1661-8726/08/020397-12
DOI 10.1007/s00015-008-1266-0
Birkhäuser Verlag, Basel, 2008

Swiss J. Geosci. 101 (2008) 397–408

Inversion tectonics, interference pattern and extensional fault-related folding in the Eastern Anti-Atlas, Morocco

Charles Robert-Charrue* & Martin Burkhard†

Key words: Anti-Atlas, inversion tectonics, thick vs thin skinned tectonics, variscan, extensional fault-related folding

ABSTRACT

The Anti-Atlas belt of Morocco is a Variscan chain which appears as a huge anticlinorium oriented NE-SW. In the internal part of this structure, the actual relief shows the basement cropping out as inliers (Piqué 2001) or *boutonnières*. The cover, a thick pile of Paleozoic sediments up to 12 km thick, is gently folded and of low grade metamorphism in its lower level. The lack of major *décollement*, of a deformation front or thrust-fault makes the Anti-Atlas an unusual type of belt, which does not fit with classic schemes. The Anti-Atlas has been considered to be a thick skinned fold belt, with the crystalline basement involved in the horizontal shortening and where the folding of the cover fits to a "buckle fold" mode (Burkhard et al. 2006). This structural style is determined by two key parameters: the total thickness of Paleozoic cover series and the relative abundance of shale vs. competent marker beds.

The Eastern Anti-Atlas has particular features which are not found elsewhere in the Anti-Atlas. Its location at the intersection between the NW-SE Ougarta chain and the ENE-WSW main body of the Anti-Atlas, produces an egg-box interference pattern. The significance of minor folds and thrusts in the competent beds and their particular orientation is examined. The fact that the cover in the Eastern Anti-Atlas is only 6 km thick, which changes the shale vs competent beds ratio, influences its structural style. The feature that distinguishes the most Eastern Anti-Atlas is the presence of large E-W normal faults affecting the whole structure and creating extensional fault-related folding in the cover.

1. Introduction

The Moroccan Anti-Atlas belt (Choubert & Faure-Muret 1971)(Fig. 1) is located along the northern border of the West-African Craton (WAC), between the Tindouf Paleozoic basin to the South and the High Atlas to the North. The latter results from a Cenozoic inversion of a Mesozoic basin (Frizon de Lamotte et al. 2000). Laterally limited by the Atlantic Ocean to the South-West, the Anti-Atlas s.s. disappears eastward below an Upper Cretaceous-Cenozoic plateau (the so-called "Hamada du Guir") in the Tafilalt region (Fig. 2). The Anti-Atlas possibly corresponds to a Paleozoic foreland fold-belt, which can be regarded as the deformed foreland of the Variscan chain present in Morocco in the "Moroccan Meseta" (Hoepffner et al. 2006; Raddi et al. 2007) (Fig. 1). According to Helg et al. (2004), Caritg et al. (2004) and Burkhard et al. (2006), the Anti-Atlas should be regarded as an unusual type of fold belt due to a generalized thick-skinned style and an abundance of weak layers in the Paleozoic sedimentary pile. The particular interest of the Eastern Anti-Atlas is its location at the intersection between the NW-SE Ougarta chain (Haddoum et al. 2001) and the ENE-WSW main body of the Anti-Atlas (Fig. 1). The aim of this study is, on the one hand, to analyse the structural pattern resulting from this interference and, on the other hand, to discuss the age and tectonic significance of large E-W normal faults, which are described here for the first time.

Detailed geological mapping and structural analysis have been conducted in the Eastern Anti-Atlas in order to characterize the structural style at different scales. Reflexion seismic lines from industry provides additional constraints to establish cross-sections and propose a regional kinematic model.

2. Geological framework

At large scale (Fig. 1), the Anti-Atlas appears as a huge anticlinorium oriented NE-SW (Choubert & Faure-Muret 1971).

Institut de Géologie et d'Hydrogéologie, Université de Neuchâtel, 11, rue Emile-Argand, CH-2009 Neuchâtel, Switzerland.
*Corresponding author: Charles Robert-Charrue. E-mail: ch.robert-charrue@bluewin.ch

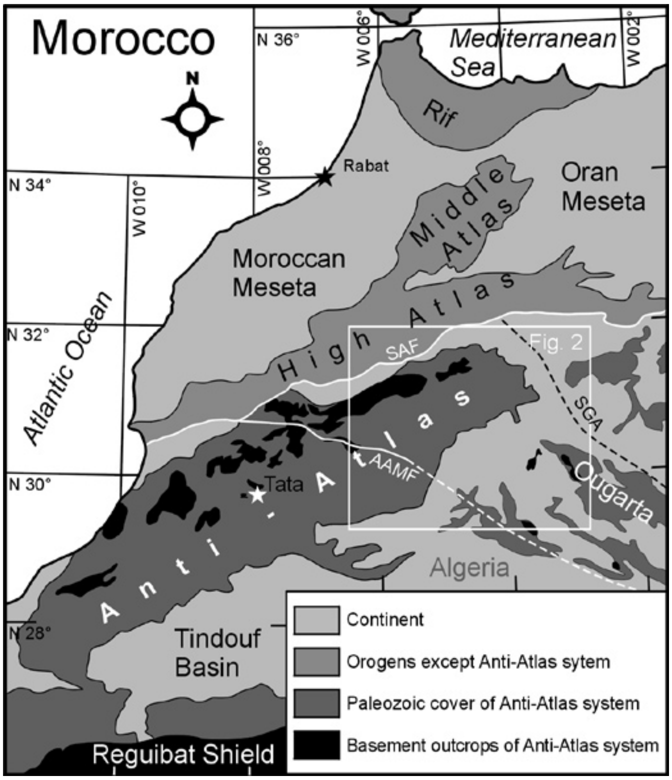

Fig. 1. Geographic situation and geological context of the Anti-Atlas. AAMF: Anti-Atlas Major Fault; SAF: South Atlas Fault; SGA: Saoura gravimetric anomaly.

Locally, the Panafrican and older basement is cropping out in some inliers (Piqué 2001) among which the Saghro and Ougnat are the easternmost ones (Fig. 2). Above the basement, a 6–8 km thick Paleozoic cover is gently folded and exhibits in its lower levels a low grade metamorphism (Ruiz et al. this volume). Both basement and Paleozoic cover are unconformably covered by Upper Cretaceous to Neogene flat lying sediments.

2.1. Basement

The Eastern Anti-Atlas shows two main basement outcrops: the Saghro and the Ougnat inliers (Fig. 2). In their ENE prolongation, a third one is hidden below the Cretaceous and Neogene sediments. It is testified by small outcrops of rhyolites (Ouarzazate supergroup) located along the north-east edge of the Tafilalt half-window.

The crystalline basement has a complex history (Ennih and Liégeois 2001). It was last consolidated during the Panafrican orogeny (Brabers 1988). Exposed further west in the Bou Azzer inlier, the Major Anti-Atlas Suture or Anti-Atlas Major Fault (AAMF on Fig. 1) were interpreted as the old border of the African shield (Choubert & Faure-Muret 1971). Recent workers, however, consider it as part of a "metacratonic" belt bordering the West African Craton (Hefferan et al. 2000; Ennih & Liégeois 2001, 2003; Liégeois et al. 2005). A major unconformity in the sediments of the end of the Proterozoic, is interpreted as the onset of a new rifting cycle. The successive opening of Rheic and Paleotethys oceans (Stampfli & Borel 2002) along the NW border of the West African Craton have left their imprint in the area of the future Anti-Atlas belt. Rifting aborted early, but it is structurally very important, since it led to a normal fault-block geometry in the basement of the future Variscan Anti-Atlas. Syn-rift sediments of the "Ouarzazate and Anti-Atlas supergroups" formations are mainly volcanoclastic rocks (Piqué et al. 1999; Piqué 2003), but the thickness of this unit is very thin in the Eastern Anti-Atlas compared to the Western Anti-Atlas (Fig. 4). From a mechanical point of view, the basement and the overlying syn-rift conglomerates and volcanic rocks acted together as a single lower rigid block.

