the relationship between the kinematics and state of stress in folded strata derived from meso-scale striated faults.

Indeed, the photograph illustrated by Fig. 4 shows two angular unconformities between:

— Messinian–Early Quaternary and Serravalian–Lower Tortonian strata (Fig. 4a);

— Early Quaternary series and Upper Eocene strata (Souar Formation) (Fig. 4b).

The Sfina and surrounding areas are marked with NE-trending the major faults which have limited the NE- trending Neogene basin such, were in structural agreement with some NE-trending Neogene basin in the Tunisian foreland basin [41, 42]. During the Late Cenozoic shortening deformation these NE-trending faults have played a key role in the tectonic inversion of the Neogene basin of Tunisia [32, 37, 41, 43].

Indeed, in the Siliana area the NE-SW faulting trending is marked by the NE–SW-trending the major thrust fault of the Zaghouan (Fig. 2).

In the Sfina region, the NE–SW-trending faults are indicative of oblique-slip and reverse faults (Fig. 3a).

This kinematics is well shown at the booth edge of the Neogene Sfina Basin. The field observations carried out along the southern side of this accommodation zone, show that the Late Eocene strata and the Cretaceous series have come in direct contact in the northern limb of the Bellouta anticline (Figs. 9a–9c).

At this locality, we observe that the limestones series of the Turonian–Lower Campanian (Kef Formation) and the Upper Eocene outcrops constitute a very level of decollement phenomenon (Figs. 9c, 9d).

On the other hand and on the northern edge of the Neogene Sfina basin, we observe the NE–SW-trending fault planes show numerous oblique slickenlines with dextral-reverse displacement (Figs. 9e, 9f).

At the southern side, we observe a major NE–SW-trending reverse fault put in contact the Upper Eocene and Oligocene series in contact with the Segui Formation (Messinian–Lower Quaternary) (Figs. 9g, 9h).

All these deformations, in different scale, and reactivated structures prove the impact of the compressional stress phase. In kinematic point of view, all the microtectonic sites (Fig. 3a: S1–S6) analyzed using the slickenlines along the major faults planes show a NW-striking compressional direction with a homogenous stress field NW-trending maximum principal stress axis (σ1) (Fig. 10).

The numeric calculated regimes showing a compressional to transpressional tectonic deformation:

— sites 1, 2 and 6 show a compressional tectonic regime (σ3 stress is vertical, σ2 and σ1 stresses are horizontal) (Fig. 10: S1, S2 and S6);

— sites 3, 4 and 5 shows a transpressional tectonic regime (σ1 and σ3 stresses are horizontal, σ2 stress is vertical) (Fig. 10: S3–S5).

On the other hand along the Southern side of the Sfina Basin we observe numerous normal faults that affected the Kef Formation, overlain by the Pleistocene strata with angular unconformity, with N–S-and-E–W-trend. The fault planes show two generations of stria (Figs. 11a, 11a', 11a").

The calcite steps along the fault plane show that the first slickenlines with normal displacement cross-cutting by the second one with dextral-reverse movement (Fig. 11a").

The computed stress tensors of this microtectonic site reveal a NW–SE-trending compressional regime (Fig. 11b).

However, the separation of data sets of the stress tensor show a NE–SW-trending extensional (first generation of stria) and N-S-trending compressional phase with N–S-to-NNW–SSE-trending (σ1) (second generation of stria). This kinematic analysis proves that these normal faults are reactivated during the Pleistocene in reverses one (Figs. 11b, 11b', 11b").

This compressional phase, as recorded in Tunisia by many studies and as known by the Post-Villafranchian phase [53, 60]. This compressional tectonic phase, through the Sfina area, is clearly testified by the angular unconformity of the Early Quaternary series in the pre-Neogene outcrops (Fig. 4b).

RESULTS AND DISCUSSION

Neogene basins in the Tunisian Atlas domain are located on structures inherited from the pre-Miocene tectonic phases involving the foreland zone of the Tellian Chain [5, 41, 50]. In our research, tectonic analysis of structures, from the field observations, carried out in the Tunisian Atlas domain (Siliana area), in the western Mediterranean Sea, allow us to establish the recent behavior of the Neogene Sfina Basin, which resulted from the interaction between the inherited NE–SW-trending dextral-reverse faults segments and the continued convergence between Africa and Europe plates.

Pre-Miocene Tectonic Deformation

The Atlas of Tunisia, part of the North African passive margin, had undergone a regional extensional phase during Jurassic to Early Cretaceous times, in relation with the Tethyan and Atlantic oceans rifting [16, 38, 46, 57].

