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Structural Geological Analysis of the High Atlas (Morocco): Evidences of a Transpressional Fold-Thrust Belt

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1. Introduction

The High Atlas of Morocco, representing the southernmost element of the Perimediterranean Alpine belts, is a typical example of intracontinental belt (Mattauer et al., 1977). It was formed within the North African plate during convergence of the African and European plates during the Cenozoic (Dewey et al., 1989; Gomez et al., 2000). Like other intracontinental mountain belts, the High Atlas shows a double sense of vergence and a complex evolution of timing and sequence of thrusting.

Many studies have emphasized the role of the inversion tectonics in the evolution of the High Atlas system (Proust, 1973; Jacobshagen et al., 1988; Giese and Jacobshagen, 1992; Laville and Piquè, 1992; Beauchamp et al., 1996, 1999; Mustaphi et al., 1997; Hafid, 2000). Thrust and fold structures would result from the reactivation (inversion), caused by the Cenozoic compressional events, of the preexisting extensional faults associated with the Triassic-Liassic Atlasic rifting.

In this context several authors considered strike-slip faulting as an important component of the Alpine evolution of the High Atlas belt (Mattauer et al., 1977; Fraissinet et al., 1988; Froitzheim et al., 1988; Laville and Piquè, 1991, 1992; Morel et al., 2000; Piquè et al., 2002). However, more recent studies (Frizon de Lamotte et al., 2000; Teixell et al., 2003, 2005; Arboreleya et al., 2004; Ayarza et al., 2005; Missenard et al., 2006) have been aimed to the definition of the geodynamic model for the Alpine evolution of the High Atlas belt. As a consequence structural studies have been performed within a regional scale geodynamic pure compressional framework, neglecting the kinematic meaning of data. Therefore, despite the fact that the geometries of deformation structures are locally well known, the details of Alpine struc-

tural evolution of the High Atlas belt, particularly kinematic information, are still poorly known.

In this contribution we present the results of a structural and kinematic study we have carried out in Morocco along a transect crossing the Western High Atlas and along the southern margin of the Central High Atlas in the Tinerhir-Boumalne area, two key sectors of the High Atlas belt. A main objective of this paper is to establish the possible relationships between the described structures to better understand the general processes of intracontinental mountain building that have constructed the High Atlas belt.

Our structural and kinematic study, suggesting main transpressional imbricate systems, indicates that strike-slip movements played an important role in the deformation evolution of the High Atlas fold and thrust belt. We propose that the main Alpine deformation of High Atlas belt was transpressional in character, with efficient kinematic strain partitioning focussing the strike-slip component along pre-existing major faults. The potential influence of pre-existing tectonic boundaries on weakness and evolving tectonic fabrics on kinematic strain partitioning can be therefore emphasized.

2. Regional geology

The High Atlas represents the highest mountain belt of Morocco, with peaks of over 4000 m a.s.l. (Mt. Toubkal, 4165 m), crossing the country along the SW-NE direction from the Atlantic Ocean to Algeria for a length of about 2000 km (800 km in Morocco) and a width ranging from about 50 km to 100 km, framed between the Meseta domains (Morocco Meseta and Oran Meseta) to the north, and the northern boundary of the West African Craton (Anti Atlas belt) to the south (Figure 1).

The High Atlas fold and thrust belt is formed by a Precambrian and Paleozoic basement and a Mesozoic-Cenozoic succession. The pre-Mesozoic basement is exposed in several inliers of the High Atlas, forming the most elevated areas of the Western High Atlas. The Mesozoic successions, mostly Jurassic in age, crop out almost exclusively in the Central High Atlas and the Atlantic basin south of Essaouira (Figure 1). The Cenozoic deposits, substantially absent along the belt axis, characterize the High Atlas boundaries with the plains where the Neogene formations deposited.

In the Western High Atlas, the Precambrian basement crops out mostly in the Ouzellarh Block, being composed by metamorphic rocks and granitoids topped by late Precambrian volcanics. The Paleozoic succession ranges from Lower Cambrian to Carboniferous and it is mostly characterized by clastic rocks deformed during the Variscan orogeny. In particular, the Late Visean-Early Westphalian tectonic event (Main Variscan Phase; Michard et al. 2008 and references) produced tight folds associated with metamorphism and granite intrusions. These folds show NE-SW to N-S axes and sub-vertical to generally E-dipping axial planes (western vergence) and developed a pervasive axial plane cleavage. The P-T conditions of metamorphism did not exceeded low-grade greenschist-facies conditions during the main Variscan folding, except in the regions close to the granite intrusions (Michard et al., 2008).

However the Variscan structural pattern is dominated by ENE-WSW to NE-SW major dextral fault zones (e.g. Tizi n'Test, Medinat, Erdouz) which broke up the Western High Atlas into several structural blocks (Proust et al., 1977; Ouanaimi and Petit, 1992; Houari and Hoepffner, 2003; Hoepffner et al., 2005). A recent paper (Dias et al., 2011) emphasises the occurrence of WNW-ESE sinistral shear zones, already documented by Fraissinet et al. (1988), in the framework of conjugated fault systems with the ENE-WSW dextral shear zones developed during the main Variscan phase.

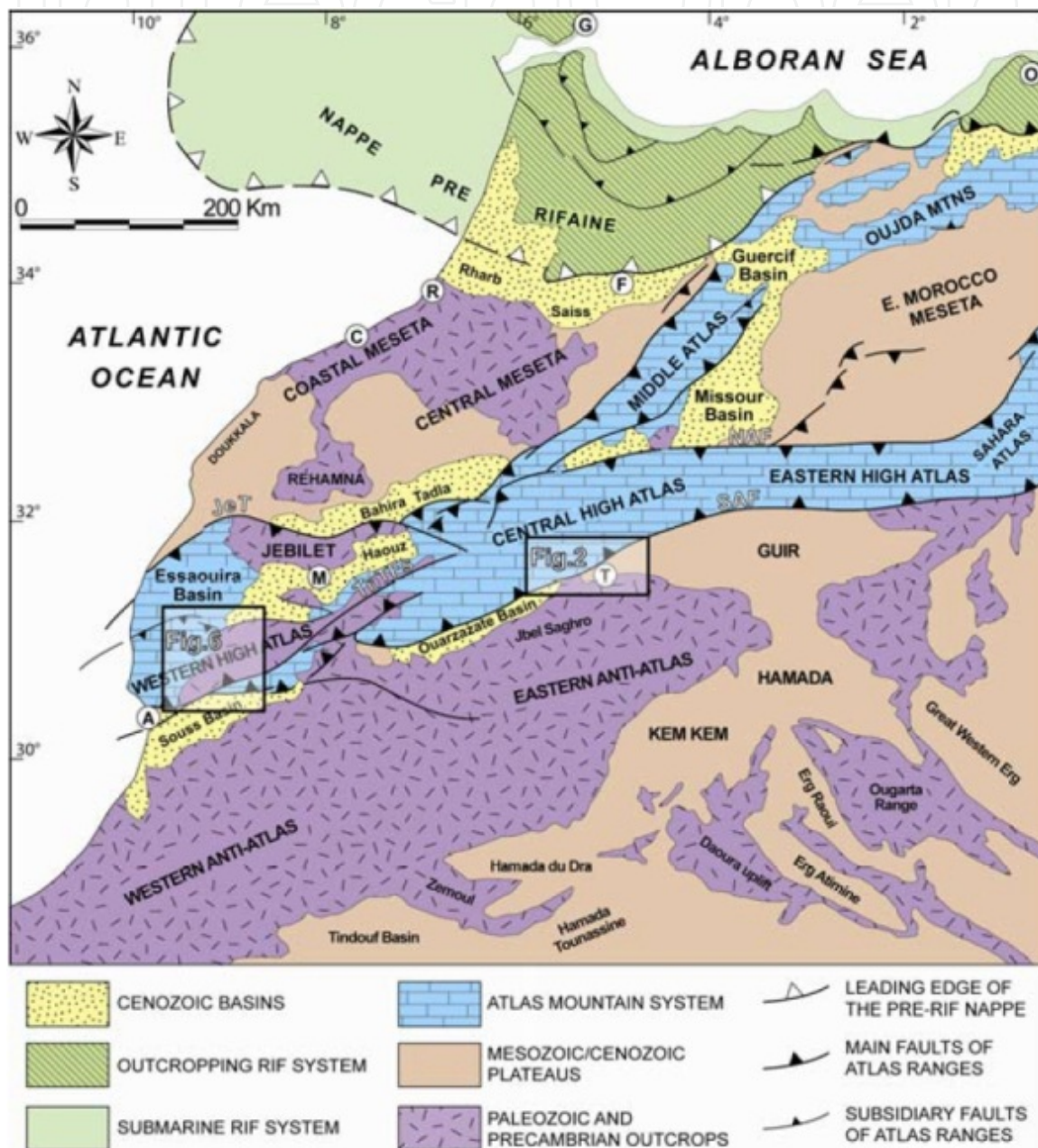


Figure 1. Schematic structural map of Morocco with location of Figures 2 and 6 (modified after Hafid et al., 2006 and Michard et al., 2008). SAF: South Atlas Fault; NAF: North Atlas Front; TnTFs: Tizi n'Test Fault system; JeT: Jebilet Thrust; A: Agadir; C: Casablanca; F: Fes; G: Gibraltar; M: Marrakech; O: Oujda; R: Rabat; T: Tinerhir.

The Mesozoic succession of the High Atlas belt started with the Late Permian-Triassic red beds (conglomerates, sandstones, siltstones and mudstones), unconformably resting on the Lower Paleozoic rocks or on the Precambrian basement. These continental deposits (Fabuel-Perez et al., 2009) represent the detrital infilling of basins developed during the Late Permian-Triassic Atlasic pre-rifting phase when the Variscan shear zones were reactivated as normal and strike-slip faults. The pre-rift deposits are capped by tholeiitic basalt flows of the CAMP (Central Atlantic Magmatic Province) that provide absolute ages of about 200 Ma corresponding to the Triassic-Jurassic transition (Fiechtner et al., 1992; Knight et al., 2004; Marzoli et al., 2004).

The overlying limestones and dolomites represent the transgressive Lower Liassic platform. Within the Liassic the transition from massive carbonates to a layered sequence of marls and limestones indicates a platform-basin boundary documenting the progressive disruption and drowning of the Liassic platform (Jossen and Filali-Moutei, 1992). The Upper Liassic-Lower Dogger (from Toarcian to Bajocian) are varicolored marls and reefal limestones underlying Bathonian red sandstones and silty shales pointing to a continental sedimentation (e.g. Ellouz et al., 2003). The Cretaceous is characterized by red sandstones and conglomerates ("Infracenomanian"; Gauthier, 1957) evolving to platform white limestones of Cenomanian-Turonian age which mark a global transgression to the scale of the entire Atlas domain (Ettachfini and Andreu, 2004). During the Upper Cretaceous-Paleogene the sedimentation is mainly continental and lacustrine with minor marine bioclastic limestones of Eocene age (Marzoqi and Pascal, 2000).

