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A structural transect through the High and Middle Atlas of Morocco

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Abstract

The surface and crustal structure of the Atlas ranges of Morocco are described by a structural section from the foreland basin of the Rif to the Sahara craton. The Atlas ranges derive from inversion of Jurassic extensional or transtensional troughs during the Cenozoic, and they consist of dominantly thick-skinned thrusts and folds separated by tabular plateaux. Paleozoic basement is downwarped in synclinal areas up to 3 km below sea level, but is exposed at the surface in the peripheral plains, thus lying at a higher regional elevation than in much of the interior of the ranges. Synorogenic basins are poorly preserved. Based on the surface geology and available geophysical data, a reinterpretation of the crustal structure is proposed, in which the thrust system of the High Atlas is interpreted to cut into the lower crust and offset the Moho. The moderate amount of shortening along the transect (about 12%) contrasts with the elevated Atlas topography, which cannot be explained by crustal thickening alone. The presence of Cenozoic alkaline volcanics, widespread in the Middle Atlas, together with low seismic velocities suggest the existence of a thermally anomalous mantle contributing to uplift in the region.

Keywords: Intra-plate tectonics; Atlas; Morocco; Africa

1. Introduction

The High and Middle Atlas of Morocco are intracontinental fold-thrust belts situated in the foreland of the Rif orogen. The High Atlas and its eastern continuation in Algeria and Tunisia is an ENE–WSW to E–W trending belt about 2000 km long and 100 km wide from which branches the Middle Atlas with a SW–NE trend and about 250 km length (Fig. 1).

The Atlas mountain chains are flanked by comparatively less deformed areas which nevertheless have high topographic elevation (Moroccan Meseta, High Plateaux and Anti-Atlas).

The Atlas chains developed from the inversion of Jurassic rift or transtensional basins as a consequence of continental convergence between Africa and Europe during the Cenozoic (Choubert and Faure-Muret, 1962; Mattauer et al., 1977; Schaer, 1987; Jacobshagen et al., 1988; Laville and Piqué, 1992; Beauchamp et al., 1996; Gomez et al., 2000; Frizon de Lamotte et al., 2000; Teixell et al., 2003). The cited papers describe aspects of the structural geometry and kinematic evolution of the ranges, but there are few works that document the overall structure of the High and Middle Atlas. In this paper we present a comprehensive geological transect that crosses both mountain ranges and allows us to address poorly resolved questions as to the crustal structure, the amount of tectonic shortening and the origin of topography.

2. Stratigraphic setting

The High and Middle Atlas are essentially made up of Mesozoic rocks, with minor pre-Mesozoic and

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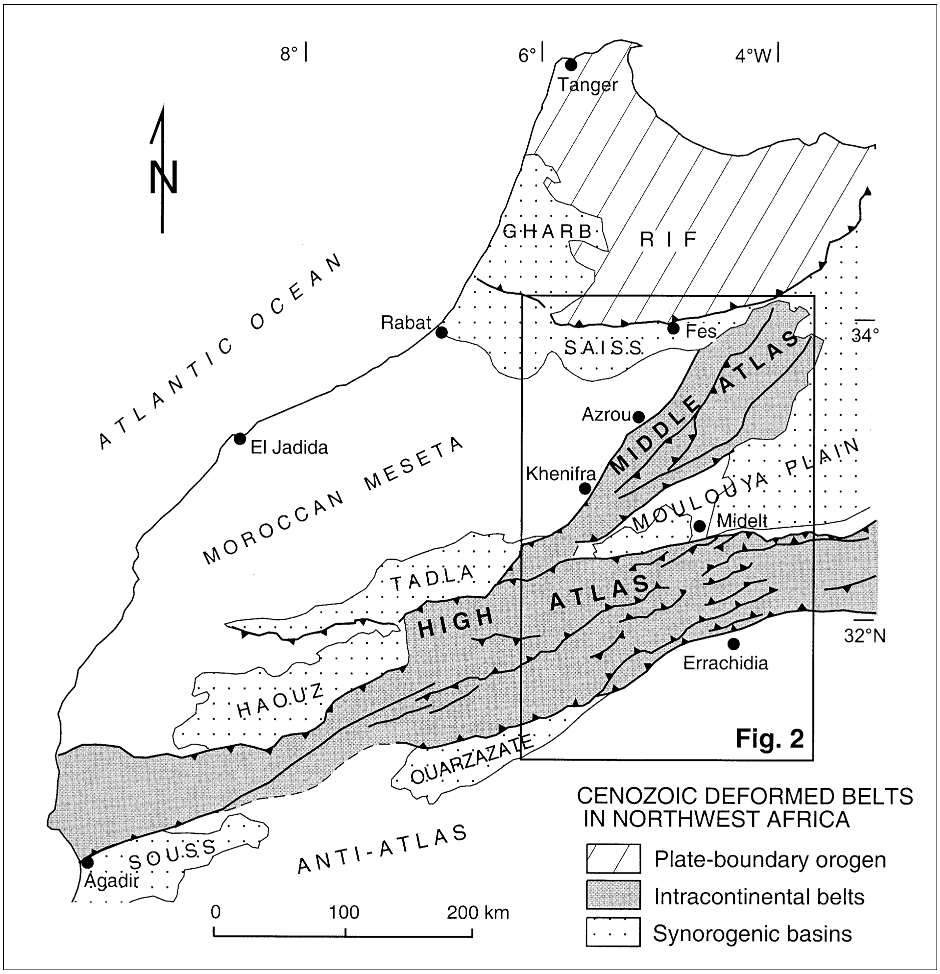

