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Deep-rooted “thick skinned” model for the High Atlas Mountains (Morocco). Implications for the seismic Eurasia-Africa plate boundary region

Modelo de cabalgamiento profundo para el Alto Atlas (Marruecos). Implicaciones sísmicas en la zona de colisión entre Eurasia y Africa

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ABSTRACT

Previous crustal models of the High Atlas suppose the existence of a mid-crustal detachment where all the surface thrusts merged and below which the lower crust was continuous. However, both seismic refraction data and gravity modeling detected a jump in crustal thickness between the High Atlas and the northern plains. Here we show that this rapid and vertical jump in the depth of Moho discontinuity suggests that a thrust fault may penetrate the lower crust and offset the Moho (deep-rooted “thick skinned” model). The distribution of Neogene and Quaternary volcanisms along and at the northern part of the High Atlas lineament can be related to the beginning of a partial continental subduction of the West African plate to the north underneath Moroccan microplate. Allowing from the complex problem of the plate boundary in the western zone of the Mediterranean, we propose to interpret the South-Atlasic fault zone as the actual northwestern boundary of the stable part of the African plate rather than the Azores-Gibraltar fault currently used.

Key words: High Atlas, Moho, thick skinned model, subduction, Mediterranean plate tectonics, geophysical data.

RESUMEN

Los modelos geodinámicos existentes sobre la estructura profunda del alto Atlas suponen la existencia de un despegue medio-cortical donde convergen los cabalgamientos superficiales y bajo el cual la corteza inferior es continua. Los datos de sísmica de refracción y gravimetría, sin embargo, indican la existencia de una discontinuidad en el grosor de la corteza (profundidad del Moho) bajo el Alto Atlas.

En este artículo ponemos de manifiesto que este salto rápido en la profundidad del Moho puede ser causado por un cabalgamiento que penetra la corteza inferior, desplazando la base de la misma (“deep-rooted thick skinned model”).

La distribución del volcanismo Neógeno y Cuaternario a lo largo de y al norte de la alineación del Alto Atlas pueden estar relacionados con el comienzo de una subducción continental parcial de la placa Africana occidental hacia el norte, bajo la microplaca marroquí. La expresión en superficie de este cabalgamiento, la zona de falla sud-atlásica, refleja la influencia de una sutura continental heredada de orogenias anteriores (panafricana, hercínica y rifting Jurásico). Por tanto, proponemos que este frente heredado representa el límite meridional de la zona de colisión mediterránea y el margen noroccidental de la porción estable de la placa africana.

Palabras clave: Alto Atlas (Marruecos), Moho, modelo “thick skinned”, subducción, Tectónica de placa mediterránea, datos geofísicos.

Introduction

The Atlas Mountains of North Africa (known as the High and Middle Atlas in Morocco, the Saharan Atlas in Algeria and Tunisian Atlas in Tunisia) are considered as an intracontinental range and stretch unbroken for 2,000 km from the Atlantic in the West to Tunisia in the East (fig. 1). This is the largest

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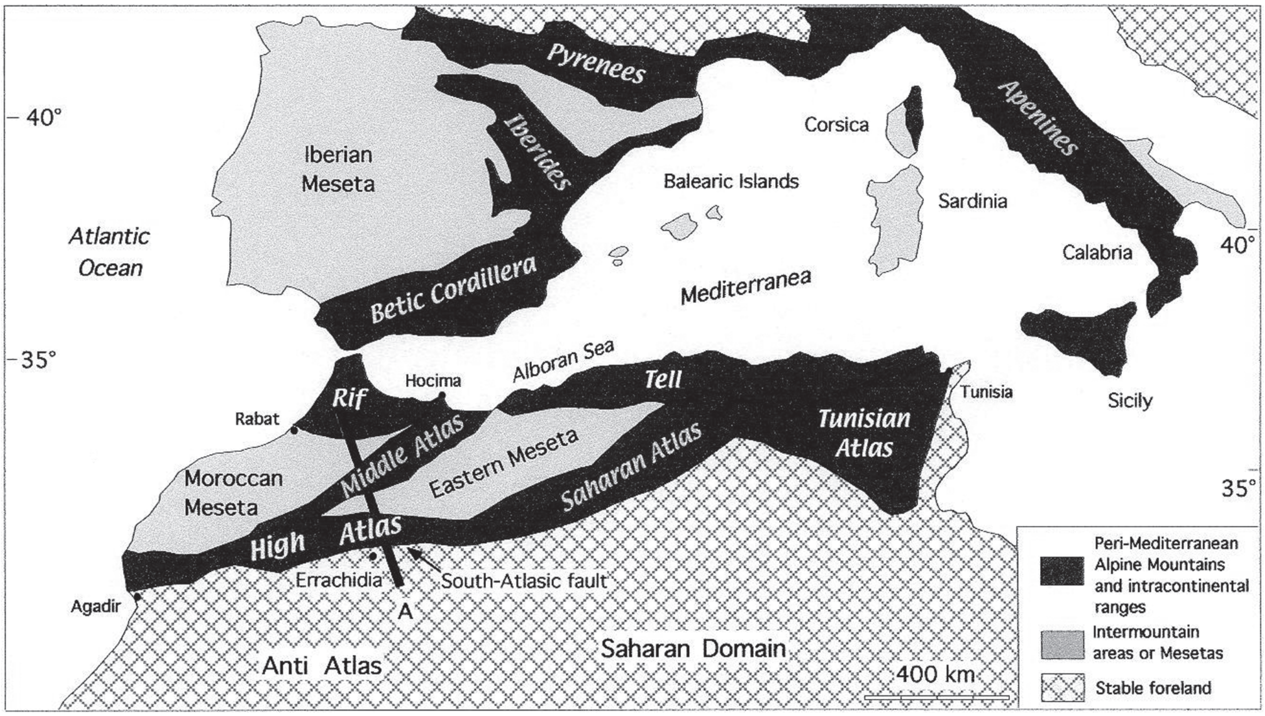