The Neogene continental deposits, occurring above a regional unconformity, resulted essentially from the syndeformation erosion of the mountain belt (Miocene-Pliocene molasses).

The post-Jurassic deposits which probably formed a rather continuous cover overlying the High Atlas and the surrounding areas (Meseta and Anti Atlas domains) are now exposed mainly in the areas bordering northward and southward the High Atlas (Haouz, Souss and Ouarzazate basins), while they have been largely eroded into the High Atlas being preserved only in few limited outcrops.

The Alpine (Atlasic) tectonic evolution of the High Atlas fold and thrust belt has been generally considered to be characterized by at least two main deformation steps spanning in age from Late Eocene to Oligocene-Miocene and from Pliocene to Early Quaternary, respectively (Gorler, 1988; Jacobshagen et al., 1988; Giese and Jacobshagen, 1992; Frizon de Lamotte et al., 2000; El Harfi et al., 2001, 2006; Missenard et al., 2007). Teson and Teixell (2006) documented a rather continuous thrusting at the southern border of the High Atlas (Boumalne area) active from the Oligocene to the Pliocene. Nevertheless Quaternary tectonics, deforming alluvial terraces, has been also documented (e.g. Morel et al., 2000; Sebrier et al., 2006; Cerrina Feroni et al., 2007; Delcaillau et al., 2010).

The present-day seismicity along the marginal zones of the High Atlas testifies that the orogenic movements are still active.

The tectonic style characterizing the High Atlas is mainly thick-skinned, as the basement was involved in the compressional deformation (e.g. Frizon de Lamotte et al., 2000; Teixell et al., 2003; El Harfi et al., 2006). However, the structures of the southern border have been interpreted as evolved within a thin-skinned style of deformation (e.g. Beauchamp et al., 1999; Bennami et al., 2001; Teixell et al., 2003).

The limits that bound, to the north and to the south, the High Atlas orogenic system are represented by two tectonic lineaments of regional importance.

In particular, the northern boundary of the Western High Atlas is represented by a complex system of thrusts and high angle faults that divides the main range from the Haouz Plain.

The northern border of the Central High Atlas belt is marked by a N-verging thrust, associated with strike-slip faults, that finds its westernward extension with the thrust that subtends and bounds northward the Jebilet range (Figure 1). On the contrary, the southern boundary of the Central High Atlas matches the South Atlas Fault Zone (Russo and Russo, 1934), a major tectonic feature extending from Morocco, where the High Atlas belt is juxtaposed to the Anti Atlas, to Tunisia (Bracene et al., 1998). In the Western High Atlas the South Atlas Fault Zone corresponds to the western termination of the Tizi n'Test Fault system.

3. The studied sectors

We have focused our study in two selected sectors corresponding to the southern boundary of the Central High Atlas in the Tinerhir-Boumalne area and to the Western High Atlas transect between Imi n'Tanoute and Taroudant region (Figure 1).

In these sectors, the occurrence of Mesozoic-Cenozoic deposits allowed to describe the geometry and kinematics of the main Alpine structures and define the ages of the tectonic events that characterize the polyphase deformation of the High Atlas borders. The availability of industry seismic data, discussed in earlier papers (e.g. Mustaphi et al., 1997; Hafid et al., 2006; Sebrier et al., 2006), provided further useful information.

In particular, the structural study of the Tinerhir-Boumalne area is important in the understanding of the kinematics induced by the South Atlas Fault Zone. The Western High Atlas is a privileged sector where it is possible the study of the entire mountain belt along a relatively short transect (about 50 km) between its northern and southern boundaries, that is to say from the Imi n'Tanoute Fault to the Tizi n'Test Fault Zone.

Actually, whereas the Imi n'Tanoute Fault is located at the northern boundary of the Western High Atlas at the margin of the Haouz Plain, from a structural point of view it does not represent the northern belt front as the Jebilet range, north of Marrakech (Figure 1), must be considered as part of the High Atlas itself (Hafid et al., 2000, 2006; Michard et al., 2008). Nevertheless, along the Western High Atlas transect it is possible to acquire new data about the characterization of fault and thrust-fold systems evolving from northern to southern vergences crossing the belt from north to south.

3.1. Central High Atlas (Tinerhir-Boumalne area)

3.1.1. Geological setting

The study area corresponds to the NE-SW trending zone, from Boumalne and Tinerhir, between the Central High Atlas to the north, and the Eastern Anti Atlas (Saharan Craton) to the south (Figures 1 and 2). The geological setting is characterized by the eastern termination of the Ouarzazate basin, a topographic low where most of the Miocene-Pliocene and Quaternary deposits sedimented. It represents the physiographic separation between Central High Atlas and Eastern Anti Atlas belts. In the Tinerhir area, where the Ouarzazate basin ends, the two belts face each other, being separated only by the Cretaceous-Eocene succession.

The structural pattern of the southern boundary of the Central High Atlas between Boumalne and Tinerhir is dominated by the high angle faults belonging to the South Atlas Fault system showing an overall direction of about N70E. In particular the South Atlas Fault main zone corresponds to a strike-slip fault that juxtaposes a northern block represented by the Central High Atlas belt s.s. and a southern block characterized by the Mesozoic-Cenozoic succession unconformably overlapping the Paleozoic basement outcropping north the Proterozoic rocks of the Jebel Saghro. The Mesozoic-Cenozoic succession of the southern block is deformed by a south-verging fold-thrust system that affects also the underlying Paleozoic basement. The latter is formed by terrigenous clastics with subordinate carbonate sediments ranging in age from Lower Cambrian to Carboniferous (Viséan-Namurian). The Paleozoic succession is characterized by a polyphase deformation consistent with the Late Carboniferous Variscan evolution (Michard et al., 1982; Hoepffner et al., 2006; Cerrina Feroni et al., 2010). Nevertheless, a post-Variscan tectonics, connected with the Cenozoic Atlasic orogeny, has been documented in the Eastern Anti Atlas (Malusà et al., 2007).

In the Tinerhir area, the Mesozoic-Cenozoic succession which unconformably overlies the Paleozoic basement is characterized by a basal unit formed by Upper Cretaceous continental conglomerates and sandstones ("Infracenomanian") which directly overlaps the Paleozoic and Proterozoic basement (Figure 2). The pebbles of the conglomerates are formed by Precambrian and Paleozoic rocks of the Anti Atlas domain; the basal unconformity sealed the structures generated by the Variscan deformation.

Above the Infracenomanian deposits the succession evolves upward to Upper Cretaceous-Eocene mainly marine deposits which can be subdivided in many lithostratigraphic units (Figure 2B). The overlying deposits consist of red pelites and fine sandstones with gypsum lenses and intercalations of sandstones and conglomerates (e6-e7); this lagoonal-continental succession corresponds to the Hadida-Ait Ouglif formation which has been referred to the Upper Eocene-Early Oligocene (El Harfi et al., 2001).

The uppermost part of the Mesozoic-Cenozoic succession is characterized by a very thick (up to more than 700 m) Miocene-Pliocene formation constituted by polygenic conglomerates with pebbles of Precambrian to Paleogene rocks. It is deposited in an alluvial fan environment evolving to shales and lacustrine limestones and to alluvial fan

conglomerates mainly composed by Jurassic limestone clasts. The Miocene-Pliocene deposits lies unconformably over all the previous formations comprising the

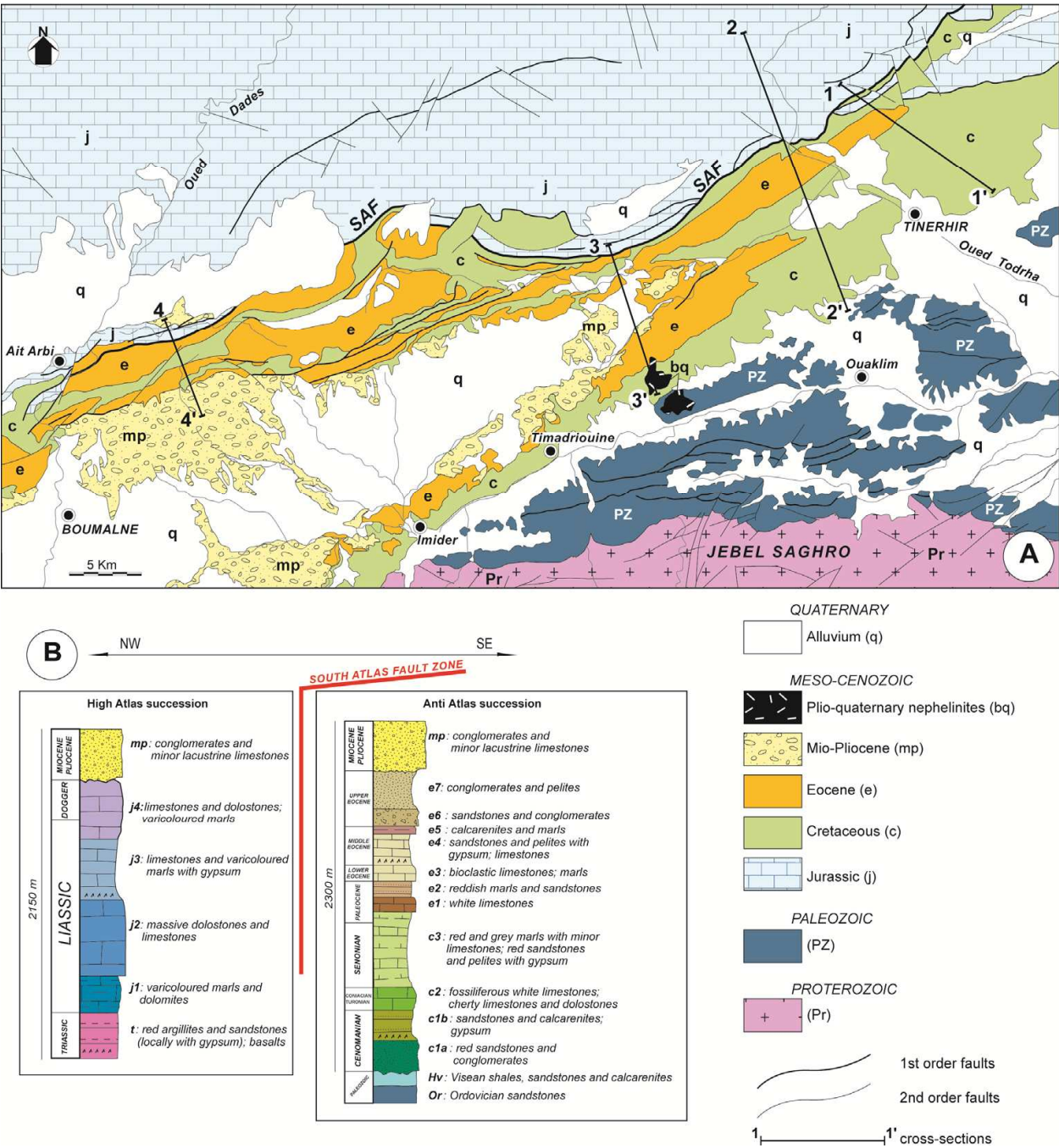


Figure 2. A: Geological map of the Tinerhir-Boumalne area (simplified after Hindermayer et al., 1977, and Milhi, 1997.) indicating the geological cross-sections of Figure 3. SAF: South Atlas Fault. B: Lithostratigraphy of geological cross-sections in Figure 3.

