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Fold interference patterns in the Late Palaeozoic Anti-Atlas belt of Morocco

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ABSTRACT

We document two phases of folding within the central part of the Late Palaeozoic Anti-Atlas chain of Morocco. A first generation of SW–NE folds involve a horizontal shortening of 10–20%, accommodated by polyharmonic buckle folding of contrasting wavelengths in Ordovician Jbel Bani quartzites and Devonian Jbel Rich carbonates. A second generation of folds with similar style and wavelengths in an E–W direction lead to complex interference patterns. Dome and basins are developed within the Jbel Rich and within Lower Cambrian dolomites. Both folding phases are related to thick-skinned uplift of Precambrian basement in a Laramide style. In contrast to the typical Rocky Mountain foreland style, however, cover deformation in the Anti-Atlas is mostly decoupled from the undying basement along thick incompetent horizons such as the Lower Cambrian Lie-de-Vin and Silurian shales.

Geological setting

The Anti-Atlas chain of Morocco belongs to the Appalachian–Variscan–Hercynian orogenic belt. Now separated by the Atlantic ocean, a small hinterland part of the larger Appalachian chain is found along the north-western rim of the African craton where it is known as the Mauritanides and Anti-Atlas (Michard, 1976). The Anti-Atlas is a foreland fold-belt similar to the external Appalachian Valley and Ridge (Fig. 1). Northern parts of the chain display large domes of Precambrian basement inliers. The crystalline basement was consolidated during the Panafrican orogeny. A new Wilson-cycle starts in the Latest Proterozoic and lasts for most of the Palaeozoic, leading to the accumulation of an up to 10-km-thick passive margin series (Bertrand-Sarfati *et al.*, 1991; Villeneuve and Cornee, 1994). The so-called PIII conglomerates and volcaniclastic series are now recognized as synrift deposits of Late Proterozoic age (Soulaimani *et al.*, 2003). The overlying post-rift sediments are dominated by detrital series of siltstones, shales and sandstones. Platform carbonates are deposited in the lowermost Cambrian and again during the Devonian – Lower Carboniferous (Piqué and Michard, 1989).

The stratigraphy and regional geology are very well known and mapped (Choubert, 1956; Choubert *et al.*, 1970, 1980; Destombes *et al.*, 1988). In comparison, structural and tectonic studies remain scarce (Faik *et al.*, 2002; Guiton *et al.*, 2003). Intriguing large-scale tectonic features of the Anti-Atlas are the so-called 'boutonnières', basement uplifts with tens of kilometres of horizontal dimension amidst the folded Palaeozoic cover. Sections across the Anti-Atlas depict these basement inliers as large, gentle anticlines or horsts (Choubert, 1971; Michard, 1976; Soulaimani, 1998) akin to the 'plis de fonds' of Argand (1924, figure 5). Many authors postulated a component of dextral wrenching (Mattauer *et al.*, 1972; Weijermars, 1993). Rodgers (1987) classified the Anti-Atlas basement as 'uplifts within cratons marginal to orogenic belts'. In contrast to the type examples such as the Rocky Mountain Wind River uplifts, Anti-Atlas basement domes are surrounded by intensely folded cover series, seemingly in a 'thin-skinned' style (Rodgers, 1995).

Here we present new structural observations from a central portion of the Anti-Atlas fold belt, near Tata, where the general strike of the chain changes abruptly from SW–NE to E–W.

Fold- or thrust-belt?

Folds of competent Palaeozoic marker beds are the predominant geomorphic and structural feature of the Anti-Atlas, nicely illustrated through satellite images (NASA, 2002) and aerial photographs (Fig. 2). Fold trains within cover series of Ordovician and younger age are highly regular on a regional scale, trending mostly NW–SE with subhorizontal fold axes and subvertical axial planes. Different lithostratigraphic levels have their own characteristic fold amplitude and wavelength. Ordovician quartzites of the Jbel Bani (Fig. 1) with an overall thickness of around 500 m exhibit a fold wavelength and amplitude of 3–5 km. By contrast, competent Devonian limestones and sandstones of the Jbel Rich, with a much smaller thickness of 100–200 m, display folds with wavelength and amplitude in the 1-km range. These two series are separated by a thick interval of Silurian shales accounting for the disharmony. Overall shortening estimates obtained from the restoration of both Devonian and Ordovician fold trains provide similar values of 15–20% (Caritg, 2003; Helg *et al.*, 2003). The Lower Cambrian Lie-de-Vin formation of purple shales acts as an important detachment level. Despite some tight folding observed locally within the thick carbonate series below, estimated horizontal shortening of about 10% is less important than higher in the stratigraphic column, however. The question of where exactly the missing shortening is compensated at depth remains to be determined. Despite excellent outcrop conditions around the basement inliers, we were unable to detect any

