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Kinematic evolution and quantification of deformation in external orogenic zones: a case study from the Tunisian Atlas

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Abstract: The quantification of deformation is one of the main objectives studied by geologists in order to control the evolution of tectonic structures and their kinematics during different tectonic phases. One of the most reliable methods of this theme is the direct calculation of quantity of deformation based on field data, while respecting several parameters such as the notion of tectonic inheritance and reactivation of pre-existing faults, or the relationship between the elongation and shortening axis with major faults. Thus, such a quantification of deformation in an area may explain the relations of thin- and thick-skinned tectonics during this deformation. The study of structural evolution of the Jebel Elkebar domain in the southern-central Tunisian Atlas permits us to quantify the deformation during the extensional phase by a direct calculation of the vertical throw along normal faults. This approach is verified by calculation of thickness of eroded strata in the uplifted compartment and of resedimented series, named the Kebar Formation, in the downthrown compartment. The obtained results confirm the importance of the Aptian-Albian extensional tectonic regime. The extent of deformation during the compressional phase, related to reactivation of pre-existing faults, is less than that of extensional phases; indeed the compressive reactivation did not compensate the vertical throw of normal faults. The geometry of the Elkebar fold is interpreted in terms of the "fault-related fold" model with a décollement level in the Triassic series. This permitted the partition of deformation between the basement and cover, so that the basement was allowed for a limited transport only, and the maximum of observed deformation was concentrated in the thin-skinned tectonics.

Keywords: fault inversion; quantification of deformation; tectonic inheritance; tectonic phases; thin- and thick-skinned tectonics.

Introduction

The early Mesozoic break-up of Pangaea was accompanied by opening of the Alpine and Mediterranean Tethys during the Middle Triassic (Bortolotti et al. 2007). From the late Oligocene to early Miocene, the Ligurian-Provençal and Tyrrhenian basins were established during the continuing N–S convergence of Africa and Eurasia and the deformation front advanced towards the Alpine foreland (Casado et al. 2001). From the Late Miocene onward, the African-Eurasian convergence acquired a NW direction. The African-Eurasian convergence continued with the post-Villafranchian phase and has persisted with the N–S oriented shortening axis until recent times, which is expressed by the incipient closure of the Ligurian Basin (Larroque et al. 2001). Based on sparse focal mechanism solutions, the first-order seismo-tectonics framework for the Eastern Mediterranean was presented by McKenzie (1972). Geodetic measurements by Satellite Laser Ranging (SLR) and then GPS led to a remarkable improvement of the plate kinematic reconstructions. Nocquet (2012), referring to the available GPS data from southern part of the Tellian Atlas to the southern margin of the Ligurian–Provençal Basin, estimated the convergence rate at about 4–5 mm/year. However, more precise estimates are hampered by lack of GPS data from Tunisia and Libya. In general, the plate kinematic boundary conditions indicate the convergence rate at 5.5–6 mm/year.

Most of these studies were based on quantification of plate movements in the internal orogenic zones, without conside ration of deformation parameters in external zones. In addition, the choice and localization of the study area are important constraints for deciphering evolution of tectonic structures developing under different tectonic regimes. Tunisia is located at the northern limits of the African plate and, particularly, at the eastern margin of the Atlas Range, which position enables us to register the maximum information about the deformation processes during opening of the Atlantic and closing of the Tethys oceans.

The aim of this contribution is to quantify the deformation during the rifting-related extensional phases of tectonic evolution, recorded by movements along the normal faults, and then during their compressional reactivation in the external zones of the Atlas Mts in south-central Tunisia.

Methods

The methodology in this work is guided by the three main objectives:

1. Quantification of deformation based on fault displacement during the extensional period and the geometry of inversion-related folds during the compressional reactivation of pre-existing normal faults. For this purpose, we propose model solutions presented in the chapter "Parameters of deformation" below.
2. Determination of the chronology of tectonic events and kinematics of deformation structures resulting in reconstruction of the structural evolution of the studied area.
3. Finally, the correlation between the thin- and thick-skinned deformation processes.

The proper choice of the study area is one of the most important conditions to verify the tectonic complication in order to interpret the chronology of tectonics events and the evolution of geological structures. For this aim we have chosen the southern-central Tunisian Atlas (Fig. 1). The choice of this area is not arbitrary, because it records a maximum of registered tectonic phases; unlike the northern Atlas that occurs at the front of the Africa and Eurasia convergence and is strongly tectonized. In contrast, the central-southern Atlas represents the wide external zone in which the different stages of the structural evolution can be clearly distinguished.

The principal parameters controlling the tectonic evolution of the external orogenic zones

In order to gather some fundamental parameters, it is important to quantify deformation in the external zone of the Atlas Mountains. These parameters should then be verified in any study of deformation during successive tectonic phases.

The inheritance tectonics

The tectonic inheritance concept is based on the interpretation of the evolution of tectonic structures and their kinematics during different tectonics regimes. The Atlasic structures in the North African Craton are guided by particular dynamics over the geological time, especially since the opening of the Tethys in the Late Triassic, associated with extensional structures, until the current N-S convergence of Africa to Eurasia accompanied by a compressive tectonic regime (Caire 1971; Dercourt et al. 1985; Zargouni et al. 1985; Frizon de Lamotte et al. 2009).

One of the main parameters that have to be considered in this concept is the relationship between the direction of the elongation axis during the distensive phase and the shortening axis during the compressive reactivation. The Tunisian Atlas is distinguished almost by the same NW–SE direction of both events. The Tunisian Atlas, particularly the Southern-Central Atlas, shows normal faults trending NE–SW perpendicular to

