Journal of the Geological Society, London, Vol. **153**, 1996, pp. 389–402, 9 figs. Printed in Northern Ireland

Active tectonism in the intracontinental Middle Atlas Mountains of Morocco: synchronous crustal shortening and extension

FRANCISCO GOMEZ[1], MUAWIA BARAZANGI[1] & MOHAMMED BENSAID[2]

[1]*Institute for the Study of the Continents and Department of Geological Sciences, Snee Hall, Cornell University, Ithaca, New York 14853, USA*

[2]*Direction de la Geologie, Ministere de L'Energie et des Mines, Agdal-Instituts, BP 6208, Rabat, Morocco*

Abstract: Geological field observations are integrated with digital topography, LANDSAT imagery, and earthquake focal mechanisms to investigate the Middle and Late Quaternary tectonism in the intracontinental Middle Atlas mountain belt in northern Morocco. The NE–SW-trending Middle Atlas Mountains, approximately 80 km in width and about 200 km long, are part of the Atlas system of northwestern Africa and represent an inverted rift that developed into an intracratonic mountain system in the foreland of the Alpine collisional zone. The Middle Atlas is composed of two provinces, the Folded and Tabular Middle Atlas, representing the palaeo-rift and a flank of the palaeo-rift, respectively. Evidence for Late Quaternary tectonism is provided by the analysis of stream morphology in addition to geological relations. Kinematic analysis of fault-slip data and earthquake focal mechanisms demonstrate the coexistence of both extensional and compressional deformation in different areas of the Middle Atlas with a common sinistral component of slip along NE–SW-striking fault zones. Compressional features dominate the Folded Middle Atlas, whereas extension predominates in the Tabular Middle Atlas. Extension is also manifested by widespread Middle to Late Quaternary alkali volcanism. The observed kinematic variations appear to correlate with the Mesozoic palaeogeography; one possible model may involve tectonic escape. This suggests that differences in the structures inherited from the Mesozoic and Palaeozoic may influence the responses of the different regions to the Cenozoic Alpine collision between Europe and northwest Africa.

Keywords: Morocco, neotectonics, intracontinental belts, kinematics, digital cartography.

One of the most prominent examples of an active intracontinental mountain belt is the Atlas system of North Africa, a 2000 km long mountain chain that developed in the foreland of the Cenozoic Alpine collision. Intracontinental mountains such as the Atlas, the Palmyride Mountains of Syria, and the Tien Shan in central Asia are located at considerable distances inboard of their respective plate boundaries and commonly involve reactivated basement structures (e.g., Rodgers 1987; Letouzey 1990). They are further characterized by the absence of several diagnostic features present in typical interplate mountains, including nappe structures, ophiolites, regional metamorphism, and granitoid intrusions. This study takes a multidisciplinary approach to examine kinematic aspects of active tectonics in the Middle Atlas region of Morocco. The NE–SW-trending Middle Atlas Mountains are located 200–300 km east of the Atlantic coast, and they mark the transition between the interplate Betic-Rif and the intraplate High Atlas mountain systems (Fig. 1). The Middle Atlas and High Atlas belts are inverted Mesozoic rift systems (Mattauer *et al.* 1977). These mountain belts together with the Rif collectively evolved in response to the convergence of the African and Eurasian plates (e.g., Jacobshagen *et al.* 1988; Brede *et al.* 1992) which resulted in a complex collisional plate boundary separating Africa from continental Europe.

Transpressive tectonics are believed to be presently involved in the Middle Atlas (e.g., Jacobshagen *et al.* 1988). A left-lateral component of motion along the North Middle Atlas fault (Fig. 2) has been reported by Brede & Heinitz (1989) and Scheele (1992). However, the nature of present-day deformation has not been well constrained. Based on published seismicity maps (e.g., Hatzfeld & Frogneux 1981; Tadili & Ramdani 1983; Ben Sari 1987), it can be observed that the Middle Atlas marks the central segment of a linear band of seismicity extending from the Agadir region along the Atlantic seaboard to the Mediterranean coast with a notable cluster of events in the southwestern part of the mountain belt. On this basis, Jacobshagen (1992) speculated on the role of the Middle Atlas as part of the discontinuous, left-lateral trans-Alboran fault system suggested by Hernandez *et al.* (1987) to extend from North Africa into southern Spain. For such a large scale synthesis, a better understanding of the kinematics is essential, and this can be studied using earthquake focal mechanisms and Quaternary fault-slip data.

In this paper, we examine the Middle Atlas segment of the proposed trans-Alborn fault system. Field observations and stream morphology are used to document the activity of major faults within the Middle Atlas. We then combine new observations of fault-slip data with other published data and earthquake focal mechanisms to summarize the active kinematics. In addition, we use digital topography and LANDSAT imagery to distinguish structural differences between two major tectonic provinces within the Middle Atlas defined by Martin (1981). Finally, we relate these observations to regional tectonics in a kinematic model involving synchronous shortening, extension, and possible tectonic escape in Morocco.

Geological setting

The geological history of the Middle Atlas Mountains can be traced at least as far back as the Triassic, when the area was undergoing rifting associated with the opening of the

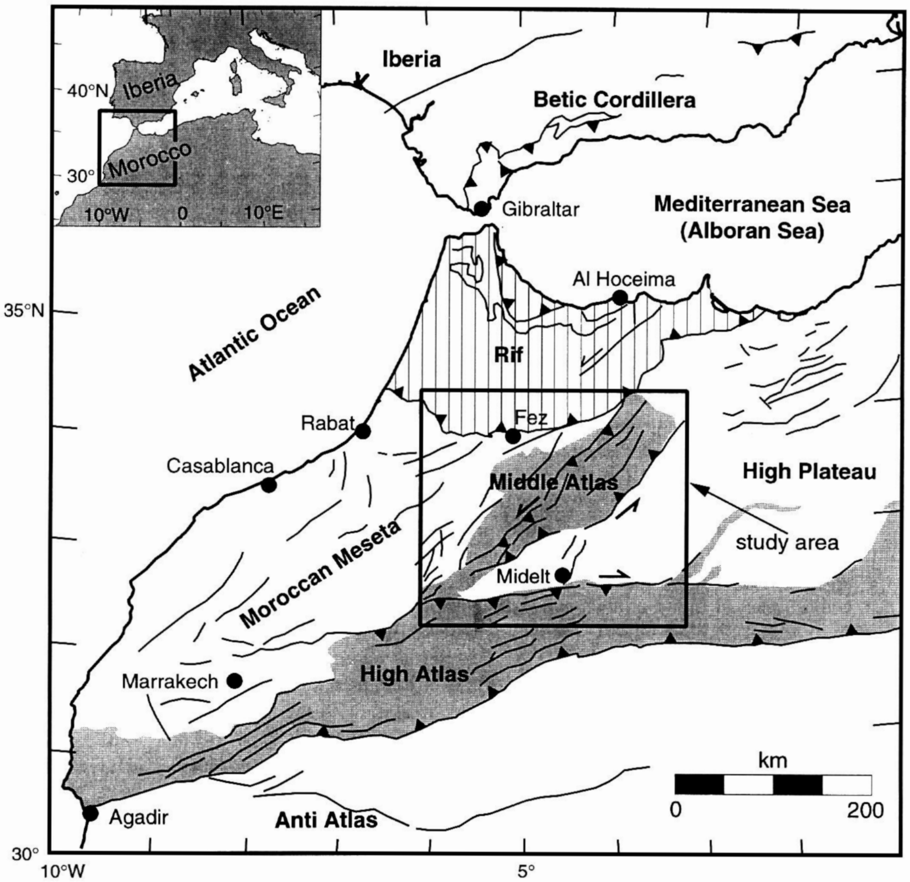

Fig. 1. Map of northern Morocco showing major structural and physiographic features. Modified from Medina & Cherkaoui (1992).

Atlantic ocean (e.g., Brede *et al.* 1992) and possibly western Tethys (Jacobshagen *et al.* 1988). Mattauer *et al.* (1977) and Laville & Piqué (1991) suggested that rifting was guided by pre-existing fractures inherited from the Palaeozoic Hercynian orogeny and evolved as pull-apart structures due to strike-slip movement along the Azores–Gibraltar fault (Laville 1981). The North Middle Atlas and the South Middle Atlas faults (see Fig. 2) were activated as the main rift-bounding faults of the Middle Atlas rift (Fedan 1988). This suggestion is supported by the deposition in the Folded Middle Atlas region (see Fig. 2) of thicker and deeper basin facies during the Early Jurassic (Du Dresnay 1988). Herbig

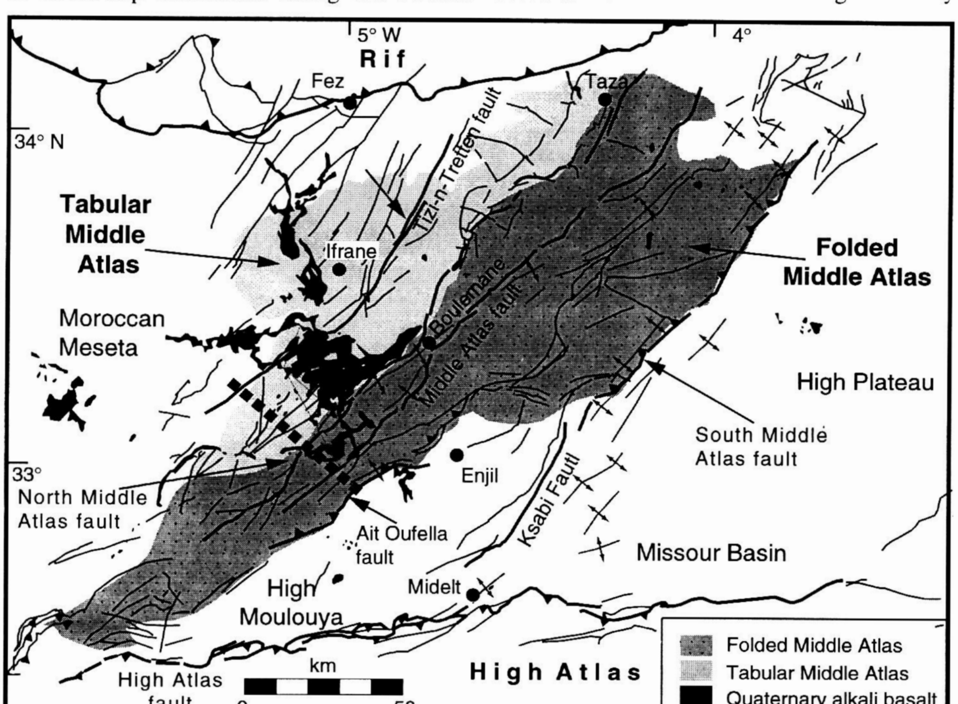

Fig. 2. Map of Middle Atlas region depicting faults (mapped from LANDSAT imagery in the Middle Atlas; from Faure-Muret *et al.* (1994) in other regions) and Quaternary basalt (dark gray). Anticlinal ridges parallel each of the major faults (heavy dark lines) within the Folded Middle Atlas. The boundaries of the geomorphic provinces are based on the descriptions by Martin (1981) and Du Dresnay (1988). The heavy dashed line depicts the approximate location of the schematic cross section in Fig. 3.

