

Evidence of fault-propagation folds in foreland basin: the case of Chemsî and Belkhir anticlines of southern Tunisian Atlas

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Abstract Structural analysis of Jebel Chemsî and Belkhir located in southern Tunisian Atlas lead to propose the fault-propagation fold as a model for these anticlines. Geometric analogy is settled after dip surveys and observation of several anticline kinks. Several, independent geomorphologic observations support the hinge migration kinematics characterizing this numerical model. The geomorphological hallmarks used matches to (1) alluvial fan progradation, (2) knick points on longitudinal profiles of channel streams and (3) anomalies on the drainage net in the eastern limits of the fold. These anomalies proved a centrifugal hinge migration of, at least, last folding stages in the direction prospected by the model. Results of numerical modelling using Ramp EM software showed detachment layer at 5.5 km that matches to Triassic series. Shortening amplitude is about 2 km for Jebel Chemsî and 1.5 km for Jebel Belkhir. Locally, we highlighted the role of inherited faults in locating and controlling the compressive deformation. In active tectonic region, the use of geomorphological approach is suitable to highlight the folding kinematics and thus to prove the deformation model. In our case study, many special conditions, such as excellent outcropping resulting of arid climate, constant base level and good lithological contrast, allow objective interpretations

Keywords Fault propagation fold · Fault related fold · Kinematics · Hinge migration · Gafsa basin

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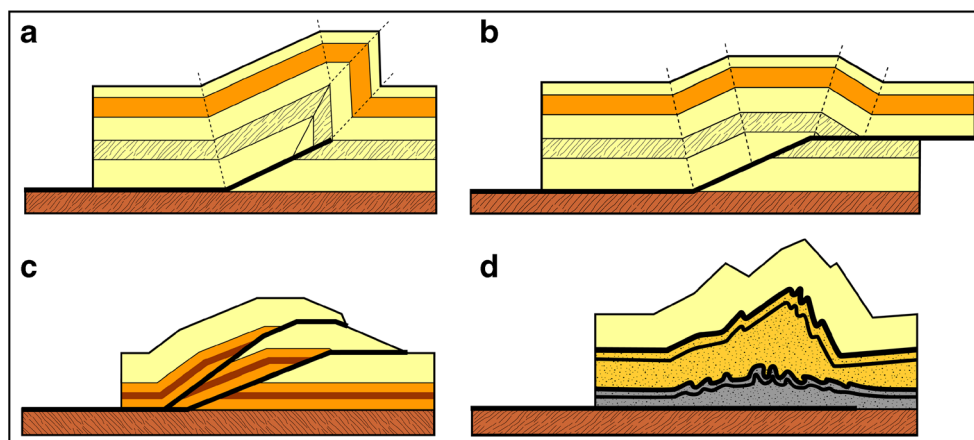
Introduction

Fold models have been subjected to a sustained interest in the two last decades, during which several numerical and analogue models have been published. Theoretical or numerical models are used to describe the geometric stages of folding from initially non-deformed strata to a given finite deformation stage. (e.g., Boyer and Eliot 1982; Suppe 1983–1985; Medwedeff 1984; Mitra 1990–1992; Mercier 1992–1995). These models describe, basically, the kinematic evolution of folding.

Analogue models (e.g., Casas et al. 2001; McClay et al. 2004; Ellis et al. 2004; Cobbold et al. 2004) are powerful method for understanding the fold kinematics. However, they present some weaknesses in respecting the similitude conditions with natural material and stress parameters. Moreover, the relationship between numerical and analogue models remains subject to controversies. On the other hand, the numerical models are purely mathematical formulas made, and had theoretically resolved the mechanical and kinematic problems of folding, but they still need demonstration with real natural examples.

In nature, many numerical fold models have been recognized and described (e.g., Ouattani et al. 1995; Bulnes and Aller 2002; Ahmadi et al. 2006). The most popular fold models include the fault-propagation fold, the fault-bend fold and the duplex structures (Fig. 1.). Nevertheless, other numerical models exist in theory, and they still await further field examples to be confirmed (e.g., Chester and Chester model (Chester and Chester 1990), trishear model (Erslev 1991), Alsaffar model (Alsaffar 1993), roll-over fault-propagation fold (Storti and Salvini 1996) and Jabbour's model (Jabbour 2011)). For most described natural fault-related folds, workers usually rely on the geometric features to deduce the model. They neglect or underestimate the kinematics, which remain modelling (Fig. 2).

Fig. 1. Most described folding models in nature. **a** Fault-propagation fold (Suppe 1985; Mercier 1995; Salvini & Storti 1997). **b** Fault-bend fold (Mercier 1995). **c** Duplex structure (Boyer & Elliot 1982). **d** Disharmonic folding (Homza & Wallace, 1995)



Proving a fold model is a time-consuming task. The progressive changes in fold geometry provide the most convincing data for identifying the model (Fig. 2). Therefore, the kinematic arguments are fundamental for proving a model. In some published work, the methods for deducing the folding kinematics have explored this key point. The used methods are sedimentological, based on growth strata geometry (Riba 1976; Graham et al. 1986; Medwedeff 1989; Rafini and Mercier 2002; Ahmadi et al. 2013), or geomorphological arguments (Delcaillau, 2004; Ahmadi, 2006). These methods give possibilities to explore the time dimension of the evolution of a given fold and to highlight some former deformation stages. The major problem remains in choosing and using the field data that are sometimes controversial to build up the model itself. In fact, the natural examples are much more complicated than the numerical model made folds inasmuch as the inherited fault networks complicate the tectonic history. Moreover, the erosion and the recent sediments hide a part of surveys, which needed to build up a realistic balanced cross section.

Objectives

The present work represents a methodological approach to perform a fold modelling study in a foreland sedimentary

basin. The study area includes gentle anticlinal folds. This increases the chances of fitting with numerical models by avoiding their late-stage complications. The study area fulfilling these conditions is located within the southern Tunisian Atlas. This region is affected by Quaternary (Deltail 1982; Zouari 1995; Swezey 1996; Bouaziz et al. 2002) to present-day tectonics (Dlala and Hfaiedh 1993; Ahmadi et al. 2006; Said, Dominique et al. 2011a; Ahmadi et al. 2013; Gharbi et al. 2015) that have resulted in gentle deformation.

In this work, the procedure involves two major steps:

- i. The geometric approach: the structural observations and the field surveys (bed dips and cross sections) characterize the fold geometry and give clues as to possible fitting numerical models.
- ii. The kinematics study: the evidence from geomorphological features and anomalies will help to highlight the dynamics of folding and to demonstrate the numerical folding model.

Geological setting

The southern Tunisian Atlas is a part of the oriental Atlas of North Africa (Fig. 3a). It includes foreland basins that

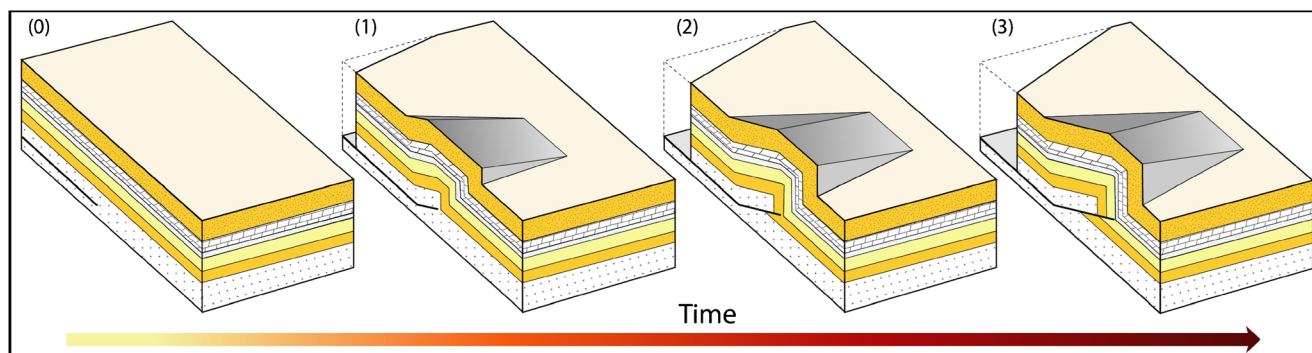


Fig. 2. Kinematics is the pathway that describes stages between initial and deformed structure. Although some models do have clear and precise kinematics, in nature, it is difficult to argue its lack of arguments