Fig. 1.—Sketch map of the western Mediterranean region showing the Atlas Range and the peri-Mediterranean alpine belt. A: cross sections of figures 2, 3 and 4.

Phanerozoic mountain range in Africa and it is similar in size and extent to the Appalachians and the Urals (Beauchamp *et al.,* 1999).

Four mountain ranges form the Atlas system of Morocco (fig. 1): —The Rif chain in the North faces the Mediterranean Sea; —The Anti Atlas, the southernmost Atlas chain, is a marginal updoming of the Precambrian West Africa craton which acted as stable crust during Alpine orogeny; —The Middle and High Atlas (Atlas belt) are developed from Mesozoic rift grabens. These rifts are reversed in Cenozoic times to form the present-day Atlas Range, which rises to 4,165 m, one of the highest peaks in the peri-Mediterranean Alpine system. These mountain belts are separated by two rigid and stable Palaeozoic blocks named: the Moroccan Meseta and the Eastern Meseta.

The Atlas Mountains (Middle and High Atlas) of Morocco is considered as an intracontinental range (Mattauer *et al.,* 1977; Laville, 1985; Giese and Jacobshagen, 1992; Beauchamp *et al.,* 1999; Piqué *et al.,* 2002) located in the foreland of the Mediterranean Alpine belt (Betic Cordillera, Rif, Tell, e.g., fig. 1).

The High Atlas is separated from the West African craton (Anti Atlas) by a clear physiographic boundary often referred to as the "South-Atlasic fault" ("SAF", Russo and Russo, 1934). It was generally accepted that this fault (or a system of faults) is an important geosuture zone, which extends for about 1,900 km from Morocco to Tunisia. Weijermars (1987) even proposed a prolongation to the Adana region in southeastern Turkey. Unfortunately, at present, we have no subsurface data on the prolongation of this "SAF" farther north. Do the flat-lying faults which constitute the overthrust continue far towards the north, under the Atlas, as suggested by Giese and Jacobshagen (1992), or are they actually rooted in a steeply dipping fault system which represents the edge of the pre-existing Mesozoic trough? (El Harfi, 2001; Chorowicz *et al.,* 2001; Piqué *et al.,* 2002).

The Atlas belt is a tectonically complex area and is a part of the Eurasia-Africa plate boundary region. The deformation of the overall region is dominated by the converging and colliding African and Eurasian continents. Since the 1970s many tectonic and geodynamic models have been proposed to account for the origin and the specific structure of the intracontinental Atlas Range. However, there seems to be little literature about the deep structural make-up of the Moroccan Atlas.