(1988) suggested that a gradual, constant uplift commenced during the Mid- to Late Jurassic, based on the appearance of gentle, progressive unconformities, but the main episode of uplift of the Middle Atlas began during Neogene time, probably in the late Miocene (e.g., Charrière 1981; Martin 1981; Brede *et al.* 1992), and this activity has continued through to the Quaternary. The existence of a mid-crustal decollement has been suggested on the basis of resistivity modelling (e.g., Schwarz & Wigger 1988; Giese & Jacobshagen 1992) whereas other workers have suggested crustal scale strike-slip faults (e.g., Hernandez *et al.* 1987; Bernini *et al.* 1994)

The Middle Atlas Mountains can be divided into two geomorphological provinces (Fig. 2): the Tabular Middle Atlas in the northwest and the Folded Middle Atlas in the southeast (Martin 1981). The northwest boundary between the Tabular Middle Atlas and the Moroccan Meseta is a topographic feature. The meseta has a general westward slope and a noteworthy change in elevation. This corresponds with the outcropping of Hercynian metamorphic rocks. Thus, the boundary between the two provinces is the Palaeozoic–Mesozoic unconformity. The Tabular Middle Atlas is characterized by generally sub-horizontal calcareous rocks of Jurassic and Cretaceous age, and this subdued structure results in the relatively flat topography that is observed. Furthermore, much of the Tabular Middle Atlas is covered by a veneer of Quaternary alkali basalts, and in these areas the landscape is covered by recent volcanic constructs. The boundary between the Tabular and Folded Middle Atlas corresponds in general with the North Middle Atlas fault (Fig. 2). The structure of the Folded Middle Atlas is more dramatic, an observation also reflected in the topography. Four long anticlinal ridges span significant lengths of the Folded Middle Atlas (Colo 1964). These folds lie subparallel to the North Middle Atlas, Ait Oufella fault, South Middle Atlas , and Middle Atlas faults. The thickening of the Middle Jurassic sedimentary rocks away from the crests of anticlinal ridges suggests a Mesozoic origin for some these folds (Du Dresnay 1988). The southeast boundary of the Folded Middle Atlas is the South Middle Atlas fault along the Missour Basin and the Ait Oufella fault along the High Moulouya Rise (Fig. 2). The High Moulouya Rise is considered by some (e.g., Du Dresnay 1988) to be part of the Middle Atlas system and is geomorphically similar to the Tabular Middle Atlas. It is a flat region characterized by sub-horizontal strata. It is bounded on the east by the Ksabi fault and the High Plateau/Missour Basin. Figure 3 shows a schematic regional cross section across the central Middle Atlas from the Moroccan Meseta to the High Moulouya Rise. Both apparent reverse and normal displacements are observed, and it is one purpose of this paper to provide evidence as to which of these faults may be active and in what manner.

Quaternary alkali volcanism is one of the prominent neotectonic features of the area (Fig. 2). The composition of these extrusive rocks ranges from basanite to alkali basalt (Morel & Cabanis 1993). They cover an area of about 1500 km^2 and are predominantly situated within the Tabular Middle Atlas, although lesser amounts of basalt are present within the Folded Middle Atlas and the High Moulouya Rise. Harmand & Cantagrel (1984) obtained K–Ar ages ranging from 1.5 Ma to 0.5 Ma from these rocks. The timing of the oldest eruption coincides with the beginning of the present regional stress field in the Rif as reported by several workers (e.g., Aït Brahim & Chotin, 1984; Morel 1989). Du Dresnay (1988) noted that the volcanic centres are approximately aligned in a NNW–SSE direction, parallel to the trend of the present-day orientation of the maximum principal stress (Aït Brahim & Chotin 1984). This is also parallel to the approximate direction of convergence between North Africa and Iberia predicted by the global plate circuit models (e.g., DeMets *et al.* 1990) for the past 2–3 Ma. However, in the northern part of the Middle Atlas and continuing into the Guercif Basin, volcanic centres align along the NE–SW-trending crests of anticlines, and it has been suggested that these are related to crustal scale strike-slip faults (e.g., Hernandez *et al.* 1987; Bernini *et al.* 1994).

Data

In this section, the different datasets utilized in this study are described. Discussions of the analytical methods are saved for the appropriate sections with the results.

Structural measurements of Mid–Late Quaternary faulting provide the database for a fault kinematic analysis. Quaternary fault slip measurements were collected during field work conducted over the summer of 1994. The sense of shear along fault surfaces was determined primarily by the examination of calcite steps and tool marks on slickensides observed within fault zones. The age constraints of our fault slip data are derived from the existing geological maps for the Middle Atlas (see Fig. 5 for locations). Along the Tizi-n-Tretten fault and North Middle Atlas fault, we measured the most recent movement on fault surfaces along segments which truncate these mapped, middle Quaternary deposits. Thus, the observations represent the late Quaternary activity of these faults. In addition, other published data for the region (Morel *et al.* 1993) have been incorporated. To complement the fault-slip data analysis, published focal mechanisms for crustal earthquakes (Tadili & Ramdani 1986; Medina & Cherkaoui 1992) are included in the kinematic study.

Regional geomorphological analyses were facilitated by digital data sets of topography and LANDSAT Multi-Spectral Scanner (MSS) imagery. The topographic data set has a horizontal resolution of about 90 m and a vertical resolution of about 25 m and is of comparable resolution to the 30 min digital elevation models (DEMs) available from the US Geological Survey. The 80 m horizontal resolution of MSS data is comparable to that of the digital topography. Where possible, existing geological maps (e.g., Carte Geologique du Maroc 1985) of the study area have been digitized for ease of manipulation in the study.

Evidence for neotectonic activity

In order to study the Quaternary and recent fault kinematics, it is necessary to identify which faults have been active recently. Most of the earthquakes in the Middle Atlas are small ($M < 4.0$) and consequently have poorly constrained epicentre locations. As a result, the modern tectonic activity cannot easily be attributed to specific faults without further evidence of activity. However, there is much field evidence for Neogene and Quaternary faulting within the Middle Atlas. We observed the Tizi-n-Tretten fault (north of Ifrane) and the North Middle Atlas fault (north of Boulemane) truncating Quaternary travertine and colluvial deposits in several locations. The Ait Oufella fault places altered Triassic basalts over Early Quaternary conglomerates in the southern part of the Middle Atlas. Similar observations have been documented in the Middle Atlas by

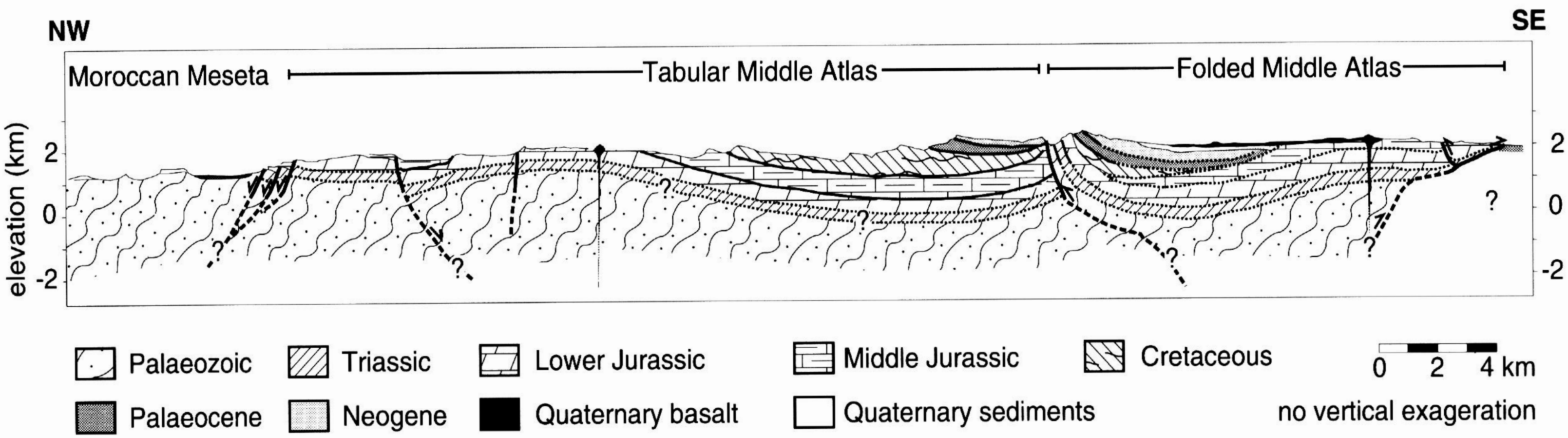

Fig. 3. Schematic regional cross section of the central Middle Atlas region (modified from Martin 1981).