Fig. 1. Tectonic map of Morocco indicating the geological setting of the Atlas Mountains.

Cenozoic occurrences (Fig. 2). Pre-Mesozoic basement rocks affected by the Hercynian orogeny crop out in antiformal culminations within the High and Middle Atlas, and more extensively in the Moroccan Meseta, west of the Middle Atlas, and in the Anti-Atlas, south of the High Atlas. Mesozoic sedimentation in the Atlas domain was initiated within Triassic rift basins whose NE–SW structural trend was inherited from Hercynian structures (Laville and Petit, 1984; Froitzheim et al., 1988; Laville et al., 1995), and that were filled with detritic red beds and tholeiitic basalts. Lower Lias platform limestones and dolomites sealed the Triassic rifts (Laville et al., 1995). In the Upper Lias the subsidence increased and the carbonate platforms were drowned and disrupted by the formation of subsiding basins, where thick series of marls, calciturbidites and limestones accumulated up to Dogger times. Two models have been proposed for the tectonic origin of these basins: (1) a strike-slip system with pull-aparts and intervening compressional step-overs (Laville, 1985, 1988; Fedan, 1988; Fedan et al., 1989), and (2) an extensional system with minor strike-slip components (a rift opened obliquely in the case of the High Atlas; Warme, 1988; El Kochri and Chorowicz, 1995). The Jurassic record ends with Dogger red beds indicative of a generalized regression (Choubert and Faure-Muret, 1962; Jenny et al., 1981). However, these beds are rarely preserved in the study transect. The Jurassic basin troughs coincide approximately with the present location of the High and Middle Atlas mountain belts, and their evolution was accompanied by intrusion of mid-Jurassic alkaline gabbros (Hailwood and Mitchell, 1971; Laville and Piqué, 1992).

The Cretaceous is made up of fluvial red beds, platform limestones and phosphatic layers. These rocks form a thin cover cropping out in synclines in the interior of the chains or overlapping the peripheral plateaux, where they may directly overlie the Paleozoic; thus, they can be interpreted as an expansive post-rift sequence. Latest Cretaceous red beds show local evidence of growth folding, indicating to some authors the early stages of the Alpine compression in the Atlas domain (Laville et al., 1977; Froitzheim et al., 1988; Herbig, 1988; Charroud, 1990; Amrhar, 1995). The Cretaceous