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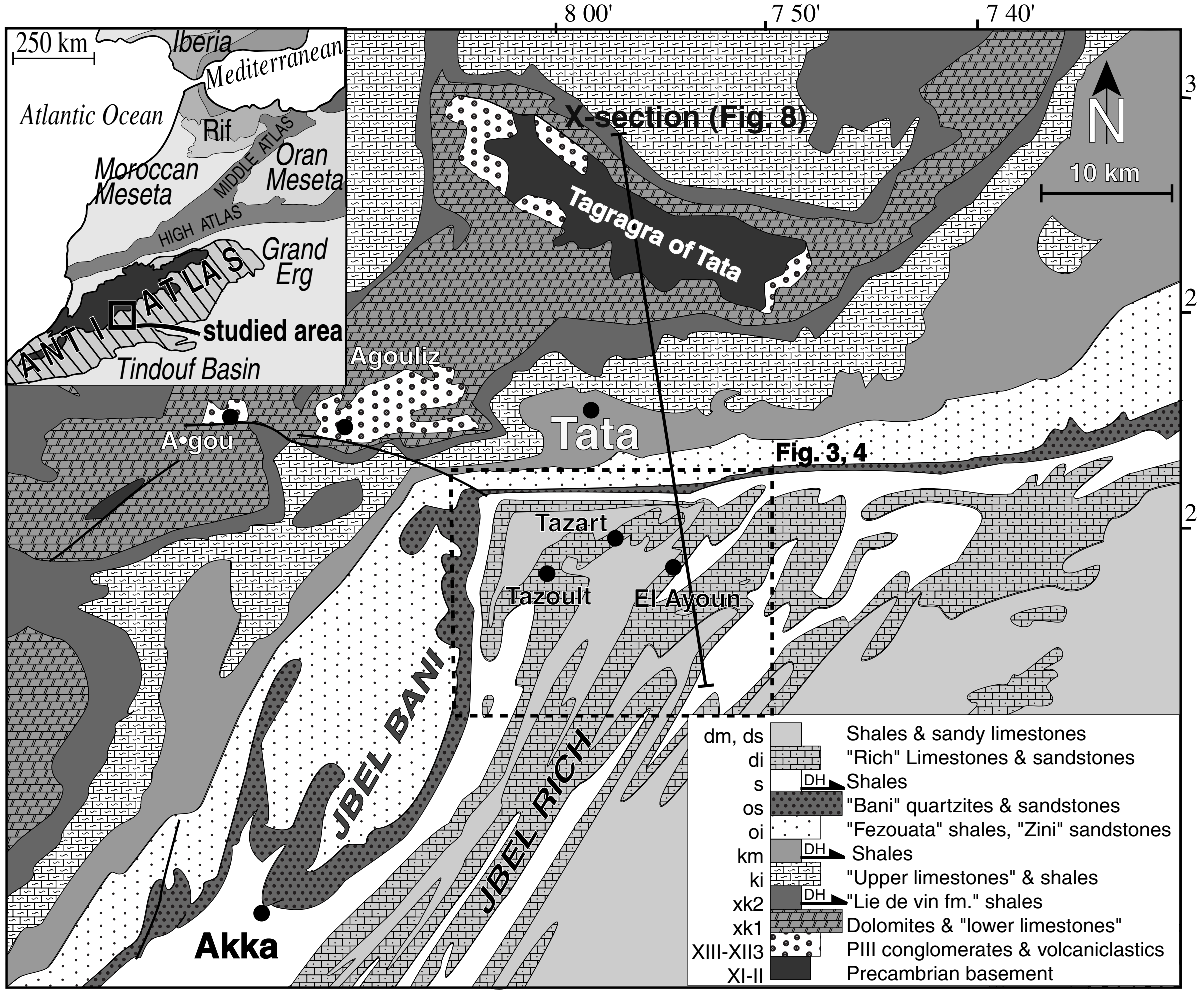


Fig. 1 Geological map of the Akka–Tata area, modified from Choubert and Ennadifi (1970). Abbreviations used in the stratigraphic column are as follows: DH, detachment horizon; X, XI-II, XIII-XII3, upper and terminal stages of the Precambrian; ki, km, lower and middle Cambrian; oi, os, lower and upper Ordovician; s, Silurian; di, dm, ds, lower, middle and upper Devonian. Inset: location of the Akka–Tata study area in the Anti-Atlas belt of southern Morocco.

evidence for a regional, thin-skinned décollement that might have existed prior to the formation of the basement uplifts. Such a décollement would have to be rooted more internally, far to the NW (Belfoul *et al.*, 2002). Instead of such a speculative and remote origin for cover folding of the Anti-Atlas – in a truly thin-skinned fashion – we propose a multitude of locally rooted basement thrust faults bounding the observed basement inliers. These thrust faults are held responsible for the basement uplifts in a Laramide style (Stone, 1993; Marshak *et al.*, 2000; Bump, 2003). Rather than cut upward through the entire cover series, however, thrust faults of the Anti-Atlas basement uplifts affect only the lowermost stratigraphic series (PIII and lower carbonates) before levelling out into a flat detachment within the Lie-de-Vin formation and other minor but abundant shale horizons. Another important décollement exists in Lower Carboniferous shales, which separate the tight Jbel Rich folds from the overlying monoclinal Jbel Ouarkziz, a typical triangle zone mountain front (Burkhard *et al.*, 2001; Helg *et al.*, 2003).

Fold interference patterns

On the scale of the south-western Anti-Atlas, folds within Ordovician and younger strata trend in a very consistent NE–SW direction. Deviations from this cylindricity occur near basement inliers, mostly within carbonates of the Lower Cambrian. An important bend in the Anti-Atlas fold belt is observed near Tata, where the dominant direction changes abruptly from SW–NE to W–E. Quartzites of the Jbel Bani form a near vertical W–E-orientated cliff for over 30 km eastward of Tata. Carbonates of the overlying Jbel Rich are folded into a complex pattern, with a seemingly abrupt termination of SW–NE-striking folds abutting against the subvertical Jbel Bani (Figs 1 and 2). In order to examine the structural relationships in this area, we constructed a horizontal cross-section at an altitude of 550 m a.s.l., based on a geological map (Choubert and Ennadifi, 1970), aerial photography and our own detailed mapping (Fig. 2a). The

