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Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control

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Abstract

Detachment folding has been studied on the basis of field and subsurface examples from the Central and Eastern Zagros (Iran). We discuss different aspects of detachment folding well illustrated in the studied area. In particular, we focus on: salt mobility, multiple décollements and late basement control. Salt mobility concerns the 'Hormuz' basal detachment and the 'Gachsaran' upper detachment. For the latter, it is shown that mobility results not only from folding-related diapirism, but also from early gravity-driven migration from growing anticlines towards intervening synclines. Concentric folding between two detachment levels is directly observed in the Izeh zone (Central Zagros) where it is shown that the wave-length depends on the distance between the two active décollements and that the fold shape is a function of the level of erosion. Throughout the Zagros, detachment folds mainly developed during an initial thin-skinned phase of deformation, which was followed by the current thick-skinned stage. This succession is particularly well expressed in the Eastern Zagros where basement faults cut early detachment folds obliquely.

Keywords: Detachment; Detachment fold; Salt mobility; Thin-skinned tectonics; Thick-skinned tectonics; Zagros Mountains (Iran)

1. Introduction

Numerous fold-and-thrust belts are formed by detachment of sedimentary layers above an incompetent unit, such as shale or evaporite (Davis and Engelder, 1985). Historically, a good example of control exerted by such a detachment zone is the Jura at the front of the western Alpine orogen where stiff Mesozoic layers (mainly carbonate) are folded upon weak Triassic evaporite (Buxtorf, 1916; Goguel, 1952; De Sitter, 1956; Laubscher, 1977). If the detachment zone (or décollement level) is thick enough, the development of detachment folds (i.e. 'an unfaulted fold train above a through-going detachment'; Dahlstrom, 1990) is expected. The kinematics of detachment folds remain a matter of debate because of the absence of an unequivocal relationship between the final geometry and the kinematic path (Poblet and McKlay, 1996; Homza and Wallace, 1997; Mitra, 2003). However, the importance of the mechanical stratigraphy of the sedimentary pile involved in the folds is consistently recognised. In connection to this last aspect, a question of major importance in detachment folds is the role of diapirism and, more generally, of salt mobility.

The Zagros Mountains of Iran resulted from the opening and then the closure of the neo-Tethys ocean between the Central Iran domain and the Arabian plate (Ricou, 1971; Berberian and King, 1981; Alavi, 1994). Within this orogenic belt, the external zones, the so-called «Zagros Simply Folded Belt» (ZSFB) (Stocklin, 1968; Falcon, 1969; Blanc et al., 2003; Sherkati and Letouzey, 2004; McQuarrie, 2004; Molinaro et al., 2005a) (Fig. 1) represent the palaeomargin of the Arabian plate folded during Cenozoic times. The ZSFB is often cited as one of the regions in the world showing the best examples of large scale detachment folds (Colman-Sadd, 1978) as shown by their regular and well-rounded geometry (Fig. 2). This is due to a very efficient décollement level (the Hormuz salt) located at the base of a

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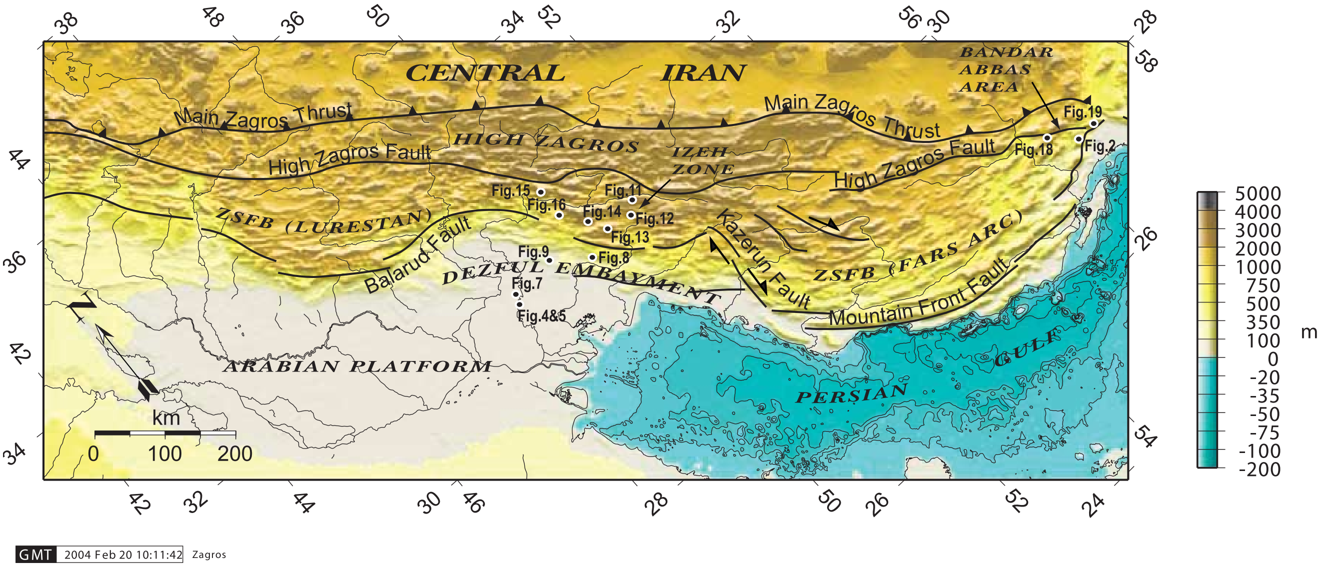


Fig. 1. Physical map (source: GEBCO data) and main structural features of the Zagros fold-thrust belt with location of the figures. ZSFB: Zagros Simply Folded Belt.

thick (up to 10,000 m) sedimentary sequence. More precisely, O'Brien (1950, 1957) was the first to divide the stratigraphic pile into five structural/mechanical ensembles namely: (1) the basement group (Panafrican crystalline basement), (2) the lower mobile group (Hormuz salt), (3) the competent group (Cambrian to Lower Miocene platform sediments), (4) the upper mobile group (Miocene salt) and (5) the incompetent group (Miocene to recent molasses). However, this mechanical stratigraphy, defined originally in the Dezful Embayment, is not uniform throughout Zagros and varies strongly depending on the considered region (Fig. 3). The ZSFB allows us to address different questions about the mechanisms active during folding in fold–thrust belts including: (1) the role of salt mobility, (2) the role of multiple décollements in the sedimentary cover, (3) the interference between different phases of deformation and, finally, (4) the role of the basement during folding.

The aim of this paper is not to present new models of detachment folds, but (1) to discuss the different aspects listed above on the basis of examples and (2) to give an overview of the geometry and kinematics of folds in the ZSFB. Data and interpretations were mainly derived not only from field observations and mapping, but also from a comparison with seismic profiles. We will successively focus on three particular regions where recent field work has been done (Sherkati and Letouzey, 2004; Molinaro et al.,

Fig. 2. The Namak fold in the Eastern Zagros (see location on Fig. 1): an example of concentric fold in the ZSFB. The rounded shape is underlined by the Guri limestone.