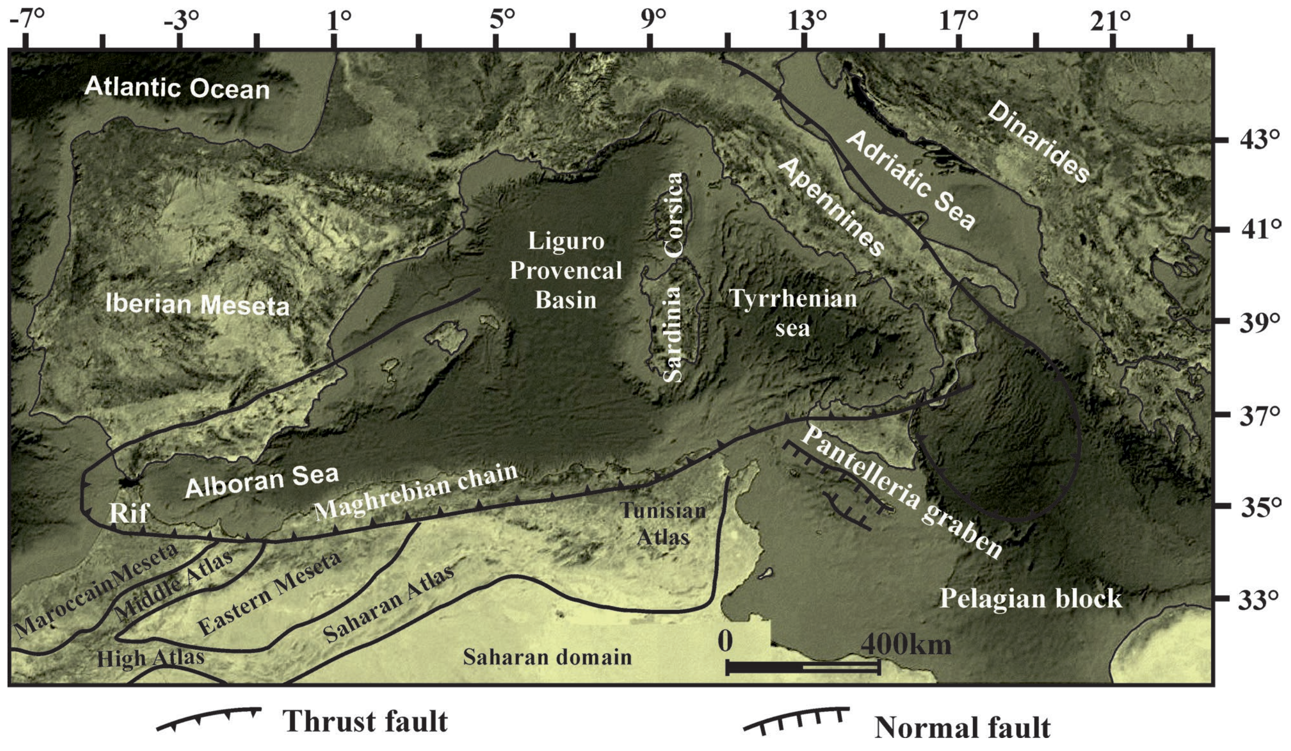

Fig. 1. Position of the Tunisian Atlas in the Mediterranean Alpine chains. The Tunisian Atlas occupies the eastern limit of the Atlas structures that were guided by opening of the Tethys in the Middle–Late Triassic and its subsequent closure continuing until the recent times.

the NW–SE main elongation axis. The normal faults are reactivated during the Alpine compressional phase along a shortening axis trending NW–SE to NNW–SSE (Ouali et al. 1986; Ben Ayed 1993; Hlaiem 1999; Belguith et al. 2011), whereby the Atlasic folds with NE–SW to E–W direction developed parallel to the pre-existing normal faults (Frizon de Lamotte et al. 2009).

Partitioning of shortening-related deformation in pre-existing fault systems

Generally, the faults with a strike-slip component have the principal compressional and extensional stress axes (σ_1 and σ_3) in a horizontal position. In a collision zone with the generally transpressive stress regime, where the pre-existing faults are oblique to the convergence vector, deformation is concentrated in the vertical strike-slip faults instead to involve an oblique-slip movement along an inclined fault. Hence, applying the principle of fundamental physics to minimize the dissipated energy, movement along an inclined fault, which has a larger projected surface, is hampered by a more important friction than the strike-slip movement along a vertical fault. Consequently, it is more favourable to accommodate the strike-slip component along a vertical fault than along an inclined fault, while the compressive component is accommodated by thrusting along the inclined fault (see Fig. 2). Therefore, it is important to verify the angle of convergence in the deformed area on the one hand and the strike and inclination of the pre-existing fault's plane on the other hand.

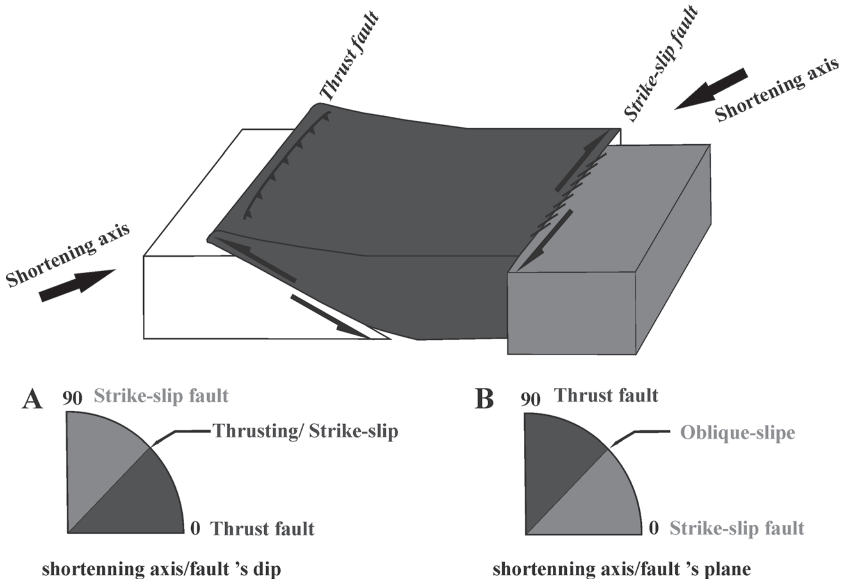

Fig. 2. Partitioning of deformation based on relationships between the horizontal shortening axis and the dip direction of a pre-existing fault (**A**) and strike of the fault's plane (**B**): **A** — in case the angle of a fault dip is less than 45° and approaches 0°, thrust faulting is generated, while if this angle exceeds 45° and increases toward 90°, the strike-slip faulting will be dominating in non-orthogonal shortening; **B** — if the angle between the shortening axis and the fault trend is more than 0 and less than 45° towards an inclined fault, than the strike-slip fault activity will be initiated, whereas oblique-slip to thrusting will dominate for angles more than 45°. The particular case with zero angle between the shortening axis and subvertical fault direction means no reactivation of the pre-existing fault. Further explanations in the text.

Thin and thick-skinned notion

The problem of the thin- and thick-skinned concept is one of the fundamental parameters to quantify the orogenic deformation. Two concepts are generally available: (a) the basement is involved in deformation of the cover (Belguith et al. 2011, confirmed this style in the central Tunisian Atlas), or (b) it has a passive role and it is only the sedimentary cover which is tectonized (detachment style; e.g. Amamria et al. 2013). In this latter case the thin- and thick-skinned segments are separated by a surface known as the décollement level.

