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The Neogene structural evolution of the western margin of the Pelagian Platform, central Tunisia

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Abstract—The deformation front of the Atlas Mountains in central Tunisia is a structure termed the North–South Axis. To the west of Kairouan, the North–South Axis consists of NE–SW to NNE–SSW-trending folds and thrusts. A main décollement thrust in Triassic evaporites has been mapped, with secondary detachment of out-of-sequence thrusts in Tertiary rocks and backthrusts at the base of the Tertiary and in Upper Cretaceous sediments. The Upper Cretaceous and Tertiary sediments are backfolded in the hangingwalls of the backthrusts, which are in turn folded in the SE-verging anticlines. The backthrusts are roof thrusts to 'passive roof' duplexes and imply the extensive development of thin-skinned 'blind' SE-verging thrusts. A similar structural style is seen further west in the Tunisian Atlas, but major NW-verging backthrusts are not exposed. Adjacent to the Pelagian Platform, the thrust structures are affected by later strike-slip faults.

The thin-skinned thrusting at the deformation front is Middle Miocene in age and was synchronous with Africa–Europe collision. The North–South Axis is therefore interpreted as the frontal structure of a collision-related thrust belt. The thrust belt is underlain by a NW–SE- to E–W-trending Middle Jurassic to Early Cretaceous rift basin with probable 'mid' Cretaceous to Oligocene post-rift fill. The NE–SW-trending thrust belt is detached from NW–SE- to E–W-trending syn-rift basement faults, but changes in thrust belt geometry across the syn-rift faults indicate that basement structures have compartmentalized the thrust belt. The later strike-slip faulting resulted from the reactivation of the syn-rift basement faults in the post-collisional framework of the thrust belt. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The Atlas Mountains are a major orogenic belt which affects basins developed along the northern margin of the African craton. The evolution of the Atlas Mountains is related primarily to the collision of Africa and Europe in the Tertiary. In Tunisia, the Atlas Mountains are subdivided into an 'internal' Tell Atlas unit and 'external' zones which lie to the southeast (Fig. 1). In many of the peri-Mediterranean mountain belts, the external zone structures are thin-skinned thrust belts, detached from basement on regionally extensive décollement thrusts. In the Pyrennean and the Alpine–Swiss Molasse Basin thrust belts for example the regional décollement is in Triassic evaporites (Williams 1985, Vann *et al.* 1986). In the Atlas of Tunisia, the thrust belt model has not gained wide acceptance, despite the analogous structural position of the Tunisian Atlas and the North–South Axis to the external zone thrust belts bordering the western Mediterranean Basin. Recent structural models relate the external zone deformation in Tunisia to a more traditional view of basement fault reactivation (Ouali *et al.* 1987, Boccaletti *et al.* 1988, Snoke *et al.* 1988). However, basement fault inversion has not been demonstrated convincingly because the basement structural pattern has not been fully examined. The models invoking basement reactivation are therefore based largely on circumstantial evidence (for example, a congruence between the locations of the anticlines and the suspected locations of inferred basement faults). The applicability of an alternative thrust belt model, however, can be tested relatively easily because thrust belts exhibit particular families of structures (Bally *et al.* 1966, Dahlstrom 1970), and the folds generated during thrusting have characteristic geometries (Rich 1934, Butler 1982, Suppe 1983, Williams & Chapman 1983, Jamison 1987).

In the first part of this paper the available published evidence for basement structural trends and the crustal structure in central Tunisia is examined. This is followed with an investigation of the structural style and the timing of the deformation at the mountain front of the Atlas Mountains in Tunisia, using field evidence from the Atlas to the west of Kairouan (Fig. 1). This area has not figured prominently in recent structural models, and hence provides new information and new opportunities to study the structural evolution of the eastern Atlas Mountains.

GEOLOGICAL SETTING

Atlas Mountains structure and evolution

The structure of the Atlas Mountains in Tunisia is reviewed in several papers (e.g. Salaj 1978, Zargouni & Abbes 1985, Bishop 1988, Boccaletti *et al.* 1990, Ben Ferjani *et al.* 1990). The overall structural style is relatively simple and consists of dominantly SE-verging folds and thrusts. However, the tectonic significance of the Atlas in Tunisia is controversial.

Relative convergent motion between the African and

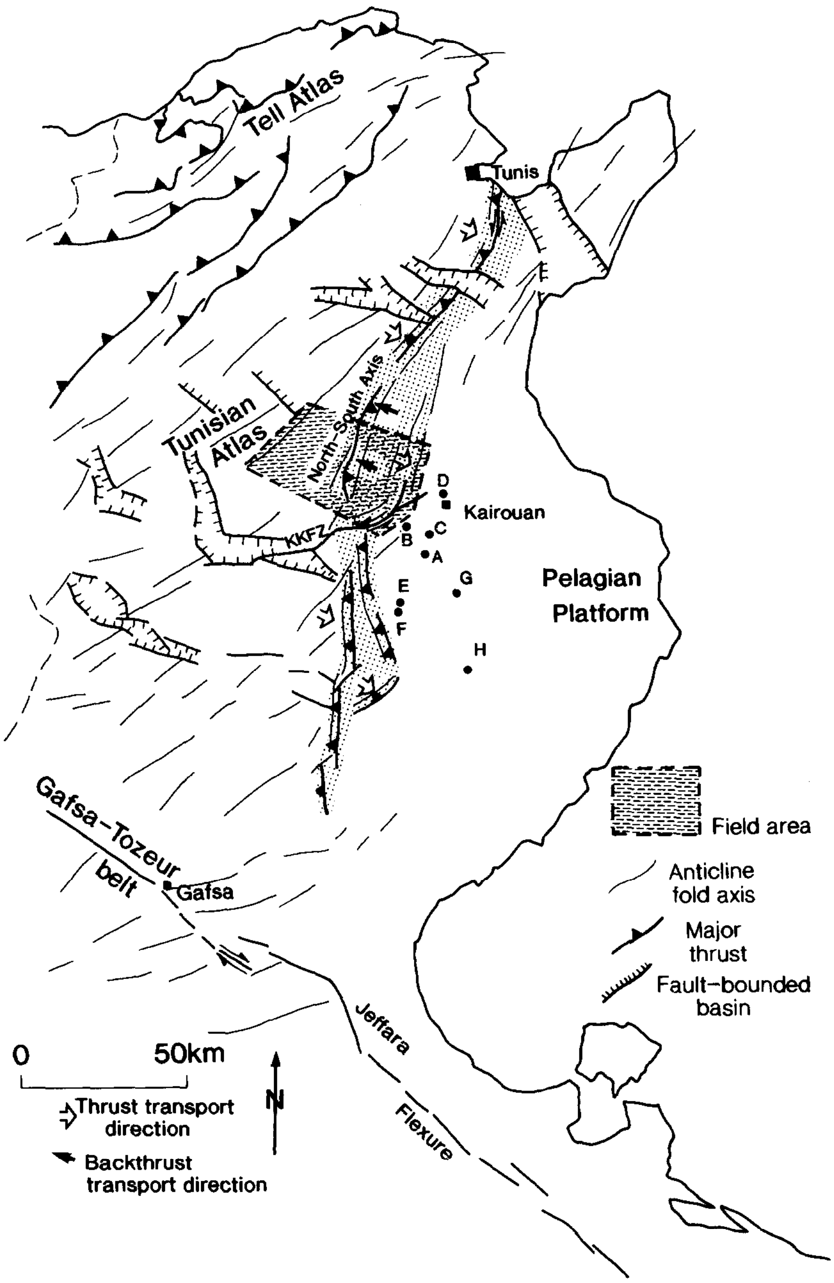

Fig. 1. The structural domains of central and northern Tunisia. The North–South Axis is highlighted in stipple. KKFZ: Kairouan–Kasserine Fault Zone. ●A–H are the locations of exploration wells on the Pelagian Platform.

European continental plates since Late Cretaceous times (Dewey *et al.* 1973, 1989), caused subduction of the Neo-Tethys Ocean and resulted in collision of the rifted northern margin of the African craton with the southern margin of the European plate. Dewey *et al.* (1989) date the collision as Burdigalian in age. Widespread thrusting resulted in northern Tunisia and offshore to the north in the Straits of Sardinia, with probable detachment of folds and thrusts on a décollement in Triassic evaporites in the Tell Atlas (Cohen *et al.* 1980, Boccaletti *et al.* 1990). The major thrust deformation onshore occurred approximately in the Middle Miocene (Rouvier 1977, Cohen *et al.* 1980), in reasonable agreement with the age of collision. Snoke *et al.* (1988) however, proposed that thrust deformation in the Tell Atlas may have commenced as early as latest Oligocene times. This earlier deformation must therefore be related to the latest phases of subduction associated with the destruction of the Neo-Tethys Ocean. Further southeast, the Tunisian Atlas has been interpreted by Boccaletti *et al.* (1990) as a Middle Miocene fold belt, but without major thrusts. Snoke *et al.* (1988) however related the Tunisian Atlas folds to inversion of inferred NE–SW-trending syn-rift basement faults.

The North–South Axis forms the deformation front of the Atlas Mountains at the western margin of the Pelagian Platform. The structural evolution of the North–South Axis is poorly understood. Boccaletti *et al.* (1988) interpreted the northern North–South Axis as a transpressive 'flower' structure, generated during sinistral strike-slip on an inferred N–S-trending basement fault. These authors have proposed a Late Miocene to Early

Pliocene age for the faulting and folding and therefore interpreted the North–South Axis as a post-collisional structure. A similar interpretation was proposed by Ouali *et al.* (1987) for the southern North–South Axis. Truillet *et al.* (1981) and Delteil (1981) however proposed that deformation in the southern North–South Axis commenced in Early Miocene times and involved detachment-style thrusting and folding. The latter age for the North–South Axis encompasses Africa–Europe collision and can be used as evidence that the mountain front is part of the collision-related thrust belt.