Better knowledge of the crustal structure in the Atlas system of Morocco is important to better

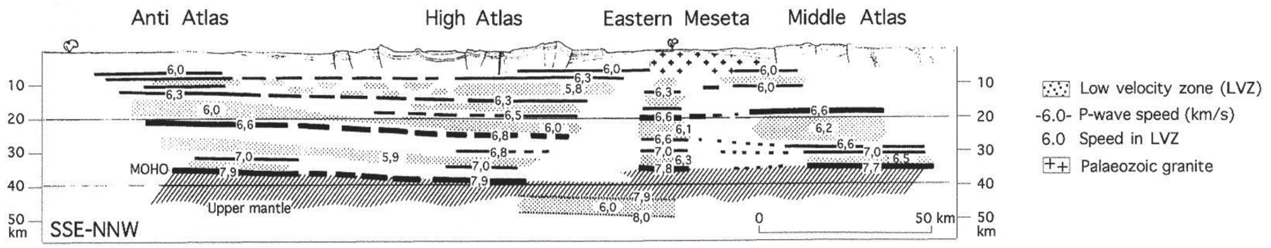

Fig. 2.—SSE-NNW crustal section of the High and Middle Atlas Mountains. The seismic refraction profiles along this section shows that the whole crust is strongly structured by alternating high and low seismic velocity zones (LVZ). Maximum crustal thickness (42 km) is found under the northern border of the High Atlas. The LVZs in the upper crust under the High Atlas dip slightly to the North, but a continuous transition to the NNW is not proven by the data. Note the presence of the subcrustal velocity inversion at 45-50 km depth between the lower crust and the upper mantle above the High/Middle Atlas (after Wigger *et al.,* 1992; e.g., fig. 1 for section location).

understand the past and present tectonic and geodynamic evolution in the Eurasia-Africa plate boundary region. A detailed crustal model will also improve the origin and the accuracy of locating local and regional earthquakes that might put Mediterranean people at risk. In this paper we’ll briefly expose and discuss the results of the seismological and electromagnetic data of the deep structure of the Atlas Mountain Range. Through a synthesis of recent structural and sedimentological results, we’ll present a comprehensive geotectonical model that crosses the High Atlas belt, and we’ll discuss the immediate far-reaching implications.

Compilation of geophysical data along a traverse crossing the High and Middle Atlas Mountains of Morocco

Seismic refraction studies

A compilation of the seismic refraction profiles along a NNW-SSE section (Wigger *et al.,* 1992; figs. 1 and 2) demonstrates that there exists a lateral variation in the distribution of the LVZs (Low Seismic Velocity Zones), and the maximum is beneath the northern part of the High Atlas, in the area of maximal crustal thickness. The LVZs in the upper crust under the High Atlas dip slightly to the North, but a continuous transition to the NNW is not proven by the data. Moreover, the observed seismic data cannot prove how far the LVZ’s sequences continue to the North beneath the Middle Atlas. Other major observation is the presence of the subcrustal velocity inversion and the LVZ at 45-50 km depth between the lower crust and the upper mantle above the High/Middle Atlas (fig. 2). This is supported by the relative low Pn velocity of 7.7-7.9 km/s.

Additional information has been recently obtained by receiver function studies of Sandvol *et al.* (1998) and Van der Meijde *et al.* (2003). The results of Van der Meijde *et al.* (2003) show that the Mohorovicic (Moho) discontinuity under Midelt (in the plains north of the High Atlas) is located at 39 km. Sandvol *et al.* (1998) found, in fact two velocity jumps, at 36 and 39 km; the shallowest one was interpreted by them as the crust-mantle boundary, whereas the deepest one remained uninterpreted.

Moho depth and crustal thickness

The recent result of the international MIDSEA (Mantle Investigation of the Deep Suture between Eurasia and Africa) project is the elaboration of a new map for the Moho discontinuity in the Eurasia-Africa plate boundary region (Marone *et al.,* 2003). The reliable results, obtained for the northern African coasts, show that the western part of the African continent is characterized by a rapid change from a relatively deep Moho (down to 42 km) below the Atlas Mountain Range to the thin crust (< 20 km) of the southwestern Mediterranean Sea. According to detailed Seismic refraction studies of Wigger *et al.* (1992), the crustal thickness beneath the High Atlas is about 35-40 km, being about 30-35 km in the peripheral plains (fig. 2). In comparison, deep seismic data for the Rif show that the Moho lies at a depth of 30-32 km in its central part and 20-25 km north of the Rif in the Alboran Sea (Michard *et al.,* 2002).