If the basement is involved in shortening, deformation in the cover will be similar in two adjacent areas. On the contrary, when the basement is not integrated in the deformation of the cover, the resulting structures show great variations from one area to another. This is an effect related to inheritance tectonics controlled by pre-existing fault systems in the cover complexes.

Geological setting

The typical example to demonstrate the deformation style in an African Alpine collisional orogen is the eastern limit of the Atlas chain, such as the Tunisian Atlas (Fig. 3A). This area records firstly the response to opening of the Atlantic Ocean and secondly the rotation of Africa and its approach to Eurasia. For our analysis, we have chosen the central Tunisian Atlas in particular, which forms the boundary between two different structural domains (Fig. 3B): the northern, strongly tectonized area and the southern, only moderately deformed domain that gradually passes into the stable Saharan Platform.

The study sector occupies the central position of the central Tunisian Atlas, named the Elkebar chains (Fig. 3C). It is a large-scale anticline with 60–80° axial direction (Fig. 3D) bounded in the east by the north-south trending axial plunge, which represents a structural limit between two different palaeogeographic domains at the same time (Oriental Platform; Fig. 3C).

The Jebel Elkebar chain is geographically located on the southern border of the town of Sidi Bouzid, bounded by the following geographic coordinates: at latitudes from 34°56'42"N to 34°59'42"N and at longitudes from 9°27'54"E to 9°33'18"E. We will consider especially

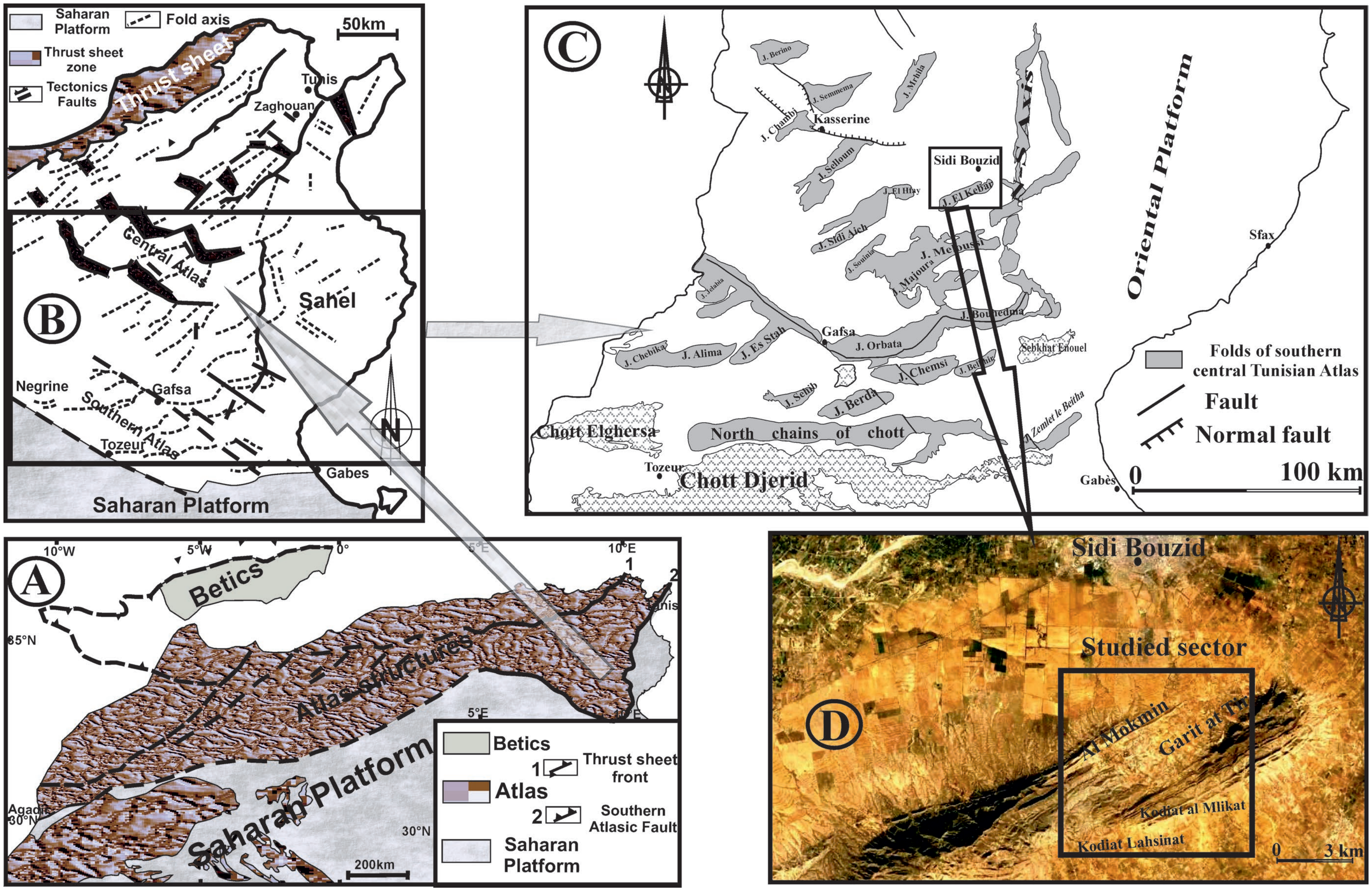

Fig. 3. Localization of studied area: **A** — position of the Tunisian Atlas at the eastern termination of the Atlas chains; **B** — delimitation of the southern central Tunisian Atlas with the northern Tunisian Atlas to the north, the Saharan Platform to the south and the North-South axis to the East; **C** — the position of the Jebel Elkebar domain in the central Tunisian Atlas; **D** — the NE–SW trending anticlinal structure of Jebel Elkebar.

the eastern boundary of the Jebel Elkebar domain, in which the geometry and evolution of structures provide valuable data that facilitate interpretation of the kinematics and quantification of deformation.

