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Geodynamics

Post-Cretaceous kinematics of the Atlas and Tell systems in central Algeria: Early foreland folding and subduction-related deformation

Narimane Benaouali-Mebarek [a], Dominique Frizon de Lamotte [b,*], Eduard Roca [c], Rabah Bracene [d], Jean-Luc Faure [a], William Sassi [a], François Roure [a]

[a] *Institut français du pétrole, BP 311, 92852 Rueil-Malmaison cedex, France*
[b] *Département des sciences de la Terre et de l'environnement, CNRS UMR 7072, université de Cergy-Pontoise, 95031 Cergy-Pontoise cedex, France*
[c] *Departament de Geodinàmica i Geofísica, Universitat de Barcelona, 08028 Barcelona, Spain*
[d] *SONATRACH explo, av. du 1er-Novembre, Boumerdès, Algeria*

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Abstract

Available surface and industrial subsurface data provide the basis for a general balanced cross-section from the Sahara platform to the Mediterranean Sea in central Algeria. This section gives an overview of the whole Maghrebian orogen comprising from south to north the following structural domains: the intra-continental Atlas system; the External Tell system, deriving from the African palaeo-margin; the Flyschs domain, representing the cover of the former oceanic domain and, finally, the Kabylides domain of European affinities. Restoration of the southern segment of the section, comprising the Atlas and External Tell systems, yields a minimum value of 40 km (20%) of horizontal shortening. For this part of the section, a four-step kinematic scenario, built using the THRUSTPACK software, illustrates the main stages of the deformation history: (1) Late Eocene 'Atlas' deformation pulse, (2) Early Miocene deposition of a thick flexural sequence, (3) Middle–Late Miocene emplacement of the Tell nappes and (4) Late Miocene to present out-of-sequence thrusting. On this basis, a conceptual geodynamic model is proposed for the whole Maghrebian orogen. After the Atlas event, which just preceded the roll-back of the Tethyan slab, the model emphasises the role of subduction responsible for: (1) flexuration of the subducting plate (slab pull effect), (2) development of both accretionary prism and back-arc basin, and (3) late uplift linked to slab break-off. ***To cite this article: N. Benaouali-Mebarek et al., C. R. Geoscience 338 (2006).***

Résumé

Cinématique post-Crétacé de l'Atlas et du Tell en Algérie centrale : plissement précoce de l'avant-pays et déformation liée à la subduction. L'accès aux données de surface et de subsurface a permis de réaliser une coupe équilibrée complète depuis la plate-forme saharienne jusqu'à la mer Méditerranée, en Algérie centrale. Cette coupe donne un aperçu sur l'ensemble de l'orogène alpin d'Afrique du Nord, qui comporte les domaines structuraux suivants, du sud au nord : (1) le système intracontinental atlasique, (2) le Tell externe, hérité de la paléo-marge africaine, (3) le domaine des Flyschs, représentant la couverture sédimentaire de

* Corresponding author.
E-mail address: dfrizon@geol.u-cergy.fr (D. Frizon de Lamotte).

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l'ancien océan téthysien et (4) le domaine Kabyle, dont les affinités sont européennes. La restauration de la partie sud de la coupe, c'est-à-dire la partie comprenant l'Atlas et le Tell externe, conduit à estimer un raccourcissement horizontal minimum de 40 km (20%). Pour cette partie de la coupe, un modèle cinématique en quatre étapes a été construit en utilisant le logiciel THRUSPACK. Ces quatre étapes correspondent aux principaux événements de l'histoire tectonique : (1) phase atlasique de la fin de l'Éocène, (2) dépôt au cours du Miocène inférieur d'une épaisse séquence sédimentaire flexurale, (3) mise en place des nappes telliennes au Miocène moyen, (4) développement de chevauchements hors séquence du Miocène terminal à l'Actuel. Sur cette base, un modèle géodynamique conceptuel est proposé pour l'ensemble de l'orogène maghrébin. Après la phase atlasique qui précède immédiatement le retrait du plan de subduction, le modèle insiste justement sur le rôle majeur joué par le mécanisme de subduction qui est à l'origine : (1) de la flexuration de la plaque subduite (par traction due à son poids), (2) du développement d'un prisme d'accrétion et d'un bassin d'arrière-arc et enfin (3) du soulèvement tardif lié à la déchirure de la plaque subduite. ***Pour citer cet article : N. Benaouali-Mebarek et al., C. R. Geoscience 338 (2006).***

Keywords: Balanced cross-section; Kinematic modelling; Subduction; Cenozoic; Northern Algeria

Mots-clés : Coupe équilibrée ; Modèle cinématique ; Subduction ; Cénozoïque ; Algérie du Nord

1. Introduction

The crustal and lithospheric geometry of western Mediterranean is mainly the result of a Late Cretaceous–Neogene convergence between Europe, Iberia and Africa, which generates the subduction of the Maghrebian Tethys Ocean underneath the southern continental margin of the Iberian plate [4,8,43] and the tectonic inversion of pre-existent continental Mesozoic rift systems. By the Oligocene, the inferred 'southward' but also 'westward' and 'eastward' retreat of the subducting Tethys oceanic slab promoted the formation of an array of extensional basins (València trough, Liguro-Provençal, Alboran, Tyrrhenian and Algerian basins) by back-arc spreading in the upper Iberian plate. This subduction zone was also responsible for the development of the complex system of orogens present along the southern Iberian and northern African continental margins (Betic-Balearic thrust system and Maghrebides, respectively).

