ELSEVIER

Journal of Structural Geology 28 (2006) 721–728

JOURNAL OF STRUCTURAL GEOLOGY

www.elsevier.com/locate/jsg

The geomorphologic responses to hinge migration in the fault-related folds in the Southern Tunisian Atlas

Riadh Ahmadi [a], Jamel Ouali [a], Eric Mercier [b,*], Jean-Louis Mansy [c], Brigitte Van-Vliet Lanoë [c], Patrick Launeau [b], Farhat Rhekhiss [a], Silvain Rafini [b]

[a] *Laboratoire de Géologie, Ecole Nationale d'Ingénieur de Sfax, BP W, 3038 Sfax, Tunisia*

[b] *Planétologie et Géodynamique (UMR 6112), Université de Nantes, BP 92208, 44322 Nantes cedex 3, France*

[c] *Sédimentologie et Géodynamique (FRE 2255) Université de Lille 1, 59655 Villeneuve d'Ascq cedex, France*

Received 29 June 2004; received in revised form 7 January 2006; accepted 22 January 2006
Available online 7 March 2006

Abstract

In kinematic models of fault-related folds hinges must be mobile during fold growth, yet hinge migration has been rarely demonstrated in nature. Several complementary and independent geomorphological responses are presented here that indicate fold hinge migration in the Southern Tunisian Atlas. The deformation of the overlying Quaternary pediment suggests recent migration of the forelimb synclinal hinge as predicted by the Rafini and Mercier model. The uplift of the first order transverse drainage network, the poor maturation and shallow incision features of limb drainage networks toward the base of the limb slope suggest that new and un-eroded material was regularly uplifted from the down-slope, flat plains as predicted by the fault-propagation fold model.

Keywords: Fault-related fold kinematics models; Hinge migration; Geomorphology; Southern Tunisian Atlas

1. Introduction

1.1. Background

Since the formalisation of balanced cross-sections (Goguel, 1948; Dahlstrom, 1969; Elliott, 1976; Boyer and Elliott, 1982) several kinematic fold models have been proposed (e.g. Suppe, 1983, 1985; Jamison, 1987; Chester and Chester, 1990). These models respect the excess area law at all kinematic stages. Dahlstrom (1990) emphasises that, respecting this law, at least one hinge (often several) migrates during fold growth. Hinge migration (Fig. 1a) is thus a very important and significant concept that several workers have attempted to confirm or invalidate.

Early validation tests were based on microstructural studies (Fig. 1b) attempting to detect traces of the hinge migration through the fold limbs. These works supported the absence of hinge migration and stated, on the contrary, that fold amplification occurred with limb rotation around a fixed axis (Fischer et al., 1992; Fisher and Anastasio, 1994; Hedlund and Anastasio, 1994; Mansy et al., 1995). It emerges from these investigations that if hinge migration does take place then microstructural signatures are very weak to non-existent. Limb length does increase to allow fold amplification but this requires the outward migration of hinges as a necessary condition of the kinematic models. The paucity of hinge migration traces may be, at least partially, due to the intense flexural slip occurring along limbs during folding (Fig. 1b).

Syntectonic sedimentation on fold limbs provides a useful record of fold geometries at successive stages of development and constitutes an effective tool for investigating hinge kinematics. Several authors (Suppe et al., 1992; Hardy and Poblet, 1994, 1995) showed that growth strata geometrical patterns mimicked the hinge behaviour during deposition. For example, numerical modelling performed by Rafini and Mercier (2002) stipulates that a shoulder-like shaped growth strata on a forelimb syncline is the unequivocal consequence of hinge migration during deposition of the growth strata (Fig. 1c), whereas upward concavity indicates limb rotation (DeCelles et al., 1991; Vergés et al., 1996). The 'flap', a kind of 'collapse structure' described by Harrison and Falcon (1934), has also been interpreted as a marker of hinge migration (Mercier et al., 1994; Saint-Bezar et al., 1999).

* Corresponding author. Fax: +33 2 51 12 52 68.
E-mail address: eric.mercier@univ-nantes.fr (E. Mercier).