Stratigraphic data

The sedimentary complexes outcropping in the study area range from the Late Jurassic to Quaternary, with dominance of Cretaceous formations. The succession begins with the Sidi Khalif Formation of Tithonian age that is composed of alternation of calcareous clay and marly deposits dated by ammonites. This formation is overlain by alternating sandstones and reddish dolomites of the Meloussi Formation of Berriasian to Valanginian age, with the thickness of 300 metres. The Boudinar Formation of basal Hauterivian age is characterized by dominance of coarse-grained sandstones with fossil wood remnants; its thickness is 150 metres. It is overlain by limestone and dolomite of the Bouhedma Formation, which is of Hauterivian to Barremian age determined by ostracods, gastropods and echinoderms. It has a variegated composition with alternation of carbonate beds, clay, sand and gypsum with local intercalations of palaeosols. The total thickness of this formation is about 200 metres. The Sidi Aich Formation, Barremian in age, consists of white sands with oblique stratification and thickness not exceeding 10 metres. The Orbata Formation of Aptian age, determined by orbitolinids, is formed by a dolomitic layer at the base, followed by calcareous marl alternations; it is 20 metres thick and constitutes a competent sequence representing positive relief forms. The Cretaceous series finishes with the Zebbag Formation (Albian–Cenomanian up to earliest Turonian age); it is a marl-carbonate alternation with rare intercalations of gypsum. The formation is capped by a massive dolomitic layer of the Guettar Member with a thickness of 10 to 15 metres. The total thickness of the Zebbag Formation is 200 metres.

It should be noted that there is another typical formation occurring in the Jebel Elkebar area. It is named the Kebar Formation — these are redeposited conglomerates and variable deposits like sands, clays, gypsum and carbonates. These deposits are the lateral equivalents of the Orbata, Sidi Aich, Bouhedma formations and of a large part of the Boudinar Formation for a period ranging from the Hauterivian to Aptian. The Kebar Formation is attributed to the basal Albian (Trabelsi et al. 2010). The temporal and spatial distribution of the Kebar Formation is an important parameter which will be used in the interpretation of the kinematics and quantification of deformation.

Geodynamics study

The tectonic interpretation of the investigated area is based mainly on precise mapping associated with construction of detailed geological cross sections. The geological map of the study zone shows an asymmetric anticline of ENE–WSW direction; its northern flank is subhorizontal, dipping less than 15°, while the southern flank is subvertical with dips of about 70° (Fig. 4). The asymmetry between the two limbs is also observed in the dissimilar distribution of sedimentary formations in both. The core of the anticline is occupied by the Sidi Khalif Formation, the limbs are dominated by the Meloussi and Boudinar formations (Fig. 4). This anticline is cut out in the axial part by a pre-existent fault of N80 direction, which was subsequently reactivated during the compressional tectonic regime. We utilize it as the principal phenomenon controlling the evolution of tectonic structures in the area.

The A–A’ cross-section is with NW–SE direction parallel to the main shortening axis and perpendicular to the anticline axis and direction of the pre-existing fault. This cross-section confirms firstly the asymmetry of the anticline and on the other hand it shows the asymmetric distribution of sedimentary series in two flanks of the anticline. The southern flank is formed by the Sidi Khalif, Meloussi and Boudinar formations unconformably overlain by the Zebbag Formation, while the north side is formed by an almost complete succession from the Sidi Khalif Formation at the base to the Zebbag Formation on the top (Fig. 5). Note that the northern flank of the Jebel Elkebar anticline also includes the specific Kebar Formation (Fig. 6) that is inserted between the Orbata Formation of the Aptian age and the Albian–Cenomanian Zebbag Formation. The problems to be analysed are: 1) the sedimentary gap of the missing Bouhedma, Sidi Aich, and Orbata formations in the southern flank and 2) the presence of the Kebar Formation in the northern flank of the anticline, knowing that this formation is characterized by a variable shape of conglomerate pebbles (angular, subangular and rounded) and also variability of origin and facies (sand, clay, sandstone and carbonate) which are lithologically recall the Boudinar, Bouhedma, Sidi Aich and Orbata formations (Fig. 5). These problems cannot be resolved without deciphering the chronology of tectonic events and kinematics of development of this structure.

Consequently, it is important to consider that the absence of several sedimentary units in the southern flank, indicated by a direct contact of the Boudinar Formation with the Zebbag Formation, is justified by the deposition of the Kebar Formation only in the north limb and between the Albian and Aptian strata. The inferred erosion and redeposition should not have occurred over a long period, since the resedimented Kebar Formation occurs between two successive concordant series — the Orbata and Zebbag formations. This situation requires the formation of a palaeo-slope following some extensional tectonic activity (synsedimentary fault) allowing a rapid erosion of the southern uplifted block on one hand, and down-throw of the northern compartment to create a depocentre area for the Kebar Formation.

The detailed examination of slickensides in the Garet at Tir area (fault F2 trending N80 in Fig. 4) revealed normal activity by contacting the Meloussi Formation with that of Bouhedma. In the southern compartment of this fault, the