In this setting, the Maghrebian Cenozoic orogenic domain is classically separated in two different systems: the Tell–Rif or Maghrebides and the Atlas (Fig. 1a). Fringing the west Mediterranean Sea, the Tell–Rif system (Tell in Algeria and Tunisia, Rif in Morocco) is assumed to be an 'Alpine chain' ([18] and references therein), that means a chain resulting from the closure of an oceanic domain. More precisely, the Tell system comprises: (1) the Internal Zones (or Kabylides), of European affinities [8], (2) the Flyschs domain, which corresponds to the former sedimentary cover of the Maghrebian Tethys, and (3) the External Zones (Tell s.s.) corresponding to the inverted African palaeomargin of the Maghrebian Tethys. By contrast, the Atlas system is an 'intra-continental' (i.e. intra-plate) chain developed in the foreland of the Tell–Rif in the site of a pre-existing continental extensional basin [34].

The present paper aims at clarifying and improving the kinematic and chronological relationships between the Tell and the Atlas in central Algeria. The question of relationships with the opening of the Mediterranean Sea will be also addressed. For this purpose, we present a regional north–south-balanced cross-section, modified from preliminary sections by Bracène [9] and Roca et al. [44] (Fig. 2). This section cuts through the whole orogenic system in central Algeria from the Sahara platform to the Mediterranean Sea and provides the first estimates of north–south horizontal shortening for this segment of the orogenic system. It is based on ancient geological mapping and interpretation of unpublished subsurface data (industry lines and exploration wells). On this basis, an original kinematic and geodynamic scenario is proposed, in which the major role of the subduction in the development and subsequent uplift of the Tell are emphasised.

2. Tectonostratigraphy and structural geology of northern Algeria

The Atlas and the External Tell (Fig. 1) were parts of the southern Tethyan margin during the Mesozoic. Their geodynamic evolution since Triassic times comprises (see review in [44,49]): (1) a rifting episode during the Late Triassic and Early Jurassic; (2) a post-rift episode of thermal subsidence and Tethyan oceanic accretion from the Middle Jurassic up to the Late Cretaceous and (3) convergence and compressional episodes during the Cenozoic.

As indicated above and according to their specific geodynamic settings as well as to structural and stratigraphic characteristics during their Tethyan/Alpine evo-

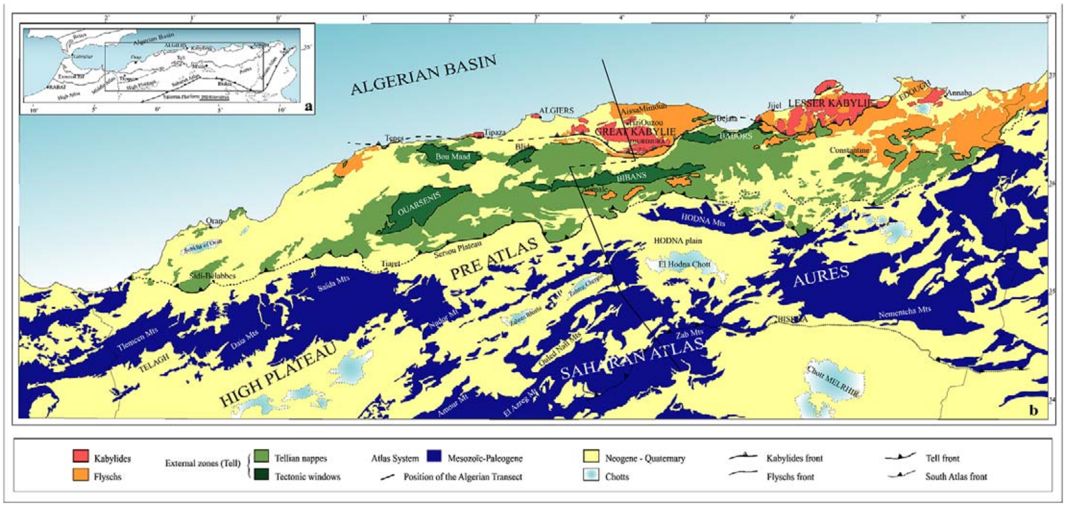

Fig. 1. Structural map of North Algeria (modified from the Geological Map of Algeria (scale: 1:500 000 and [27,50]): (**a**) location map.

Fig. 1. Carte structurale de l'Algérie du Nord (modifié d'après la carte géologique de l'Algérie à 1:500 000 et [27,50]) : (**a**) carte de localisation.

lution, several domains have been identified in northern Algeria. They are, from south to north: the Sahara platform, the Atlas and External Tell systems, the Flyschs and finally Kabylides domains (Fig. 1).

The Sahara platform consists of a Precambrian basement deformed during the Panafrican orogeny, overlain by a flat and weakly deformed Palaeozoic and Mesozoic sedimentary cover (see reviews in [5,53]). It is separated from the Atlas by the South-Atlas Front (SAF). South of the SAF, Alpine inversion, although visible in many places [9,20,31], remains weak and localized. So we will focus on the domains situated north of the SAF (Fig. 1).