2.2. Paleozoic cover

Throughout the Paleozoic, the Anti-Atlas "basin" is dominated by shallow marine conditions. In the Western Anti-Atlas, the series reach a thickness of 10 km, while in the Eastern Anti-Atlas it is only about 6 km thick (Burkhard et al., 2006). The major part of the Paleozoic sediments are made of fine grained shales, siltstones and mudstones. Competent marker beds are subordinated in abundance and thickness, and distributed among the series. Relatively thin, these competent beds appear morphologically as cuestas and some of these crests can be followed throughout the Anti-Atlas range. The local name of each crest has given the name to the formations (Ordovician: *Jebel Bani*; Devonian: *Jebel Rich*; Carboniferous: *Jebel Ouarkziz*). Not formally accepted as lithostratigraphic terms, they are widely known and used by all the workers in the region.

In the studied area, the Lower Cambrian "Adoudounian series" is lacking or is very thin (Fig. 4). Above some thin basal conglomerates and soft mudstones and shales, the first competent layers are the Cambrian "Green Sandstones". The next marker bed is the Ordovician "First Bani" which is very thin compared to the western region. The major Ordovician cuestas, creating the topographic heights in the Tafilalt, can be linked to the "Second Bani" and are mostly made of quartzites and sandstones. The Silurian shales are very soft and outcrops are exceedingly rare. They are responsible for large valleys in-between the two cuestas of the "Second Bani" and the Devonian "Richs". However, in the middle of the Silurian shales a single limestone marker bed is well known for its echinoderms and some graptolithes at its base. It can be seen as the first member of the carbonate series developed during the Devonian time, contrasting with the first half of the Paleozoic series dominated by silts and sandstones. The Devonian series are characterized by fossiliferous dark-bluish carbonates. The Upper Devonian is marked by a return to detrital sedimentation that dominates throughout the Carboniferous where marker beds of fluvial and/or deltaic sandstones, produce a strong contrast to the carbonates found further west.

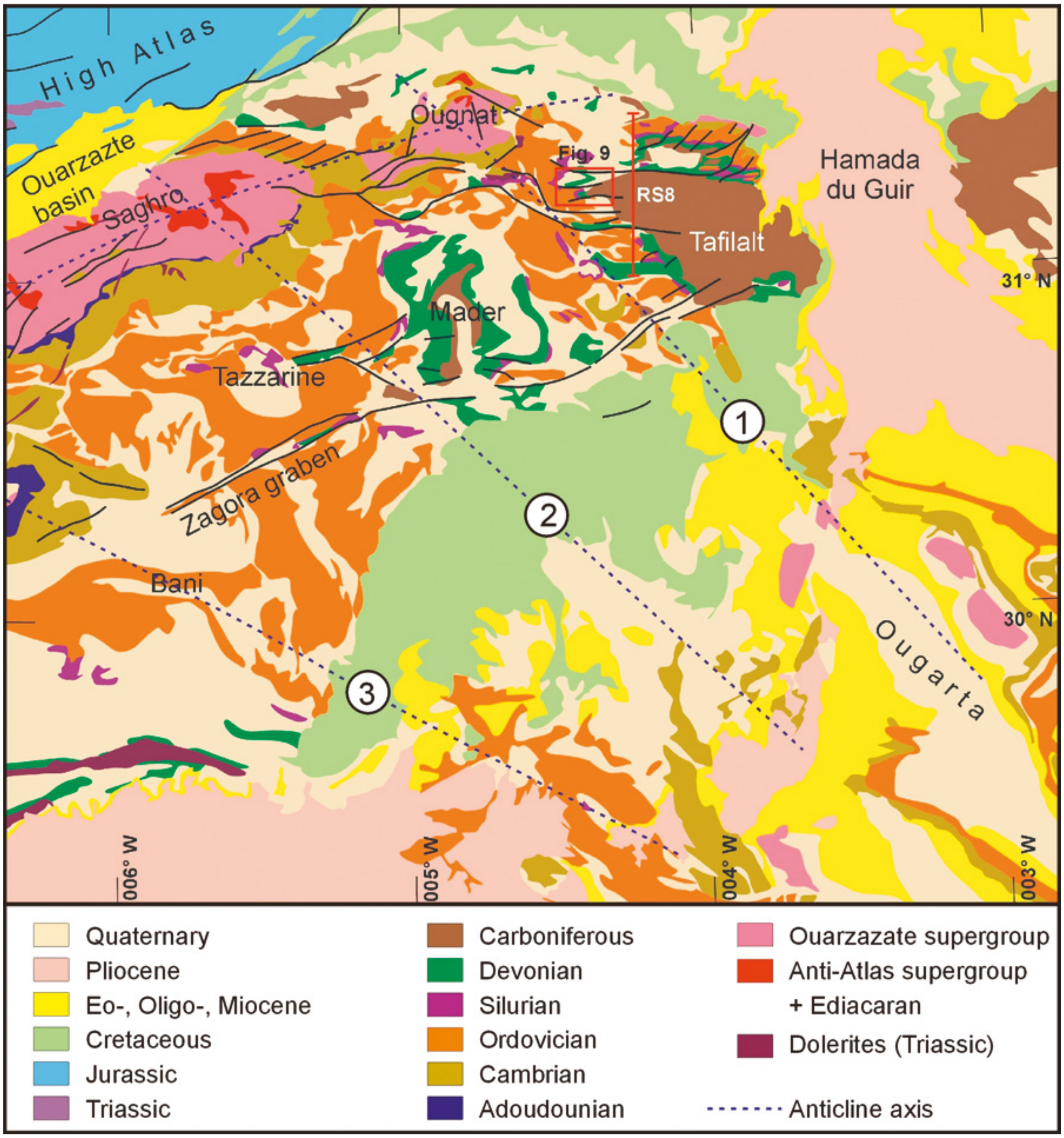

Fig. 2. Simplified geologic map from the Eastern Anti-Atlas. Drawn from the "*Carte Géologique du Maroc*" 1:1'000'000 (1985). 1: the Ougnate – Ouzina anticline, 2: the Saghro – Oum Jrane anticline, 3: the Bou Azzer anticline.

From a mechanical point of view, the abundance of weak layers dictates a particular tectonic style where each stiff layer is independently deformed between thick detachment levels (Fig. 5).

2.3. Mesozoic and Cenozoic

The whole Anti-Atlas domain is unconformably covered by the so-called Hamadas (Fig. 2), which are gently dipping plateaus made up of Upper Cretaceous to Neogene sedimentary rocks. Permian to Lower Cretaceous sediments are absent contrarily to what is observed in the adjacent High Atlas, where Triassic-Jurassic series are deposited in rift-related basins. In the Anti-Atlas, dolerite dykes and sills, dated between 206 and 195 Ma (Sebai et al. 1991) are related to this rifting episode. However, up to now, very few evidence of normal faulting has been found in the Anti-Atlas except the Zagora graben (Fig. 2).