Jebel Saghro Precambrian rocks (outside the area represented in the geological map of Figure 2A). The Miocene-Pliocene basal contact represents a regional unconformity as the Miocene-Pliocene deposits directly overlap also the Middle Jurassic rocks belonging to the stratigraphic succession of the Central High Atlas, north of the South Atlas Fault zone (Figure 2B).

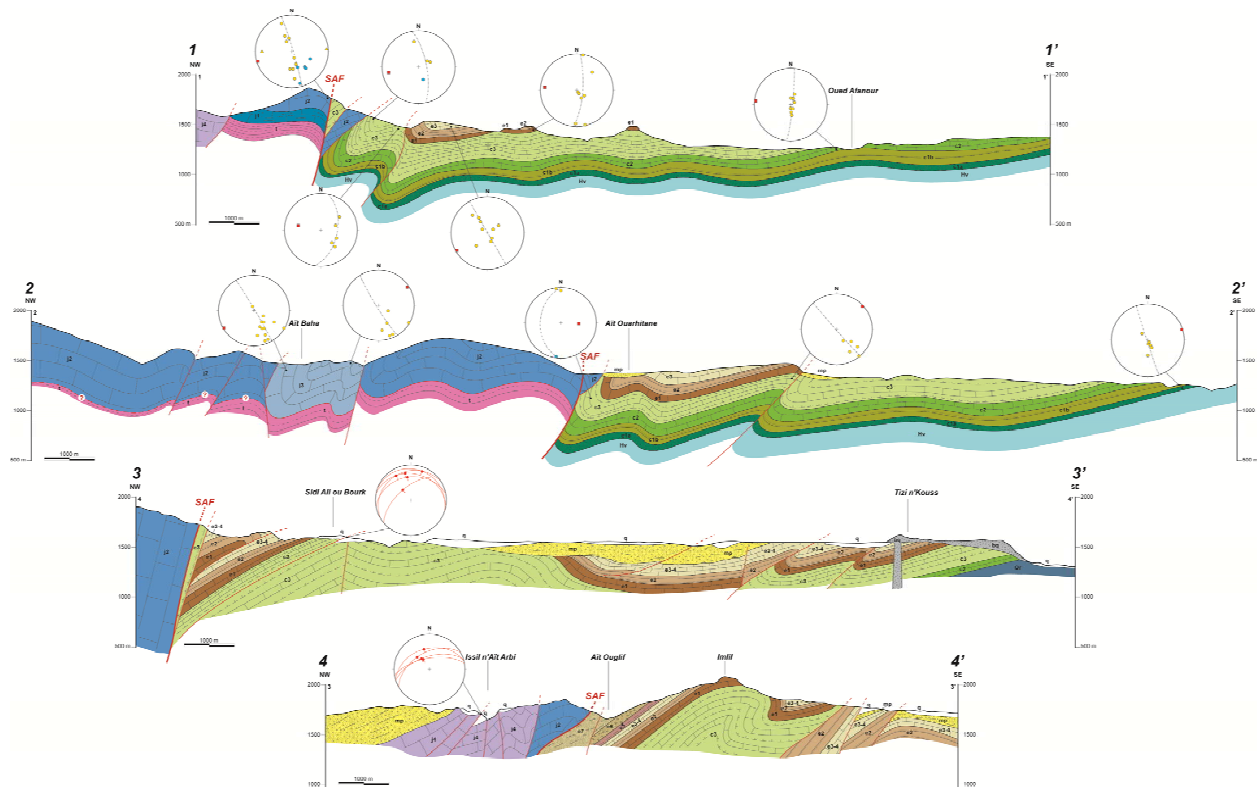


Figure 3. Geological cross-sections through the South Atlas Fault zone between Tinerhir and Boumalne (location in Figure 2). In sections 1-1' and 2-2' stereonet diagrams (Equal area projection, lower hemisphere) represent poles to bedding (yellow circles: normal beds; blue circles: overturned beds), and measured fold axes (yellow triangles); the β axes are indicated (red squares). In sections 3-3' and 4-4' stereonet diagrams represent fault planes and striae.

The Central High Atlas succession exposed in the study area consists of Triassic red siltstones, sandstones and basalts evolving upward to Liassic-Dogger mainly massive limestones and dolostones and varicolored marls, locally with gypsum (Figure 2B).

3.1.2. Structure geometry and kinematics

The geological-structural data collected in the field allowed to produce four cross-sections that describe the geometry and kinematic of the main structures occurring at the southern margin of the Central High Atlas between Boumalne and Tinerhir villages (Figure 3).

The outstanding structure is the South Atlas Fault zone along which the mainly Lower Jurassic rocks of the Central High Atlas succession are juxtaposed to the Cretaceous-Eocene succession of the Anti Atlas block. The main fault zone is characterized by NE-SW trending high angle fault planes displaying horizontal to oblique slickensides that indicate an overall dextral displacement (Figure 4A). The kinematic analysis allowed to obtain two palaeostress tensors by inversion of the fault data collected along the South Atlas Fault zone northwest of Tinerhir (Figure 5). The Imarirene site of measurement evidences an homogeneous population of NE-SW dextral strike-slip faults compatible with a strike-slip palaeostress tensor with a sub-horizontal maximum compression σ_1 axis directed roughly E-W. The dextral

strike-slip faults collected at Ait Snane are conjugated with NNW-SSE sinistral strike slip faults. This fault system is consistent with a strike slip palaeostress regime (sub-vertical intermediate compression axis σ_2) and a sub-horizontal σ_1 axis showing a NNW-SSE direction (Figure 5). This strike slip tensor is kinematically compatible with the ENE-WSW trending inverse faults occurring in the same site of measurement.

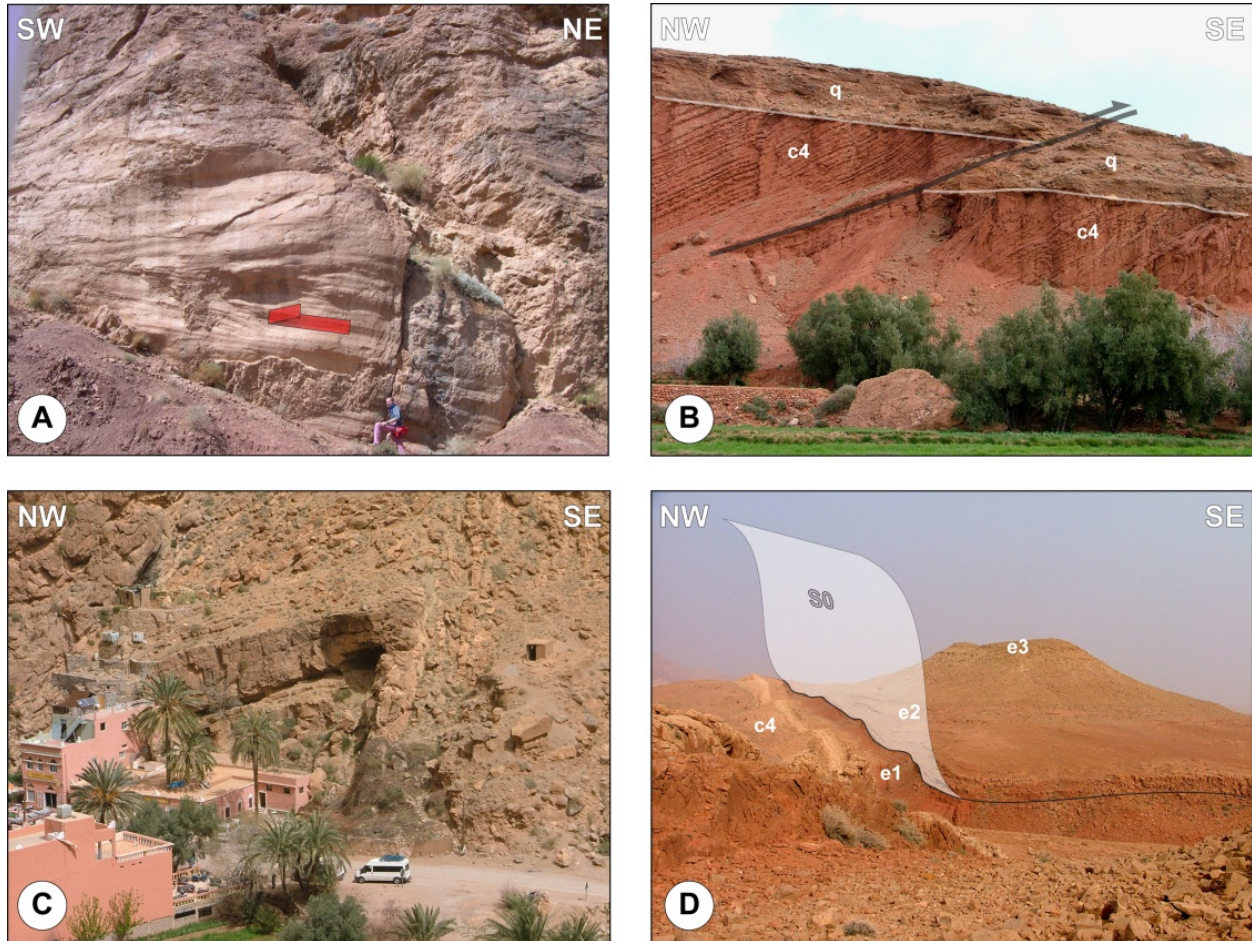


Figure 4. Geometrical and kinematic features along the South Atlas Fault zone in the Tinerhir-Boumalne area. A: Main South Atlas Fault plane corresponding to the Lower Jurassic rock wall. The direction of the red arrow corresponds to the movement of the missing block, indicating a dextral sense of movement. B: Thrust surface affecting the Quaternary deposits. The thrust plane is characterized by the same direction of the South Atlas Fault zone with a top to the South sense of movement. C: Hectometre-scale south-vergent fold developed in Lower Jurassic rocks of the High Atlas domain. D: Hectometre-scale south-vergent fold developed in the Upper Cretaceous-Eocene succession of the Anti Atlas domain.

Thrust folds are structures characterizing also the deformation pattern of the study area, affecting the Jurassic rocks and the Upper Cretaceous-Eocene succession, as well as the Miocene-Pliocene deposits and the Quaternary terrace gravels (Figures 3 and 4B). The thrusts are directed about ENE-WSW ($\sim N70E$), broadly parallel to the South Atlas Fault zone, dipping toward NNW of 30° - 40° . The fault surfaces display down-dip slickenside striations indicating a top to the S sense of movement. The resulting palaeostress tensors are

consistent with pure compressive tectonic regimes with sub-horizontal σ_1 axes directed NNW-SSE as shown in the Ait Arbi and Sidi Ali Ou Bourk stations (Figure 5).