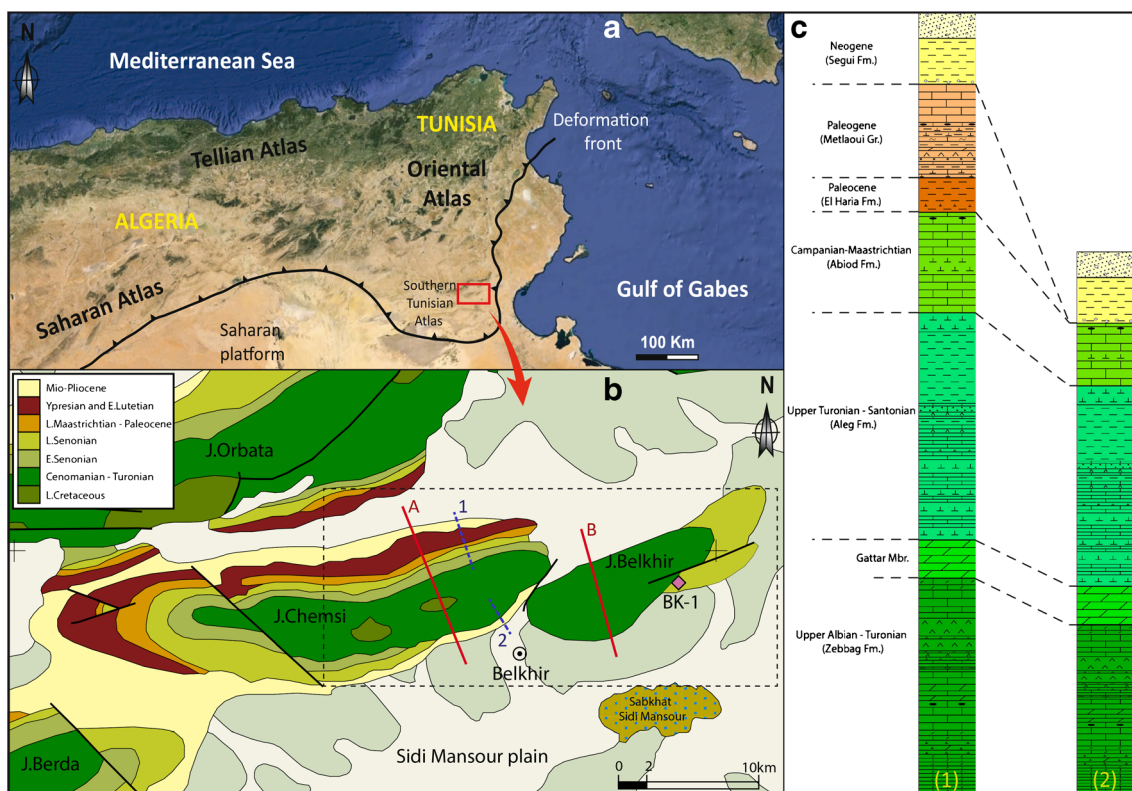


Fig. 3. Location map (a), lithostratigraphic column (c) and the simplified geological map (b) of the study area. Red lines correspond to the surface cross section of Fig. 5. Kinematics is the pathway section of Fig. 17.

Dashed blue lines correspond to lithostratigraphic column location. Detailed geological map of Chemsi-Belkhir area of Fig. 4 is shown by the dashed black frame. BK-1 well location is shown

recorded a continuous subsidence during the Mesozoic period. The extensive tectonics, dominant in the Mesozoic, correlate with the Tethys sea opening. It was followed by a Cenozoic compressive tectonic events, subsequent to the plate convergence and the collision between ALKAPCA units (Alboran: southern Spain and Morocco, Kabylides: Algeria, Peloritani: Sicily and Calabria: southern Italy) and the North African margin (Tricart et al. 1994; Carminati et al. 1998; Mascle et al. 2001; Devoti et al. 2001). According to these authors, the collision took place during late Miocene, but compressive tectonics occurred earlier in North Africa: since late Cretaceous, locally. Most authors are in agreement that there were two major phases related to the major compressive events: (1) Late Miocene and (2) Early Quaternary (Deltail 1982; Aissaoui 1984; Ouali 1984; Yaïch 1984; Zouari 1995). In Tunisia, from the North to the South of the Atlas folds, the shortening becomes weaker and more recent. Therefore, in the southern Atlas, the Quaternary major phase is the main contributor to the present relief. These folds and fold ranges are located in the frontal zone of the foreland basin, in which a simple deformation is identified: most of folds have a low development rate, generally less than 15%. Between folds and fold ranges, large flat plains exist (Ahmadi 2006). Most of this area belongs to the Gafsa basin; our study area is a part of it.

The Jebels Chemsi and Belkhir are Quaternary-aged anticlines. These folds form a pair of E-W-oriented en echelon fault-related anticlines (Zargouni 1985; Zouari 1995; Hlaïem 1998; Bouaziz et al. 2002; Riley et al. 2011; Said, Baby et al. 2011b). The fold axes deviate progressively to NE-SW (N060-N070) in the eastern part of both anticlines (Fig. 3b). These anticlines are geomorphically represented by mountains due to the beds of erosion-resistant dolomite of the Zebbag Formation (Cenomanian and Turonian) in the core of both folds. The dolomite crops out as two prominent cliffs occupying the core of the fold. In Jebel Chemsi, the erosion exposes the top of the Aptian dolomite (Orbata Formation) in a restricted area in the central part of the anticline. However, the white yellowish chalky limestones of the Abiod Formation (Campanian-Maastrichtian), the Paleogene shales and carbonates, and the Neogene clastics make the border of the fold. The Neogene rocks are composed of eroded materials from growing anticline and confirmed by the thick beds of conglomerate deposited in a fan shape splays.

The stratigraphic data is derived from outcrops and well exploration. The explored lithostratigraphic column presents formations ranging from Triassic to Quaternary (Fig. 3c). Early Cretaceous siliceous deposits are represented by the Meloussi Formation (Late Jurassic-Hauterivian), the Boudinar Formation (Hauterivian) and the Sidi Aich

Formation (Barremian). These formations are followed upwards by the shallow marine Bouhedma Formation (Barremian-Aptian) and a shelf facies carbonate of the Orbata Formation (Aptian). The late Cretaceous is composed of the shallow marine carbonates, interbedded with the claystone and the evaporite of the Zebbag Formation (Albian-Turonien). The Senonian age is represented by the marine claystone and marl of the Aleg Formation (Turonian-Campanian), overlain by the white chalky limestones of the Abiod Formation (Campanian-Maastrichtian). The Mesozoic outcrops consist of a thin Paleocene-Eocene marine carbonates and clays (El Haria Formation and Metlaoui Group) mainly developed to the north of Jebel Chemsî, capped by siliceous Miocene to Quaternary deposits that belong to the Segui Formation (Fig. 4).

Structural evidence

In the Jebel Chemsî, the presence the massive Aptian and Turonian carbonates that occupy the core of the fold allows good measuring conditions. In the Jebel Belkhir, the top of the Turonian bed, which refers to the Gattar Member (a massive dolomitic bar indicating the top of the Zebbag Formation), extends from the northern to the southern flank with none or few incised areas (Fig. 4). The lack of erosion in these formations confirms the recent folding age.

The Jebel Chemsî cross section (Fig. 5a) shows asymmetric anticline with gentle dips in the northern flank (29° N) and

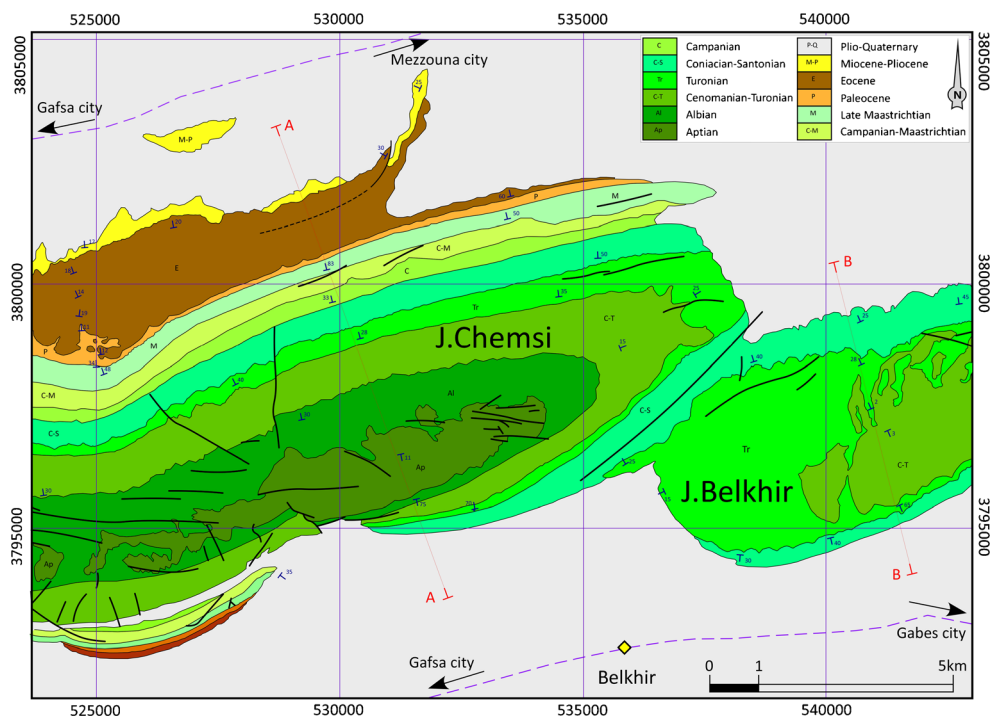
steep dips in the southern one (76° S). The anticline hinge is a wide flat area that ties with kinks to the flanks. Similarly, the Jebel Belkhir shows asymmetric anticline with southward hanging axial plan (Fig. 5b). The northern flank is dipping 28° to the north, while the southern flank has a 65° dip to the south. The anticline roof is represented by a flat area gently dipping to the south with a maximum of 5° S. Both anticlines show kinked geometry. Figure 6 shows many examples of these kinks mostly in the southern flank. Indeed, this kinked geometry is evidenced by the geological map of the eastern part of the Jebel Chemsî (Fig. 7), which shows a sudden bed direction change.

