Pergamon

Journal of Structural Geology, Vol. 20, No. 8, pp. 999 to 1011, 1998
© 1998 Elsevier Science Ltd
All rights reserved. Printed in Great Britain
0191-8141/98 $19.00 + 0.00

PII: S0191-8141(98)00031-5

Kinematics of large scale tip line folds from the High Atlas thrust belt, Morocco

B. SAINT BEZAR and D. FRIZON de LAMOTTE

Département des Sciences de la Terre (CNRS ESA 7072), Université de Cergy-Pontoise,
95 011 Cergy-Pontoise Cedex, France. E-mail: frizon@u-cergy.fr

and

J. L. MOREL

Laboratoire de Géologie Structurale, Université de Paris-Sud, Bat. 504, 91 405 Orsay Cedex, France

and

E. MERCIER

Département des Sciences de la Terre (CNRS ESA 7072), Université de Cergy-Pontoise,
95 011 Cergy-Pontoise Cedex, France

(*Received* 26 *July* 1997; *accepted in revised form* 16 *March* 1998)

Abstract—The kinematics of several tip line folds situated along the South Atlas Front near Goulmima (Morocco) is established using both forward modelling and analysis of syn-folding deformation. From the Sahara foreland to the Atlas, the two successive major structures forming the mountain front in this area fit geometrically with a 'generalised fault propagation fold' model and a model of 'fault propagation fold' altered by late transport on the upper flat, respectively. Field evidence shows that the two folds are developed more or less synchronously. The analysis of minor structures helps address the question of migrating hinges vs fixed hinges during the fold's growth. © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

Among fault related folds, tip line folds (i.e. folds developed at blind thrust tips; Elliott, 1976) are now recognised as widespread in fold-thrust belts. The particular category of tip line folds developed at the tip of a ramp has been formalised and called 'fault-propagation folds' by Suppe and Medwedeff (1984) and Suppe (1985). On the other hand, various late alterations of the simple step models have been analysed by Jamison (1987), Suppe and Medwedeff (1990) and Mercier (1992) and formalised by Mercier *et al.* (1997). The basic fault propagation fold model assumes the conservation of bed length and bed thickness and the migration of fold hinges (Fig. 1a). This implies that the limbs of the folds rotate instantaneously when they go through the migrating active axial surfaces and, additionally, that the deformation in the limbs is accommodated instantaneously by bedding-parallel simple shear (Fig. 1b).

The kinematic history of folds and, in particular, the question of fold development by progressive or instantaneous limb rotation has been intensively studied using growth strata geometry (Suppe *et al.*, 1992; Zoetemeijer and Sassi, 1992; Hardy and Poblet, 1994; Mercier, 1994; Poblet and Hardy, 1995; Zapata and Allmendinger, 1996; Suppe *et al.*, 1997). Unfortunately growth strata are relatively scarce in fold–thrust belts. Another way is to search for structural evidence supporting the basic mechanisms inferred by the different folding modes. This point has been discussed recently by Fisher *et al.* (1992), Fisher and Anastasio (1994), Anastasio *et al.* (1997) and Erslev and Mayborn (1997) who, studying several fault-related folds from the Rockies and Appalachians, favoured progressive limb rotation as the basic mechanism of folding. On the contrary, a combination of geometric and kinematic studies led Thornbjorsen and Dunne (1997) to interpret the Barclay anticline (Appalachian) as resulting from breakthrough thrusting with hinge migration. Similarly, on an example from the Corbières (SE France), Frizon de Lamotte *et al.* (1997) used anisotropy of magnetic susceptibility (AMS) measurements to validate a kinematic model of a 'generalised fault propagation fold' with hinge migration (Chester and Chester, 1990).

The aim of this paper is to propose a kinematic forward model of a couple of tip line folds situated along the South Atlas Front near Goulmima (Morocco). The main interest of this area is that it provides field arguments allowing a discussion of several increments of the kinematic evolution.

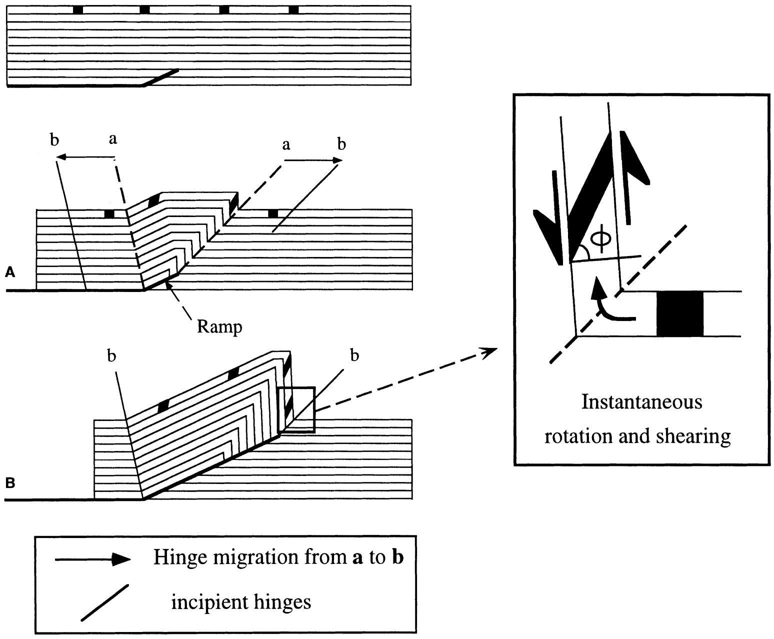

Fig. 1. Sketch illustrating the basic assumptions of the fault propagation fold model *sensu* Suppe (1985): the hinges migrate through time and the dips of forelimb and backlimb are produced instantaneously when an element of rock goes over a hinge.

GEOLOGICAL SETTING

Regional geology

The South Atlas Front is the southern deformation front of the Atlas Fold and Thrust belt (i.e. the structural boundary between the Atlas Mountains and the African Craton or Sahara platform; Fig. 2a). This major thrust structure runs continuously from Agadir (Morocco) to Tunis (Tunisia) (see Bracène *et al.*, 1998). The studied area is situated between the Ouarzazate and Er Rachidia provinces, north of the little town of Goulmima (Fig. 2b).

South of Goulmima the Sahara domain exposes mainly Precambrian basement (Anti-Atlas) overlain by carbonate platform deposits of the Devonian Erfoud Formation. These units were deformed together during the Variscan orogeny and then truncated by an erosional unconformity with red Upper Jurassic–Lower Cretaceous sandstones and siltstones including evaporites above it. Cenomanian–Turonian marine limestones and Senonian continental siltstones overlie the Lower Cretaceous rocks (Fig. 3). The whole Mesozoic pile constitutes an horizontal tableland (locally called Hamada) which bounds the Atlas Mountains (Fig. 2b).

To the north of the Goulmima tableland, Lower Mesozoic rocks pertaining to the Atlas basin are exposed in the core of the main anticlines (Bernasconi, 1983). The stratigraphic sequence consists of red beds and basalts of Triassic age overlain by Lower to Middle Jurassic limestones. Within Liassic beds, a platform–basin boundary is exposed in the Jebel Ta'bbast. It is expressed by a very rapid south to north transition from a massive carbonate platform to a layered sequence indicative of open sea conditions. The Upper Liassic strata consist of a thin argillaceous formation underlying layered limestones of Dogger age. Upper Jurassic rocks are red continental sandstones which grade into the Cretaceous sequence described above. It is worth noting the lack of angular unconformities within the Mesozoic sequence. Consequently, the rocks are inferred to have been parallel-bedded prior to deformation.