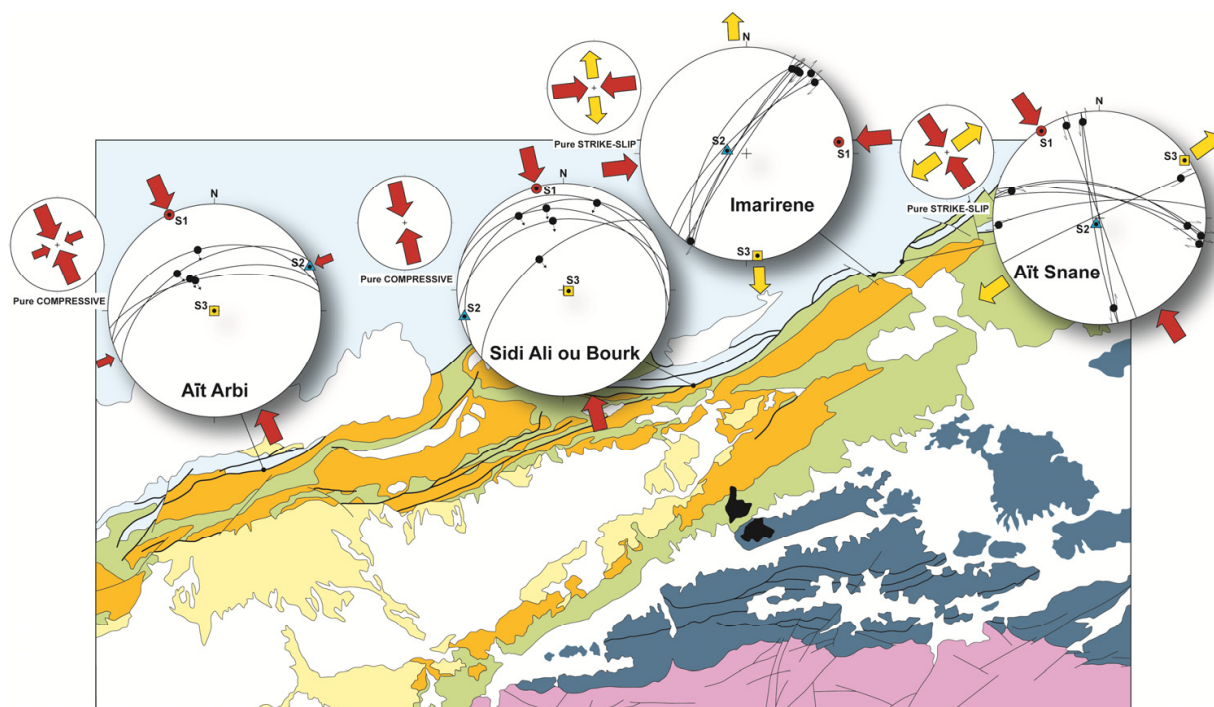


Figure 5. Geological sketch map with stress inversion results (TENSOR program; Delvaux, 1993). Stereograms (Schmidt net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses; the principal stress axes (S1, S2, S3) and type of stress tensor are reported.

Northwestward this thrust system links to the high angle faults (South Atlas Fault system) displaying an overall asymmetrical positive flower structure geometry (Figure 3).

The thrust system is associated with a fold system characterized by anticlines and synclines showing steeply dipping axial planes; the fold axes, generally showing sub-horizontal plunging, trend from N70E to about E-W, again sub-parallel to the South Atlas Fault trend (Figure 4C and 4D). The fold asymmetry indicates a southward vergence. The sub-vertical limbs of the folds are often affected by thrust faults that cut off the anticline-syncline hinge zones (Figure 3).

The analysis of the geological cross-sections indicates that the deformation is not homogeneously distributed in the study area: deformation zones constituted by folds and thrusts are more developed close to the South Atlas Fault zone, while moving to the SE the deformation decreases generating more spaced open syncline and anticline folds.

The geometric-kinematic analysis suggests that thrusting and folding can be linked to the development of contemporaneous strike-slip faulting in a complex polyphase tectonic evolution. In fact, the relationships of the Miocene-Pliocene deposits that unconformably sealed the fold structures of the Upper Cretaceous-Eocene succession, and the deformation affecting the Quaternary deposits indicate two distinct tectonic phases characterizing the Alpine evolution of the southern boundary of the Central High Atlas belt.

3.2. Western High Atlas

The studied sector of the Western High Atlas develops between Imi n'Tanoute village and Menizla village (SE of Argana), at the northern limit of the Souss Plain (Figure 6).

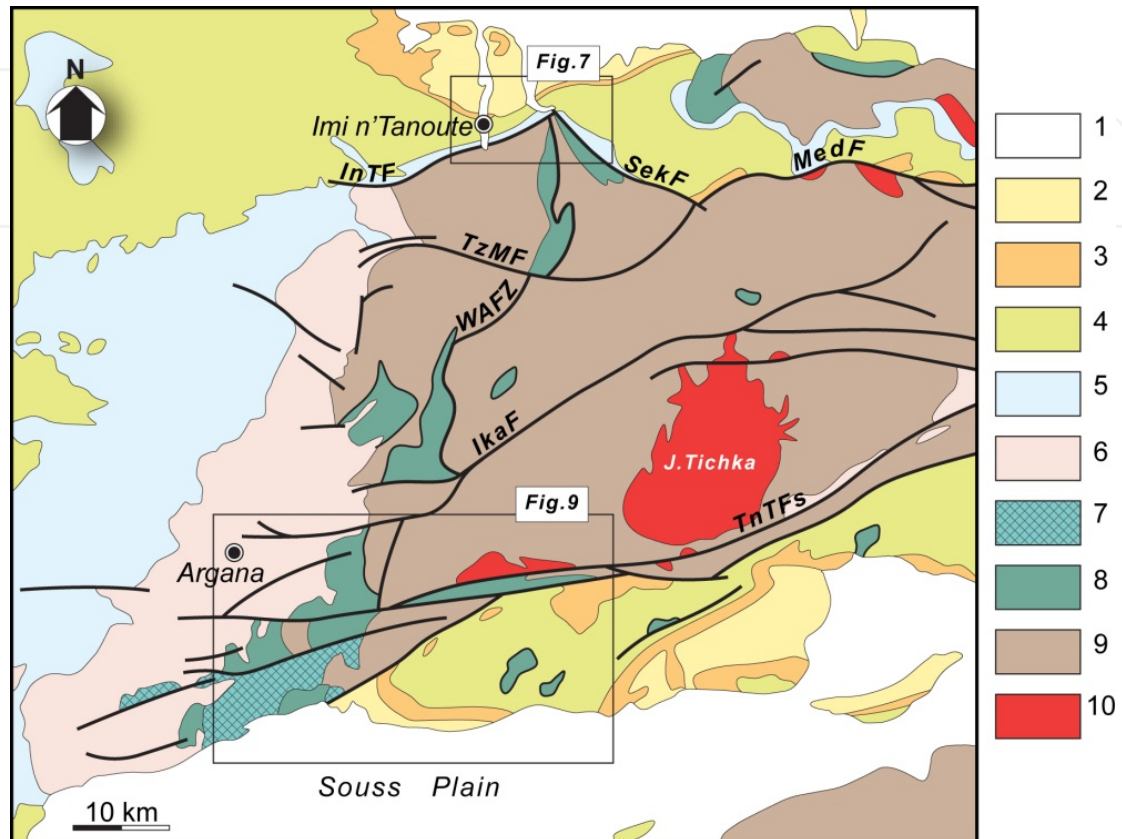


Figure 6. Schematic structural map of the Western High Atlas with location of Figures 7 and 9 (modified after Hollard et al, 1985). 1: Quaternary; 2: Neogene; 3: Eocene; 4: Cretaceous; 5: Jurassic; 6: Permian-Triassic; 7: Carboniferous; 8: Ordovician, Silurian and Devonian; 9: Cambrian; 10: Variscan Granites. InTF: Imi n'Tanoute Fault; SekF: Seksaoua Fault; MedF: Medinat Fault; TzMF: Tizi Maachou Fault; IkaF: Ikakern Fault; TnTFs: Tizi n'Test Fault system; WAFZ: Western Atlasic Fault Zone.

The central part of the belt is formed by a 10 km thick Paleozoic succession, mostly represented by the Cambrian metasediments (sandstones, schists and greywackes). East of the Western Atlasic Fault Zone (Cornée and Destombes, 1991), a major N-S trending Cambrian tectonic lineament (Figure 6), the Lower Cambrian succession is characterized by volcano-detritic schists with conglomeratic lenses overlying a complex of schists with arkoses, volcano-detritic and calcareous intercalations. The Paleozoic succession evolves up to Ordovician sandstones and to Silurian-Devonian units respectively composed of black/reddish schists and sandstones and conglomerates with lens of limestones.

The Carboniferous formations are restricted to the Ida Ou Zal basin in the southwestern sector of the Western High Atlas (Figure 6). It is composed by 1800 m thick succession of conglomerates followed by sandstones, pelites, coal seams and argillaceous sandstones alternating with dolomitic calcareous layers (De Koning, 1957). The succession was accumu-

lated during Stephanian-Autunian time span in this basin which has been interpreted as a Late Variscan basin created along a strike-slip fault system in a transextensional regime (Saber et al., 2001). The Stephanian-Autunian deposits of the Ida Ou Zal basin were deformed by a folding phase with E-W to ESE-WNW axial direction developed in a transpressional tectonic regime (Saber et al., 2001). A more complex tectonic evolution has been proposed by Qarbous et al. (2003) consisting in superimposed folding and faulting deformations in alternating compressional and extensional regimes. The last deformation stage, connected to the Alpine tectonics, produced the reactivation of the ENE-WSW faults as reverse faults in the context of a roughly N-S compression.

The western boundary of the Western High Atlas is characterized by the Upper Permian-Triassic deposits (sandstones and siltstones) whose outcrops are limited to a NNE-SSW trending basin (Argana Corridor). This basin evolves westward to the Agadir-Essaouira basin where the Mesozoic-Cenozoic succession developed. The Argana Corridor deposits are affected by a network of ENE-WSW, NE-SW and WNW-ESE faults (Tixeront, 1974) that extend eastward cutting the Paleozoic basement.

The Mesozoic-Cenozoic succession characterizes also the northern and southern marginal sectors of the Western High Atlas, respectively north the Imi n'Tanoute Fault at the margin with the Haouz Plain and south the Tizi n'Test Fault system at the margin with the Souss Plain. The Souss Plain, which acted as the High Atlas foreland basin during the Cenozoic, constitutes an E-W oriented depression separated from the Ouarzazate basin by the Siroua high plateau (Figure 1).

The Haouz Plain, on the contrary, is interpreted as an intra-mountain basin located between the Jebilet and the High Atlas (Michard et al., 2010) and characterized by Miocene-Pliocene molasse deposits.