Gravity data and isostatic state

Gravity and magnetic data displayed together with digital topographic data were provided by Makris *et al.* (1985); Tadili *et al.* (1986) and Beauchamp *et al.*

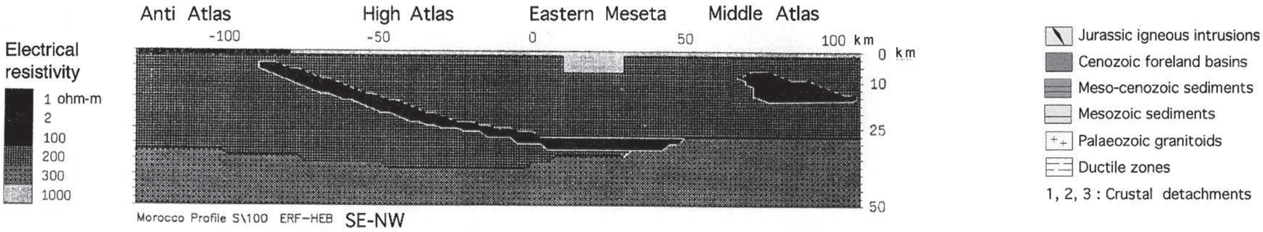

Fig. 3.—SE-NW electrical resistivity model across the High Atlas. Electrical resistivity of the middle and lower crust beneath the Anti Atlas was determined to about 200 ohm m, the same as for the lower crust of the High and Middle Atlas. The model has a highly resistive (1000 ohm m) uppermost mantle. This Model (S100) shows a rather steeply dipping high conductivity zone (HCZ), stretching from the southern border of the High Atlas almost down to Moho depth (36 km) beneath the Eastern Meseta and Middle Atlas (after Schwarz *et al.,* 1992; e.g., fig. 1 for section location).

(1999). Remarkable results of these investigations are the asymmetry of the High Atlas Mountains and the fairly homogeneous crustal thickness, without large crustal roots in spite of the high topography. As summits may exceed 4,000 m in the High Atlas and 3,000 m in the Middle Atlas, several authors have proposed that the Atlas Mountains are in an uncompensated isostatic state (Makris *et al.,* 1985; Gómez *et al.,* 2000). Recently, Seismic wide angle and receiver function results, obtained by Ayarza *et al.* (2005), have been used as constraints to build a gravity-based crustal model of the central High Atlas of Morocco. Ayarza *et al.* (2005) concluded that gravity modelling suggests moderate crustal thickening and a general state of Airy isostatic undercompensation.

Magnetotelluric investigations

The electrical resistivity structure of the crust and upper mantle of the Atlas Mountain System was studied by Schwarz *et al.* (1992) using magnetotelluric and geomagnetic deep soundings. The final electrical model (2D S100) obtained by Schwarz *et al.* (1992) shows a crustal low resistivity layer with total conductance (thickness-resistivity ratio) of about 2,000 Siemens which stretches from the southern border of the High Atlas towards the Middle Atlas (fig. 3). In this model, the highly conductive zone (HCZ) dips steeply northwards plunging deep into the upper mantle beneath the Eastern Meseta. This model suggests that there is a deep fault (or fault system) that may extend down to the upper mantle.

Proposal of a new geodynamical model

Previous crustal models of the High 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). However, several questions are left unanswered by these previous models. furthermore, what explanation is there for?:

— The occurrence of a ramp of upper mantle (a jump in crustal thickness, figs. 2 and 3) beneath the northern border of the High Atlas. This ramp is shown up both by electrical resistivity modelling (Schwarz *et al.,* 1992), seismic refraction data (Wigger *et al.,* 1992) and gravity modeling (Makris *et al.,* 1985).

— The origin of the subcrustal velocity inversion (LVZ), observed at 45-50 km depth, between the lower crust and the upper mantle above the High/Middle Atlas (fig. 2).

— The origin of the two receiver-function velocity jumps of Sandvol *et al.* (1998) and Van der Meijde *et al.* (2003). Their results show that the Moho discontinuity under Midelt is located at 36 and 39 km.

— The occurrence of a significant gravimetric anomaly (values of less than –150 mgal) for the southern slopes of the central and eastern High Atlas (Van den Bosch, 1971; Qureshi, 1986; Afrique 2002).

— The continuity of the LVZ layer at a depth of 10-20 km interpreted by Giese and Jacobshagen (1992) as horizontal detachment horizon. The observed seismic refraction data (fig. 2) cannot prove how far the LVZ layer in the upper crust under the High Atlas continues to the North beneath the Middle Atlas. Indeed, no continuous transition to the NNW is proven by the data.