In the Siliana area, the examination of the lithostratigraphic correlation enables us to notice that several NW–SE- and-NE–SW-trending faults of the Siliana region have been controlled the Late Cretaceous subsidence.

Indeed, in our study area, the NW–SE correlation line shows thickness and facies variations of the Late Cretaceous series (Fahdene el Kef and Abiod formations) from SE toward NW (Fig. 5).

The Late Cretaceous series suggest that the NW block of the NE-trending Zaghouan fault was a subsidente area during the Late Cretaceous times. Several works have highlighted the role of the NE-trending Zaghouan fault during the Mesozoic times [26, 30].

On the other hand, the NE–SW-trending across the Sers grabens shows an important thickness variation of the Late Cretaceous series (Abiod formation) (Fig. 5). This testifies that the eastern and western edge of the Sers graben are separated by two conjugates normal faults with NE–SW-trending extension as proved by Mahmoudi et al. [37].

The thickness change along the NW–SE-and NE–SW-trending faults underlines an extensional episode and the role of the normal component, which is exhibited by the NE–SW-trending Zaghouan fault segments that limited the NE-trending Sfina Basin, going through Jebel Serj anticline.

Herein, the thickness variations that affected the Late Cretaceous series and the numerous synsedimentary normal faults that affected the Upper Cretaceous and Paleogene formations, testifies a NE–SW-trending extensional regime initiated at the Late Cretaceous times (Figs. 6a–6f).

This later extensional phase with NE–SW-trending σ3 is proved by some example of paleostress inversion (Figs. 6g, 6h).

This extensional phase caused the Cretaceous series to thicken mainly at the Sers and Siliana grabens as well as at the northwestern block of the Zaghouan fault (Fig. 5). This extensive tectonic phase is well documented in the Tunisian Atlas foreland of the Maghrebides [15, 16, 30, 38, 60].

During the Eocene times, Tunisia recorded a NW–SE-trending compressional tectonic phase is known the "Pyrenean tectonic phase." This NW- trending shortening reactivated some inherited normal faults to thrust, back thrusts and strike-slips [12, 24, 26, 34, 38, 59, 60].