In the following paragraphs we will discuss separately the structural geology of two sectors of the Western High Atlas, respectively the Imi n'Tanoute area (northern sector) and the Menizla area (southern sector).

3.2.1. Northern boundary (Imi n'Tanoute Fault)

The geological setting of the northern sector (Imi n'Tanoute area) is characterized by the contact between the Paleozoic basement and the Mesozoic-Cenozoic succession which develops northward in the Haouz Plain. This contact corresponds to the Imi n'Tanoute Fault, a major fault zone showing an about N70 direction (Figure 7). However, ESE of Imi n'Tanoute village the unconformable overlap of the Jurassic succession, starting with purple conglomerates and sandstones, above the Paleozoic rocks is preserved. This unconformity is well visible also at the map scale for the strong discordance between the sub-horizontal Jurassic beds and the Paleozoic succession. The latter displays a sub-vertical attitude, resulted from the Variscan tectonics which produced N-S directed folds associated with a pervasive sub-vertical cleavage. Further, this area is characterized by a N-S trending thrust, connected to the WAFZ, that duplicated the Paleozoic succession with an east vergence.

gypsum of Barremian FIGURE 8 age) followed by a thick Cenomanian-Turonian sequence formed by grey and red marls with anhydrite and by Senonian red and white sandstones with lumachellic limestones and white marlstones. The overlying Maastrichtian conglomerates and phosphatic sandy marls and limestones were deposited above an unconformity and evolved up to the Paleocene-Eocene reddish sandstones and brown marls. Slightly north of the Imi n'Tanoute village, up to 20 m thick white conglomerates with limestone and chert pebbles, considered to be Oligocene in age, are also documented unconformably overlapping the Eocene succession (Zuhlke et al., 2004). Nevertheless the main unconformity inside the Cenozoic succession corresponds to the basal contact of the Miocene conglomerates and sandstones (molassic deposits) that rest directly above different levels of the Upper Cretaceous-Eocene succession, sealing the thrusting and folding deformation of the first tectonic phase of the Western High Atlas belt.

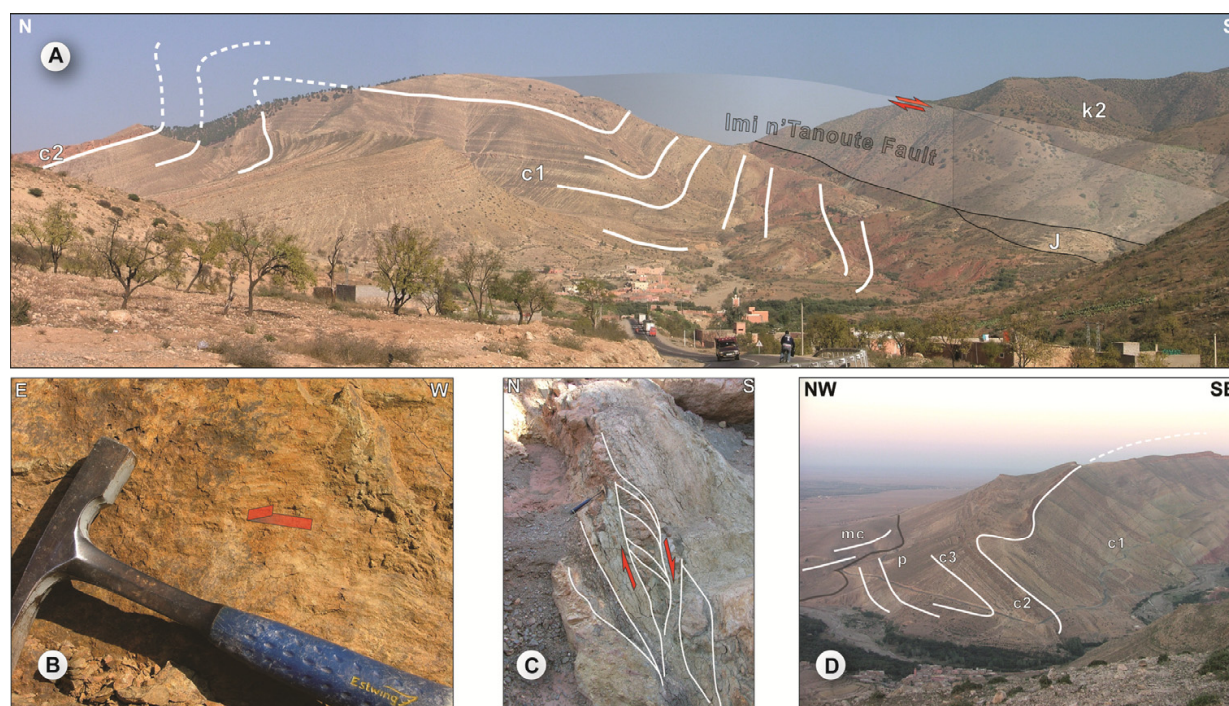


Figure 8. Geometrical and kinematic features along the northern boundary of High Atlas in the Imi n'Tanoute area. A: Panoramic view of the north-vergent folding in the Cretaceous succession associated to the dextral sense of movement of the Imi n'Tanoute Fault. B: Detail of a fault plane (Middle Cambrian) bearing oblique slickenlines with a dextral strike-slip movement. The direction of the red arrow corresponds to the movement of the missing block. C: Shear zone developed in the Lower Cretaceous rocks along the Imi n'Tanoute Fault. D: Kilometer-scale north-vergent fold developed in Cretaceous-Paleogene successions, characterized by a secondary fold with rabbit-ear geometry. The deformed strata are unconformably overlain by the Miocene clastic deposits.

In the study area, the geological structures at the Western High Atlas northern border can be observed along a natural cross-section directed roughly N-S (Figure 8A). The Cambrian metamorphic rocks are juxtaposed to the Cretaceous sedimentary sequences along the Imi n'Tanoute Fault. A slice of Jurassic rocks is also isolated inside the fault zone. The foliation attitude of the Cambrian metasandstones and metapelites, that normally shows a sub-

vertical N-S direction, close to the fault zone suffered a virgation produced by the fault activity becoming sub-parallel to the fault itself and showing a northward high angle dipping (Figure 7). North the Imi n'Tanoute Fault, the Lower Cretaceous red marlstones and sandstones belong to the southern vertical limb of a syncline-anticline-syncline system showing northward vergence. This folding system involved the entire Mesozoic-Cenozoic succession of the Imi n'Tanoute area up to the Paleocene-Eocene deposits, as can be observed northwest the Houdjanene village (Figure 8D) where the Turonian limestones evidence a spectacular secondary fold that can be interpreted as a rabbit-ear fold (Narr & Suppe 1994; Missenard et al., 2007). In the Houdjanene cross-section the sub-horizontal (slightly dipping) Miocene conglomerates are unconformable above the sub-vertical Paleocene-Eocene beds (limestones and sandstones).

The overall axial direction of the described fold system is directed sub-parallel to the Imi n'Tanoute Fault, i.e. N70E as evidenced also by the spatial arrangement of the bedding data collected in the Cretaceous-Eocene succession (Figure 7).

The kinematic data collected along the main fault zone of the Imi n'Tanoute Fault indicate a main dextral strike-slip movement (Figure 8B and 8C) consistent with a strike-slip tectonic regime displaying a sub-horizontal WNW-ESE directed maximum compression axis, where the associated roughly E-W directed normal faults are compatible too (Figure 7).

In the Cambrian metasandstones a population of NNE-SSW directed dextral strike-slip faults have been also collected, being compatible with a different palaeostress tensor where the sub-horizontal axis is directed ENE-WSW.

3.2.2. Southern boundary (Tizi n'Test Fault system)

The Paleozoic succession of the Menizla area is characterized by the occurrence of the Upper Carboniferous deposits of the Ida ou Zal basin. Unlike the northern boundary of the Western High Atlas, the Mesozoic-Cenozoic succession starts with the Lower Cretaceous red sandstones directly overlying the Ordovician rocks outcropping in two small inliers north of Addouz (Figure 9). The upper part of the succession is characterized by the Maastrichtian-Ypresian phosphate series and by the Miocene-Pliocene continental deposits.

The Mesozoic-Cenozoic succession at the southern boundary of the Western High Atlas was deformed by southward verging fold systems comprehensively formed by two wide anticlines separated by a wider syncline. The sub-vertical, locally reversed, southernmost limb of the southern anticline represents the margin with the Quaternary deposits of the Souss Plain.

For the main object of our study, we analyzed the relationships between the folding structures and the Tizi n'Test Fault system in the area of Tafrawtane (Figures 9 and 10). The main fault that juxtaposes the Cambrian rocks with sub-vertical principal foliation to the Upper Cretaceous deposits is a sub-vertical dextral strike-slip fault directed about E-W. The relative kinematic data allow defining a strike-slip palaeostress tensor with a sub-horizontal NW-SE trending σ_1 axis (Figure 9).