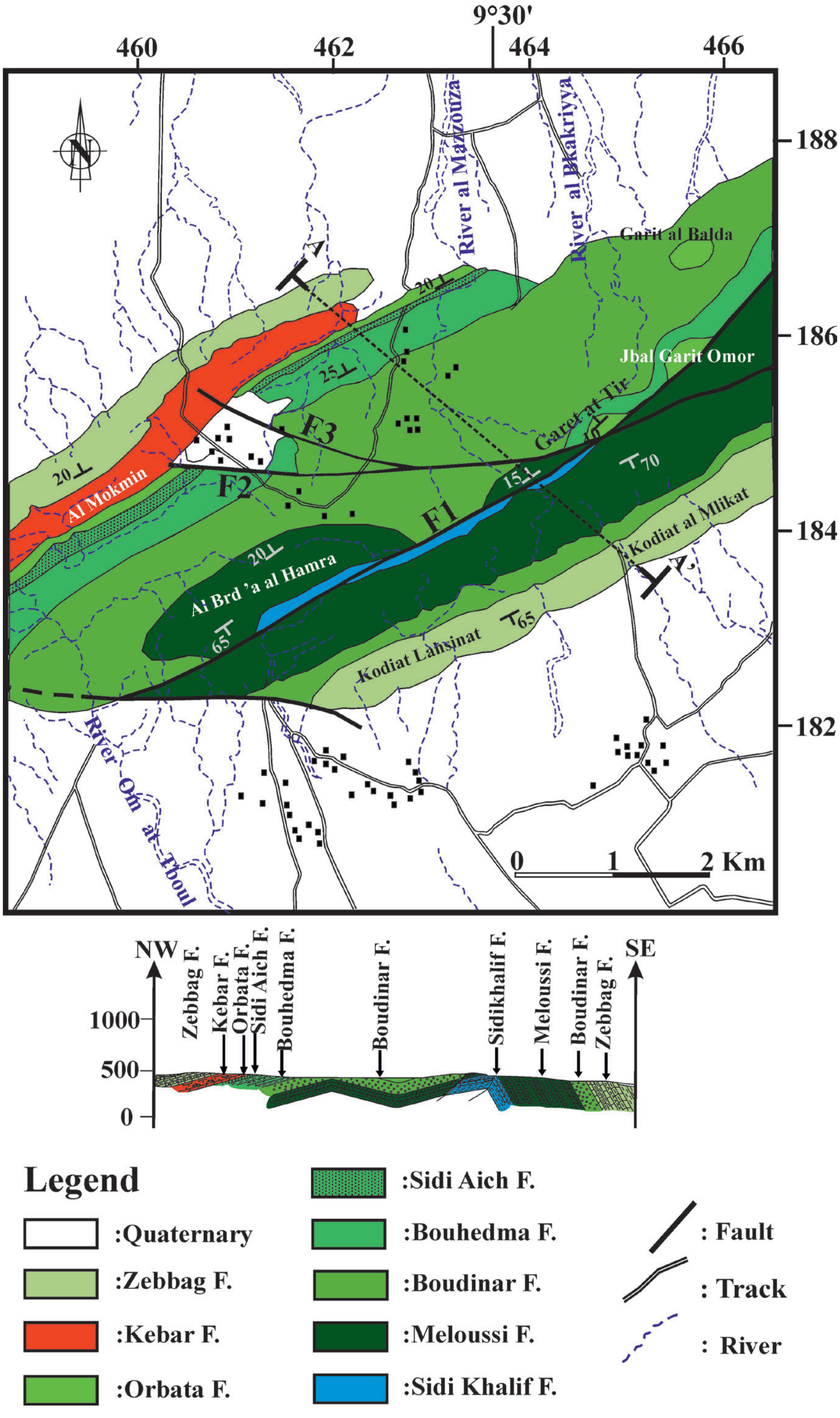

Fig. 4. The geological map and cross-section A–A' of the Jebel Elkebar structure (localization according UTM coordinates), showing an asymmetric anticline of the ENE–WSW direction, where its axial part is affected by a pre-existing ENE–WSW trending fault (F1). The cross section is oriented parallel to main Alpine shortening axis.

formations of Orbata, Sidi Aich, Bouhedma and part of the Boudinar Formation are not exposed, whereas in the northern compartment the whole succession with intercalation of the Kebar Formation is cropping out.

Based on the tectonic development of the Jebel Elkebar structure and erosion and redeposition of sedimentary formations during changed geological events, we have tried to propose a kinematic scenario and to quantify the deformation processes.

Parameters of deformation

The quantification of deformation is one of the most important parameters for resolving the structural evolution. The calculation of the amount of deformation in the Jebel Elkebar site is closely related to the tectonic evolution and chronology of successive extensional and compressional phases. In principle, this zone was affected by two principal tectonic regimes: the first one extensional, which was later replaced by compression. Methodologically, we will reconstruct the evolution of the main pre-existing fault during the extensional phase and its reactivation during the ensuing compression.

Quantification of extensional deformation

In this case, the deformation controlling the evolution of the structure is the linear deformation that can be determined by the formula:

$$\varepsilon = \frac{\Delta l}{l0} = \frac{lf - l0}{l0},$$

where ε is the linear strain.

To verify this notion it is important to determine the range of fault-slip movement, whatever lateral or vertical. The structural study of the Jebel Elkebar structure revealed an asymmetric anticline affected by a pre-existing fault in its axial part. The problem in this study is the determination of separation of the stratigraphic markers that were displaced on both sides of the fault, since the markers can be completely hidden in the downthrown fault block, or eroded in the uplifted block. To resolve this problem, we have determined the vertical offset along the synsedimentary fault by calculations of the volumes of eroded strata in the uplifted block and the resedimented formation in the downthrown block. The facies asymmetry of the Jebel Elkebar structure resulted from erosion-related extensional activity along the fault, subsequently partly recovered by compression. This fault, designated as the Garet at Tir Fault (F2 in Figs. 4 and 7), is a north-dipping normal fault of Aptian age with prevailing dip-slip movement confirmed by the slickenside measurements: N80, 70NNW, 50W (Fig. 8).

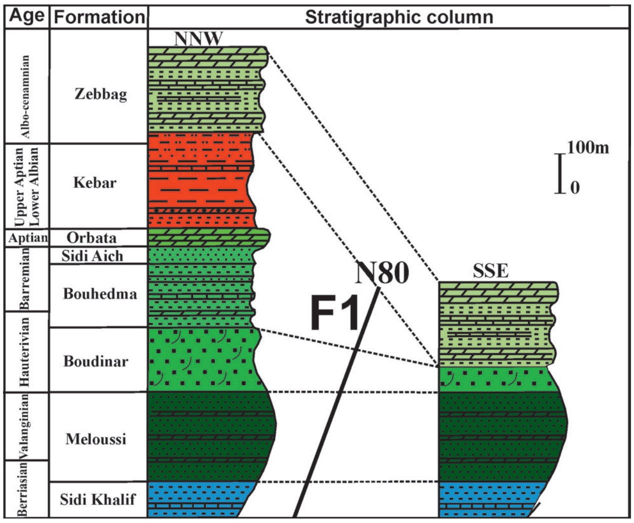

Fig. 5. Stratigraphic correlation between the two flanks of the Jebel Elkebar anticline. Note the dissymmetry of distribution of sedimentary formations expressed by omission of the Bouhedma, Sidi Aich, Orbata and a part of the Boudinar formations in the southern flank associated with occurrence of the resedimented Kebar Formation in the northern flank.

The synsedimentary activity of the Garet at Tir Fault is documented by erosion of the Orbata, Sidi Aich and Bouhedma formations, as well as a great part of the Boudinar Formation in the southern uplifted compartment. The eroded material was redeposited in the subsided northern compartment as the Kebar Formation intercalated between the Aptian Orbata and Albian Zebbag Formation (Fig. 5; cf. Trabelsi et al. 2010). Based on the constant thickness of the Zebbag Formation on both sides of the fault, the proposed model requires that the top of Orbata Formation collapsed and was put in contact with the Sidi Khalif Formation.