Because of the continuous Cretaceous cover, the transition between the Sahara Craton to the south and the Early to Mid Jurassic Atlas basin to the north is not exposed in the field. Based on data from boreholes and seismic profiles, Jossen and Filali-Moutei (1992) assumed the existence of an evaporite basin situated around Er Rachidia. However, there is no evidence of such a basin in the Goulmima area. It is the reason why, in our prefolding restoration, we assume that the Lower Mesozoic sedimentary sequence forms a quite simple sedimentary wedge affected by few normal faults. An equivalent geometric pattern has recently been imaged by seismic reflection profiles near the front of the Sahara Atlas (Algeria) by Bracène *et al.* (1998).

Structure of the South Atlas Front in the Goulmima area

The structure of this region was first mapped at the 1/500,000 scale by A. Faure-Muret (in Choubert,

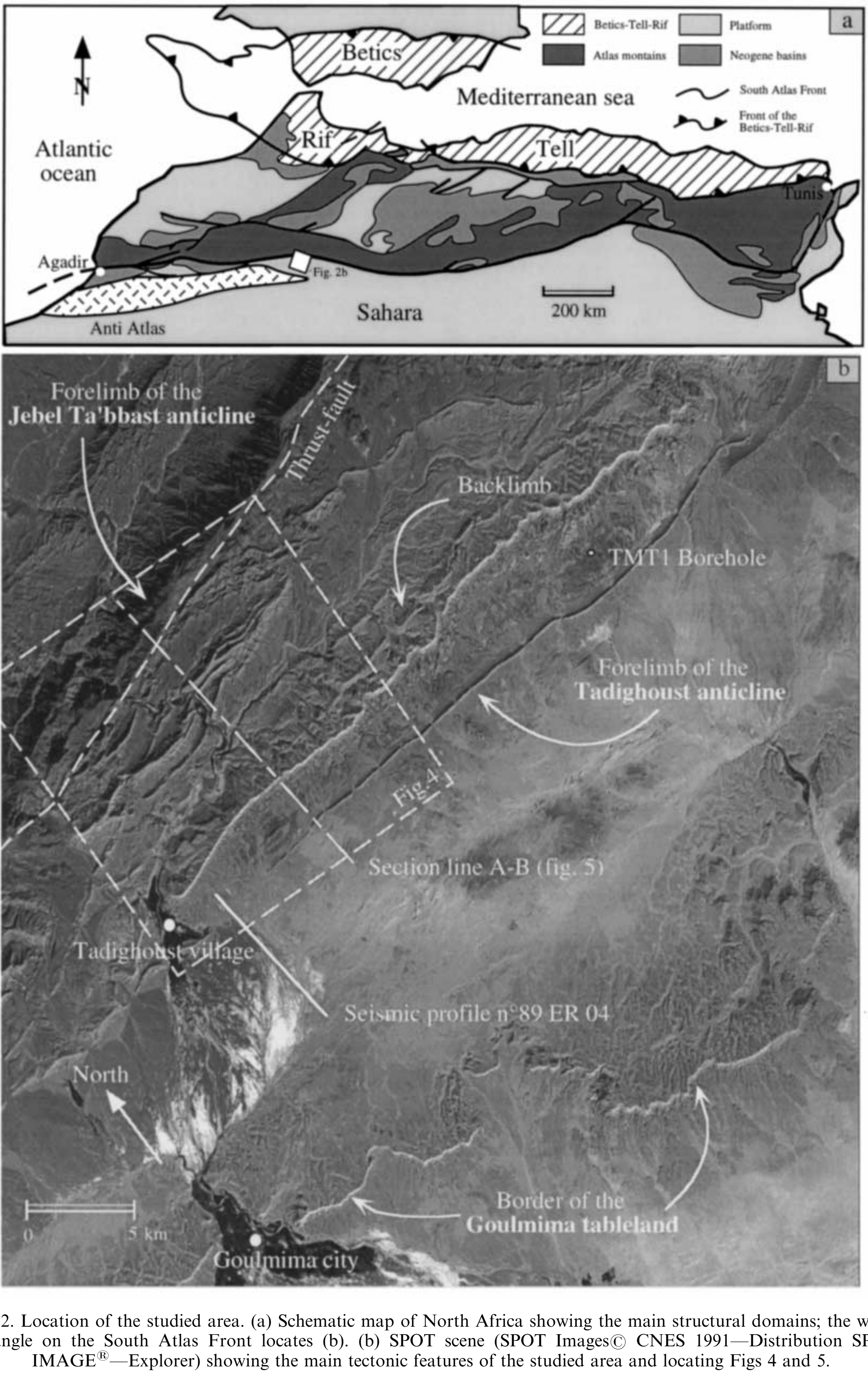

Fig. 2. Location of the studied area. (a) Schematic map of North Africa showing the main structural domains; the white rectangle on the South Atlas Front locates (b). (b) SPOT scene (SPOT Images© CNES 1991—Distribution SPOT IMAGE®—Explorer) showing the main tectonic features of the studied area and locating Figs 4 and 5.

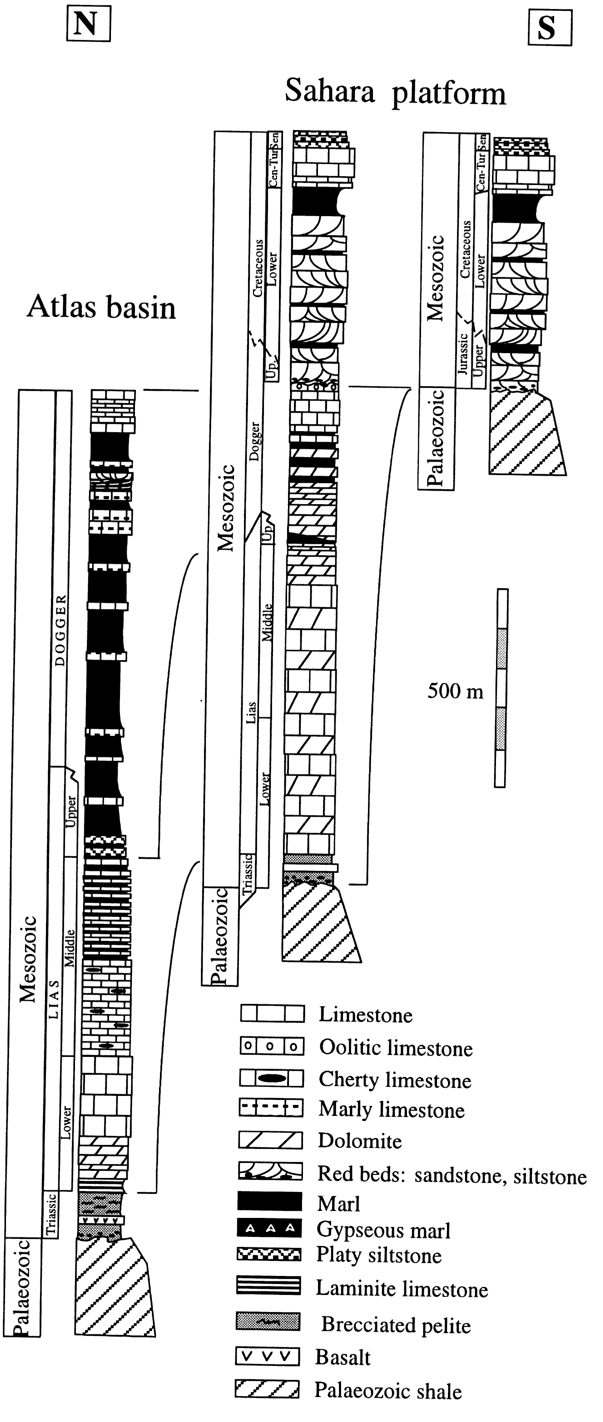

Fig. 3. Schematic stratigraphic columns showing the main units of the Goulmima area. Modified from Bernasconi (1983) and Jossen and Filali-Moutei (1992).