Post-collisional deformation of the Atlas Mountains in Tunisia is Late Miocene to Recent in age (Boccaletti *et al.* 1990). Repeated extension and refolding of the Tell Atlas thrust belt structures (Rouvier 1977) was interpreted by Boccaletti *et al.* (1990) as the result of post-collisional changes in the thrust wedge dynamics. The Tunisian Atlas and the North–South Axis are affected by NW–SE- to E–W-trending fault-bounded post-collisional basins, orthogonal to the Atlas structures. The relationship of the post-collisional basins to basement faults is discussed below.

Basement structures

Recent published models have related the Tunisian Atlas and North–South Axis structures to inversion of basement faults (Ouali *et al.* 1987, Boccaletti *et al.* 1988, Snoke *et al.* 1988). Figure 2 illustrates the main tectonic episodes which have affected the Tunisian sector of the north African margin since Mesozoic times. Ben Ferjani *et al.* (1990) and Peybernes (1991) have presented structural and stratigraphic evidence for a rifting event of Middle Jurassic to Early Cretaceous age in Tunisia. The crustal structure of Tunisia is consistent with this rifting event (Fig. 3a), which is interpreted to have generated a NW–SE- to E–W-trending rift basin. The Gafsa–Jefarra faults and the Kairouan–Kasserine fault zone are examples of major syn-rift basement faults. Tectonically thickened syn-rift sequences are present on the northern, downthrown sides of the faults (Ben Ferjani *et al.* 1990, Peybernes 1991). The post-collisional basins which affect the Tunisian Atlas and the North–South Axis are parallel to the syn-rift basement fault orientations and have constant aspect ratios consistent with strike-slip 'pull-apart' basins. These observations led Boccaletti *et al.* (1990) to propose strike-slip reactivation of the NW–SE- to E–W-trending syn-rift basement faults in the post-collisional tectonic framework. The locations of the post-collisional basins may therefore reliably reflect the positions of the underlying syn-rift basement faults.

N–S-trending contours on the regional Bouguer gravity map to the south of Kairouan (Fig. 3b), may indicate a N–S-trending component to the basement structure beneath central Tunisia. During the rifting, E–W- to NW–SE-trending extensional faults affected central Tunisia and the North–South Axis (Ben Ferjani *et al.* 1990), implying that N–S-trending basement faults were not reactivated. The gravity data also show that north of Kairouan, the North–South Axis and the Tunisian Atlas are underlain by basement structures parallel to the rift basin trend. There is little evidence on the gravity map for a N–S-trending basement structure to the north of Kairouan.

THE WESTERN MARGIN OF THE PELAGIAN PLATFORM, WEST OF KAIROUAN

Stratigraphy

Figure 2 summarizes the stratigraphy of the North–South Axis and eastern Tunisian Atlas to the west of Kairouan. Syn-rift Lower Cretaceous and Jurassic sediments are not exposed, but are known to exist from exploration drilling. The post-rift 'mid' Cretaceous to Oligocene succession consists of interbedded open marine shales and shallow marine carbonate sediments. The Oligocene to Lower Miocene sediments are a regressive sequence passing upwards from Oligocene shallow shelf–deltaic depositional environments to Early Miocene fluvial sedimentation. Deposition of the latest Oligocene to Early Miocene sediments spans the onset of thrusting to the northwest. The regressive nature of the sedimentation may therefore relate to infilling of an early foreland basin. The Segui Formation consists of fluvial flood plain sediments which lie unconformably on older sediments in the field area.

Structure

The structure of the Atlas Mountains to the west of Kairouan is illustrated in Fig. 4. NE–SW-trending topographic ridges, termed Djebels, are major anticlines. The anticlines are separated by SW- and NE-plunging synclines where the stratigraphy is at 'regional' elevation. The folds are of parallel class with angular, kink-band geometries and long, planar limbs. The folds are mainly SE- or ESE-verging, but NW-directed backfolding of the Upper Cretaceous and younger sediments occurs at Djebels Bou Dabouss and Ousselat (Fig. 5).

Localities A–I in Fig. 4 are locations where intraformational thrusts have been mapped. At localities B, C, D, F and G, duplex structures characteristic of a thin-skinned thrust style have been mapped. Isolated thrusts have been identified at localities A, B, C, E, H and I and out-of-sequence thrusts mapped at locality D.

Backrotated thrusts in the backlimbs of the main anticlines (Fig. 6a) and downward-facing thrusts in the forelimbs (Fig. 6b), imply that the intraformational thrusting pre-dated the main phase of folding. Where the thrusts are backrotated, the anticline backlimbs are locally steepened to dips of 60–70° NW (Fig. 6a).

The structural geometries of the main anticlines are outlined in the following sections.

Djebel Bou Dabouss and Djebel Ousselat

The Bou Dabouss anticline is a NE–SW-trending box fold which is continuous with the Ousselat anticline

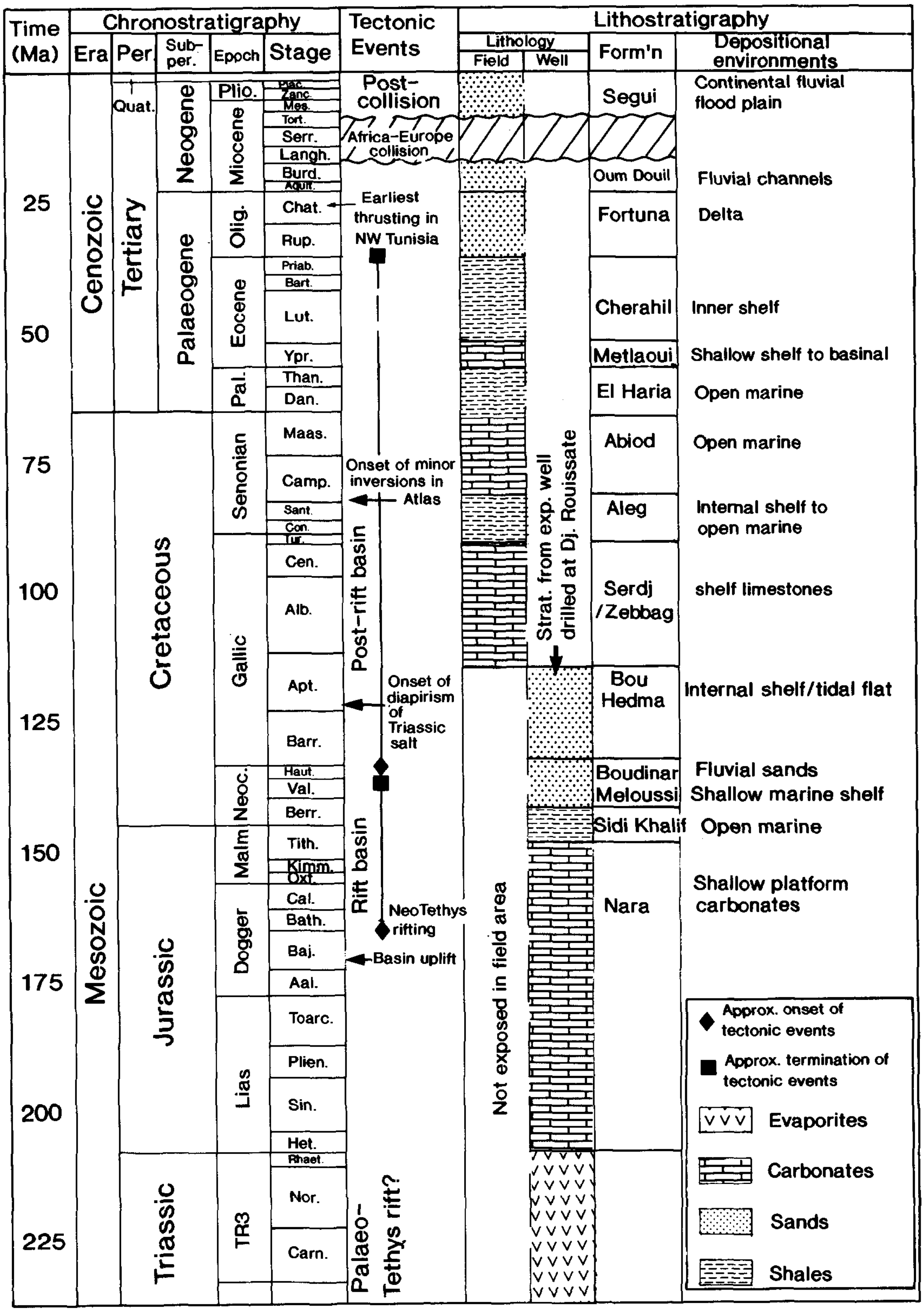

Fig. 2. The stratigraphy of the western margin of the Pelagian Platform and the main tectonic events which have affected the Tunisian margin since Mesozoic times.

further south. The Bou Dabouss fold verges SE (Fig. 5a), but at Upper Cretaceous and younger levels the northwest limb of the fold is sub-vertical as a result of backfolding in the hangingwall of a sub-horizontal fault. *S–C* fabrics in the fault gouge indicate a northwesterly movement direction for the hangingwall rocks, consistent with the sense of backfolding. Further east, the fault is bedding-parallel between the Aleg and Abiod Formations and is folded in the Bou Dabouss anticline. The fault is interpreted as a folded backthrust, with a décollement in Upper Cretaceous sediments and which cuts up-stratigraphy to the northwest through Upper Cretaceous and Tertiary rocks in the northwest limb of the anticline.

To the south, the backthrust is exposed at the west limb of the Ousselat anticline. In Fig. 5(c), the thrust dips east beneath Lower Eocene Metlaoui carbonates.