0191-8141/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2006.01.004

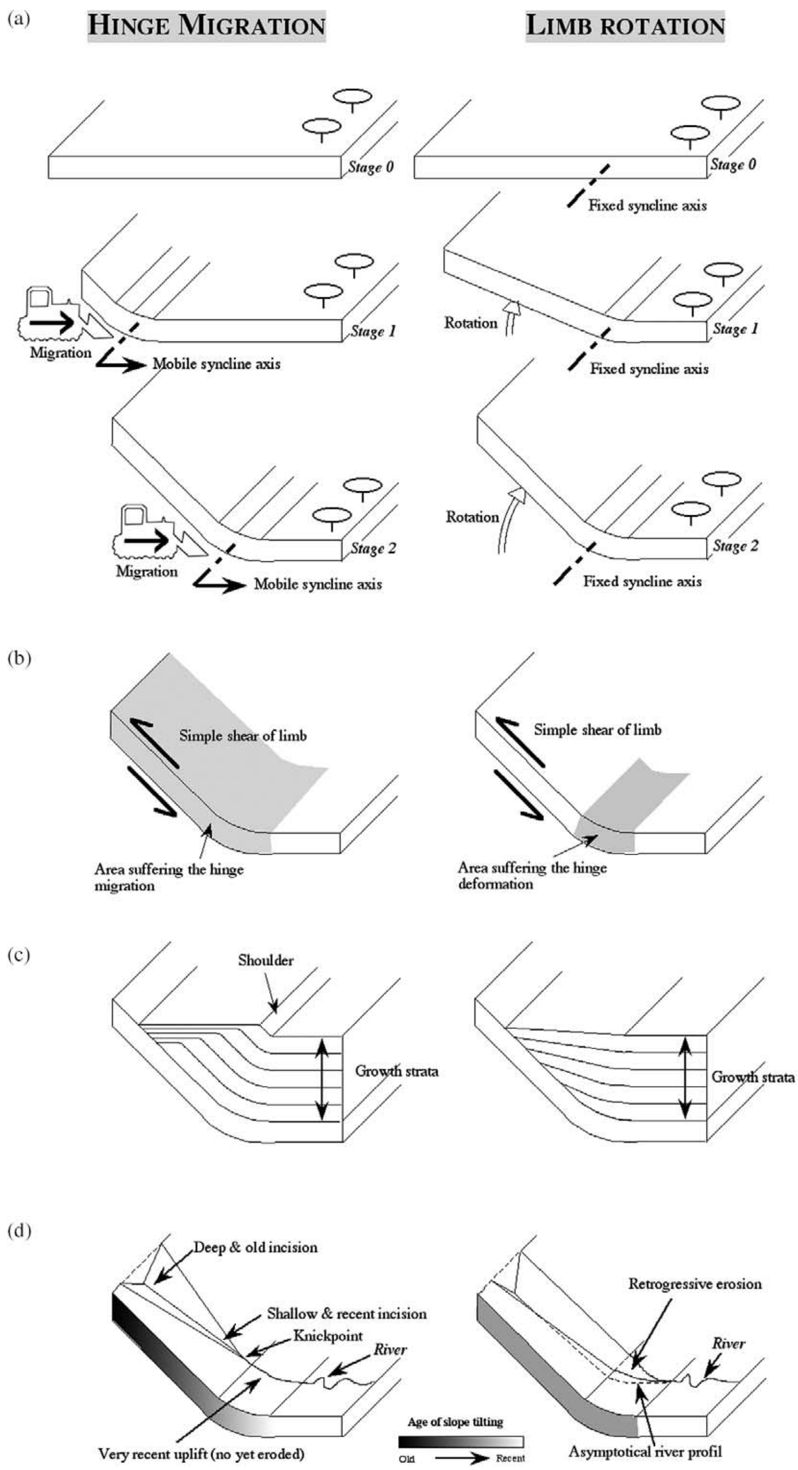

Fig. 1. Comparison between hinge migration and hinge rotation (synclinal hinge case). (a) Kinematic evolution. (b) Structural context and location of the deformation (inspired from Saint-Bezar et al., 1999). (c) Recording by growth strata (Rafini and Mercier, 2002). (d) Example of expected geomorphological features; for the limb rotation case, the slope has the same tilting age in each point, the erosion evolves regularly near the theoretical long-profile: asymptotic shape. In the limb migration case, the tilted slope is younger toward the base, so that the knick-point is continuously uplifted, entraining under-erosion in the recently outcropping areas (inspired from Seeber and Gronitz, 1983; Merrits and Hesterberg, 1994; Whipple and Tucker, 1999; Burbank and Anderson, 2001).

1.2. The aim of this work

Few natural structures have been considered as hinge migrating folds. Tectonic, morphological and sedimentological observations are combined here to provide evidence for hinge migration in the development of folds. Relief generated by fold growth is dissected by erosion into patterns that are controlled by the fold and hinge kinematics. In the case of a fixed hinge (Fig. 1c), the erosion propagates regularly upward with increasing topography as the convex slope evolution model.

Given hinge migration and a constant supply of un-eroded material to the fold slope base (Fig. 1d), it is assumed that erosion is older and deeper in the higher part of the slope and that incision in its lower part must be minimal. This conceptual model will be tested on the southern front of the Tunisian Atlas.

Medwedeff (1992) and Mueller and Suppe (1997) have tried to use this geomorphologic criteria to demonstrate hinge migration through field examples while other non-tectonic interpretations of this morphologic observation have been proposed by Bielecki and Mueller (2002).

SPOT images providing a full coverage of the Tunisian Atlas southern front were used in the present study. These low resolution images (20 m per pixel) with four channels—green, red, near infrared (NIR) and short wave infrared (SWIR 1)—have been used to identify the main rock compositions. Structural features were mainly drawn from the higher resolution (10 m per pixel) red channel by a careful mapping of shadows produced by a low sun elevation in March 1997. Petrological contrasts were enhanced using false colour composites generated from the lower resolution (20 m pixel size) channels draped over the higher resolution (10 m pixel) image in a single display using ER Mapper 6.2.

2. Geological setting

The Southern Tunisian Atlas frontal sector consists of a transitional zone between the Saharan Platform (to the south) and the more complex Central Tunisian Atlas mountain belt (to the north), which includes major thrust faults, diapirs and other older compressional structures.