The present high topography of the Anti-Atlas (up to 2700 m) does not result from the only Variscan orogeny. The Cretaceous and younger sediments of the Hamadas are softly tilted, underlying a dome shape at the scale of the whole Anti-Atlas (see Fig. 3, on the DEM and the river patterns on the

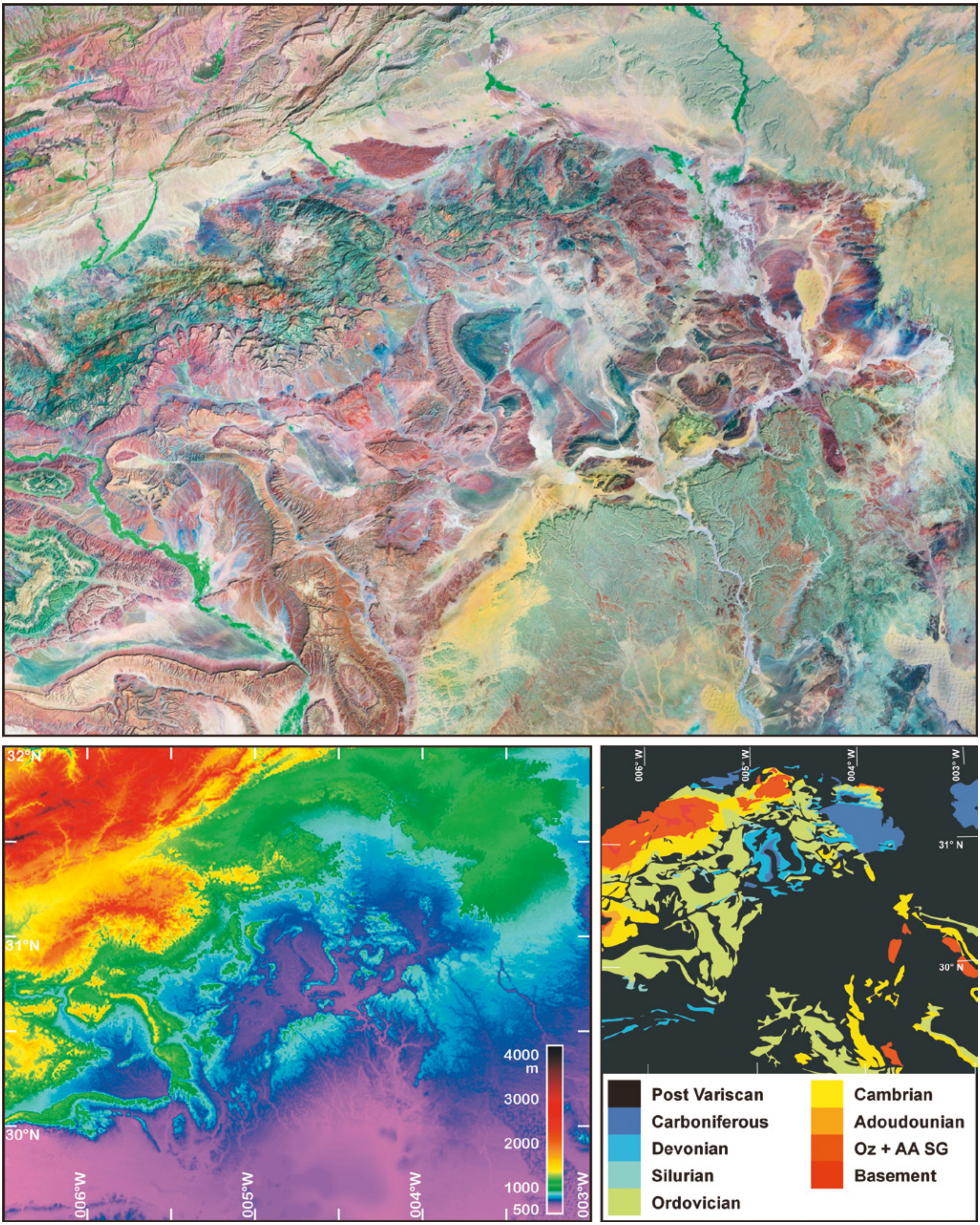

Fig. 3. The Eastern Anti-Atlas. Upper: viewed from Landsat 7 (NASA, 2000). Lower left: Digital elevation model from GTopo30. Lower right: Geologic map. The colours used in this map highlights the major structures.

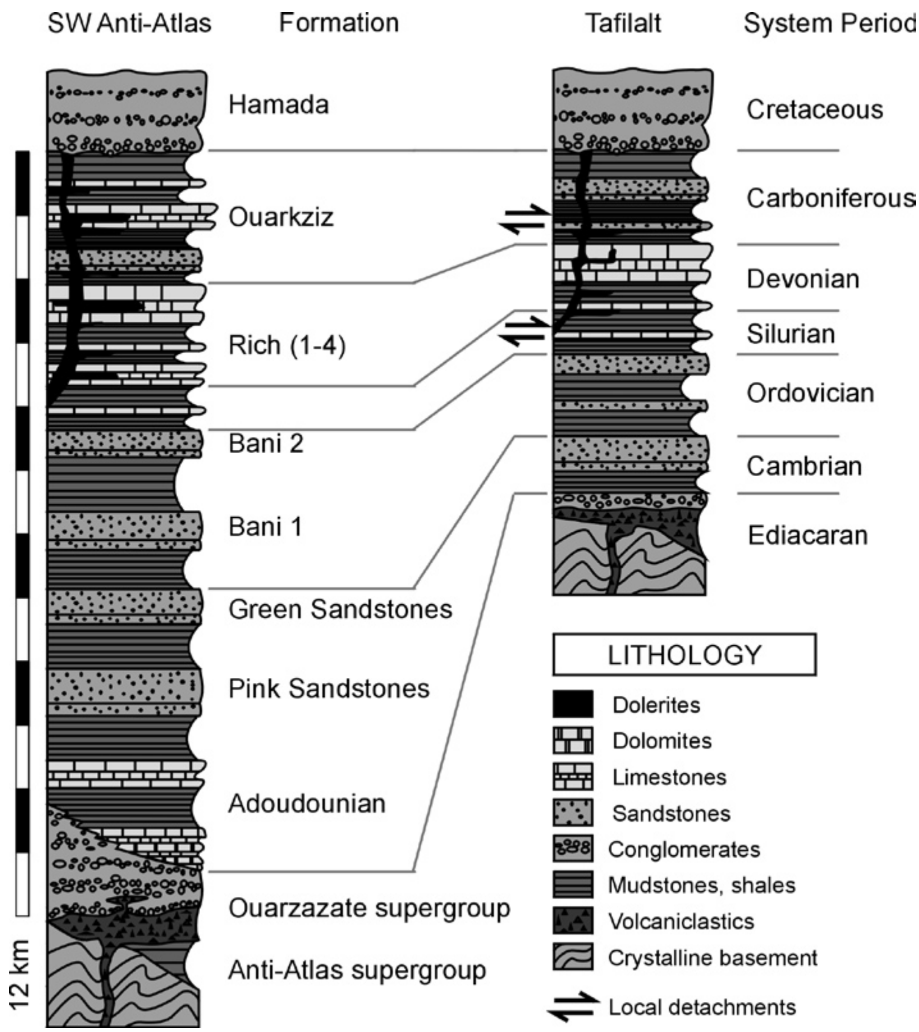

Fig. 4. Schematic lithostratigraphic logs for the Tafilalt area and the whole Anti-Atlas (modified from Soulaimani, 1997 and completed from Tafilalt geologic map, Fetah et al. 1986). The whole series (to the end of Paleozoic) reaches 12 km in the western Anti-Atlas but is decreasing eastward to about 6 km in the Tafilalt area. Some series are reduced but others, like the infra-Cambrian Adoudounian (from Basal Conglomerates to Upper Limestones) and the Early Cambrian, are lacking. Note that the real incompetent/competent layers ratio is more important than the sketch suggests.

Landsat view). The analysis of the scarp retreat by Schmidt (1992) indicates that the beginning of the uplift during late Eocene times, was followed by an increase in late Miocene/early Pliocene times. These geomorphological interpretations fit with structural observations in the High Atlas and with an analysis of the deformation of Neogene sediments (Görler et al. 1988). The structural inversion, which occurred just a few kilometres north, in the High Atlas during Eocene – Oligocene and Pliocene – Pleistocene times (Frizon de Lamotte et al. 2000, Ellouz et al., 2003), affects also the adjacent strongly compartmentalized Anti-Atlas. Moreover, some faults are recognised as active faults. Nevertheless, Missenard et al. (2006) suggest that the Anti-Atlas elevation is mainly of thermal origin and related to a Miocene thinning of the lithosphere known elsewhere in Morocco (Zeyen et al. 2005; Teixell et al. 2005; Saddiqi et al. 2005; Fullea et al. 2006).