2.1. The Atlas system

At large scale, the Atlas system is comprised between the Tell and South-Atlas Fronts (Fig. 1a). In Algeria, the Atlas system comprises the Atlas fold-thrust belt (Sahara Atlas and Aurès) and the High Plateau domain, characterized by a thin and tabular Mesozoic sequence. Along our cross-section (Fig. 2), the High Plateau domain does not exist and the contact between the Tell and Atlas systems is realized through the 'Pre-Atlas' domain, a region characterized by spaced anticlines developed above Upper Triassic evaporite or shallower décollements (Fig. 2).

The contact between the Pre-Atlas and the Sahara Atlas is underlined by a north-vergent thrust fault: the so-called North-Atlas Fault. As the South-Atlas Front, the North-Atlas Fault is a composite feature involving shallow thin-skinned deformation within the sedimentary cover [10,11,21]. However, the basement appears also involved at different steps of the deformation history [49].

The inversion and related uplift of the Atlas system of Algeria result from two main tectonic events. The first one, responsible for major deformation and the development of large NE–SW trending folds, occurred between the Middle Eocene and the Aquitanian [10,44]. The second event generates east–west-trending folds and thrusts during the Pleistocene [1,24,27,33]. Between these two compressive pulses, the Miocene was a period of relative quiescence, characterized by the deposition of a relatively thick flexural sequence deposited in continental or marine environment. Normal faulting developed in some places during this period [10]. The Miocene sequence is preserved along the cross-section (Fig. 2) in the Miocene (Burdigalian to Tortonian) M'sila basin, which rests unconformably on previously folded and faulted Cretaceous rocks belonging to the Atlas system (Fig. 3).

2.2. The External Tell system

The Tell system (Figs. 1 and 2) is located between the Flysch domain and the Atlas. It is formed by an accretionary complex deriving from the African palaeomargin of the Maghrebian Tethys. This sedimentary cover (Triassic to Neogene) is composed of thick sedimentary sequences of dominantly marly character.

The Tell system overthrusts the Atlas and the overlying Miocene sequences of the M'sila basin. This basin supports a thick pile of allochthonous terranes, the so-called 'Tellian nappes', which are gravity-driven nappes forming a quite complex imbricated fan [32].

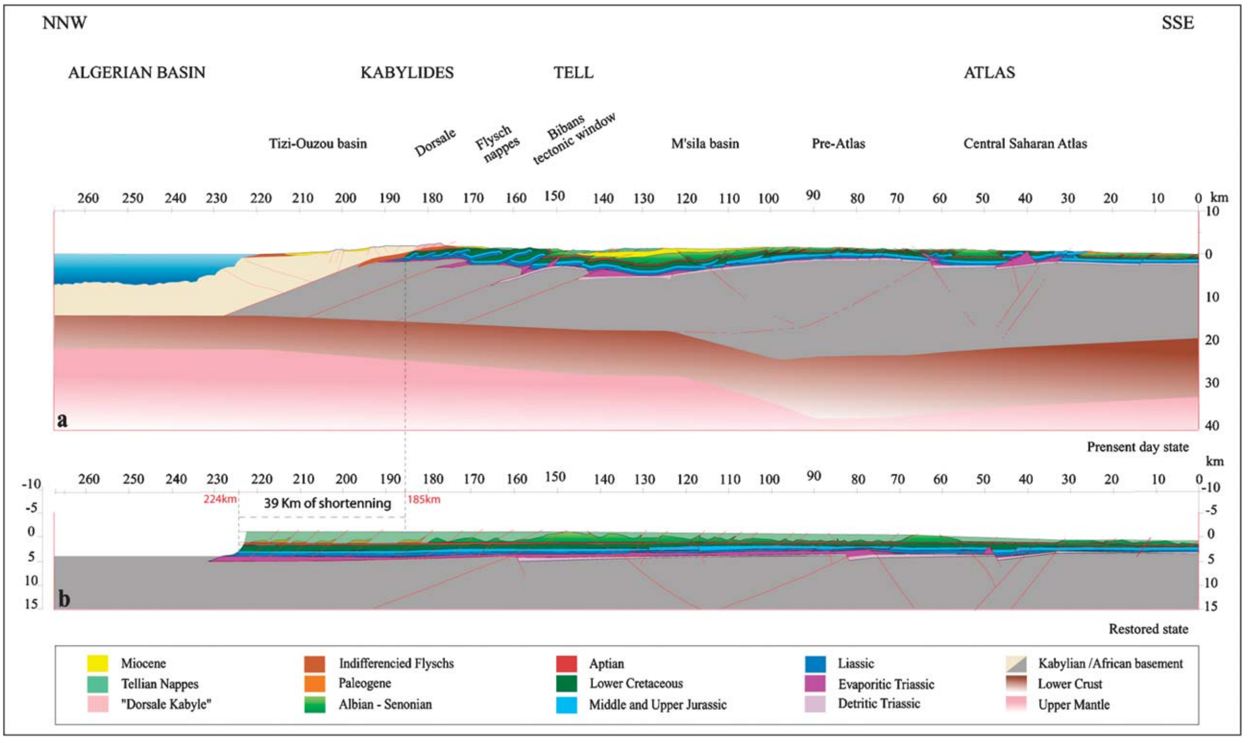

Fig. 2. General balanced cross-section from the Sahara Platform to the Algerian Basin: (**a**) present-day state, (**b**) restored section, for the Atlas and the External Tell only, at the end of Cretaceous times.