Several east–west anticlines emerge from this Basin including the Northern Chott Range, Jebel Sehib, Metlaoui Range (Jebel Stah, Jebel Alima and Jebel Bliji). The marine Cretaceous–Eocene series are overlaid by continental Neogene formations (Fig. 2). The main folding is of Plio-Pleistocene age (probably Villafranchian) and still active considering current seismic activity (Dlala and Hfaiedh, 1993). According to Outtani et al. (1995), Ahmadi (2002) and Ahmadi et al. (2002) using seismic profiles and forward modelling, it has been established that the Gafsa Basin folded structures are the result of thin-skin tectonics. Most of the folds observed in the Basin, especially Metlaoui Range and Jebel Sehib, are 'fault-propagation folds' as defined by Suppe (1985) (Fig. 3). This interpretation of folding in terms of 'fault-propagation folds' in the study area has significant morpho-structural implications in that kinematic models for fault-propagation folds predict the

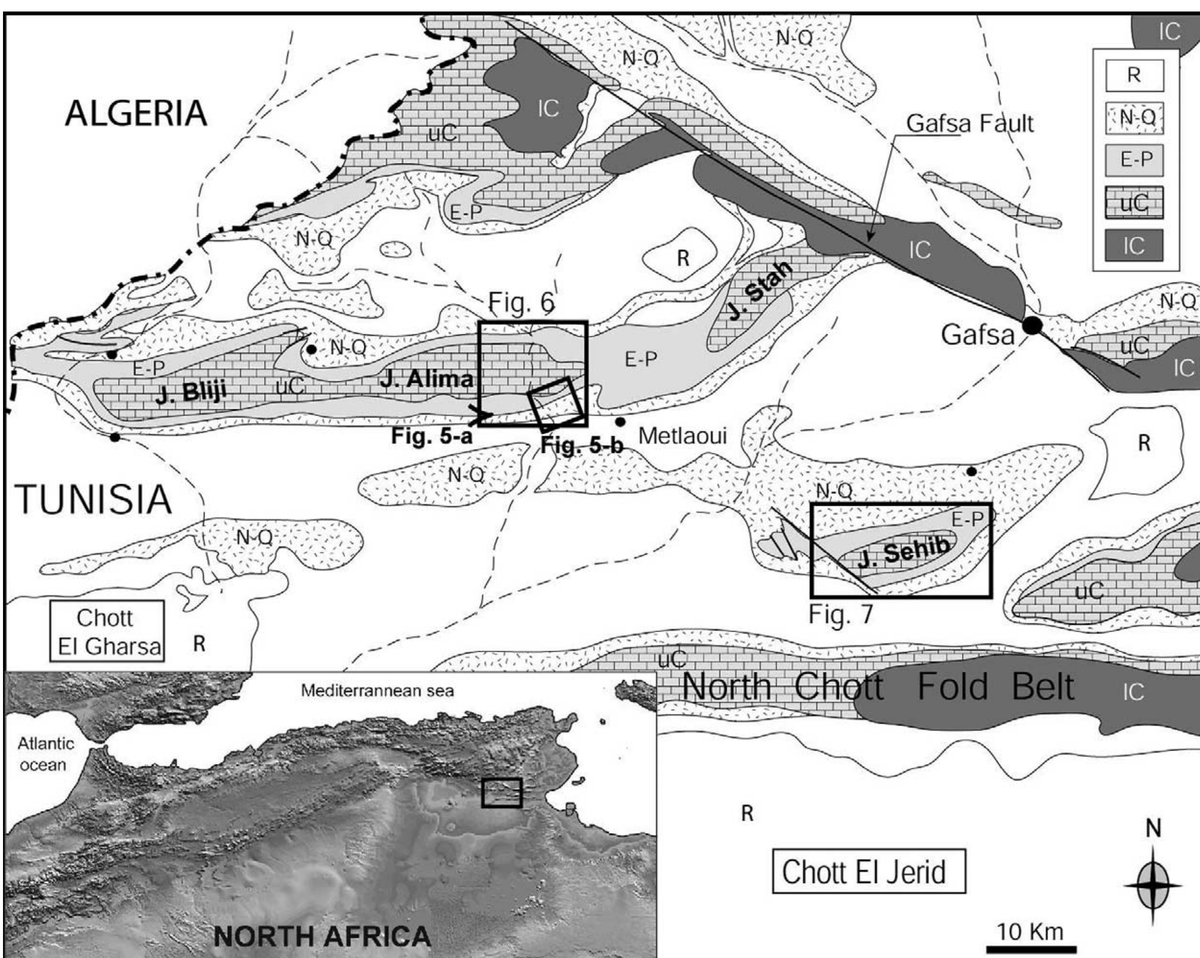

Fig. 2. Geologic map of studied area (with location of figures and photos). lC = lower Cretaceous; uC = upper Cretaceous; E-P = Paleocene and Eocene; N-Q = Neogene and Quaternary; R = Recent.