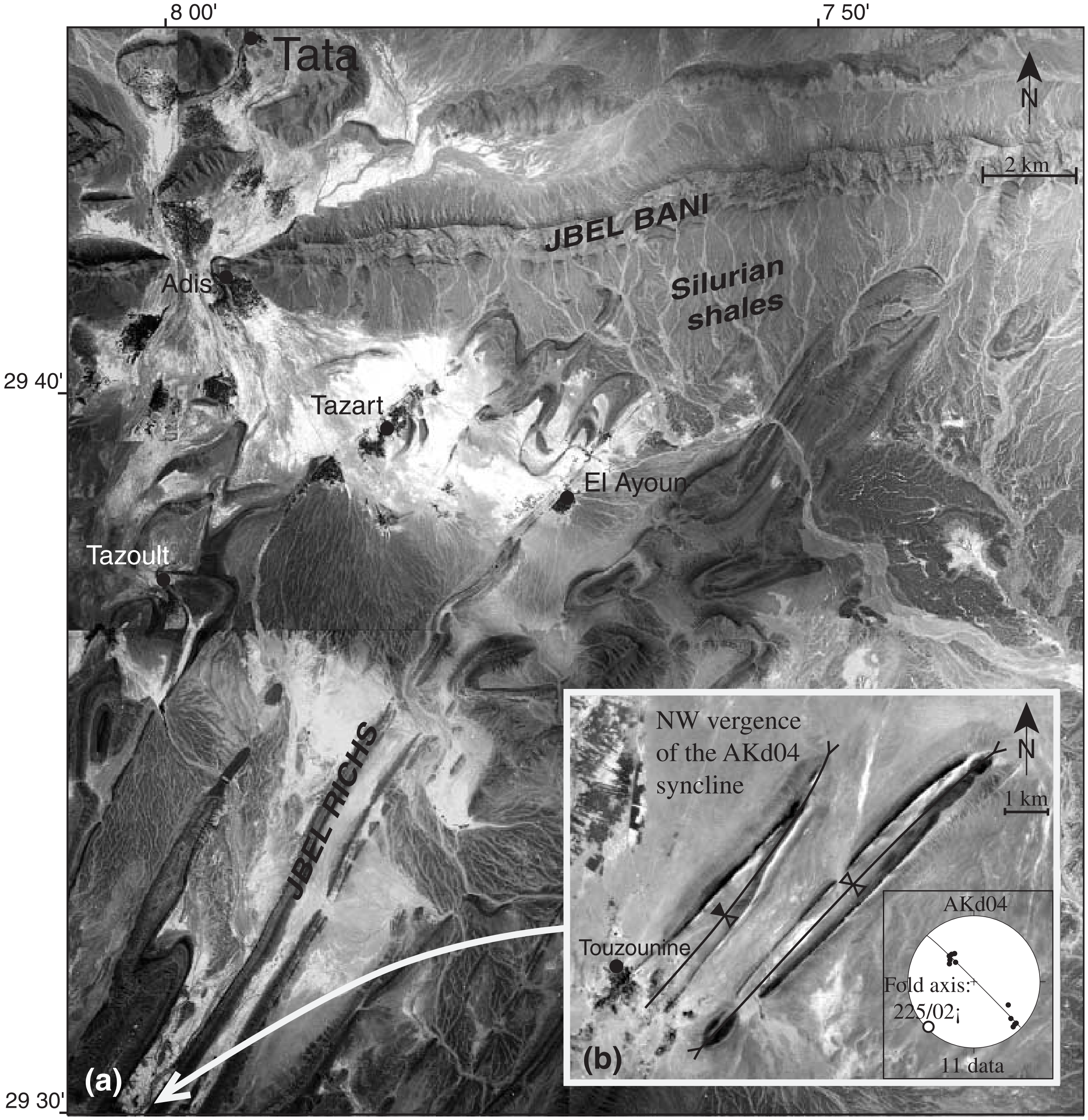


Fig. 2 (a) Mosaic of aerial photographs of the Akka–Tata area. Note excellent outcrop conditions of the competent levels (upper Ordovician Jbel Bani, and lower Devonian Jbel Rich) contrasting with erosional valleys characteristic of the shale horizons. (b) Folds with horizontal fold axis are highly cylindrical: example of the AKd04 syncline near Touzounine village.

advantage of this horizontal section with respect to classical maps is the removal of all topographic intersection effects. Any fold or bend seen in a horizontal section is a real change in strike and structure (Fig. 3). The three-dimensional (3-D) shape of a marker horizon ('third Rich', di4) has been constructed from hundreds of dip measurements and a series of vertical cross-sections (Fig. 4). Together, the horizontal section and the 3-D rendering document the complex pattern of fold interference of type 1 or intermediate between type 1 and 2 according to Ramsay and Huber (1987, figure 22.16).

Our newly collected field data include more than 1500 trend and dip measurements. Subsets from individual folds have been used to construct local fold axis directions for 46 sites (Fig. 5). First-generation, NE–SW-orientated folds are nearly cylindrical over considerable horizontal distances with interlimb angles between 40° and 60° (Fig. 2b). These folds are best described as parallel, class 1B of Ramsay and Huber (1987, p. 347).

