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Inversion Tectonics of intracontinental Ranges: High and Middle Atlas, Morocco

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With 4 figures

Zusammenfassung

Der Hohe und der Mittlere Atlas sind intrakontinentale Gebirge im mobilen Vorland des mediterranen Rif-Orogens. Ihre Entwicklung weist drei Perioden auf: Die erste (Perm-Bathonium) kulminierte im Lias mit der Bildung von Riftgräben entlang spätvariskischer Bruchzonen und Tholeiit-Ergüssen. Im Intervall Callovium-Eozän deuten tektonische Beruhigung und geringere Sedimentation auf eine allmähliche Abkühlung der Lithosphäre hin. Seit dem Oligozän steht die Region unter Kompression. Der Hohe und der Mittlere Atlas haben sich zeitgleich mit den Hauptphasen der Kompression im Rif herausgehoben. Refraktionsseismische Untersuchungen haben einen flachen Lagenbau der Kruste mit mehreren low-velocity-Zonen aufgewiesen, deren tiefste mit einer Zone hoher elektrischer Leitfähigkeit zusammenfällt und als bedeutende Abscherungszone gedeutet wird.

Aus der geotektonischen Entwicklung des Hohen und des Mittleren Atlas und aus der heutigen Krustenstruktur wird folgendes Modell abgeleitet: In der frühmesozoischen Rift-Phase wurde die Kruste über den Mantel-Aufwölbungen durch Zerrungsbrüche und durch Zergleiten an subhorizontalen Scherflächen ausgedünnt. Während der känozoischen Kollisionen im Rif-Atlas wurden diese Scherflächen dann gegenläufig bewegt, die Riftgraben-Füllungen dabei bis zu geringer Krustenverdickung eingeengt und anschließend herausgehoben. Die Inversion der beiden Atlas-Gebirge ist somit nicht nur isostatisch bedingt, sondern auch durch Aufpressung bei thick-and-thin-skinned-Tektonik verursacht.

Abstract

The High and Middle Atlas are intracontinental mountain belts situated within the mobile foreland of the Mediterranean Rif orogen. They developed in three stages. The first period (Permian – Bathonian) culminated during the Lias with extended rift grabens and tholeiite extrusions. From Callovian to Eocene, the tectonic activity and the rates of sedimentation were reduced, both pointing to a cooling of the lithosphere. Since the Oligocene, the whole region is submitted to compressional stress. The High and the Middle Atlas were uplifted within two phases, which were correlated with main phases of Rif orogenesis. Refraction seismic measurements have recently revealed there a flat layered structure of the crust with several low velocity zones. The deepest one coincides with a layer of high electric conductivity, which is interpreted as a zone of detachment.

From the geotectonic evolution of the High and Middle Atlas and from the structure of the crust, the following model was deduced: During Early Mesozoic rifting, the crust on top of the mantle elevations was thinned by both extensional fracturing and by gliding along intracrustal detachment planes. During the Cenozoic collisions of the Rif, these shear planes were reactivated by thrusting in opposite directions. Compressional deformation of the graben fillings led now to a moderate thicken-

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ing of the crust, e.g. up to 40 km beneath the High Atlas. Subsequent uplift and inversion was not only caused by isostasy, but also by squeezing upward due to thick- and thin-skinned tectonics.

Résumé

Le Haut Atlas et le Moyen Atlas sont des chaînes intracontinentales situées dans l'avant pays mobile de l'orogène méditerranéen du Rif. Elles se sont développées en trois périodes. La première (du Permien au Bathonien) a culminé au Lias avec la formation de fossés de rift accompagnés d'effusions tholéiitiques. Au cours de la deuxième période (du Callovien à l'Eocène), l'activité tectonique et les taux de sédimentation étaient réduits, indice d'un refroidissement de la lithosphère. Depuis l'Oligocène, la région est soumise à une compression. Le Haut Atlas et le Moyen Atlas se sont soulevés en deux phases, coïncidant avec les phases principales de compression du Rif. Les sondages sismiques ont mis en évidence une structure de la croûte en couches subhorizontales comportant plusieurs zones à faible vitesse dont la plus profonde coïncide avec une zone de haute conductivité électrique interprétée comme un vaste décollement.

En conclusion, nous proposons le modèle suivant pour le Haut et le Moyen Atlas: pendant la phase de rifting du Mésozoïque inférieur, la croûte a été amincie au-dessus de bombements du manteau, non seulement par des fracture d'extension mais aussi par glissement le long de décollements subhorizontaux. Durant les collisions cénozoïques du Rif, ces décollements ont été réactivés en charriages par glissement en sens inverse. Ce processus, en rétrécissant les remplissages des grabens, a provoqué un léger épaississement de la croûte (jusqu'à 40 km sous le Haut Atlas) et le soulèvement final. L'inversion des chaînes atlasiques n'a donc pas seulement été l'effet de l'isostasie, mais aussi d'une tectonique »thin-and-thick-skinned«.

Краткое содержание

Высокогорный и средний Атлас являются интерконтинентальными горами в подвижном предгорье средиземноморского рифового орогена. Развитие их отмечено тремя периодами: первый (перм-бат) имеет свою наивысшую точку в лейасе, когда вдоль поздневарисской разломной зоны появились рифтовые грабены и произошло излияние толеитов. В интервале келловейский век – эоцен отмечается период тектонического спокойствия и незначительное осадконакопление, что говорит о постепенном охлаждении литосферы. Начиная с олигоцена вся область перетерпевает сжатие. Поднятие высокогорного и среднего Атласа происходит почти одновременно с основной фазой сжатия в рифе. С помощью геофизического метода переломных волн установили пологое строение слоев коры с многочисленными зонами низкой скорости прохождения волн, причем сама глубинная зона залегания совпадает с зоной наивысшей электропроводимости, что разрешает предполагать наличие значительной зоны скола.

Основываясь на геотектоническом развитии высокогорного и среднего Атласа, а также на структурах коры сегодняшнего дня, составили следующую модель: В раннемезозойской фазе рифта кора образовывала, вероятно, над мантией свод в результате разрывов растяжения и была утоншена в результате имеющихся субгоризонтальных плоскостей скола. Во время кайнозойских коллизий в рифе Атласа эти плоскости скола оказались сдвинутыми по отношению друг ко другу, грабены рифа, хотя и заполнялись отложениями, но давали очень незначительное утолщение мощности коры; и, наконец, произошло их поднятие. Т.о. инверсия обеих горных цепей Атласа обусловлена не только изостатическими процессами, но и выдавливанием при процессах тектоники, называемыми »thick-and-thin-skinned-tectonics«.