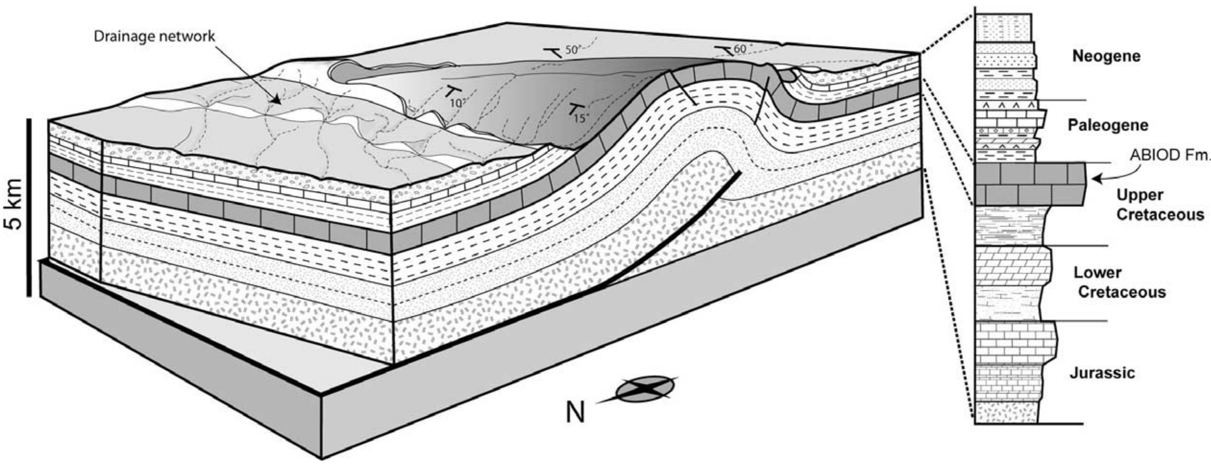

Fig. 3. Diagram showing the Jebel Sehib deep geometry, the main morphostructural features and the lithostratigraphic column. The Sehib anticline is a fault-propagation fold related to a lower Jurassic detachment layer. The main structural relief consists only of the massive Abiod limestone formation; most post-Cretaceous strata have been eroded.

migration of three hinges (detailed in Fig. 4) with the fourth remaining almost fixed (Suppe and Medwedeff, 1990). The morphological responses that appear to have been generated by the migrating synclinal hinges are investigated here.

3. Observations

In the Southern Tunisian Atlas, tectonics and climate are the only significant factors controlling the erosion rate. Most of the drainage basins are endoreic or have been since the Oligocene indicating that eustacy has not controlled the accommodation space for sedimentation and that the regional base-level (Chott El-Gharsa) has remained constant during fold growth. The present day arid climate conditions have permitted, by photo-interpretation, the physiographic evolution of the area recognition dominant erosion processes and location of sediment accumulation areas. The Jebel Alima and Jebel Sehib structures, where erosional processes have already removed most of the post-upper Cretaceous series in anticlines cores, were the focus of the present study. The main structural relief features are armoured by the massive Abiod Formation limestone. The well preserved integrity of the structures, together with the active tectonics, provides interesting possibilities for comparisons between the roles of erosion dynamics and fold tectonics.

3.1. The south facing pediments

Along the basal slope of Southern Tunisian Atlas, several generations of pediment have been recognized (Coque, 1951). These pediments are characterized by a regular slope of 3–5° and consist essentially of fine to gravely layers, generally between 0.5 and 1 m thick, with sub-angular boulders toward the base. These, often polygenic, pediments lap on older series with a sharp angular unconformity. Locally, they are covered or incised by younger Pleistocene alluvial splays or scree fans

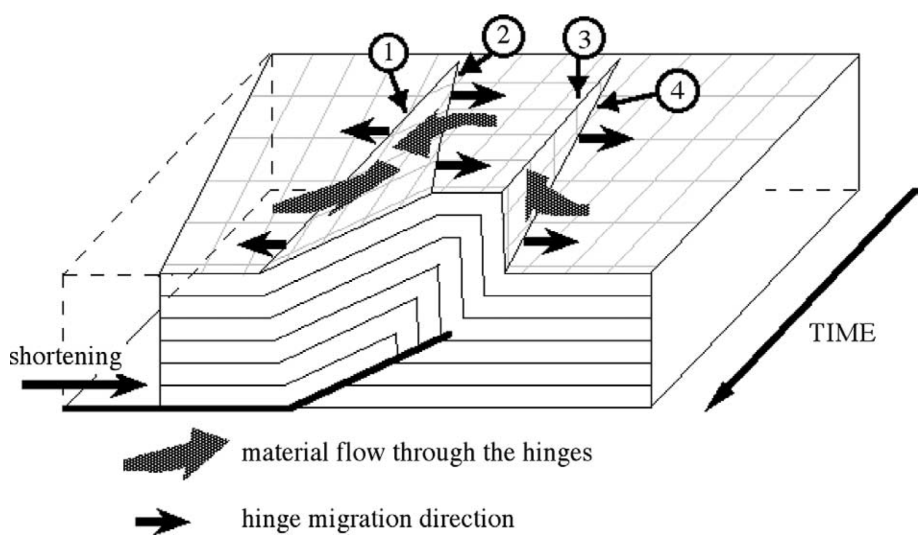

Fig. 4. Kinematic evolution of fault-propagation fold. Due to an increase in shortening, both syncline hinges ((1) and (4)) migrate and new material from near-by plains become deformed and uplifted toward fold slopes. One of the anticline hinges (2), migrates and transfers material from the upper anticline flat to the back-limb. The fourth hinge (3) remains practically fixed during fold development.