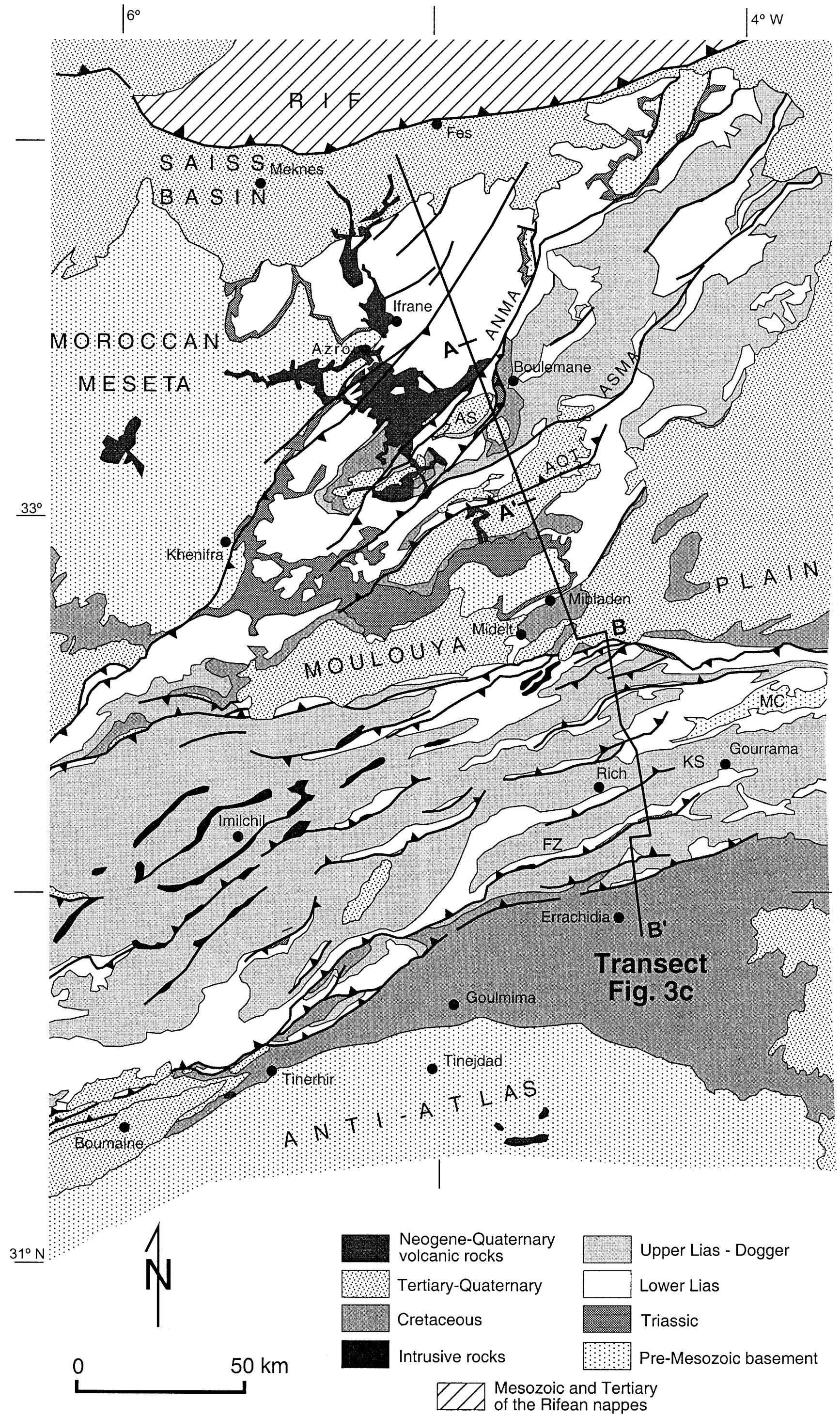

Fig. 2. Geological map of the studied part of the High and Middle Atlas indicating the cross-section lines of Fig. 3 (based on the synthesis by Hollard, 1985, and own data). AA′ and BB′ correspond to Fig. 3a and b, respectively. ANMA: North Middle Atlas fault; AS: Ain Nokra syncline; ASMA: South Middle Atlas fault; AOT: Ait Oufella thrust; MC: Mougueur basement culmination; KS: Kerrando syncline; FZ: Foum Zabel thrust.

is followed by Paleogene limestones and shales preserved only in the Middle Atlas part of the study transect.

Continental deposits of Neogene to Quaternary age, comprising alluvial conglomerates and lacustrine limestones, are contemporaneous with the main compressional deformation and uplift (Monbaron, 1982; Görler et al., 1988; Fraissinet et al., 1988; Morel et al., 1993; etc.). They are found in some of the plains bordering the Atlas Mountains and in some small synclinal outcrops within the chains (Martin, 1981; Zouine, 1993), but their development is poor: the peripheral forelands of the Atlas ranges are often free of these deposits, being Mesozoic or even Paleozoic basement rocks exposed at the surface (Figs. 1 and 2). This is so in the study transect. Contemporaneous with the Cenozoic convergence, is the remarkable occurrence of alkaline magmatism, which is especially abundant in the Middle Atlas (e.g., Harmand and Cantagrel, 1984).