In the southern flank of the Jebel Belkhir, many surface decollement levels, taking place in the Senonian claystone, are observed. These levels generate several small-scale detachment folds and thrusts (Fig. 8). On the northern flank of the Jebel Chemsî, the cross section shows a reverse fault on the Abiod massive limestone bar. The local extent of this thrust indicates that it likely originates from the Senonian decollement level.

Chemsî and Belkhir anticlines show particular geometric features summarized as below:

- an asymmetric anticline with a gentle dipping backlimb and a steep forelimb dip;
- the flat anticline hinge area is almost horizontal in the Jebel Chemsî and gently dipping southward in the Jebel Belkhir;
- the kinked geometry characterizes both anticlines and hinges (Fig. 6 and Fig. 7).

Fig. 4. Detailed geological map of the study area based on field mapping. Locations of the cross sections of Fig. 5 are shown. Coordinate system is UTM zone 32, WGS 84 system (metres)



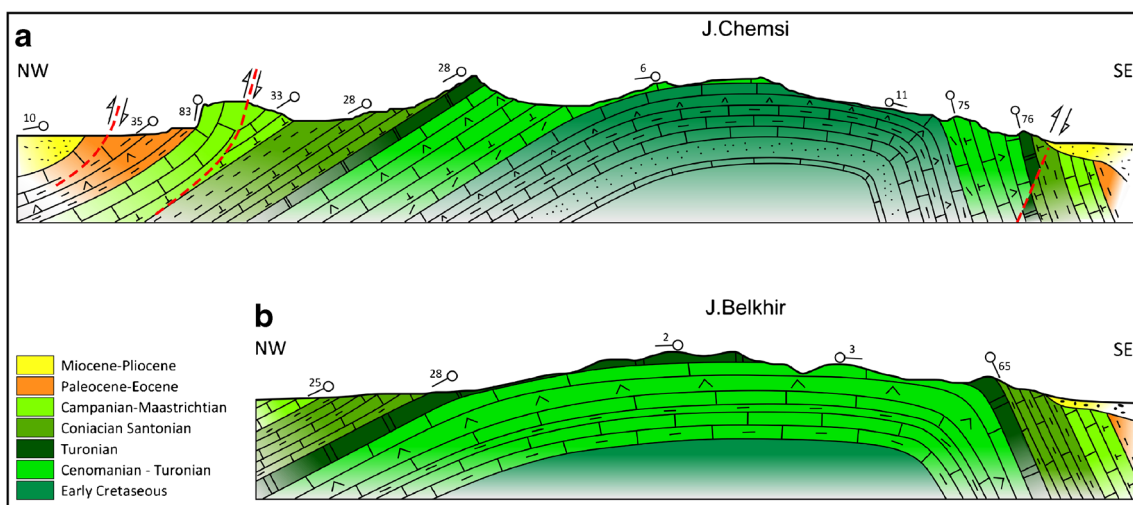


Fig. 5. Geological cross sections across the Jebel Chemsî (a) and Jebel Belkhir (b). For location, refer to Figs. 3 and 4

Geomorphic evidence

The recovered geometric data are not decisive on geometry and kinematics. However, the geomorphologic tools have a significant role in proving the kinematics of tectonic phenomena such as active faults and thrust sheets, seismicity and recent folding. The use of these tools is based on local observations of geomorphic anomalies affecting the drainage network or other cut-off surfaces and pediments (Delcaillau

2004; Delcaillau et al. 2006; Ahmadi et al. 2006; Mercier et al. 2007) in order to settle time-related interpretations that could give noticeable idea about kink kinematics.

In the study area, the growth strata are made of clastic sediments mainly composed of Neogene conglomeratic sandstone, siltstone and claystone. These unconsolidated clastics are deeply eroded in the border of folds, which allows the presence of locally exposed survey windows beneath active alluvial fans.

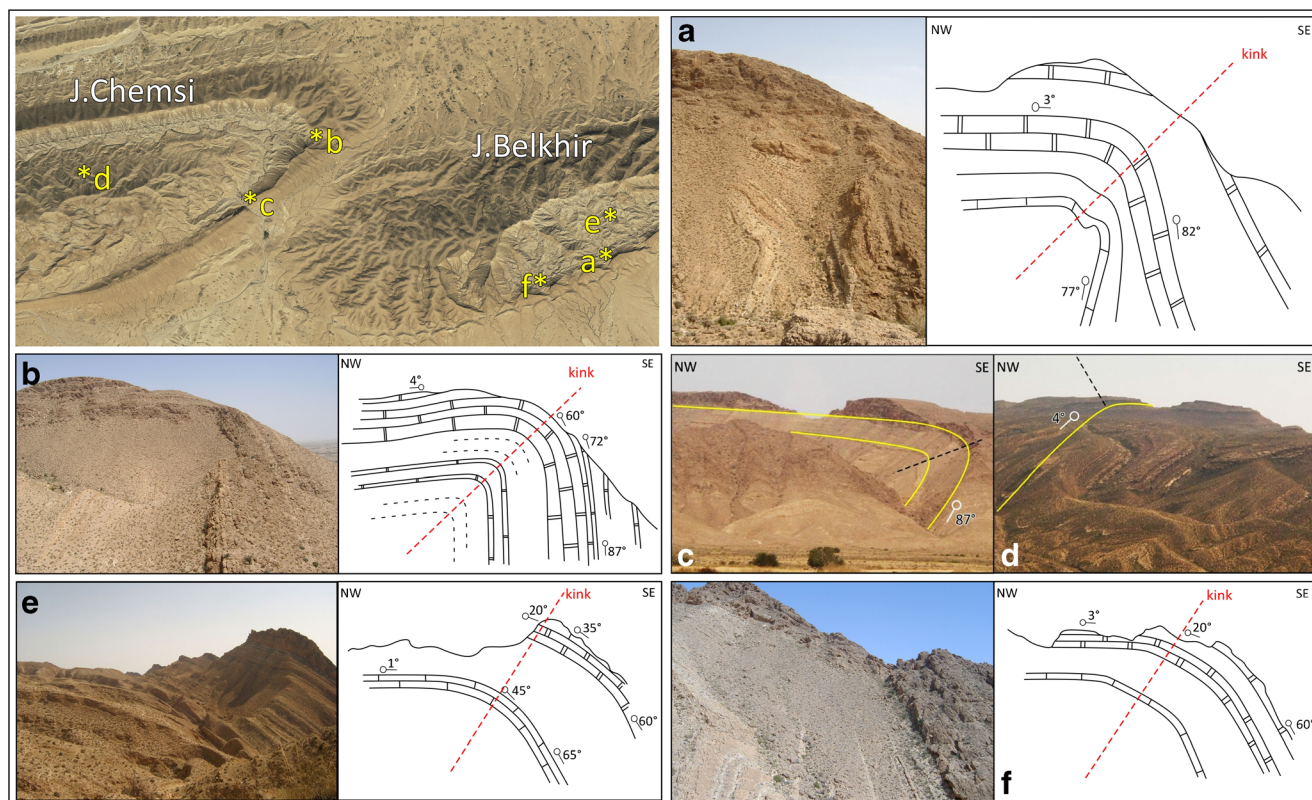


Fig. 6. Field observations of kinks in the Jebel Chemsî and Jebel Belkhir anticlines. Picture locations are shown in the satellite image

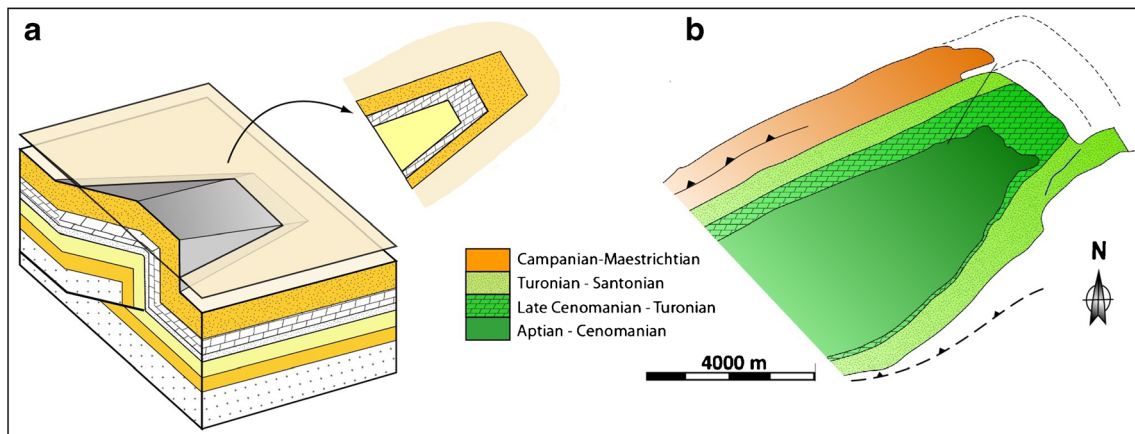


Fig. 7. a Geological map of the eastern termination part of the Jebel Chemsî anticline showing box shape closure. The change angle area is typically indicating a kinked folding as interpreted in (b) horizontal cut-off map of fault-propagation fold model