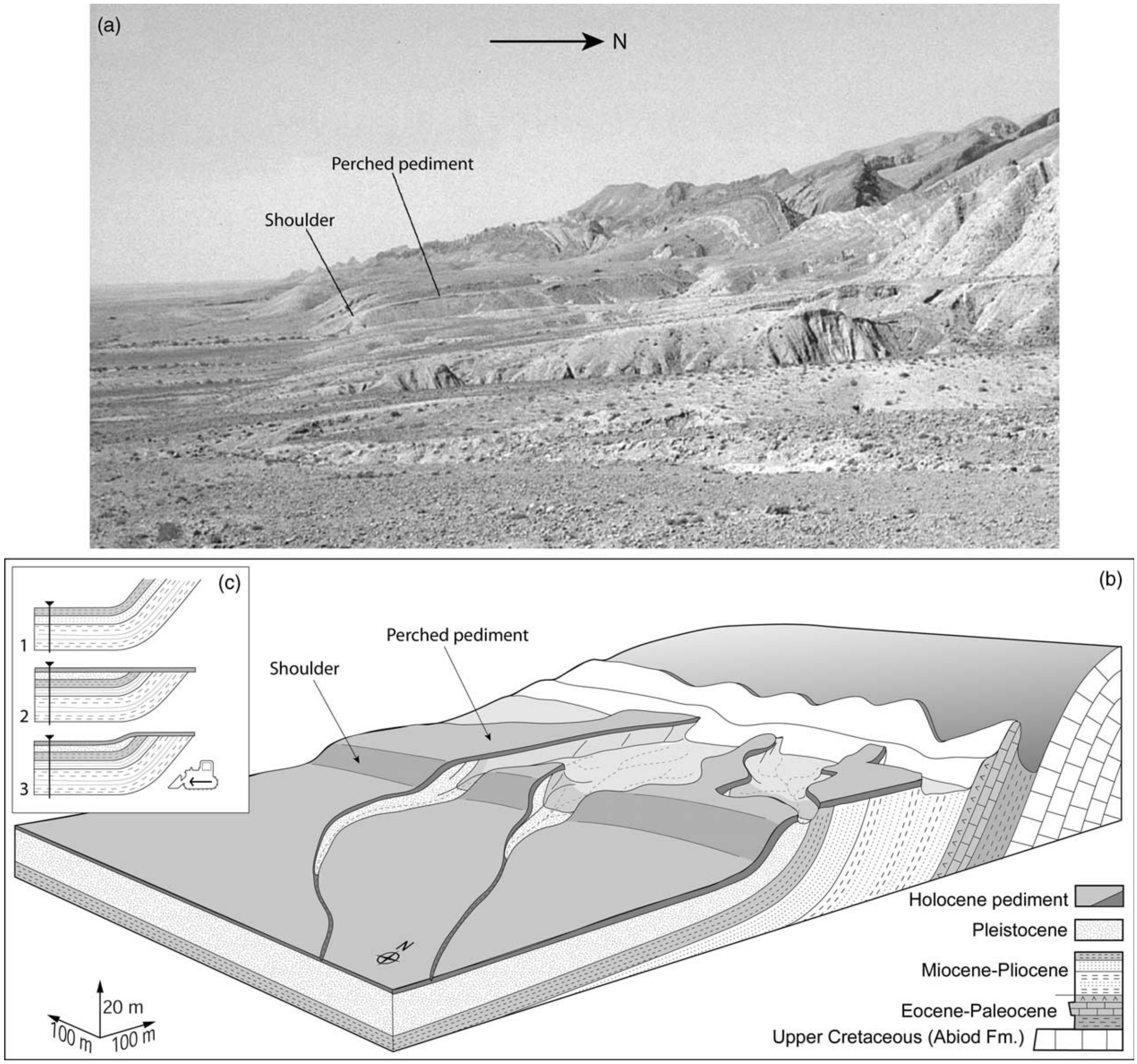

Fig. 5. Morphostructural features of quaternary pediment southern slope of Jebel Alima. (a) Field photography (view to west) of the southern slope of Jebel Alima. (b) Diagram showing geometrical relationship between last generation of Quaternary pediment and Neogene continental strata. (c) Kinematic evolution drawn with Rafini and Mercier (2002) software, using field geometric parameters. The model results fit perfectly the deformation observed on the southern Alima fold affirming the real migration of the southern syncline hinge. The diagram simulates only the last pediment generation deformation.

and end with a gypsicrete. On the south facing slopes of Jebel Sehib, Bliji and Alima (Fig. 2), a local bulge (shoulder) deforms the continuity of the Pleistocene pediments (Fig. 5a and b). This shoulder reaches a 10 m offset in the youngest uplifted pediment and more than 30 m in the oldest. The highest portions of the oldest pediments are dissected by marked erosional features and are fragmented into residual hills by gullies.

3.2. The first order transverse drainage networks

The basal layer of the clayey El Haria Formation, overlying the Abiod Formation, generates a strong erosional contrast. Peripheral rivers developed in the foothills of the main relief features connect various radial drainage networks from the anticline. On gentle slopes, peripheral canyons locally develop from collecting channels (first order streams), which are locally perched at ca. 100 m above the foot slope. Such features are also exhibited in the eastern edge of Jebel Alima and in the western edge of Jebel Sehib. Although perched on the anticline these streams are always in connection with the upstream base level, forming a narrow canyon that deeply incises the structural surface (Fig. 6). Note that the structural surface located below the uplifted first order stream (northern side in Fig. 6) is significantly less incised than that uphill, suggesting that this area was recently exposed to erosional processes.

3.3. Organization of the drainage system

Due to the strong mechanical resistance of the Abiod limestone (hard lithology and thick layers), its structural surface constitutes the core of the fold and allows a comparison