It is inferred that erosion of the uplifted block was mainly caused by gravity-driven and possibly earthquake-induced, down-slope mass wasting along the developing fault scarp. River erosion is less probable, since it reached the Boudinar Formation composed mostly of sandy lithologies that are only partly eroded. In case of the river erosion, a complete removal of this formation would be expected. The proposed model is based on two known principal parameters: the dip angle of the fault (α) and its vertical throw (Rv). The vertical displacement brought about the contact between the Orbata Formation in the northern compartment with the upper level of the Sidi Khalif Formation, so the vertical offset (Rv) is

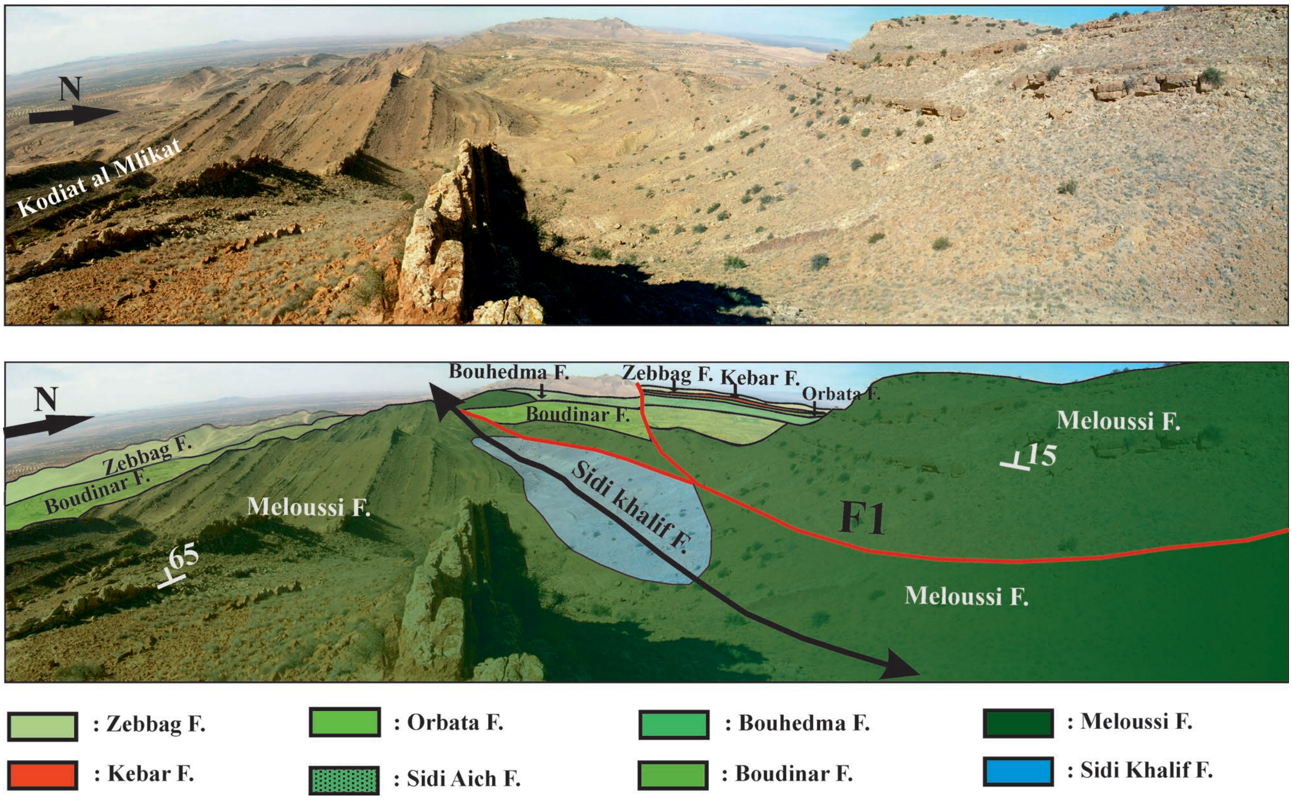

Fig. 6. The geometry of the Elkebar anticline shows an asymmetry of geometry and facies distribution between two limbs — the steeper southern flank is characterized by subvertical bedding and omission of some formations (Orbata, Sidi Aich, Bouhedma, and a part of Boudinar), the slightly tilted northern flank is characterized by a complete succession with intercalation of the Kebar Formation.

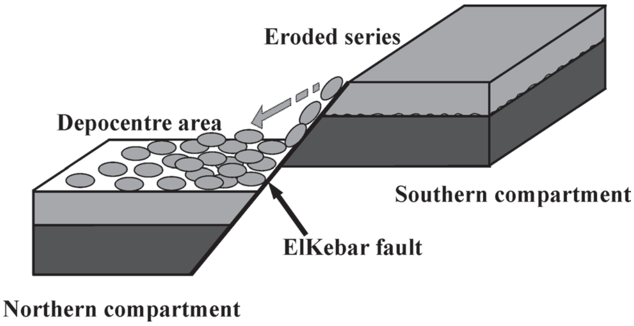

Fig. 7. The normal activity of the ElKebar fault during the Aptian that explains the erosion of Boudinar, Bouhedma, Sidi Aich, and Orbata Formation in the southern compartment and redeposition of Kebar Formation in the northern compartment.

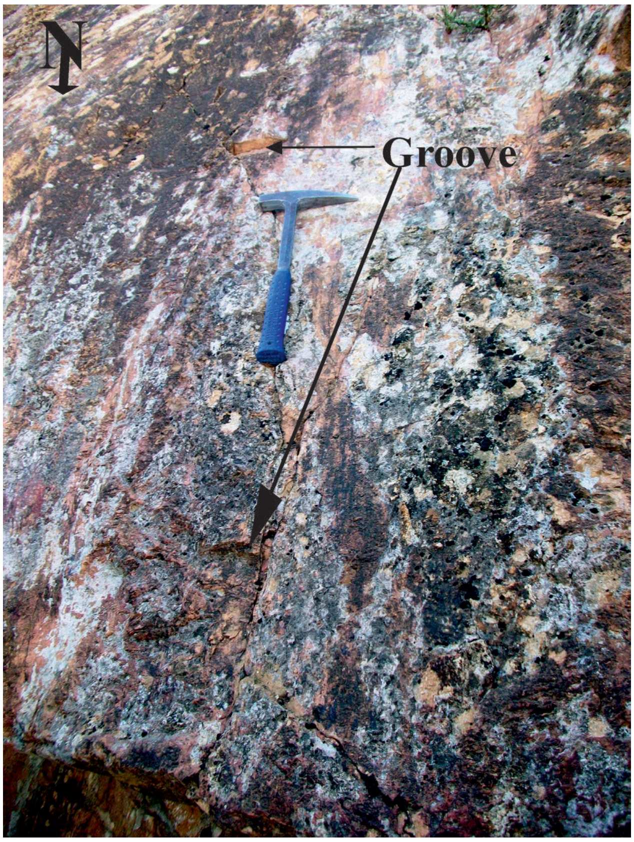

Fig. 8. The slickenside plane related to the Garet at Tir fault shows striations and grooves still indicating the normal kinematics, despite its reactivation during the compressive phase.