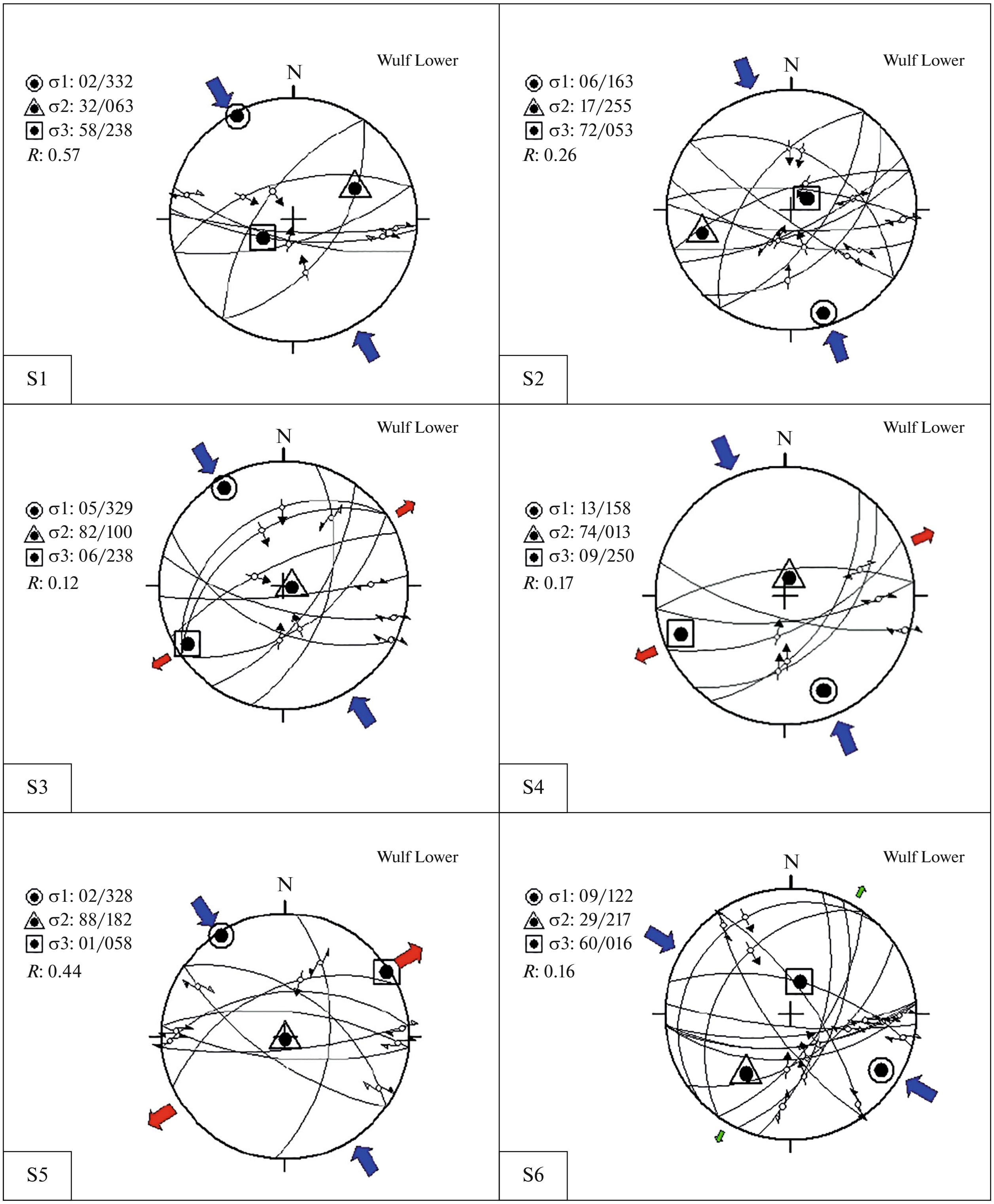

Fig. 10. Results of paleostress analysis in the Sfina Basin.

Both tectonic events of the Pre-Oligocene times have affected the Pre-Neogene series and formed the inherited weakness zones which have controlled later the extensional and compressional structures of Sfina area.

Oligocene–Lower Miocene Tectonic Deformation (Extensional Deformation and NE–SW-Trending Faults Activity)

In the Sfina Basin, the Fortuna, Messiouta, and Saouaf series show a NE-trending extensional tec-