These questions can be understood and solved with the adoption of the electrical model (HCZ, 2D S100) as geophysical solution for the interpretation of the deep structure of the High Atlas. Most probably, there is a clear correlation between

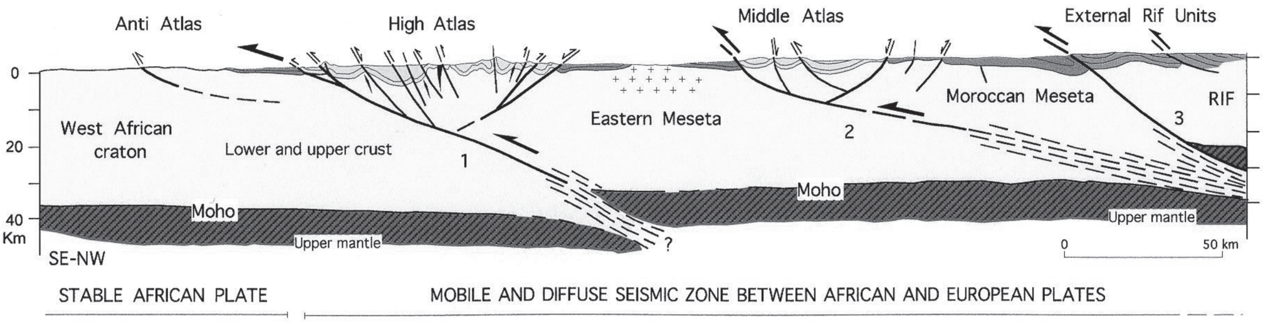

Fig. 4.—SE-NW Conceptual crustal section through the major intracratonic ranges of the Atlas System of Morocco: High Atlas, Middle Atlas and Rif (modified and adapted from Giese and Jacobshagen, 1992; e.g., fig. 1 for section location). The comprehensive crustal section of the High Atlas is based on available geological data and a reinterpretation of geophysical data (El Harfi, 2001). The transect is supplemented by data collected by: Bernini *et al.* (2000) for the Middle Atlas, Seber *et al.* (1996) and Michard *et al.* (2002) for the Rif and MIDSEA (Mantle Investigation of the Deep Suture between Eurasia and Africa) Project (Marone *et al.,* 2003) from the map of the Moho discontinuity.

the high conductive structure (HCZ), the jump in crustal thickness, revealed by seismic refraction data, and the southernmost boundary zone of the High Atlas chain (“SAF”). This crustal-scale thrust fault, whose existence was recently suggested by Ayarza *et al.* (2005) on the basis of gravity modelling, is also compatible with electrical resistivity modelling of Schwarz *et al.* (1992), and seismic refraction data of Wigger *et al.* (1992). In this solution, the conductive layer (HCZ), that can be interpreted as a zone of intense deformation with high fluid pressure, reaches Moho depths beneath the eastern Meseta.

These results provide a system which supports large crustal overthrusting events that has involved the whole crust under pure compression or transpressive deformation. This interpretation involves that the lower crust of the west African plate being overthrust (subduction) by the Moroccan and eastern Mesetas microplates, implying a crustal imbrication or a Moho duplication beneath the High Atlas.

The geometry of the large crustal faults and their extension at depth points to the occurrence beneath the northern border of the High Atlas of a deep lithospheric detachment, which roots in the lower crust and the upper mantle (fig. 4).

This is consistent with recent studies of Zeyen *et al.* (2005) and gravity data of Ayarza *et al.* (2005) which suggest that localized thickening appears restricted to the vicinity of a north-dipping crustal-scale thrust fault, that offsets the Moho discontinuity and defines a small crustal root which accounts for the minimum Bouger gravity anomaly values. Gravity modelling of Ayarza *et al.* (2005) indicates that this root has a northeasterly strike, slightly oblique to the ENE general orientation of the High Atlas belt.

This result is also consistent with studies which anticipate that the tectonic of the High Atlas may be at least partly due to the inversion of steeply deep and inherited extensional fault from the Jurassic rifting (Piqué *et al.,* 1987; Piqué and Michard, 1989; Laville and Piqué, 1991; Piqué *et al.,* 1998).

It was generally accepted that the “SAF” is an important geosuture zone originated in pre-Permian times, because Permian and Triassic basins extended only to the north of that line. Recently, Ennih and Liégeois (2001) concluded that, during the Pan-African orogeny, the northern limit of the West African craton was located at the “SAF”. Indeed, only regions located to the north of this fault have been strongly affected by Phanerozoic orogenies. This fault zone coincides, furthermore, with the southern margins of Jurassic marine troughs (Rod, 1962; Piqué and Michard, 1989; Gomez *et al.,* 2000). In the High Atlas, the inherited zone of crustal weakness (“SAF”) is sufficiently weak to create separate crustal blocks within the diffuse plate boundary (Gomez *et al.,* 2000; El Harfi, 2001; El Harfi *et al.,* 2006). Dewey *et al.* (1973) assumed that this fault was a dextral transcurrent fault which separated a Mediterranean microplate from Africa in Mesozoic times. Indeed, Weijermars (1987) included this fault into the plate tectonic concept for the Mediterranean region and connected it with the Hayes transform fault of the Atlantic Ocean.