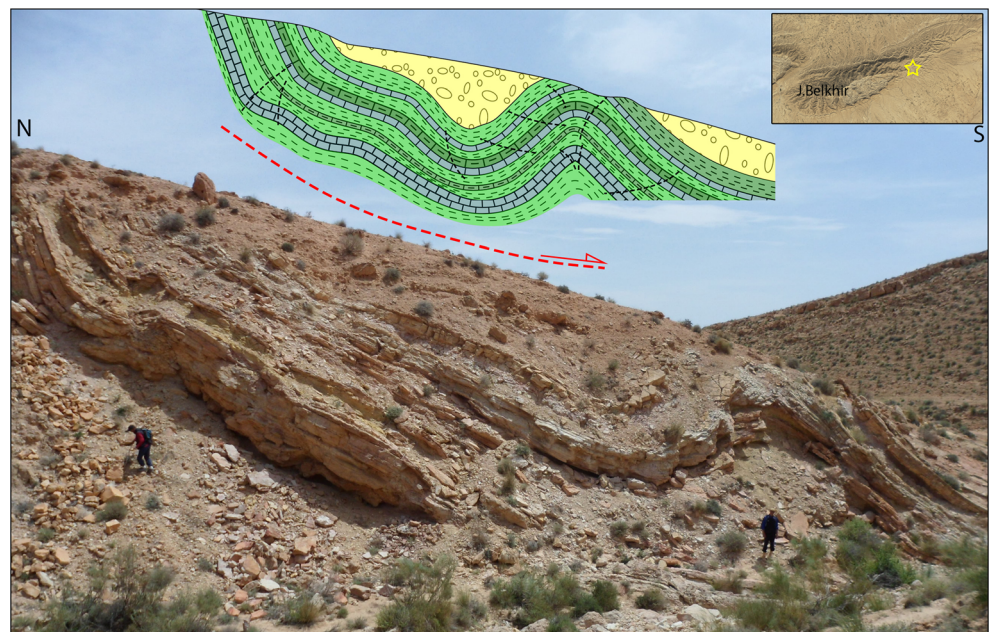
Alluvial fan migration

In the Jebel Chemsî, many torrent water streams drain the southern flank up to the core of the anticline and deposit debris flow materials in the foothill reliefs in the alluvial fans. From the apex point of the fan, the equilibrium profile goes above the topography and the sediments deposited by alluvial fan accumulations. In the southern foothill of the Jebel Chemsî, three generations of alluvial fans are found on a progressive southward migration (Fig. 9a, b). Two of these fans are old and abandoned, while the third is recent and active. The chronology of these fans is determined by their erosion and superposition. The oldest fan (F1 in Fig. 9b) is subject to erosion as evidenced by the presence of active

drainage network. The middle age fan (F2 in Fig. 9b) overlays the southern part of the first one. This second generation of alluvial fan is incised by a deep stream channel, which indicates that it is no longer subject to sedimentation. Further to the south, the third fan shows an active deposition.

The direction of the major stream channel is characterized by a sudden change when it moves from the first to the second fan. At the foothill zone, the valley is captured and deviated eastward. The abandoned channel stream, called wind gap (Medwedeff 1992), resulted from the change in both equilibrium profile and relative area of erosion/deposition (Fig. 9b). In fact, the channel altitude difference between the two streams at the cross point is 11 m (265 m for the old stream and 254 m for the current stream).

Fig. 8. Photography and interpretation of field-scale folds affecting the Senonian series. These structures are originated from a superficial decollement level in the same formation



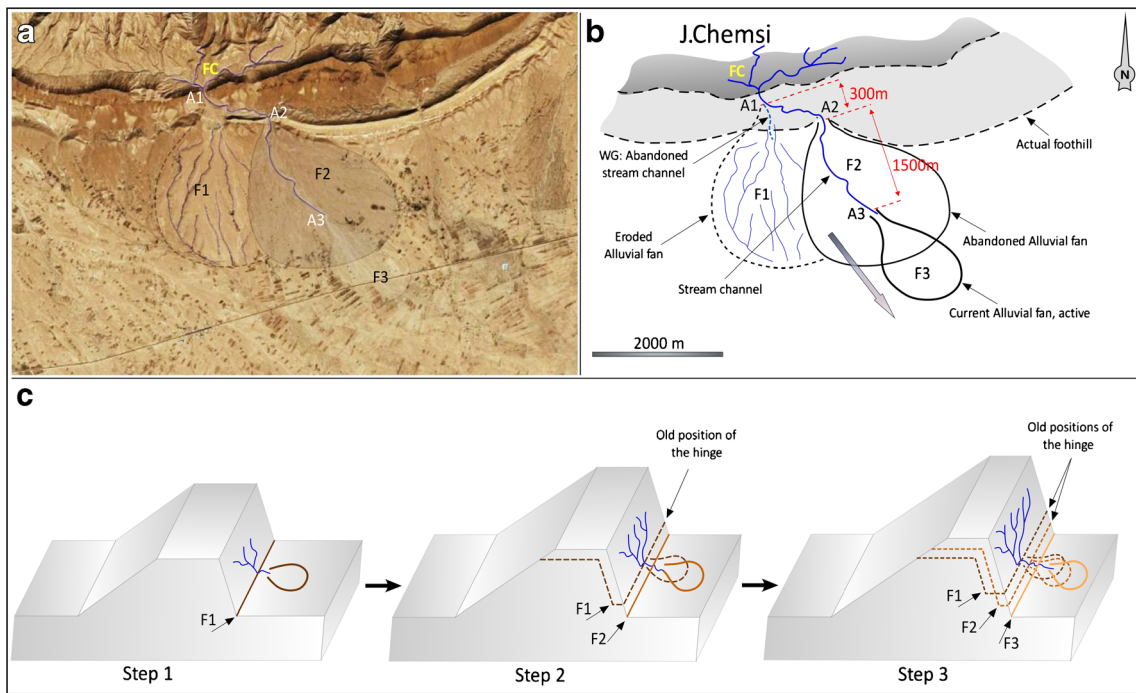


Fig. 9 Alluvial fan migration observed in the southern foothill of the Jebel Chemsî. **a** Satellite image. **b** Interpretation of alluvial fans' generations. **c** Proposed model assuming hinge migration to explain alluvial fan progradation. *FC* feeder channel, *A* apex point, *WG* wind gap, *F* alluvial fan

Longitudinal profile of stream channels

Several authors used the longitudinal profiles of stream channels to describe the deformation kinematics (e.g., Stanley et al. 2000; Delcaillau et al. 2007; Ambili and Narayana 2014). These profiles are usually converging toward a classical concave equilibrium shape. This theoretical line, which controls the areas of erosion and deposition, is highly sensitive to vertical movements. This permits to identify and interpret anomalies that affect the longitudinal profile. A normal longitudinal profile (not disturbed) has a curved shape with an upward concavity and a gentle slope near the mouth that becomes gradually steeper upward the headwaters.

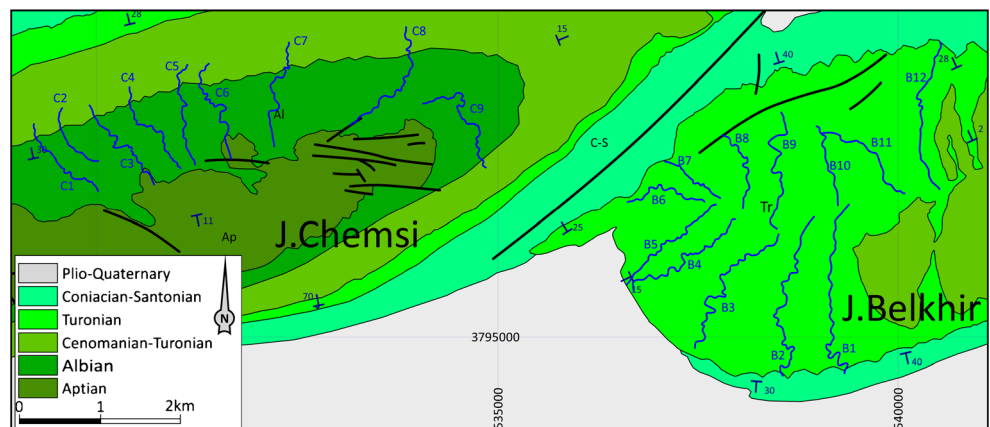
In our case of study, 21 major stream channels, draining the totality of the investigated area, are selected: 12 of them are

located in the Jebel Belkhir and 9 are situated in the Jebel Chemsî (Figs. 10, 11 and 12). The selected streams are considered to be representative of the morpho-dynamic conditions in the study area. Among these channels, all longitudinal profiles show, at least, one knick point located at the mountain foothill.