Fig. 2. Coupe équilibrée générale à travers l'Algérie du Nord depuis la plate-forme saharienne jusqu'à la Méditerranée : (**a**) état actuel ; (**b**) coupe restaurée à la fin du Crétacé (la restauration ne concerne que les domaines atlasique et tellien).

From a lithostratigraphic point of view, these nappes are formed by Upper Cretaceous to Lower Miocene series [50].

To the north, the décollement flooring the Tell nappes rests upon the large east-trending imbricated stack of south-directed thrusts made up of Jurassic to Albian strata cropping out in the Bibans tectonic window (Fig. 3). In our interpretation, these imbricated strata constitute the former substratum of the Tellian nappes that were detached from it along under-compacted and over-pressured horizons located at the top of the Albian strata. Accordingly, the Bibans window is interpreted as a large duplex with a roof thrust within Albian strata and a floor thrust along Triassic evaporites.

As in the Atlas, basement rocks do not crop out in the External Tell system, at least along our cross-section (Fig. 2), and the involved cover thrust units show a geometry (i.e. folds) indicating that the basement beneath them is nearly flat. This indicates that the basement is not involved beneath the Tell thrust system (and therefore that basement deformation took place more to the north) or that it is deformed forming a duplex with a relatively flat roof thrust (hypothesis chosen in Figs. 2 and 4).

The Jurassic to Albian rocks cropping out in the Bibans window are affected by a synfolding cleavage, which is moreover expressed everywhere in the 'external massifs' of the Tell–Rif system [3,19,21,41]. Due to the lack of such a cleavage in the Upper Cretaceous rocks of the Tellian nappes, it has been interpreted by some authors [41] as evidence for Upper Cretaceous compressive tectonic events. On the contrary, in our interpretation, the difference in tectonic style between Lower and Upper Cretaceous levels is related to a strong de-coupling between the hanging wall of the duplex roof thrust and the horses of the duplex. As a consequence, the roof layers were detached to form the Tellian nappes whereas internal deformation, expressed by cleavage, was concentrated in the horses of the duplex.

2.3. The Flyschs domain

North of the Bibans tectonic window, the Flyschs domain (Fig. 1) is interpreted as the sedimentary cover of the Maghrebian Tethys [18,25,50]. This domain is presently exposed in large thrust sheets (nappes), which are sandwiched between the Bibans imbricated thrust stack and the Kabylides but also superimposed to them.

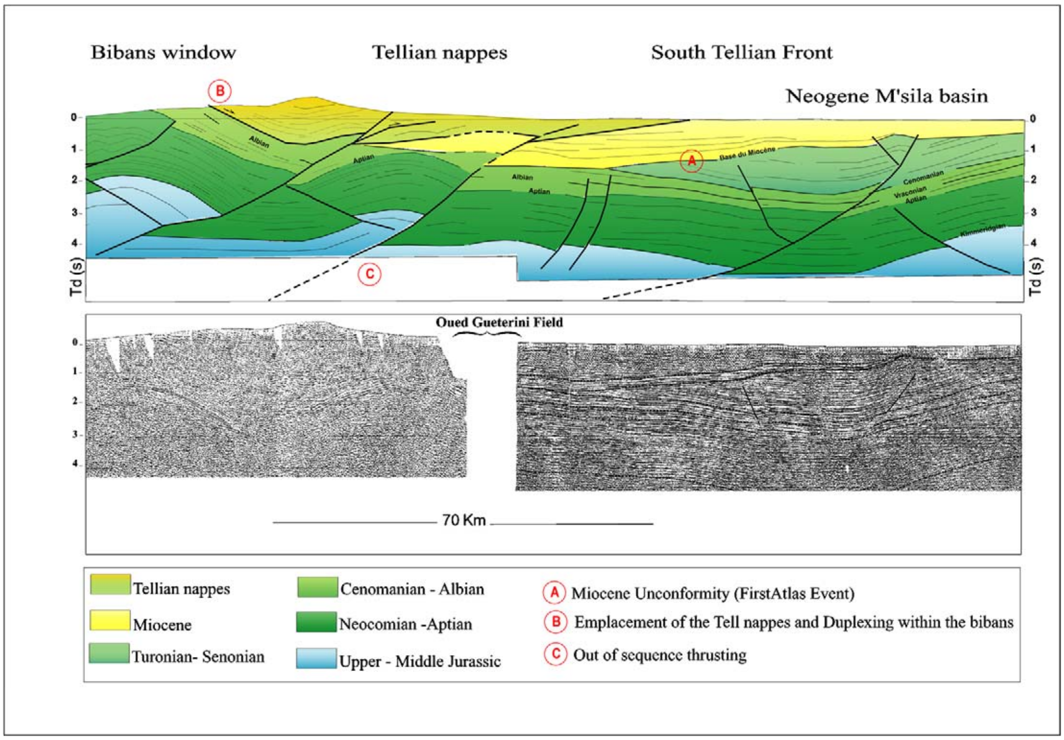

Fig. 3. Seismic profiles and interpretative time section showing the relationships between: the Tell Foreland, 'the M'sila Neogene basin', the Tellian nappes and the Bibans window.