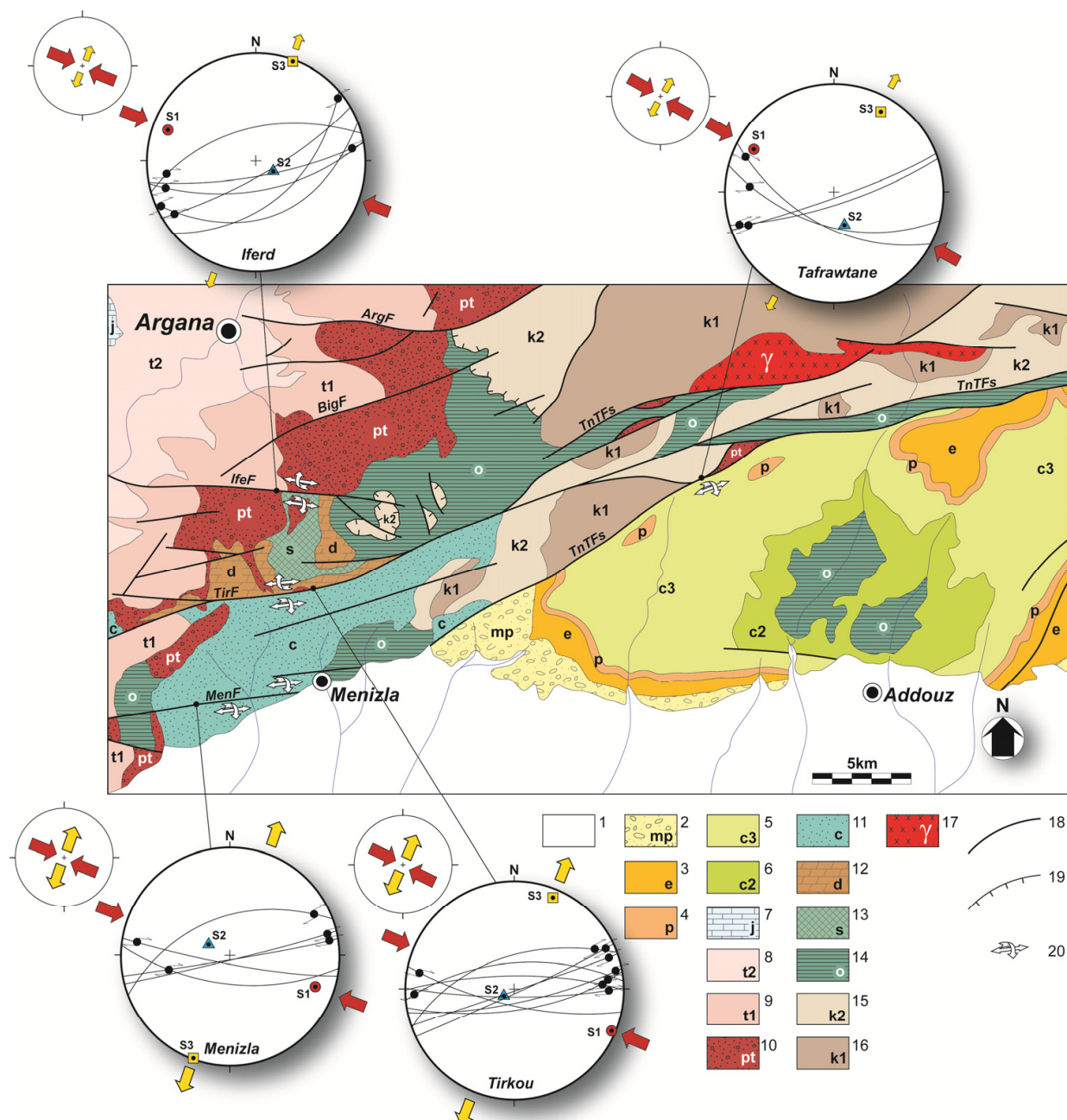


Figure 9. Geological map of the southern boundary of the High Atlas in the Menizla area (modified after Choubert, 1957 and Tixeront, 1974). 1: Quaternary; 2: Miocene-Pliocene; 3: Eocene; 4: Paleocene; 5: Upper Cretaceous; 6: Cenomanian-Turonian; 7: Jurassic; 8: Upper Triassic; 9: Middle Triassic; 10: Permian-Triassic; 11: Carboniferous; 12: Devonian; 13: Silurian; 14: Ordovician; 15: Middle Cambrian; 16: Lower Cambrian; 17: Variscan Granites; 18: Main faults; 19: Tectonic Boundaries; 20: Direction of tectonic transport. ArgF: Argana Fault; BigF: Bigoudine Fault; IfeF: Iferd Fault; TirF: Tirkou Fault; TnTFs: Tizi n'Test Fault system. Stereograms (Schmidt net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses are reported for the Iferd, Menizla and Tirkou Faults and for Tizi n'Test Fault system in the Tafrawtane area. The principal stress axes (S1, S2, S3) and type of stress tensor are indicated.

Actually, the main fault zone is characterized by a slice of Permian-Triassic red sandstones interposed between the Cambrian and the Cretaceous rocks that are also affected by a south-verging thrust that roots into the main sub-vertical fault plane.

The Upper Cretaceous marls and limestones are affected by complex, disharmonic, fold structures showing a general southward vergence. As a result bedding is variable in orientation but it generally strikes ENE-WSW, sub-parallel to the main direction of the Tizi n'Test Fault system; bedding dips follow the fold structures, being progressively steeper approaching the fault zone. The axis of the fold system is directed about N70E, sub-parallel to the Tizi n'Test Fault system direction, showing a slight eastward plunging.



Figure 10. Panoramic view of the south verging folding in the Upper Cretaceous associated to the dextral sense of movement of the Tizi n'Test Fault system in the Tafrawtane zone.

However, from a structural point of view, the most important feature occurring in the Menizla area is the Tizi n'Test Fault system and in particular the western component of this major tectonic lineament consisting of different anastomizing branches, the main three of which (Menizla Fault, Tirkou Fault, Iferd Fault; Baudon et al., 2012) have been studied with more detail (Figure 9).

Starting from the margin with the Souss Plain, the southernmost fault is the Menizla Fault characterized by strike-slip movements associated with mostly south-verging thrusts sub-tending sub-vertical limbs of folds that deformed the Carboniferous rocks. In particular, the Menizla Fault developed dextral strike-slip faulting along high-angle planes directed about E-W. The relative palaeostress tensor indicates a maximum compression directed WNW-ESE (Figure 9); in this tectonic context oblique-normal faults can be also compatible and some of these have been detected.

Moving toward the north, the first main fault is the Tirkou Fault showing a direction varying from E-W to NE-SW. The structural analysis was performed where the Tirkou Fault trends ENE-WSW between the Carboniferous deposits and the Devonian dolostones and shows a very thick (300-400 m) fault zone cutting off a slice of Permian-Triassic red sandstones (Figure 9). The mesoscale observations evidenced that the Tirkou Fault is characterized by folds linked to the development of double-verging thrust systems that root in sub-vertical fault planes comprehensively describing a positive flower structure (Figure 11A, C). Fold styles vary from structures with rounded hinges to kink-like or chevron folds with steeply dipping axial planes. On average, the fold axes trend sub-parallel to the direction of the Tirkou Fault zone (~N100E) with shallow plunging. The fold limbs are cut

by interlinked faults producing imbricate zones; the fault array associated with these folds provided striations indicating inverse-oblique displacement. As a consequence, the SSE-dipping and the NNW-dipping thrusts display roughly north and south vergences respectively. The occurring sub-vertical faults are characterized by nearly horizontal slickensides showing dextral displacements (Figure 11B). The fault data collected for the strike-slip faults of the Tirkou Fault zone indicate a dominant ENE-WSW fault direction and allow to obtain a palaeostress tensor characterized by a sub-vertical σ_2 axis and sub-horizontal σ_1 and σ_3 axes oriented N110E and N10E respectively (Figure 9). Within the obtained palaeostress tensor, ESE-WNW directed normal faults, such as that observable in Figure 11A, can be also compatible.

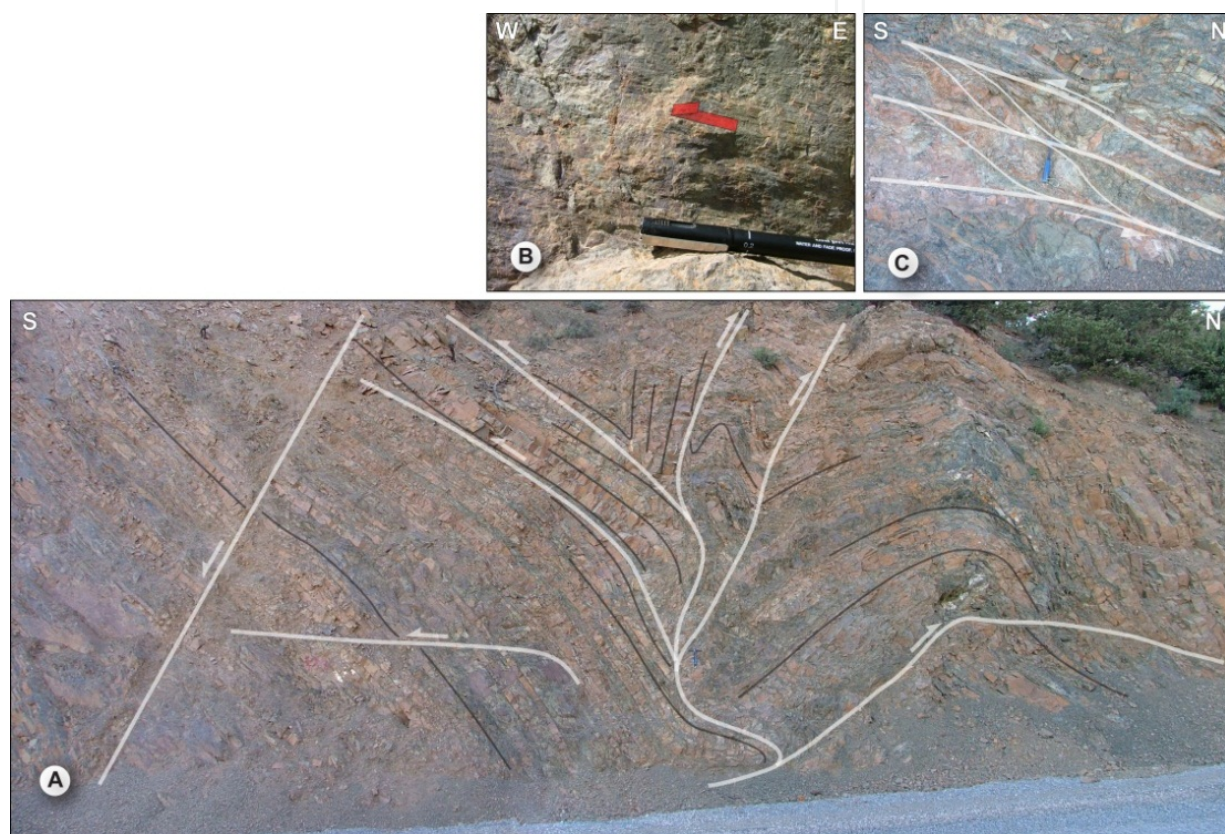


Figure 11. Geometrical and kinematic features along the southern boundary of High Atlas in the Tirkou Fault zone.

A: Mesoscale positive flower structure developed in the Carboniferous succession. This structure is characterized by double-verging thrust systems that root in sub-vertical fault planes, associated to the development of double-verging folds that trend subparallel to the faults.

B: Detail of a fault plane bearing oblique slickenlines with a dextral strike-slip movement (Carboniferous). The direction of the red arrow corresponds to the movement of the missing block.

C: Shear zone developed in the Carboniferous rocks with top to the south sense of movement.

Likewise, the Iferd Fault is outlined by double-verging structures within an overall dextral strike-slip fault zone, locally juxtaposing Silurian rocks and Permian-Triassic deposits (Figure 9). The flower structures that characterize the Iferd Fault zone are well developed in the Silurian schists consisting of a series of anastomosing convex-upward reverse faults

which steepen progressively at depth into sub-vertical strike-slip faults. The reverse faults are directed about E-W steeply dipping toward N and S and display opposite senses of shear, that is southward and northward respectively (Figure 12A). The inversion of strike-slip fault data has resulted in a palaeostress tensor similar to that obtained for the Tirkou Fault (Figure 9). In the Ifern Fault zone the possible development of normal faults, due to the permutation of σ_1 and σ_2 axes, has been documented by the occurrence of curved striations on a single fault plane suggesting a dextral-oblique to oblique-normal movement (Figure 12B).