1954). More recently, in a regional paper, Jossen and Filali-Moutei (1992) give a schematic cross-section (their fig. 10) cutting through a part of the studied area. From the south to the north one can distinguish two major structures, the Tadighoust and Jebel Ta'bbast anticlines, that we have mapped in detail at 1/25,000 scale (Fig. 4).

The Tadighoust anticline is an asymmetric south-verging fold exhibiting a gently dipping backlimb and very steep (up to vertical or overturned) forelimb (Figs 2, 4 & 5). The Tadighoust anticline exposes Dogger to Cenomano–Turonian rocks. The TMT-1 borehole drilled in 1961 at about 1.4 km south of the frontal hinge gives the following information about the geometry at depth (BRPM internal report, 1964): the well has intersected a normal Dogger and Liassic sequence down to 1500 m. At this depth an important blind fault leads to a repetition of the Lower Liassic sequence. Triassic beds were not encountered during the drilling but they are probably not very far from the bottom of the hole. Both well data and direct observation of the kink-like geometry of the hinges (Fig. 5) suggest that the Tadighoust anticline is a ramp-related fold. More precisely, the data fit very well with a 'generalised fault propagation fold model' (Chester and Chester, 1990; see below). We recall that this model combines a fault bend fold at depth (here in the stiff Liassic dolomites) and a fault propagation fold in the overlying strata (here in the Dogger to the Upper Cretaceous rocks).

The Jebel Ta'bbast anticline is also an asymmetric fold but wider than the Tadighoust one. It exposes the complete Mesozoic sequence from the Triassic to the Cenomano–Turonian. The core of the anticline formed by Liassic rocks exhibits a quite simple geometry with a gentle backlimb, a sub-horizontal roof and a steep forelimb (Fig. 5). More complicated structures are expressed at the front of the fold. The layered limestones of Dogger age are folded into sharp chevron folds and locally thrusted onto inverted Cretaceous strata (Fig. 6a). A puzzling structure, exposed within these rocks, is a large south-vergent recumbent syncline formed in the Cenomano–Turonian limestones (Fig. 6b). This recumbent fold can be followed 15 km along strike. Across strike, the length of the inverted limb is at least 300 m. Geometrically the main structure of the Jebel Ta'bbast anticline fits with a fault propagation fold model altered by late transport on the upper flat (Jamison, 1987). From the geometric modelling (Mercier *et al.*, 1997), the upper and lower flats are situated within the Paleozoic substratum and Triassic levels, respectively. The relationships between the stages of the building of the fold and the structures developed at its front will be described below.

The two major Tadighoust and Jebel Ta'bbast anticlines are separated from each other by a set of tight anticlines and synclines affecting Cretaceous rocks (Figs 2, 4 & 5). These folds, which are locally cut by minor thrust planes, vary between north and south vergent along strike. Because of their concentric style, we assume that they are detachment folds. An excess area calculation (Hossack, 1979) leads to the conclusion that they are built above a shallow décollement level situated at the top of the Dogger sequence. An important point is that the recumbent syncline

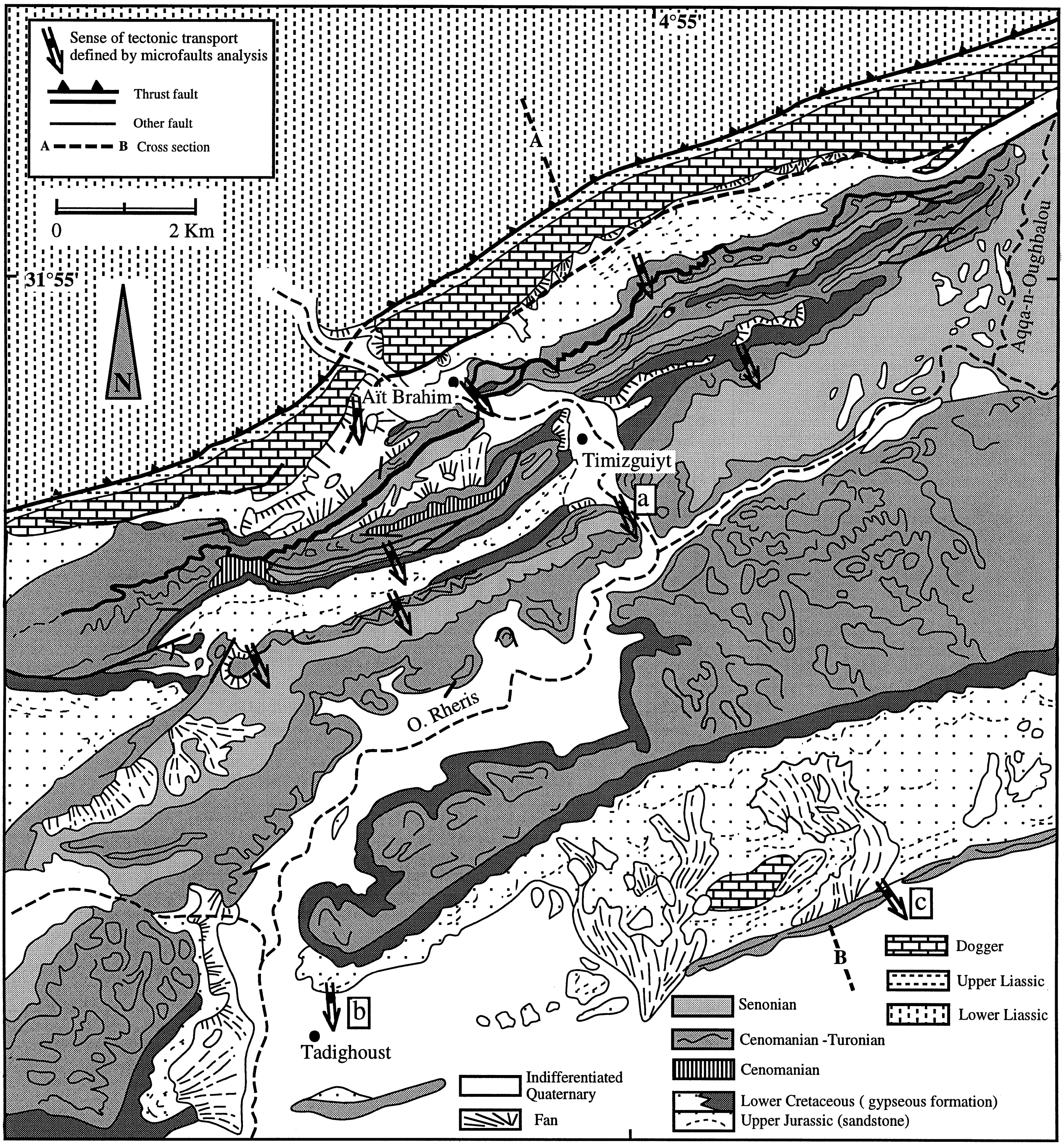

Fig. 4. Simplified geological map of the studied area. The A–B line locates the modelled cross section (see Figs 5 & 8). (a), (b) and (c) locate the Fig. 7 localities.

described above is refolded by this late generation of folds (Fig. 5).