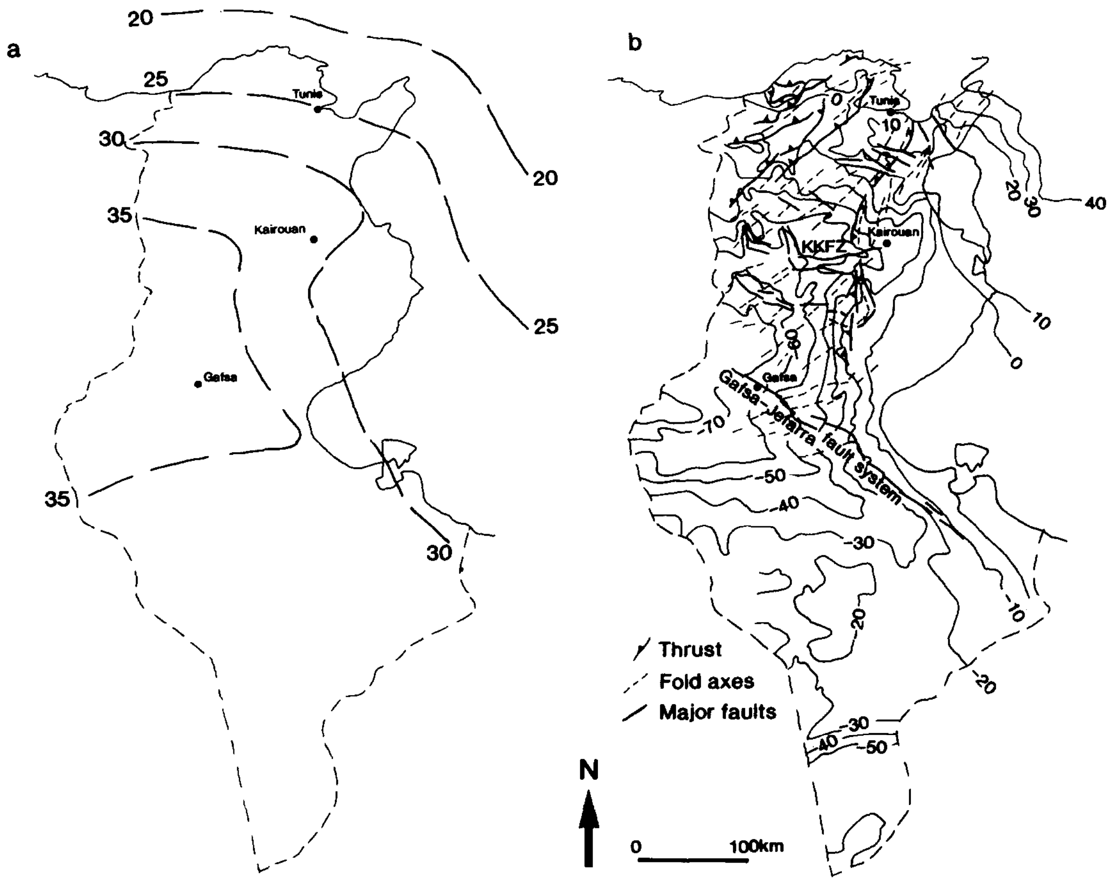

Fig. 3. (a) Depth to the Moho in kilometres following the results of the southern segment of the European Geotraverse Project. (b) The regional Bouguer gravity map of Tunisia (from Midassi 1982). The main structural elements of the Atlas region are shown for comparison.

At locality J (Figs. 4 and 5b), the thrust is exposed as a bedding-parallel fault near to the base of the latest Cretaceous–Palaeocene El Haria Formation. The thrust is extrapolated east where it is inferred to be folded in the Halfa anticline. To the west of locality J, the thrust cuts sub-horizontally through the SE-dipping forelimb of the Zemlia anticline. The Zemlia anticline has been refolded into a NW-verging tip-line fold in the hangingwall of the thrust, whilst the Zemlia anticline retains its original SE-verging geometry in the footwall. The backthrust therefore post-dates the Zemlia anticline but formed before, or synchronously with, the Halfa fold.

The internal geometry of the Bou Dabouss anticline is complex. Triassic evaporites are folded in Upper Cretaceous sediments and outcrop in the footwall of the backthrust at locality K (Fig. 4). This structural geometry is similar to the Cherichira anticline to the southeast, where an out-of-sequence thrust interpretation is possible to explain Triassic sediments interleaved with Cretaceous and Tertiary rocks.

Djebel Kessera and Djebel Serdj

Djebel Kessera and Djebel Serdj form a NE–SW-trending anticline located at the eastern margin of the Tunisian Atlas. The Serdj–Kessera anticline verges to the southeast and is separated from the North–South Axis folds by the SW-plunging Ousseltia syncline.

The fold interlimb angle tightens northwards from the northern part of Djebel Kessera (Fig. 5c) to Djebel Serdj (Fig. 5a), as a result of a general steepening of the fold forelimb. This northward fold tightening is accompanied by an increase in uplift so that 'mid' Cretaceous Serdj Formation carbonates are the oldest rocks exposed at Djebel Serdj, compared with Lower Eocene Metlaoui carbonates further south at Djebel Kessera. At Kef el Garia (Fig. 5d), the forelimb of the Kessera anticline is steeply dipping and is displaced southeast relative to the fold forelimb further north. The change in position of the forelimb is accommodated by a NW–SE-trending transfer fault.

Djebel Cherichira

Djebel Cherichira is a SE-verging anticline located at the eastern margin of the North–South Axis (Fig. 7a). The structure of the anticline can be described with reference to the three separate Djebels, Oulad Kredija and el Halfa (Fig. 7b) and el Houffia (Fig. 7c), that comprise the fold.

At Djebel el Houffia (Fig. 7c), Triassic and Cretaceous–Tertiary sediments form a NW-dipping thrust sheet, thrust to the southeast over steeply dipping Eocene rocks in the forelimb of the anticline. Triassic evaporites are folded in the thrust hangingwall but sands

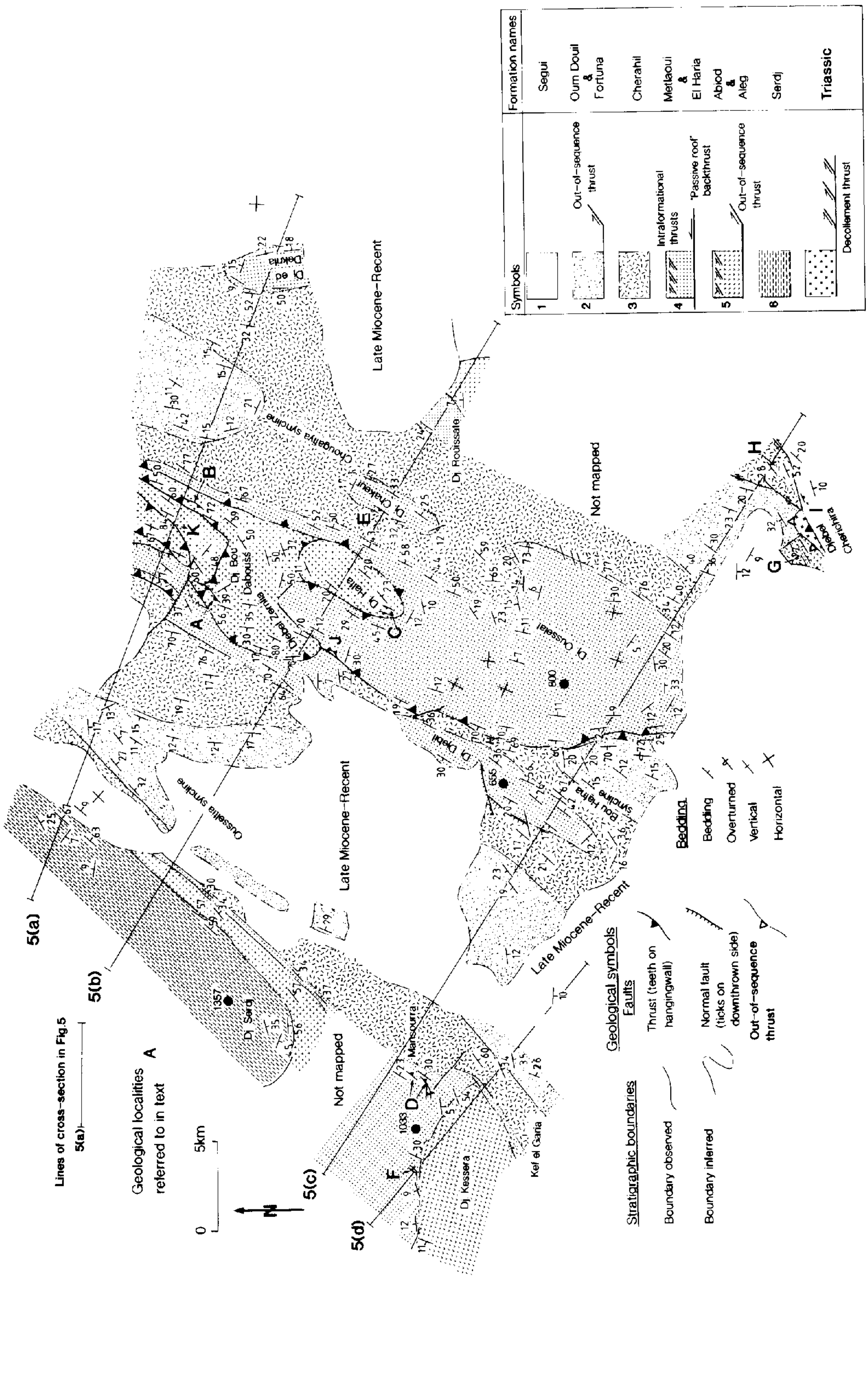

Fig. 4. Geological map of the North–South Axis and Tunisian Atlas west of Kairouan.