Differential maturation of the drainage network

The upper Cretaceous formations contain several massive carbonate beds ranging from the massive Abiod limestones (Campanian-Maastrichtian) to the Zebbag dolomites (Cenomanian-Turonian). These formations, having strong mechanical resistance, occupy the core of the fold, which provides good conditions to compare the morphological impacts

Fig. 10. Geological map showing the position of the studied longitudinal stream channel. The coordinate system is UTM zone 32, WGS 84 system (metres)



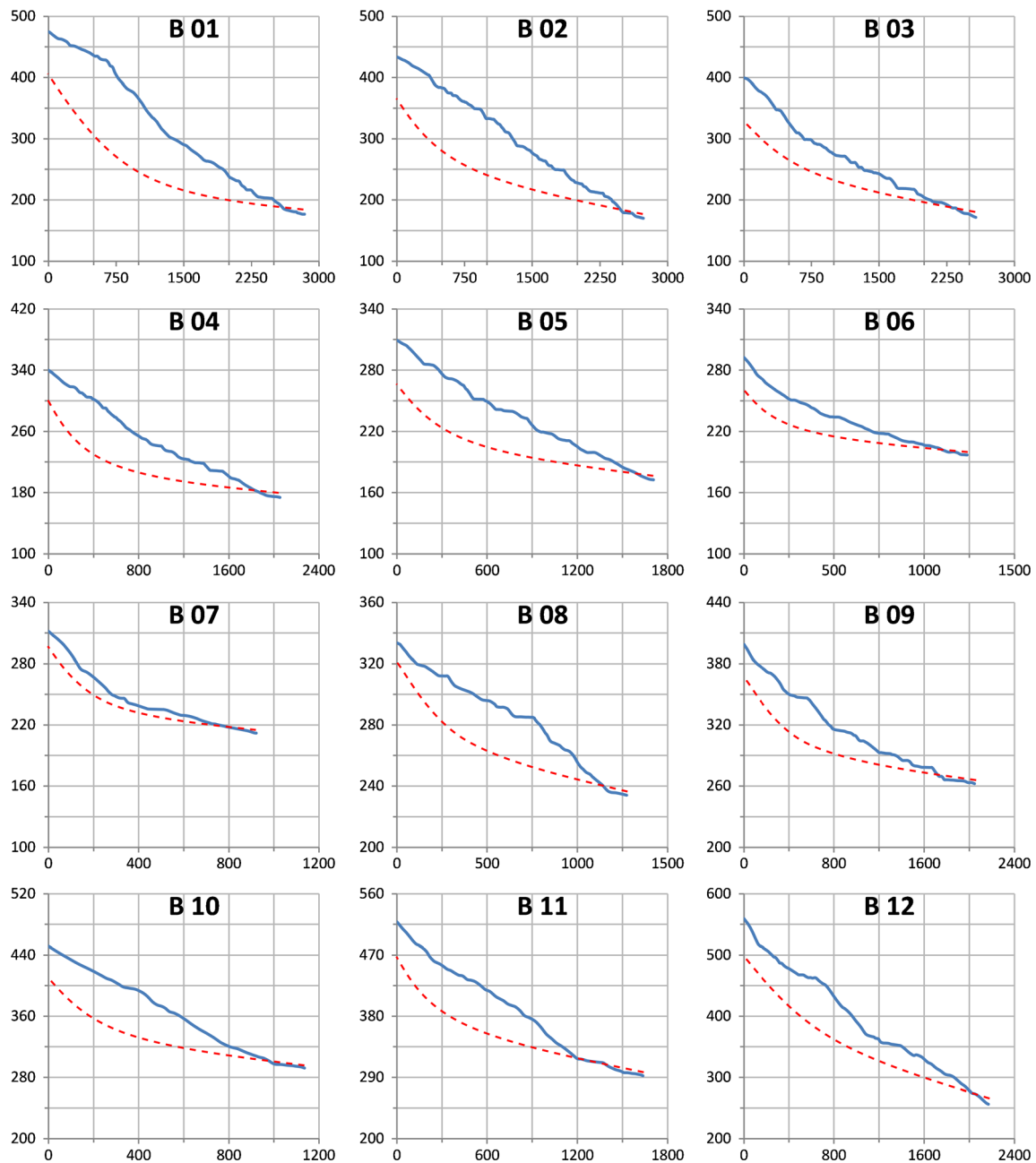


Fig. 11. Longitudinal stream channel profiles along the Bekhir anticline. Positions of the studied rivers are shown in Fig. 10. Dashed red lines show the equilibrium profiles

of the erosion on various portions. These exceptional outcropping conditions allow comparing the erosion effect around the fold.

On the western part of the Jebel Belkhir, the channel confluences in the northern flank become obviously more frequent toward the anticline hinge. The drainage network appears to be more mature upward, despite the lithology remains the same over the slope (Fig. 13). The maturity is quantified by the surface incision and the order of the channels. On the satellite images, the channel width displays the rate of incision, which decreases toward the base of the hill. Moreover,

the drainage network in the Jebel Belkhir changes from dendritic type in the top part to parallel type at the flanks base (Fig. 13).

Interpretation and discussion

The kinked fold geometry of the Jebel Chemsî and Belkhir fits with fault-related fold models. Based on the field observations two numerical models are proposed:

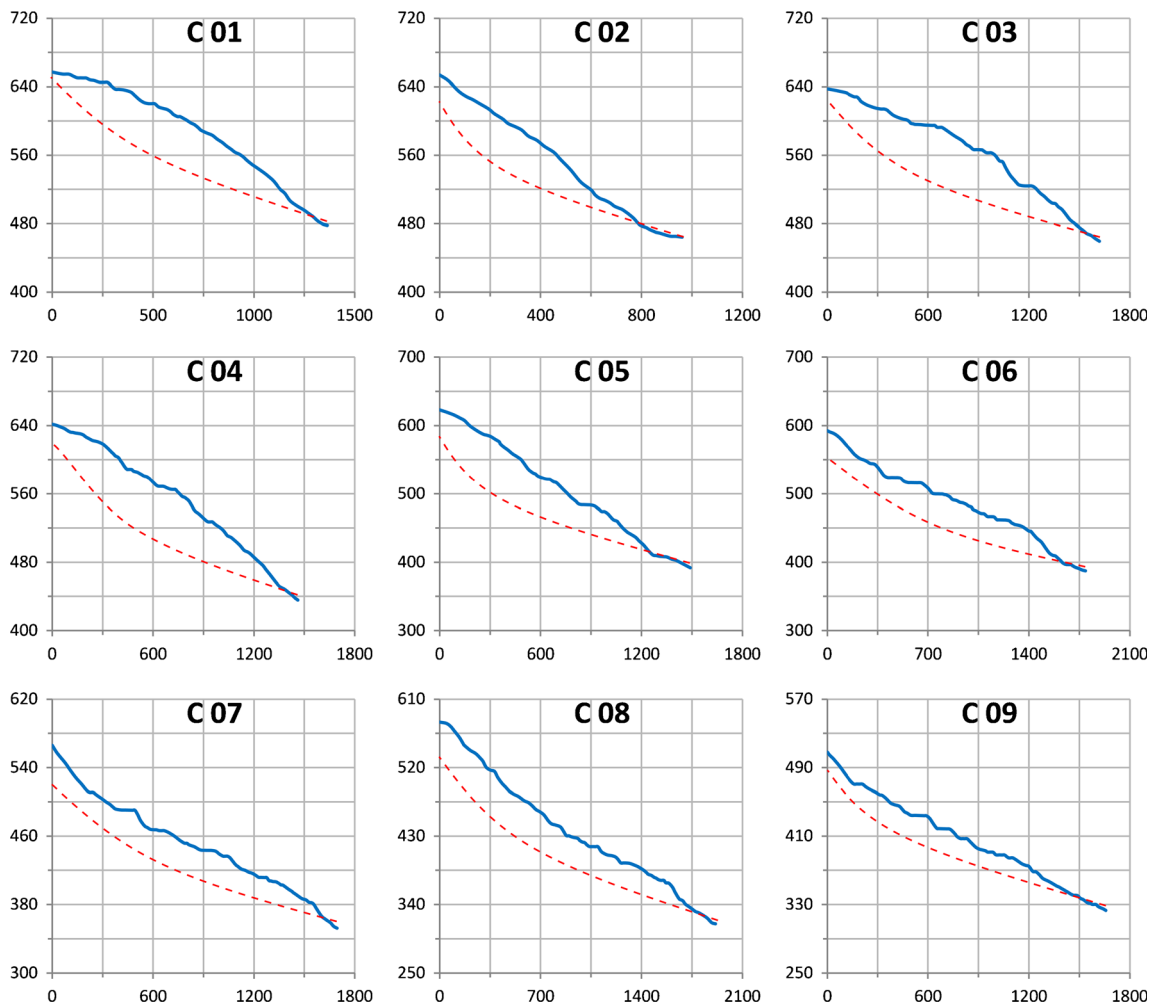


Fig. 12. Longitudinal stream channel profiles along the Chemsî anticline. Positions of the studied rivers are shown in Fig. 10. *Dashed red lines* show the equilibrium profiles

- i. The fault-propagation fold model (Fig. 14a): it includes many similar numerical models, which derive from the original simple-step fault-propagation fold model of Suppe (1985). The most cited ones are the trishear fault-propagation fold model (Erslev 1991; Allmendinger 1998), shear fault-propagation fold model (Suppe et al. 2004) and the Jabbour model (Jabbour 2011). Actually, field and geometry data are not enough to distinguish between these similar fold models. Therefore, we will focus on simple-step fault-propagation fold (Suppe 1985) using the forward modelling program Ramp EM (Mercier 1995).
- ii. The fault-bend fold model (Suppe 1983) (Fig. 14b): it is a developed from the ramp anticline of Eliot (1976), which has limited number of models with respect to the fault-propagation folding. At least two models can be distinguished: the shear fault-bend fold (Suppe et al. 2004) and the duplex folding that consists of imbricated fault-bend fold (Mitra 1986).

As a first approach, simple models for both anticlines are considered. This assumes that neither the Jebel Chemsî nor Jebel Belkhir has reached the late-stage complication as described by Mercier et al. (1997). At surface, the kinematics is the unique difference between the fault-propagation and the fault-bend fold models. In fact, the deformation stages leading to these two models have different kink kinematics (position of mobile and fixed hinges during deformation). Growth strata geometry or geomorphologic hallmarks are the possible methods to explore this difference.