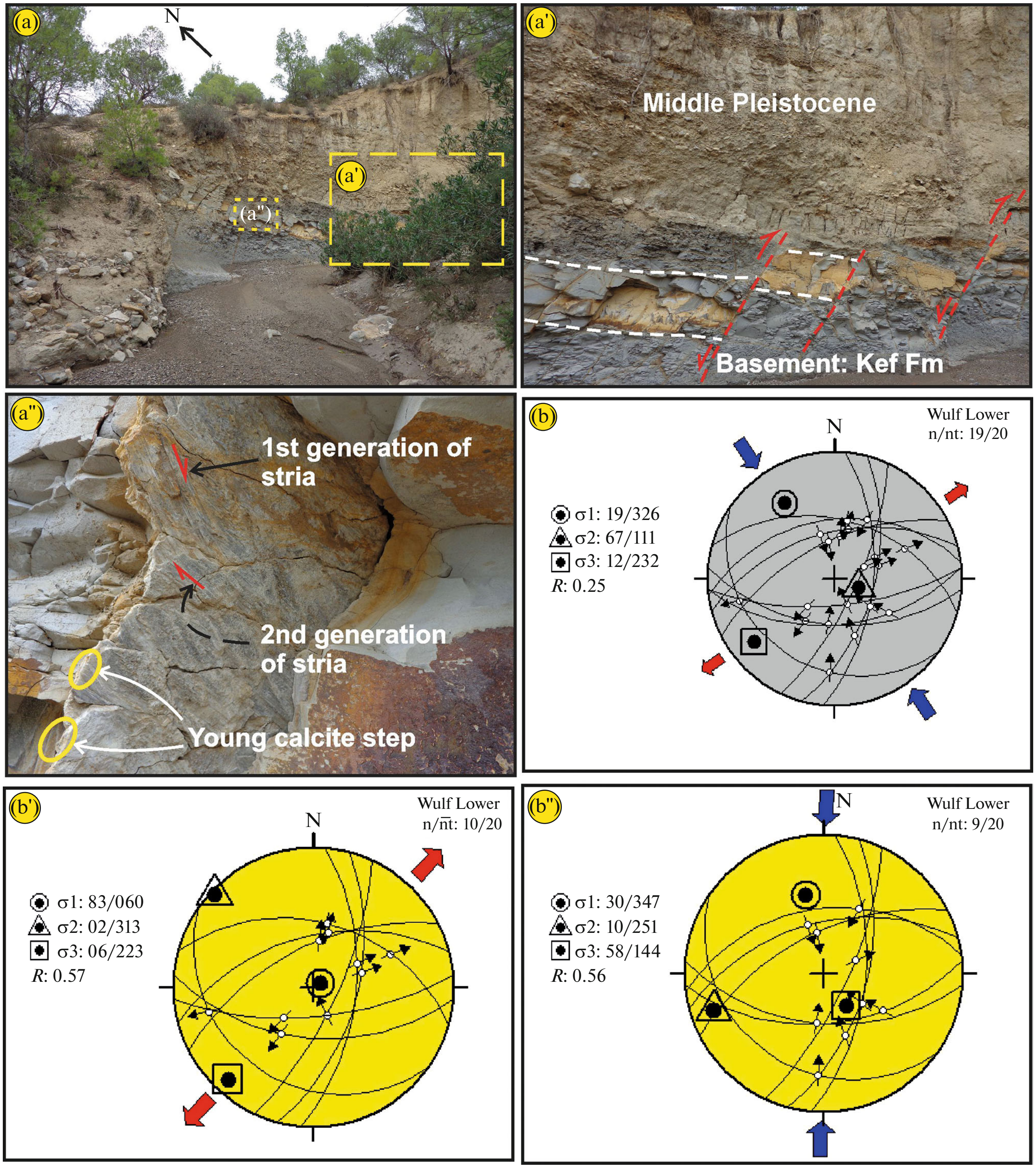

Fig. 11. Photo of a normal fault and NE–SW-trending fault plane reactivated to reverse faults during the Lower Quaternary compressional phase.

tonic phase that proved numerous synsedimentary normal faults (Figs. 7a–7h). During this episode the NW–SE-trending faults of the Sers and Siliana grabens structures have been activated as dip-slip [37, 38].

However, the NE-trending segments, of the Sfina Basin, acting as transtensional fault zones which led to the Sfina Basin opening as releasing step-over (Fig. 12b).

Herein, we propose a new Neogene Basin along the Zaghouan major fault where the NE-trending two segment faults acting during the Oligocene–Middle Miocene as right-lateral transtensional fault areas