3. Structural cross-section of the High and Middle Atlas

The cross-section presented here is the transect Fes-Midelt-Errachidia (Figs. 2 and 3), which is oriented NNW–SSE, perpendicular to the general trend of the High Atlas and slightly oblique to the Middle Atlas. As illustrated in Fig. 3, both belts are bivergent and characterized by narrow deformation zones (anticlines and thrust faults) separated by wide synclines and tabular plateaux. Exposed rocks were deformed in upper crustal conditions, with very weak or no metamorphism. The deformation style is dominantly thick-skinned, and many thrust faults are associated with Mesozoic stratigraphic changes, corroborating tectonic inversion as a general process during the Cenozoic Alpine convergence. Convergence continues until present times, as indicated by field evidence (Dutour and Ferrandini, 1985; Morel et al., 1993) and seismicity (Coisy and Frogneux, 1980; Medina and Cherkaoui, 1991). The general convergence direction is NNW–SSE (Mattauer et al., 1977; Morel et al., 1993; Gomez et al., 2000), which led many authors to propose large strike-slip movements along the NE–SW faults of the High and Middle Atlas. However, field evidence of lateral motions is not abundant, and microtectonic data often indicate NW–SE compression or shortening directions in the vicinity of the principal faults within the study zone (El Kochri and Chorowicz, 1995; Gomez et al., 1998), suggesting local stress reorientations which resulted in only moderate strike-slip components during the Cenozoic.

3.1. Surface structure

Structural aspects of the Middle Atlas were described by Termier (1936), Duée et al. (1977), Fedan (1988), du Dresnay (1988), Charroud (1990) and Gomez et al. (1996, 1998). The internal deformation structures are oriented NE-SW, parallel to the general trend of the chain (Fig. 1). At its northern boundary, the Middle Atlas plunges under the Neogene sediments of the Saïss basin, the foreland basin of the Rif orogen (Figs. 1 and 2). The northern half of the Middle Atlas has a tabular structure only disrupted by minor normal and thrust faults (“Causse Moyen Atlasique”; Fig. 3a). A central folded and thrust belt is separated from this tabular zone by the so-called North Middle Atlas fault (ANMA in Fig. 3), a compression-reactivated Jurassic normal fault, which is still active during the Quaternary (Martin, 1981; Fedan, 1988). The structure of this central deformed belt consists of two synclines (Ain Nokra and Oudiksou synclines, Fig. 3b) preserving Cretaceous to Tertiary beds, separated by a complex thrust zone. Latest Cretaceous and Tertiary rocks of the synclines exhibit bed fanning indicative of growth folding during the Alpine compression. The three-dimensional fanning geometry of the Ain Nokra syncline is indicative of a left-lateral component along the ANMA according to Duée et al. (1977). The Cretaceous of the Oudiksou syncline is unconformable on the southeastern continuation of the Tichoukt anticline, a fold originated during Mesozoic extension (Charroud et al., 1993) and later tightened. To the south of this zone is the South Middle Atlas fault (ASMA in Fig. 2), a Jurassic normal fault associated with a marked sedimentary thickness variation, which appears little reactivated in the study transect. This fault branches laterally to the Ait Oufella fault, a structure interpreted as a left-lateral strike-slip fault by Morel et al. (1993), and later reinterpreted by Gomez et al. (1996) as a thrust. Variations of structural elevation of Jurassic beds indicate that basement must be involved in the structures of this central deformed zone of the Middle Atlas. The front of the Ait Oufella thrust overrides Quaternary deposits and bounds to the south another tabular area (Engil Plateau and Moulouya plain), characterized by a reduced Mesozoic and Neogene succession in which the basement crops out in the Mibladen mining district.