In the Atlas range, which is a domain of moderate shortening, crustal thickness along the central High Atlas profiles cannot entirely explain the observed topography and therefore, these mountains are not isostatically compensated. It follows that isostatic compensation has not been reached, and that there must be some additional mechanism to support the High Atlas elevation that is unrelated to shortening and crustal thickening (Beauchamp *et al.,* 1999; El Harfi, 2001; Ayarza *et al.,* 2005). An explanation for this fact lies on topography being partly supported by a thin, hot and less dense lithosphere (Seber *et al.,* 1996). Strong lines of evidence are the existence of abundant alkaline volcanism in the Atlasic domain and the low P-wave velocities detected by Wigger *et al.* (1988) under the High Atlas. They suggest that the asthenosphere may occupy an anomalously high position helping to support the topography (Seber *et al.,* 1996; Zeyen *et al.,* 2005).

Finally, the occurrence of the subcrustal velocity inversion (LVZ), observed at 45-50 km depth, between the lower crust and the upper mantle, coupled with the distribution of Neogene and Quaternary volcanisms along and at the northern part of the High Atlas lineament, could be seen as a result of the beginning of a partial continental subduction of the West African plate under the Moroccan microplate (El Harfi 2001; Chorowicz *et al.,* 2001). In the same case of the High Atlas Mountains, the two receiver-function velocity jumps at 36 and 39 km of Sandvol *et al.* (1998), has been interpreted as a Moho duplication by Ayarza *et al.* (2005). Such geodynamical mechanism is also detected in lithospheric structure of other small Alpine orogenic belts (e.g., the Pyrenees; Souriau and Granet, 1995; Roure and Choukroune, 1998; Beaumont *et al.,* 2000; Vergés *et al.,* 2002).

In addition, Tertiary and Quaternary alkaline volcanism (Harmand and Cantagrel, 1984; Berrahma and Delaloye, 1989; Ibhi, 2000), has been identified in the Middle Atlas, the Moroccan Meseta, the eastern Meseta, the northern part of the High Atlas, and in the Anti Atlas. The tectonic context in which this volcanism appears is not fully understood yet and was explained by Harmand and Moukadiri (1986) as the result of upper mantle deformation which permitted partial melting in a compressive regime.

This interpretation is also supported by Hatzfeld and Frogneux (1981), Medina and Cherkaoui (1991), who describe the depth range of 30-55 km beneath the High/Middle Atlas contact area as a seismic gap continued by an active seismic zone down beyond 60 km. Although, the authors cannot exclude the possibility that deep seismicity in this region represents the remains of subducting crust.

The Atlas belt in the Mediterranean Collision Zone (MCZ)

Cenozoic plate motions across the Mediterranean region have previously been determined using Atlantic Ocean magnetic anomalies and closing the Africa-North America-Eurasia plate circuit (Dewey *et al.,* 1989). Plate motions in this region have been accommodated over a broad zone comprising the Atlas Mountains as well as the Alpine chains along the Mediterranean coast. The recent work on the timing, kinematics of the positive inversion and magnitude of shortening (Beauchamp *et al.,* 1999; Gomez *et al.,* 2000; El Harfi, 2001; El Harfi *et al.,* 2001) suggest that the High Atlas belt accommodated a significant fraction (17%-45%) of the plate convergence between Europe and Africa from the beginning of Eocene times.

The comparison of the deformed and restored sections of the High and Middle Atlas (Beauchamp *et al.,* 1996, 1999) yields an Alpine shortening of some 36 km for this transect of the African plate, distributed in 31 km for the High Atlas and 5 km for the Middle Atlas, the latter being a value comparable to that previously obtained by Gomez *et al.* (1998). As demonstrated by the balanced cross section of Beauchamp *et al.* (1999), overthrusting at the margins of the central High Atlas nearly triples the magnitude of horizontal shortening across the 105 km wide mountain belt from 10% to 25%. Overthrusting is significant because it permits the High Atlas range to accomodate considerably more horizontal shortening, involving steep faults. The thrust system of the High Atlas, which accommodates most of the shortening, is interpreted to penetrate into the deep crust and offset the Moho discontinuity, with a predominantly southern vergence. If the High Atlas Mountains has accommodated such a large fraction of the total plate convergence, then it should more properly be regarded as a significant element of the wide plate-boundary zone in the western Mediterranean.