In order to give an account of the kinematics of the South Atlas Front in the studied area, data from striated microfaults from 10 localities were collected. These deformations are preferentially concentrated in zones situated in the vicinity of minor thrust planes cutting the forelimbs of the folds and, consequently, indicative of the late stages of folding. In each locality, most of the faults strike parallel to the trend of the major structures and most of the slickenside striations are down dip. The population of faults includes low angle ($<30°$) reverse and normal faults dipping to the NNW and the SSE, respectively. The slip along these fault planes is consequently synthetic to the SSE tectonic transport defined by the asymmetry of the folds (Fig. 7). Less abundant high angle ($>45°$) antithetic normal and reverse faults are also observed in some sites. This rather complex pattern of microfaults is quite classical in thrust belts and expresses a bulk

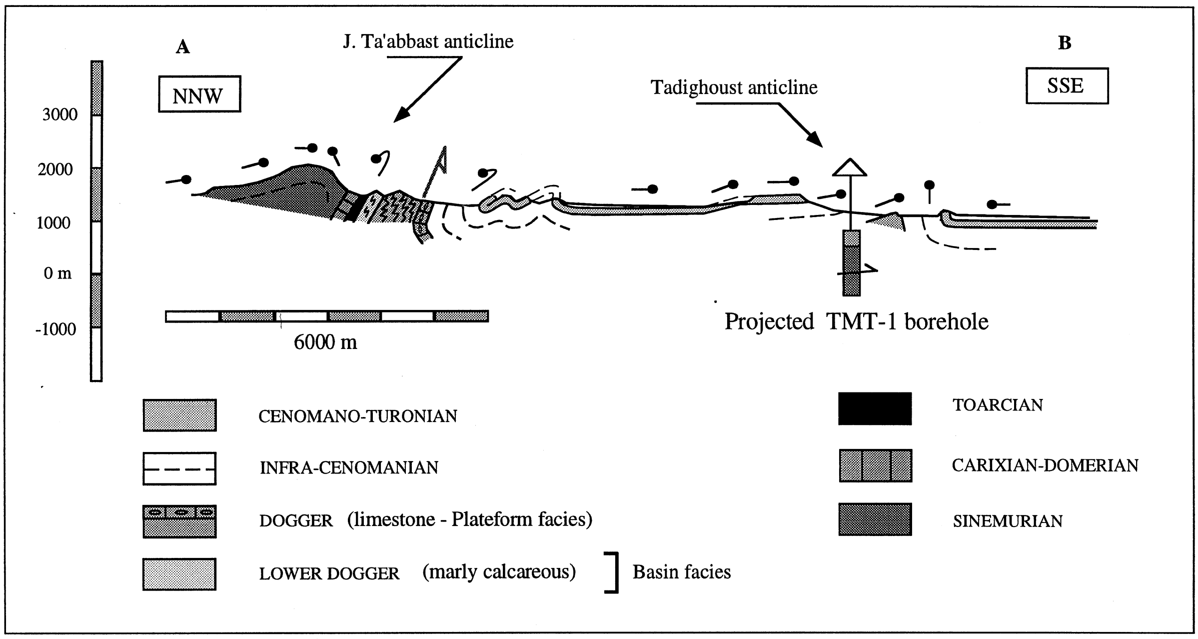

Fig. 5. Section line across the Jebel Ta'bbast and Tadighoust anticlines compiled from the available surface and sub-surface data (see Figs 2 & 4 for location).

non-coaxial strain regime in the vicinity of the thrust planes (Wojtal, 1986; Casas and Sabat, 1987; Guézou *et al.*, 1991). For the purpose of this paper, the important point is that the tectonic transport is normal to the main structures. On the other hand, as the internal deformation remains weak, we can construct balanced cross sections parallel to that direction.

KINEMATICS OF THE JEBEL TA'BBAST AND TADIGHOUST ANTICLINES

In foreland fold-thrust belts, forward models provide a powerful tool to balance sections (Endignoux and Mugnier, 1990; Contreras, 1991; Mercier *et al.*, 1997). Such models are based on the requirement that an interpretation is plausible only if each step between the restored stage and the present day state is kinematically and physically acceptable. Additionally, these models allow the prediction of the deformation paths followed by each element of rock involved in the folds. Consequently, a way to validate a forward model is to give independent evidence supporting the main mechanisms of the chosen folding modes. Using the forward kinematic software elaborated by Mercier (in Mercier *et al.*, 1997), we will describe five steps of a geologically consistent scenario for the sequential building of the Jebel Ta'bbast and Tadighoust anticlines and the associated minor structures (Fig. 8). As emphasised by Mercier *et al.* (1997), we wish to stress here that the identification of fault propagation folds in the studied area simplifies the balancing problem because the modelling fixes both depth to décollement and the slip value along this décollement.

Step 1—This first stage (Fig. 8) is a palinspastic restoration of the studied area based on surface and subsurface data kindly provided by ONAREP the Moroccan National Oil Company: TMT-1 borehole and four strike and dip seismic profiles. They give evidence of the control of the paleogeography on the structural style of the thrust belt. From the south to the north, the thickness of the deformed sequence increases from 500 m to more than 2000 m. It is assumed that thickness and facies changes occurred mainly across basement faults which were active during Triassic and Jurassic times. Morever, such a basement normal fault can be observed below the Tadighoust anticline on the seismic profile 89ER04 (ONAREP, unpublished data; the profile is located on the Fig. 2). The Upper Jurassic–Cretaceous cover is approximately of similar thickness and overlies the whole system.

Step 2—This stage corresponds to the development of the Jebel Ta'bbast anticline as a basement involved fault-propagation fold. The Jebel Ta'bbast anticline is superimposed on and located by the northernmost basement fault described above. It is worth noting that the fault is not truly reactivated. A short cut through the substratum occurs (i.e. the thrust decapitates a piece of an old scarp) as a consequence of the development of a new low angle ramp coming from an intra-Paleozoic detachment. Slip along the ramp is completely accommodated by folding. The inferred ramp remains blind.

In the Middle Jurassic strata, the overturned forelimb of the Jebel Ta'bbast anticline exhibits plurimetric scale drag folds (Fig. 9). They exhibit a constant asymmetry indicating an upward (i.e. toward the frontal anticline hinge) bed-parallel shear combined with down-dip-parallel shortening. The shearing is consist-