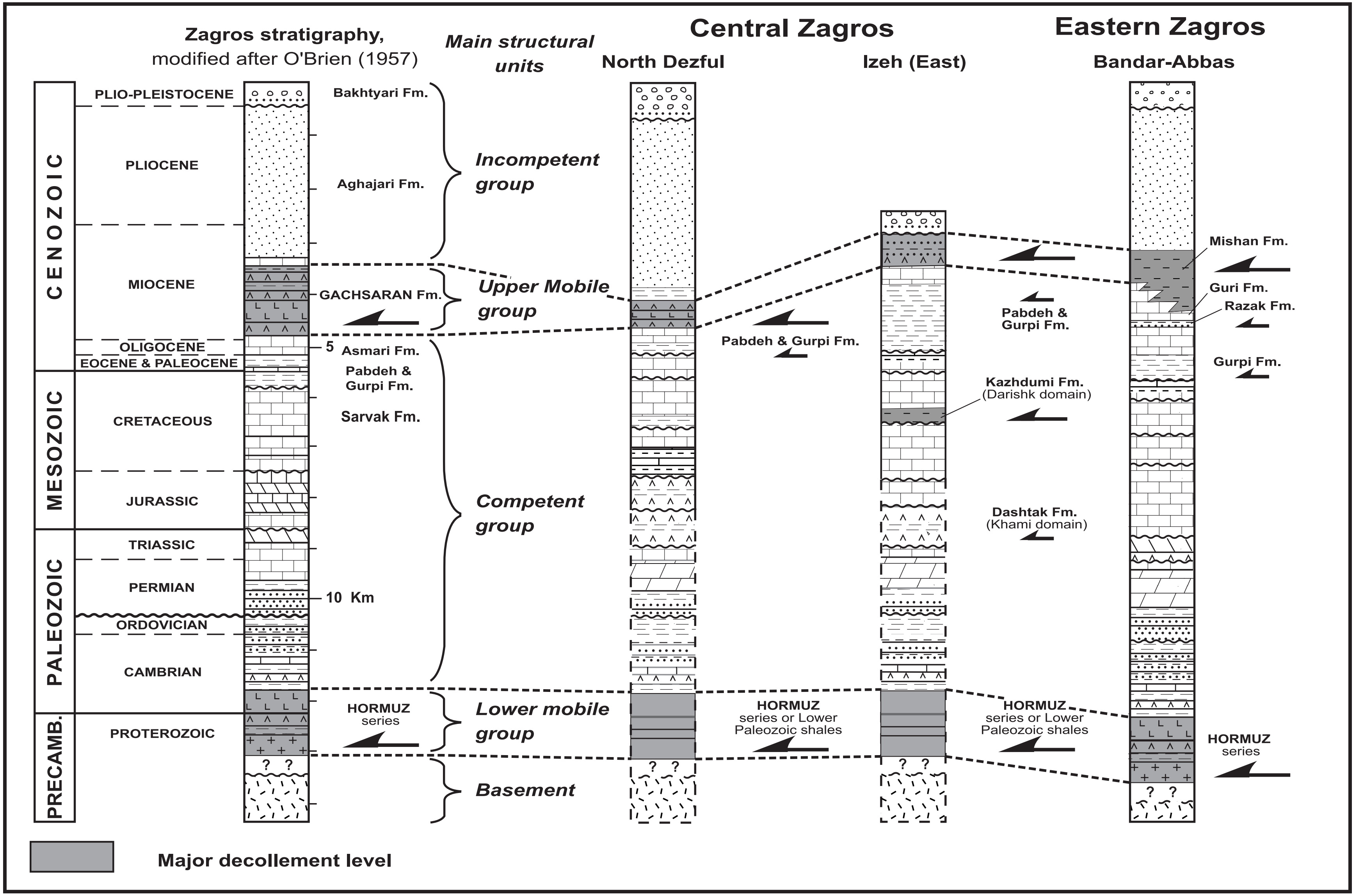


Fig. 3. Generalised stratigraphic column indicating the main detachment horizons in the Central and Eastern Zagros. The mechanical properties are not uniform throughout the belt (the mechanical stratigraphy proposed by O'Brien (1957) is given for the record). Units with dashed boundaries (Izeh and Dezful zones) are extrapolations of regional averages.

2004; Molinaro et al., 2005a): the Dezful Embayment and Izeh zone, which are both situated in the central Zagros, and the Bandar Abbas area in south-eastern Zagros (Fig. 1).

2. Syntectonic sedimentation and salt mobility: examples from the Dezful Embayment (Central Zagros)

The Dezful embayment is the region where, historically, O'Brien (1957) proposed a conceptual kinematic model to explain why in this region and 'contrary to the accepted trends of diapiric movements' the Miocene salt has moved from anticlinal areas into synclinal areas. Sections from this author in this area display the singular characteristic of superficial synclines in contact with anticlines at depth. The Miocene salt is thus squeezed from areas of almost zero thickness to areas of huge accumulations of salt (salt bulges). These sections are now classical and have been reproduced recently by several workers (Egdell, 1996; Sattarzadeh et al., 2000; Bonini, 2003) as an example of extreme disharmonic folding. It is worth noting that these authors do not discuss O'Brien's model in which the folding occurs very late (i.e. after the deposition of the Mio-Pliocene molasse) and diapirism plays a major role. New available data, presented here, show that the folding occurred during at least two steps and that diapirism is probably only one aspect of the salt mobility.

The Dezful embayment is situated in the Central Zagros, southwest of the Mountain Front Fault, where it forms a re-entrant between the Lurestan and Fars Arcs (Fig. 1). Directly connected to the Persian gulf, it corresponds to an alluvial plain of low altitude passing northward into dissected foothills entirely formed by Tertiary molasses.

In South Dezful, the so-called 'competent group' (O'Brien, 1950) forms a single structural unit sandwiched between a lower detachment (the Hormuz salt or lower mobile group) and an upper detachment (the Gachsaran Fm. or upper mobile group) (Fig. 3). An intermediate décollement level (Dashtak Fm. of Triassic age) is known from the South Dezful, but seems to be of only minor importance (Sherkati and Letouzey, 2004). The lower detachment is buried at depth (down to 10 km) and cannot be reached nor imaged by the available seismic data. By contrast, the upper detachment can be seen in the field and recognised on seismic profiles. These conditions are particularly suitable for analysing the progressive activation of this upper décollement during the folding of the underlying carapace.

Seismic profiles across the periclinal termination (Fig. 4) and the central zone (Fig. 5) of the Ab Teymur anticline illustrate the fold geometry at a very early stage of development. On both sections, a salt pillow (or salt bulge) formed by accumulation of salt from the lower Gachsaran Fm. is visible along the southern limb of the fold. At the base of Gachsaran Fm. some disturbance in the reflectors could represent drag folds (Fig. 4), indicative of salt migration. Unfolding of the Aghajari molasse situated above the Gachsaran Fm. leads to a pre-Aghajari geometry in which the salt bulge already exists (Fig. 6b). This suggests that the 'pinch-and-swell' geometry of the Gachsaran Fm. was developed before the deposition of the lower Aghajari. This thickening could result from either a depositional accumulation or an early migration. Both cases necessarily require a first step in the folding process (Fig. 6b). As the salt was at or near surface during this folding process (as shown by growth strata in the upper Gachsaran layers; Fig. 8), we conclude that it was, at least partially, driven by gravity toward the depressions (i.e. toward the syncline). During the subsequent folding (recorded by growth strata visible in the upper Aghajari Fm.; Fig. 5), the existence of the bulge induced the development of an arch in the overlying sediments explaining why the position of the fold hinges at top-Asmari and above Gasharan do not coincide (Fig. 4). During this second step, the Gachsaran salt probably thickened further (Fig. 6d). The main difference with O'Brien's (1957) model is that in our view a first folding step occurred early during or just after the Gachsaran deposition allowing a downward migration and accumulation of salt within the synclines. In our model, the asymmetric distribution of the salt is linked to an initial asymmetry in the syndepositional folds rather than growth sedimentation.

The two sections of Ab Teymur structure (Figs. 4 and 5) can be considered as two steps in the development of the fold. In the central section (Fig. 5), the anticline is wider and exhibits steeper limbs (Fig. 4), suggesting that both limb rotation and outward hinge migration towards the adjacent synclines are active processes contributing to the folding. In both cases, accumulation of the Gachsaran salt in the forelimb is responsible for the gentle asymmetry observed near the surface. Growth strata are observed in the Upper Aghajari Fm. on both limbs of the anticline, but are better expressed along the SW forelimb. No fault is observed on the sections.

A more deformed stage can be observed on a section crossing the Ahwaz anticline (Fig. 7) situated further north (Fig. 1). A comparison with the Ab Teymur anticline (Fig. 6) shows that the Ahwaz anticline is about twice as wide and displays steeper limbs suggesting that the deformation progressed by the same mechanisms including limb rotation and hinge migration. An important element at this stage is the development of a major thrust-fault stepping up from the lower Gachsaran salt horizon and cutting through the incompetent group in the forelimb of the fold. At the same time, the Gachsaran salt continued to migrate towards the 'salt bulge' from the crest and the backlimb of the anticline, accentuating the asymmetry of the whole structure (Fig. 6e). At depth, two thrust-faults developed in the core of the anticline to form a pop-up structure. However, these two faults are only of minor importance and do not connect to the upper detachment (Fig. 7). Due to the higher deformation, the two-step process described above is less evident than in the Ab Taymur anticline.