3. Field data

3.1. Major structures

The absence of basal *décollement* or major thrust and the absence of well recognised internal deformation in the basement are some of the particularities of the Anti-Atlas fold belt. The dominant structure trend of the Eastern Anti-Atlas is ENE-WSW. This orientation is given by the inliers (Figs. 1 and 2).

A second more discret NW-SE orientation is shown by structures of "Ougarta" orientation. It is highlighted by the trace of the Ordovician Bani formation, which forms the flanks of NW-SE major folds. From east to west the Figure 2 shows: the Tafilalt syncline, the Ougnate – Ouzina anticline, the Mader syncline, the Saghro – Oum Jrane anticline – the Tazzarine syncline and the Bou Azzer anticline. This succession of synform and antiform axes continues to the west forming a large fan. In the easternmost Anti-Atlas, the axes have a NW-SE orientation. This orientation move to WNW-ESE in the central

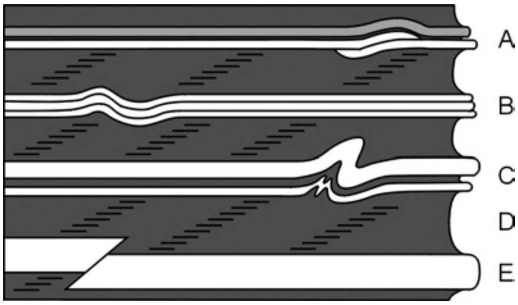

Fig. 5. Schematic effects of layer parallel shortening in competent beds. A: Fishtail structure. B: Buckling. C: Disharmonic oblique fold(s). D: Multitude of small thrusts. E: Reverse fault.

Anti-Atlas to reach an E-W orientation at Tata (see Fig. 1 for location) (Caritg et al. 2004). These two distinct trends (Anti-Atlas and Ougarta) interfere to form a large scale egg-box pattern (Figs. 2 and 3). The Saghro and Ougnat inliers being anticlinal-anticlinal intersections, the Tafilalt and Mader syncline-syncline intersections. Saddle structures such as between the Saghro and the Ougnat *boutonnières*, are syncline-anticline intersections. Given the fanning of the ougartian structures, the angle between the two orientations becomes more acute to the West (Fig. 2).

3.2. Minor structures

Folds and thrusts (Fig. 6) are found in the entire Eastern Anti-Atlas and are observed in each stiff layer independently (Fig. 5), depending on the relative thickness of the stiff and weak layers respectively. Discret thrusts are found in the weak detachments levels.

The small scale structures represent also the interference pattern between an "Anti-Atlas" and an "Ougarta" orientation (Fig. 7). Globally, folds and thrusts south of the inliers show a NW-SE trend. In the Tafilalt and around, this orientation is identical to the one observed in the major structure. South of Ougnat inlier, which exibits a ENE-WSW trend, the small scale features persist with a NW-SE orientation. In the Tazzarine region, south of the Saghro, both orientations coexist at outcrop scale. North of the inliers axis, the orientation of the small scale structures is ENE-WSW fitting with the major structure, except folds north of the Ougnat where the axes remain NNW-SSE.

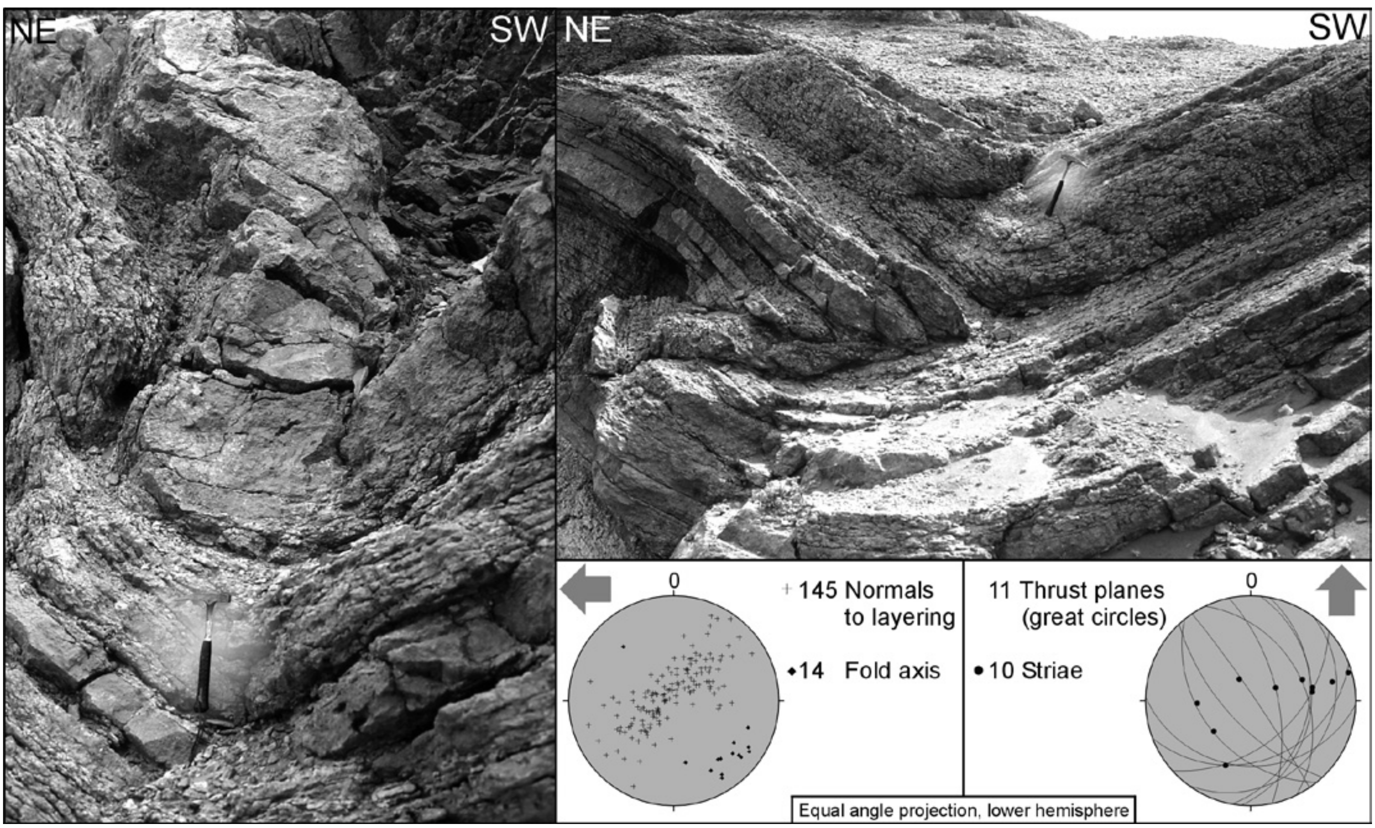

Fig. 6. Small scale structures in the cliff of Jebel Amelane (in the North-East of fig. 9). Left picture: folds in the Middle Devonian; Left stereogramm: poles of bedding planes in folds and folds axes for Jebel Amelane region; Right picture: thrust fault and layer parallel shortening; Right stereogramm: great circles of thrust-planes and striae for Jebel Amelane region.