Fig. 3. Profils sismiques et coupe « temps » interprétative, montrant les relations entre l'avant-pays tellien, le bassin néogène de M'sila, les nappes telliennes et la fenêtre des Bibans.

This last position had generated vigorous debates about its initial position (see discussion in [50]). However, following the stratigraphic and sedimentologic arguments developed in [50], it is presently acknowledged that its initial position was between the 'Dorsale calcaire', which represents the Mesozoic cover of the Kabylides, and the External Tell. So, the present-day position of the Flysch nappes, either beneath or above the Kabylides, should result from partitioning in front of the backstop formed by the Kabylian massifs.

In the Flyschs domain, a major décollement is situated between the siliciclastic levels of Lower Cretaceous age and their Jurassic substratum (Achaïches series), which is only known in a small tectonic window below the Lesser Kabylie massif [7]. This décollement allowed the development of a major north-directed backthrust involving only the youngest flysch sequences (i.e., Lower Cretaceous and younger sequences), whereas older Mesozoic basinal sequence were underthrust below the Kabylies massifs. The Oligocene–Lower Miocene levels are also detached from their substratum, forming the Numidian thrust sheet. This upper nappe is primarily composed of an up to 2000-m-thick turbiditic sequence interpreted as a flexural sequence deposited in front of the moving Kabylides and equivalent to the one known in the southern Apennines and in Sicily [13] as well as in the Rif and western Betics [18]. A late out-of-sequence thrusting [39] is required to explain the current position of the Numidian thrust sheet and to achieve the chain building.

2.4. The Kabylides

The Kabylides form an upper crustal wedge, initially situated north of the Maghrebian Tethys [8], that overthrusts the African margin of the Maghrebian Tethys along a north-dipping major thrust fault that corresponds to the Miocene suture of this ocean. It comprises different nappe complexes equivalent to the ones known in the internal Betics and Rif as well as in northern Sicily and Calabria (see [36] for a review).

The internal structure of the Kabylies is complex, with Alpine superposition of extensional and compressive faults. It includes different nappe complexes, cut by Miocene low-angle, north-dipping extensional faults and active north-dipping [6] and south-dipping (as the fault responsible for the Boumerdès 2003 earthquake

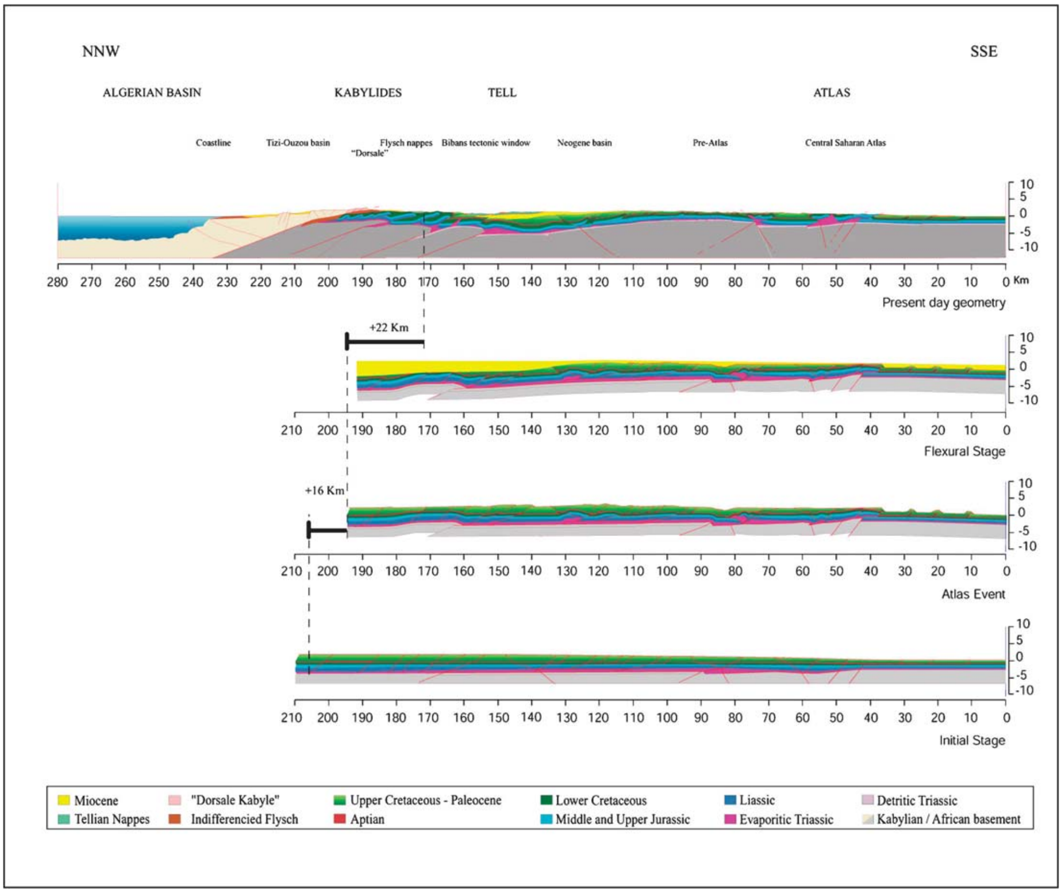

Fig. 4. A four-step kinematic model illustrating the tectonic evolution of the North Algerian domain (see the text for more details).