The structure of the High Atlas is characterized by folds and thrusts oriented approximately NE–SW, slightly oblique to the general ENE–WSW trend of the chain (Schaer, 1987; Laville, 1985; El Kochri and Chorowicz, 1995; Teixell et al., 2003). Anticlines are tight and form calcareous ridges of Liassic limestones and dolomites separated by open synclines occupied by Upper Lias–Dogger shales (Fig. 3b). Some of the anticlines have been subjected to thrusting and, to the west of the study transect, they contain Jurassic igneous intrusions in their core (Laville and Piqué, 1992). The northern border of the High Atlas at the transect is dominated by north-vergent thrusts, the frontal of which overrides the overturned limb of a syncline in Cretaceous beds of the Moulouya plain. The footwall ramp geometry of the contact precludes a large displacement for this thrust. Thrusting in this area was shown to be thick-skinned by Benammi et al. (2001), on the basis of seismic profiles. In the middle part of the section a large anticlinorium defined by Liassic limestones represents the western continuation of the Mougueur basement massif (MC in Fig. 2). As seen in outcrop, basement is involved in the core of anticlinal structures, despite their tight character. This anticlinorium is followed by the

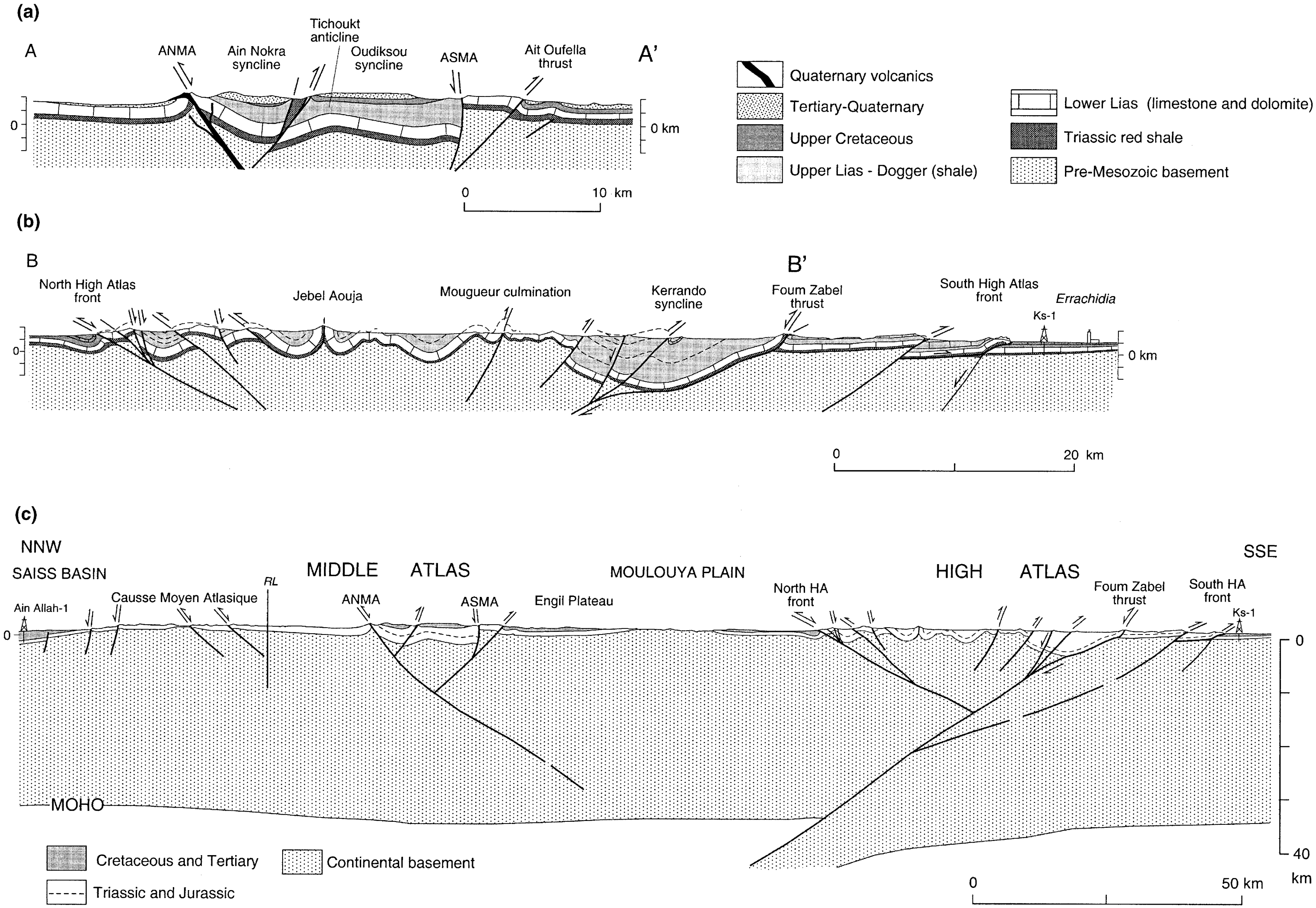

Fig. 3. Structural transect of the Atlas ranges of Morocco from Fes to Errachidia (see Fig. 2 for location): (a) cross-section of the central, deformed belt of the Middle Atlas; (b) cross-section of the High Atlas and (c) comprehensive crustal-scale section of the High and Middle Atlas based on a new interpretation of available geological and geophysical data. ANMA: North Middle Atlas fault; ASMA: South Middle Atlas fault; RL: Reference line in the restored section of Fig. 4.