1. Introduction

To the NW, the African continent is bordered by a broad mobile zone, which forms the foreland of the Alpine orogenic system of the Kabylides. Within the Moroccan segment of that zone, i.e., south of the Rif orogen, three mountain ranges have developed as intracontinental belts: The Middle and the High Atlas in central Morocco and the Anti-Atlas farther to the S (fig. 1). From a geotectonic point of view, these ranges are differently structured. The Anti-Atlas area has been in a high position nearly continuously since the Hercynian orogeny, forming the northwestern margin of the Sahara craton. The High and the Middle Atlas had, however, originated from Mesozoic depocenters situated along ancient fracture zones (see Jacobshagen, this vol.). The uplift of the present

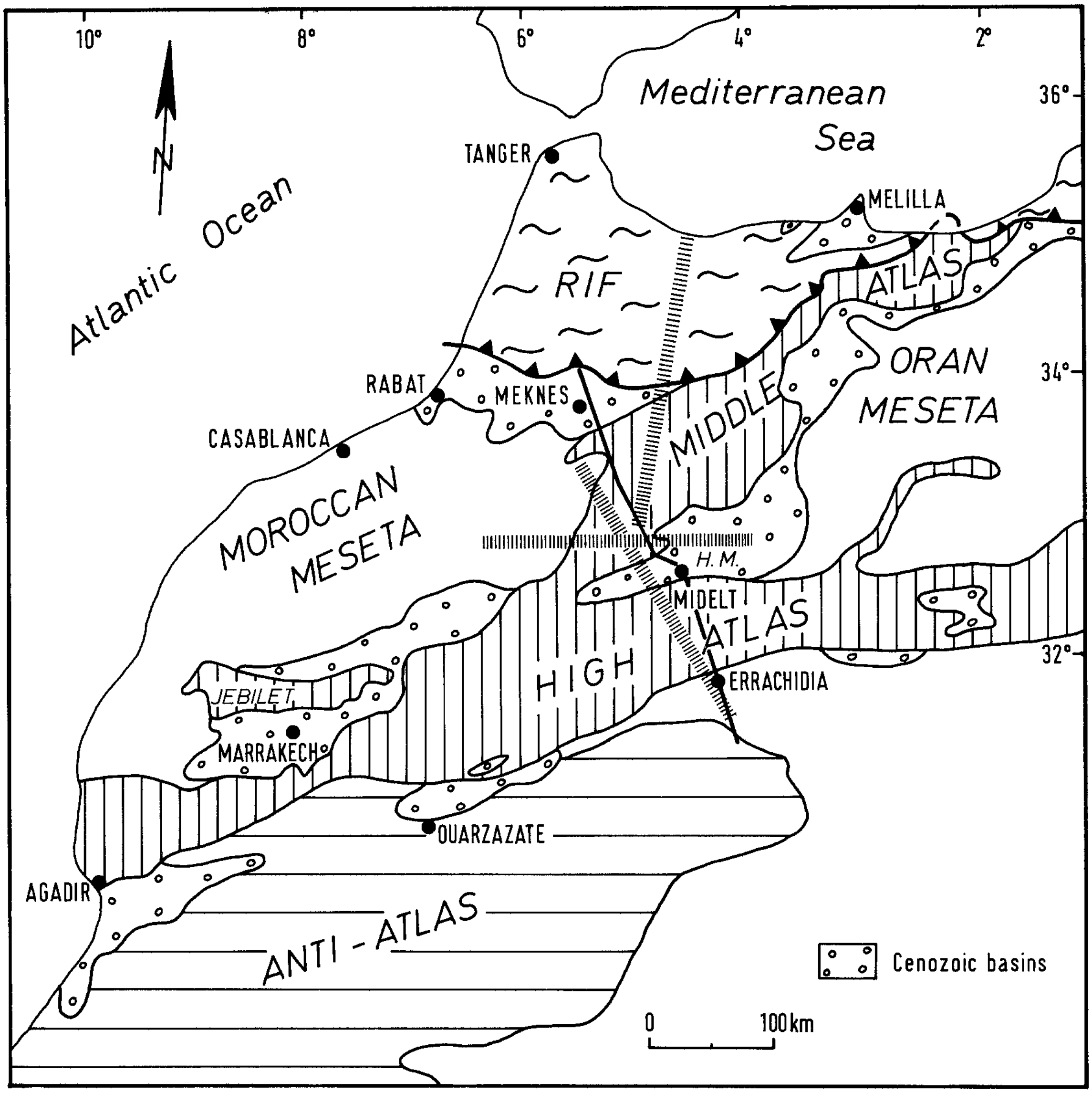

Fig. 1. Major geotectonic units of Morocco. Black line = refraction seismic profile of WIGGER et al., this vol. Hatched strip: Magnetotelluric/geoelectric profiles of SCHWARZ et al., this vol.

mountain chains took place since the Miocene. But several authors postulated a first stage of tectonic inversion already in Late Cretaceous times (e.g. STETS & WURSTER 1981; FROITZHEIM et al., 1988).

A basic question is, how far the main stages of the evolution of the Middle and High Atlas were connected with major events of plate movements and orogeny in the surrounding regions. Some authors – e.g. STETS & WURSTER (1981) – admitted only relations with the opening of the Atlantic Ocean. The great majority of researchers agree, however, that there are also clear connections with the evolution of the western Tethys, its Mesozoic opening as well as its Cenozoic closure. This would lead to the question, how stresses can be transmitted over distances of several hundred kilometers, from fold and thrust belt regions many examples prove this phenomenon. Along the western margin of the South American continent, e.g., an ocean/continent collision is active, and simultaneously a thrust and fold belt has been developed on the eastern flank of the Andes 800 km apart. The ramp-like tectonic model with its sole thrust descending from the sedimentary cover down to the upper mantle is able to transmit stress from the rear, the internal zones of the system, to the thinning external zones. Finally, we have to consider the question how far crustal thicknesses beyond the High and Middle Atlas correspond to the rates of lateral shortening derived from the sedimentary cover of these ranges.

Based upon first results of deep seismic sounding and geoelectric and magnetotelluric measurements along a S/N profile across both ranges and upon geological data mainly from the central High Atlas, the present authors had already proposed a preliminary model to explain the mechanism of inversion for these ranges (JACOBSHAGEN et al., 1988b). In the meantime, both the results of further geophysical campaigns and new geological data also from the Middle Atlas and the Haute Moulouya, enable us to precise our model and to discuss other ideas with more detail.