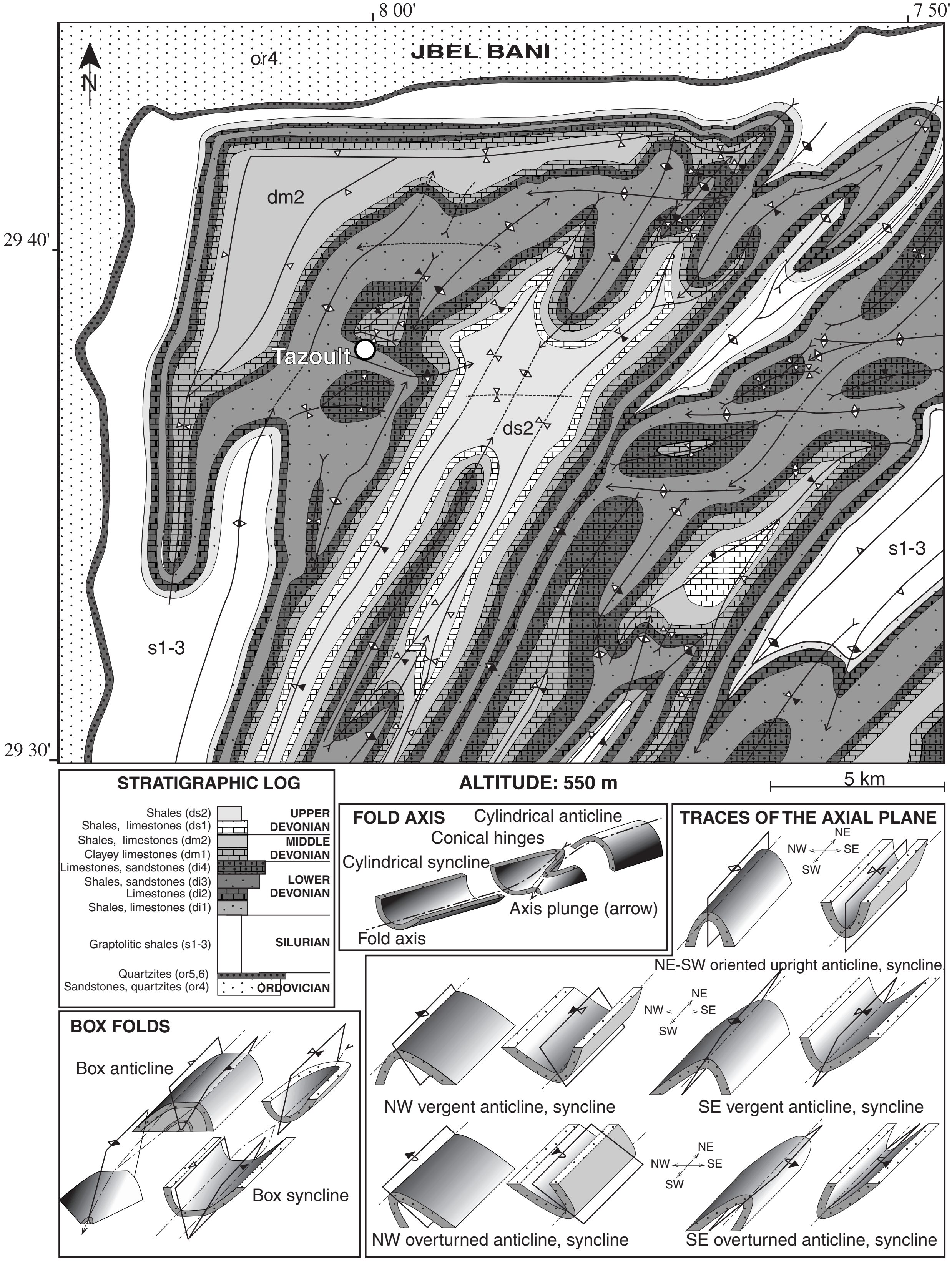


Fig. 3 Horizontal section constructed at 550 m a.s.l. south-east of Tata; for location see Fig. 1. Different fold geometries are mapped using a set of symbols explained in key to the figure.

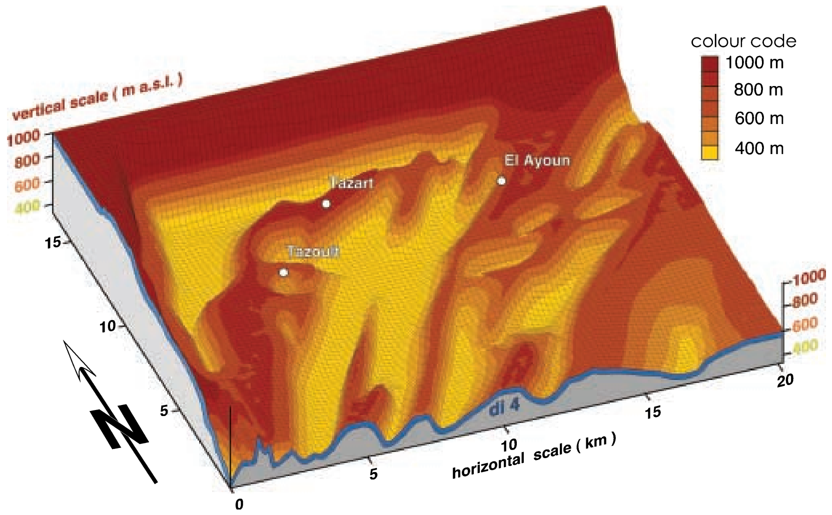


Fig. 4 Three-dimensional representation of a Devonian marker horizon ('di4' limestones and sandstones) showing fold interferences with a typical dome and basin pattern.

The second fold generation with an E–W fold axis direction is less pervasive than the first and folding intensity decreases southward. E–W-trending axial planes are most pronounced south of the Jbel Bani, where interference with the first fold set leads to pronounced dome and basin shapes, albeit with locally complexly distorted fold hinges (Figs 3 and 4).

Palaeostress analysis

Minor brittle deformation within competent marker horizons is omnipresent in the form of joints (Guiton *et al.*, 2003) and minor faults. We used the latter to determine 'palaeostress' axis orientations using standard techniques of fault inversion (Angelier and Mechler, 1977; Angelier, 1990). Fault/striae measurements were collected from over 30 sites and only faults with well-defined lineation and shear sense (Petit *et al.*, 1983; Petit, 1987) were included in inversion calculations.

Our palaeostress data set is dominated by compressional deformation, with near horizontal shortening σ_1-axes and near vertical stretching σ_3-axes (Fig. 6a). Two distinct shortening directions can be distinguished, both on the map scale and in stereograms (Fig. 6). A first set of compression axes is orientated NW–SE (110–150°), perpendicular to the first generation of Jbel Rich folds. A second set of axes is orientated roughly N–S to NNE–SSW (20°), at a high angle to the E–W-trending Jbel Bani structure (Fig. 6b,c). Locally, superposed striae on a few fault planes confirm this relative chronology.

Correlation between folding and faulting

On the regional scale, maximum palaeostress σ_1-axes (Fig. 6b,c) are systematically at a high angle to axial planes (Fig. 5). South of Tazoult (Fig. 2) two shortening directions are seen both in folds and palaeostress measurements (Fig. 7a). On the local scale, tilting of first-generation fold axes and palaeostress axes is observed, especially along the southern border of the E–W-striking Jbel Bani, east of Tata. Abnormally steep south-westward plunges (N200/50°) of first-generation fold axes (Fig. 5b) are best explained as an effect of folding/tilting by a second event of N–S shortening.