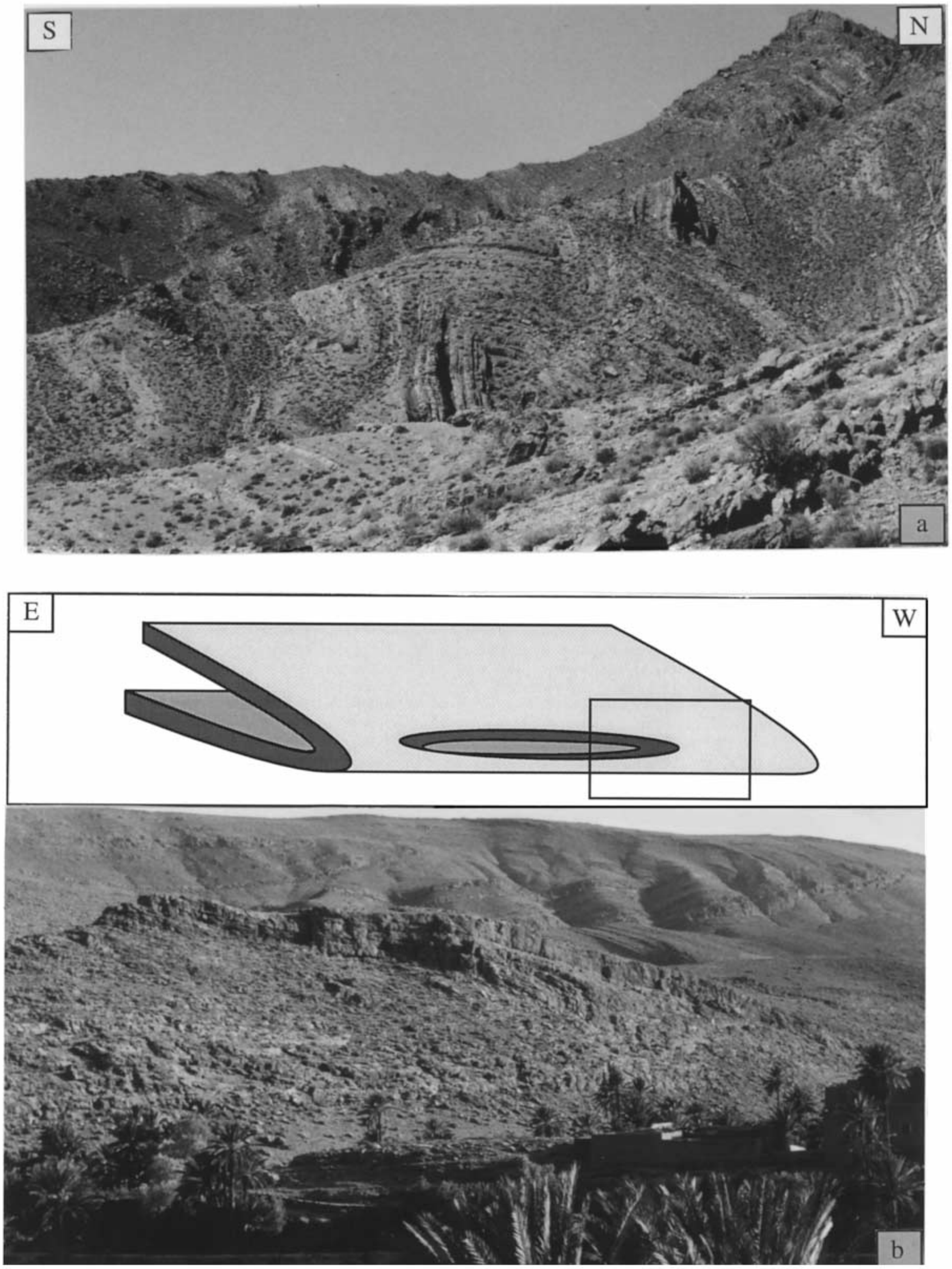

Fig. 6. Structures observed along the front of the Jebel Ta'bbast. (a) Chevron folds affecting the Dogger limestone (east of Aït Brahim); (b) The hinge of the recumbent syncline affecting the Turonian limestone (SW of Aït Brahim). Box outlines are of photograph in lower view.

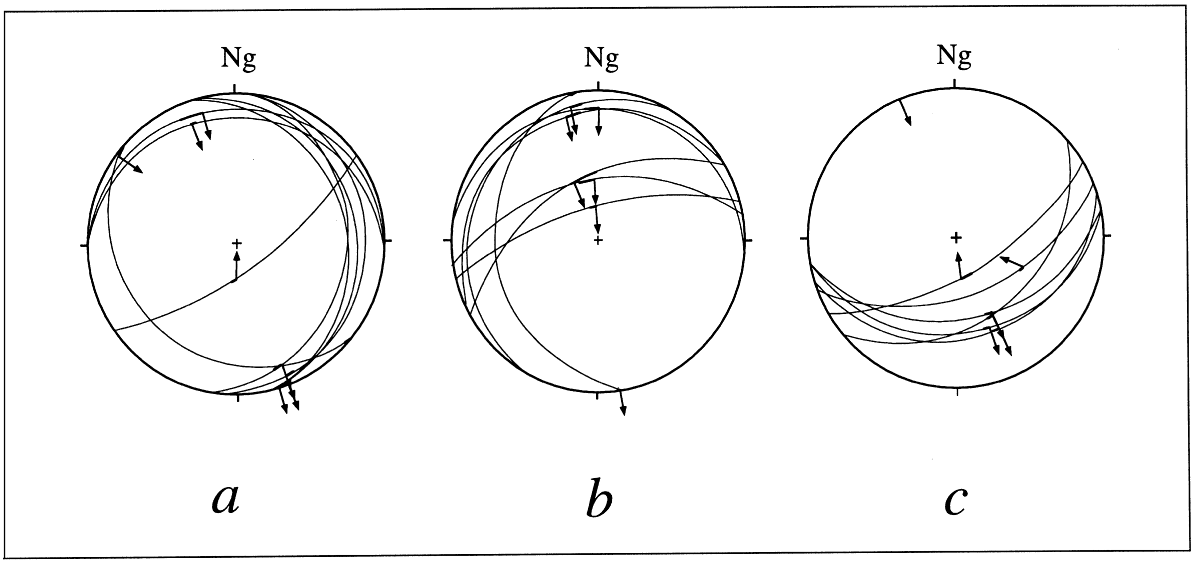

Fig. 7. Stereonets (Wulff lower hemisphere) illustrating the geometry of microfaults in typical sites of the studied area (see locations of sites on Fig. 4).

ent with the expected deformation in this part of the fold (Fig. 1). As, on the other hand, the drag folds have been observed only in the part of the fold where the expected shearing is maximum (Fig. 1), we assume that they were developed during the building of the Jebel Ta'bbast anticline. As a working hypothesis we propose that each individual drag fold is acquired as a consequence of bed parallel shear acting during the 'instantaneous' rotation required theoretically (Fig. 10). The proposed scenario is consistent with the data but is clearly not unique. More generally 'finite strain' measurements are not discriminating because both fixed hinge and migrating hinge models require the same amount of bed parallel shearing. However, as we will see below, a way to validate one of these two models will be to compare the deformation of the forelimb with the ones observed in the adjacent limbs (in the foreland and the roof of the fold, respectively). Unfortunately, middle Jurassic strata are not exposed in the front nor in the roof of the Jebel Ta'bbast.

Step 3—At this stage, the Jebel Ta'bbast ramp reaches and follows an upper décollement situated within Triassic levels. The Jebel Ta'bbast anticline is then transported on this upper flat. The slip generated along it is totally transferred to the front where the Tadighoust anticline develops. The geometry of this new fold is consistent with a 'generalised fault propagation fold' (Chester and Chester, 1990; see the previous section). Among other interests, this model gives a consistent explanation for the additional kink observed in the backlimb of the anticline (Fig. 5). Flexural slip on bedding planes is expressed by shear fibres observable on each bed of the forelimb. Calcite accretion steps indicate relative movement of top towards the hinge of the anticline. Such kinematic indicators are missing in the tabular foreland as well as in the roof of the anticline. This observation is important because, as shown in the Fig. 11, it is not consistent with any model of folding in which the mechanism is flexural slip. In particular, a progressive kink-band folding with fixed hinges imposes flexural slip on all fold limbs (Fig. 11a). If, as observed in the field, flexural slip is restricted to the vertical limb, then a migration of hinges is needed. This migration can be local (Fig. 11b), general (Fig. 11c) or any combination between these two end member models. The main difference between the two models is that in the first one (Fig. 11b), the axial planes rotate during folding whereas in the other (Fig. 11c), they keep a constant dip. It is worth noting that this last process is the only one agreeing with both the field data and the assumptions of the fault propagation fold model (Fig. 1).

A geometry similar to the Tadighoust one (including the short cut) has been obtained by physical modelling (Letouzey *et al.*, 1995). These authors also show how the existence of two décollement levels results in blind rather than emergent thrusts. We emphasise that, at this stage, the two structures are active synchronously (Boyer, 1992) and that modelling uses only fault propagation folds (Suppe, 1985), their variant (Chester and Chester, 1990) and their late-stage evolution (Jamison, 1987; Suppe and Medwedeff, 1990; Mercier *et al.*, 1997).