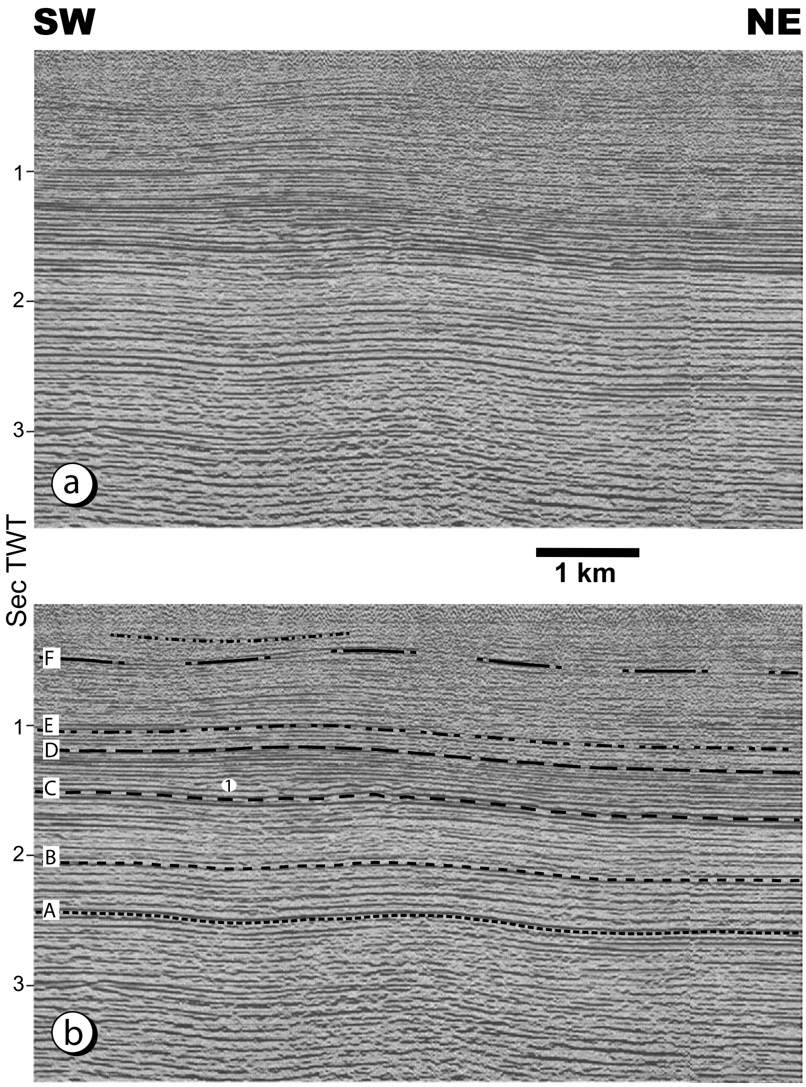


Fig. 4. Non-interpreted (a) and interpreted (b) versions of a seismic profile cutting the periclinal termination of the Ab Teymur anticline (see location on Fig. 1). Vertical scale is in seconds of two-way travel time (TWT). The profile illustrates initial stage of folding. An incipient salt bulge is observable in the Gachsaran Fm. Disharmonic features (labelled 1) close to the bottom of this formation suggest that displacements occurred along this interface. Note that fold hinges in the pre-Asmari and post-Asmari formations do not coincide. Note also the presence of growth strata and top-laps in the Upper Aghajari Fm. See Fig. 6A–D for the proposed kinematic model. A, top Kazhdumi Fm.; B, top Sarvak Fm.; C, top Asmari; D, top Gachsaran Fm.; E, top Mishan Fm.; F, within Aghajari Fm.

The final stage of deformation can be observed on another seismic profile situated further northeast within the Dezful Embayment. On this profile (Fig. 8), situated very close to the mountain front (Fig. 1), two anticlines (Parsi and Karanj) can be distinguished at depth, but only one is seen at surface. Compared with the Ahwaz anticline, the progress in deformation is expressed by different phenomena:

- Within the competent group, forelimb-thrusts, indicative of southward shear, contribute to the accentuation of the symmetry of the folds (Fig. 8). Additionally, the activation of intermediate detachments leads to typical structures such as 'rabbit ears' (Dalhstrom, 1990; Letouzey et al., 1995) flanking the two limbs of the anticline (Fig. 8). On the profile, the most evident of these secondary detachment horizons is the Pabdeh–Gurpi marls located between the Sarvak and Asmari limestones.
- Within the incompetent group overlying the upper detachment, the deformation is controlled by a complete migration of the Gachsaran Fm. toward the 'salt bulge' filling the space situated between two anticlines of the underlying competent group. This leads to a spectacular geometry characterised by Aghajari synclines jammed against underlying Asmari anticlines. At this stage, the deformation above and below the upper detachment is completely decoupled.

A very important observation is that the reflectors corresponding to the upper Gachsaran layers are

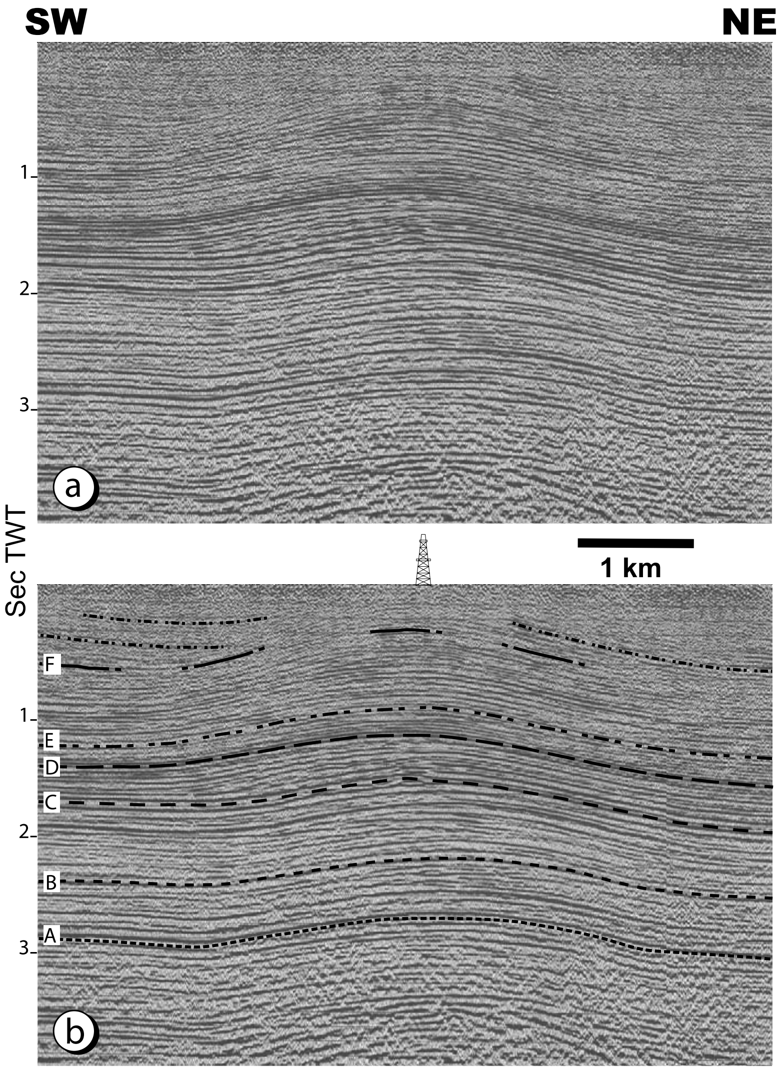


Fig. 5. Non-interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Ab Teymur anticline (see location on Fig. 1). Vertical scale and seismic horizons are the same as in Fig. 4. By comparison with Fig. 4 and assuming that deformation increases from periclinal termination to the middle of the anticline, this profile shows that the size of the anticline and limb dip increase simultaneously during the first steps of folding. Note growth strata in the Upper Aghajari Fm. See Fig. 6A–D for the proposed kinematic model.

pinched out along the crest and the northern limb of the southern anticline (Fig. 8). This shows that, as suggested above, the salt, situated immediately below, had migrated before the deposition of the upper Gachsaran Fm. as a result of a first folding event. Compared with the Gachsaran, the lower Aghajari Fm., situated immediately above, shows a more or less constant thickness, suggesting that it was deposited during a period of relative quiescence in deformation. Folding of the Aghajari Fm., accompanied by the extrusion of salt up to the surface (Fig. 6f), occurred only in a second step likely during the deposition of the upper Aghajari (not visible on the profile).