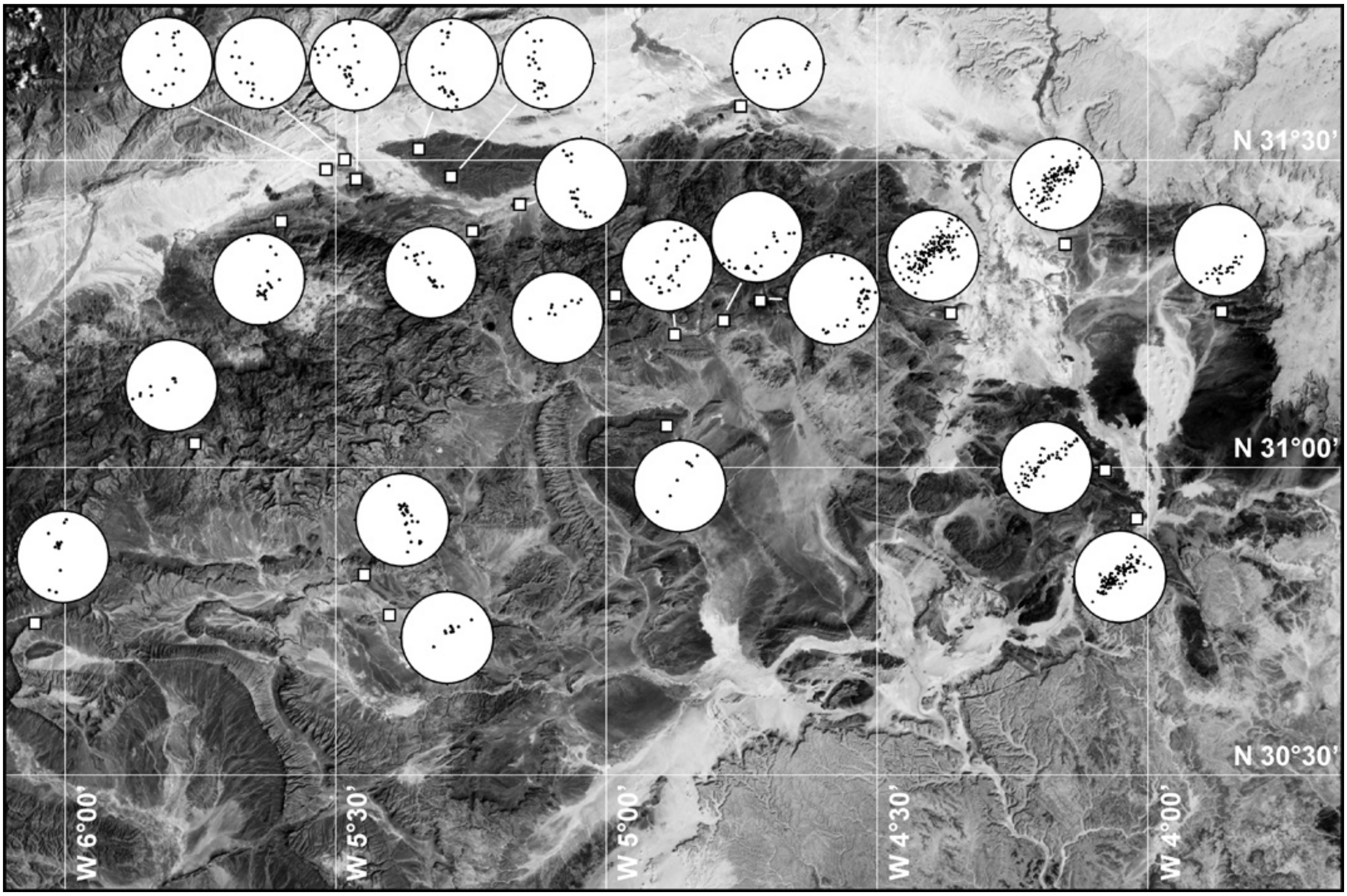

Fig. 7. Landsat 7 view with stereoplots of minor folds. The stereoplots show the normals to layering measured in the folds (equal angle projection, lower hemisphere).

Fig. 8. View to the East of folded Carboniferous sediments. Location is north of the saddle between Ougnat and Saghro inliers. The deformation is more intense north of the inliers with the development of a cleavage.

It is worth noting that in the northern region, the deformation is more intense with the development of a cleavage (Fig. 8). North of the inliers, thrusts faults are not limited to the stiff layers but affect all the Paleozoic series. In spite of the fact that this area is close to the later inverted High Atlas, this intense deformation is only due to Variscan inversion since it is sealed by flat lying Cretaceous sediments which are only lightly tilted.

3.3. Relative chronology

On a large scale, the Carboniferous unit is affected by both orientations without any major tectonic unconformity. South of the Ougnat inlier, it is quite unlikely that small scale folds with an "Ougarta" orientation develop after the setting up of the large scale structures of "Anti-atlas" orientation.

Though, at Tata, the NE-SW folds are clearly refolded by the "Ougarta" folds, which here have an E-W orientation (Caritg et al. 2004). However this relationship is not necessarily applicable to the eastern domain, which is situated in a more internal domain of the Ougarta chain.

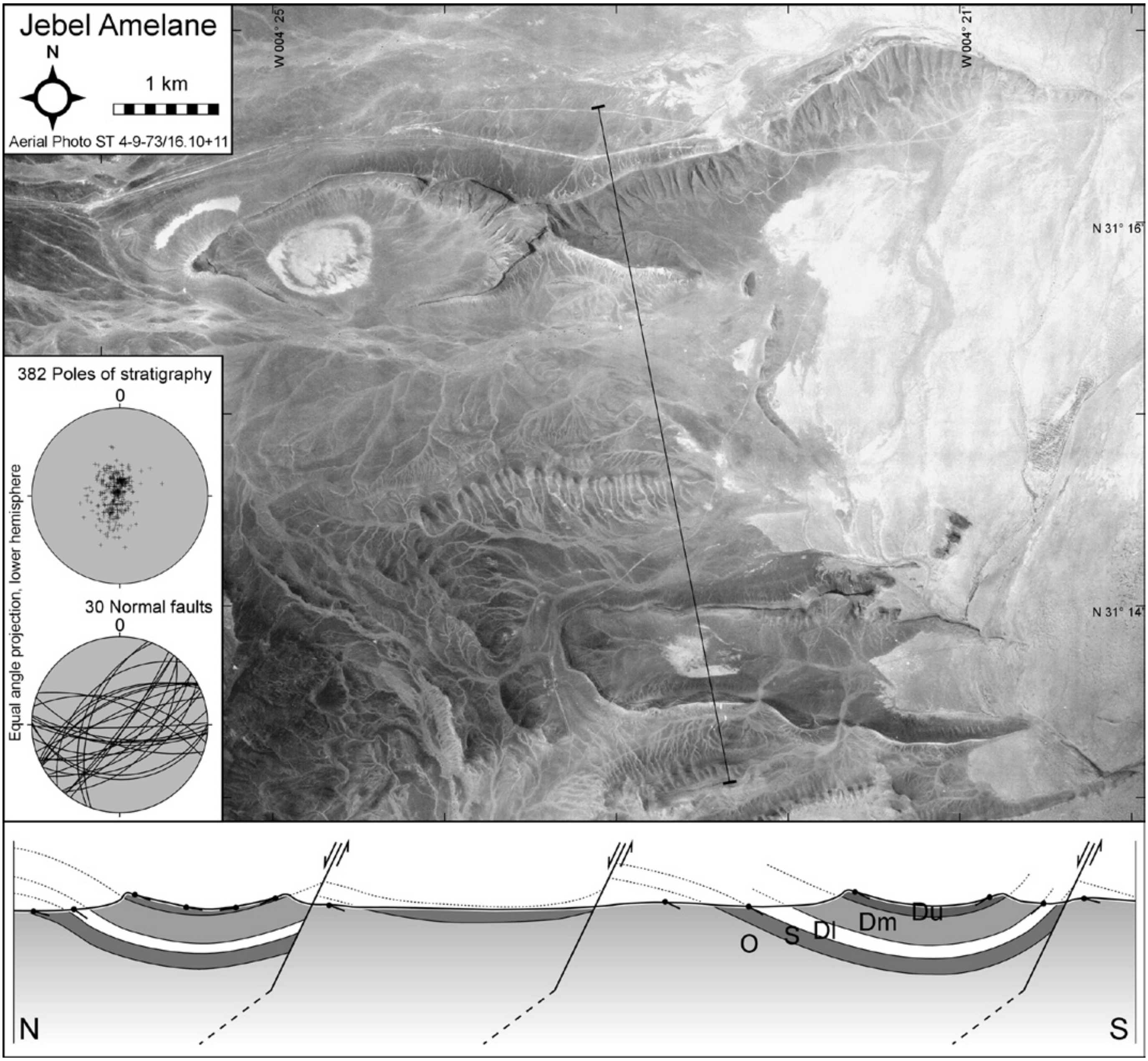

Fig. 9. Aerial mosaic view of Jebel Amelane/Jebel Mech Idrane (Service Topographique du Maroc), 10 km west of Rissani (see Fig. 2 for location); Stereogramms of bedding planes and normal faults; Cross-section. O: Ordovician, S: Silurian, Dl: Late Devonian, Dm: Middle Devonian, Du: Upper Devonian.