Southward prograding alluvial fans in the Jebel Chemsî are in the same direction with the fold hinge migration. The measured progradation of the fan apex point is about 300 m from the first fan to the second one and 1550 m from second to the third fan (Fig. 9b). This may indicate an active thrust tectonics and/or a base level drop. In our case of study, all regional drainage networks converge toward a continental depression ‘Sebkhat Sidi Mansour’ that has a constant level during the

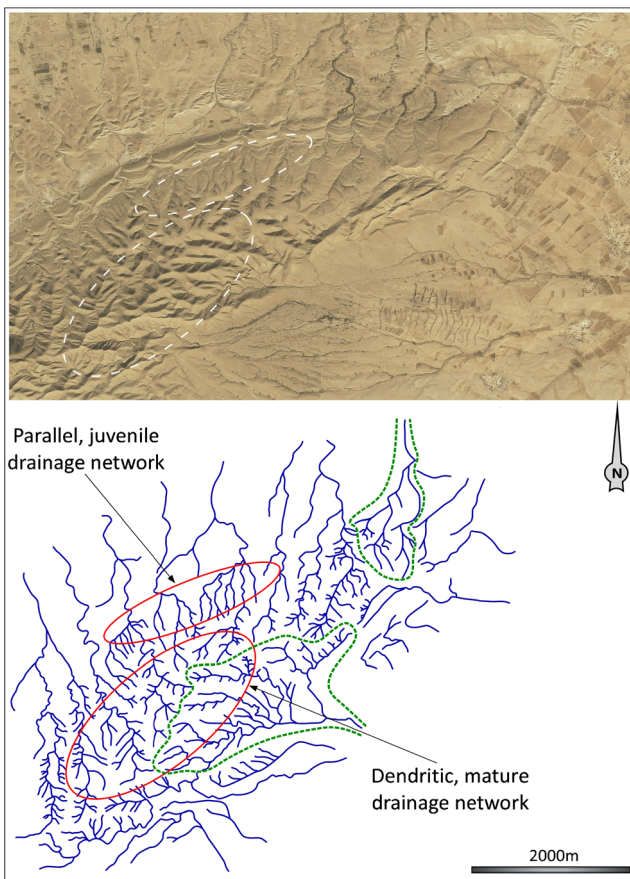


Fig. 13. Satellite image showing the drainage net network on the eastern termination part of the Jebel Belkhir. We note clearly a differential of maturation that we interpret by a new material uplift to the flanks

Neogene. Thus, the alluvial fan migration and the drainage network capture bring insight to the active tectonics of the studied fold structures. The kink of the southern syncline hinge is fixed in the allochthonous for the fault-bend fold and is migrating southward for the fault-propagation fold (Fig. 9c). The fixed kink leads to fixed foothills, and accordingly, alluvial fans should remain fixed or growing backward toward reliefs because of erosion. On the contrary, mobile hinges displace

progressively the foothill, which is the critical point of erosion/deposition process in torrent systems. However, surface thrust fault and reverse fault at foothill position could engender the same observed field geometry.

The studied stream channels across the Jebel Chemsî and Belkhir show many knick points in their longitudinal profiles. Basically, this anomaly could be interpreted by (i) a sea level change, (ii) a lithology contrast and (iii) an active folding or an active thrusting.

- i. In the study area, the drainage network is controlled by the continental Sebkhât, for which the topographic levels did not show any major change during the Neogene (Swezey 1996; Patriat et al. 2003). Therefore, sea level change does not control the erosion/deposition process in this area (Ahmadi 2006). Moreover, the studied stream channels are torrents and, consequently, are relief-related.
- ii. The stream profiles are not related to the lithology contrast because in most drainage basins, only one massive dolomitic bed is exposed. In the Jebel Belkhir, most of the studied stream channels belong to the Turonian dolomitic bed. Moreover, those of the Jebel Chemsî drain the Albiens dolomitic bed (Fig. 10). The feeder channels show the knick point anomaly as such as the other feeding streams independently from the lithology change.
- iii. Faults exist nearby the studied channel knick points. However, there is no evidence of fault control. Therefore, fault position cannot explain all the stream anomalies that show the knick points at the foothill position in the flank.

As a result, it can be concluded that active folding is the mechanism responsible of this longitudinal profile anomaly.

Fault-propagation and fault-bend folds do not show the same kinematic path. In both models, mobile and fixed hinges exist. However, the direction and the position of the mobile hinges change. The mobile hinges are a typical kinematics of the fault-related folds. They allow material flowing to the fold limbs and permit the increase of the fold

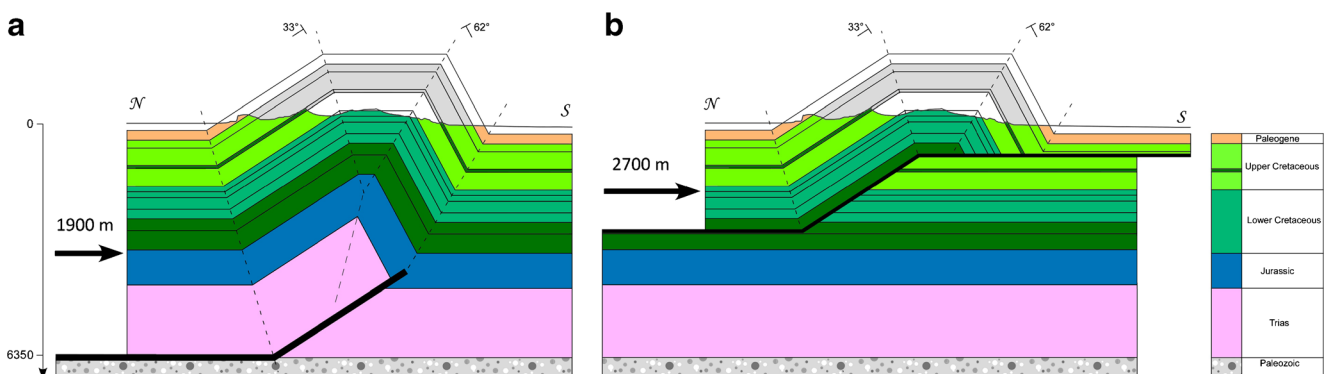


Fig. 14. Fault-propagation fold (a) and fault-bend fold (b) adapted to flanks dips of the Jebel Chemsî

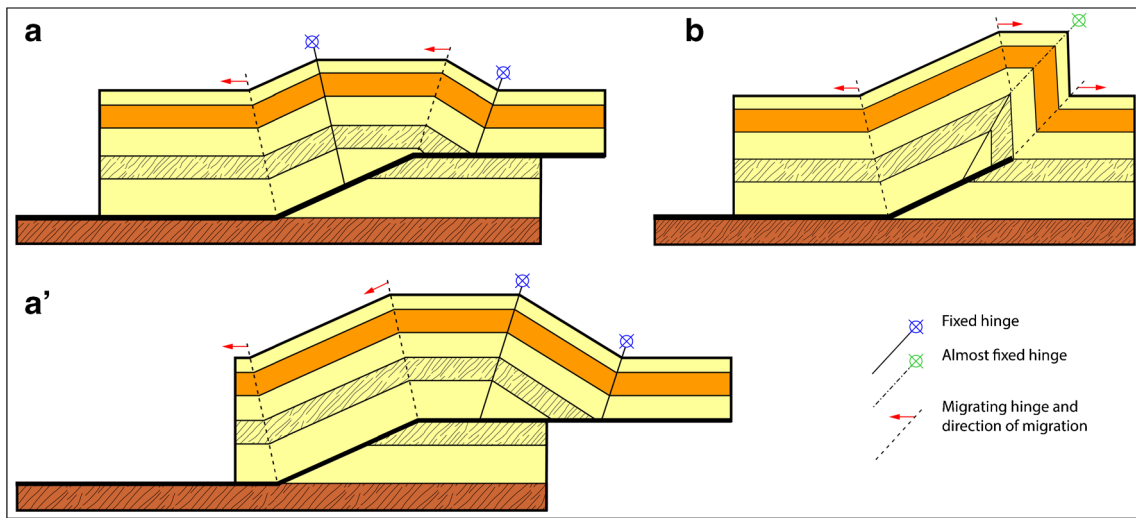


Fig. 15. Comparison between the kinematics of fault-bend fold and fault-propagation fold. The positions of fixed and mobile hinges are clearly different between both models