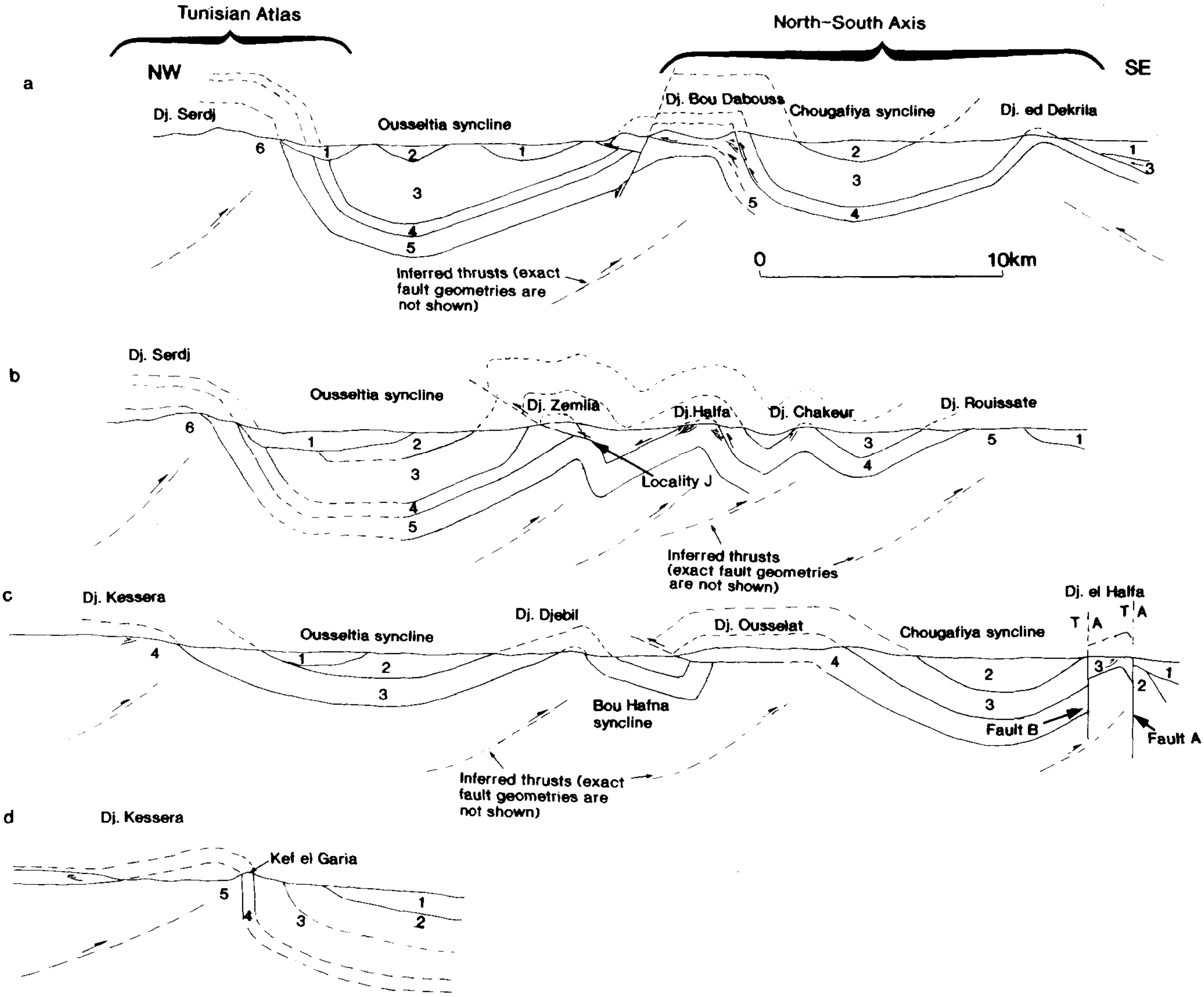

Fig. 5. Structural cross-sections through the field area. The locations of the cross-sections are shown in Fig. 4. Numbers 1–6 refer to the stratigraphy in Fig. 4. See text for discussion.

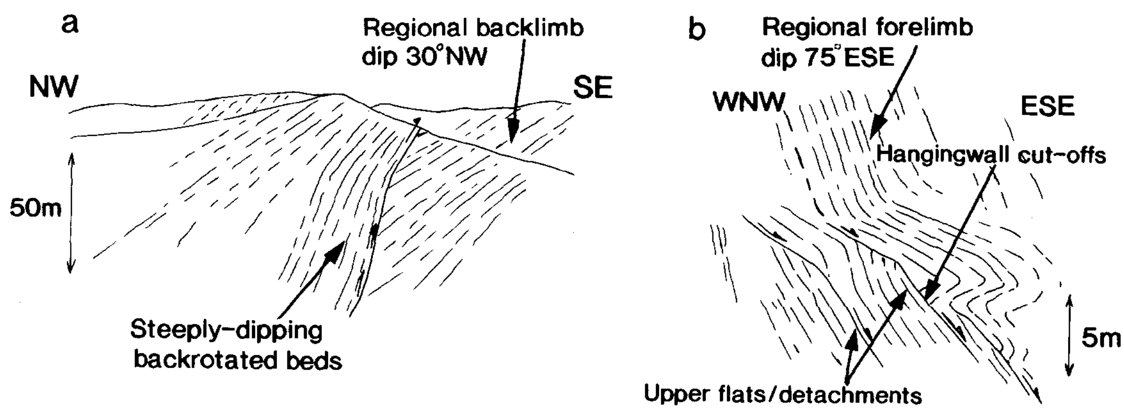

Fig. 6. Examples of intraformational thrust geometries from the field area. (a) A back-rotated thrust in the backlimb of the Bou Dabouss fold (locality A in Fig. 4). (b) Downward-facing thrusts in the forelimb of the Bou Dabouss fold (locality B in Fig. 4).

and dolomites, interbedded with the evaporites, are parallel to the thrust.

Jurassic and Lower Cretaceous sediments are missing from the thrust sheet so that Upper Cretaceous and Tertiary sediments rest on the Triassic rocks on a low-angle, NW-dipping fault. Hangingwall Upper Cretaceous and Tertiary sediments are approximately parallel to the fault, whereas Triassic beds in the footwall are truncated. The following evidence is used to argue for a thrust fault interpretation. At locality ⓘ (Fig. 7a),

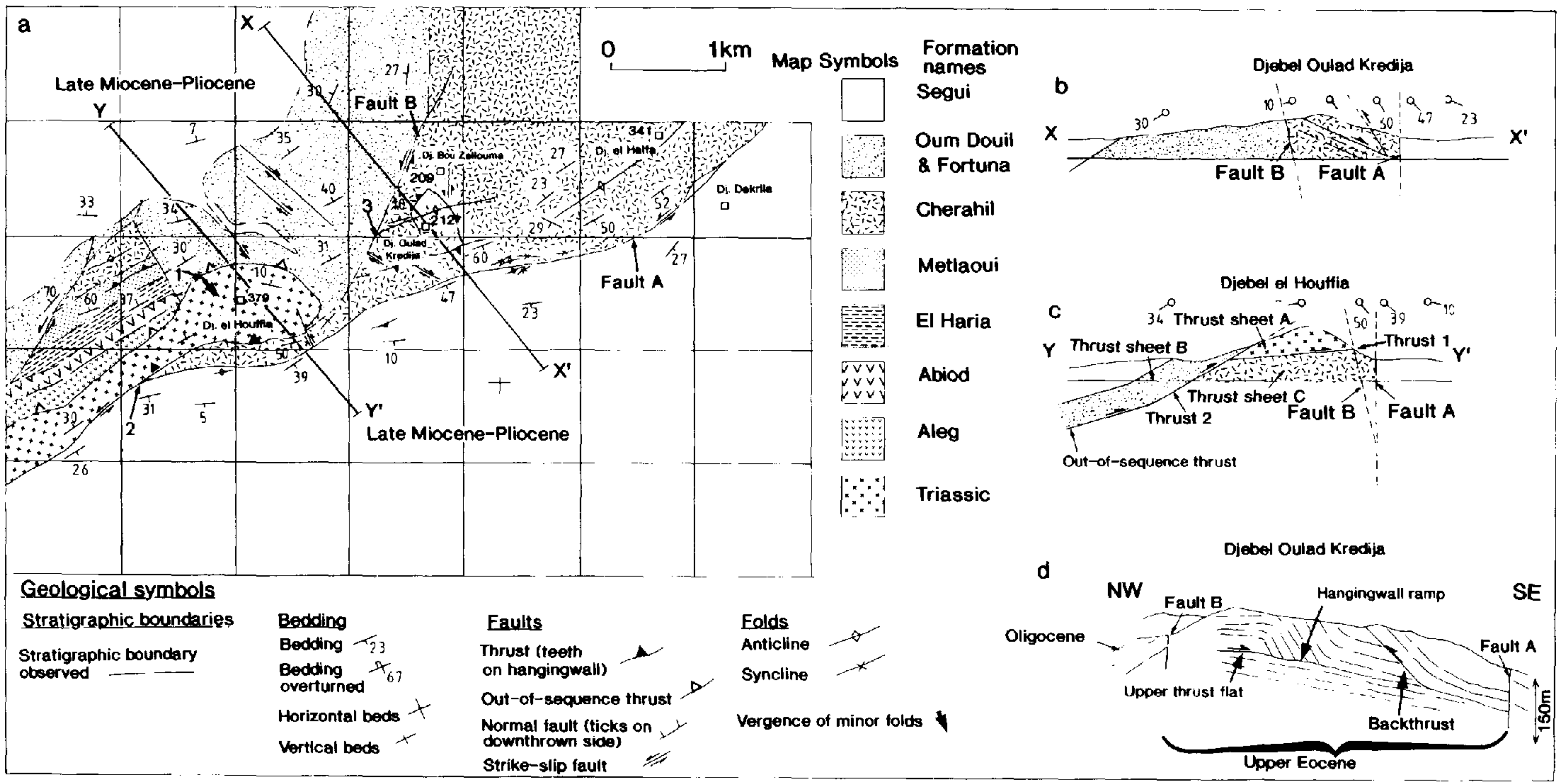

Fig. 7. (a) Geological map of Djebel Cherichira. (b) Cross-section X–X′ through the Cherichira anticline at Djebel Oulad Kredija. (c) Cross-section Y–Y′ through the Cherichira anticline at Djebel el Houffia. (d) Field sketch of the exposed geometry of the Cherichira anticline at Djebel Oulad Kredija between faults A and B. The sketch is approximately in the same location as cross-section X–X′.