3.4. Normal faults

A series of synclines appear in the competent layers of the Devonian and Carboniferous units. Their fold axes are more or less horizontal and are globally oriented E-W with some minor variations. The frequency or spacing between two synclines varies from few hundred meters to some kilometres (Fig. 9).

These synclines are always associated with normal faults. They are particularly well-expressed in the Devonian Rich Formation, which is cut out by the faults, which branch upward in the Carboniferous shales and downward in shales belonging to the Lower Devonian and Silurian. These incompetent series drape the normal faults up to be parallel to the fault plane (cross section on Fig. 9). We interpret the resulting folds as "hanging-wall synclines" or "extensional fault-related folds" (Schlische 1995). Hanging-wall synclines show flexural-slip movement along bedding plane surfaces, which can be misleading since the relative shear sense of such layer

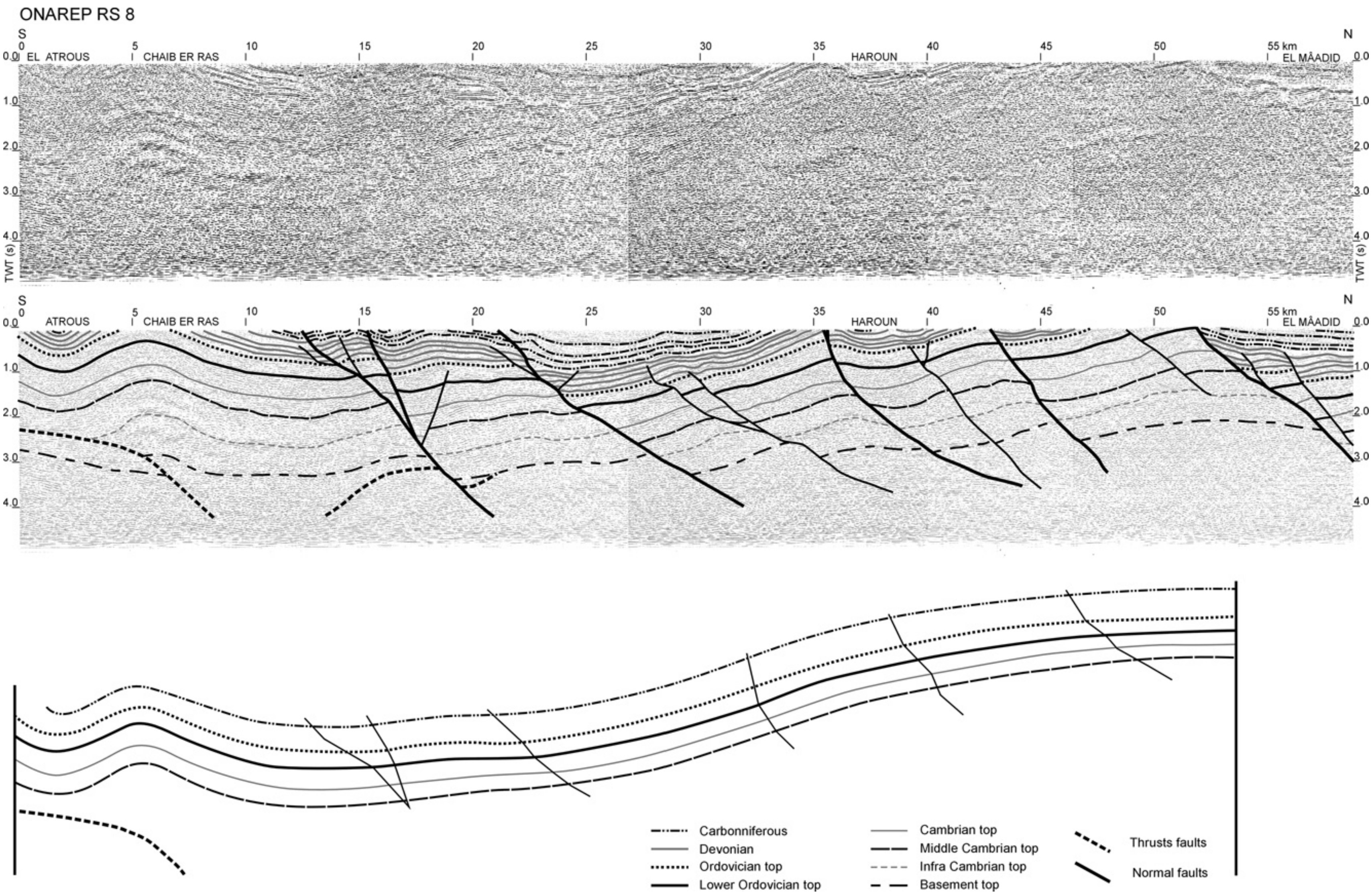

Fig. 10. Seismic line RS 8 (from ONAREP). Upper: blank; Middle: Surface from field work and geological map, interpreted at depth; Lower: reconstructed profile before normal faulting.

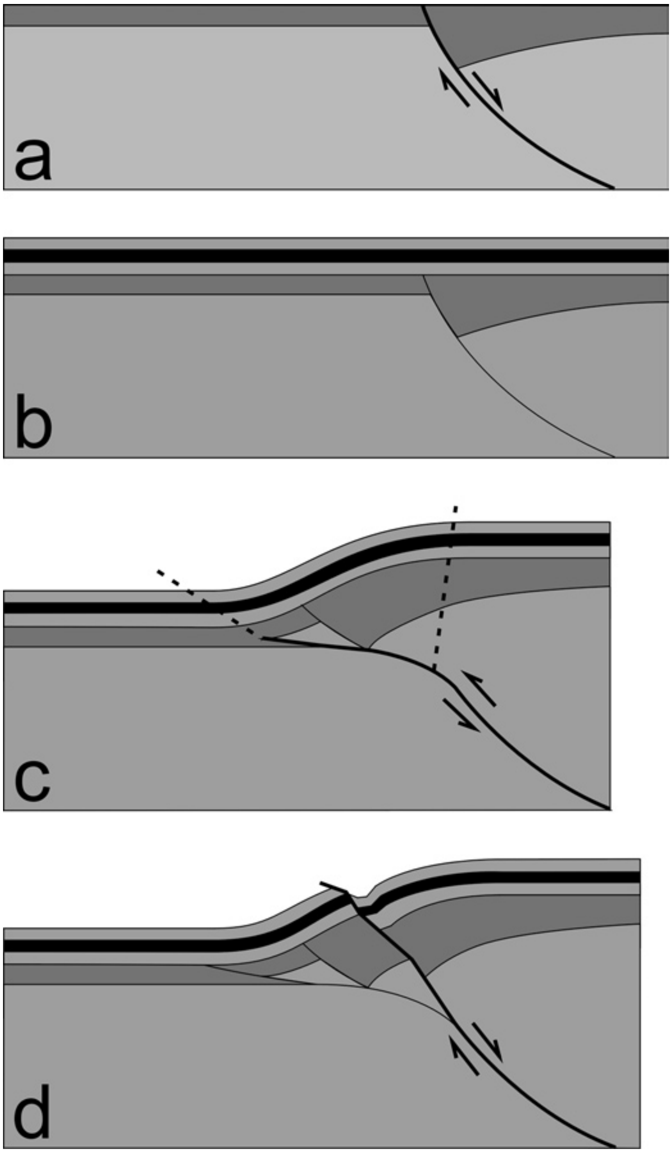

Fig. 11. Schematic illustration of the proposed kinematical model (inspired from Bump, 2003). South-North orientation perpendicular to inliers alignment, but parallel to the Ougartian trend. a: Late Proterozoic rifting with syn-rift sediments; b: Deposition of Paleozoic cover; c: Variscan inversion. The thrust fault takes a shortcut in the basement, the cover reacts in a trishear mode. The Ougartian trend does not appear on this sketch; d: New extension phase (Atlantic opening). Normal faults short cut the Paleozoic cover, its dips vary according to the competence of rocks and produce hanging wall synclines.