Fig. 4. Un modèle cinématique en quatre étapes illustrant l'évolution tectonique de l'Algérie du Nord (voir le texte pour plus d'explications).

[52]) reverse faults. At the moment, the Kabylides look like a giant crustal pop-up structure.

The Kabylides comprise from top to bottom the 'Dorsale kabyle' and the Kabylie massifs s.s. The 'Dorsale kabyle' complex consists of a pile of thrust sheets involving a thick Lower Jurassic platform carbonate resting on Upper Palaeozoic and Triassic detrital sediments and supporting a thin cover of Jurassic–Cretaceous pelagic and Cenozoic siliciclastic sediments. The 'Dorsale calcaire' is considered as the former northern passive margin of the Maghrebian Tethys [8,14]. Below the 'Dorsale calcaire', the Kabylie massifs comprise greenschist facies phyllites of Palaeozoic age resting on amphibolite facies rocks constituting the Kabylian basement. Most authors have considered this basement as rigid blocks weakly deformed during alpine orogeny. However, more recent work emphasises the importance of Alpine events (see discussion in [36,44]).

The Kabylides are covered by Chattian–Middle Burdigalian molasses [23]. These so-called 'Oligo-Miocène kabyle' molasses of the French authors may be regarded as synextension sediment deposited during the rifting that preceded the opening of the Algerian basin [2,25]. The 'Oligo-Miocène kabyle' molasses support tectonic slices pertaining to the Flysch nappes. The tectonic position of these slices is the product of a major backthrust over the Kabylies domain. Finally, the molasses and the nappes are overlain by marine sediments that are Langhian-Early Serravallian in age (i.e., Tizi Ouzou basin) [2,25].

3. Shortening estimates and kinematic evolution of the Tell and Atlas systems

3.1. Shortening estimates

Due to the important uncertainties on the geometry at depth, the Flyschs and Kabylies domains cannot be restore with sufficient confidence. So, we have limited our analysis to the Atlas and Tell systems. For these domains, we have restored the regional cross-section to its original predeformational length using the classical line length restoration technique with the help of the Locace software [40] (Fig. 2). Restoration of the entire section (External Tell and Atlas only) yields a minimum value of 39 km (17%) of horizontal shortening within the Mesozoic cover. This total shortening is distributed as follows: 13 km of shortening (11%) in the Atlas and 26 km (24%) in the External Tell. Restoration of the basement structures in the whole section yields approximately 25 km of shortening corresponding to an 11% ratio, which is significantly lower than in the cover. This implies an important decoupling between the sedimentary cover and the basement everywhere along the section (Fig. 2).

The shortening obtained for the Atlas system is comparable with the ones proposed by Frizon de Lamotte et al. [22] for other sections crossing the Sahara Atlas or the Aurès in Algeria and by [48] for sections through the Moroccan High Atlas. Concerning the External Tell, our estimate (24%) is the first one proposed for this orogenic system in particular and for the Tell–Rif system in general. It could appear as relatively low for a region where large nappes are identified since a long time (see review in [18]), but we must keep in mind that these nappes result from the gravity unroofing of para-autochthonous domains (such as the imbricate stack of thrusts cropping out in the Bibans tectonic window) along shallow décollements. They are consequently quite different from the classical Alpine nappes in which at least the whole sedimentary cover is involved. As a matter of fact, in the Tell, the displacement of some individual Tellian nappes can be larger (>40 km) than the total shortening calculated for the whole orogenic system.

Despite these estimated shortenings in the Atlas and Tell systems as well as the presence of significant compressive deformation in the Flyschs and Kabylides domains at upper crustal levels, the crust and lithosphere do not show evidence of significant thickening south of the Algerian basin. Gravity and heat-flow models [37] show fairly constant crustal thickness of 35 km that decrease rapidly near the coastline to reach the low crustal values of the offshore Algerian basin. Accordingly, the earthquakes are superficial along the Algerian margin as well as in the Tell (see review in [52]). Such lack of thickening at both deep crustal and lithospheric mantle levels could be explained by the presence of a detachment at the base of the upper crust and by the subduction of the underlying levels beneath the Iberian plate. Moreover, seismic tomography provides evidence for a deep detached slab below the Tell [12,42,46,47]. Such a process is also strongly supported by the petrological features of the Neogene magmatism [15,35]. This detached slab would represent the remnant of the subduction responsible for the formation of the whole Maghrebides chain, once connected through the Gibraltar Arc to the Betics and through Sicily to the Apenninic slabs [46].

3.2. *Cenozoic kinematics of the Tell and Atlas systems*

Previous work done in the Tell and Atlas systems rarely focused on the timing and kinematics of the orogenic processes. Using the THRUSTPACK software [45], a four-step kinematic scenario is proposed in this work, which is the first one for the whole Tell and Atlas systems (Fig. 4). We acknowledge that our scenario remains oversimplified due to the lack of accurate bracketing of tectonic events.