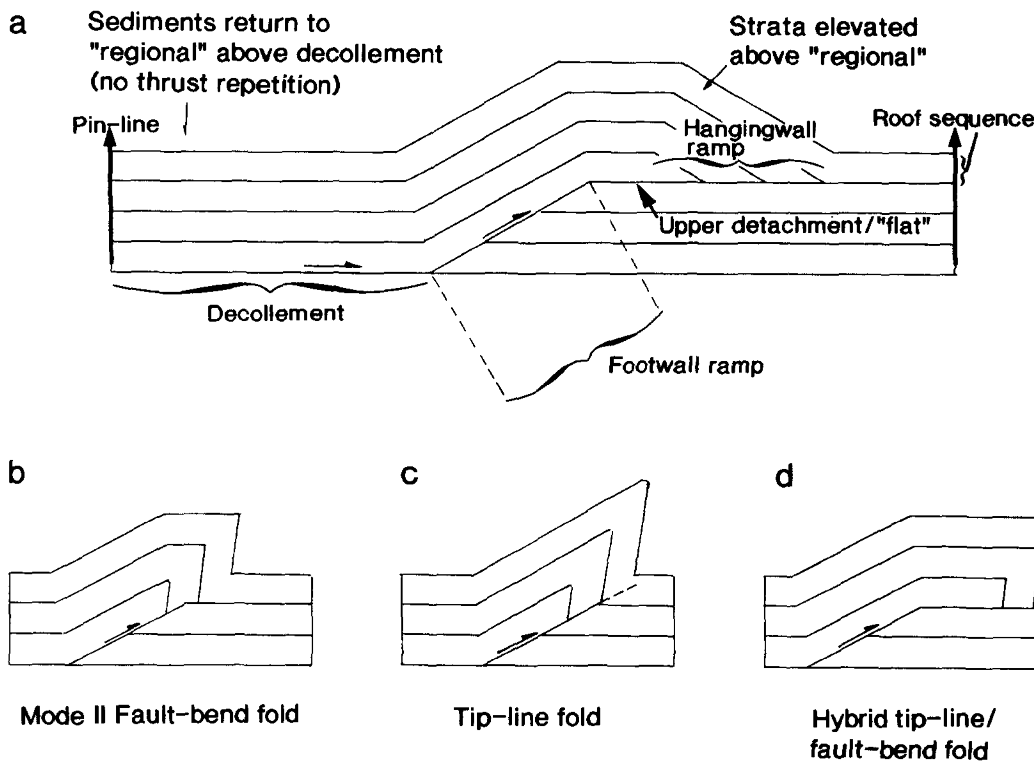

Fig. 8. The geometry and terminology of thin-skinned thrusts and associated thrust-folds. (a) A thin-skinned thrust with an associated Mode I fault-bend fold. (b) Mode II fault-bend fold, (c) tip-line fold, and (d) hybrid tip-line–fault-bend fold.

Triassic evaporites in the immediate footwall of the fault have been folded into SE-verging minor folds, consistent with the Tertiary sediments thrust southeast over the Triassic. The fault and cut-off geometries are consistent with rocks in the footwall, truncated by a low-angle thrust which is parallel to rocks in the hangingwall. The relationship of younger rocks thrust over older rocks is consistent with a low-angle 'out-of-sequence' thrust. The thrust sheet at Djebel el Houffia is therefore subdivided into thrust sheet A, consisting of Triassic emplaced on thrust 1, and thrust sheet B containing Cretaceous and Tertiary rocks emplaced on out-of-sequence thrust 2 (Fig. 7c).

Thrust 1 truncates a SE-verging anticline exposed in Eocene to Miocene rocks. At Djebel Oulad Kredija (Figs. 7b & d), SE-dipping Eocene beds in the forelimb of the anticline are truncated downwards on a less steeply dipping fault which is bedding-parallel with rocks in the footwall. There is a close correspondence between this structural geometry and the geometry of the downward-facing thrusts and folds in Fig. 6(b). The anticline is therefore interpreted as a SE-verging thrust fold with the forelimb truncated downwards on a thrust. The thrust at Djebel Oulad Kredija is downward-facing in the forelimb of an underlying fold. To the southeast, a major SE-dipping backthrust outcrops. The backthrust detaches at the same level as the downward-facing thrust in the forelimb of the anticline.

The Cherichira anticline is cut by sub-vertical sinistral strike-slip faults (Fig. 7a). Fault A truncates the thrust at Djebel el Houffia at locality ②. Fault B truncates the axis of the Cherichira anticline at locality ③. This geological evidence suggests that the strike-slip faults post-date the thrusting.

INTERPRETATION OF THE STRUCTURAL STYLE

Geometric properties of thin-skinned thrusting

In order to establish whether the style of deformation in the field area is thin-skinned, it is necessary to show that the thrusts have certain geometric characteristics, and that the associated folds could have been produced during the thrusting. Inversion involving strike-slip or dip-slip reactivation of basement faults, will not produce the structures characteristic of regional-scale thin-skinned thrust belts, although isolated thin-skinned structures can develop in strike-slip settings (e.g. Yeats 1983).

Thin-skinned thrusts flatten into a décollement (Fig. 8), and consist of flat sections linked by thrust ramps which cut across bedding (Dahlstrom 1970, Boyer & Elliott 1982, Butler 1982). The level of décollement can be defined as lying at the base of the rocks in the hangingwall which are parallel to, and in contact with, the thrust. Décollement thrusts form regional levels of detachment. Rocks are elevated above 'regional' when transported over a thrust footwall ramp and onto younger sediments.

Certain fold styles are generated during thin-skinned thrusting. Transport on a ramp–flat thrust produces a fold in the hanging-wall (Rich 1934), termed a fault-

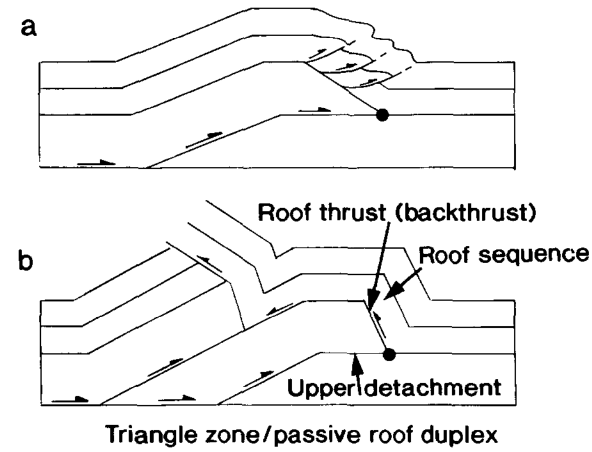

Fig. 9. Two geometric solutions to the problem of line-length balancing 'blind' thrust structures in which the roof sequence does not restore to the same length as the rocks shortened by the thrust. (a) The roof sequence is shortened by foreland-verging thrusts and folds (e.g. Thompson 1981). (b) The roof sequence is detached from the thrust shortened rocks on a backthrust (e.g. Price 1981, Banks & Warburton 1986).

bend fold by Suppe (1983, 1985). Mode I fault-bend folds are symmetric, parallel class, with angular kink-band geometries (Fig. 8a). Mode II fault-bend folds have similar geometric characteristics but form with steeply-dipping forelimbs (Fig. 8b).

Fault-bend folds result from transport of the hangingwall rocks over an already formed irregular thrust surface. Tip-line folds (Fig. 8c), form simultaneously with thrust ramp propagation and result from the strains developed around the tip of a propagating thrust (Williams & Chapman 1983). Tip-line folds are tight and verge in the direction of thrusting. Geometrically, tip-line folds can be difficult to distinguish from Mode II fault-bend folds. Jamison (1987) discussed the geometric properties of tip-line folds transported over later-formed ramp–flat thrust hinges. These folds, referred to here as 'hybrid' folds, have steeply-dipping forelimbs, but with broad, flat-bedded hinge regions (Fig. 8d). Consequently, hybrid folds can have geometries similar to mode II fault-bend folds formed on thrusts with large displacements.