2. Post-Hercynian evolution of the High and Middle Atlas

Our contribution may be opened by a brief summary of the main stages of the post-Hercynian geotectonic evolution of the High and Middle Atlas, with the aim to achieva a solid basis for interpretations and discussions.

Permian-Bajocian

The post-Hercynian history of the High and Middle Atlas was initiated by activities along major fracture systems in northeasterly (»Atlantic«) or easterly (»Mediterranean«) directions, which had originated within the Hercynian crust during a late phase of that orogeny (MATTAUER et al., 1972, 1977). Small basins subsided in Permian, larger ones in Triassic times (VAN HOUTEN, 1976; LORENZ, 1988), both being filled with continental redbeds, with thicknesses from several hundreds up to 4500 m. About the Triassic/Jurassic boundary, subsidence increased, and the depositional environment changed to lagoonal and, subsequently, marine conditions. The separat Triassic basins grew together to graben-like structures with several depocenters. This geotectonic change was, moreover, marked by wide-spread eruptions of continental tholeiites in the Rhaetian/Lower Sinemurian interval (FIECHTNER, 1990; FIECHTNER et al., this vol.). In the area of the »Atlas Gulf« (CHOUBERT & FAURE-MURET, 1962) which comprises the Middle Atlas and the central and eastern High Atlas, marine deposition continued up to the Middle Dogger, with thickness up to 2500 m within the depocenters and only zero to some tens of meters on the adjacent platforms of the Moroccan and the Oran Mesetas (e.g. FEDAN, 1988; CHARRIERE, 1990; HAUPTMANN, 1990). Excessive values of 8000 m, as reported by STUDER (1980) for the Jurassic beds in parts of the central High Atlas, were not generally accepted up to now.

Within the Atlas grabens, synsedimentary block-faulting reached considerable degrees (e.g. STUDER & DRESNEY, 1980; DRESNAY, 1987; WARME, 1988; FEDAN et al., 1989; HAUPTMANN, 1990). Since the fundamental study of MATTAUER et al. (1977), it was related to rightlateral movements along the Atlas faults, but it is very difficult to prove the existence of pre-Tertiary lateral displacements and pull-apart basins.

In general, this first stage of Atlas evolution reflects the break-up of Pangaea and the opening of the North Atlantic and the Tethys oceans. Rifting culminated with the tholeiite effusions and rapid subsidence of the Atlas grabens in the Sinemurian/Bajocian interval. Volcanic activity ceased, however, during the Lias, and subsidence decreased during the Middle Jurassic.

Bathonian-Eocene

From a geotectonic point of view, this second period of Atlas evolution can not be analysed, at present, in satisfying detail. Generally, subsidence slowed down, and the rates of sedimentation within and outside the Atlas grabens were not so different from one another as they had been before. The sea retreated from the Atlas Gulf, and sedimentation changed from lagoonal limestones to near-shore and, finally, continental redbeds, up to the Lower Cretaceous. In Middle Cretaceous times, large parts of Morocco and, moreover, of North Africa were flooded by flat seas which transgress from the Atlantic and the Tethys oceans. Post-Turonian redbeds testify to an Upper Cretaceous regression. It was followed by the well-known Palaeocene and Eocene transgressions which flooded large parts of Southern and Central Morocco. It is important to mention that, notwithstanding the decrease of subsidence, Cretaceous and Tertiary sedimentation exceeded the High Atlas graben to the S covering parts of the Anti-Atlas or, at least, the previous graben shoulders. That development points to a gradual cooling of the crust.

Tectonic activity was strong in Callovian times, with block-faulting and strike-slip movements.

Compressional deformation was, however, confined to limited areas (SEUFERT, 1988; HEINITZ, 1989) and probably caused by lateral displacement (see also LAVILLE, 1985). Later on, block-faulting seems to have decreased, but Cretaceous sedimentation was severely influenced by contemporaneous faulting at least in the Middle Atlas (ENSSLIN, this vol.). Many authors have, furthermore, assumed a new peak of tectonic activity in Late Cretaceous times (phase finicétacée of French authors), and several of them interpreted it to have been a first stage of tectonic inversion of the Atlas chains (e.g. STETS & WURSTER, 1981; ZIEGLER, 1988). But distinct traces of a considerable »Senonian« uplift are confined only to the northern margins of the western High Atlas (FROITZHEIM, 1984; FROITZHEIM et al., 1988) and the Middle Atlas (HERBIG, 1988) and should be referred to more local events. Pebbles of typical Atlas rocks (e.g. Liassic limestones), which would indicate general uplift and erosion of those ranges, do not appear in Upper Cretaceous or Lowermost Tertiary deposits. Furthermore, it was recently shown by HERBIG (1986, 1990) and TRAPPE (1989 and this vol.) that at least the western and central High Atlas had been flooded subsequently by Early Tertiary seas, at least up to the end of the Bartonian. Therefore, a general inversion of the Atlas chains in Upper Cretaceous times has to be rejected.

Magmatic activity is documented by undersilified alcaline intrusions and local extrusions in the central High Atlas (e.g. CHEVREMONT, 1977; STUDER, 1980; HARMAND & LAVILLE, 1983), but their geochemical compositions are not yet known in detail, and radiometric data are poor and scattered over the whole interval under discussion (e.g. HAILWOOD & MITCHEL, 1971; TISSERANT et al., 1976). At least Callovian and Eocene ages are certain. Anyway, the character of magmatism points to a continental environment in contrast to Early Mesozoic rifting.

Oligocene – present

In Oligocene times, the geotectonic evolution of the High and Middle Atlas changed totally. The previous rift grabens underwent compressional/transpressional deformations with lateral shortening up to 20% in the central High Atlas (JACOBSHAGEN, 1986; JACOBSHAGEN et al., 1988) and, subsequently, a strong uplift, which is documented by the frequent appearance of Atlas pebbles within the molassic basins along the southern rim of the High Atlas. According to GÖRLER et al., (1988), the first stage of uplift and erosion of that range culminated during the Early Miocene, as indicated in the basins by very thick conglomerates which are nearly completely composed of pebbles of Liassic limestones. Uplift released large-scale gravity sliding on both flanks of the Central High Atlas (LAVILLE et al. 1977, FERRANDINI & LE MARREC, 1982; GÖRLER et al., 1988). Synchronously, the Anti-Atlas subsided and was partly covered by molassic deposits. The end of that stage is marked by wide-spread lacustrine sediments of a late Middle Miocene to Upper Pliocene age.