Fedan (1980), Charrière (1981), Martin (1981), and Fedan & Thomas (1986), and along the High Atlas by Morel *et al.* (1993). Evidence for uplift along the North Middle Atlas fault is also provided by deposition at the head of large alluvial fans which suggests that the rate of uplift is greater than the rate of discharge from the mountain front (Keller 1985). A large alluvial fan located west of Boulemane along the western front of the Folded Middle Atlas is spectacular example of such a feature, and is easily observed in aerial photographs.

Despite the accessibility and prominence of the Middle Atlas region, very few quantitative studies focusing on the neotectonics and active structures have been published. Offset geological features are extremely rare; however, Fedan & Thomas (1986) reported that a Quaternary lava flow west of Boulemane had been truncated by a small fault associated with the North Middle Atlas fault zone. This feature can be observed in air photos with an apparent left-lateral offset of 80 m. As a consequence of poor age control and the lack of suitable piercing points, slip magnitudes and rates along the faults have been poorly constrained. Fedan & Thomas (1986) and Brede & Heinitz (1989) noted evidence for Neogene activity along the North Middle Atlas fault, but the age constraints were very broad. Scheele (1992) reported folding of Eocene gypsum about vertical axes consistent with sinistral deformation. Morel *et al.* (1993) studied the Neogene–Quaternary evolution of the High and Middle (Missour Basin) Moulouya basins, including the Ait Oufella fault in the southern Middle Atlas. Citing evidence for left-lateral along the Ait Oufella and Ksabi faults and right-lateral slip along the High Atlas fault, they suggested a possible model similar to tectonic escape (e.g., Burke & Sengöer 1986) for the Missour Basin/High Plateau region.

Stream analysis

Stream morphology can also be used to identify evidence for recent fault activity. Longitudinal stream profiles are examined here to provide qualitative evidence of uplift where the rate of uplift exceeds that of erosion. Stream profiles have been used by many authors to identify areas of active uplift along major plate boundaries (e.g., Seeber & Gornitz 1982; Merritts & Vincent 1989) and intracontinental settings (e.g., McKeown *et al.* 1988; Rhea 1988). Convex inflections in stream profiles are believed to reflect changes in the nature of the stream with respect to (1) increase in discharge, (2) significant changes in lithology over which the stream is flowing, or (3) localized tectonic uplift. For such studies, low order streams (first- and second- order according to the method of Strahler 1957) are typically selected, as these streams provide the best indications of slow uplift since they require more time to adjust to a relative change in base level than higher order streams (Merritts & Vincent 1989). The streams selected for this study (Fig. 4a) typically consist of one major trace (not many tributaries), and there are no severe climatic gradients along the profiles (Martin 1981). Significant inflections in the profiles observed do not coincide with anything indicative of increased stream discharge, and we selected streams that cross the main faults but generally remained within similar lithologic units. Based on these criteria, most perturbations in the stream profiles are probably associated with tectonic activity, especially if the inflections coincide with the presence of independantly mapped faults.

The drainage network (Fig. 4a) was extracted from the digital topography by calculating the watershed surface and local flow directions using standard algorithms provided by ARC/INFO geographic information system (GIS) software. Preprocessing of the data included the filling of sinks to remove the effects of minor artefacts in the data. Once the streams were mapped, they were assigned stream orders according to the method of Strahler (1957). Appropriate streams were selected for the study by combining the stream map with digitized geological maps. To produce each profile, elevation points from the topographic data set were selected every 250 m along each selected stream. This analysis was performed on 22 streams in the Middle Atlas region, highlighted in Fig. 4a.

Figure 4b shows five typical profiles that cross the main fault zones of the Middle Atlas. For comparison, one unfaulted profile (Profile F) flowing westward off the High Plateau is included as an example of an unperturbed stream profile crossing unfaulted Jurassic carbonate sediments. The first inflection in profile E corresponds with a lithological change from calcareous limestone to gypsiferous shale, and such a change in lithology can result in significantly different slopes due to differences in erodability of the rock types (e.g., McKeown *et al.* 1988). The locations of the North Middle Atlas fault, Ait Oufella fault, South Middle Atlas fault, and Tizi-n-Tretten fault are denoted on the appropriate profiles, and it can be observed that these coincide with inflections in the streams. These inflections are consistent for all studied profiles crossing the same structure. For example, the profiles crossing different sections of the Tizi-n-Tretten fault (profiles B & D) both show large convex inflections where they cross the fault. This observation strengthens the interpretation that these are true perturbations and not the results of local errors in the topographic data set. These stream profiles indicate recent uplift along the North Middle Atlas, South Middle Atlas, Tizi-n-Tretten, and Ait Oufella fault zones.

Drainage pattern anomalies may also reflect fault activity (e.g., Wallace 1968; Allen *et al.* 1984). A regional analysis of northern Morocco was performed by Deffontaines *et al.* (1992). Using streams from 1:500 000 scale topographic maps, they classified regions of neotectonic activity and identified major faults. This type of study, however, only uses the large streams, and these drainage anomalies reflect a longer tectonic history. While the digital topography is more accurate than 1:500 000 scale topographic maps, it is not satisfactory for identifying discrete offsets, which would provide a more constrained analysis. Consequently, such an analysis is not attempted with the extracted map.

Field observations and analysis of stream morphologies provide evidence for recent uplift in the Middle Atlas. Recent deformation is observed in the Tabular Middle Atlas as uplift along the Tizi-n-Tretten fault, as well as in the Folded Middle Atlas. In order to provide a better understanding of the possible mechanisms responsible for the uplift, we will integrate these observations with a kinematic analysis of fault-slip data from the respective fault zones.

Fault kinematics and nature of deformation

Fault slip data provide a quantitative means of analysing the nature of neotectonic processes. The data for such analysis comprise the fault plane orientation, fault slip direction, and

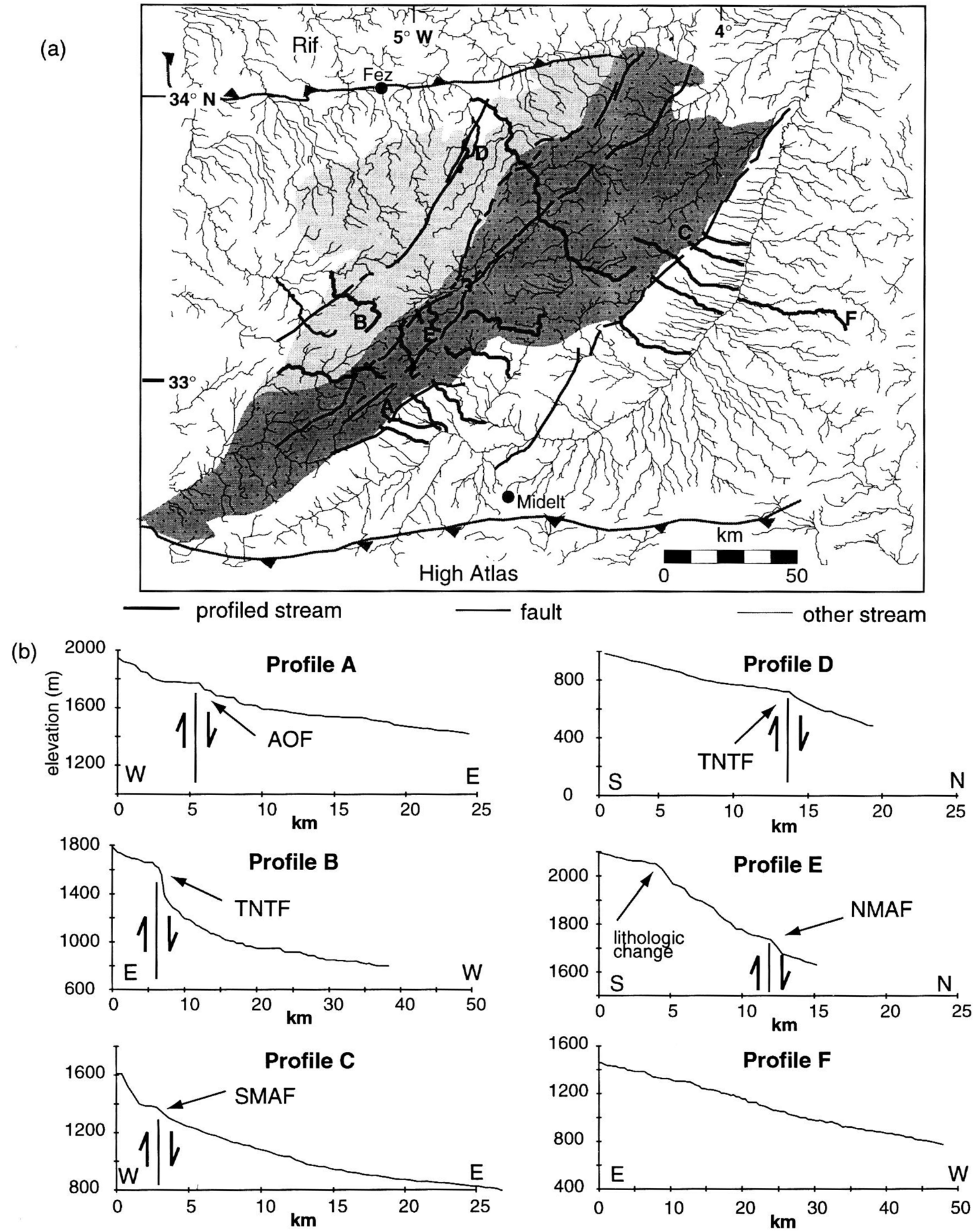

Fig. 4. (**a**) Map of stream network for the Middle Atlas region extracted from the digital elevation model (DEM) with main faults from Fig. 2; and (**b**) selected stream profiles. Fault zones are denoted with vertical lines on the profiles, as the stream profiles do not describe the dip of the fault plane.

sense of shear. There have been several studies in Morocco using dynamic analysis of fault-slip data (e.g., Aït Brahim & Chotin 1984; Morel 1989) to reconstruct palaeostress histories. While these methods provide information about mean stress tensor orientations, they do not directly describe the deformation without *a priori* knowledge of the fault zone geometry. For a regional kinematic analysis, such as this, the method of geometric moment tensor summation discussed by Marrett & Allmendinger (1989) provides a useful quantitative procedure. By employing this method, variations in the styles of deformation can be observed within the Middle Atlas. Since we are examining Mid–Late Quaternary deformation, the active fault kinematic results can be combined with existing crustal earthquake focal mechanisms to create a larger database.