Blind thrusts (i.e. thrusts which did not propagate to the topographic surface), with ramp–flat geometries such as those shown in Figs. 8(a), (b) and (d), will not line length balance. A line-length restoration of the structure in Fig. 8(a) for example, would result in the pin-line on the left of the diagram being sheared to the right (i.e. the roof sequence restores with a shorter line length than the rocks shortened by the thrust). To restore with a vertical pin-line implies that a considerable length of the roof sequence was displaced into the foreland on the upper detachment of the thrust. Geometric solutions have been proposed to solve this problem (Fig. 9). In Fig. 9, no thrust displacement has occurred on the foreland side of the black dots which mark the location of the youngest beds in the hangingwall cut-off on the thrust. In Fig. 9(a), additional line length is added to the roof sequence by folding and thrusting, so that a line-length balance can be achieved (Thompson 1981). Alternatively, the roof sequence can be detached from the underlying thrust or duplex by a roof thrust with backthrust sense (Fig. 9b). During the foreland-directed thrusting, the roof rocks are uplifted, but remain stationary relative to the developing thrust system. Additional line length can be added to the roof sequence by shortening on the backthrust. These structures are termed 'Triangle Zone' structures (Price 1981, 1986) or 'Passive roof' duplexes (Banks & Warburton 1986, Jadoon *et al.* 1992). The geometry of the 'passive roof' duplex can be varied principally by varying the initial spacing between the thrusts and the amount of thrust displacement (Mitra 1986) (Fig. 10).

Thin-skinned thrusting at Djebel Cherichira

The Cherichira anticline consists of three main thrust sheets (Fig. 7c). Thrusts 1 and 2 define two separate levels of detachment according to the model of thrust geometry in Fig. 8(a): a lower décollement in Triassic evaporites for thrust 1 and an upper level of décollement in Tertiary rocks for the out-of-sequence thrust 2. A cross-section west of the NW–SE-trending normal fault west of locality ① (Fig. 7a) would require detachment of the out-of-sequence thrust 2 at the base of the Upper Cretaceous sediments. The NW–SE-trending normal fault is therefore interpreted as a hangingwall drop fault, accommodating changes in the level of detachment at the base of thrust sheet B. The exposed sections of thrusts 1 and 2 are footwall ramps as the thrusts truncate rocks in the footwall and are parallel to rocks in the hangingwall. Triassic and Cretaceous–Tertiary rocks are elevated above regional in the Cherichira anticline by transport over the footwall ramp of thrust 1. The 30°NW dip of the fold backlimb is consistent with a single NW-dipping footwall ramp which joins the regional décollement beneath the Chougafiya syncline where the stratigraphy is at regional elevation.

The geometry of thrust sheet C, truncated in the footwall of thrust 1, is also consistent with a thin-skinned thrust style. At Djebel Oulad Kredija, the structural geometry of thrust sheet C equates to part of the leading edge and the hangingwall cut-offs of a foreland-dipping duplex (see Fig. 10), cut by two later strike-slip faults (faults A and B in Fig. 7). The backthrust to the southeast detaches at the same level as the exposed downward-facing thrust and is therefore interpreted as a roof thrust to a foreland-dipping 'passive roof' duplex.

Sequence of thrusting at Djebel Cherichira

Thrusts 1 and 2 are out-of-sequence thrusts because they propagated in the hangingwalls of earlier thrusts. Figure 11 illustrates how the thrust structures could have developed during thin-skinned thrusting. Displacement on thrust 3 in Fig. 11(a), generated a thrust fold in the Mesozoic and Tertiary sediments. This fold is equivalent to thrust sheet C in Fig. 7(c). Thrust 1 propagated from the Triassic décollement beneath the Chougafiya syn-

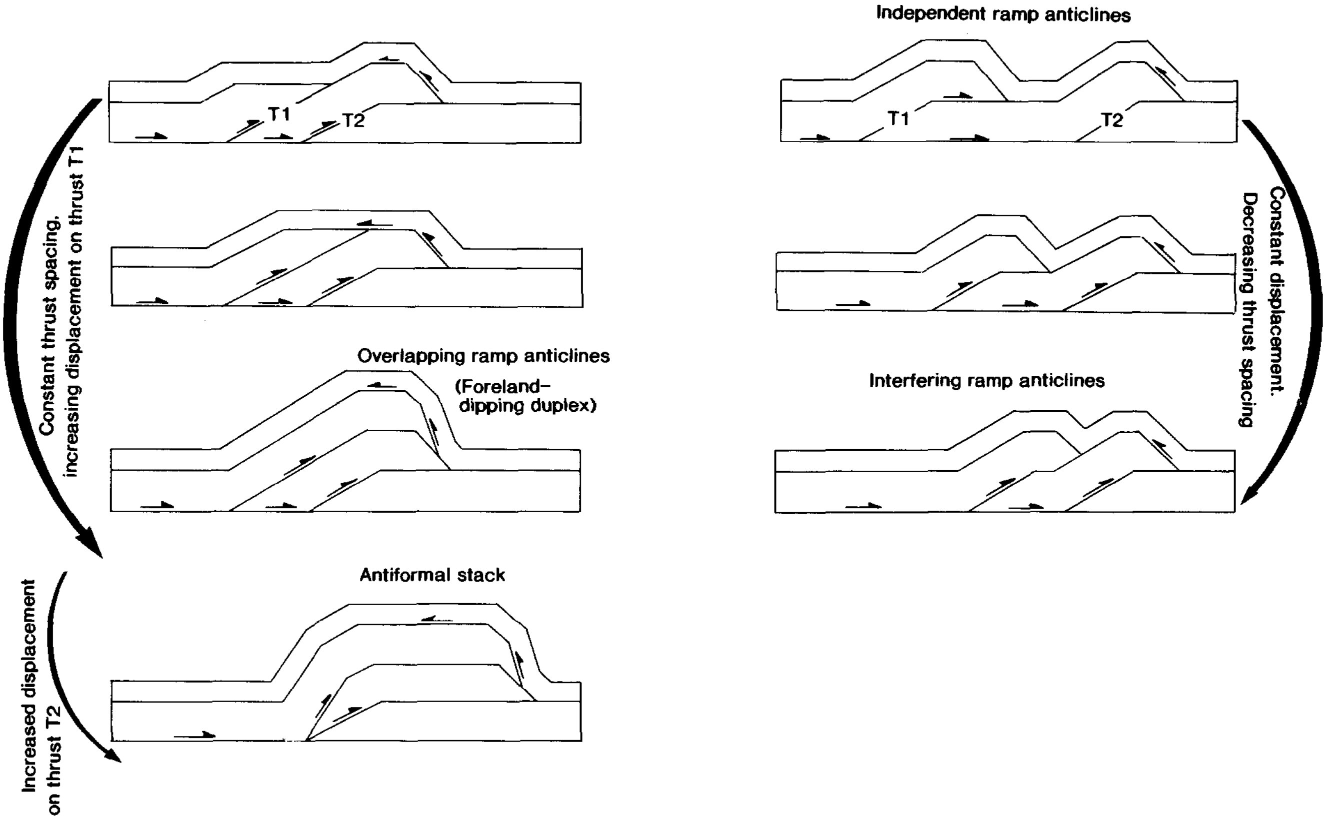

Fig. 10. Variations in duplex geometry. The duplex geometry terminology follows Mitra (1986). The principal controls on duplex geometry are thrust displacement and the initial thrust spacings. On the left, displacement on thrust T1 is increased from the top diagram to the bottom diagram. Displacement on thrust T2 remains constant until the final diagram of the sequence where the displacement on thrust T2 is increased. On the right, the sequence of diagrams indicates how thrust-fold geometry can vary by decreasing the initial spacing between the thrusts.

cline to the northwest, truncating thrust sheet C in its footwall (Fig. 11b). Tertiary and Upper Cretaceous rocks in thrust sheet B were then thrust SE over Triassic sediments on thrust 2 (Fig. 11c), removing Jurassic and Lower Cretaceous sediments from thrust sheet A. Thrust 2 could have cut up-stratigraphy from the décollement in Triassic sediments further northwest. Movement of the Jurassic to Miocene sediments over the footwall ramp A of thrust 2 would be expected to generate a thrust-fold to the northwest of Djebel Cherichira. The Ousselat anticline is a candidate structure for this thrust-fold.

Thin-skinned thrusting at Djebel Ousselat and Djebel Bou Dabouss

In the Ousselat-Bou Dabouss anticline the stratigraphy is elevated 1 to 4 km above regional elevation, but without major SE-directed thrusts at outcrop. It is argued therefore that the uplift and folding has resulted from southeast transport of Mesozoic and Tertiary sediments in the hangingwall of thin-skinned thrusts which do not reach the topographic surface. The geometries of the folds support this interpretation; the Ousselat–Bou Dabouss anticline is consistent with an ESE-verging tipline or hybrid thrust-fold. The limitation of investigating this hypothesis further is that the structure is not eroded sufficiently to expose the underlying thrust systems. On the other hand, shallow level backthrusts are exposed which could be interpreted as a system of roof thrusts to a 'passive roof' duplex, providing additional evidence for detachment-style thrusting in the field area. This interpretation can be validated geometrically with a balanced cross-section (Fig. 12a).