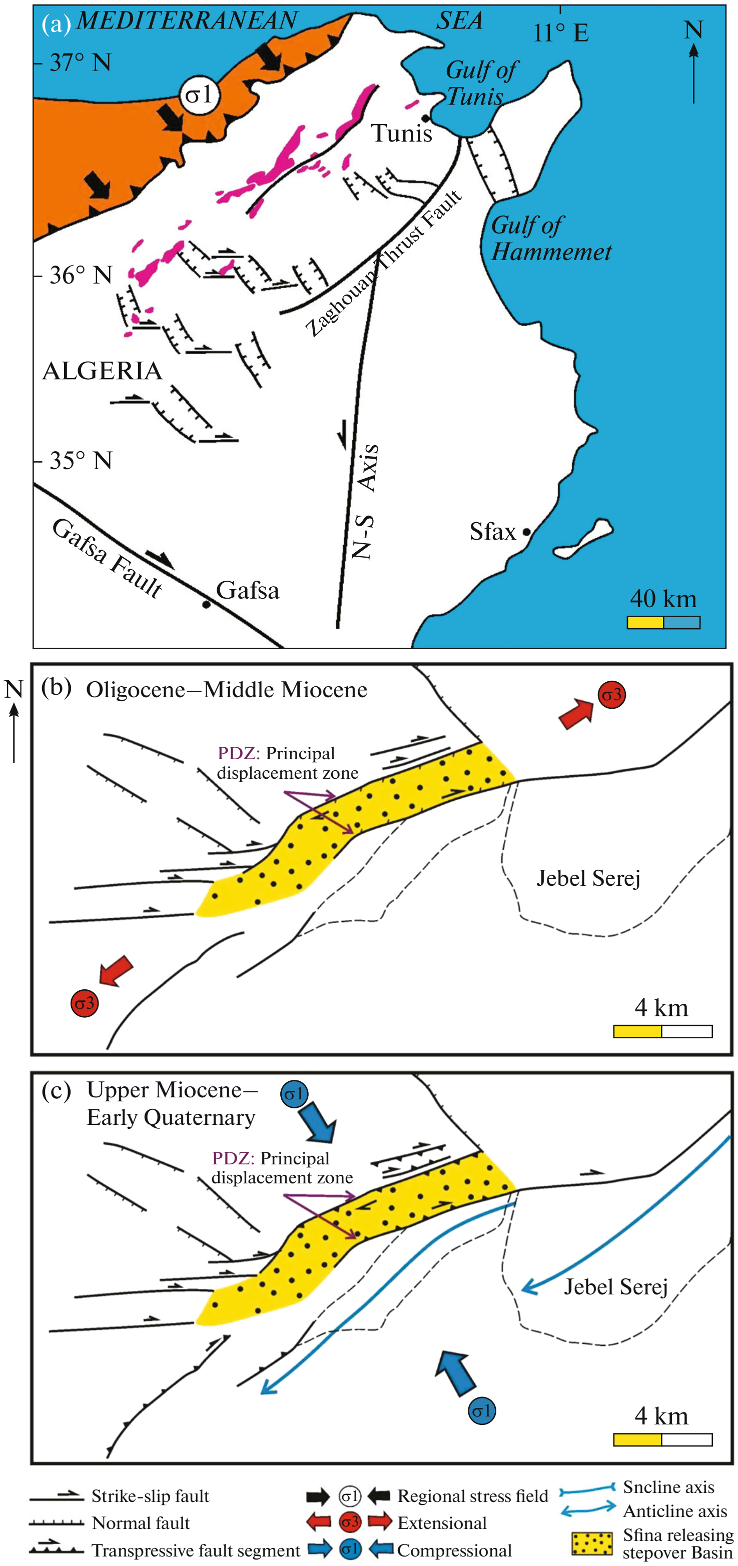

Fig. 12. Distribution of new discovered Neogene Sfina Basin in the foreland basin of North Africa and their chronology of the tectonic deformation, from Oligocene–Early Quaternary in relationship with the regional stress field resulted from the African and Eurasian plate convergence.

under an overall NE–SW-trending minimum principal stress axis σ3. The Oligocene and Lower-Middle Miocene series were deposited within releasing stepover (Fig. 12b).

Similar subsidence mechanisms influenced by oblique-slip movements are described in the Northeastern of Tunisia [4–6, 38, 43], in the Cordillera Basin, Colombia [50] and Esk Trough Basin, Australia [36].

Ezzine et al. [26] suggested that the Sfina-Jebel Bellouta zone is a compressional structure. However, the kinematics of preexisting fault and field observation carried out in the Siliana zone allow us to propose a transtensional basin model for the Neogene Sfina Basin (Fig. 12b).

During this time, the Northern Tunisia belonged to a global subduction overpowering the Western Mediterranean which was responsible for the thrust sheet mobilization from northwest to southeast [3, 4, 17, 45] and the 20°–35° anti-clockwise rotation of the Corsica–Sardinia block [1].

Herein, we suggest that the extensional/transtensional phase which led to the Sfina Basin, during the Oligocene–Middle Miocene, is a result of a locale switch σ1/σ2 near the NE-trending pre-existing faults (Fig. 12b).

This transtensional tectonic regime has been described in numerous studies and has been considered is the origin of the E–W-and-NW-trending graben structures opening such as the el Kef and Sers grabens [3, 5, 17, 37, 38].

Late Miocene–Early Quaternary Tectonic Inversion (Transpressional Deformation and Paleostress Perturbation)

Since the Late Miocene until the Early Quaternary, the geodynamic process in Northern Tunisian changes, subduction is blocked and translated to continental collision [17, 49]. During the Late Miocene and Early Quaternary episode, the el Kef-Sers-Siliana area was affected by two major's compressional phase with NW–SE- and-NNW–SSE-trending, respectively [37, 38] (Fig. 12c).

In the Sfina region these Neogene tectonic shortening are recorded by two angular unconformities between the Segui and Saouaf formations and between Early Quaternary series and pre-Miocene series (Figs. 4a, 4b).

The first Neogene shortening (Late Miocene) is responsible for the formation of the NE-SW-trending folds axis such as the Jebel Bellouta and Jebel Serj anticlines, in the Sfina Basin (Fig. 3a).

In addition, this compressional event reactivated the pre-existing weakness inherited, at least, from the Late Cretaceous.

During this Late Miocene compressional phase, the shearing along the NE-trending faults are expressed by numerous map-scale NE–SW-trending folds, detachment levels, observed in numerous site, that developed under a NW-trending strike-slip to transpressional stress regime (Figs. 9a–9i).

This tectonic inversion has generated an intensely tectonic activity by forming a detachment levels, facilitating the thrusting along the NE-trending faults (Figs. 9e, 9f) as well as the formation of folds and drag folds structures, which interpreted in Naji et al. [44] as a slump.