A second stage of inversion is indicated by coarse conglomerates of Upper Pliocene or even Lower Pleistocene age (GÖRLER et al., 1988), both in the southern molassic basins (»Villafranchien«, GAUTHIER 1957) and even on the Haute Moulouya, i.e. in the Oran Meseta. The latter had been an elevated platform between the Atlas grabens from the Triassic to the Miocene, but was now overtopped by the rising High and Middle Atlas chains. Uplift culminated probably in Lower Quaternary times and continues up to present. Again, it occurred within a compressional regime as was proved by microtectonic and seismological studies (DUTOUR & FERRANDINI, 1985; AÏT BRAHIM et al., 1990), but compression was not as strong as during the first stage. Anyway, the Middle Atlas is upthrust to the SE upon the Lower Pleistocene conglomerates, and along the southern rim of the High Atlas, even Mio/Pliocene thrust sheets can be observed between scales of Mesozoic rocks (e.g. CHOUBERT et al., 1980; ZYLKA, 1988). Discussion is, however, open, whether these marginal structures could be explained by gravity sliding.

Finally, it has to be mentioned that the uplift of both the Rif and the Anti-Atlas coincided with the second stage of Atlas inversion.

Upper Cenozoic volcanism was active in Morocco from Upper Miocene to Middle Quaternary times. Its centres are distributed in a SW trending zone, which extends from the Mediterranean coasts around Melilla to the Anti-Atlas. They expose a great variety of undersilified alcaline rocks, reaching from phonolites to ultramafics. In the Middle Atlas, two phases of eruptions could be discerned by HARMAND & CANTAGREL (1984), being 15–6 Ma and 1.8–0.5 Ma in age. The High Atlas is free of young volcanoes, but from the Anti-Atlas centres, Mio/Pliocene ages are known as well (CHOUBERT et al., 1968, SCHERMERHORN, personal communication).

Within a previous publication (JACOBSHAGEN et al., 1988b) it was shown that both stages of High and Middle Atlas uplift happened immediately after the main orogenic phases of the Rif. Looking for the young volcanic phases, one may speculate also upon a relation between volcanism and inversion, but connections are not yet clear, at present.

The third period of the geotectonic evolution of the Atlas system was, thus, dominated by compression and subsequent uplift of the Middle and the High Atlas, which happened within two stages. During the second one (Plio-Quaternary), the Anti-Atlas was uplifted as well. The role of synchronous ultramafic to intermediate alcaline volcanism, which is confined to the Middle Atlas on one hand and to the Anti-Atlas on the other, is not well understood, up to now.

3. Geophysical constraints

The new geophysical results obtained in NW Morocco (SCHWARZ et al. this vol., WIGGER et al. this vol.) provide new important information on the problem of crustal structure in tectonic inversion regimes. The main geophysical characteristics on the area under study are the following ones.

The Bouguer anomaly field shows two pronounced minima (VAN DEN BOSCH, 1971). The northern anomaly is situated in the foredeep south of the Rif Atlas. The southern minimum, showing an amplitude of −120 mgal, coincides with the central part of the High Atlas, and in addition it incorporates at its NE end the Haute Moulouya. Thus, the Bouguer anomaly forms a broad minimum between the High and Middle Atlas along the seismic refraction profile. In general the northern flank of the gravity minimum is somewhat steeper than the flank at the southern side. It must be noted that south of the High Atlas an average Bouguer gravity level of −50 mgal is present. Therefore, the Bouguer difference attributable to a mountain root amounts only to about −70 mgal.

The results of the seismic refraction measurements are described by WIGGER et al. (this vol.). A simplified crustal section with the main seismic and magnetotelluric results is shown in fig. 2. The crustal thickness along the seismic refraction profile, which runs between the Anti-Atlas and the Middle-Atlas, varies only slightly between 35 and 40 km.

From the Anti-Atlas towards the High Atlas, the crust/mantle boundary dips down from 35 km to about 40 km. The upper crust is made up of a sequence of thin high velocity layers and a broader low velocity zone (WIGGER et al., this vol., fig. 8). Along this part of the profile the lower crust shows only a moderate low velocity inversion. Generally the intensity of velocity reduction increases in northern direction in the upper as well as in the lower crust.

A distinct change of the velocity structure takes place beneath the Haute Moulouya and the

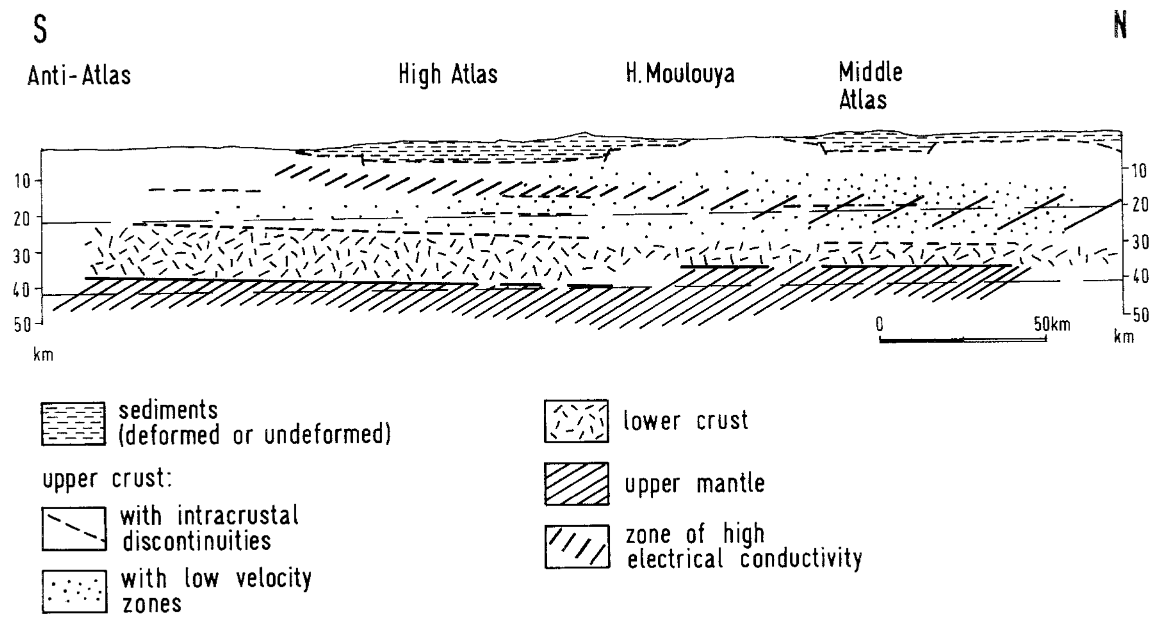

Fig. 2. Schematic crustal section across the intracratonic ranges of the Atlas system.