It has previously been recognised that stable forelands in Africa and Europe are separated by a broad intensively Alpine deformed zone, referred to here as the Mediterranean Collision Zone (MCZ, fig. 5; Dewey *et al.,* 1973; Weijermars, 1987; Gomez *et al.,* 2000). This later involves several stable and rigid microplates (Moroccan Meseta, Eastern Meseta, Iberian Meseta, Alboran block...) which can be interpreted in a fashion similar to the impingement of the Indian plate with Tibet before

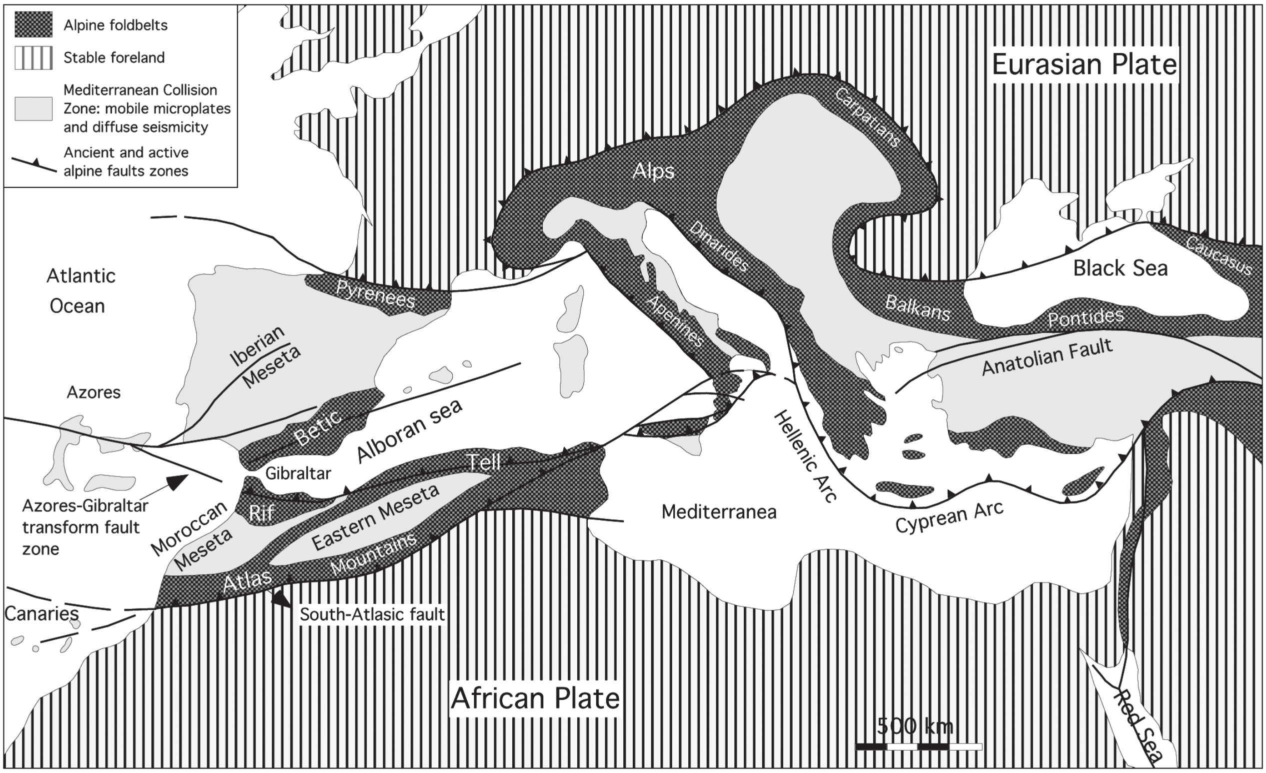

Fig. 5.—Tectonic map of the seismic Mediterranean Collision Zone (MCZ) between the African and Eurasian plates (modified and adapted from Weijermars, 1987). The northern boundary of this zone is outlined by the Pyrenees, Alps, Carpats, Balkan Chain and Caucasus. The former southern boundary of this zone coincides approximately with Hellenic-Cyprean subduction Arcs and the Azores-Gibraltar transform fault zone. We propose in this paper to define the South-Atlasic fault lineament (geosuture) as the present southern boundary of the MCZ (northwestern boundary of the African Plate) than the Azores-Gibraltar fault currently used. This new limit explains clearly the still nowadays seismicity and the widely scattered distribution of earthquake foci localized to the North of the High Atlas lineament (Western Mediterranean Collision Zone).

continental collision. The northern boundary of this zone is outlined by the Pyrenees, Alps, Carpats, Balkan Chain and Caucasus (fig. 5). The southern boundary coincides approximately with Hellenic-Cyprean subduction Arcs and the Azores-Gibraltar transform fault zone.