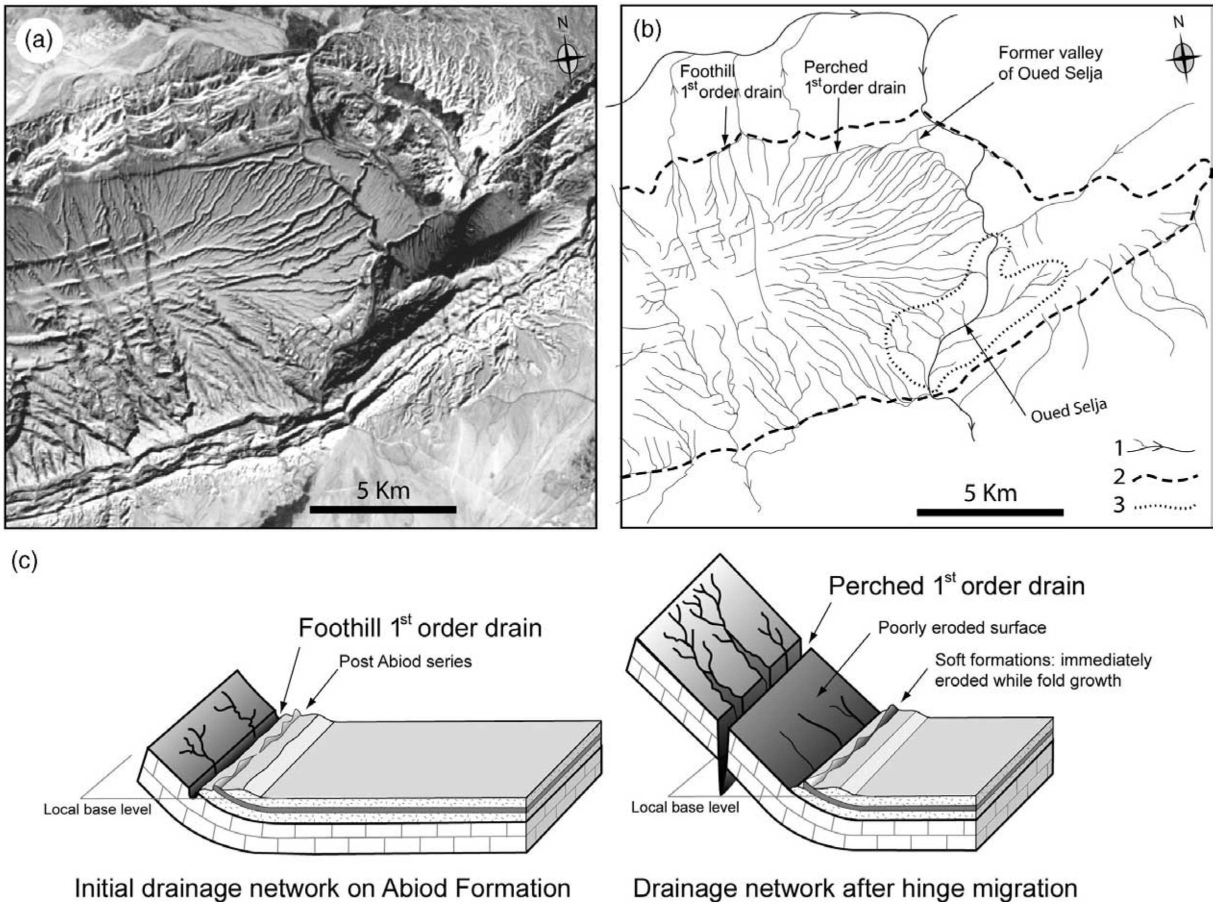

Fig. 6. (a) SPOT 4 view of Jebel Alima (eastern end). (b) Drainage network established on the main structural relief: the massive of Abiod limestone formation: (1) drainage network, (2) limits of anticline main relief (Abiod Formation), (3) transverse valley. (c) Kinematic diagram explaining the perched collector position as a consequence of a northern syncline hinge migration.

of the erosional effects to be made all around the fold on the same lithology. This is particularly spectacular on the Jebel Sehib surface (Fig. 7a and b), where channel confluences become more frequent up the northern slope toward the anticline hinges. The drainage network thus appears to be more mature upward, despite the similarity in lithologies over the slope (see example on Fig. 7b). This abnormal network pattern is common to all the regional anticlines.

3.4. Incision of the drainage system

On the SPOT images, channel widths can be correlated with the depth of their incisions. The Jebel Sehib's north facing flank displays an obvious shallowing of incisions towards the base of the hill until they become undetectable on the satellite image (Fig. 7). The degree of preservation of the roof surface from the Abiod Formation (Fig. 7c) illustrates the erosional activity at specific locations. The well developed incision and erosion of Jebel Alima (Fig. 6) is characterised by the formation of a transverse valley and the development of a rough surface in the middle-southern part of the fold. This contrasts with the smooth surface, locally incised by thin parallel channels, close to the northern foothills of the fold.

4. Interpretation: the geomorphological responses to hinge migration

Drainage networks developing on the anticlines of the Tunisian Atlas frontal zone, as well as deformation of their pediments, demonstrate the occurrence of hinge migration according to the following interpretations:

(a) The subsidence rate is low in the downstream depression. To explain the erosion and dissection of the pediment a tectonic uplift rather than a lowering of the base level must be considered. The absence of an obvious fault and the spatial correlations between the pediment's shoulder and the upturned Segui Formation outcrops (Fig. 5) fits with the geometries predicted by the structural modelling produced by Rafini and Mercier (2002) (Fig. 5c). More precisely, numerical modelling of growth strata suggests that (1) the southern hinge has continued to move after incision of the Pleistocene pediment, and (2) this deformation is related to a southward syncline hinge migration process.