Field observation in the Dezful embayment permits us to illustrate and add details to some of the topics discussed above. Growth strata in the upper Aghajari are exposed in numerous places (Fig. 9) confirming that, in this area, folding (in fact a second step of folding as shown above) occurred during the deposition of this formation. The conglomerates of the Bakhtyari Fm. were deposited unconformably on already folded layers before subsequent faulting (Fig. 9). This important geometric evidence, which has already been emphasised by Molinaro et al. (2005a) and seems quite general throughout the Zagros, indicates that folding and faulting are not coeval, but distinct events separated by important erosion and widespread deposition of the Bakhtyari conglomerates. From this point of view, the folds of the Dezful Embayment, and more generally of the ZSFB, belong to the category of ‘break-thrust’ folds (Willis, 1893) in which folding precedes fault propagation.

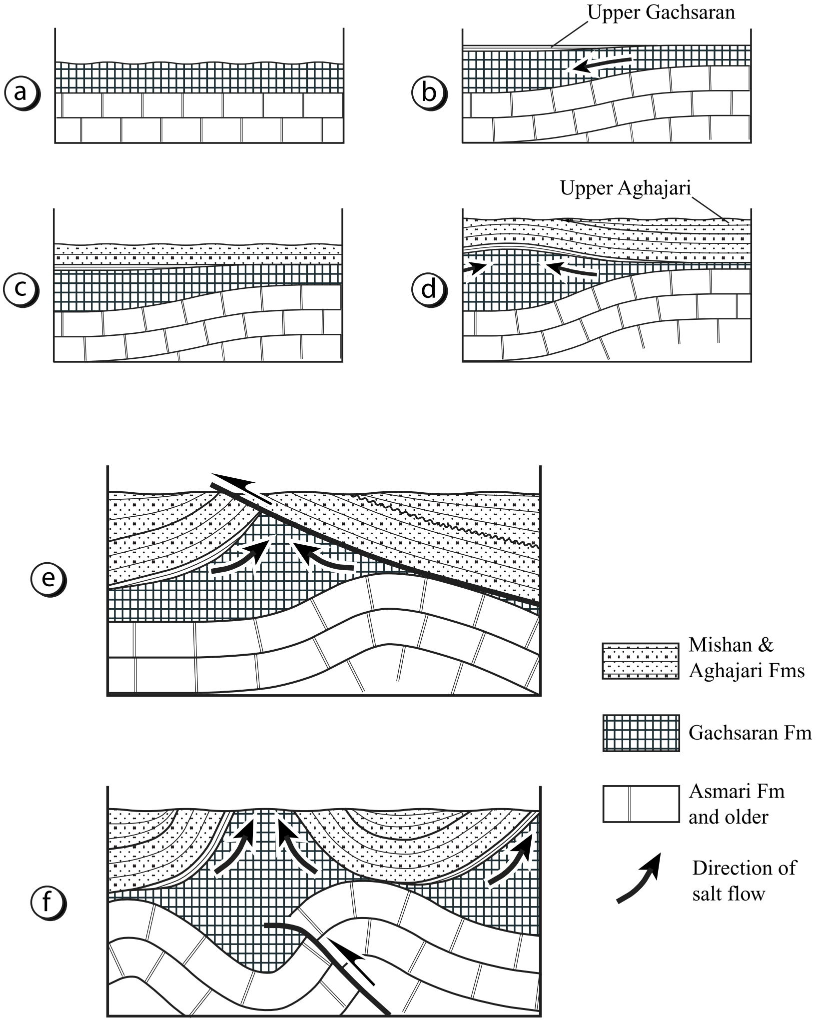


Fig. 6. Conceptual kinematic model explaining the two-step migration of Gachsaran salt. A, initial deposition; B, first folding step and coeval migration of the salt towards the intervening synclines during the deposition of the Upper Gachsaran; C, deposition of Mishan and Lower Aghajari Fms; D, second step of folding during the deposition of the Upper Aghajari Fm. With coeval diapiric movement of the salt; E and F, late folding stages with development of thrust-faults.

3. Folding between two detachments, role of intermediate and secondary detachments: examples from the Izeh zone

Dahlstrom (1969) emphasises that concentric folding implies the existence of detachment levels separating concentrically folded structural units (Fig. 10). The necessity for a lower detachment is always evident, but the role of the upper detachment is less frequently discussed (see Harrison and Bally, 1988; Bonini, 2003), because, in many places, this 'upper detachment' does not exist and corresponds simply to the interface between rock and air/water. The Izeh zone provides surface structures to support such a discussion.

The Izeh zone is situated in the Central Zagros between the High Zagros Fault to the northwest and the Mountain Front Fault to the southeast (Fig. 1). Due to erosion of the molasse, the competent group outcrops abundantly in the whole zone directly exposing a structural style characterised by 'ideal' parallel folds in which the layers follow a series of quasi-circular arcs. In the studied area, the Izeh zone is divided from north to south into the Darishk and Khami domains. From a tectono-stratigraphic point of view (Fig. 3), the main characteristic of the Darishk domain is the existence of an intermediate detachment located within the Kazdhumi Fm. of Albian age (Sherkati and Letouzey, 2004). This intermediate detachment does not exist in the Khami domain, where, instead, a lower intermediate detachment has been recognised within the Dashtak Fm. (Triassic) (Fig. 3). As we will show, the size of structures, which is the principal difference between the two sub-domains, is directly dependent on the position of the intermediate detachments.

Northeast of the town of Izeh, in the Darishk domain, the Kuh-e-Rig and Kuh-e-Dodurou structures (Fig. 11) form a pair of rounded anticlines defined by the Asmari limestone