In spite of the Azores-Gibraltar seismicity clearly outlines the Eurasian-African plate boundary, a diffuse and scattered distribution of earthquake foci is recognized beyond this southern limit until the borders of the High Atlas chain (Thio *et al.,* 1999, Buforn *et al.,* 2004). Seismicity in this region is associated with the plate boundary and may be correlated with the main geological structures present in the area. Consequently, we propose to extend the southern limit of the MCZ to the South-Atlasic fault (subduction feature) lineament than the Azores-Gibraltar fault currently used (fig. 5). Plate kinematic models for the region have estimated convergence rates from 4mm/yr at the West to 7.6 mm/yr in the East along the western plate boundary between Eurasia and Africa (Buforn *et al.,* 2004; Argus *et al.,* 1989). The MCZ is also characterised by the mobility of the rigid and involved blocks (Moroccan Meseta, Eastern Meseta, Iberian Meseta...) which is responsible for recent deformation and uplifting of the Atlas Mountains and the Pyrenees. Furthermore, as indicated by field evidence (Morel *et al.,* 1993; 2000) and still nowadays seismicity (Argus *et al.,* 1989; Cherkaoui, 1991; Medina and Cherkaoui, 1991; Buforn *et al.,* 1995; Sébrier *et al.,* 2006), convergence and deformation in the Atlas system of Morocco continue until present times.

Conclusions

Another interpretation of the geological data is therefore presented here. The vertical jump in the depth of the Moho across the High Atlas, reported by Wigger *et al.* (1992), coupled with the occurrence of the subcrustal velocity inversion (LVZ), observed at 45-50 km depth, can be interpreted as a beginning of a partial continental subduction feature (crustal imbrication or a Moho duplication). The dip of the fossil plate which could explain the abrupt displacement of the Moho would be northward and agree with the subduction directions beneath the Pyrenees and Alps. The continental collision of Iberia and Europe produced the formation of the Pyrenean orogen with a partial subduction of the Iberian lithosphere to the north (Muñoz, 1992; Roure and Choukroune, 1998; Beaumont *et al.,* 2000). This possibility was confirmed by the magnetotelluric survey along the ECORS profile (Vacher and Souriau, 2001). These studies shows a steep north-dipping, high conductivity body, which reaches a depth of about 70 km and has been interpreted as subducted partly melted lower crust and lithospheric mantle.

Allowing from the complex problem of the plate boundary in the western zone of the Mediterranean, we propose to interpret the "SAF" zone as the actual northwestern boundary of the stable part of the African plate as proposed by Dewey *et al.* (1973) and Weijermars (1987). However, the importance of a purely strike-slip component evoked by the latter workers and by Mattauer *et al.* (1977) to explain the Alpine structuring of the High Atlas is not supported by recent fault kinematic results (Jacobshagen, 1992; Errarhaoui, 1998; Beauchamp *et al.,* 1999; El Harfi 2001; El Harfi *et al.,* 2001).

The problem of the significance of the "SAF" zone is thus currently posed in this way: Strike-slip faultings or overthrustings?. Either it is a succession of strike-slip faults of variable orientation and displacement, or it could be a set of thin-skin overthrusts directed towards the south. It is not certain whether these two interpretations are mutually exclusive, since the South-Atlasic boundary can react differently from one section to another as a function of the pre-existing segmentation. In any case, additional studies and reflection seismic surveys remain necessary in this area to highlight and clarify the deep structure of the High Atlas and to specify the trajectory and the prolongation of the "SAF".

Unfortunately, research groups studying active faults and seismicity in the Western Mediterranean do not include the High Atlas in their programmes. Nevertheless, better knowledge of the crustal structure in the Atlas system of Morocco is important not only for solving the complex nature of the plate boundary between Africa and Eurasia but also to increase the accuracy of predicting earthquakes that might put Mediterranean people, particularly in Spain, France, Portugal, Morocco, Algeria and Tunisia, at risk.

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