Herein, we interpret these compressional structures (small-folds) in the Sfina Basin as a result of the reactivation of the pre-existing normal fault of Zaghouan during this tectonic inversion, in opposition with Naji et al. [44]. In kinematic point of view, the variation in reactivations between fault trends, in a geological region, is explained by the perturbation of the regional field stress axis near the pre-existing accidents [4, 5, 38].

The stress tensors realized in the Neogene Sfina basin (Fig. 10: S1–S6) prove a homogenous NW–SE-striking maximum principal stress axis σ1 in concordance with the Late Miocene compressional phase known in Tunisia by Atlasic folding [5, 17, 38]. However, near the E–W-trending strike-slip and the NE-trending Sfina border faults the stresses position indicates that the NW-trending compressional event is associated with strike- slip deformation (transpressional and strike-slip tectonic regime) (Fig. 10: S3–S5).

This heterogeneous stresses spread is explained by the local stress permutation between σ2/σ3; near these preexisting weaknesses. During this Neogene shortening phase, the main NE–SW-trending faults of the Sfina Basin have underlined by a partitioned transpressional deformation in which a significant normal component is accommodated by a discrete oblique-slip component (Fig. 11c).

This later explains the transition from the compressional to transpressional tectonic deformation (Fig. 10: sites 1–4). In addition, our field observations show that from the Early Quaternary time the Sfina Basin recorded a second compressional tectonic phase proved by the angular unconformity between the Segui and Pleistocene series (Fig. 4a).

This shortening is with NNW–SSE-trend and was responsible for the deformed series inside the Sfina Basin and the reactivation of some pre-existing normal faults to reverses one (Fig. 11).

During this second Neogene compressional phase the stress perturbation were continued which explained the Early Quaternary subsidence strata in this Basin. At large scale, the Early Quaternary compressional activity increased, with reverse and folds formations at the Atlas foreland of the Maghrebides chains and would have augmented the genesis of the compressional mountains chains of the North Africa [4, 28, 38, 53].

Despite the intensity of the Neogene folding phases, in the Sfina region, it is very difficult to clearly observe the tectonic inversion along the NE–SW-trending faults, in some sites (Figs. 8a; 11a').

This is explained by the fact that the inverse components of these NE–SW faults were unable or not sufficient to compensate the earlier normal component (the Late Mesozoic and Lower-Middle Miocene extensional phase). This is clearly documented by the fault escarpment in the southeastern of the Siliana graben (Fig. 8a).

In summary, our structural analysis and field observations shows that the newly defined basin is a local pull-apart basin developed between two majors NE-trending dextral-reverse faults controlled, at large scale by the continental collision between the African and Eurasian tectonic plates (Fig. 12c).

CONCLUSIONS

(1) The Tunisian Atlas domain belt shows well-exposed types of oblique-slip tectonics along NE-SW-trending faults segments such as the Zaghouan major fault. In this research paper, our new defined NE-trending Sfina Basin (Tunisian Atlas domain) reveal a large influence of the NE–SW basement Zaghouan fault on regional tectonic deformation from the Late Cretaceous to the Early Quaternary times. We interpret that during the Late Cretaceous–Lower Miocene, the Sfina Basin developed as a local releasing stepover between the overlapping NE–SW dextral oblique-normal segments of the Zaghouan regional faults.

(2) Our results of paleostress analysis support a strike-slip tectonic phase with homogenous maximum principal stress axis (NW-to-NNW-trend $\sigma 1$) during the Late Miocene–Early Quaternary which is subvertical to the most NE-trending faults segments. Then, the far-field stress from the NW-trending Cenozoic convergence of Africa–Eurasia inverted the tectonic architecture of the Sfina Basin, where the tectonic inversion was mainly focused along the basin borders as right-reverse transpressional deformations.

ACKNOWLEDGMENTS

This research paper is another part the results Thesis, entitled “Extensional structures of the Tunisia’s Atlas northern center (The Sers and Siliana graben structures): Contribution of the sedimentary register, rheology and regional tectonics” by author N. Mahmoudi supervised by deceased Prof. Lassaâd Chihi (died June 13, 2021).

We are thankful to academician K.E. Degtyarev, the Editor-in-Chief and the Editorial Board, for the constructive comments and for help in improving the clarity of the paper. Authors are grateful to anonymous Reviewers for useful comments. Authors extend their gratitude to Editor M.N. Shoupletsova (Geological Institute RAS, Moscow, Russia) for careful editing.

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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