Kerrando syncline (Fig. 3a), a high amplitude syncline which contains the thickest Jurassic succession of the transect and is bounded to the south by the Foum Zabel thrust. There is an important thickness variation of the Jurassic sediments between the hangingwall (at least 4000 m) and footwall (about 1000 m) of this thrust. This, together with the presence of Paleozoic slivers at the thrust surface suggests that it is an inverted normal fault. However, the thrust carries Triassic materials in a hangingwall flat disposition, superposed on a high-angle footwall ramp. The geometric relationships between both suggest that the Kerrando syncline cannot be attributed to this footwall ramp, but instead must be a structure inherited from the Mesozoic extension (Teixell et al., 2003). In the northern limb of the syncline there is an intraformational unconformity within Dogger marine beds that supports this interpretation. The southern part of the High Atlas has again a tabular structure, disrupted by spaced thrust faults. The most external of them shows a well developed fault-propagation fold and is probably detached at the Triassic (Saint Bezar et al., 1998), representing the only thin-skinned structure of the transect. This frontal thrust overrides a very reduced and undeformed Mesozoic succession of the Sahara craton.

The thick-skinned nature of most of the transect is a common trend along the Moroccan Atlas, where thin-skinned thrusting is limited to the southern border of the central High Atlas (see local descriptions in Laville et al., 1977; Beauchamp et al., 1999; Teixell et al., 2003). Nevertheless, thin-skinned tectonics is prevalent in the Saharan and Tunisian Atlas (Frizon de Lamotte et al., 2000).

3.2. Synthesis of geophysical data and crustal structure

Seismic and gravity estimates on the thickness of the crust beneath the Atlas ranges and surroundings were provided by Makris et al. (1985), Tadili et al. (1986) and Wigger et al. (1992). A remarkable result of these investigations is a fairly homogeneous crustal thickness, without large crustal roots in spite of the high topography. As summits may exceed 4000 m in the eastern High Atlas and 3000 m in the Middle Atlas, several authors have proposed that the Atlas Mountains are in an uncompensated isostatic state (Van den Bosch, 1971; Makris et al., 1985; Gomez et al., 1998). The Moho discontinuity lies at some −32 km beneath the Saiss basin and northern Middle Atlas, deepening only to some −35 km beneath the folded Middle Atlas (Tadili et al., 1986). Under the Moulouya plain is again at −33 to −35 km, and the maximum crustal thickness appears abruptly beneath the northern border of the High Atlas (some 39 km, according to seismic refraction data of Wigger et al., 1992). In the remainder of the section, the thickness decreases gradually to some 34–35 km.

Previous crustal models of the High and Middle Atlas suppose the existence of a mid-crustal detachment where all the surface thrusts merged and below which the lower crust was continuous (Giese and Jacobshagen, 1992; Beauchamp et al., 1999). However, both refraction seismics (Wigger et al., 1992) and gravity modelling (Makris et al., 1985) detected a jump in crustal thickness between the High Atlas and the northern plains, which in our view suggests that a thrust fault may penetrate the lower crust and offset the Moho. This fault branches upward into the upper crustal thrusts. This interpretation is consistent with the seismic image of other small Alpine orogenic belts, from which there is information of reflection profiling (e.g., the Pyrenees), and is also compatible with a solution of electrical resistivity modelling in the Atlas (Schwarz et al., 1992, their Fig. 6a). A crustal model with this new interpretation, which accounts for the surface geology and the available geophysical data, is presented in Fig. 3c.