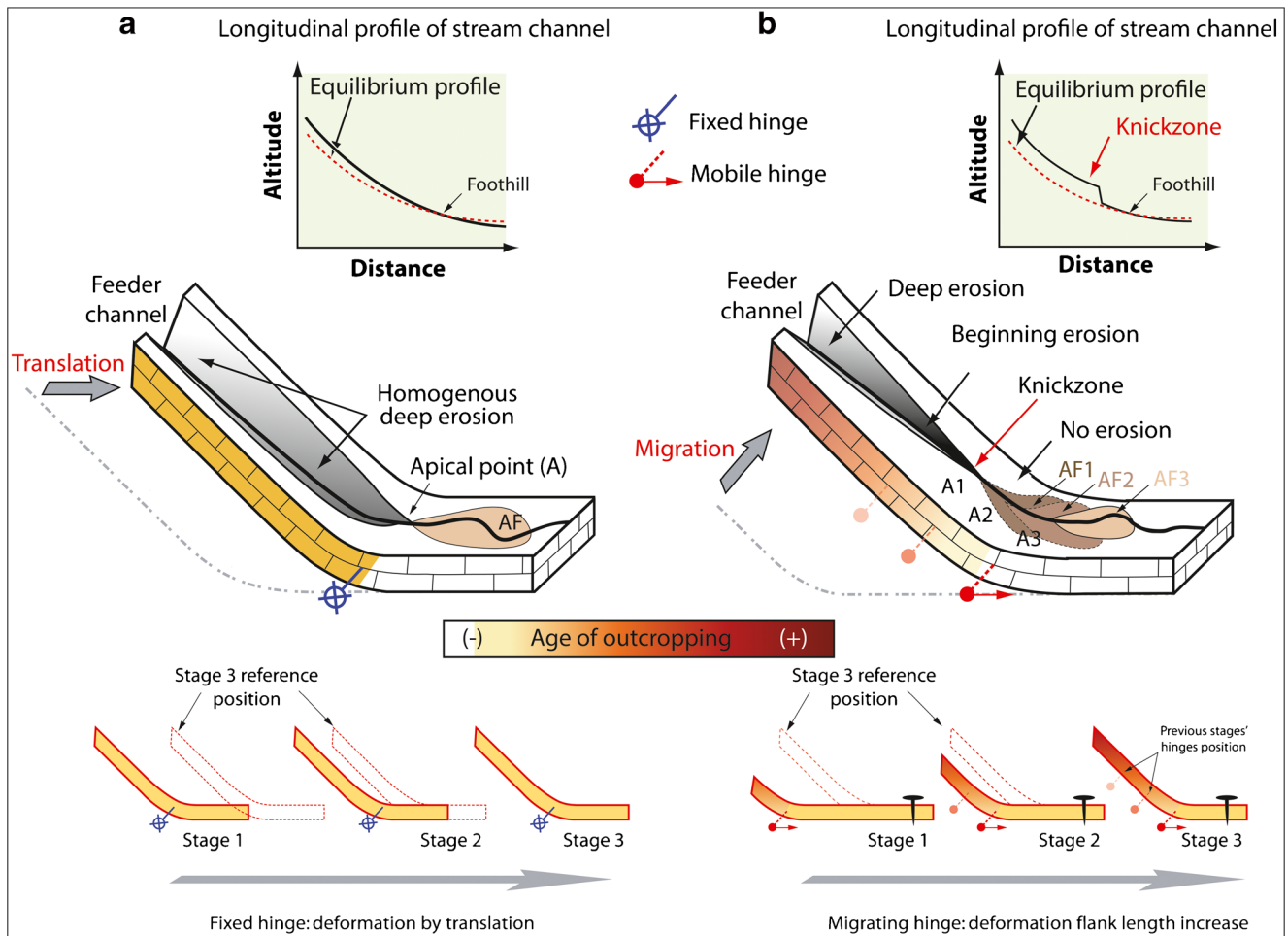


Fig. 16. Theoretical behaviour of erosional process in limb translation (forelimb of fault-bend fold) (a) versus hinge migration (forelimb of fault-propagation fold) (b). Limb translation will allow normal progressive erosional process with no noticeable anomaly: the entire flank is

exposed to erosion at the same time. Flanks developing with hinge migration are exposing regularly fresh surfaces to relieve, and this creates rejuvenation of all erosion-related processes such as kink zone, longitudinal stream profiles and alluvial fan disturbance

deformation. In fault-bend fold, the fore syncline hinge (southern hinge in our case study) is fixed in the allochthonous during folding. The back syncline hinge is always migrating backward of the deformation direction. However, the anticline hinges switch from fix to mobile and from mobile to fix considering the kink position with respect to the ramp (Fig. 15a, a'). On the other hand, in the fault-propagation fold, the fore syncline hinge is actively migrating in the same direction of the deformation (southward in our case study). The back anticline and the back syncline hinges are always migrating backward of the deformation direction. The only almost fixed hinge is the fore anticline one (Fig. 15b).

The folding growth with fixed hinges leads to convex shape stream similar or close to the equilibrium profile. In fact, during folding, the whole flank is exposed to the erosion from the initial deformation stages and has no particular anomaly such as a knick zone (Fig. 16a). As such, the longitudinal profile gets mature progressively and conformably to the equilibrium shape. However, with the hinge migration kinematics, new materials feed the flanks and new areas outcrop at the foothill. Later, these areas become subject to the erosion. This creates a knick zone at the previous apex point (Fig. 16b). New alluvial fan apex takes place, which leads to alluvial fan migration. In our case of study, this could be a direct demonstration of the southern syncline hinge migration toward the deformation or the thrust control.

On the western termination of the Jebel Belkhir, the drainage network is mature to the top and juvenile to the base near the foothills. This can be explained by the different time exposure of the flanks, which is compatible with the hinge migration kinematics. In the same way, the N-E periclinal limit of the fold migrates northeast allowing lateral propagation of the deformation (Fig. 17). In fact, this lateral propagation is a fold development process in active tectonics that has been recognized since Shelton (1966). Nevertheless, this process operates only by hinge migration kinematics.

The drainage system development is traditionally considered as a result of successive captures, related to the increase of confluence and incision rates that leads to a maturation augmentation (Strahler 1964; Schumm 1986). Considering homogenous lithology, the north-facing slope of the Jebel Belkhir is, therefore, diachronic, and the lowermost portion of this slope is the youngest. This implies a progressive migration of the northern hinge toward the north. Concerning the hydrographic networks incision, the channel's longitudinal slope is classically evolved to a steady state by erosion after uplift. The retrogressive erosion controls this evolution and propagates normally upward. It starts particularly in the transition zone between the slope and the downhill plains. In Jebel Belkhir north facing slope, this retrogressive erosion is not yet active. This observation supports the assumption of the occurrence of an age grading along the slope, from the youngest down slope to the oldest at mid slope. This age grading is

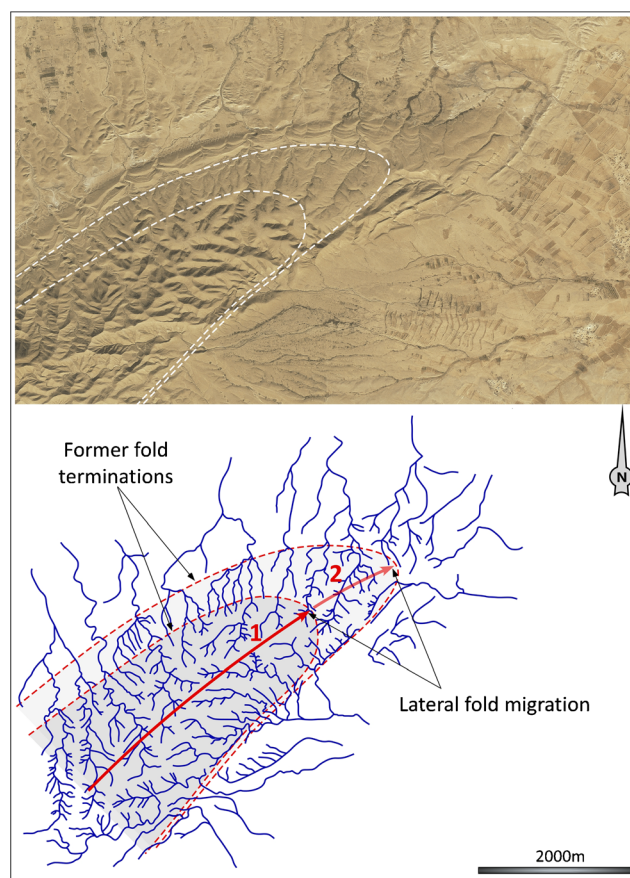


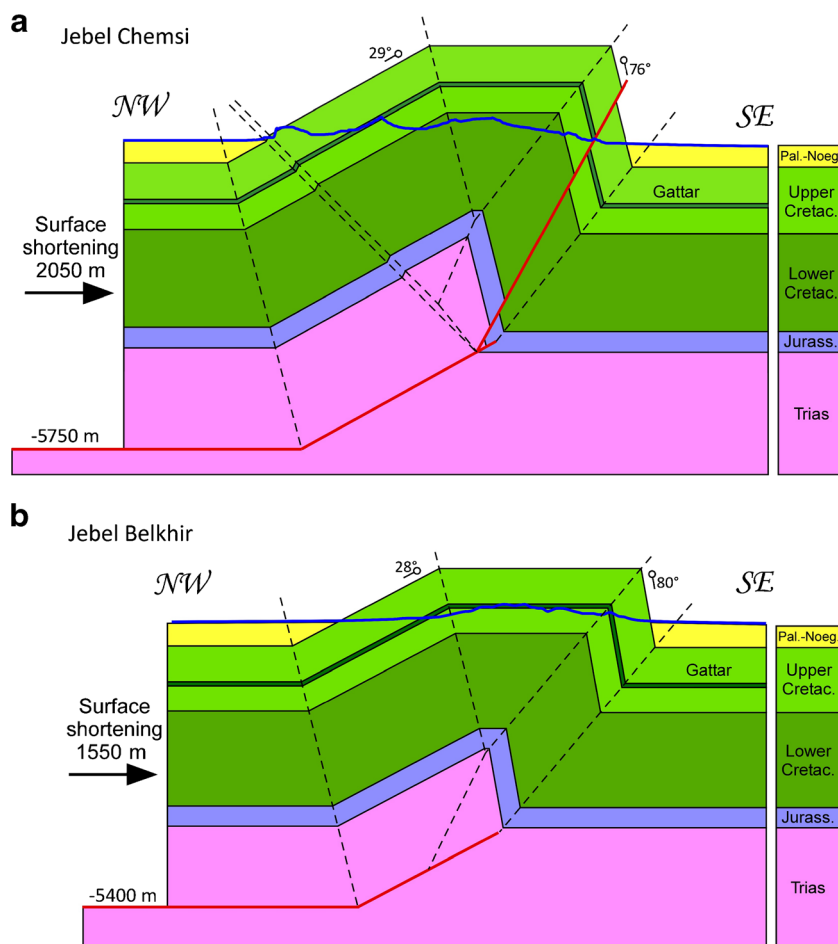
Fig. 17. Satellite image showing the drainage net on the eastern termination part of the Jebel Belkhir. The anticline fold axis migrates toward the north by hinge migration kinematics, and so for the northwestern north-western flank

caused by a rejuvenation of the long-profile at each step of the structure amplification. The continuous reposition (uplifting) of the knick zone proves the rejuvenation of the erosion, which supports the northern syncline hinge migration.