equivalent to the collective thickness of the formations Orbata (20 metres), Sidi Aich (10 metres), Bouhedma (200 metres), Boudinar (150 metres), Meloussi (300 metres) and the upper level of the Sidi Khalif Formation (20 metres). Hence the cumulative vertical throw of the Garet at Tir Fault is above 700 metres (Fig. 9).

The lateral separation (Rl) of a fault can be derived from the relation: $tg\alpha = Rv/Rl$. The total horizontal component of movement along a fault then corresponds to the displacement Δl. To determine the initial length (l_0) of the scaled model, it is enough to remove firstly the initial horizontal displacement caused by the fault and secondly the strata dip produced by the superimposed compressional reactivation. Assuming that the dip of fault (α) is 70° (Fig. 9B), the horizontal displacement would be:

$$Rl = \frac{Rv}{tg\alpha} = \frac{700}{2.74} = 255.47\,m$$

The resulting deformation then amounts:

$$\varepsilon = \frac{\Delta l}{l0} = \frac{255.47}{2000} = 0.127$$

Quantification of the compressional deformation

During the superposed compression and inversion of the Jebel Elkebar structure, the Garet at Tir normal fault was reactivated as a thrust fault. It is important to note that the shortening axis is parallel to the preceding elongation axis, so the principal compressive stress axis σ_1 is perpendicular to the strike of the pre-existing fault and parallel to its dip. This relation between shortening axis and pre-existing normal fault is indicated by development of folds of the "fault propagation fold" or "fault bend fold" type verified by the geometry of the Elkebar anticline. As a result, the Jebel Elkebar anticline is formed by two asymmetric flanks; the southern one shows dipping of layers to the south with angle of ca. 65 degrees, whereas the dip of in the northern flank is north-dipping at angles not exceeding 15 degrees (Fig. 7). The Elkebar anticline is moulded about the old normal fault inverted to a reverse fault with thrusting of the northern compartment over the southern one.

The quantification of the compressive deformation is determined by the vertical offset along the inverted fault during thrusting that corresponds to the thickness of the Meloussi Formation (Fig. 9D):

$$Rl = \frac{Rv}{tg\alpha} = \frac{300}{2.74} = 109.48\,m$$

$$\varepsilon = \frac{\Delta l}{l0} = \frac{109.48}{2000} = 0.054$$

In this study, the quantity of deformation during extensional and compressional phases with the parallel lengthening and shortening axes enabled reactivation of the pre-existing normal fault as a reverse fault. Although these quantities of deformation are variable indeed, the amount of extensional deformation (0,127) exceeds that of the compressional deformation (0,054) approximately twice. Accordingly, the compressive phase did not compensate the total offset of the pre-existing Garet at Tir normal fault (Fig. 8), which still shows the normal offset in spite of its compressional reactivation.