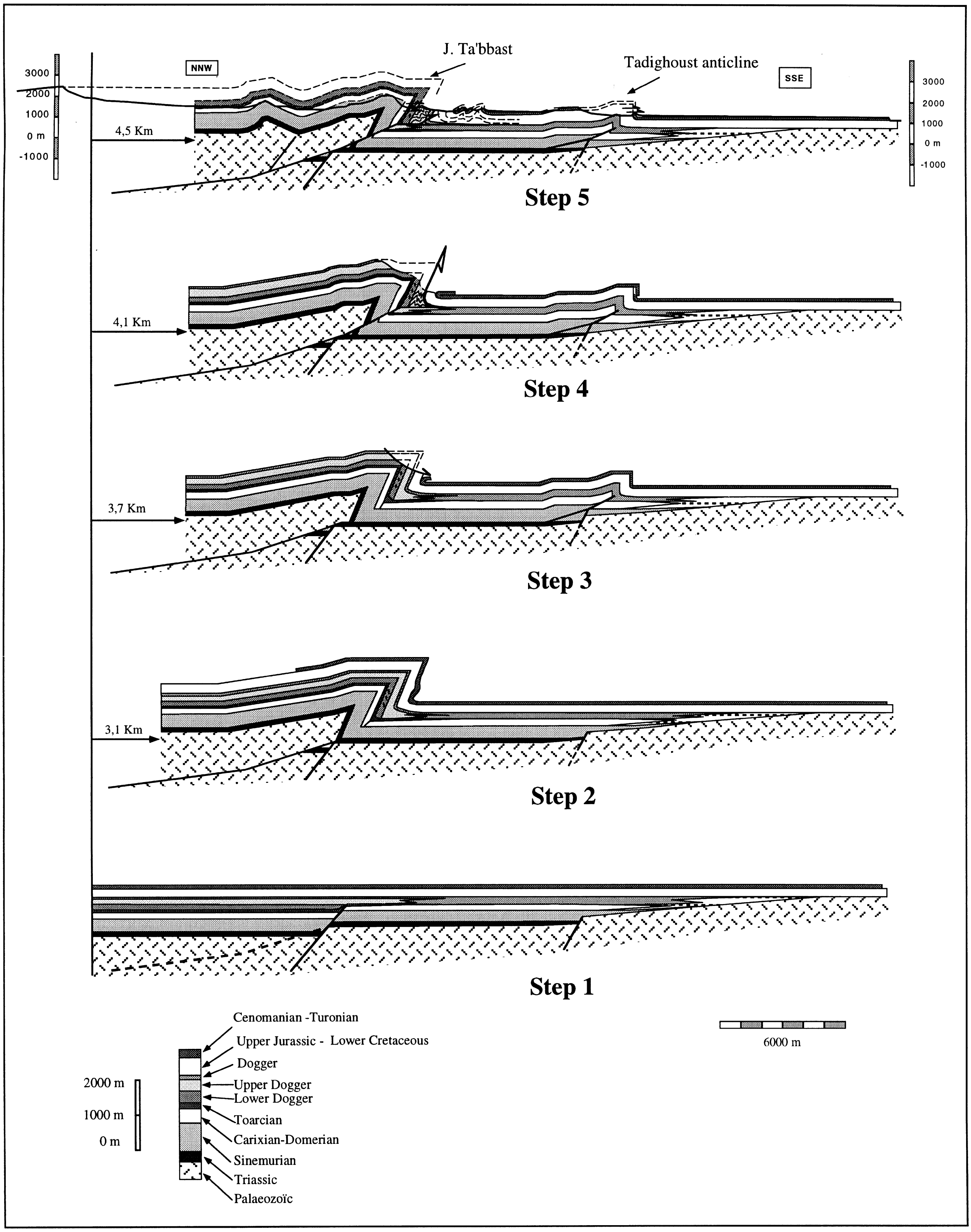

Fig. 8. Kinematic evolution of the Jebel Ta’bbast and Tadighoust anticlines modelled using the Rampe E.M. software (Mercier *et al.*, 1997). See explanations in the text.

Fig. 9. Drag folds within the Middle Jurassic strata from the forelimb of the Jebel Ta'bbast (east of Aït Brahim).

Step 4—Blockage of the propagation of the second ramp allows an overstep reactivation of the first ramp following a process described by Mercier and Mansy (1995). From it, a breakthrough fault develops and cuts through the Jebel Ta'bbast anticline. This new segment does not reach the surface but branches in a shallow décollement situated within Middle Jurassic strata (Dogger) which terminates rapidly southward. It is probably the reason why the slip generated along this is not transferred a long distance away but is accommodated locally by the chevron folds described above. Frontally this fold stack acts as a wedge decoupling the Cretaceous strata from their substratum. At this stage, the collapse of the Cenomano–Turonian limestones along the forelimb or the development of an 'out of the syncline thrust' (Butler, 1982) allow the initiation of the frontal recumbent syncline ('flap' *sensu* Harrison and Falcon, 1934) (Fig. 6b) which is subsequently accentuated as the wedge is translated southward (Fig. 12). According to Mercier *et al.* (1994), we emphasise that, during such a process, the syncline hinge situated at the tip of the wedge within Cretaceous beds cannot be fixed (Fig. 8).

Step 5 and end—A new blockage allows the activation of a shallower décollement at the top of the Dogger strata (attested by the excess area calculation see above). Slip along this plane allows the development of detachment folds in the above lying beds. The

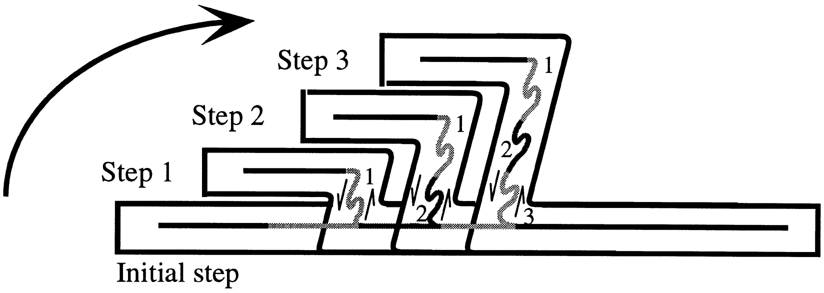

Fig. 10. Kinematic sketch illustrating a possible scenario for the development of drag folds in the forelimb of the Jebel Ta'bbast anticline (see Fig. 6a).