For the kinematic analysis, the fault-slip data are

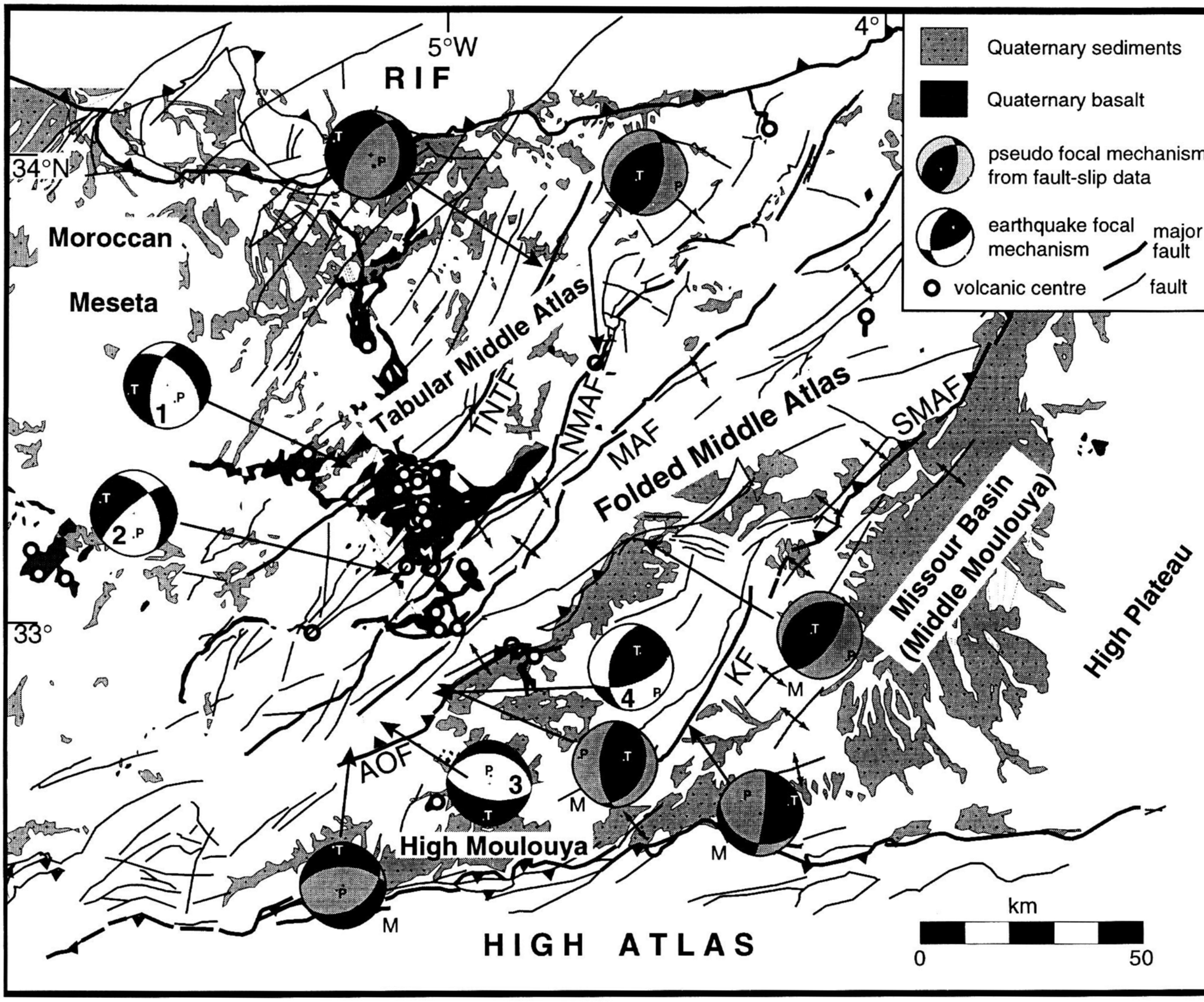

Fig. 5. Active fault kinematics of the Middle Atlas based on analysis of fault-slip data and earthquake focal mechanisms. Focal mechanisms are plotted as equal area and lower hemisphere projections. Focal mechanisms 1 (M 4.5, $h = 12$ km), 2 (composite focal mechanism), and 4 (M 4.0, $h = 7$ km) are from Medina & Cherkaoui (1992). Focal mechanism 3 (M 4.4, $h = 21$ km) is from Tadili & Ramdani (1986). Fault-slip results labeled 'M' incorporate data from Morel *et al.* (1993). The major faults are shown with heavy black lines and labeled as follows: TNTF, Tizi-n-Tretten fault; NMAF, North Middle Atlas fault; MAF, Middle Atlas fault; SMAF, South Middle Atlas fault; AOF, Ait Oufella fault; KF, Ksabi fault.

converted into 'P' and 'T' axes for each observation, which represent the infinitesimal shortening and extension axes, respectively. These axes are located at 45° to both the slip vector and pole of the fault plane. Ten to twelve measurements for each location were then geometrically summed in a manner similar to seismic moment tensor summation (Marrett & Allmendinger 1989). Marrett & Allmendinger (1989) have demonstrated scale-invariant (fractal) behavior of fault kinematic data, and so each measurement was given equal weighting. The resulting strain axes are depicted as fault-plane solutions for comparison with earthquake focal mechanisms in Fig. 6.

Using the fault kinematic results and published earthquake focal mechanisms (e.g., Tadili & Ramdani 1986; Medina & Cherkaoui 1992) the kinematics of the Middle Atlas are summarized in Fig. 5 along with the mapped structures. The kinematic analysis of earlier data (from Morel *et al.* 1993) shows some differences from the original analysis. For example, along the Ait Oufella fault, the kinematic analysis suggests predominantly thrusting whereas the original dynamic analysis was used to suggest sinistral shear (Morel *et al.* 1993). The thrusting is more consistent with mesoscopic structures observed in the field. Fault-slip data and earthquake focal mechanisms show noteworthy consistency where they overlap. The data provide enough regional coverage to identify a significant difference between the Tabular and Folded regions. All of the data indicate a minor left-lateral component of movement along the northeast striking fault planes. However, the Tabular Middle Atlas data demonstrate a component of extension along the Tizi-n-Tretten fault zone, while the three strain axes in the Folded Middle Atlas show reverse faulting. The

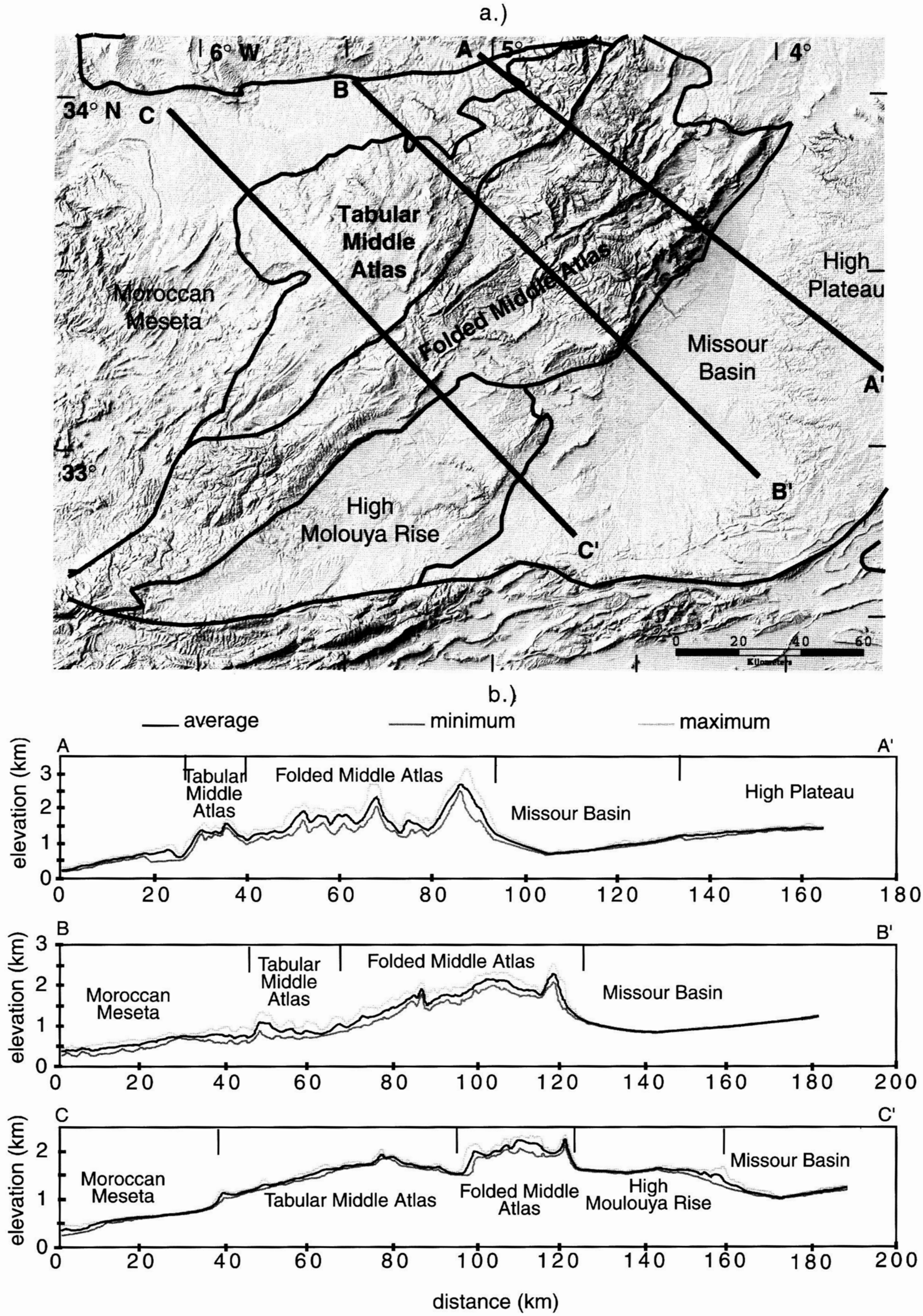

Fig. 6. (**a**) Topography represented as a shaded relief map and (**b**) profiles of the Middle Atlas study area. The topographic expression of the Folded Middle Atlas is more pronounced and displays higher frequency variations compared with the Tabular Middle Atlas.