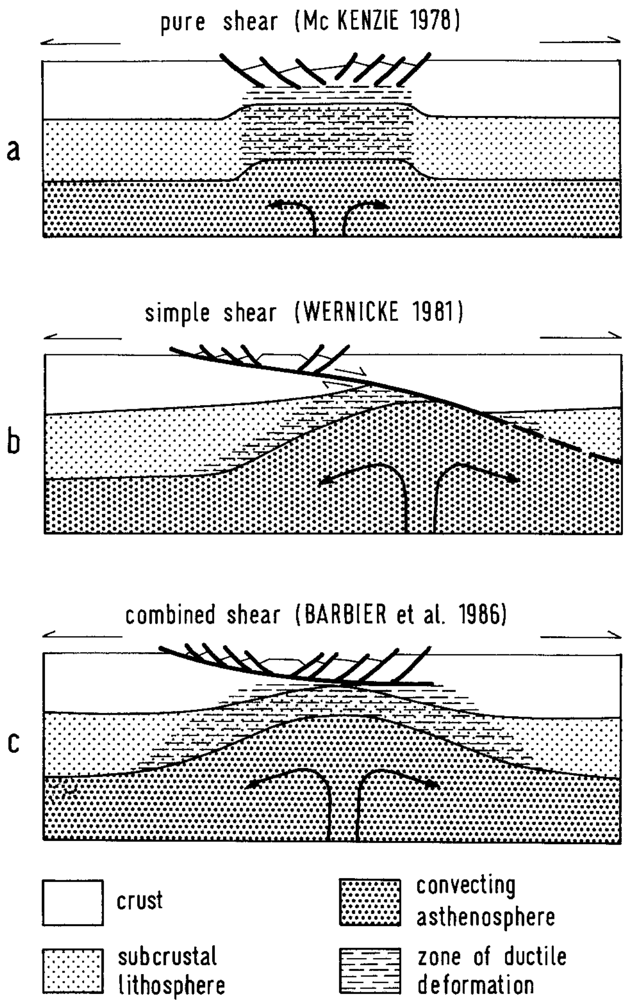

Fig. 3. Geotectonic models of rift zones (from P. A. ZIEGLER, 1988).

Middle Atlas. Here the crustal section is built up of a sequence of low velocity layers down to the base of the crust with embedded thin high-velocity layers. In this northern half of the section the average crustal thickness is 35 km.

A very important contribution to understanding the rheological and tectonic behaviour of the crust in the Atlas system is provided by magnetotelluric studies (SCHWARZ et al., this vol., fig. 6). These investigations have proved the existence of a high-conductivity layer starting in the upper crust beneath the southern margin of the High Atlas and dipping down continuously northwards penetrating the middle or even the lower crust beneath the Middle Atlas. Due to the ambiguity of data inversion, two slightly different models have been presented by SCHWARZ et al. (this vol., fig. 8), which demonstrate the depth range of possible solutions. Within these bounds a steplike model with northwards descending high conductivity layers is possible as well. Such a model would correspond with a ramp-like tectonic configuration. Although the petrological and geological interpretations of such high conductivity layers are non-unique, many authors favour an interpretation as a zone of reduced shear strength acting as detachment or sole thrust plane.

4. Tectonic models

The first stage of the Atlas evolution was characterized by the development of basins and grabens along fracture zones with thick sedimentary fillings. Several models have been proposed for the development of intracontinental basins. These models can be divided into three main groups (ZIEGLER, 1988). The first rifting model with uniform stretching or as pure shear model has been elaborated by MCKENZIE (1978). An equal amount of stretching of the crust and upper lithosphere confined to the actual rifting zone (fig. 3a) is assumend. This model is characterized by a broad symmetrical shoulder uplift.

The other type of models, the simple shear model, has been proposed by WERNICKE (1981). During the extensional period, which is probably accompanied by an increased heat flow from below, the development of intracrustal shear zones is required, along which upper crustal tension by faulting occurs. Along discrete shear zones, that dip laterally into lower crustal levels and possibly into the upper mantle, a structure is produced which is clearly asymmetric in respect of the axis of the basin (fig. 3b). In this model, the nonattenuated upper crust would become progressively uplifted during the rifting stage and during a late or post-rifting stage it would develop into a thermal subsidence basin. BARBIER et al. (1986) have extended the simple shear model by incorporating the rheological stratification of the crust (fig. 3c). The upper crust behaves as a rigid layer with faulting which soles out in the transition from brittle to ductile deformation. This model suggests that tensional strain is dissipated at lower crustal and subcrustal lithospheric levels by ductile flow over a wide zone beyond both margins of the upper crust (ZIEGLER, 1988). This model seems to be the most likely one to describe the first phase of the Atlas evolution.

The second stage of the Atlas development was governed by an uplift of the former graben zones, i.e. by inversion. A number of models have been elaborated aiming to understand this inversion. A transpression model has been proposed by SANDERSON & MARCHINI (1984). The block uplift during the Cenozoic is explained in terms of left-lateral transpression together with some shortening in N/S direction. A further inversion model, elaborated for the development of the Pyrenees, has been suggested by BALLY (1984). This concept can be transferred to the Atlas system, too.

A simple half-graben, following the concept of WERNICKE, is generated in the extensional phase and filled with sediments. The subsequent compressional movements, which reactivated already existing faults, but in opposite directions, produced an uplift of the former graben zones, now forming a positive structure.

The cross sections shown in fig. 4 may sketch the situations during the rifting (fig. 4a) and during the compressional phase (fig. 4b). For the stretching phase two separated shear planes (one for the High Atlas and another one for the Middle Atlas) are assumed. Taking into account the magnetotelluric results the same concept is applied during the compressional phase. Beneath the High Atlas it is assumed that the detachment takes place within Paleozoic sediments in the upper crust. Northwards beneath the Haute Moulouya a ramp is introduced and the shear plane plunges into the middle and lower crust, which behave as ductile zones. The Middle Atlas starts with a new detachment which dips down northward as well. A third main fault system must be introduced in front of the Rif Atlas, which caused the young compressional tectonics in the foothills of this mountain system.

Thus the ramp-like structure of northwestern Morocco is controlled by the sequence of undeformed blocks, the Anti-Atlas, the Haute Moulouya and the Meseta, and deformable graben zones, the High and Middle Atlas, each of them with its own sole thrust system.

5. Some quantitative estimations

The northwestern edge of the African block was part of the Hercynian orogenic system, which extended from central Europe to the Appalachian mountain system. The present crustal thickness in central Europe as well as along the eastern coast of North America measures about 30–32 km, a value which can be assumed as well for the crustal thickness in NW Africa at the beginning of the rifting phase in early Mesozoic times.