(b) The occurrence of perched first order transverse streams can be explained by the following conceptual model: a stream first located at the foot slope, which is then uplifted

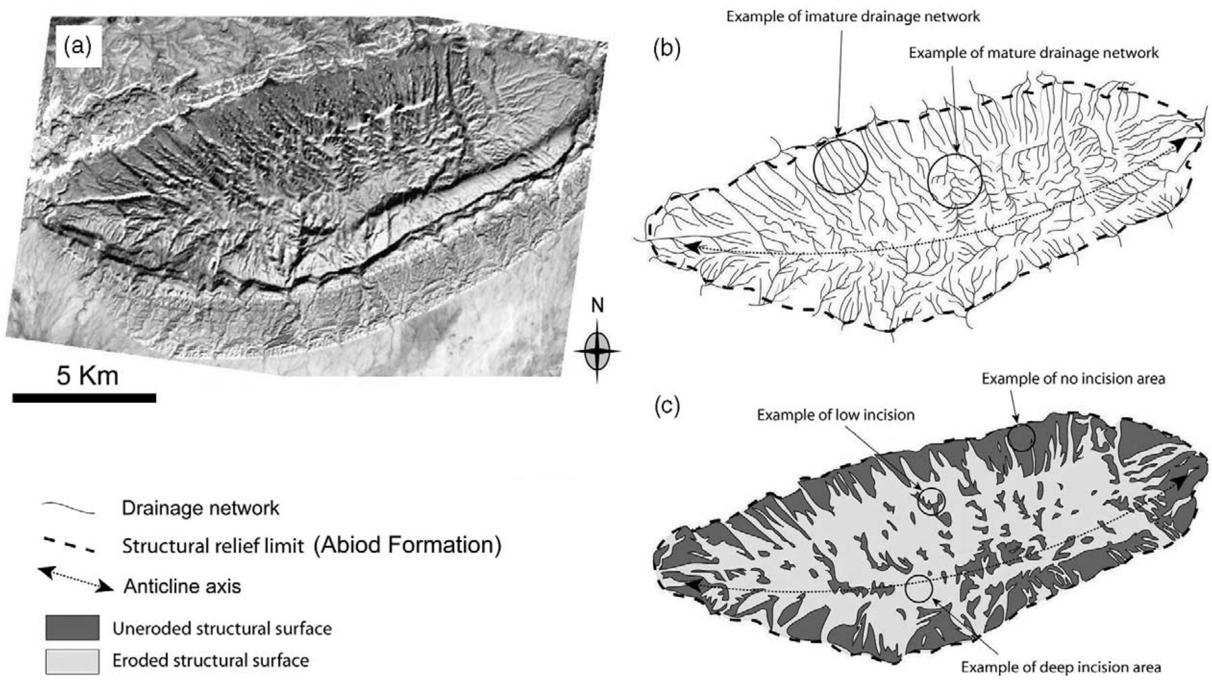

Fig. 7. (a) SPOT 4 view of Jebel Sehib. (b) Drainage network established on the main structural relief; massive Abiod limestone formation. (c) Structural surface incision map (in white) of the Abiod Formation roof.

by hinge migration, according to the process illustrated in (Fig. 6c). Such a hypothesis is supported by the adaptation of the Oued Selja, characterised by a contouring shape where crossing the fold. This contouring is in fair continuity with the peripheral collector. The parallelism between fold trace at ground level and the perched collector on satellite images cannot be explained by the antecedence only, especially considering the lack of erosional evidence below this perched collector. In addition, the lateral propagation of the fold toward the east is indicated by an abandoned canyon, contouring the anticline's former eastern closure (Fig. 6b).

(c) Considering homogenous lithology, the development of the drainage system is traditionally considered to be the result of successive captures, related to higher rate in confluence development and an increase in maturation (Schumm, 1956; Strahler, 1964). The north facing slope of Jebel Sehib is for this reason diachronic, the lowermost portion of the slope being shaped the youngest. This implies a progressive migration of the northern hinge to north. Concerning the incision of the river networks, the longitudinal slope of the channels classically evolves by erosion after uplift to steady state (Snyder et al., 2000). This evolution is controlled by retrogressive erosion, which normally propagates upward, particularly in the transition zone between the slope and the adjacent plains. On Jebel Sehib's north facing slope, this retrogressive erosion is not yet active. This suggests a grading of age along the slope, from the youngest down slope to the oldest at mid slope, caused by a rejuvenation of the long-profile at each step of the fold amplification. The continuous repositioning (uplifting) of knick-point that disturbs the normal drainage network maturation in down slope position demonstrates a rejuvenation of the erosion that is in conformity with the centrifuge hinge migration model (Fig. 1d).

5. Conclusion

The Gafsa Basin anticlinal structures are proven fault-propagation folds, as demonstrated by balanced cross-sections, seismic profiles and forward modelling. However, previous studies have only confirmed the geometric analogy between the present finite deformation and the conceptual theoretical model. The theoretical kinematic evolution of fault-propagation folds is confirmed here, with three complementary and independent geomorphological arguments. As a result, the prevailing role of hinge migration during development of these folds is corroborated confirming, in turn, the numerical models. This represents an advance in forward modelling, as it has been shown geomorphology can provide timing constraints for hinges propagation. Finally, for the first time, morphostructural arguments have been presented to demonstrate the occurrence of hinge migration during fault-related folding.

Acknowledgements

This work is based on R.A.'s DEA and PhD research at "Ecole Nationale d'Ingénieurs de Sfax" (Tunisia) and at UMR 6112 of "Université de Nantes" (France). We received support from the 'ISIS' program of 'CNES' in the form of a set of SPOT images and financial support from the "Comité Mixte franco-tunisien de Coopération Universitaire". This paper benefited from the constructive reviews by D.A. Medwedeff, A. Densmore and A. Meigs. We thank G.M. Manby for English corrections of the final version.

References

Ahmadi, R., 2002. Caractérisation morphostructurale et modélisation des structures plissées dans l'Atlas méridional Tunisien. Mémoire de DEA, Université de SFAX, 111pp.