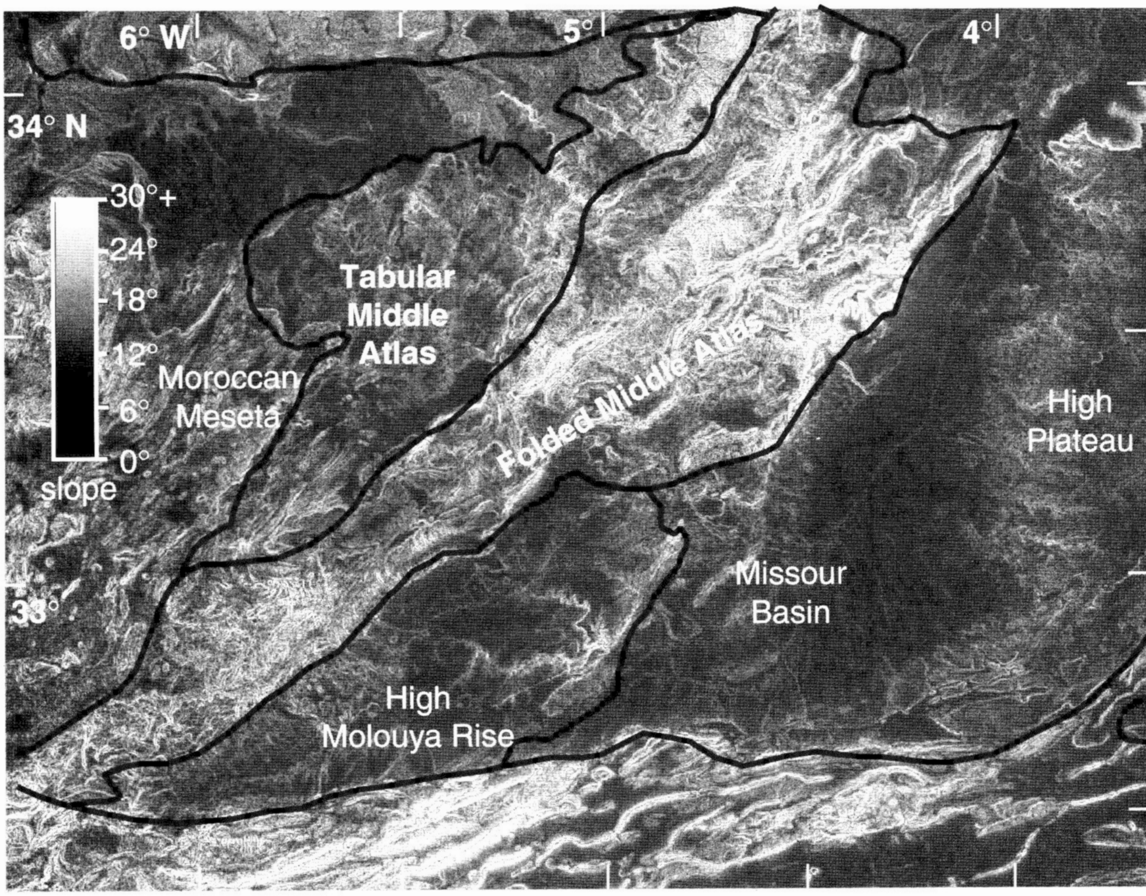

Fig. 7. Slope map derived from the digital topography using a 360 m × 360 m moving window. The Folded Middle Atlas is characterized by greater hillside slopes than the Tabular Middle Atlas.

apparent normal faults in the Tabular Middle section regional cross section (Fig. 3) correspond with the Tizi-n-Tretten fault, a Quaternary normal fault based on these results. The one peculiarity is observed with the data in the southwest Middle Atlas which show a component of north–south-directed extension. This may reflect a local variation in strain due to complexities developing in the vicinity of the intersection of the Middle and High Atlas systems.

Digital topography and remote sensing imagery analysis

Analysis of high resolution digital topographic data and LANDSAT MSS imagery over the region provides a means of characterizing some first order differences between the Folded and Tabular Middle Atlas. Inspection of the topography, displayed as a shaded relief image (Fig. 6a), shows the aforementioned difference between the rugged topography of the Folded Middle Atlas in contrast with the smoother Tabular Middle Atlas. The physiographic differences between the provinces are very clear in topographic profiles (Fig. 6b–d). Ten kilometre-wide swaths of topography were averaged every 250 m along the profile to produce a local average profile. The greater elevation and relief of the Folded Middle Atlas are easily observed compared with the neighboring regions.

A better view of the magnitude of short-wavelength roughness can be provided by analysis of hill slopes extracted from digital topography (e.g., Fielding *et al.* 1994). Figure 7 shows a map of slope magnitudes of the Middle Atlas extracted from the topographic data set using a moving window of four pixels by four pixels (*c.* 360 m by 360 m); the orientations of the slopes can be observed in Fig. 6a. Dark pixels indicate shallow slopes, and bright pixels indicate the steepest slopes. The contrast between the flat, smooth Tabular Middle Atlas and the rugged Folded Middle Atlas is easily observed. This processing accentuates the four steep, narrow anticlinal ridges (Colo 1964) which characterize the Folded Middle Atlas as bright bands with a narrow dark line in the middle. This may be in part due to differential erosion which would be expected due to the difference in erodibility of the lower Jurassic Carbonates and the Middle Jurassic interbedded marls and limestones. However, the large magnitudes of such slopes would not be maintained without late Cenozoic uplift (e.g., Bloom 1983). Steep slopes may also result from compressional tectonics.

The orientations of faults and other tectonic lineaments are analyzed in the Middle Atlas where these features are mapped using LANDSAT MSS imagery, digital topography, and field observations, as well as existing geological maps. Although relatively low resolution compared to its counterparts (e.g., LANDSAT Thematic Mapper and SPOT), MSS imagery combined with the digital topography proves to be important in delineating fault traces and lineaments, when geological maps are not available, as is the

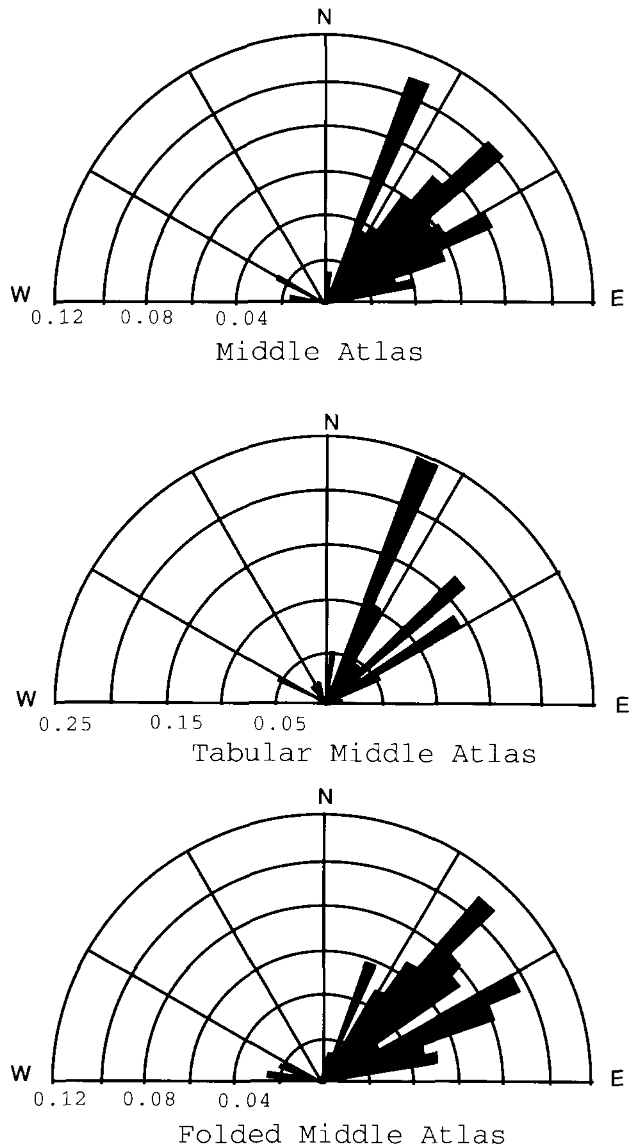

Fig. 8. Rose diagrams depicting the fault and tectonic lineament orientations in the Middle Atlas based on lineament mapping using LANDSAT MSS imagery. The orientations are weighted by the trace length of the lineaments and grouped into bins of 5°. The scaling represents the fraction of the total line length represented by the bin. Note the difference in orientations between the Tabular and Folded Middle Atlas.

case for most of the Middle Atlas. The MSS imagery was accurately registered with topography, which resulted in precise locations of these features. Potentially active features in the were identified and selected on the basis of Neogene–Quaternary geology and regional seismicity. The mapped faults and lineaments of the Middle Atlas (Fig. 2) were then divided between the Tabular and Folded Middle Atlas, and average orientations were measured and linearly weighted by the length of the feature. The weighted rose diagrams of their orientations are displayed in Fig. 8. It should be noted that the North Middle Atlas, South Middle Atlas, Ait Oufella, and Tizi-n-Tretten faults account for significant areas of the rose diagrams.