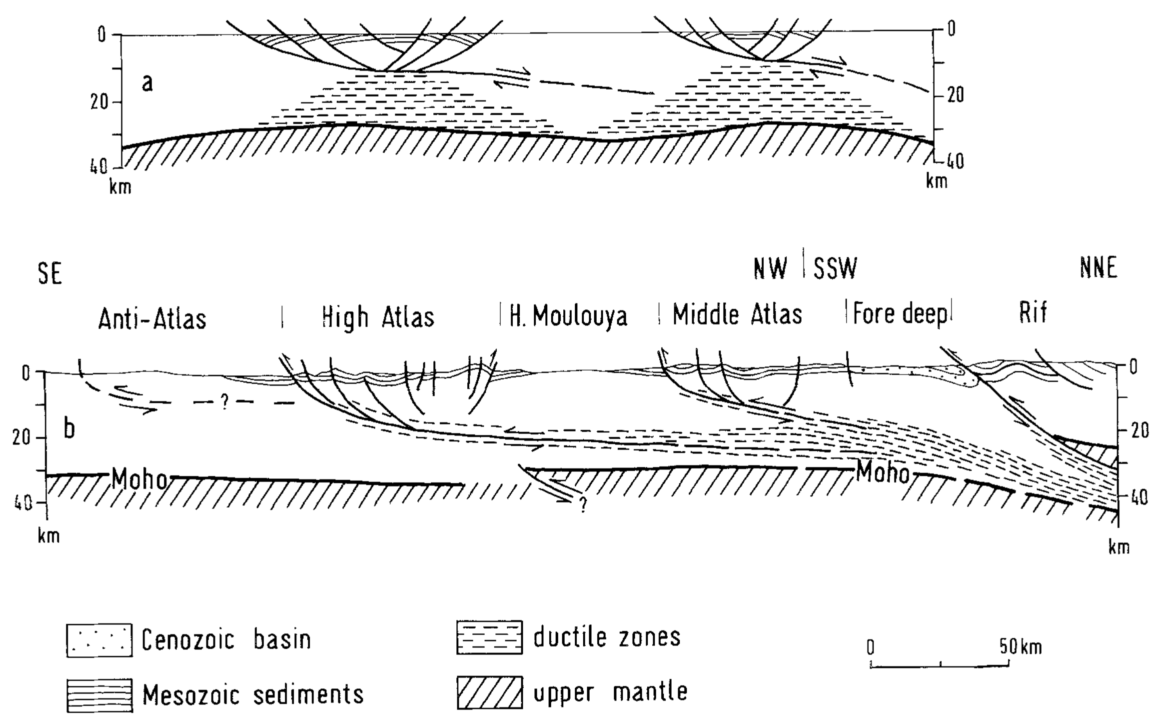

Fig. 4. Geotectonic models of Early Mesozoic rifting (a) and Cenozoic inversion (b) of the intracratonic ranges of the Atlas system.

Using AIRY's concept of isostasy and taking into account an average thickness of 3 km for the sedimentary cover, we may derive a Cenozoic uplift of the crust/mantle boundary of about 2 km for the central parts of the High Atlas (density: sediments 2.5 g/cm^3, crust: 2.8 g/cm^3, upper mantle 3.2 g/cm^3). Thus the total crustal thinning by stretching amounts to 5 km assuming 100 km as width of the Atlas grabens before compression, the stretching factor is 1.2 (fig. 4a). This very simplifying calculation regards only isostatic equilibrium and neglects any thermal effects as assumed e.g. by MCKENZIE (1978).

Extension and subsidence ceased during the Lower Tertiary and was followed by compressional movements in Upper Oligo/Miocene and Plio/Ouaternary times. The section in fig. 4b is kept as simple as possible assuming that the compressional movements reactivated the same faults and shearing planes which have already been used during the extensional period.

Compression produced a moderate crustal thickening of about 7 km, a value which is in agreement with the observed Bouguer anomaly of −(120−50) mgal on one side and with the average elevation of 1−1.5 km of the High Atlas on the other.

6. Conclusions

From the geological history and the geophysical structure of the Atlas system, as far as the latter is known today, we derive a geotectonic model as follows:

a) One may suppose that the crust of Central Morocco had reached a normal thickness of 30−32 km at the end of the Palaeozoic, after the Hercynian orogeny and subsequent erosion.
b) Early Mesozoic rifting was related to zones of updoming of the upper mantle and, in turn, reduction of crustal thickness (fig. 4a). The mechanisms of crustal thinning were discussed in chapter 4. We prefer the model of BARBIER et al. (1986) shown in fig. 3c, which refers to an enlargement of the ductile zone of the crust by ascending heat and intracrustal shearing during extension. Regarding the thickness of Atlas rift-graben fillings, the crust may have thinned, then, to about 28 km in the rift-zones.
c) Cenozoic collisons at the northwestern margin of the African plate, i.e. the Rif orogeny, caused a change from extension to compression. The Early Mesozoic shear-planes postulated above were reactivated with an opposite sense of movements, giving rise to moderate thin- and thick-skinned overthrusts. In fig. 4b only the most important planes were drawn, which served as sole thrusts. Probably, further shear-planes existed higher up and might be a reason for the complicated intracrustal layering shown in the section of WIGGER et al. (this vol., fig. 8). The major crustal blocks, e.g. the Anti-Atlas, the Haute Moulouya and the Moroccan Meseta (not shown in fig. 4) formed large ramps which controlled the geometry of intracrustal thrusting. This is also reflected by the structural asymmetry of both the High and the Middle Atlas with relatively higher rates of up- or over-thrusting along their southern or respectively, southeastern rims. Early Mesozoic crustal thinning was now compensated or even overcompensated by thrusting and compression (e.g. 38−39 km beneath the northern part of the High Atlas, 35 km for the Middle Atlas in the section of WIGGER et al., this vol.). Inversion would, thus, be the result of both thrust movements and isostasy. This view is also in good harmony with the tectonic structures, which testify to shortening amounts up to 20% in the High Atlas and about 10% in the Middle Atlas, and with the present morphology of elevated mountain chains.

The problem of Anti-Atlas uplift remains, however, unsolved. One may speculate (as we tentatively did in fig. 4b) that an additional shear-plane exists even beneath that range in a more shallow depth, which may ascend at this southern border of the range and possibly join the eastern, W/E striking branch of the Anti-Atlas fault (see JACOBSHAGEN, this vol., fig. 2). But at present, we have no proof for that idea. Anyway, the Anti-Atlas was uplifted synchronously to the other Atlas chains in Plio-Quaternary times.