Similar observations have been made near basement inliers in the vicinity of the villages of Aigou and Agouliz (Fig. 1). The overall regional trend of this basement high is orientated in a NE–SW direction (Soulaimani *et al.*, 2001). Tight box folds within the Adoudounian dolomites display N–S-trending fold axes, however (Fig. 5b). Particularly steep fold axis plunges of 36–52° towards the south are observed above a NE–SW-trending reverse fault within PIII conglomerates. The same fold train can be followed southward where it levels out to subhorizontal (10°) within less than 1 km. These field observations strongly suggest that first-generation folds within the Adoudounian have been tilted southward by a second event of reverse faulting affecting both basement and PIII conglomerates. This suite of events is confirmed by palaeostress analyses (Fig. 6c). Mapped reverse faults affecting PIII have vertical throws of at least 200 m (Fig. 8).

Kinematic interpretations and discussion

The geometry of folds and palaeostress analyses in the Akka–Tata area provide strong evidence for two superimposed deformation phases in the Palaeozoic cover of the Anti-Atlas belt. A first horizontal shortening in a general NW–SE orientation (N110–N150°) led to the formation of a regionally dominant set of cylindrical folds in the Devonian Jbel Rich (Fig. 8II). This first event of folding is easily correlated with similar fold trains further south-west. Despite an apparent thin-skinned folding style, we could not identify any signs for a major regional-scale thin-skinned décollement. We conclude that shortening seen in the Palaeozoic cover is essentially accommodated locally, within the underlying basement. Similar amounts of shortening due to folding are observed within the Jbel Bani and Jbel Rich. Folding is strongly disharmonic, decoupled by thick incompetent shale and silt horizons such as the Cambrian Lie-de-Vin and Silurian shale formations. At the lowermost stratigraphic levels, PIII and Adoudounian, shortening seems to be less important than stratigraphically higher. We interpret this discrepancy as due to a longer wavelength, dictated by the underlying stiff basement and missing detailed observations between the tops of the poorly outcropping basement 'anticlines'. An important change in structural style is observed between basement and cover. Whereas shortening is taken up mostly by symmetric buckle folding within Palaeozoic cover rocks, the Precam-

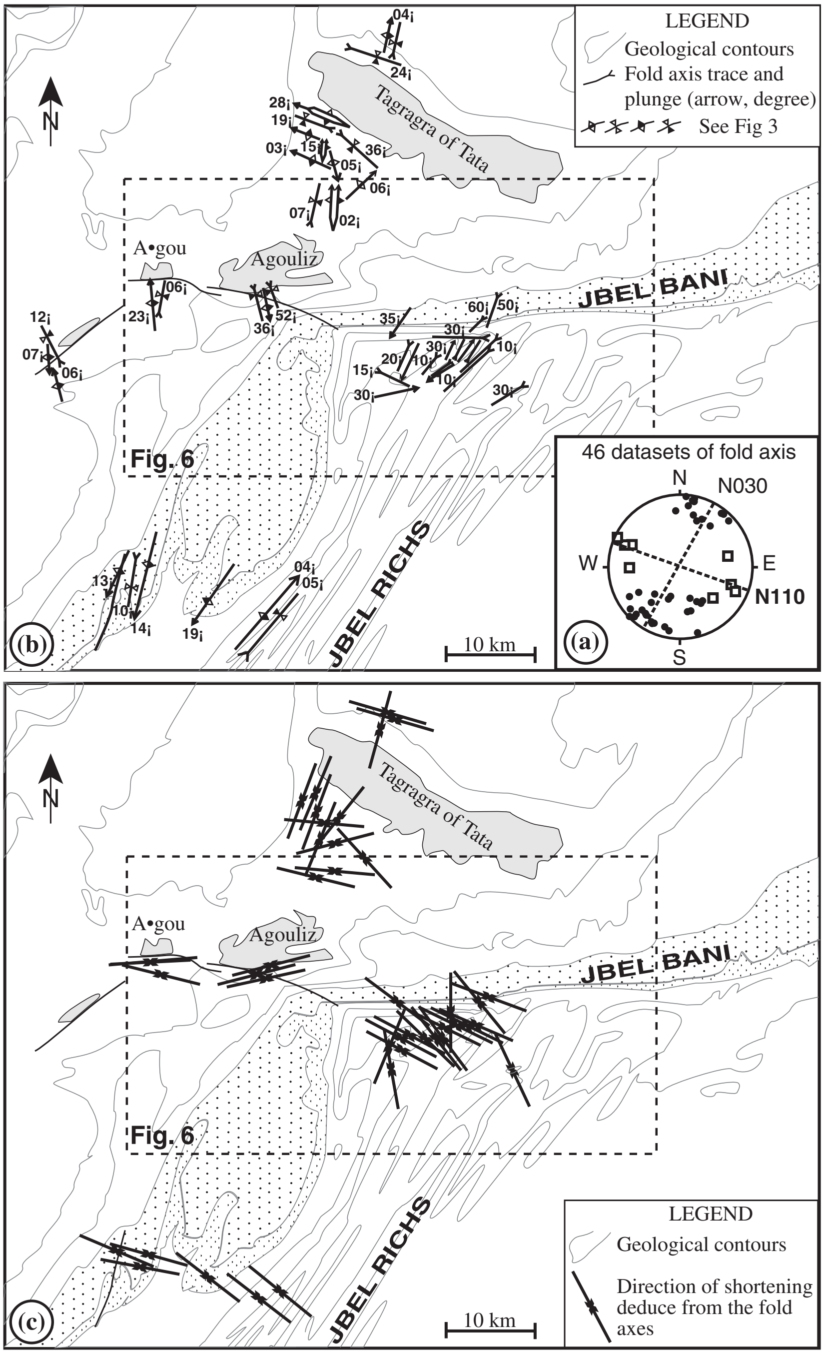


Fig. 5 (a) Wulff stereonet (lower hemisphere) with fold axes calculated from bedding measurements. First-generation folds are indicated by black dots, second-generation folds by white squares. (b) Fold axes and their plunges are shown on a structure map of the Akka–Tata area. (a,b) See corresponding geological map in Fig. 1. The dashed-line rectangle is the localization of the palaeostress maps of Fig. 6. (c) Shortening directions obtained from folds of the Akka–Tata area.

brian basement and overlying PIII is shortened by steeply dipping thrusts. There is ample room for further hidden blind thrust faults of this kind at depth.