The Tabular and Folded Middle Atlas show significant differences in the orientations of the faults and lineaments. In the Tabular Middle Atlas, most of the features are oriented between 20° and 25° NE. There is a lack of features between 30° and 40°, and a limited number between 50° and 60°. In contrast, the Folded Middle Atlas exhibits a peak orientation of faults and lineaments between 30° and 45° NE, while there is a very limited number oriented less than 30° and a substantial proportion at angles greater than 60°.

A similar analysis of lineaments was conducted by Bensaid & Mahmood (1987) in the area to the west and southwest of the Middle Atlas. These authors reported on the significance of the NNE–SSW and ENE–WSW trends in the Moroccan Meseta (Central Massif). This bimodal distribution is similar to what is observed in the Rose diagram of the Tabular Middle Atlas (Fig. 8). The histogram for the Folded Middle Atlas is similar to the trends described by Bensaid & Mahmood (1987) in the central High Atlas in that lineaments trend predominantly NE–SW with a notable lack of NNE–SSW orientations. This comparison provides a regional context in which to place our results and suggests that the structural grain of the Tabular Middle Atlas is more similar to that of the Meseta than to the Atlas palaeo-rift system, whereas the Folded Middle Atlas is similar to the rest of the Atlas system in central Morocco. Another possible interpretation may be that the Meseta and the Tabular Middle Atlas may have rotated counter-clockwise with respect to the Middle and High Atlas. However, palaeomagnetic results (e.g., Najid *et al.* 1981) do not support such a rotation.

Discussion

Field observations and the stream profile perturbations (Fig. 4) suggest that tectonic activity has occurred throughout the Middle Atlas region during the Late Quaternary. However, the topographic expression of this activity varies between the Folded and Tabular Middle Atlas. This may be the result of either: (1) the style of deformation is homogeneous throughout the Middle Atlas, but the rates of deformation vary significantly, or (2) there are significant regional kinematic variations regardless of strain rates. Model (1) implies that the topographic variations reflect differences in the deformation rates relative to erosion, whereas model (2) suggests that the topography is, in part, tectonically influenced. The regional kinematic analysis (Fig. 5) supports the second case.

Many of the structures are believed to be inherited from the Mesozoic (e.g., Fedan 1988) and probably Palaeozoic (and possibly even Precambrian) tectonic history (e.g., Piqué *et al.* 1987; Laville & Piqué 1991). Bensaid & Mahmood (1987) noted the prevalence of the generally NE–SW trends in the Palaeozoic terranes. The NE–SW trend is parallel to the Palaeozoic and Mesozoic structural trends in Morocco including Triassic dykes that cross the Anti-Atlas and High Atlas (see Carte Geologique du Maroc 1985), suggesting the older heritage of these structures. If this is the case and the generally NE–SW-trending structures are inherited, then the variations in fault and tectonic lineament trends (Fig. 8) may reflect differences in the inherited structural fabric of the Mesozoic rift (Folded Middle Atlas) and the stable margin of the rift (Tabular Middle Atlas). The kinematic changes correspond with variations in the regional structural fabric as demonstrated by the analysis of topography and LANDSAT MSS imagery, although the neotectonic role of these lineaments comprising this regional fabric is not well constrained.

One of the key questions concerns the role of strike-slip faulting in the Middle Atlas. The fault-slip analysis and earthquake focal mechanisms demonstrate oblique-slip with a minor left-lateral component of slip along northeast striking fault zones. This sinistral motion is consistent with the idea that the Middle Atlas is part of a discontinuous zone of left lateral faulting (e.g., Jacobshagen 1992). However, the magnitude of strike-slip movement does not appear to be very great. There are very few geomorphic indicators of lateral slip. Our field investigations yielded no evidence in support of suggested strike-slip movement along the Ait Oufella fault. Furthermore, there do not appear to be any large geological offsets either.

The other interesting issue involves the coexistence of compressional and extensional structures (Fig. 5). In general, the reverse faulting kinematics are consistent with the NNW–SSE directed collision between Morocco and Spain, but an explanation for the north–south or east–west extension is not as clear. Simultaneous shortening and extension has been reported in the Himalayas (e.g., Molnar & Tapponier 1978; Burchfiel & Royden 1985; Ni & Barazangi 1985; Mercier *et al.* 1987; Hodges 1992). In that case, there is a strong correlation between extensional deformation and high topography, and extension is believed to be a result of gravitational instability of the over thickened crust (Molnar 1988). We do not believe that this is the case for Morocco. In Morocco, no such a correlation between extension and topography is observed, and furthermore, the crust is not sufficiently thick as to be unstable. The crustal thickness beneath these 2–3 km high mountains is only 33–35 km as determined from seismic refraction studies (e.g., Wigger *et al.* 1992) and geobarometric analysis of upper mantle xenoliths found in the alkali basalts (Harmand & Moukadiri 1986).

Several earlier workers have attempted to explain extension and volcanism as local, secondary features. Morel & Cabanis (1993) suggested that the volcanism occurred along large secondary tension joints. They noted that the volcanism appears to be concentrated in an area surrounding a bend of about 30° in the general structure of the Middle Atlas and suggested that the re-orientation of the regional maximum principal stress from NW–SE to NNW–SSE during the late Quaternary (e.g., Morel 1989; Aït Brahim & Chotin 1984) resulted in a geometry where this bend prevented the relief of this stress along the northeast striking fault zones. Consequently, the stress was relieved by E–W extension within the bend. However, this does not seem plausible based on the orientation of the principal stresses and the structures in question. Furthermore, earthquake focal mechanisms imply the present activity of left-lateral, oblique-slip normal and reverse faults within this bend (see Fig. 5). Similarly, Aït Brahim & Chotin (1990) suggested that the volcanism is aligned along inherited NNW–SSE-striking fractures that were reactivated as extensional joints within the alleged strike-slip regime. However, this model, as well as that of Morel & Cabanis (1993), does not explain the normal faulting along northeast striking faults in the Tabular Middle Atlas. Harmand & Moukadiri (1986) also suggested that the volcanism may be associated with alleged strike-slip faulting in the Middle Atlas as a system of extensional step-overs and releasing bends in the fault system. However, the map pattern of the faults (Figs 2 & 5) is inconsistent with this idea. The general bend observed in the fault traces (see Figs 2 & 5) is typical of a constraining bend for a left-lateral fault system and is incompatible with a releasing step required to cause extension. As previously stated, the degree to which this can be considered a strike-slip system is not clear.

Another possibility is that extension may characterize much of the Moroccan Meseta as well as the Tabular Middle Atlas. Extension is reported along the NE–SW-striking faults in this area. For example, neotectonic left lateral, oblique-slip normal faults have been mapped to the west in the Moroccan Meseta by Deffontaines *et al.* (1992), Aït Brahim (1991) and Faure-Muret *et al.* (1994). Quaternary basaltic volcanism is also present to the west in the Meseta (Carte Geologique du Maroc 1985). One possibility is that all of these features are related to pervasive extension in the Meseta. This suggests that to a first order, the variation of deformation corresponds with the Mesozoic rift palaeogeography. The Tabular Middle Atlas and the Moroccan Meseta represent an area of relative stability during Mesozoic. Thus, one would expect the Folded Middle Atlas to be inherently weaker than the shoulders of the palaeo-rift and the meseta. The WSW–ENE-directed extension could be related to a westward tectonic escape of the Moroccan Meseta, in contrast to the marked shortening observed in the structures associated with the palaeo-rift (the Folded Middle Atlas) (Fig. 9). The only reported meso-scale structural evidence for sinistral shear is along the North Middle Atlas fault (e.g., Brede & Heinitz 1989; Scheele 1992) which is the boundary between the two regions. The oceanic interface farther to the west presents a zone into which the block can escape. However, the magnitude of escape and sinistral slip would be minimal. Morel *et al.* (1993) proposed a model involving the eastward tectonic escape of the High Plateau (another area of Mesozoic stability) based on the analysis of fault-slip data. However, this continental block is confined and will have nowhere to escape unless some internal shortening occurs within the High Plateau. One possibility could be that it is underthrusting beneath the Tel Atlas thrust belt in Algeria, and this may account for the present-day thrusting involved with the Tel Atlas in contrast to the Rif.

The coexistence of neotectonic compressive and extensional structures has been described at the eastern end of the Atlas system in Tunisia (e.g., Rebai 1993). This may be similar to what we are reporting in Morocco in that the intracontinental mountain chain (Tunisian Atlas) is obliquely oriented and intersects the fold and thrust belt (Tel Atlas). In Tunisia, most of the extension is located to the southeast of the Saharan Atlas, outside of the High Plateau region. Once again, there is an unconfined continental region that could be permitted to escape toward the east.