The initial stage (Fig. 4), corresponding to our restored cross-section in Fig. 2, is supposed to represent the state of the region at the end of the Eocene times, just before the beginning of the inversion process related to the convergence between the Africa and Europe plates. It is known that this convergence, which was active since the Late Cretaceous, has been already recorded by some deformation observed in Upper Cretaceous and Palaeocene–Lower Eocene sediments (see review in [26]). However, the effects of these early tectonic pulses remain small and can be neglected at the scale of our section.

The second stage (Fig. 4) corresponds to the Eocene–Oligocene boundary (35 Ma). In the Atlas system, the widely observed angular unconformity between the Oligocene and older sediments is indicative of an important pulse of deformation (Atlas phase) occurring before the emplacement of the Tell units. The same unconformity is observed in the Tell below the M'sila basin [10], but seems absent in the Tell nappes where the passage from Upper Eocene to Oligocene is transitional [51]. Accordingly, Late Eocene deformation has been considered negligible in the External Tell and, therefore, only significant in the Atlas. The lack of compressive deformation in the External Tell, the predominant south-directed vergence of Atlas cover structures and the lack of basement structures beneath the Pre-Atlas and M'sila basin suggest that the boundary between the Atlas and Tell belongs to a major north-dipping basement fault, which accommodated most of the shortening observed in the Pre-Atlas cover structures.

The third stage (Fig. 4) illustrates the development of the thick clastic wedge of Lower to Middle Miocene sediments as a response to the progressive flexure of the

African plate towards the north in front of the moving Kabylides. This clastic wedge covered the whole region and lies unconformably, in the central and southern parts of the section (Fig. 2), over the deformed Mesozoic cover of the Atlas. From a tectonic point of view, the Late Oligocene-Middle Miocene is characterized by non-significant tectonic activity in the Atlas and External Tell: only some normal faulting is reported in the Atlas system (see review in [10]). However, more to the north an accretionary prism involving the Flyschs units was already developed in front of the Kabylies on the subducting Maghrebian Tethys.

The final stage corresponds to the present-day cross-section (Fig. 4). To achieve this geometry, at least two deformation events are required. The first event (Middle Miocene) corresponds to the development of the Tell system with the emplacement of the Tellian nappes and the coeval development of the Bibans duplex. The second one belongs to a compressive deformation affecting all the section and expressed by late out-of-sequence thrusts that cut through the previous tectonic pile (Fig. 3). This second step is post-Miocene and already active.

4. Cenozoic geodynamic evolution of Central Algeria

In the Maghrebian region, African plate started to be really involved in the Alpine orogeny by Late Eocene, just before the beginning of the slab retreat of the subducting Tethys Ocean in the whole Mediterranean region [29]. This suggests a genetic relationship between the 'Atlas' phase in Africa and the onset of the back-arc extension in the western Mediterranean, as already emphasised by Frizon de Lamotte et al. [21] and Roca et al. [44]. Atlas deformation resulted from the moderate