3.3. Implications of a restored cross-section

A restored version of the transect to the pre-compressional state is presented in Fig. 4. A degree of uncertainity arises from the obliquity of some of the individual structures to the section line, but out-of-plane movements in the High Atlas were considered to be minor (around 4%) by Zouine (1993). In the case of the Middle

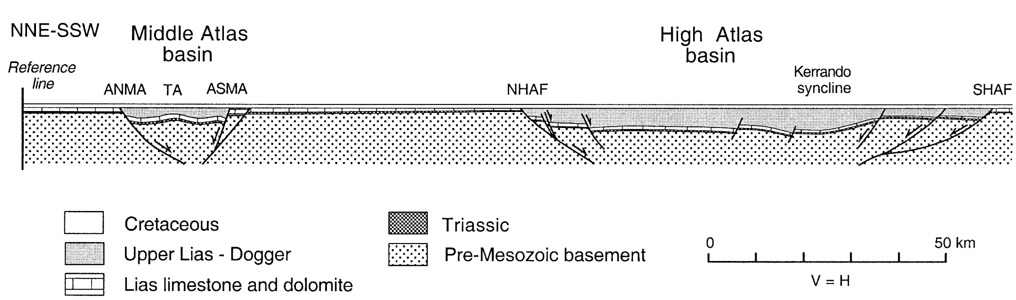

Fig. 4. Palinspastic reconstruction of the High and Middle Atlas to the pre-compressional state (datum: base of the Cretaceous). ANMA: North Middle Atlas fault; TA: Tichoukt anticline; ASMA: South Middle Atlas fault; NHAF: North High Atlas front; SHAF: South High Atlas front.

Atlas, obliquity of structures to the regional compression direction is larger, so the restoration results are only good indicators of order of magnitude. The precursors of the High and Middlle Atlas appear as rather symmetrical extensional basins, flanked by marginal zones with much reduced sedimentary thickness.

At this stage, it is worth mentioning that the stress field during the Triassic and Jurassic basin-opening episodes was characterized by NW–SE tension, developing NE-SW normal faults (Mattauer et al., 1977; Ait Brahim et al., 2002). In this context, the Middle Atlas can be regarded as an orthogonal rift, whereas for the High Atlas we favour an oblique rift model as envisaged by El Kochri and Chorowicz (1995). Major strike-slip movement along the principal faults cannot be proved, and the gentle synsedimentary folding of Jurassic beds described at Tichoukt and Kerrando (Figs. 3 and 4), and reported elsewhere by Jenny et al. (1981) and Laville and Piqué (1992), may have been produced in an extensional tectonic regime (Jenny et al., 1981; El Kochri and Chorowicz, 1995). We do not find unequivocal evidence of a regional shortening event during late Jurassic or early Cretaceous time (e.g., Mattauer et al., 1977; Laville, 2002), and some of the small-scale ductile deformation features around Jurassic intrusions (Laville et al., 1994) could be due to igneous emplacement mechanisms (“diapiric folding”: Schaer and Persoz, 1976).

The comparison of the deformed and restored sections yields an Alpine shortening of some 31 km for this transect of the African plate, distributed in 26 km for the High Atlas and ca. 5 km for the Midlle Atlas, the latter being a value comparable to that obtained previously by Gomez et al. (1998). These moderate shortening values are consistent with the little crustal thickening suggested by geophysical data, and pose an interesting problem when trying to account for the high elevation of the Atlas chains. This subject was discussed by Teixell et al. (2003), who related the high topography to the Cenozoic alkaline magmatism and the detection of low seismic-wave velocities in the sub-Atlas mantle, facts that suggest that the relief of the Atlas belts and the flanking plateaux is partly supported by a thermally anomalous mantle or a thin lithosphere (Seber et al., 1996). Given the regional compression prevailing during the Cenozoic, this phenomenon appears unrelated to the tectonic regime, and must be related to the internal mantle dynamics.

4. Conclusions

The presented transect illustrates the structural geometry of the High and Middle Atlas mountain ranges of Morocco. The contractional deformation within these chains is heterogeneously distributed: relatively narrow deformed belts of folds and thrusts are separated by wide tabular plateaux, the former being localized in previously weakened zones, corresponding to Mesozoic-age extensional basin troughs. Both thrust faults and fold systems are dominantly thick-skinned, involving both the Mesozoic–Cenozoic cover and the Paleozoic basement.

The restoration of the geological cross-section yields a moderate amount of shortening for the Atlas Mountains (some 31 km, that is, 12%), and accordingly, crustal thickening beneath them is limited, in contrast with the elevated topography. The thrust system of the High Atlas, which accomodates most of the shortening, is interpreted to penetrate into the deep crust and offset the Moho discontinuity, with a predominantly southern vergence.

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