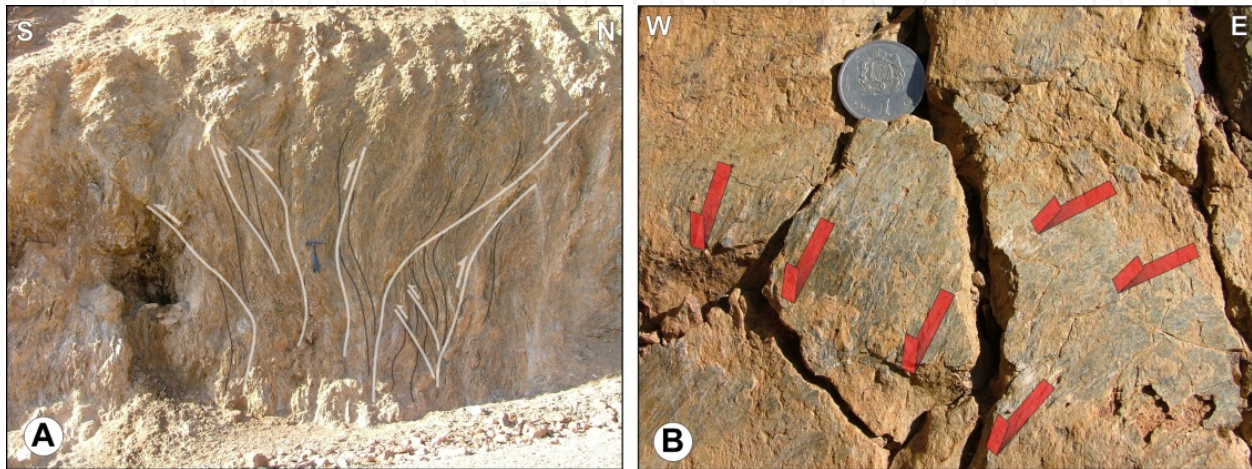


Figure 12. Geometrical and kinematic features along the southern boundary of High Atlas in the Iferd Fault zone. A. Anastomosing reverse faults root progressively at depth into sub-vertical strike-slip faults in the Silurian schists (positive flower structure). The reverse faults are characterized by opposite senses of shear. B. Fault plane bearing curved slickenlines suggesting the transition from dextral-oblique to oblique-normal movement.

3.2.3. The major faults of the inner belt sectors

In the Western High Atlas, between the Tizi n'Test Fault system and the Imi n'Tanoute Fault, other two major faults, cutting both the Paleozoic basement and the overlying Permian-Triassic succession, occur: the Ikakern Fault and the Tizi Machou Fault (Figure 13A).

In the studied outcrops the Ikakern Fault zone is formed by nearly E-W dextral strike-slip/oblique faults (Figure 13C) consistent with a palaeostress tensor with a sub-vertical σ_2 axis and sub-horizontal σ_1 and σ_3 axes directed WNW-ESE and NNE-SSW respectively (Figure 13A). Several thrust faults associated to the main fault zone have been observed, showing north and south vergences.

The Tizi Machou Fault shows a dextral map-scale offset evidenced by the displacement of the Western Atlasic Fault Zone. However the sense of shear along individual faults can be rarely deduced at the outcrop scale since kinematic indicators are only sporadically preserved. The kinematically defined structures suggest a predominance of high-angle dextral-oblique faults clustered along two trends: NNE-SSW and NE-SW (Figure 13A and 13B). In addition, few about E-W normal faults occur, showing moderate south-dipping.

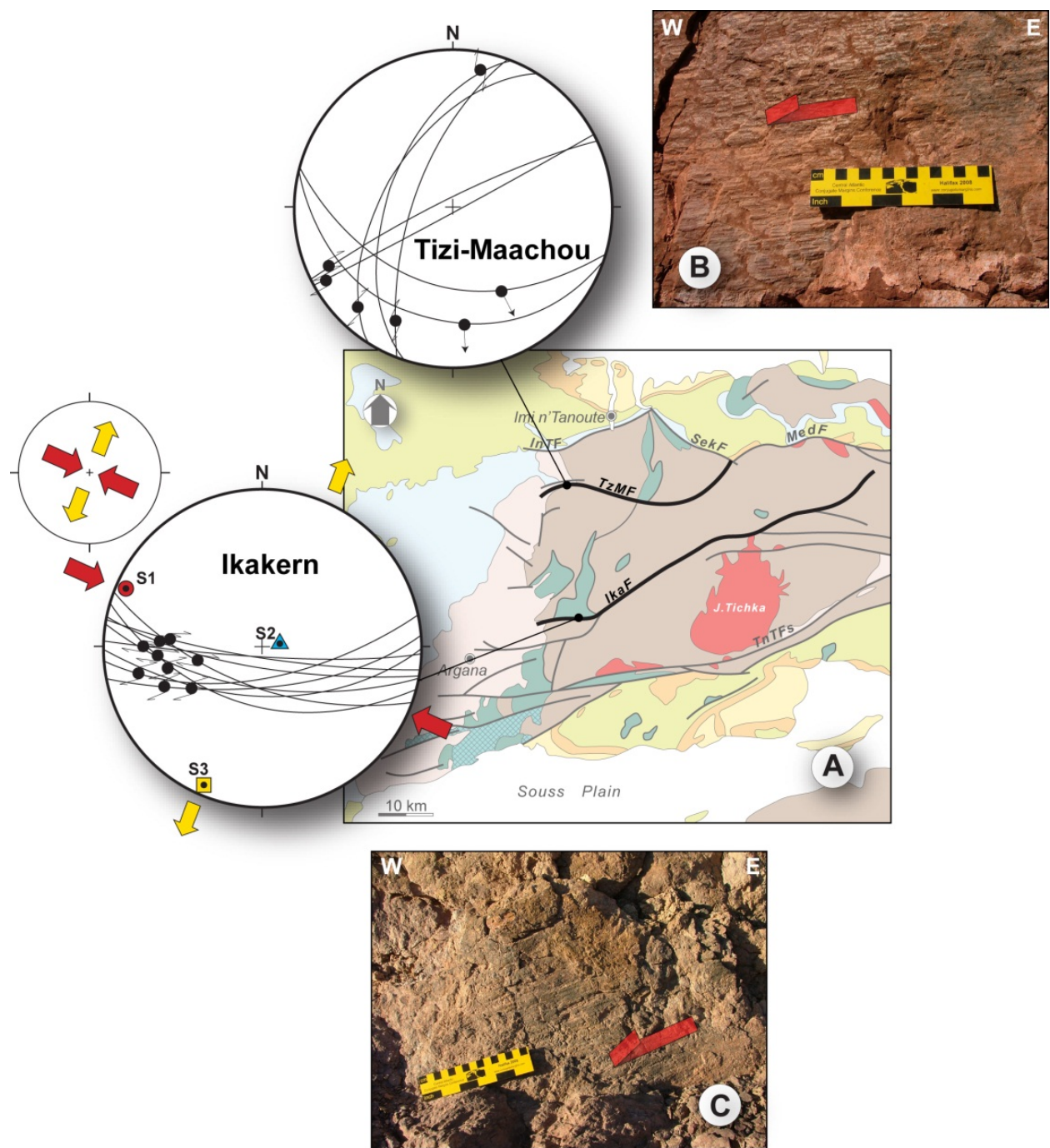


Figure 13. Kinematic data from the inner belt sector. A. Schematic structural map of Figure 6. The two principal fault zones, the Tizi Maachou and Ikakern Fault, are evidenced, for which stereograms (Schmidt net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses are reported. The principal stress axes (S1, S2, S3) and type of stress tensor are indicated for the Ikakern Fault only. B. Fault plane bearing oblique slickenlines with a dextral strike-slip movement developed in the Triassic rocks along Tizi Maachou Fault. The direction of the red arrow corresponds to the movement of the missing block. C. Fault plane bearing oblique slickenlines with a dextral strike-slip movement developed in the Cambrian rocks along Ikakern Fault. The direction of the red arrow corresponds to the movement of the missing block.

4. Discussion

The results of our field study highlight widespread Cenozoic deformation on both the southern boundary of the Central High Atlas and on the northern and southern boundaries of the Western High Atlas. The main deformation structures are represented by NE-SW trending high angle dextral strike-slip faults and sub-parallel thrust faults linked together forming asymmetric positive flower structures. The overall deformation of these structures is completed by fold systems associated with the fault and thrust systems and involving mainly the Mesozoic-Cenozoic successions. The flower structures are typical structures developed under a transpressional tectonic regime where the deformation is partitioned between high-angle strike-slip faults and lower angle reverse faults (Wilcox et al, 1973; Sanderson and Marchini, 1984; Tikoff and Teyssier, 1994). Large scale geometries and mesoscale data indicate that reverse faults merge into the main NE-SW oriented strike-slip faults. Strike-slip faults are not offset by the thrusts and vice versa, this supporting that thrusts are genetically related to the sub-parallel strike-slip faults. The observed structure relationships support therefore that the analysed sectors of the High Atlas belt were affected by a transpressional evolution during the Alpine tectonics.

Along the southern boundary of West and Central High Atlas the fault-thrust-fold systems, belonging respectively to the Tizi n'Test Fault system and the South Atlas Fault, show clear southward vergences. On the contrary, the structures of the northern margin of the Western High Atlas are connected with the Imi n'Tanoute Fault activity, being characterized by northward vergences.

The kinematic inversion of the collected fault-slip data in the Western High Atlas indicates that deformation is controlled by sub-horizontal maximum and minimum stress axes, within a strike-slip tectonic setting with a WNW-ESE directed σ_1 axes (Figure 7, 9 and 13). The lack of pure compressive tensors is probably due to the general scarce preservation of kinematic indicators on the thrust planes of the analysed outcrops. Pure compressional stresses of NW-SE direction have been sometime documented in the northern part of the Western High Atlas (Amrhar, 2002).

The transpressional character of deformation is confirmed by the relevant occurrence of oblique striations on the fault planes, thus that pure strike-slip and/or pure inverse faults are relatively few.

The WNW-ESE trending normal faults, which have been collected within some transpressional fault zones, should be also inserted in the documented tectonic pattern of the Western High Atlas attesting a NNE-SSW extension in the late stages of the Cenozoic Alpine evolution.

On the contrary, palaeostress determinations from the Boumalne-Tinehrir area provide both strike-slip and compressional tensors, with a quite steady sub-horizontal σ_1 axis trending NNW-SSE. The maximum compression σ_1 axes obtained from the palaeostress tensors from the Central High Atlas are consistent with the palaeostress fields reconstructed in the same area for the Pliocene-Quaternary stage of the High Atlas tectonic evolution by Ait Brahim et al. (2002).

Our observations documented a WNW-ESE compression that was never detected before as individual phase for the Cenozoic deformation of the Western High Atlas and comes to enrich the palaeostress evolution of the High Atlas. In fact, analogous WNW-ESE directions of compression have been also evidenced by Qarbous et al. (2003) but referred to the Carboniferous (Namurian-Westphalian) phase and therefore to the Variscan orogeny, and to the Middle Permian tectonics of the Tizi n'Test Fault system. As the WNW-ESE compression derived from the fault-slip data collected along fault zones clearly affecting also the Mesozoic-Cenozoic successions at the High Atlas belt boundaries (Tizi n'Test Fault system at Tafrawtane; Imi n'Tanoute Fault) we can consider this compressional direction referable to the Alpine orogeny.