These observations demonstrate that the intracontinental region of northern Morocco (the area in the foreland of the Rif) accommodates some of the convergence between Africa and Europe and that this accommodation is achieved in various ways. Crustal shortening is observed in the Mesozoic rift systems, and WSW–ENE-directed transtensional deformation appears to be occurring in the 'stable' areas adjacent to the palaeo-rifts. The kinematics are consistent with the NNW–SSE direction of convergence between Africa and Spain (based on DeMets *et al.* 1990). Some accommodation is occurring within the Betic-Rif zone (Fig. 10); earthquake focal mechanisms (e.g., Medina & Cherkaoui 1992; Buforn & Udias 1991) as well as fault-slip

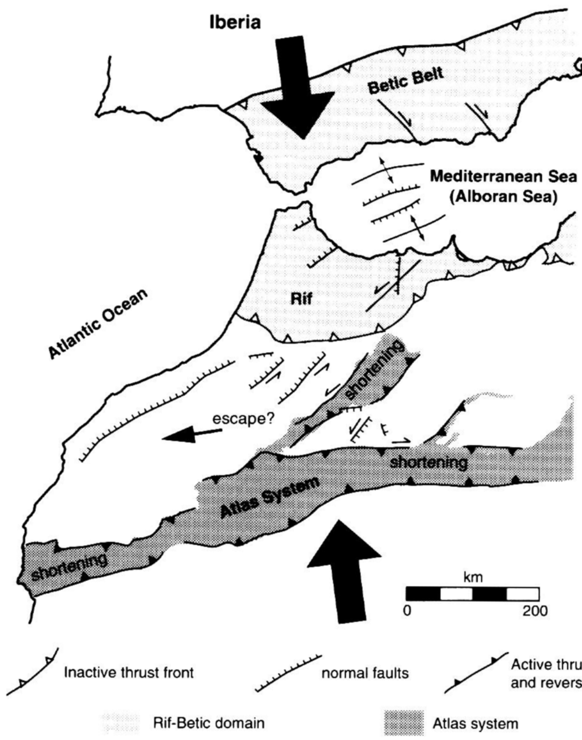

Fig. 9. Schematic representation of active deformation kinematics in northern Morocco. The large arrows represent the general direction of collision between North Africa and Spain.

data (e.g., Aït Brahim 1991; Morel 1989) demonstrate that strike-slip and normal faulting are predominant in this region. In contrast, Quaternary folding has been reported in the offshore area of the Alboran Sea (Bourgois *et al.* 1992). Overall, the kinematic scheme of Morocco and southern Spain results from greatly varying styles of deformation (Fig. 9). This is consistent with the interpretation that there is no simple plate boundary between Europe and Africa east of the Strait of Gibraltar (e.g., Weijermars 1987). Instead, there is a wide zone characterized by diffuse and varied deformation.

Conclusions

Our field observations, analysis of high resolution digital topography data, and LANDSAT MSS imagery indicate that the intracontinental Middle Atlas is an area of neotectonic activity presumably related to the tectonic interactions and convergence between North Africa and Iberia. Evidence for Quaternary and recent tectonism in the Tabular and Folded Middle Atlas is provided by geology, stream morphology, and limited seismicity. Analysis of digital topography data and remote sensing imagery highlights gross structural differences between the geomorphic provinces of the Middle Atlas. The Folded Middle Atlas is characterized by steeper slopes which reflect the folded structure, while the Tabular Middle Atlas topography is relatively subdued. A more quantitative comparison involving the analysis of fault and tectonic lineament orientations reveals subtle, but distinct, differences in the orientations of structures within (Folded Middle Atlas) and outside (Tabular Middle Atlas) of the palaeo-rift. These structures may be inherited Mesozoic features reactivated by the present tectonic processes.

The Tabular Middle Atlas is characterized by two key geological elements: the transtensional Tizi-n-Tretten fault and Quaternary alkali volcanism. Both are indicative of extension during the Mid- and Late Quaternary. Activity of the Tizi-n-Tretten fault is supported by inflections in stream profiles. Fault-slip data and seismicity provide evidence for transtensional deformation.

The Folded Middle Atlas possesses several distinct fault zones. Most prominent are the North and South Middle Atlas faults, which mark the boundaries of the early Mesozoic rift zone, and the Ait Oufella fault. These faults are presently active with reverse-slip components of movement. Fault kinematic data for the North Middle Atlas and Ait Oufella faults are provided by field observations and earthquake focal mechanisms. Evidence for recent sinistral slip is minimal, at best. Left-lateral offsets (up to 80 m) are observed in some Quaternary lava flows along faults associated with the North Middle Atlas fault.

There appears to be a first order correlation between the kinematics of active tectonics and the Mesozoic palaeogeography. The palaeo-rift of the Folded Middle Atlas area demonstrates transpressive deformation, while the semi-stable shoulders of the palaeo-rift represented by the Moroccan Meseta and High Plateau regions appear to be involved with transtensile tectonism and expulsion toward the west and east, respectively. This may reflect differences in the inherent strength of crustal blocks, which were imposed during the Mesozoic rifting if not earlier (Palaeozoic). Future studies of the neotectonics and seismicity will provide more constraints on the regional kinematics and rates of deformation. In particular, these should enlighten us as to whether the reported extension is a local feature in the Tabular Middle Atlas or a characteristic of the Moroccan Meseta region. Either way, the kinematic variations within northern Morocco emphasize the role performed by inherited structures in areas of intracontinental deformation.

The authors greatly appreciate the input of D. Seber. His discussions and constructive criticisms were important for the development of the paper. W. Beauchamp provided assistance in the field as well as an in-house review of the manuscript. R. Allmendinger also provided helpful suggestions and reviewed the manuscript. Other in-house reviews of the manuscript were provided by R. Litak, A. Calvert, and G. Brew. G. Potts and J.-L. Morel provided helpful reviews and made valuable suggestions for revisions. This study would not have been possible without the assistance of our Moroccan colleagues at the Geological Survey of Morocco. We would like to acknowledge the support of M. Dahmani and the assistance in the field provided by A. Er-Raji and M. Zebrog. We are also grateful for assistance provided by the Centre National de Coordination et de Planification de la Recherche Scientifique et Technique. L. Aït Brahim provided helpful advice prior to the field work. The first author is supported under a National Science Foundation Graduate Research Fellowship. The research was partially supported by NSF Grant EAR-9205257. Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the ACS (ACS-PRF #29505-AC2) for partial support of this research. INSTOC contribution 218. Correspondence to F. Gomez (e-mail: fgomez@geology.cornell.edu).

References

Aït Brahim, L. 1991. *Tectoniques cassantes et etats de contraintes recents au nord du Maroc*. Thèse 3ème cycle, Faculté de Science Rabat.

——, & Chotin, P. 1984. Mise en évidence d'un changement de direction de compression dans l'avant-pays rifain (Maroc) au cours du Tertiaire et du Quaternaire. *Bulletin de la Société Géologique de France*, **8,** 681–691.

——, & CHOTIN, P. 1990. Oriental Moroccan Neogene volcanism and strike-slip faulting. *Journal of African Earth Sciences*, **11**, 273–280.

ALLEN, C. R., GILLESPIE, A. R.,YUAN, H. , SIEH, K. E., BUCHUN, Z. & CHENGNAN, Z. 1984. Red River and associated faults, Yunnan Province, China: Quaternary geology, slip rates, and seismic hazard. *Geological Society of America Bulletin*, **95**, 686–700.

BENSAID, M. & MAHMOOD, A. 1987. The use of LANDSAT imagery in structural studies of middle Morocco. *Advances in Space Research*, **7**, 87–94.

BEN SARI, D. 1987. *Connaissance Geophysique du Maroc*. Centre National de Coordination et de Planification de la Recherche Scientifique et Technique.

BERNINI, M., BOCCALETTI, M., MOKHTARI, J.EL, GELATI, R., MORATTI, G. & PAPANI, G. 1994. *The Neogene Taza-Guercif Basin: Excursion Guidebook*.

BLOOM, A. 1983. *Geomorphology. A Systematic Analysis of Late Cenozoic Landforms*. Prentice-Hall, Inc.

BOURGOIS, J., MAUFFRET, A., AMMAR, A. & DEMNATI, A. 1992. Multichannel seismic data imaging of inversion tectonics of the Alboran Ridge (Western Mediterranean Sea). *Geo-Marine Letters*, **12**, 117–122.

BREDE, R. & HEINITZ, W. 1989. Durchgepauste tektonik im Mittleren Atlas Marokkos. *Zeitschrift der Deutschen Geologischen Gesellschaft*, **140**, 161–171.

——, HAUPTMANN, M. & HERBIG, H. 1992. Plate tectonics and intracratonic mountain ranges in Morocco—The Mesozoic-Cenozoic development of the Central High Atlas and the Middle Atlas. *Geologische Rundschau*, **81**, 185–197.

BUFORN, E. & UDIAS, A. 1991. Focal mechanism of earthquakes in the Gulf of Cadiz, south Spain and Alboran Sea. *In*: MEZCUA, J. & UDIAS, A. (eds) *Seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region*. Publicacion de Instituto Geografico Nacional, Monografias, **8**, 29–40.

BURCHFIEL, B. C. & ROYDEN, L. H. 1985. N-S extension within the convergent Himalayan region. *Geology*, **13(10)**, 679–682.

BURKE, K. & SENGÖER, C. 1986. Tectonic escape in the evolution of the continental crust. *In*: BARAZANGI, M. & BROWN, L. D. (eds) *Reflection seismology; the continental crust*. Geodynamic Series, **14**, 41–53.

CARTE GEOLOGIQUE DU MAROC 1985. 1:1 000 000. Service Geologique du Maroc.

CHARRIÈRE, A. 1981. Évolution néogène de bassins continentaux et marins dans le Moyen Atlas central (Maroc). *Bulletin de la Société Géologique de France*, **26(6)**, 1127–1136.

COLO, G. 1964. *Contribution à l'étude du Jurassique du Moyen-Atlas spetrentrional*. Notes et Mémoirs du Service Géologique du Maroc, **139**, 226 p.

DEFFONTAINES, B., CHOTIN, P., AÏT BRAHIM, L. & ROZANOV, M. 1992. Investigation of active faults in Morocco using morphometric methods and drainage pattern analysis. *Geologische Rundschau*, **81**, 199–210.

DEMETS, C., GORDON, R. G., ARGUS, D. F. & STEIN, S. 1990. Current plate motions. *Geophysical Journal International*, **101(2), 425–478.**

DU DRESNAY, R. 1988. Recent data on the geology of the Middle-Atlas (Morocco). *In*: JACOBSHAGEN, V. (ed.) *The Atlas System of Morocco*. Springer-Verlag, Berlin, 293–320.

ELMRABET, T., LEVRET, A., RAMDANI, M. & TADILI, B. 1991. Historical seismicity in Morocco: Methodological aspects and cases of multidisciplinary evaluation. *In*: MEZCUA, J. & UDIAS, A. (eds.) *Seismicity, Seismotectonics and Seismic Risk of the Ibero-Maghrebian Region*. Publicacion de Instituto Geografico Nacional, Monografia, **8**, 115–130.