Ahmadi, R., Ouali, J., Mercier, E., 2002. Signatures géomorphologiques de la migration des charnières dans les plis de rampes; exemples dans l'Atlas Tunisien. RST, Nantes, pp. 46–47.

Bielecki, A.E., Mueller, K.J., 2002. Origin of terraced hillslopes on active folds in the southern San Joaquin Valley, California. Geomorphology 42, 131–152.

Boyer, S.E., Elliott, D.E., 1982. Thrust systems. AAPG Bulletin 66 (9), 1196–1230.

Burbank, D.W., Anderson, R.A., 2001. Tectonic Geomorphology. Blackwell Science. 274pp.

Chester, J.S., Chester, F.M., 1990. Fault-propagation folds above thrusts with constant dip. Journal of Structural Geology 12 (7), 903–910.

Coque, R., 1951. La Tunisie présaharienne (Etude géomorphologique). CNRS et Gouvernement Tunisien. 475pp.

Dahlstrom, C.D.A., 1969. Balanced cross-sections. Canadian Journal of Earth Sciences 6, 743–757.

Dahlstrom, C.D.A., 1990. Geometric constraints derived from the law of conservation of volume and applied to evolutionary models for detachment folding. AAPG Bulletin 74 (3), 336–344.

DeCelles, P.G., Gray, M.B., Ridgway, K.D., Cole, R.B., Srivastava, P., Pequera, N., Pivnik, D.A., 1991. Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana. Geological Society of America Bulletin 103, 1458–1475.

Dlala, M., Hfaiedh, M., 1993. Le séisme du 7 Novembre 1989 à Metlaoui (Tunisie Méridionale): une tectonique active en compression. Compte Rendu de l'Académie des Sciences Paris 317 (II), 1297–1307.

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

Fischer, M.P., Woodward, M.B., Mitchell, M.M., 1992. The kinematics of break-thrust folds. Journal of Structural Geology 14 (4), 451–460.

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

Goguel, J., 1948. Introduction à l'étude mécanique des déformations de l'écorce terrestre 1948. 530pp.

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

Hardy, S., Poblet, J., 1995. The velocity description of deformation. Paper 2: sediment geometries associated with fault-bend and fault-propagation folds. Marine and Petroleum Geology 12, 165–176.

Harrison, J.V., Falcon, N.L., 1934. Collapse structures. Geological Magazine LXXI, 529–539.

Hedlund, C.A., Anastasio, D.J., 1994. Kinematics of fault-related folding in a duplex, Lost River Range, Idaho, USA. Journal of Structural Geology 16, 571–584.

Jamison, W.R., 1987. Geometric analysis of fold development in overthrust terranes. Journal of Structural Geology 9 (2), 207–219.

Mansy, J.L., Meilliez, F., Mercier, E., Khatir, A., Boulvain, F., 1995. Le rôle du plissement disharmonique dans la tectonogense de l'allochtone ardennais. Bulletin de la Société Géologique de France 166, 295–302.

Medwedeff, D.A., 1992. Geometry and kinematics of an active, laterally propagating wedge thrust, Wheeler Ridge, California. In: Mitra, S., Fisher, G.W. (Eds.), Structural Geology of Fold and Thrust Belts. Johns Hopkins University Press, Baltimore, MD, pp. 3–28.

Mercier, E., De Putter, T., Mansy, J.L., 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 Rundschau 83, 170–179.

Merrits, D., Hesterberg, T., 1994. Stream networks and long-term surface uplift in the New Madrid seismic zone. Science 265, 1081–1084.

Mueller, K., Suppe, J., 1997. Growth of Wheeler Ridge anticline, California: geomorphic evidence for fault-bend folding behaviour during earthquakes. Journal of Structural Geology 19, 383–396.

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

Rafini, S., Mercier, E., 2002. Forward modelling of foreland progressive unconformities. Sedimentary Geology 146, 75–89.

Saint-Bezar, B., Frizon de Lamotte, D., Morel, J.L., Mercier, E., 1999. Kinematics of large scale tip line folds from the High Atlas thrust belt (Morocco). Reply. Journal of Structural Geology 21, 691–693.

Schumm, S.A., 1956. The evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geological Society of America Bulletin 67, 597–646.

Seeber, M.A., Gronitz, V., 1983. River profiles along the Himalayan arc as indicators of active tectonics. Tectonophysics 92, 335–367.

Snyder, N.P., Whipple, K.X., Tucker, G.E., Merritts, D.J., 2000. Landscape response to tectonic forcing: digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California. Geological Society of America Bulletin 112 (8), 1250–1263.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: Chow, V.T. (Ed.), Handbook for Applied Hydrology. McGraw-Hill, New York section 4-II.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal of Science 283, 684–721.

Suppe, J., 1985. Principles of Structural Geology. Prentice-Hall, Englewood Cliffs, New Jersey. 537pp.

Suppe, J., Medwedeff, D.A., 1990. Geometry and kinematics of fault-propagation folding. Eclogae Geologicae Helvetiae 83 (3), 409–454.

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

Vergés, J., Burbank, D.W., Meigs, A.J., 1996. Unfolding: an inverse approach to fold kinematics. Geology 24, 175–178.

Whipple, K.X., Tucker, G.E., 1999. Dynamics of the stream-power river incision model: implication for height limits of mountain ranges, landscape response timescales, and research needs. Journal of Geophysical Research 104 (B8), 17661–17674.