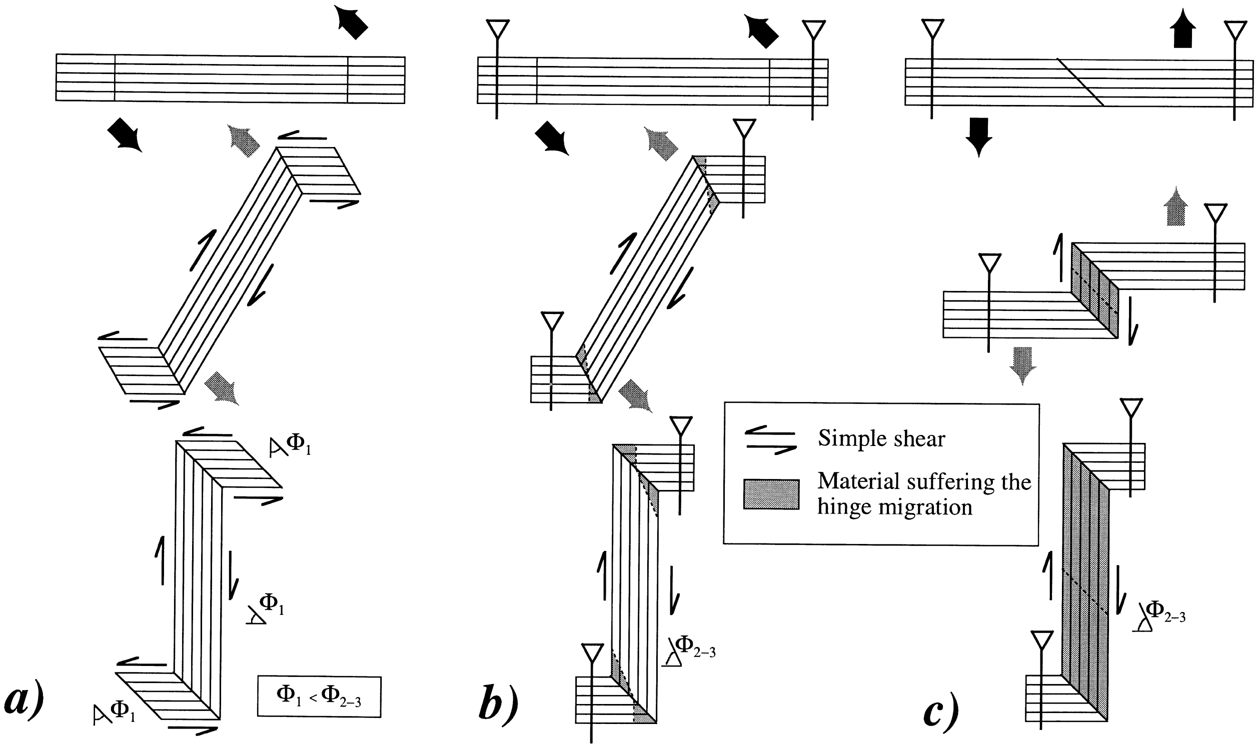

Fig. 11. Schematic diagram showing three basic models of kink-band folding. (a) fixed hinges model (with forelimb rotation); (b) quasi-fixed hinges model (with forelimb rotation); (c) migrating hinge(s) model (fixed forelimb dip). Models (b) and (c) are consistent with field data; (c) is additionally consistent with the assumptions of the fault propagation fold model (Fig. 1).

relative chronology is unquestionable because, at the front of the Jebel Ta'bbast anticline, a detachment fold is superimposed on the pre-existing recumbent fold. The part of the slip generated along the Cretaceous décollement that has not been accommodated by folding could be responsible for the small scale forelimb thrusts observed in numerous places at the front of the Tadighoust anticline.

The latest increments of deformation are expressed by out-of-sequence thrusting which locally places the Jebel Ta'bbast forelimb onto inverted Cretaceous strata, and by secondary folding above the Jebel Ta'bbast anticline ramp.

CONCLUSIONS

The Tadighoust and Jebel Ta'bbast anticlines (Er Rachidia province, Morocco) are large scale, tip line folds which developed in the Mesozoic Atlas sedimentary pile during the building of the High Atlas Mountains. Because of the lack of Tertiary rocks, an accurate timing cannot be defined in the studied area. By reference to the adjacent Ouarzazate basin where synsedimentary rocks are known, we can infer that the deformation took place since the Lower Miocene (Laville *et al.*, 1977).

As in other regions along the South Atlas Front in Tunisia, Algeria and Morocco (Frizon de Lamotte *et al.*, 1990; Creuzot *et al.*, 1993; Outtani *et al.*, 1995; Ouali and Mercier, 1997; Bracene *et al.*, 1998; Frizon de Lamotte *et al.*, 1998), the structures are consistent with south-verging thrusting. The main thrust fault is blind and consequently not exposed in the field. However, the decrease from north to south in the amount of total shortening suggests a northward increase in thrust displacement and consequently a bulk southward propagation of the thrust tip line. In detail, the sequence appears more complicated: at numerous steps of the tectonic forward model, breakback thrusting occurs. In addition, the two major folds are active sometimes synchronously and sometimes separately. From a more general point of view, our work suggests a method to validate a kinematic model. The geometrical analysis alone is insufficient to determine the kinematics of folding. However, it is clear on the studied example that the quest of a kinematic consistency between two adjacent folds places numerous additional constraints on the kinematics of each individual structure. This must be completed by an analysis of minor structures, their relative chronology and

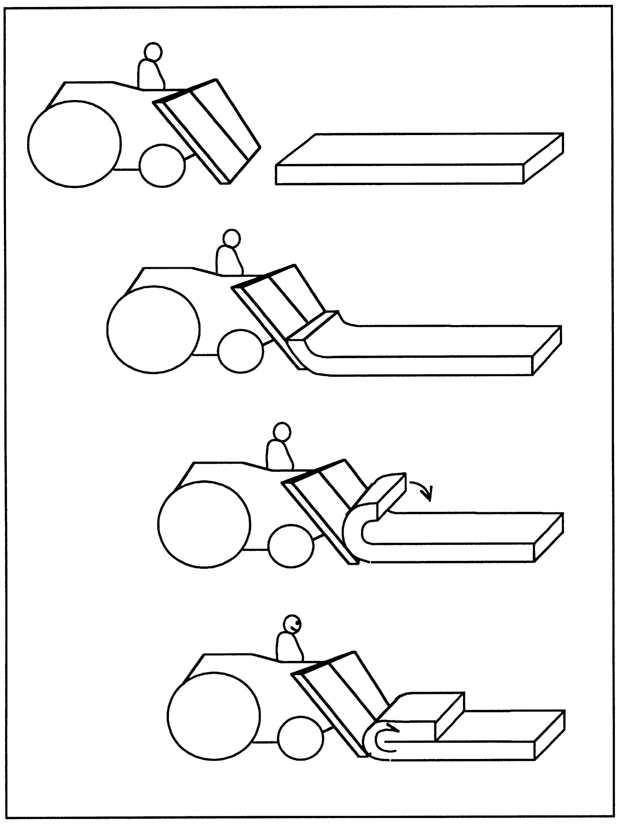

Fig. 12. Kinematic sketch illustrating the development of the recumbent syncline at the front of the Jebel Ta'bbast anticline. The syncline is initiated along the forelimb of the anticline and then propagates southward like a band of a caterpillar tractor (see Fig. 2b).

their consistency with the supposed mechanisms of folding.

Acknowledgements—This paper is a contribution to the Peri-Tethys Programme ("South Atlas Front project"). The authors wish to thank Dr M. Dahmani (Ministère de L'Energie et des Mines, Rabat, Morocco) for his constant help, Dr M. Damnati (ONAREP, Rabat, Morocco) for providing subsurface data and the people of Goulminma who made us welcome everywhere in the field. We are grateful to Benjamin Frizon de Lamotte for his help during field investigations. Helpful reviews by Rob Butler, Richard Norris and Geoff Rait are gratefully acknowledged.

REFERENCES

Anastasio, D. J., Fisher, D. M., Messina, T. A. and Holl, J. E. (1997) Kinematics of décollement folding in the Lost River Range, Idaho. *Journal of Structural Geology* **19,** 355–368.

Bernasconi, R. 1983. Géologie du Haut Atlas de Rich. Unpublished PhD Thesis. University de Neuchâtel (Switzerland).

Boyer, S. E. (1992) Geometric evidence for synchronous thrusting in the southern Alberta and northwest Montana thrust belts. In *Thrust Tectonics*, ed. K. R. McClay, pp. 377–390. Chapman and Hall, London.

Bracène, R., Bellahcene, A., Bekkouche, D., Mercier, E. and Frizon de Lamotte, D. (1998) The thin-skinned style of the South Atlas Front in central Algeria. In *Petroleum Geology of North Africa*, eds D. S. Macgregor, R. T. J. Moody and D. D. Clark-Lowes, pp. 391–400. Geological Society Special Publication **133**.

Butler, R. W. B. (1982) The terminology of structures in thrust belts. *Journal of Structural Geology* **4,** 239–245.

Casas, J. M. and Sabat, F. (1987) An example of three-dimensional analysis of thrust-related tectonites. *Journal of Structural Geology* **9,** 647–657.

Chester, J. S. and Chester, F. M. (1990) Fault-propagation folds above thrusts with constant dip. *Journal of Structural Geology* **12,** 903–910.