FAURE-MURAIT, A. & MOREL, J.-L. & DAHMANI, M. 1994. *Carte Neotectonique du Maroc*. 1:1 000 000 scale. Direction de la Géologie, Ministere de L'Energie et des Mines, Rabat.

FEDAN B. 1980. *Etude structurale du versant sud du Moyen Atlas central d'Enjil des Ikhatarn à Imouzzer des Marmoucha (Moyen Atlas)*. Thèse 3ème cycle, Faculté de Science Rabat.

—— 1988. *Évolution géodynamique d'un bassin intraplaqe sur décrochements: le Moyen Atlas (Maroc) durant le Méso-Cénozoïque*. Travaux de l'Institut scientifique, Série Géologie et Géographie physique, **18**.

—— & THOMAS, G. 1986. Découverte de dépôts néog~enes déformés par l'accident nord-moyen-atlasique (Maroc). Implications sur son activité mio-plio-quaternaire au Norde de Boulemane. *Géologie Méditerranéeane*, **13(4)**, 151–154.

FIELDING, E., ISACKS, B., BARAZANGI, M. & DUNCAN, C. C. 1994. How flat is Tibet?. *Geology*, **22**, 163–167.

GIESE, P. & JACOBSHAGEN, V. 1992. Inversion tectonics of intracontinental ranges: High and Middle Atlas, Morocco. *Geologische Rundschau*, **81**, 249–259.

HARMAND, C. & CANTAGREL, J. M. 1984. Le volcanisme alcalin Tertiaire et Quaternaire du Moyen Atlas (Maroc): chronologie K/Ar et cadre géodynamique. *Journal of African Earth Sciences*, **2**, 51–55.

—— & MOUKADIRI, A. 1986. Synchronisme entre tectonique compressive et volcanisme alcalin: exemple de la province quaternaire du Moyen Atlas (Maroc). *Bulletin de la Société Géologique de France*, **8**, 595–603.

HATZFELD, D. & FROGNEUX, M. 1981. Intermediate depth seismicity in the western Mediterranean unrelated to subduction of oceanic lithosphere. *Nature*, **292**, 443–445.

HERBIG, H. 1988. Synsedimentary tectonics in the northern Middle Atlas (Morocco) during the late Cretaceous and Tertiary. *In*: JACOBSHAGEN, V. (ed.) *The Atlas System of Morocco*. Springer-Verlag, Berlin, **15**, 321–337.

HERNANDEZ, J., DE LAROUZIERE, F. D., BOLZE, J. & BORDET, P. 1987. Le magmatisme néogene bético-rifain et le couloir de décrochement trans-Alboran. *Bulletin de la Société Géologique de France*, **8**, 257–267.

HODGES, K. V., PARRISH, R. R., HOUSH, T. B., LUX, D. R., BURCHFIEL, B. C., ROYDEN, L. H. & CHEN, Z. 1992. Simultaneous Miocene extension and shortening in the Himalayan Orogen. *Science*, **258**, 1466–1470.

JACOBSHAGEN, V. 1992. Major fracture zones of Morocco: The South Atlas and the Transalboran fault systems. *Geologische Rundschau*, **81**, 185–197.

——, GÖRLER, K. & GIESE, P. 1988. Geodynamic evolution of the Atlas System (Morocco) in post-Palaeozoic times. *In*: JACOBSHAGEN, V. (ed.) *The Atlas System of Morocco*. Springer-Verlag, Berlin, **15**, 481–499.

KELLER, E. 1985. Investigation of active tectonics: Use of surficial earth processes. *In*: WALLACE, R. E. (ed.) *Active Tectonics*. National Academy Press, Washington, DC, 136–147.

LAVILLE, E. 1981. Role des decrochements dans le mecanisme de formation des bassins d'effondrement du Haut Atlas Marocain au cours des temps triasique et liasique. *Bulletin de la Société Géologique de France*, **23**, 303–312.

—— & PIQUÉ, A. 1991. La distension crustale atlantique et atlasique au Maroc au début du Mésozoïque: le rejeu des structures hercynienne. *Bulletin de la Société Géologique de France*, **162**, 1161–1171.

LETOUZEY, J. 1990. Fault reactivation, inversion and fold-thrust belt. *In*: LETOVZEY, J. (ed.) *Petroleum and Tectonics in Mobile Belts*. Paris, 101–128.

MARTIN, J. 1981. *Le Moyen-Atlas central. Etude géomorphologique*. Notes et Mémoirs du Service Géologique du Maroc, **228**.

MARRETT, R. & ALLMENDINGER, R. 1989. Kinematic analysis of fault-slip data. *Journal of Structural Geology*, **12**, 973–986.

MATTAUER, M., TAPPONNIER, P. & PROUST, F. 1977. Sur les mécanismes de formation des chaînes intracontinentales. L'exemple des chaînes atlasiques du Maroc. *Bulletin de la Société Géologique de France*, **7**, 521–526.

MCKEOWN, F. A., JONES-CECIL, M., ASKEW, B. L. & MCGRATH, M. A. 1988. *Analysis of stream profile data and inferred tectonic activity, eastern Ozark mountains region*. US Geological Survey Bulletin, **1807**.

MEDINA, F. & CHERKAOUI, T. 1992. Mécanismes au foyer des séismes du Maroc et des régions voisines (1959–1986): Conséquences tectoniques. *Eclogae Geologicae Helvetiae*, **85**, 433–457.

MERCIER, J., ARMIJO, R., TAPPONNIER, P., CAREY-GAILHARDIS, E. & LIN, H. T. 1987. Change from Late Tertiary compression to Quaternary extension in southern Tibet during the India-Asia collision. *Tectonics*, **6**, 275–304.

MERRITTS, D. & VINCENT, K. R. 1989. Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Mendocino triple junction region, northern California. *Geological Society of America Bulletin*, **100**, 1373–1388.

MOLNAR, P, 1988. A review of geophysical constraints on the deep structure of the Tibetan Plateau, the Himalaya and the Karakoram, and their tectonic implications. *Philosophical Transactions of the Royal Society of London*, **26**, 33–88.

—— & TAPPONNIER, P. 1978. Active tectonics of Tibet. *Journal of Geophysical Research*, **85**, 5361–5375.

MOREL, J.-L. 1989. Etats de contrainte et cinématique de la chaîne rifain (Maroc) du Tortonien à l'actuel. *Geodinamica Acta*, **3**, 283–294.

——, MOSTAFA, Z. & POISSON, A. 1993. Relations entre la subsidence des bassins moulouyens et la création des reliefs atlasiques (Maroc): un exemple d'inversion tectonique depuis le Néogène. *Bulletin de la Société Géologique de France*, **164**, 79–91.

MOREL, J.-M & CABANIS, B. 1993. Mise en évidence d'une association magmatique dans le volcanisme plio-quaternaire du Moyen-Atlas marocain. *Comptes Rendus de l'Academie des Sciences, Serie II, Fascicule 2, Sciences de la terre et des planete*, **316**, 357–362.

NAJID, D., WESTPHAL, M. & HERNANDEZ, J. 1981. Paleomagnetism of Quaternary and Miocene lavas from north-east and central Morocco. *Journal of Geophysics*, **49**, 149–152.

NI, J. & BARAZANGI, M. 1985. Active tectonics of the western Tethyan Himalaya above the underthrusting Indian Plate: The upper Sutlej River Basin as a pull-apart structure. *Tectonophysics*, **112**, 277–295.

PIQUÉ, A., DAHMANI, M., JEANNETTE, D. & BAHI, L. 1987. Permanence of structural lines in Morocco from Precambrian to present. *Journal of African Earth Sciences*, **6**, 247–256.

REBAI, S. 1993. Recent tectonics in Northern Tunisia: coexistence of compressive and extensional structures. *Annales Tectonicae*, **7**, 129–141.

RHEA, S. 1988. Evidence of uplift near Charleston, South Carolina. *Geology*, **17**, 311–315.

RODGERS, J. 1987. Chains of basement uplifts within cratons marginal to orogenic belts. *American Journal of Science*, **287**, 661–692.

SCHEELE, J. 1992. Convergent wrench fault tectonics in the central Middle Atlas (Morocco). *In*: *Abstracts from the Final Workshop Structure and Evolution of the Atlas Mountain System in Morocco and Structure and Evolution of the Central Andes in Northern Chile, Southern Bolivia and Northwestern Argentina*.

SCHWARZ, G. & WIGGER, P. J. 1988. Geophysical studies of the earth's crust and upper mantle in the Atlas system of Morocco. *In*: JACOBSHAGEN, V. (ed.) *The Atlas System of Morocco*. Springer-Verlag, Berlin, **15**, 339–358.

SEEBER, L. & GORNITZ, V. 1982. River profiles along the Himalayan arc as indicators of active tectonics. *Tectonophysics*, **92**, 335–367.

STRAHLER, A. N. 1957. Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union*, **8**, 913–920.

TADILI, B. & RAMDANI, M. 1983. Computer file of Moroccan earthquakes. *Bulletin of the Seismological Society of America*, **73(2)**, 653–654.

—— & —— 1986. La sismicité du Moyen Atlas. *Gerlands Beiträge zur Geophysik*, **95**, 469–476.

WALLACE, R. E. 1968. Notes on stream channels offset by the San Andreas fault, southern Coast Ranges, California. *Stanford University Publications in the Geological Sciences*, **11**, 6–21.

WEIJERMARS, R. 1987. A revision of the Eurasian–African plate boundary in the western Mediterranean. *Geologishe Rundschau*, **76**, 667–676.

WIGGER, P., ASCH, G., GIESE, P., HEINSOHN, W., EL ALAMI, S. & RAMDANI, F. 1992. Crustal structure along a traverse across the Middle and High Atlas Mountains derived from seismic refraction studies. *Geologische Rundschau*, **81**, 237–248.

Received 9 June 1995; revised typescript accepted 4 January 1996.
Scientific editing by Alex Maltman.