In a general view, Cenozoic inversion of the Middle and High Atlas appears in the well-known sequence of extension/subsidence and compression/uplift and was induced by West Mediterranean collisions several hundred kilometers farther to the north. But different from sections, which were drawn e.g. for Central Europe (P. A. ZIEGLER 1988), we have distinct indications that compressional energy was transmitted far into the lower plate by intracrustal shearing and thick-skinned tectonics. The view seems to be supported by several detailed reflexion seismic profiles across different parts of Morocco, which were presented by BALLY and ZIZI during a poster session in Rabat 1990.

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References

AÏT BRAHIM, L. & CHOTIN, P. (1984): Mise en évidence d'un changement de direction de compression dans l'avantpays rifain (Maroc) au cours du Tertiaire et du Quaternaire. – Bull. Soc. géol. France, (VII), **26,** 681–692, Paris.

—, CHOTIN, P., TADILI, B. A. & RAMDANI, M. (1990): Failles actives dnas le Rif central et oriental (Maroc). – C. R. Acad. Sci. Paris (II), **310,** 1123–29, Paris.

BALLY, A. W. (1984): Tectogénèse et sismique reflexion. – Bull. Soc. géol. France (VII), **14,** 279–285, Paris.

BARBIER, F., DUVERGE, J. & LE PICHON, X. (1986): Structure profonde de la marge Nord-Gascogne. Implications sur le mécanisme de rifting et de formation de la marge continentale. – Bull. centre Rech. Expl. – Product. Elf-Aquitaine, **10**(1), 105–121, Pau.

BOSCH, J. W. H. van den (1971): Carte gravimétrique du Maroc, au 1:500000. – Notes et Mém. Serv. géol. Maroc, **234,** Rabat.

CHARRIERE, A. (1990): Héritage hercynien et évolution géodynamique alpine d'une chaîne intracontinentale: Le Moyen-Atlas au S. E. de Fes (Maroc). – Thèse Doct. Etat Univ. Toulouse, 589 p., Toulouse.

CHEVREMONT, P. (1977): Les roches éruptives basiques des boutonnières de Tassent et Tasraft et leurs indices métallifères (Haut Atlas central, Maroc). – C. R. Acad. Sci. Paris (D), **284,** 1493–1496, Paris.

CHOUBERT, G. & FAURE-MURET, A. (1962): Evolution du domaine atlasique marocain depuis les temps paléozoiques. – Livre Mém. P. Fallot, 1960, **1,** 447–527, Paris (Soc. géol. France).

—, CHARLOT, R., FAURE-MURET, A., HOTTINGER, L, MARÇAIS, J., TISSERANT, D. & VIDAL, P. (1968): Note préliminaire sur le volcanisme messinien-pontien au Maroc. – C. R. Acad. Sci. Paris (D), **266,** 197–199, Paris.

—, DESTOMBES, J., GAUTHIER, H. & HINDERMEYER, J. (1980): Carte géologique du Maroc au 1:200000. – Jbel Saghro-Dadès, Rabat.

DUTOUR, A. & FERRANDINI, J. (1985): Nouvelles observations néotectoniques dans le Haut Atlas de Marrakech et le Haouz (Central Maroc). Apports sur l'évolution récente d'un segmente du bâti atlasique. – Revue géol. dyn. Géogr. phys., **26,** 285–297, Paris.

DRESNAY, R. DU (1987): Jurassic development of the region of the Atlas Mountains of Morocco: Chronology, sedimentation and structural significance. – In: C. D. Cornelius, M. Jarnaz & E. P. Lehmann (eds.): Geology and culture of Morocco: 79–99, Tripolis (Earth Sci. Soc., Libya).

FEDAN, B. (1988): Evolution géodynaique d'un bassin intraplaque sur décrochements: Le Moyen Atlas (Maroc) durant le Méso-Cénozoique. – Thèse Doctorat es-Sci. Univ. Rabat, 318 S., Rabat.

—, LAVILLE, E. & EL MEZGUELDI, A. (1989): Le bassin jurassique du Moyen Atlas (Maroc): exemple de bassin sur relais de décrochements. – Bull. Soc. géol. France, (VIII), **5,** 1123–1136, Paris.

FERRANDINI, J. & LE MARREC, A. (1982): La couverture jurassique à paléogène du Haut Atlas de Marrakech est allochtone dans la »zone des cuvettes« d'Ait Ourir (Maroc). – C. R. Acad. Sci. Paris (II.), **295,** 813–816, Paris.

FIECHTNER, L. (1990): Geochemie und Geochronologie frühmesozoischer Tholeiite aus Zentral-Marokko. – Berliner geowiss. Abh., **A 118,** 76 S., Berlin.

FROITZHEIM, N. (1984): Oberkretazische Vertikaltektonik im Hohen Atlas SW von Marrakech/Marokko – Rekonstruktion eines Bewegungsablaufs im Frühstadium der Atlas-Orogenese. – N. Jb. Geol. Paläont. Mh., **1984,** 463–471, Stuttgart.

—, STETS, J. & WURSTER, P. (1988): Aspects of western High Atlas tectonics. – In: V. H. Jacobshagen (ed.): The Atlas system of Morocco. Studies on its geodynamic evolution. – Lect. Notes Earth Sci., **15,** 219–244, Berlin (Springer).

GAUTHIER, H. (1957): Contribution à l'étude géologique des formations post-liasiques du bassin du Dadès et du Haut-Todra (Maroc méridional). – Notes Mém. Serv. géol. Maroc, **119,** 212 S., Casablanca.

GÖRLER, K., HELMDACH, F.-F., GAEMERS, P., HEISSIG, K., HINSCH, W., MÄDLER, K., SCHWARZHANS, W. & ZUCHT, M. (1988): The uplift of the central High Atlas as deduced from Neogene continental sediments of the Ouarzazate province, Morocco. – In: V. H. Jacobshagen (ed.): The Atlas System of Morocco. – Lect. Notes Earth Sci., **15,** 361–404, Berlin-Heidelberg (Springer).

HAILWOOD, E. A. & MITCHELL, J. G. (1971): Palaeomagnetic and radiometric dating results from Jurassic intrusions in South Morocco. – Geophys. J. R. astr. Soc., **24,** 351–364, London.

HARMAND, CH. & CANTAGREL, J.-M. (1984): Le volcanisme tertiare et quaternaire du Moyen Atlas (Maroc): chronologie K/Ar et cadre géodynamique. – J. Afr. Earth Sci., **2,** 51–55.