At least the younger, N–S shortening event is inverting former PIII extensional structures (Pique *et al.*, 1999) (Fig. 8I). Southward thrusting near the village of Aigou is associated with a penetrative cleavage developed within competent PIII conglomerates. We conclude that both deformation phases took place at near greenschist facies conditions during Late Variscan collision tectonics. Later reactivation (e.g. Late Miocene) could not have been deep seated enough to leave a ductile imprint.

The observed change in shortening direction from NW–SE to N–S near Tata is interpreted as a local phenomenon of constriction between progressively uplifted and individualized basement blocks. Alternatively, however, the Tata region could be one of the westernmost manifestations of an interference between the Anti-Atlas belt and the slightly younger intracratonic Ougarta chain (Hervouet & Duee, 1996; Haddoum *et al.*, 2001)

The age of the main folding event of the south-west Anti-Atlas is generally accepted as Late Variscan (Ball *et al.*, 1975; Michard, 1976; Huvelin, 1977; Bonhomme *et al.*, 1985; Huon *et al.*, 1987; Soulaimani *et al.*, 1997). The youngest deformed sediments are of Late Carboniferous 'Visean' age. The first dated rocks post-dating folding are the Foum Zguid dike and dolerite sills intruded into pre-existing folds. The age of these intrusives is lowermost Jurassic, related to early opening of the Atlantic ocean (Hailwood and Mitchell, 1971; Leblanc, 1973; Choubert and Faure-Muret, 1974; Bertrand and Westphal, 1977; Sebai *et al.*, 1991).

The present-day elevated topography and high relief of the Anti-Atlas requires a recent phase of uplift and erosion, potentially in response to Late Miocene inversion tectonics in the High-Atlas belt further north (Frizon-de-Lamotte *et al.*, 2000). Some minor reverse and sharp dextral faults observed near Tata (Agouliz fault, Fig. 6c) could well be associated with such a renewed Miocene phase of compression.

Conclusions

The Late Variscan Anti-Atlas of Morocco is an atypical type of foreland fold-belt. Tectonics of the Anti-Atlas in the Akka-Tata area show the following characteristics:

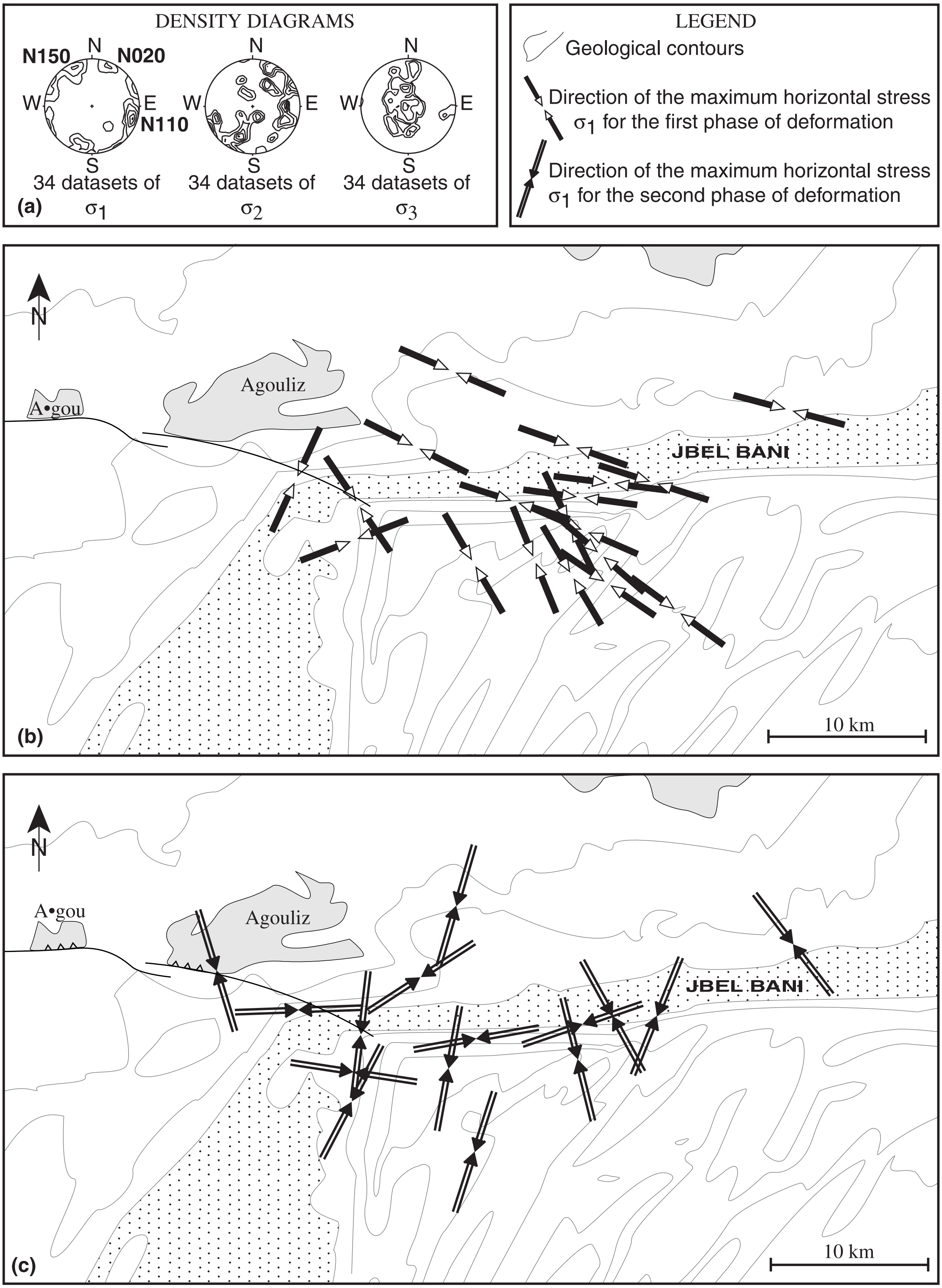


Fig. 6 Palaeostress results are shown for a small area south-east of Tata. (a) Stereographic representation of σ_1, σ_2 and σ_3 palaeostress axis orientations obtained from the inversion of fault/striae measurements. (b) Palaeostress orientation of the first tectonic event. (c) Palaeostress orientation of the second tectonic event.