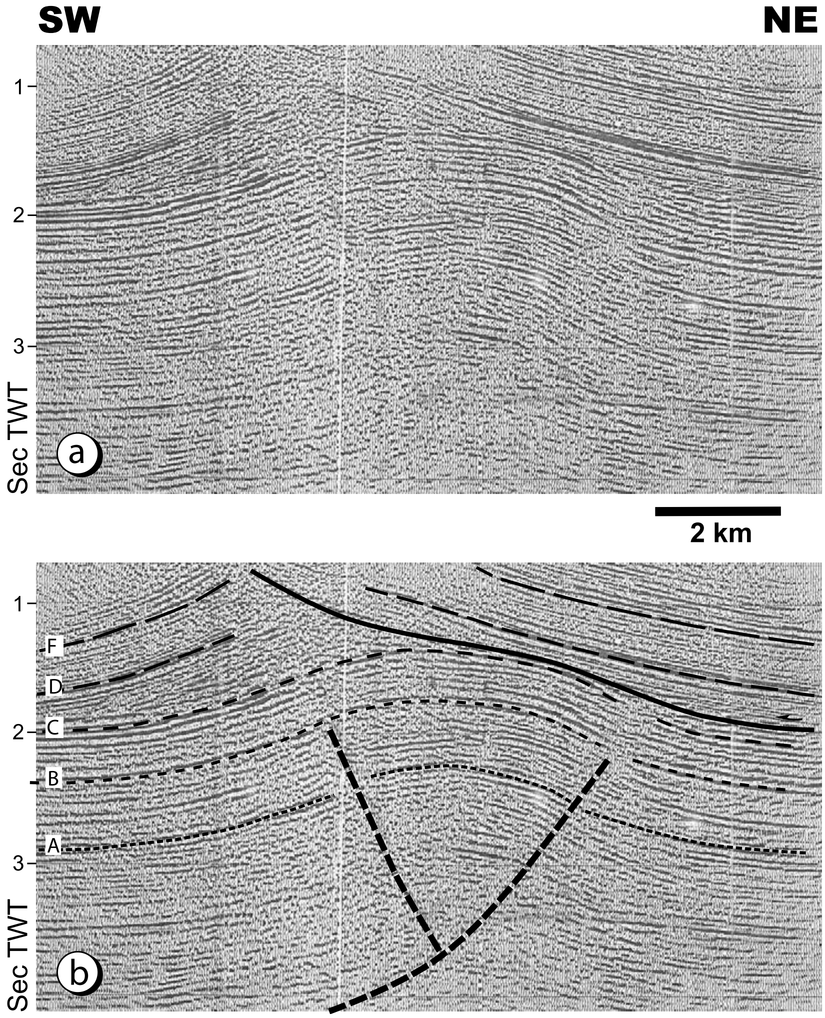


Fig. 7. Non-interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Ahwaz anticline (see location on Fig. 1). Vertical scale and seismic horizons are the same as in Fig. 4. At this stage, the incompetent and competent groups are completely decoupled. Note the development of the 'salt bulge' along the forelimb of the anticline and, by contrast, the thinning (or even absence) of the Gasharan Fm. along the backlimb and crest of the anticline. See Fig. 6E for the kinematic scenario.

and separated by a narrow isoclinal syncline cored by the lower Gachsaran Fm. For evident geometric reasons, the anticline pair was necessarily separated from the overlying rocks by a detachment zone in the presently eroded upper mobile group. The concentric mode of folding limits the thickness of the sedimentary sequence that can be folded together in the same structural unit (Goguel, 1952; Dahlstrom, 1969; Colman-Sadd, 1978). Thus, the Kuh-e-Rig and Kuh-e-Dudrou structures are also necessarily bounded by a lower detachment, although its precise location is difficult to assign. However, given the size of the anticlines, it is likely that the detachment situated at the base of the sedimentary pile is too deep to constitute this lower limit.

The Balout–Boland anticline (Fig. 12) situated 25 km farther south, but already in the Darishk domain, is a very tight chevron fold involving Sarvak limestone. Other similar anticlines have been observed in the area. Their shape requires that they are situated very close to the detachment active in this zone, which is most probably the Kazdhumi shales (Sherkati and Letouzey, 2004). It is interesting to note that the exposure of broad anticlines in association with narrow synclines (Fig. 11) or pinched anticlines (Fig. 12) with wide synclines appears to depend only on the level of erosion above the Kazdhumi detachment.

In the southern part of the Izeh zone (Khami domain, Sherkati and Letouzey, 2004), the Kazdhumi detachment is absent or less efficient. The net result is that the structures are considerably wider, suggesting a deeper detachment, either within the Dashtak Fm. (Fig. 3) or lower Palaeozoic beds (Sherkati and Letouzey, 2004). However, the structural style (concentric folding) remains unchanged with only greater radius of curvature explaining the more open geometry observed, for instance, in the Kuh-e-Sartal structure (Fig. 13).

A striking characteristic in all of these examples, is the absence or scarcity of thrust-faults: not only major thrust-faults controlling the geometry and kinematics of the folds, but also subsidiary faults, the so-called

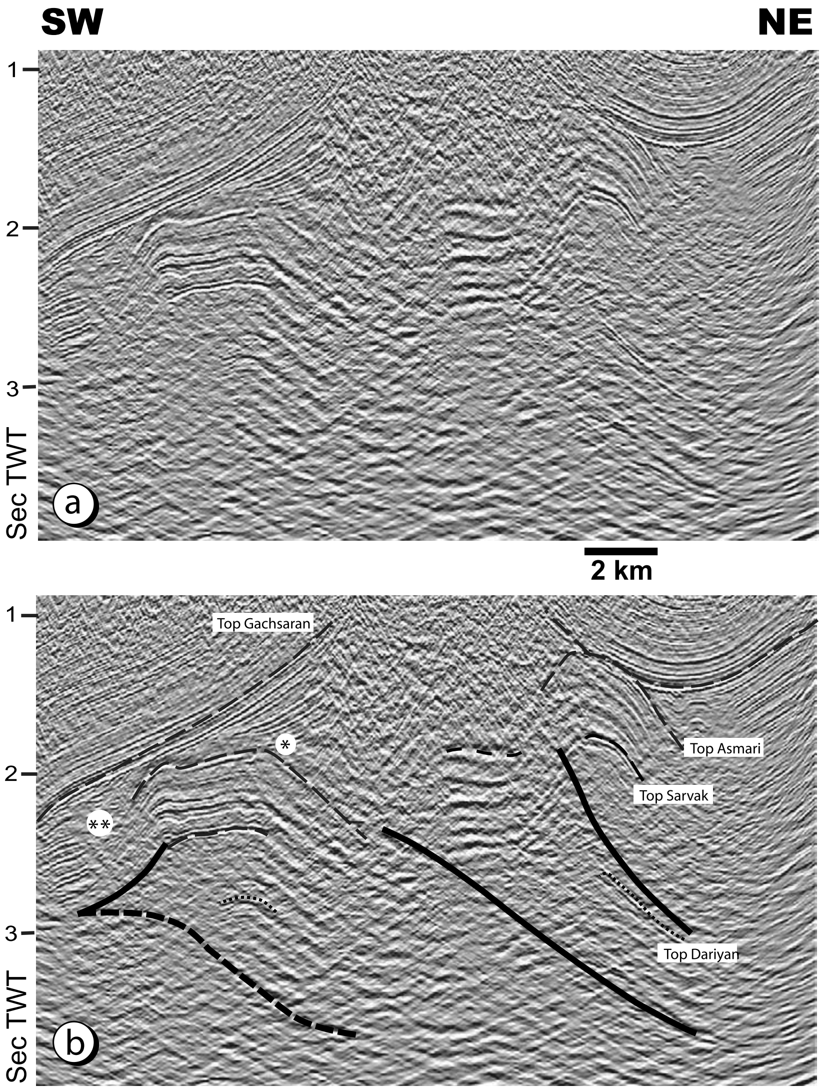


Fig. 8. Non-interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Parsi and Karanj anticlines (see location on Fig. 1). Vertical scale and seismic horizons are the same as in Fig. 4. Note the considerable accumulation of the Gachsaran Fm. within the salt bulge, leading to the development of an intervening surface anticline. Pinch outs of the Upper Gachsaran seismic reflectors (labelled by stars) indicate that folding in this area started in Middle Miocene times. Small 'rabbit ear' structure on the flank of the main anticline to the left shows involvement of Gurpi marls as a secondary décollement level. Deep forelimb thrusts cut through the carbonate platform rocks. See Fig. 6F for the proposed kinematic model.

'fold-accommodation faults' of Mitra (2002). Thus, the folds presented above are 'pure' detachment folds. As in the Dezful Embayment, continuing deformation resulted in the activation of secondary detachment levels. In particular, there are numerous field examples testifying to the role the Pabdeh–Gurpi marls play as a secondary detachment controlling the development of minor structures. Different cases can be distinguished:

(1) In some examples, the sense of shear along the secondary detachment is toward the anticlinal hinge and, consequently, opposite in both limbs of the anticline. This leads to the development of convergent drag folds often associated with small thrusts, the 'rabbit ear' structures of Dahlstrom (1970) and Letouzey et al. (1995) (Fig. 14).

(2) In more asymmetric anticlines, bed-parallel shearing along the backlimb is expressed by a flat thrust-fault propagating beyond the hinge and cutting through the steep forelimb (Fig. 15). Such structures mimic 'forelimb thrusts', but are linked to the activation of a secondary detachment and not to forward shear of the whole front limb.