HAUPTMANN, M. (1990): Untersuchungen zur Mikrofazies, Stratigraphie und Paläogeographie jurassischer Karbonatgesteine im Atlas-System Zentral-Marokkos. – Berliner geowiss. Abh., **A 119,** 90 S., 32 Abb., 15 Taf., Berlin.

HEINITZ, W. (1989): Deformationsmuster im zentralen Hohen Atlas entlang einer Traverse von Rich nach Midelt (Marokko). – N. Jb. Geol. Paläont. Mh., **1989,** 88–108, Stuttgart.

HERBIG, H.-G. (1986): Lithostratigraphisch-fazielle Untersuchungen im marinen Alttertiär südlich des zentralen Hohen Atlas (Marokko). – Berliner geowiss. Abh., **A 66,** 343–380, Berlin.

— (1990): Das Paläogen am Südrand des zentralen Hohen Atlas und im Mittleren Atlas Marokkos. Stratigraphie, Fazies, Paläogeographie und Paläotektonik. – Unveröff. Habil.-Schr., Freie Univ. Berlin, 206 S., 40 Taf., Berlin.

HOUTEN, F. B. VAN (1976): Late Variscan nonmarine basin deposits, northwest Africa: Implications for pre-drift North Atlantic reconstructions. – Amer. J. Sci., **276,** 671–693.

JACOBSHAGEN, V. (1986): Zur Baugeschichte des zentralen Hohen Atlas (Marokko). – Berliner geowiss. Abh., **A 66,** 433–454, Berlin.

–, BREDE, R., HAUPTMANN, M., HEINITZ, W. & ZYLKA, R. (1988a): Structure and post-Palaeozoic evolution of the central High Atlas. – In: V. H. Jacobshagen (ed.): The Atlas System of Morocco. – Lect. Notes Earth Sci., **15,** 245–271, Berlin-Heidelberg etc. (Springer).

–, GÖRLER, K. & GIESE, P. (1988b): Geodynamic evolution of the Atlas System (Morocco) in post-Palaeozoic times. – In: V. H. Jacobshagen (ed.): The atlas System of Morocco. – Lect. Notes Earth Sci., **15,** 481–499, Berlin-Heidelberg etc. (Springer).

LAVILLE, E. (1980): Tectonique et microtectonique d'une partie du versant sud du Haut Atlas marocain (boutonnière de Skoura, nappe de Toundoute). – Notes Serv. géol. Maroc, **41,** 81–184, Rabat.

— (1985): Evolution sédimentaire, tectonique et magmatique du bassin jurassique du Haut Atlas (Maroc). Modèle en relais multiples des décrochements. – Thèse Doct. Etat: 427 S., Montpellier.

— & HARMAND, C. (1982): Evolution magmatique et tectonique du bassin intracontinental mésozoique du Haut Atlas (Maroc): un modèle de mise en place synsédimentaire de massifs »anorogeniques« liés à des décrochements. – Bull. Soc. géol. France (VII), **24,** 213–227, Paris.

–, LESAGE, J. C. & SEGURET, M. (1977): Géométrie, cinématique (dynamique) de la tectonique atlasique sur le versant sud du Haut Atlas marocain. Aperçu sur les tectoniques hercyniennes et tardi-hercyniennes. – Bull. Soc. géol. France, (7), **19,** 527–539, Paris.

LORENZ, J. C. (1988): Synthesis of Late Paleozoic and Triassic redbed sedimentation in Morocco. – in V. H. Jacobshagen (ed.): Lect. Notes Earth Sci., **15,** 139–168, Berlin-Heidelberg etc. (Springer).

MATTAUER, M., PROUST, F. & TAPPONNIER, P. (1972): Major strike slip faults of Late Hercynian age in Morocco. – Nature, **237,** 160–162.

–, TAPPONNIER, P. & PROUST, F. (1977): Sur les mécanismes de formation des chaînes intracontinentales. L'exemple des chaînes atlasiques du Maroc. – Bull. Soc. géol. France (7), **19,** 521–526, Paris.

MCKENZIE, D. (1978): Some remarks on the developments of sedimentary basins. – Earth planet. Sci. Letters, **40,** 25–32.

SANDERSON, D. J. & MARCHINI, W. R. D. (1984): Transpression. – J. struct. Geol., **6,** 449–458.

SEUFERT, G. (1988): Jurassic sediments and synsedimentary tectonics in the Central High Atlas, Morocco. – Bull. Soc. géol. France (VIII), **4,** 375–390, Paris.

STETS, J. & WURSTER, P. (1981): Zur Strukturgeschichte des Hohen Atlas in Marokko. – Geol. Rdsch., **70,** 801–841, Stuttgart.

STUDER, M. (1980): Tectonique et pétrographie des roches sédimentaires, éruptives et métamorphiques de la région de Tounfite-Tirrhist (Haut Atlas central, Maroc). – Thèse Univ. Neuchâtel: 95 S., Neuchâtel.

STUDER, M. & DRESNAY, R. DU (1980): Déformations synsédimentaires en compression pendant le Lias supérieur et le Dogger au Tizi n'Irhil (Haut Atlas central de Midelt, Maroc). – Bull. Soc. géol. France (VII), **22,** 391–397, Paris.

TISSERANT, D., THUIZAT, R. & AGARD, J. (1976): Données géochronologiques sur le complexe de roches alcalines du Tamazeght (Haut Atlas de Midelt), Maroc. – Bull. B.R.G.M., **1976**(3), 279–283, Paris.

TRAPPE, J. (1989): Das marine Alttertiär im westlichen Hohen Atlas (Marokko). Mikrofazies, Paläogeographie, Phosphoritgenese. – Diss. Univ. Bonn: 217 S., Bonn.

WARME, J. E. (1988): Jurassic carbonate facies of the central and eastern High Atlas rift, Morocco. – In: V. H. Jacobshagen (ed.): The Atlas System of Morocco. Studies on its geodynamic evolution. Lect. Notes Earth Sci., **15,** 169–199, Berlin etc. (Springer).

WERNICKE, B. (1981): Low-angle normal faults in the Basin-and-Range province: Nappe tectonics in an extending orogen. – Nature, **291,** 645–647, London.

ZIEGLER, P. A. (1988): Evolution of the Arctic-North Atlantic and the Western Tethys. – AAPG Memoir, **43,** 198 pp., Tulsa.

ZYLKA, R. (1988): Die südliche Randzone des Hohen Atlas zwischen Toundoute und Goulmima (Marokko). – Berliner geowiss. Abh., **A 96,** 129 S., Berlin.