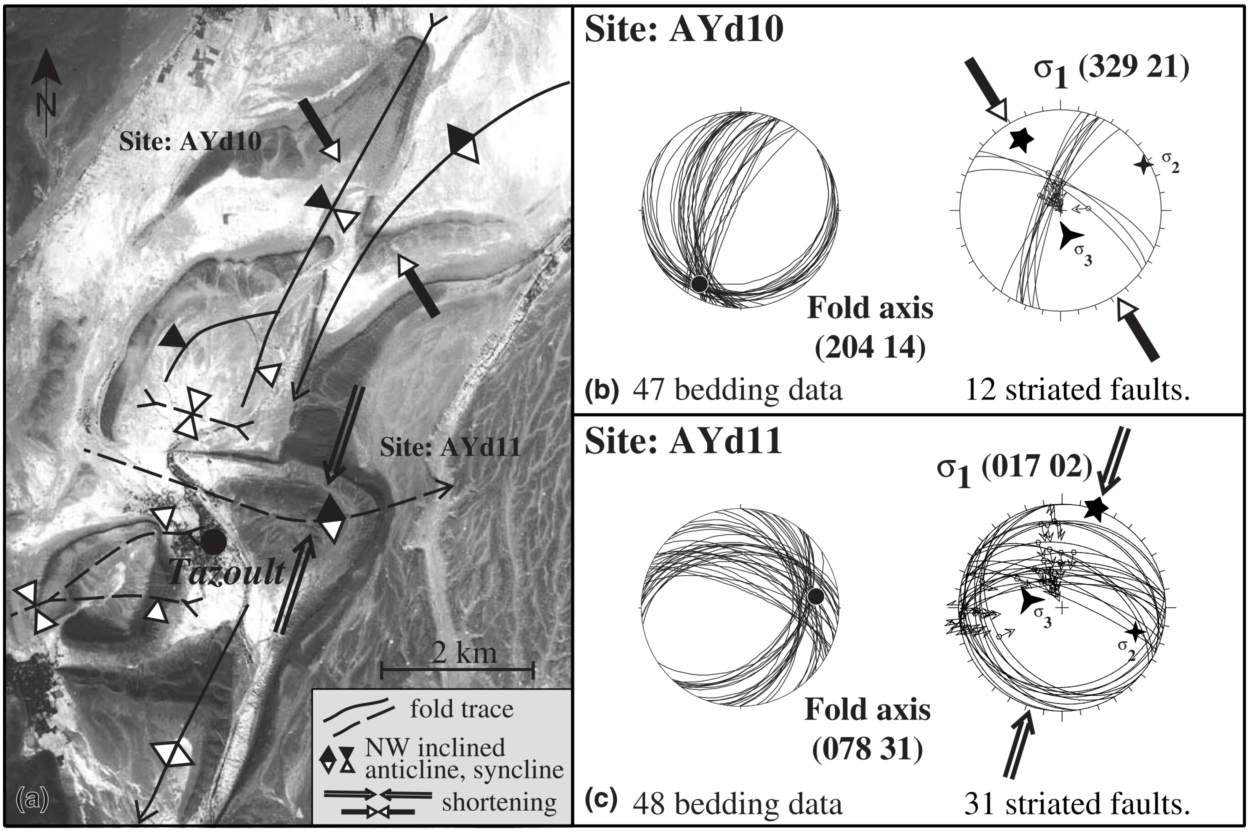
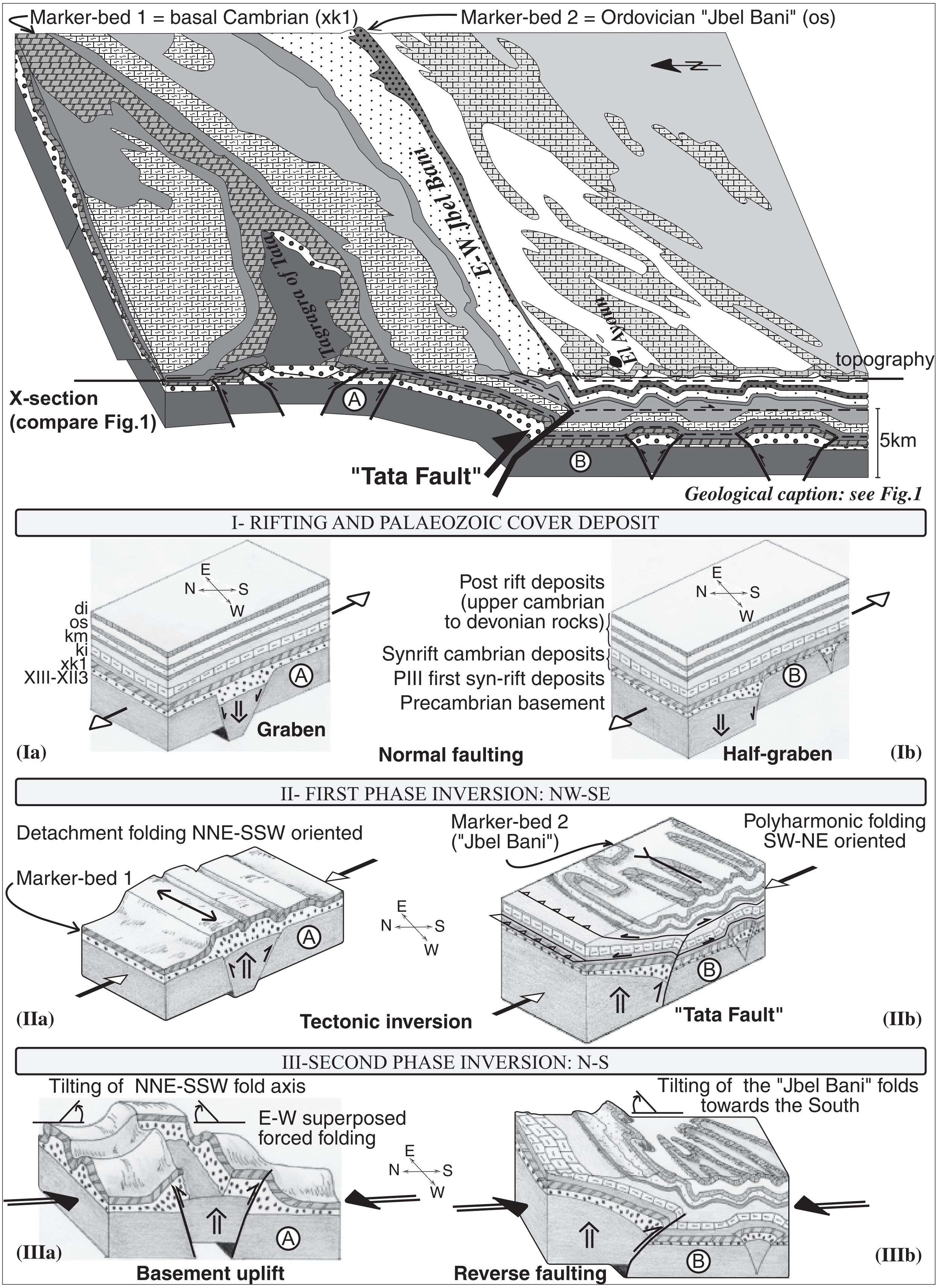