The activation of the Pabdeh–Gurpi secondary detachment can also trigger the development of the gravity collapse structures recognised long ago by Harrison and Falcon (1934, 1935). Among these structures, the most spectacular and puzzling are certainly the so-called 'flaps' defined by Harrison and Falcon (1934). Following these authors, a flap is 'a part of limestone sheet, which has bent over backward without breaking' away from the crest of the

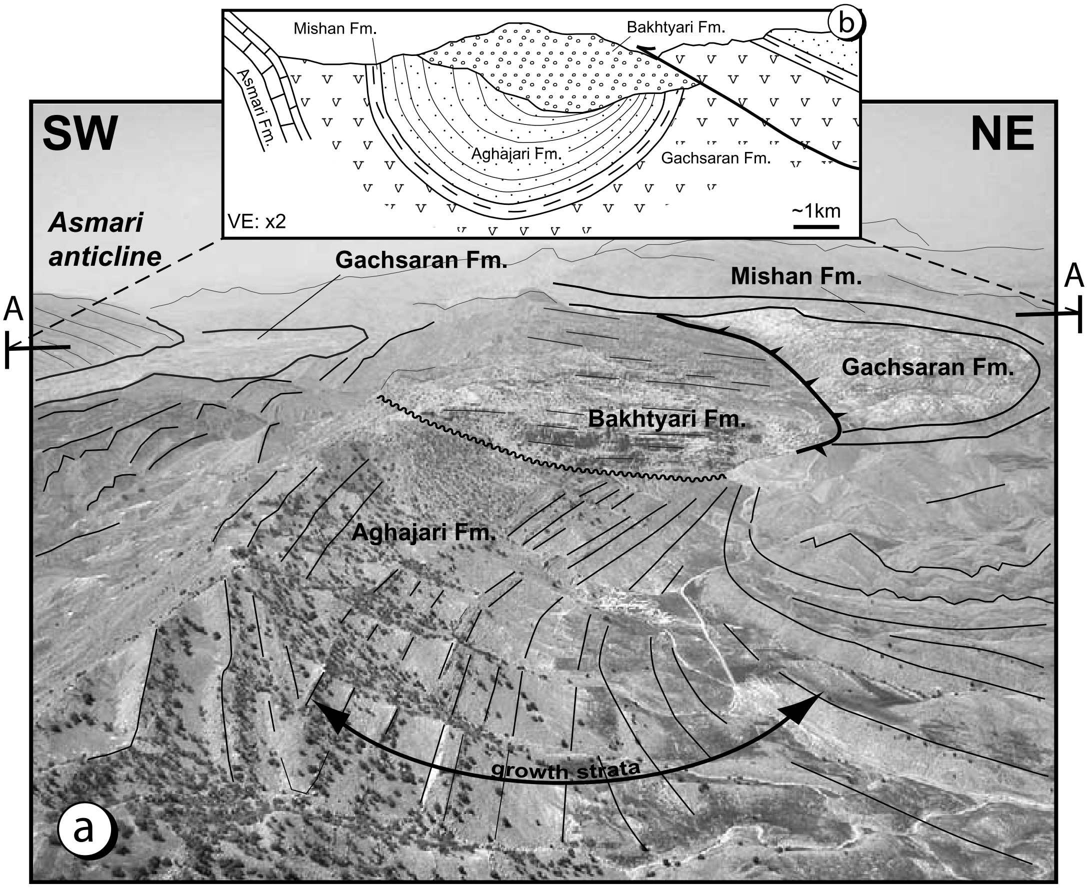


Fig. 9. (a) Photograph and (b) line drawing showing growth strata in upper Aghajari Fm., which is unconformably overlain by Bakhtyari conglomerates and subsequently over-thrust by the Gachsaran Fm. This thrust has been directly observed on the field, allowing the exclusion of the possibility that the Gachsaran salt has simply spread by gravity over the Bakhtyari Fm. It shows that folding and faulting are not coeval. Some 20 km south-west of Izeh city, north-east of Kuh-e-Asmari anticline (looking NW, see Fig. 1 for location map).

anticlines until a completely overturned attitude is reached. We have observed such flaps in the Asmari limestone situated in front of the Tanowsh anticline (Fig. 16). Harrison and Falcon (1934, 1935) interpreted flaps as purely gravitational structures resulting from the collapse of oversteepened flanks into eroded valleys. Following De

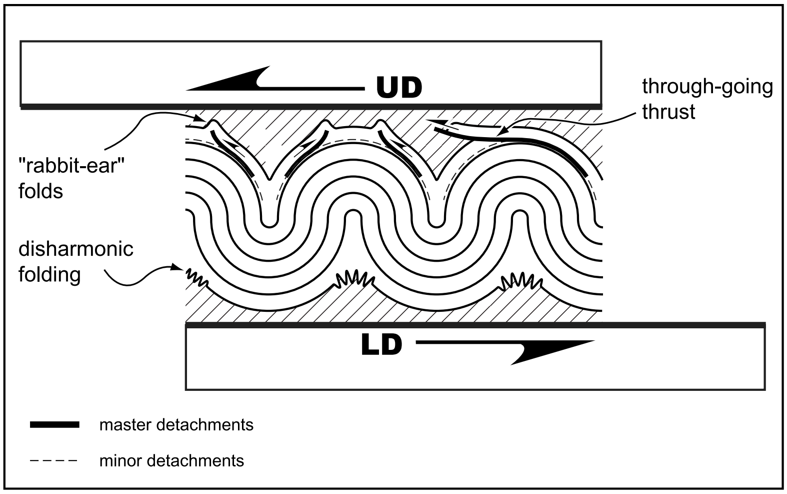


Fig. 10. Diagram illustrating why geometrically a train of concentric folds must be separated from the rocks above and below it by a detachment horizon (LD, lower detachment; UD, upper detachment) (modified from Dahlstrom, 1969). We have modified Dahlstrom's ideal model with secondary features such as 'rabbit ears' folds and through-going thrusts.

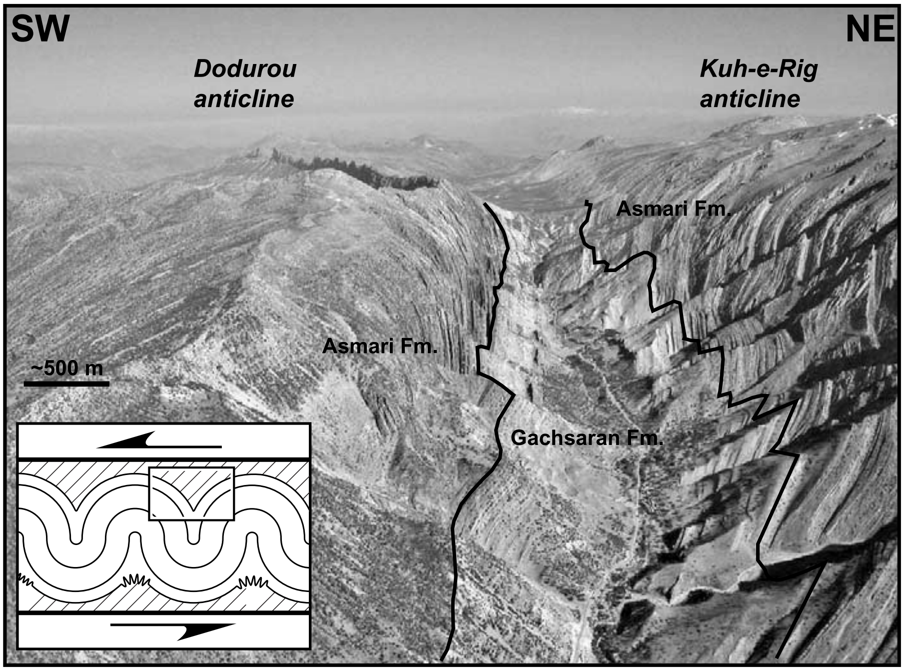


Fig. 11. Interpreted photograph showing an isoclinal syncline cored by the Gachsaran Fm. Some 10 km south of Lurdegan city (looking NW, see Fig. 1 for location map). Inset illustrates the structural position of the fold with respect to Dahlstrom's (1969) ideal model.