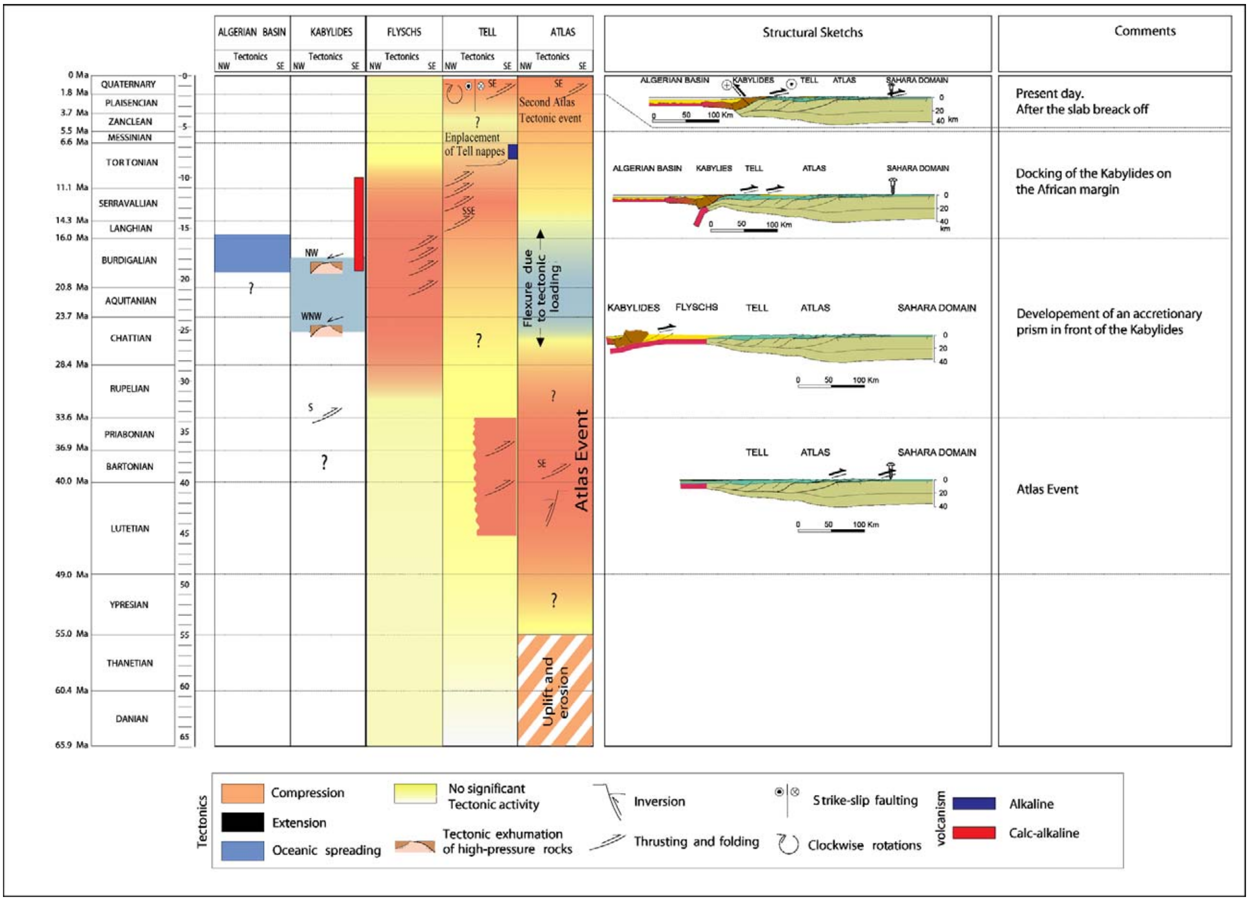

Fig. 5. Chronological table with emphasis on the main tectonic events (modified from Rocca et al. [44]) and conceptual model explaining the geodynamic evolution of North Algeria.

Fig. 5. Tableau chronologique insistant sur les principaux événements tectoniques (modifiée d'après Rocca et al. [44]) et modèle conceptuel expliquant l'évolution géodynamique de l'Algérie du Nord.

inversion of an intra-continental basin. In our section, the major reactivated faults dip northward and are located beneath the North-Atlas Fault and beneath the present-day northern boundary of the M'sila basin. The exact geodynamic significance of the Atlas phase remains questionable. However, it is now established that this deformation pulse is general at the scale of Maghreb (see in particular [30] and [28]) and predates any collision between Europe (represented here by the Kabylides domain) and Africa (Fig. 5).

By the Oligocene up to the Middle Miocene, the geodynamic history of the region is dominated by (1) the opening of the Algerian back-arc basin with the migration towards the South of the Kabylies, and (2) the flexuration of the African plate (slab pull effect), which started from the most internal zones (Flyschs domain) and progressed onward toward the continent. The space issued from this flexuration was accommodated by clastic sediments: Numidian Flysch passing southward to different sedimentary wedges covering the whole External Tell and Atlas domains. At the same time, an accretionary prism developed in the hanging-wall of the subducting plate and propagated southeastwards. Given the stratigraphic data, it is established that the sedimentary cover of the Flyschs domain was already involved in this prism by the Burdigalian. Tectonic imbrication was accompanied by large submarine gravitational detachment of rock masses coming from the hanging-wall of duplex structures developed at depth. This phenomenon explains the development of wide gravity-driven structures resulting from general decoupling along weak horizons. A major back-thrust developed in front of the Kabylies backstop and led to the emplacement of some Flyschs units over it.

At about 15 Ma (Langhian), the docking of the Kabylides against the continental African lithosphere achieved the flexural stage (Fig. 5). This accretion of a continental terrane along the margin was accompanied by the propagation of thrust faults within the African crust forming the External Tell system. It is likely that the shortening measured within this domain directly results from this event. The general uplift of the coastal range, which started during the Upper Miocene (post-11 Ma) is interpreted the result of a rebond following a break-off of the subducting slab. Evidence for such a process is given by the type of the post-collisional magmatic activity [35] and by seismic tomography imaging that, at the moment, there is no subducting slab below the Kabylides [46].

Since the beginning of the Pleistocene, the whole orogenic domain is affected by a diffuse compressive activity, which is mainly concentrated in the coastal (onshore and offshore) areas [16,17,38,52]. The convergence between the Africa and Europe plates is accommodated along large south- and north-verging reverse faults inducing the development of large pop-up structures.

5. Conclusion

Our study provides the first shortening estimates and a kinematic model for central Algeria, a segment of the former African palaeomargin of the Maghrebian Tethys. These new data are integrated in a comprehensive geodynamic model in which subduction processes played the major role.

The Late Eocene 'Atlas' event is well documented and recorded about 13 km of horizontal shortening within the African plate. It just preceded the slab roll-back and the coeval transit of the Kabylides from Europe to Africa. This important phenomenon is accompanied by general subsidence, development of an accretionary prism in the cover of the Maghrebian Tethys but insignificant deformation in the African foreland. The Middle Miocene final docking and collision of the Kabylides with Africa led to 25 km of horizontal shortening within the External Tell domain. The subsequent slab break allowed a renewal of the compressive deformation in the whole orogenic domain, which continues up to now.

In central Algeria, the horizontal movements, the sequence of deformation and their links with geodynamic processes are now quite well established. By contrast, the calibration of the associated vertical movements (subsidence vs uplift) remains under-constrained. We think that future work must focus on this aspect, which is of crucial interest to progress in the understanding of the coupling between deep-Earth and surface processes and also for a valuable evaluation of energetic resources.

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