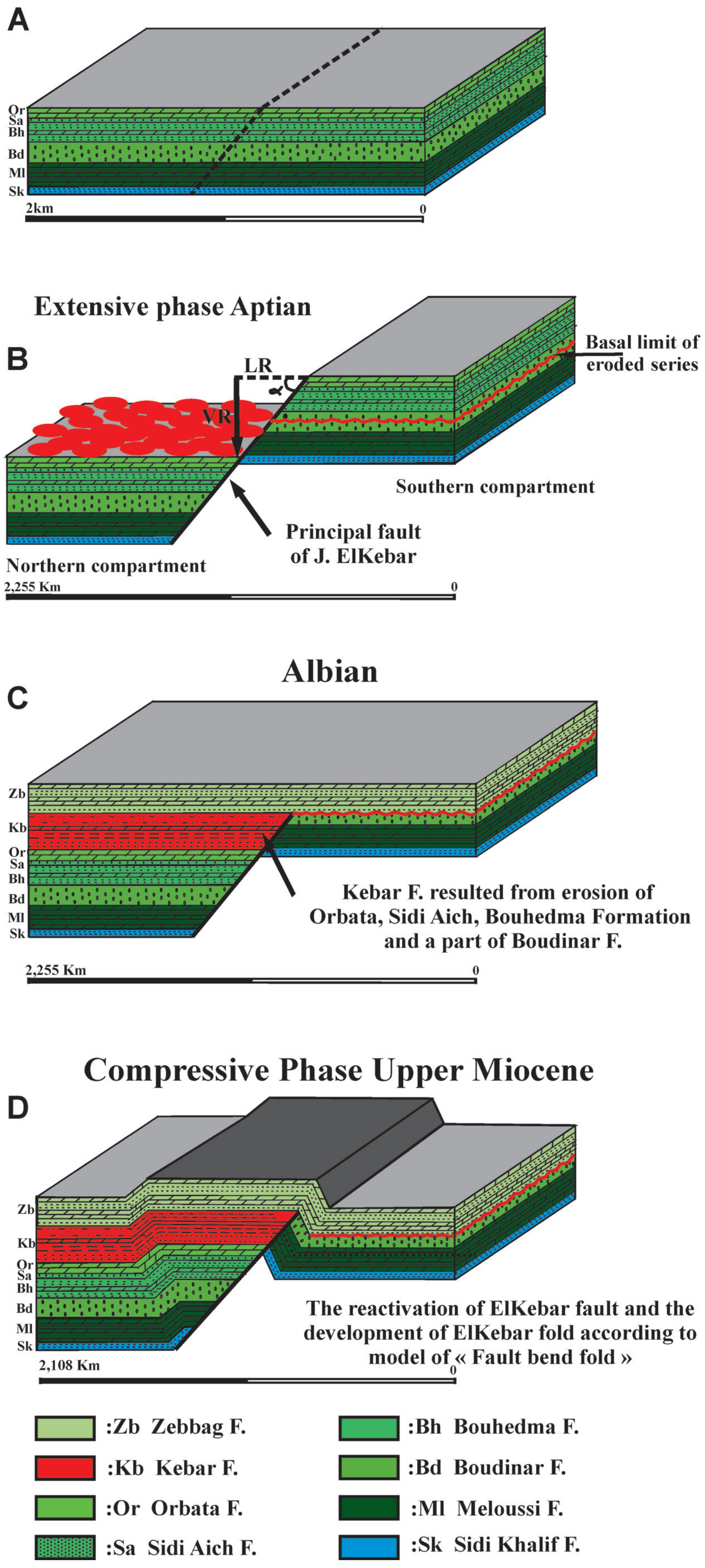

Fig. 9. The proposed evolutionary model of the Jebel Elkebar anticline: **A** — the original (pre-Aptian) disposition of sedimentary layers before deformation; **B** — the extensional activity of the Elkebar fault associated to the Aptian erosion of the southern compartment and redeposition of the Kebar Formation; **C** — after cessation of normal faulting, erosion and peneplanation, the area was sealed by the Albian Zebbag Formation; **D** — reactivation of pre-existing normal fault during the compressive phase following the model of "fault bend folding".

Synthesis and discussion

The quantification of extensional and compressional deformation in orogenic structures requires the verification of some parameters that have an important role in the interpretation of the geometries of faults and folds. It is important to choose the suitable area for applying the main parameters of the evolution of deformation. Consequently, the Jebel Elkebar anticline may serve as a representative example to control the development of tectonic structures in the central Tunisian Atlas.

One of the most important parameters to verify the deformation is the inheritance tectonics and the compressional reactivation of pre-existing normal faults. The Tunisian Atlas was subjected to two principal tectonic phases, the first one was extensional and began in the Late Triassic with opening of the Tethys Ocean (Raulin et al. 2011). In the central Tunisian Atlas, this extensional phase is well distinguished in the Cretaceous sedimentary successions by the synsedimentary control of ENE–WSW oriented normal fault F2, whose elongation axes are NW–SE directed with subsidence of north-western compartments. During extension, the volume of eroded formations in the uplifted compartment was approximately the same as that resedimented in the downthrown compartment (Kebar Formation), so there is a conservation of volumes and there was no significant lateral sedimentary discharge.

Several problems of the compressional tectonics in the Tunisian Atlas, and particularly the period of its activity, have been controversially discussed. Some studies showed that the compressive phase started during the Eocene period with the E–W shortening axis (El Ghali et al. 2003;

Khomsi et al. 2006; Mzali and Zouari 2006), which is correlated with the Eocene compressional phase in the Algerian Atlas. However, other authors confirmed that the Eocene shortening phase was not widespread throughout Tunisia as it was followed by periods of stress relaxation and extension. Therefore the main compressive phase rather corresponds to the Late Miocene Alpine phase with the NW-SE shortening axis followed later by post-Villafranchian phase with submeridional shortening axis (Boukadi et al. 1998; Frizon De Lamonte et al. 2000; Piqué et al. 2002).

Field data in this study area do not show signs of Eocene compression. The late Alpine compressional phase with NW–SE shortening axis is well documented as perpendicular to the old normal faults trending ENE–WSW, hence allowing their reactivation as reverse faults and development of anticlinal folds according to the "fault bend fold" model (Fig. 9). On the other hand, the model of "fault propagation fold" cannot be verified in this case, because its application requires conservation of thicknesses between two flanks of an anticline, whereas the Elkebar anticline shows a big variation of thicknesses and facies between its two flanks.

Another parameter that is important to verify is related to the concept of inheritance tectonics and reactivation of old normal faults and especially the direction of the shortening axis with respect to the pre-existing faults. In the presented case study, the elongation axis during extensional periods was NW–SE directed, which controlled development of normal faults trending ENE–WSW. The reactivation of these faults by a compression with shortening axis parallel to the preceding elongation axis is indicated by the inversion of normal faults and their association with thrusting structures. If the axis of shortening was oblique to the old fault, the main component would generate a strike-slip along the pre-existing normal fault and the quantity of orthogonal deformation will be much less important. According to our observations, this is not the case.

The main driver of the compressive stresses in the Atlas Mountains and northern African Craton, particularly in Tunisia, was the convergence of Africa relative to Eurasia. The resulting deformation gradually decreases away from the African-Eurasian convergence zone to the external Atlasic areas, remarkably from north to south of Tunisia, which accounts for the tectonic stability of the Saharan Africa Platform. In this aspect, it is worth checking whether the basement is integrated into the deformation in the central Tunisian Atlas.

In the northern Tunisian Atlas, the basement is incorporated in deformation which allows in many cases its outcrop to the surface. In contrast, the basement complexes in southern-central Tunisia are not involved in shortening. Previous studies in some neighbouring structures, like Jebel Orbata (Bensalem et al. 2011) and Gafsa basin (Amamria et al. 2013), have shown that the amount of deformation is very variable also between two very near areas, giving rise even to duplex structures, as for instance the comparatively thin Triassic deposits stacked above the inverted pre-existing Gafsa Fault (Amamria et al. 2013).

Investigation of these structures indicates that the primary reason for various degrees of deformation is related to the tectonic inheritance and reactivation of pre-existing faults during the compressive phase. In fact, if shortening affected the basement areas with significant sediment load (Triassic and Jurassic that can reach the total thickness of 3000 to 4000 metres), the style and amount of deformation is moderated between the two neighbouring areas. Consequently, we suppose that the basement played a passive role in the transport of deformation along the décollement level in the Upper Triassic to Lower Jurassic strata (Ahmadi et al. 2006) and the overall deformation and shortening style can be characterized as thin-skinned tectonics.

Conclusions

This contribution concerns the modes of extensional versus compressional deformation in external zones of southern-central Tunisia. The quantification of deformation in the Jebel Elkebar zone was based on the direct calculation of the amount of synsedimentary activity of normal faults. The observed sediment redeposition permitted to determine their vertical offset during extension, and consequently the quantity of deformation could be determined. On the other hand, the compressive reactivation of pre-existing faults caused the overlap and re-contacting of older formations with younger ones. Consequently, a partial compensation of the vertical offset of original normal faults was reached.

In general, it was shown that the Aptian–Albian extensional deformation resulting in development of synsedimentary normal faults was not fully compensated later by the later compressional regime. This observation can be generalized across the entire Tunisian Central Atlas, where nearly all old normal faults still predominantly record the extensional activity, in spite of their subsequent inversion due to compressional reactivation.

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