parallel slip is always indicating "thrusting" independent of the underlying mechanism of folding in either compression and/or extension. The lower units of the Paleozoic do not permit the development of such folds because of their competent behaviour. The majority of the normal faults are north-dipping (Fig. 10).

The Variscan small scale folds are refolded by these structures. Axes of these small scale folds in the south-plunging flanks of the synclines plunge to the South and those in the north-plunging flanks plunge to the North. The refolding of the Variscan structures places the extensional event after the Variscan orogeny. The fact that this extension affects also the Carboniferous sediments, places this extension in the late Lower Carboniferous at the earliest. Thus, these extensional structures cannot be fully explained by the Late Devonian extension known in the study area (Wendt 1985). The normal faults are associated with the intrusion of Late Triassic-Early Liassic dolerite dykes and sills. These two features (extension and intrusion) are geologically compatible and should be attributed to the same event.

4. Seismic data

The ONAREP (now ONHYM) RS8 seismic reflexion line (Fig. 10) crosses the Tafilalt with a north-south orientation (see location on Fig. 2). Accordingly, this line is perpendicular to extensional folding and oblique to the crustal culmination attributed to the Variscan orogeny.

The first 10 kilometres (southern part) display large scale folds with NW-SE axes. We interpret these folds as being detached along a major *décollement* at the base of the Paleozoic sedimentary pile. Cover shortening is compensated below the *décollement* by inversion of former late Proterozoic normal faults. The resulting folding structure fits well with an Ougarta trend observed on the map. The structural style of the first kilometres of the profile is thin-skinned. This part of this section is not affected by the later extension; this corroborate the fact that its structural style is thin-skinned.

The structural style of the remaining (northern) part of the transect (from km 10 to 60) is dominated by late normal faults. Our interpretation of the "pseudo-basins" seen in the seismic line, is an extensional context. Its observed geometry is explained as a related consequence of a particularly weak cover and a seismic artefact. First, the thinning of the footwall layers and the thickening of the hanging wall layers, which can be seen on the seismic line, is also observed in the image obtained by discrete-element modelling (Finch et al. 2004) specially in the case of an "ultraweak cover on rigid basement". This model is applicable to our study with the Ordivician Bani as rigid basement and the Silurian, Devonian and Carboniferous layers as ultra weak cover. Secondly, the seismic line shows the Two Ways Travel Time and not the depth. The velocity in the Carboniferous shales and mudstones must be particularly slow (probably less than 2000 m/s), while competent layers like Ordovician quartzites may attain 3000 m/s or more. This relationship leads to a pronounced velocity pull down, which tends to exaggerate the depth of the pseudo basins.

The third profile of Figure 10 describe the presumed geometry at the paroxysm of the Variscan deformation, i.e. without the later normal faults. The overall shortening is about 6 km (10%), this is a value measured at regional scale and which does not include the layer-parallel shortening observed at smaller scale. Calculations of the depth to detachment by the displaced-area method (Epard and Groshong 1993) with integration of bed internal deformations show that such distributed small scale deformation adds a substantial amount of shortening of 11 to 17% (Robert-Charrue 2006).

5. Conclusions

The Eastern Anti-Atlas structure is a complex interference between two trends of Variscan folding which lead to an egg box pattern of basins and domes. This fold-related interference pattern is subsenquently cut by a series of normal faults, most likely in response to the opening of the Atlantic in Triassic – Liassic times. The ENE-WSW Anti-Atlas global trend is the best developed in terms of deformation and inversion. The Variscan inversion of the Anti-Atlas is thick-skinned. The Paleozoic cover reacts in a "trishear way" (Erslev 1991) to accommodate basement shortening, inverting former late Proterozoic normal faults (Fig. 11.c). The deformation gradient decreases strongly from NNW to SSE, with increasing distance from the basement *boutonnières*. The NW-SE Ougarta trend is materialized throughout the Eastern Anti-Atlas by small scale folds and thrust faults. This deformation has a important thin-skinned component, with a detachment along weak layers; although the underlying cause is equally thick-skinned basement inversion. The interference between these two trends is thought to be due to the shape of the northern corner of the West African Craton, and particularly a renewed re-mobilisation of its "weak" meta-cratonic borders in late Paleozoic times. Former, normal and inverted faults are again reactivated during the Atlantic opening event. This leads to the formation of steep normal faults and to the intrusion of dolerite dykes and sills within the Paleozoic cover series. The overall weakness of the thick Paleozoic series favours the formation of extensional "drape" folding (Fig. 11.d) similar to those described by Khalil and MacClay (2002) on the margin of the Red Sea rift system. The High Atlas inversion and Neogene thermal uplift has not significantly deformed the Eastern Anti-Atlas. Only gentle doming is documented by the radial tilt and the retreat of Cretaceous cuestas.

Acknowledgments

Ongoing support by the "Ministère de l'Industrie et des Mines, Direction de la géologie" by M. Dahmani and M. Haddane and the moroccan national petroleum agency ONHYM is gratefully acknowledged. Financial support by Swiss National Science Foundation grants N° 21-52516.97/20-63790.00 and by the "Fonds Matthey-Dupraz" local fund for geology students. I am very grateful to Prof. D. Frizon de Lamotte for giving me motivation during painful times and to Prof. J.-P. Schaer for our constructive discussions. Editor Prof. Jon Mosar and the reviewers Prof. Abderrahmane Soulaïmani and Prof. Jürgen Von Raumer are thanked for their constructive reviews.

REFERENCES

Brabers, P. 1988: A plate tectonic model for the Panafrican orogeny in the Anti-Atlas, Morocco. In V.H. Jacobshagen (Ed.), The Atlas System of Morocco; Studies on its Geodynamic Evolution, Springer-Verlag, Berlin-Heidelberg-New York, 61–80.

Bump, A.P. 2003: Reactivation, trishear modeling, and folded basement in Laramide uplifts: implications for the origins of intracontinental faults. GSA Today, 4–10.

Burkhard, M., Caritg, S., Helg, U., Robert-Charrue, C., Soulaimani, S. 2006: Tectonics of the Anti-Atlas of Morocco, C.R. Geoscience 338, 11–24.

Caritg, S., Burkhard, M., Ducommun, R., Helg, U., Kopp, L., Sue, C. 2004: Fold interference patterns in the Late Palaeozoic Anti-Atlas belt of Morocco. Terra Nova 16, 27–37.

Choubert, G., Faure-Muret, A. 1971: Epoque hercynienne. In: Tectonique de l'Afrique, Sciences de la Terre, Paris, 6, UNESCO, Paris, France, 353–371.

Ellouz, N., Patriat, M., Gaulier, J.-M., Bouatmani, R., Sabounji, S. 2003: From rifting to Alpine inversion: Mesozoic and Cenozoic subsidence history of some Moroccan basins. Sedimentary Geology 156, 185–212.

Ennih, N. & Liégeois, J.-P. 2001: The Moroccan Anti-Atlas: the West African craton passive margin with limited Pan-African activity. Implications for the northern limit of the craton. Precambrian Research 112, 289–302.