The balanced cross-sections in Fig. 12 have been constructed parallel to the regional thrust transport direction, which has been deduced from the orientations of slickenline lineations on major and minor thrusts in the field area (Fig. 13). The thickness of the unexposed Jurassic and Lower Cretaceous sediments has been constrained by an exploration well at Djebel Rouissàte. The décollement level for the thrusting is inferred to be in Triassic evaporites, consistent with the structural evidence from Djebel Cherichira to the southeast. At Djebel Halfa, the structural geometry has been constructed recognising that repetition of the thickness of Jurassic to base Palaeocene sediments would elevate the Upper Cretaceous Abiod Formation from regional in the Ousseltia syncline to its present elevation in Djebel Halfa. The uplift could be accomplished on a blind thrust (thrust 4) which, on geometric grounds, would have an upper detachment at the base of the El Haria Formation. The backthrust 4A detaches the backfolded Tertiary sediments from the SE-verging Halfa fold in Cretaceous and Jurassic sediments, and flattens at the same level as the upper detachment of thrust 4. It is

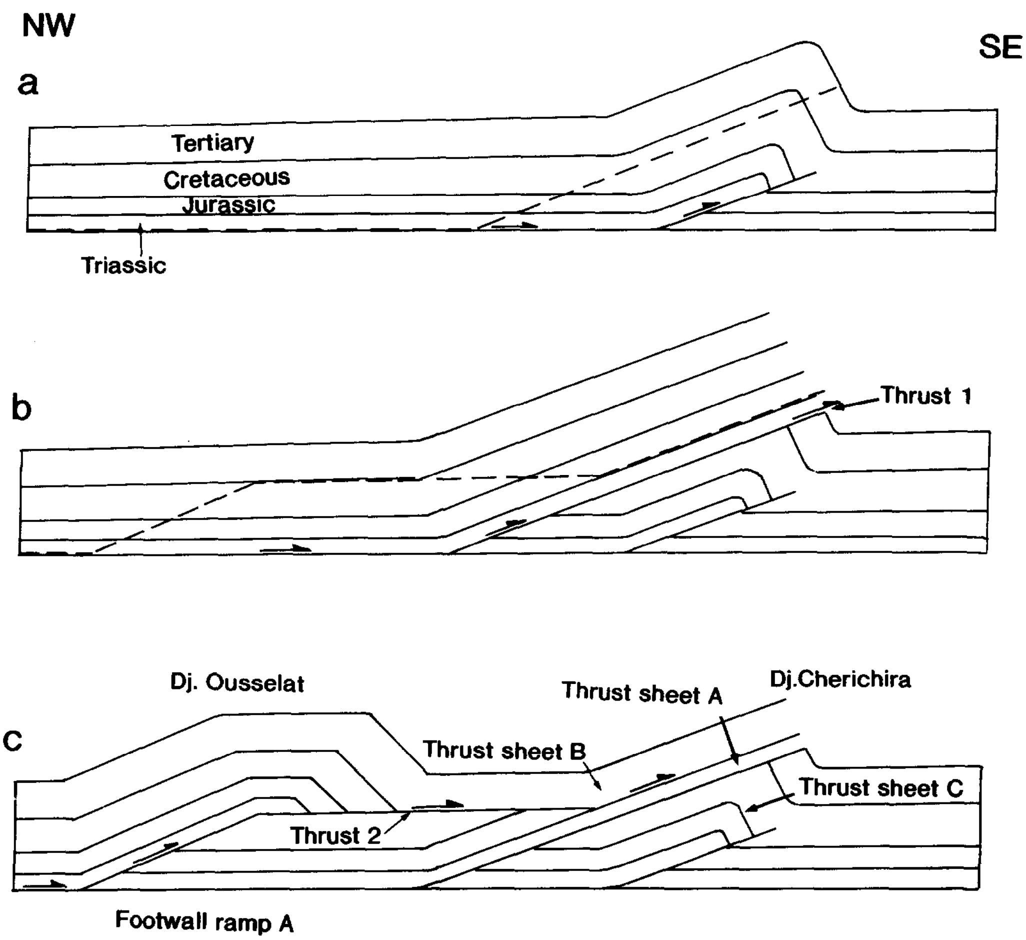

Fig. 11. A model for the sequence of thrusting at Djebel Cherichira. (a) The structural geometry following the displacement on thrust 3 which has resulted in a SE-verging thrust-fold. This SE-verging fold is equivalent to thrust sheet C in Fig. 7(c). (b) & (c) illustrate how out-of-sequence thrusting can be used to account for the geometry of the Triassic evaporites isolated in younger rocks.

argued therefore that the back-thrust shortens the Tertiary sediments above the upper detachment of a SE-verging blind thrust. Based on this interpretation, the geometry of the Halfa fold is analogous to a 'Triangle zone' backthrust structure (Fig. 9b).

The Zemlia anticline is modelled as a tip-line fold to thrust 3 in Fig. 12(a). Consideration of the geometry of this fold, with its steeply-dipping forelimb and tight interlimb angle, suggests that this is a reasonable interpretation. Thrust 3 flattens into an upper detachment in Upper Cretaceous sediments. The backthrust 4A could therefore be interpreted as an exposed section of a system of roof thrusts to a SE-verging 'passive roof' duplex in Jurassic and Cretaceous sediments.

Thin-skinned thrusting at Djebel Serdj and Djebel Kessera

Assuming a décollement in Triassic evaporites for Djebel Serdj, two plausible models for the observed uplift of the stratigraphy are repetition of Jurassic to basal Upper Cretaceous sediments in two stacked thrust sheets (Fig. 12a), or repetition of the Jurassic to Eocene sediments in a single thrust sheet. Along-strike at Djebel Kessera (Fig. 12b), the uplift of the Metlaoui carbonates above regional is exactly equivalent to the thickness of the Jurassic to basal Upper Cretaceous section. If two thrust sheets of Jurassic to basal Upper Cretaceous sediments can account for the uplift at Djebel Serdj, then the steep forelimb dips could result from the hangingwall ramp cut-offs of the upper thrust sheet resting on the SE-dipping forelimb of the underlying fault-bend fold, producing a foreland-dipping duplex similar to thrust sheet C at Djebel Cherichira. This model can also explain the different amounts of uplift between Djebel Serdj and Djebel Kessera, where in the latter structure the second thrust sheet is absent (Fig. 12b) and the amount of uplift is approximately half that seen at Djebel Serdj.

Strike-slip faults

Strike-slip faults post-date the thin-skinned thrust structures at Djebel Cherichira. The strike-slip faults are interpreted as splay faults from the eastern tip of the Kairouan–Kasserine fault and indicate that the latest movements on the Kairouan–Kasserine fault have been sinistral.

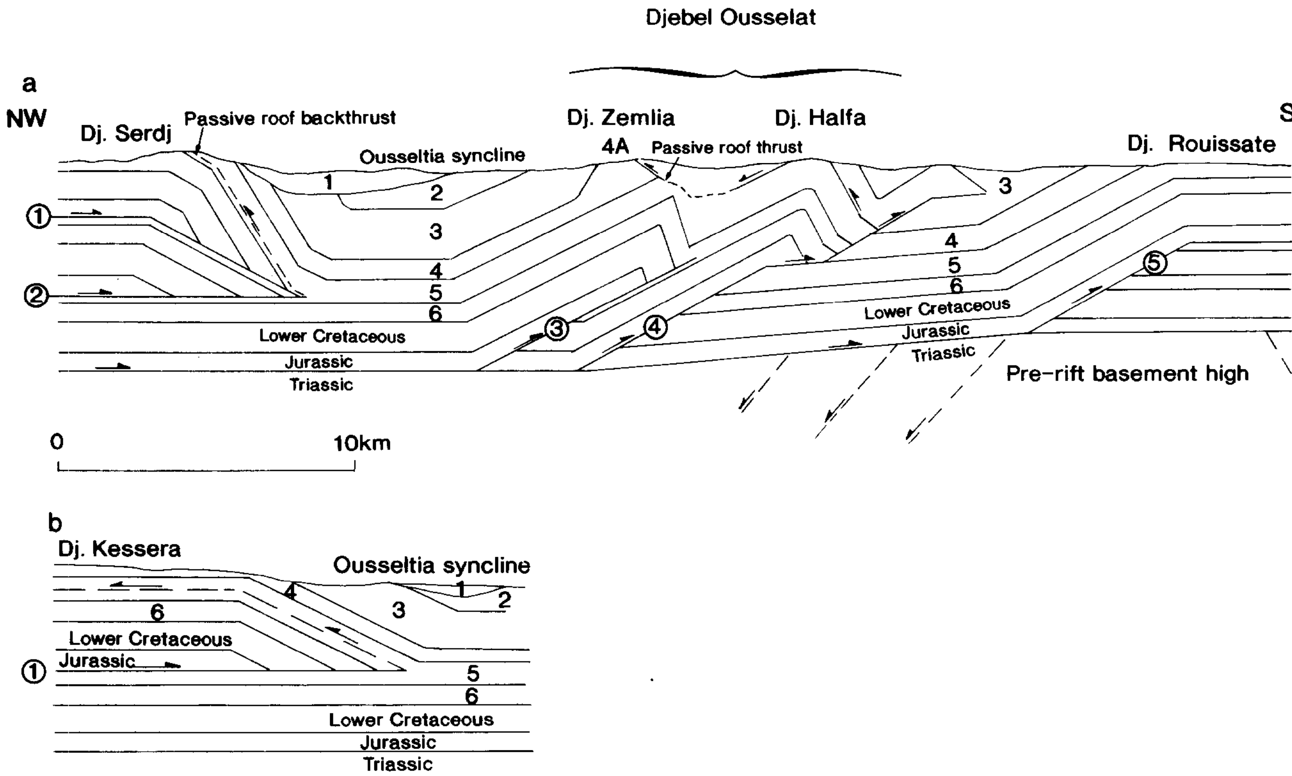

Fig. 12. (a) A NW–SE balanced cross-section through the field area in approximately the same location as Fig. 5(b). (b) A NW–SE cross-section through the Kessera anticline in approximately the same location as Fig. 5(c). Numbers 1–6 refer to the stratigraphy in Fig. 4. See text for discussion.