Fig. 7 (a) Aerial photograph of Tazoult village with traces of fold axial planes and associated shortening directions (compare with Figs 4 and 6); stereogram represents bedding data (left); palaeostress axis obtained by the method of Angelier (1990) are shown on the right, for site Ayd10 (b) and for site AYd11 (c).

1. A polyharmonic style of buckle folding within a nearly 10-km-thick Palaeozoic cover series.
2. Fold style and fold wavelength are controlled by the relative thickness of competent quartzite and carbonate layers within an abundant matrix of incompetent shales.
3. Two successive phases of folding developed first folds orientated NE–SW, second folds in an E–W direction. Interference led to a regional-scale dome and basin geometry within the Devonian Jbel Rich.
4. Both folding phases involve basement that is uplifted in a typical 'Laramide' – Rocky Mountain foreland style.
5. The age of both folding phases is most probably Late Carboniferous, corresponding to the final 'Alleghenian' phase collision in the Appalachian – Anti-Atlas orogeny.

Fig. 8 Bloc diagram of the Akka–Tata area. For location and caption see Fig. 1. Schematic diagrams illustrate a proposed tectonic evolution through time with structures exaggerated for more clarity, diagrams to the left (a) are for the Tagragra de Tata boutonnière in an internal position, and diagrams to the right (b) are for the Jbel Bani. I(a) and I(b): Late Proterozoic rifting leads to the formation of a horst and graben system with synrift deposits including Precambrian PIII conglomerates and volcaniclastics and Lower Cambrian limestones. Post-rift deposits reach Middle Carboniferous. II(a) and II(b): A first Variscan phase of NW–SE compression is responsible for a tectonic inversion. Deformation of the Palaeozoic cover is dominated by detachment folding in a polyharmonic multilayer style. II(a): Only folds within the Cambrian layers (marker bed 1) are drawn here for more clarity and in order to illustrate the basal detachment between the Precambrian basement and the Palaeozoic cover. II(b): The 'Tata fault' is a reverse fault with a sinistral strike-slip component. NE–SW folds of the first generation are locally wrenched near this fault (see marker bed 2 corresponding to the upper Ordovician layer). III(a) and III(b): Second phase of N–S shortening. III(a): First-generation folds are tilted towards both the south and north by second-phase inversion structures. Inversion and concommitant or subsequent erosion leads to the formation of the so-called 'boutonnieres' = basement inliers. III(b): The Tata fault is reactived in reverse faulting with an important throw. Marker bed 2 and first-generation folds are tilted towards the south, leading to the Jbel Bani east of Tata. South-east of Bani, the superposition of first- and second-generation folds leads to a marked dome and basin pattern within the Jbel Rich.


Marker-bed 1 = basal Cambrian (xk1)
Marker-bed 2 = Ordovician "Jbel Bani" (os)
E-W Jbel Bani
Tagragra of Tata
El Aouin
topography
X-section
(compare Fig.1)
A
B
5km
"Tata Fault"
Geological caption: see Fig.1
I- RIFTING AND PALAEOZOIC COVER DEPOSIT
E
N
S
W
di
os
km
ki
xk1
XIII-XII3
A
Graben
(Ia)
Normal faulting
Post rift deposits
(upper cambrian
to devonian rocks)
Synrift cambrian deposits
PIII first syn-rift deposits
Precambrian basement
B
Half-graben
(Ib)
II- FIRST PHASE INVERSION: NW-SE
Detachment folding NNE-SSW oriented
Marker-bed 1
A
(IIa)
Tectonic inversion
E
N
S
W
Marker-bed 2
("Jbel Bani")
Polyharmonic folding
SW-NE oriented
B
"Tata Fault"
(IIb)
III-SECOND PHASE INVERSION: N-S
Tilting of NNE-SSW fold axis
E-W superposed
forced folding
A
(IIIa)
Basement uplift
E
N
S
W
Tilting of the "Jbel Bani" folds
towards the South
B
Reverse faulting
(IIIb)

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