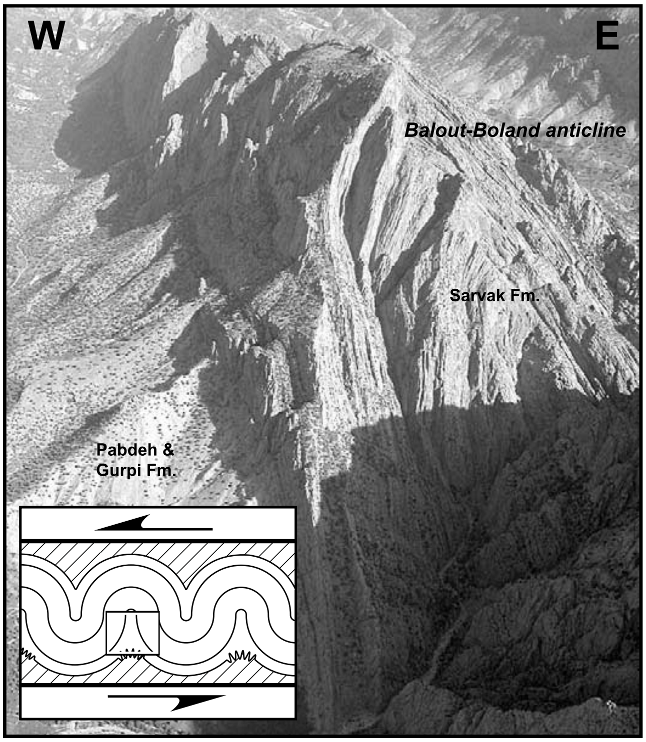


Fig. 12. Photograph showing a chevron type anticline in Cenomanian carbonates (Sarvak formation, 3.5 km wavelength). Its shape indicates that the underlying Albain shales (Kazhdumi formation) act as an efficient décollement level. Some 50 km SE of Lurdegan city (looking NW, see Fig. 1 for location map). Inset illustrates the structural position of the fold with respect to Dahlstrom's (1969) ideal model.

Sitter (1956), we think that they rather originated during folding. More precisely and following St Bezar et al. (1998), we consider that flaps are recumbent synclines formed by collapse above incompetent intervals along the limbs of anticlines and accentuated during the migration of the synclinal hinges. In any case, the development of a flap structure requires the disruption of the Asmari layers involved in the structure (Fig. 17). This disruption could have been triggered by erosion, suggesting that, in the Izeh zone, the folding process was active in sub-aerial conditions. This situation contrasts with the one observed in the Dezful Embayment (see above), where onlaps observed on both sides of the anticlines (Figs. 4 and 6) suggest that fold uplift rate was slower than regional subsidence.

4. Late basement control on the folding process: example from the Eastern Zagros

Due to the current seismic activity in the ZSFB (Berberian, 1995), it is generally acknowledged that the crystalline basement is involved in the deformation, in particular along the Mountain Front and High Zagros faults (Fig. 1). Another argument supporting the involvement of the basement is the strong difference in the level of exposure of the sedimentary cover across these major faults. This is particularly evident in the Central Zagros, between the Dezful Embayment and the Izeh zone, where the Mountain Front Fault is marked by a considerable step (about 3 km) in the elevation of the same formation (Sherkati and Letouzey, 2004). A similar step exists between the High Zagros, where

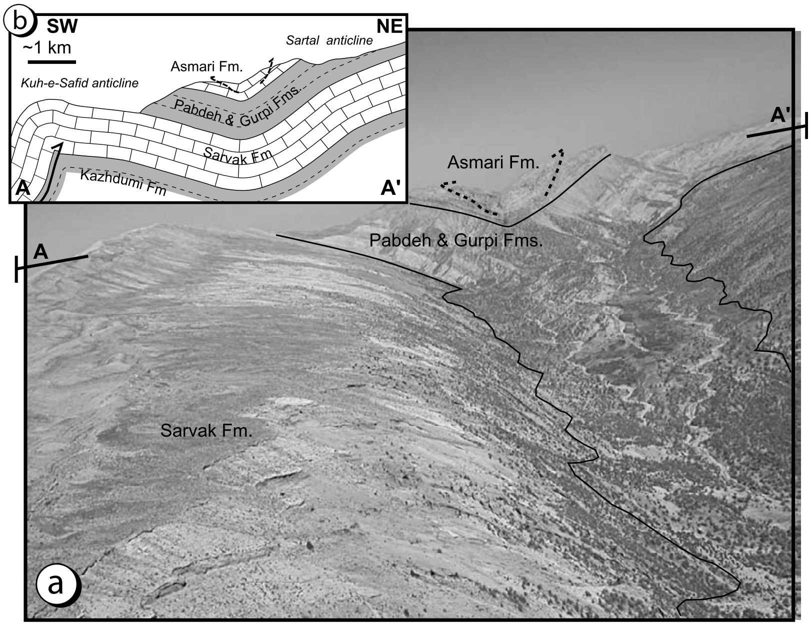


Fig. 13. (a) Photograph and (b) line drawing showing very wide structures (6–10 km wavelength) in Cenomanian carbonate (Sarvak formation) with minor effect of underlying Albian shales as intermediate décollement level (visible on the southern flank of Safid anticline). Their shape suggests a deeper intermediate décollement level, probably in Triassic evaporites (Dashtak formation). Some 60 km south-west of Lurdegan city (looking NW, see Fig. 1 for location map).

Palaeozoic rocks crop out, and the Izeh zone, where the oldest rocks exposed are of Jurassic age (Sherkati and Letouzey, 2004). However, because in the Central Zagros the basement faults are blind and strike parallel to the main surface structures, their timing and precise role in the deformation are very difficult to assess. In the Bandar Abbas area in south-eastern Zagros, by contrast, the basement faults cut across previous detachment folds obliquely (Molinaro et al., 2005a) giving rise to spectacular interference structures that are very informative.

The Eastern Zagros differs from O'Brien's (1950) general mechanical stratigraphy (Fig. 3) in the following

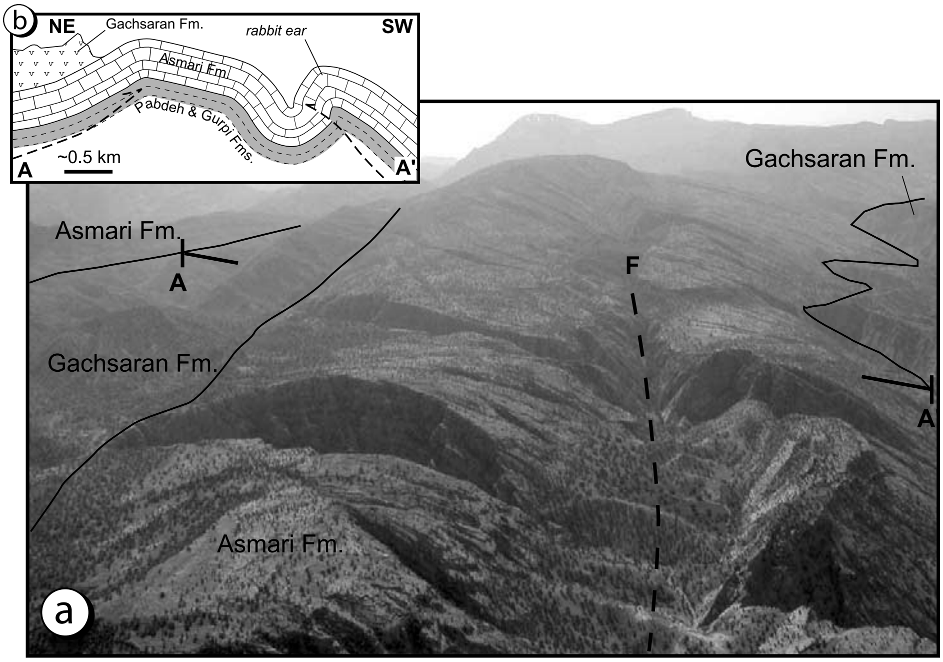


Fig. 14. (a) Photograph and (b) line drawing showing an anticline in Oligo-Miocene carbonates (Asmari Fm.). Small rabbit ear structure in southern flank shows shearing along the intermediate décollement level (Eocene marls, Pabdeh Fm.) toward the hinge of the main anticline. Some 35 km south-east of Izeh city (looking SE, see Fig. 1 for location map). See Fig. 10 for the conceptual model.