Ennih, N. & Liégeois, J.-P. 2003: Discussion, The Moroccan Anti-Atlas: the West African craton passive margin with limited Pan-African activity. Implications for the northern limit of the craton: reply to comments by E.H. Bouougri. Precambrian Research 120, 185–189.

Epard, J.-L., Groshong, R.H. 1993: Excess area and depth to detachment, AAPG bulletin, 77 (8), 1291–1302.

Erslev, E.A. 1991: Trishear fault-propagation folding. Geology 19, 617–620.

Finch, E., Hardy, S., Gawthorpe, R. 2004: Discrete-element modelling of extensional fault-propagation folding above rigid basement fault blocks. Basin research 16, 489–506.

Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., Mercier, E. 2000: The two main steps of the Atlas building and geodynamics of western Mediterranean. Tectonics 19 (4), 740–761.

Fullea, J., Fernandez, M., Zeyen, H. 2006: Lithospheric structure in the Atlantic-Mediterranean transition zone (southern Spain, northern Morocco): a simple approach from regional elevation and geoid data, C.R. Geoscience 338, 140–151.

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, Springer-Verlag (Ed.), The Atlas System of Morocco. Lecture Notes Earth Sci. 15, 361–404.

Haddoum, H., Guiraud, R., Moussine-Pouchkine, A. 2001: Hercynian compressional deformations of the Ahnet-Mouydir Basin, Algerian Saharan Platform: far-field stress effects of the Late Palaeozoic orogeny, Terra Nova 13, 220–226.

Hefferan, K.P., Admou, H., Karson, J.A., Saquaque, A. 2000: Anti-Atlas (Morocco) role in Neoproterozoic Western Gondwana reconstruction. Precambrian Research 103, 89–96.

Helg, U., Burkhard, M., Caritg, S., Robert-Charrue, C. 2004: Folding and inversion tectonics in the Anti-Atlas of Morocco. Tectonics 23, TC4006, doi:10.1029/2003TC001576.

Hoepffner C., Houari, M., Bouabdelli, M. 2006: Tectonics of the North African Variscides (Morocco, western Algeria): an outline. C.R. Geoscience 338, 25–40.

Khalil, S.M., McClay, K.R. 2002: Extensional fault-related folding, northwestern Red sea, Egypt. Journal of Structural Geology 24, 743–762.

Liégeois, J.-P., Fekkak, A., Bruguier, O., Errami, E., Ennih, N. 2005: Lower ediacaran age (630–610 Ma) for the Sarhro group. Implications for the metacratonic evolution of the Anti-Atlas, correlations with the Tuareg shield and the evolution of the pan-african orogeny in the NW Africa. 4ème Colloque International 3Ma, Agadir 2005, Abstract Volume, 2.

Missenard, Y., Zeyen, H., Frizon de Lamotte, D., Leturmy, P., Petit, C., Sérbier, M., Saddiqi, O. 2006: Crustal versus asthenospheric origin of relief of the Atlas Mountains of Marocco, Journal of Geophysical Research, Vol. 111, B03410, 13.

NASA and Earth Satellite Corporation, Landsat 7 images download website (https://zulu.ssc.nasa.gov/mrsid/), last visited 15. 04. 2008.
ONAREP (Office National de Recherches et d'Exploitations Pétrolières) Morocco. Seismic reflexion line RS 8.
Piqué, A., Bouabdelli, M., Soulaïmani, A., Youbi, N., Iliani, M. 1999: Les conglomerates du P III (Néoprotérozoïque supérieur) de l'Anti-Atlas (Sud du Maroc): molasses panafricaines, ou marqueurs d'un rifting fini-protérozoïque ?. C. R. Acad. Sci. Paris, Sciences de la Terre et des planètes 328, 409–414.
Piqué, A. 2001: Geology of Northwest Africa, Beiträge zur regionalen Geologie der Erde; Bd. 29, Gebrüder Borntraeger, 310 p.
Piqué, A. 2003: Perspective, Evidence for an important extensional event during the latest Proterozoic and Earliest Paleozoic in Morocco. C. R. Geoscience 335, 865–868.
Raddi, Y., Baiderr, L., Tahiri, M., Michard, A. 2007: Variscan deformation at the northern border of the West African Craton, eastern Anti-Atlas, Morocc: compression of a mosaic of tilted blocks. Bull. Soc. Géol. Fr. 178 (5), 343–352.
Robert-Charrue, C. 2006: Géologie structurale de l'Anti-Atlas oriental, Maroc. Ph.D. Thesis, Univ. Neuchâtel, 180 pp.
Ruiz, G.M.H., Helg, U.,Negro, F., Adatte, T., and Burkhard, M. 2006: Illite crystallinity patterns in the Anti-Atlas of Morocco. Swiss Journal of Geosciences 101/2.
Saddiqi, O., Ziad, N., Missenard, Y., Frizon De Lamotte, D., Goffe, B., Leturmy, P., El Mamoun, R., Sebti, S., Poupeau, G. 2005: Age Miocène moyen supérieur du soulèvement thermique du Haut-Atlas Central: apport des traces de fission sur apatite. 4ème Colloque International 3Ma, Agadir 2005, Abstract Volume, 45.
Schlische, R. 1995: Geometry and Origin of Fault-Related Folds in Extensional Settings. AAPG Bulletin 79 (11), 1661–1678.
Schmidt, K.-H. 1992: The tectonic history of the Pre-Saharan depression (Morocco) – a geomorphological interpretation. Geologische Rundschau 81 (1), 211–219.
Sebai, A., Feraud, G., Bertrand, H., Hanes, J. 1991: $^{40}Ar/^{39}Ar$ dating and geochemistry of tholeiitic magmatism related to the early opening of the central Atlantic rift. Earth and Planetary Science Letters 104, 455–472.
Service Topographique du Maroc, Aerial Photography, ST 1/40000, Mission 4-9-73, N° 16_10/16_11.
Soulaïmani, A., Le Corre, C., Farazdaq, R. 1997: Déformation hercynienne et relation socle/couverture dans le domaine du Bas-Drâa (Anti-Atlas occidental, Maroc). Journal of African Earth Sciences 24 (3), 271–284.
Stampfli, G.M., Borel, G.D. 2002: A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones, Earth Planet. Sci. Lett. 196, 17–33.
Teixell, A., Ayarza, P., Zeyen, H., Fernandez, M., Arboleya, M.-L. 2005: Effects of mantle upwelling in a compressional setting: the Atlas Mountains of Morocco. Terra Nova 17, 456–461.
Wendt, J. 1985: Disintegration of the continental margin of north-western Gondwana; Late Devonian of the eastern Anti-Atlas (Morocco), Geology 13 (11), 815–818.
Zeyen, H., Ayarza, P., Fernàndez, M. and Rimi, A. 2005: Lithospheric structure under the western African-European plate boundary: A transect across the Atlas Mountains and the Gulf of Cadiz, Tectonics, 24, 2, TC2001, doi: 10.1029/2004TC001639.

GEOLOGICAL MAPS

Fetah, M. Bensaid, M. Dahmani, 1986: Carte géologique du Maroc 1:200000, Tafilalt–Taouz, ministère de l'Énergie et des Mines, royaume du Maroc.
Fetah, M. Bensaid, M. Dahmani, 1986: Carte géologique du Maroc au 1:200 000, Todrha-Ma'der, ministère de l'Énergie et des Mines, royaume du Maroc.
Fetah, M. Bensaid, M. Dahmani, 1986: Carte géologique du Maroc au 1:200000, Zagora–Coude du Drâa–Hamada du Drâa, ministère de l'Énergie et des Mines, royaume du Maroc.

Manuscript received December 1, 2007
Revision accepted May 15, 2007
Published Online first July 25, 2008
Editorial Handling: Jon Mosar, Stefan Bucher