Choubert, G. (1954) Carte Géologique du Maroc à 1/500,000, feuille Ouarzazate. In *Editions du Service Géologique du Maroc*, Notes et Mémoires.

Contreras, J. (1991) Kinematic modeling of cross-sectional deformation sequences by computer simulation: coding and implementation of the algorithm. *Computers and Geosciences* **17,** 1197–1217.

Creuzot, G., Mercier, E., Ouali, J. and Tricart, P. (1993) La tectogeńse atlasique en Tunisie centrale: apport de la modélisation géométrique. *Eclogae Geologicae Helvetiae* **86,** 609–627.

Elliott, D. (1976) The motion of thrust sheets. *Journal of Geophysical Research* **5,** 949–955.

Endignoux, L. and Mugnier, J. L. (1990) The use of a forward kinematical model in the construction of balanced cross-sections. *Tectonics* **9,** 1249–1262.

Erslev, E. A. and Mayborn, K. R. (1997) Multiple geometries and modes of fault-propagation folding in the Canadian thrust belt. *Journal of Structural Geology* **19,** 321–335.

Fischer, M. P., Woodward, M. B. and Mitchell, M. M. (1992) The kinematics of break-thrust folds. *Journal of Structural Geology* **14,** 451–460.

Fisher, D. M. and Anastasio, D. J. (1994) Kinematic analysis of a large-scale leading edge fold, Lost River Range, Idaho. *Journal of Structural Geology* **16,** 337–354.

Frizon de Lamotte, D., Ghandriche, H. and Moretti, I. (1990) La flexure saharienne: trace d'un chevauchement aveugle post-Pliocène de flèche plurikilométrique au Nord du Sahara (Aurès, Algérie). *Comptes Rendu de l'Académie des Sciences* **310,** II, 1527–1532.

Frizon de Lamotte, D., Mercier, E., Dupré la Tour, A., Robion, P. and Averbuch, O. (1997) Cinématique du plissement et déformation interne des roches. L'exemple du pli de Lagrasse (Aude, France). *Comptes Rendus de l' Académie des Sciences* **324,** IIa, 591–598.

Frizon de Lamotte, D., Mercier, E., Outtani, F., Addoum, B., Ghandriche, H., Ouali, J., Bouaziz, S. and Andrieux, J. (1998) Structural inheritance and kinematics of folding and thrusting along the front of the Eastern Atlas Mountains (Algeria and Tunisia). In *Peri-Tethyan Platforms no. 3*, eds E. Barrier and S. Crasquin, 117. Mémoires du Muséum National d'Histoire Naturelle (in press).

Gueźou, J. C., Frizon de Lamotte, D., Coulon, M. and Morel, J. L. (1991) Structure and kinematics of the Prebetic nappe complex (southern Spain): definition of a "Betic Floor Thrust" and implications in the Betic-Rif orocline. *Annales Tectonicae* **5,** 32–48.

Hardy, S. and Poblet, J. (1994) Geometric and numerical model of progressive limb rotation in detachment folds. *Geology* **22,** 371–374.

Harrisson, J. V. and Falcon, N. L. (1934) Collapse structures. *Geological Magazine* **71,** 529–539.

Hossack, J. R. (1979) The use of balanced cross-sections in the calculation of orogenic contraction: a review. *Journal of the Geological Society* **136,** 705–711.

Jamison, W. R. (1987) Geometric analysis of fold development in overthrust terranes. *Journal of Structural Geology* **9,** 207–219.

Jossen, J. A. and Filali-Moutei, J. (1992) A new look at the structural geology of the southern side of the Central and Eastern High Atlas mountains. *Geologische Rundschau* **81,** 143–156.

Laville, E., Lesage, J. L. and Séguret, M. (1977). Géométrie, cinématique (dynamique) de la tectonique atlasique sur le versant sud du Haut Atlas marocain. Aperçu sur le tectoniques hercyniennes et tardi hercyniennes. *Bulletin de la Société Géologique de France.* **XIX. 3,** 527–539.

Letouzey, J., Coletta, B., Vially, R. and Chermette, J. C. (1995) Evolution of salt-related structures in compressional settings. In *Salt Tectonics*, eds M. P. A. Jackson, D. G. Roberts and S. Snelson, pp. 41–60. American Association of Petroleum Geologists Memoir, **65**.

Mercier, E. (1992) Une évolution possible des chevauchements associés aux plis de propagation: le transport sur le plat (modélisation et exemple). *Bulletin de la Société Géologique de France* **163,** 713–720.

Mercier, E. (1994) Influence du taux de sédimentation, des variations du niveau marin et de la tectonique dans la géométrie des discordances emboîtées à l'avant d'un pli de propagation (modélisation 2D). *Les bassins d'avant-chaines, Géologie Alpine (Grenoble) Série Spéciale* **4,** 74–75.

Mercier, E., De Putter, T., Mansy, J. L. and Herbosch, A. (1994) L'écaille des Gaux (Ardennes belges): un exemple d'évolution tectono-sédimentaire complexe lors du développement d'un pli de propagation. *Geologische Rundshau* **83,** 170–179.

Mercier, E. and Mansy, J. L. (1995) Le blocage du transport sur le plat des plis de propagation: une cause possible des chevauchements hors séquence. *Geodinamica Acta* **8,** 199–210.

Mercier, E., Outtani, F. and Frizon de Lamotte, D. (1997) Late evolution of fault-propagation folds: principles and example. *Journal of Structural Geology* **19,** 185–193.

Ouali, J. and Mercier, E. (1997) The Neogene structural evolution of the western margin of the Pelagian Platform, central Tunisia: Discussion. *Journal of Structural Geology* **19,** 185–193.

Outtani, F., Addoum, B., Mercier, E., Frizon de Lamotte, D. and Andrieux, J. (1995) Geometry and kinematics of the south Atlas front, Algeria and Tunisia. *Tectonophysics* **249,** 233–248.

Poblet, J. and Hardy, S. (1995) Reverse modelling of detachment folds; application to the Pico del Aguila anticline in the South Central Pyrenees (Spain). *Journal of Structural Geology* **17,** 1707–1724.

Suppe, J. (1985) *Principles of Structural Geology*. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Suppe, J. and Medwedeff, D. A. (1984) Fault-propagation folding. *Geological Society of America Abstracts with Programme* **16,** 670.

Suppe, J. and Medwedeff, D. A. (1990) Geometry and kinematics of fault-propagation folding. *Eclogae Geologicae Helvetiae* **83,** 409–454.

Suppe, J., Chou, T. G. and Hook, S. C. (1992) Rates of folding and faulting determined from growth strata. In *Thrust tectonics*, ed. K. R. McClay, pp. 105–121. Chapman and Hall, London.

Suppe, J., Sabat, F., Munoz, J. A., Poblet, J., Roca, E. and Verges, J. (1997) Bed-by-bed fold growth by kink-band migration: Sant Llorenç de Morunys, eastern Pyrenees. *Journal of Structural Geology* **19,** 443–461.

Thorbjornsen, K. L. and Dunne, W. M. (1997) Origin of a thrust-related fold: geometric vs kinematic test. *Journal of Structural Geology* **19,** 303–319.

Wojtal, S. W. (1986) Deformation within foreland thrust sheets by population of minor faults. *Journal of Structural Geology* **8,** 341–360.

Zapata, T. R. and Allmendinger, R. W. (1996) Growth strata records of instantaneous and progressive limb rotation in the Precordillera thrust belt and Bermejo basin, Argentina. *Tectonics* **15,** 1065–1083.

Zoetemeijer, R. and Sassi, W. (1992) 2-D reconstruction of thrust evolution using the fault-bend method. In *Thrust tectonics*, ed. K. R. McClay, pp. 133–140. Chapman and Hall, London.