In the inner belt sectors, the fault zones that do not cut the Cretaceous-Eocene deposits but only the Paleozoic basement and the Permian-Triassic rocks show geometric-kinematic features similar to those of the bordering fault zones. Therefore they have been interpreted as Cenozoic Alpine faults, admitting the possible reactivation of older high-angle shear zones.

Regional data and mesostructural analyses suggest the superposition of younger Cenozoic deformation on older structural trends producing reactivation of previous major fault zones. As a consequence, it is a generally shared opinion that Tizi n'Test Fault system and Imi n'Tanoute Fault were active since the Early Paleozoic and in turn reactivated more times during the successive tectonic events up to the Alpine Cenozoic phases.

Following Baudon et al. (2012), also the other about E-W oriented faults of the Western High Atlas (from south to north Tirkou, Iferd and Argana faults; Figure 9) can be interpreted as faults reactivated during the Alpine transpressional phase, after deposition of the Late Triassic deposits.

About the timing of deformation, the results of our study define two main episodes of deformation separated by the basal unconformity of the Miocene-Pliocene molassic deposits. The first episode occurred post-Eocene time, as the Upper Cretaceous-Eocene successions were deformed by fold-thrust systems that were sealed by the unconformable Miocene-Pliocene deposits.

The second tectonic event deformed the Miocene-Pliocene deposits as well as the Quaternary deposits and therefore can be assigned to a Quaternary age.

We documented the complete polyphase evolution in the Boumalne-Tinehrir area (Central High Atlas) whereas we have not new data about the Quaternary deformation in the Western High Atlas that has been already documented by Sebrier et al. (2006) in the Souss Plain. Likewise, Quaternary reactivations consisting of thrusting associated with strike-slip faulting characterize also the northern boundaries of Western and Central High Atlas and the Houaz Plain (Morel et al., 2000).

Seismic data suggest that several brittle structures along northern and southern margins of the High Atlas belt are still active. The few available focal solutions show that the southern boundary of the High Atlas is characterized mostly by strike slip faulting and subordinate

transpressional mechanisms, with the direction of the maximum compression P axes ranging from NW-SE to N-S (Serpelloni et al., 2007). In particular the focal mechanism solutions obtained for the earthquakes of magnitude $M_b=5.2$ occurred on October 23 and 30, 1992, in the Rissani region (Eastern Anti Atlas) indicate for both events a pure strike slip faulting (Hanou et al., 2003; Bensaid et al., 2009). The seismogenic zone has been interpreted to be an E-W trending structure that could corresponds to the South Atlas Fault and/or associated structures activated as a dextral strike slip fault. However, the largest earthquake ever recorded within the Atlas system corresponds to the event of $M=5.7$ occurred on February 29, 1960, which destroyed the Agadir city causing 12.000 victims.

Also the GPS data indicate that the deformation along the High Atlas is still active and accommodates about 1.5 mm/year of NW-SE compression related to the convergence between Africa and Iberia plates (Serpelloni et al., 2007).

In addition, as more general result, we propose two regional geological cross-sections representing at the belt scale the structural patterns of Western and Central High Atlas, performed on the basis of our field studies integrated with literature data (Figure 14) (Hollard et al, 1985; Froitzheim et al, 1988; Teixell et al., 2003).

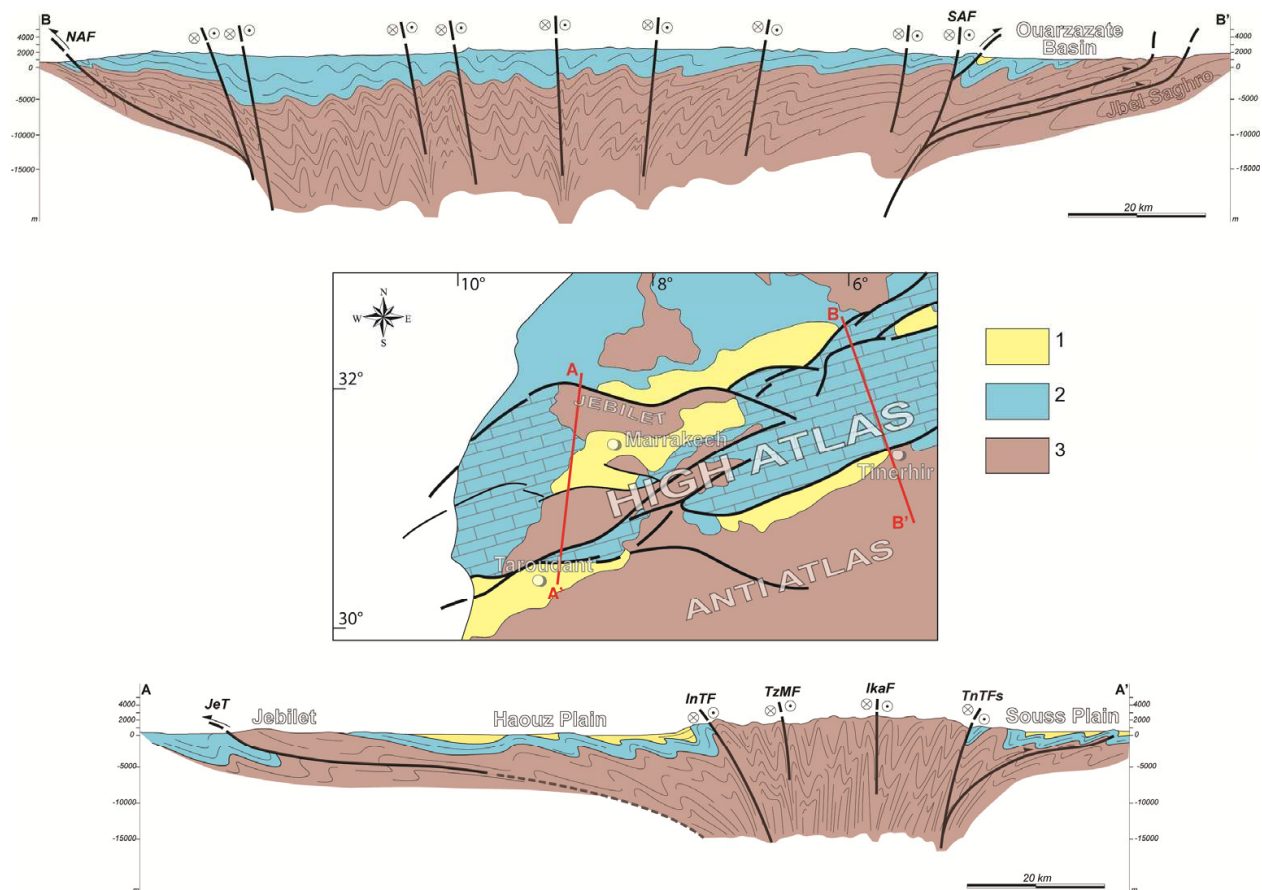


Figure 14. Simplified geological cross-sections through Western (A-A') and Central (B-B') High Atlas. 1: Neogene and Quaternary; 2: Mesozoic and Paleogene; 3: Precambrian and Paleozoic. SAF: South Atlas Fault; NAF: North Atlas Front; TnTFs: Tizi n'Test Fault system; JeT: Jebilet Thrust; InTF: Imi n'Tanoute Fault; TzMF: Tizi Maachou Fault; IkaF: Ikakern Fault.

Comprehensively, these schematic cross-sections represent a possible model of Alpine transpressional evolution for the whole High Atlas belt. The main structures are characterized by high-angle geometries and dextral strike-slip kinematics along an ENE-WSW direction. These fault zones generated also thrust planes and folds that in the inner belt sectors show double vergences at the mesoscale whereas along the bounding areas they are more developed characterizing the entire High Atlas belt by a double vergence, as at the northern margin the vergence is toward north (North Atlas Fault and Imi n'Tanoute Fault zones in A-A' and B-B' cross-sections, respectively) while at the southern margin it is toward south (South Atlas Fault zone and Tizi n'Test Fault system in A-A' and B-B' cross-sections, respectively).

The proposed geological cross-sections evidence also that the Alpine deformation was/is not limited to the High Atlas mountain range but involved/involves wider sectors. In the B-B' cross-section the Jebilet Thrust has been interpreted as a low-angle surface that roots into the high-angle transpressional zone of the Imi n'Tanoute Fault (Figure 14) and therefore Paleozoic basement and Mesozoic-Cenozoic deposits of the Haouz Plain are faulted and folded by the Cenozoic tectonic events. Along the southern boundary of the Western High Atlas we considered the Alpine tectonics deforming the Paleozoic rocks of the Anti Atlas belt as well as the Souss and Ouarzazate deposits of which they represent the basement, as already documented (Sebrier et al., 2006; Malusà et al., 2007).

5. Conclusion

The field study, mainly consisting in detailed mesostructural analyses, from the Western High Atlas transect and the Boumalne-Tinerhir region in the Central High Atlas, indicates a major role for transpressional tectonics in the Alpine structural evolution of the High Atlas belt. In particular, the deformation in the studied regions is controlled by two regional right-lateral fault systems (Tizi n'Test-South Atlas and Imi n'Tanoute-North Atlas) and their associated structures that involved, at south, the Anti Atlas belt and, at north, the Western Meseta domain (Jebilet range). Between these two major tectonic lineaments, a 50 to 100 km wide region is characterized by a complex tectonic framework, dominated by strike-slip faulting, in which strong uplift and exhumation occurred.

Kinematic measurements on major fault planes and mesoscale structural analysis reveal that the prevailing structural associations correspond to ENE-WSW trending dextral strike-slip faults and sub-parallel thrust faults, describing typical positive flower structures.

In the proposed transpressional model (Figure 14) the High Atlas belt appears to have a flower structure cross-sectional geometry with greater amount of thrust displacement along its northern and southern boundaries. This pattern showing double-verging structures requires a downward extrapolation of surface thrusts rooting into high-angle fault zones.

Fault analyses and palaeostress reconstructions suggest that flower structures and fold systems evolved into a right-lateral transpression which is related to a direction of maximum compression varying from about E-W to about N-S.

The High Atlas is a significant example of transpressional belt dominated by strain partitioning between distinct strike-slip and thrust faults which result from reactivation of pre-existing structures inherited from the pre-Alpine complex evolution.

The Cenozoic reactivation occurred during two main deformation events: Late Eocene-Oligocene and Pliocene-Pleistocene, the latter being still active.

The High Atlas can be therefore considered an example of active transpressional belt as defined by Cunningham (2005).

This study, although incomplete, furnished interesting results that indicate as structural and kinematic analyses are important methodologies and that their future development can provide new data for the better understanding crustal architecture, history of structural reactivation, partitioning of strain and distribution of present-day tectonic activity within the orogens. Particularly, in this case, the definition of the orogenic mechanisms represents the main step for interpreting the origin of topographic elevation, the principal still debated topic of the High Atlas geology.

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