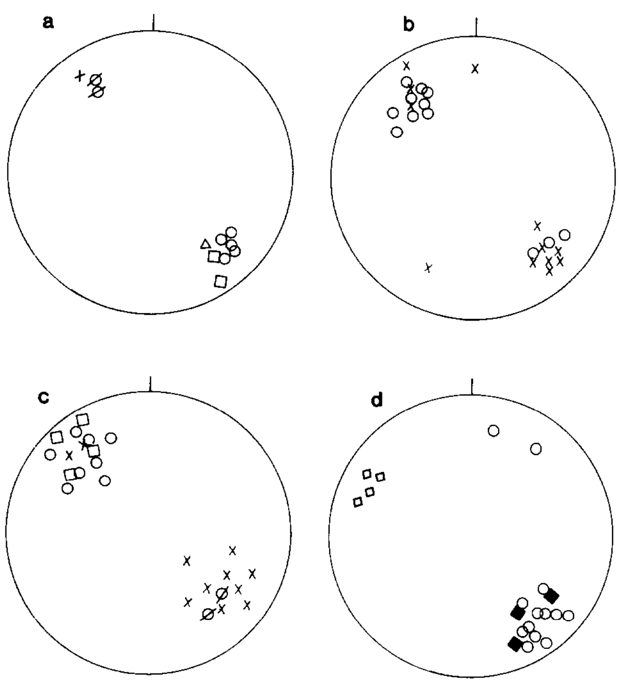

Fig. 13. Stereograms of structural data from the field area. (a) Plot of gouge lineations on the major thrusts at Djebel Cherichira. Key to data in (a): ×—poles to the downward-facing thrust in Fig. 7(d); □—pole to Triassic décollement thrust in Fig. 7(b); △—pole to the out-of-sequence thrust in Fig. 7(b); ∅—slickenlines on Triassic décollement thrust; ○—slickenlines on the downward-facing thrust in Fig. 7(d). (b) Plot of gouge lineations on all minor thrusts at Djebel Cherichira (localities G, H and I in Fig. 4). (c) Plot of gouge lineations on all intraformational thrusts mapped at localities A–F in Fig. 4. Key to data in (b) and (c): ×—poles to forethrusts; □—poles to backthrusts, ○—slickenlines on forethrusts; ∅—slickenlines on backthrusts. (d) Structural data from the backthrust at Djebel Ousselat (locality J in Fig. 4). Key to data in (d): ○—slickenline lineations; ◊—poles to thrusts; ■—poles to extensional shears.

TIMING OF THE DEFORMATION

To the southeast of Djebel Ousselat, Upper Miocene–Pliocene Segui Formation sandstones lie unconformably on older sediments. In the Cherichira anticline, the Segui Formation sands lie unconformably on Oum Douil Formation which is folded in thrust sheet B. The thrust-related deformation therefore occurred approximately in the Middle Miocene, but cannot be constrained further on the basis of this field evidence.

The Pelagian Platform to the east is relatively unaffected by the Atlas folding and thrusting. Exploration wells immediately adjacent to the North–South Axis record continuous sedimentation in the Miocene, with a rapid increase in sedimentation rates in the Langhian (Fig. 14). This is contemporaneous with thin-skinned thrusting in the eastern Atlas Mountains and can be interpreted as the response to increased rates of erosion during thrusting, and the consequent infilling of a foreland basin. Other aspects of the Middle Miocene basin evolution of the Pelagian Platform are consistent with this interpretation. Transgression of the Langhian Mahmoud Formation basinal shales over Burdigalian shallow marine Ain Grab Formation or older continental sediments of the Oum Douil Formation, indicates rapid basin deepening on the Pelagian Platform and tends to suggest a tectonic control on subsidence. In a foreland basin, the thickest sediments occur close to the thrust belt. On the Pelagian Platform, the thickest Middle Miocene sediments are found in the wells closest to the North–South Axis, consistent with a foreland basin

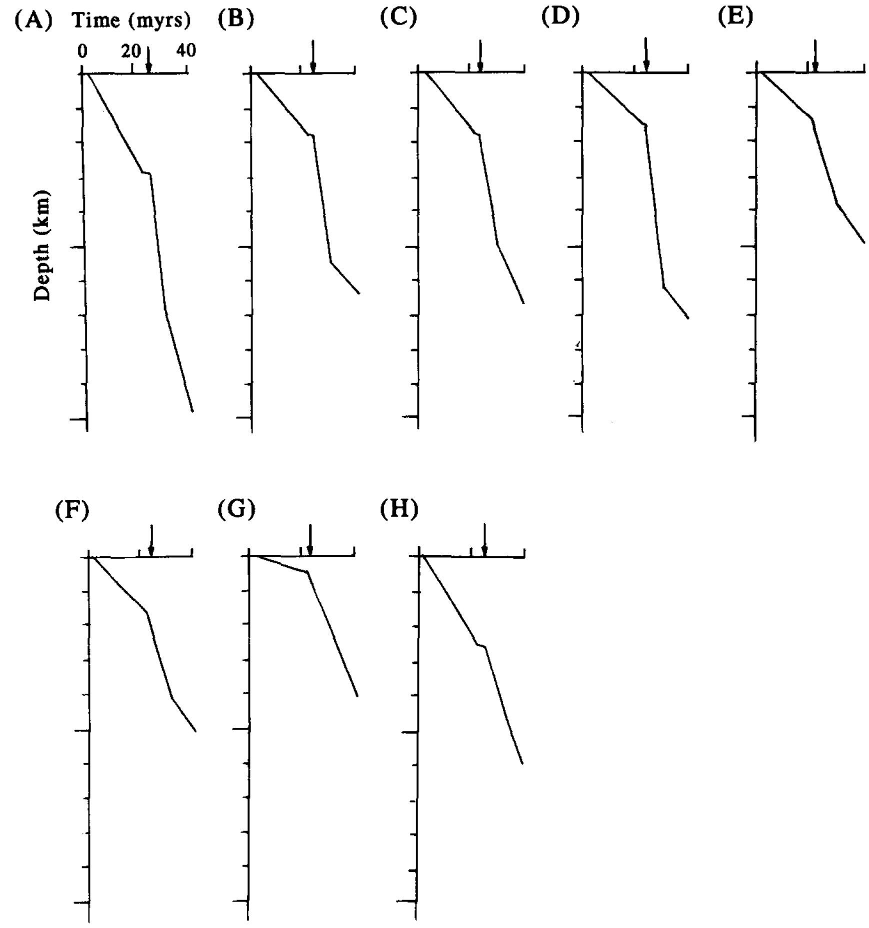

Fig. 14. Decompacted burial history curves for eight exploration wells on the Pelagian Platform (well locations in Fig. 1). The burial history curves are not 'backstripped'. Note the rapid increase in sedimentation rates in the Langhian, at 16 Ma, marked by the vertical arrows on the time scale.

model. If the foreland basin model is an acceptable explanation for this part of the Neogene sedimentation history of the western Pelagian Platform, then the onset of thrusting to the west can be more tightly constrained to the Langhian.

At Djebel Cherichira, strike-slip faulting post-dates the Langhian-aged thrusting. The strike-slip faults affect Upper Miocene rocks. The strike-slip faulting is therefore younger than Late Miocene in age.

DISCUSSION AND CONCLUSIONS

Comparison with other structural models

The major issues of controversy regarding the evolution of the Atlas Mountains centre on the role of basement fault inversion vs thin-skinned thrust tectonics, and the timing of the deformation. The geological evidence presented here suggests that the Tunisian Atlas and the North-South Axis, bordering the western margin of the Pelagian Platform, are dominated by thin-skinned thrusting. The basement inversion models are considered inappropriate for the reasons outlined below.

Dip-slip inversion of syn-rift basement faults (e.g. Snoke *et al.* 1988) is not compatible with the geological evidence. The syn-rift basement faults are E–W to NW–SE-trending and are orthogonal to the Atlas structures (Fig. 3b). This implies detachment of the Atlas folds and thrusts from the syn-rift basement structures. The predominance of fault-bend and tip-line folds in the field area also indicates transport on detachment style thrust faults rather than inversion of steep, planar basement faults.

Ouali *et al.* (1987) and Boccaletti *et al.* (1988) have linked the development of the North–South Axis to strike-slip reactivation of inferred N–S-trending basement faults. It is suggested that in these models the strike-slip and the thrusting are incorrectly interpreted as the same age; the evidence at Djebel Cherichira indicates the thin-skinned thrusting to be Middle Miocene in age, and followed by younger strike-slip faulting.

Boccaletti *et al.* (1988) based their interpretation on the northern North–South Axis, yet there is no convincing geophysical evidence for a N–S-trending basement fault north of Kairouan (see Fig. 3b), thereby depriving the transpressive model of the mechanism to generate the folding and thrusting. In a strike-slip setting, sinistral displacement of the Atlas relative to the Pelagian Platform would be accommodated by a N–S-trending sinistral 'stem' fault, separating the Tunisian Atlas from the North–South Axis. Ouali *et al.* (1987) and Boccaletti *et al.* (1988) did not provide geological evidence to confirm the presence of a 'stem' fault bounding the western edge of the North–South Axis. There is also no evidence for this type of structure to the west of Kairouan (see Fig. 5).

Regional implications

Recognition of the North–South Axis as the thrust front of a Middle Miocene thrust belt has important implications regarding the tectonic significance of the Atlas Mountains. The region affected by detachment-style thrusting includes all of the internal and external zones of the Atlas and not just the Tell Atlas as suggested in previous interpretations (e.g. Cohen *et al.* 1980, Boccaletti *et al.* 1990). Cohen *et al.* (1980) proposed a Triassic evaporite décollement for the Tell Atlas thrust sheets. Triassic evaporites also outcrop at the bases of the thrust sheets along the length of the North–South Axis, suggesting regional décollement of the thrust belt at this level.

Basement fault inversion has not played a significant role in the evolution of the Atlas thrust belt mainly because the syn-rift basement faults were approximately parallel to the direction of thrust propagation. Although there is clear evidence that the Atlas structures are detached from basement faults (Fig. 3b), the geometry of the thrust belt changes across the major syn-rift fault systems. It is suggested on this basis that the syn-rift faults compartmentalized the Middle Miocene thrust belt. The syn-rift basement faults were later reactivated during post-collisional strike-slip (Boccaletti *et al.* 1990) to generate the Late Miocene and younger basins which affect the thrust belt structures.

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