The geomorphologic analysis, by proving forelimb migration through alluvial fan progradation and longitudinal stream profile knick zone, fits with the fault-propagation fold model or with the active surface-thrusting process (Fig. 18). In fact, thrust or reverse fault exists in the Chemsî anticline in a long part over the southern flank. However, it does not affect the totality of this fold, and in the Jebel Belkhir anticline, there is no evidence of thrust or fault existence. Therefore, it is likely that the thrust contributes to the development of the Chemsî anticline by accommodating partially the deformation. Thus, it is deduced that the Chemsî anticline is a fault-propagation fold with possible forelimb breakthrough as mentioned by the model of Mercier (1992) and the Jebel Belkhir is a simple step fault-propagation fold (Suppe and Medwedeff 1984–1990).

The major decollement level, as given by the law of excess area, is calculated at almost 5.5-km depth, which matches with the Triassic evaporites. This formation consists of salt,

Fig. 18 Simplified kinematic fold models for the Jebel Chemsî (a) and Jebel Belkhir (b) anticlines. The geometry and kinematics of both folds fit better with fault-propagation fold model. However, inherited faults contribute in making the fold structure more complicated



anhydrite and claystone interbeds that could act as a potential detachment layer. In addition, fluid overpressure studies showed that this interval is hosted the highest fluid overpressure of the sedimentary column in southern Tunisia. Thus, it is believed that fluid overpressure is the most effective mechanism that decreases the base friction and determines the regional decollement surfaces. Moreover, previous studies (Ahmadi 2006; Ahmadi et al. 2006) showed that Triassic-Liassic series are the major detachment level in the Gafsa basin. Consequently, it is concluded that the thin-skinned fault-propagation fold is a credible fold model for both the Chemsî and Belkhir anticlines.

The compressional stress took place after a major normal faulting. Nevertheless, inherited fault should influence the compressive deformation. Therefore, it is supposed that the major ramp is nucleated from the E-W-inherited normal fault. The complete inversion of the normal faults seems to be unrealistic because of their high dip, which does not fit with the fault-propagation fold model. During fault-propagation fold growth, the existing faults are folded and sheared on both flanks. In the southern flank, sinistral simple shear decreases sensibly the inherited normal faults

dips, and then, a possible reworking in reverse of one of them can be supposed. Therefore, the major reverse fault observed in the southern flank represents a breakthrough of fault-propagation fold (Fig. 19). In the upper Cretaceous series, the observed minor detachments are responsible for the field-scale folds and thrusts. These superficial detachments are, probably, following the excess material deriving from the Orbata-Bouhedma fold range. This numerical model supposes that the bed thickness remains unchanged during the shortening. The flanks record simple shear in kink bands: sinistral in the forelimb and dextral in the backlimb. However, many other generic models of fault-propagation folds such as the trishear model, the shear fault-propagation fold model and the Jabbours' model suppose local thickening or thinning. This pure shear deformation is, always, associated with limb simple shear. The use of these models to simulate the Chemsî and Belkhir anticlines provides a quite satisfying fits to geometric field data. Nevertheless, there is no clear argument to privilege one specific model against another. Taking into account the existing field data, the results remain too similar to deduce the precise folding model. Therefore, it is preferable to do

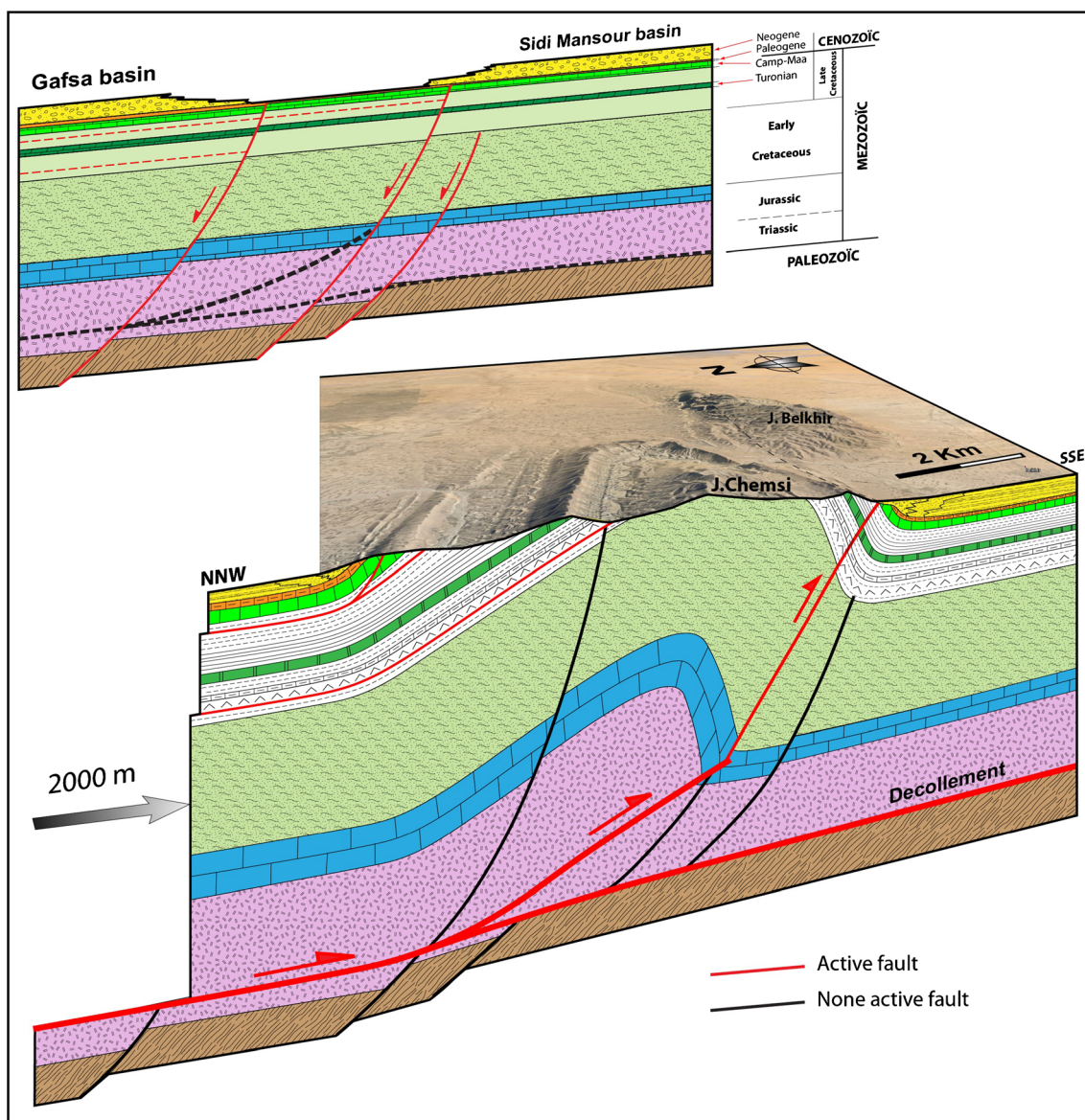


Fig. 19. Balanced and restored cross sections of the Jebel Chemsî anticline using fault-propagation fold model adapted to thickness change and inherited normal fault net network

not go further and to consider the fault-propagation fold in its large meaning.

Conclusion

The structural study of the Jebel Chemsî and Belkhir foreland basin folds located in southern Tunisian Atlas has led to identify asymmetric folds compatible with fault-related fold geometry. Abundant kinks over all the transition area between anticline hinges and both flanks characterize this style of deformation. Two numerical models could explain the observed surface geometry. These models are the fault-propagation fold and the fault-bend fold. The kinematics of these models is different. The locations of fixed and

migrating hinges are changing. Many independent geomorphologic arguments have focused on the kinematics study. Several morphological anomalies pointed up a specific kinematic path that informs about previous deformation stages. In fact, the alluvial fan progradation, the longitudinal profile of stream channels knick zones and the drainage network differential maturation proved a centrifuge migration of both syncline hinges. This statement characterizes the fault-propagation fold. The Triassic detachment level privileged by balanced cross section is already proved in this region. Moreover, this layer has high fluid overpressure that helps in canalizing and carrying out the deformation to huge surfaces in the foreland basins. This work demonstrates that geomorphological arguments are suitable for kinematic characterization of fold model in active tectonics area.

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