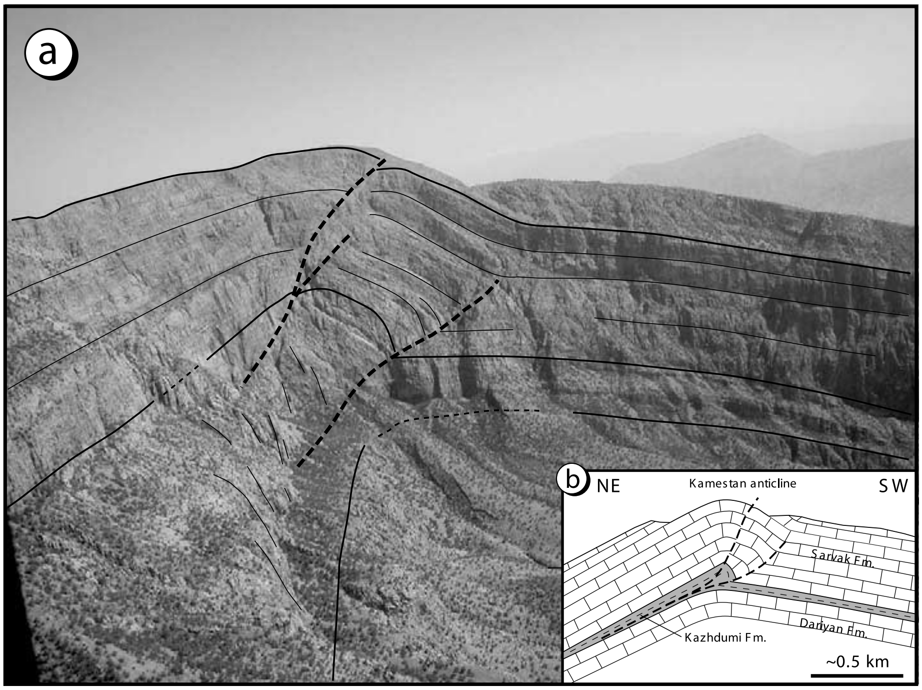


Fig. 15. (a) Photograph and (b) line drawing showing Kamestan anticline in Cenomanian carbonate (Sarvak Fm.). This structure illustrates a forelimb thrust (‘through-going thrust’, Fig. 10) at an initial stage of development with activation of the Kazhdumi shales as an intermediate décollement level.

characteristics: (1) a thick and very efficient lower mobile group (Hormuz salt), partly extruded via diapers, (2) the absence of efficient intermediate detachments within the competent group and (3) an upper mobile group represented by the Mishan marls (the Gachsaran salt being absent) (Fig. 3). This upper detachment seems to have acted as an upper flat connected through ramps to the Hormuz salt (Molinaro et al., 2005a), but does not appear efficient enough to completely decouple the deformation above and below. In other words, in the Eastern Zagros, the competent group and the overlying molasse are folded harmonically in very broad anticlines. Mesozoic or older rocks are exposed in the cores of the anticlines, whereas molasse and Bakhtyari conglomerates are preserved in the synclines. Secondary detachments, located in the Razak and Gurpi Fms, are responsible for spectacular collapses of the overlying Guri and Jahrum limestones, respectively (Figs. 3 and 18). However, flaps as in the Izeh zone have not been observed in the Eastern Zagros.

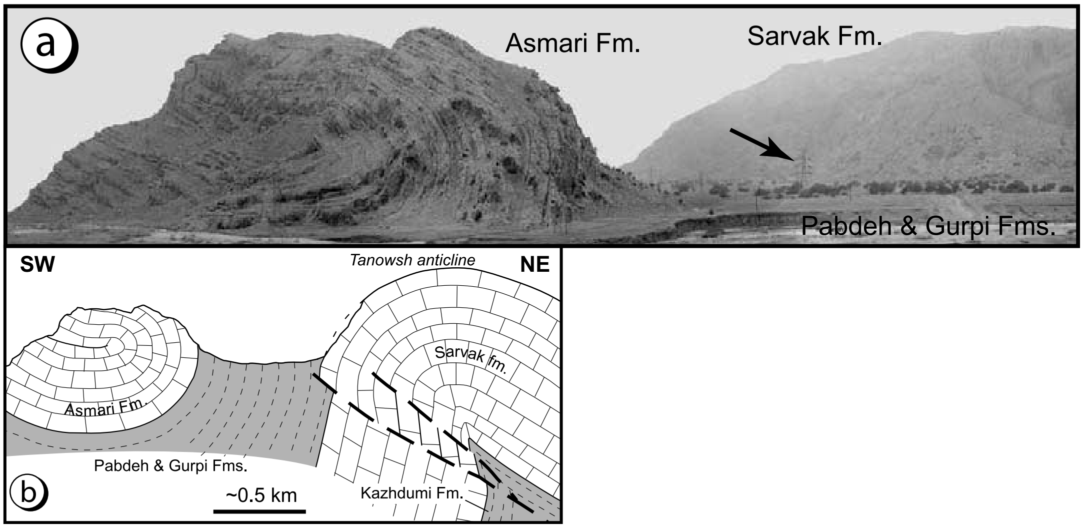


Fig. 16. (a) Photograph and (b) line drawing showing a recumbent syncline in Oligo-Miocene carbonate (Asmari formation). Some 15 km south-east of Izeh city (looking NW, see Fig. 1 for location map). Such structures were interpreted as gravity collapse structures and named ‘flaps’ by previous workers (Harrison and Falcon, 1934). In our interpretation, flaps are born by collapse above incompetent levels along the limbs of anticlines and accentuated during migration of the synclinal hinge (see Fig. 17 for the proposed kinematic scenario). Its development could have been triggered by erosion of the Asmari carbonate.

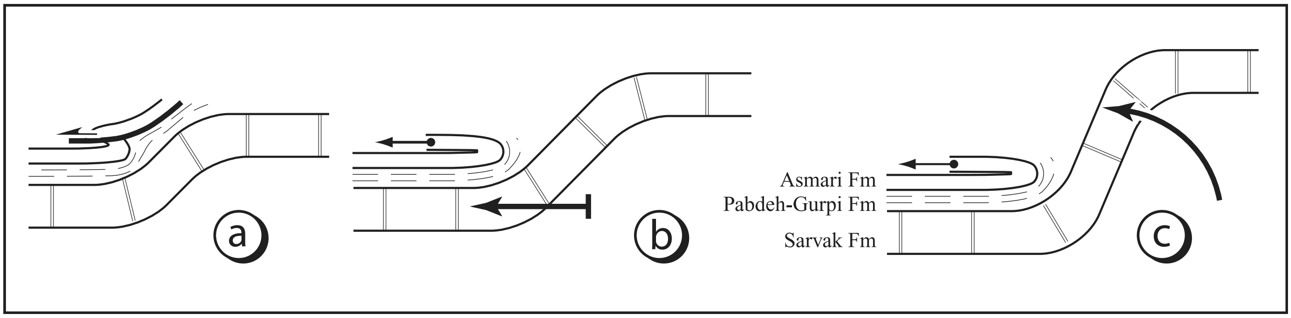


Fig. 17. Conceptual kinematic model explaining the development of a flap of eroded Asmari in front of a growing anticline. A, initial stage characterised by collapse along the front of the anticline; B, flap development by rolling up in front of a migrating hinge; C, limb rotation and progressive blockage of the forelimb; D, final stage (compare with Fig. 16).

In order to discuss the role of the basement, we will focus on one of the three giant en échelon structures (Jain, Faraghun and Kuh-e-Khush anticlines; Fig. 19a) extending NW–SE in the area north of the town of Bandar Abbas (Molinaro et al., 2005a). These structures, which belong to the High Zagros belt, overlie segments of the High Zagros Fault. In map view, the Kuh-e-Khush anticline mimics a butterfly shape (Fig. 19b). This pattern results from a two-step evolution in which a late basement fault cut through an already formed detachment fold (Fig. 19c) (Molinaro et al., 2005a).

The first step was thin-skinned in style and corresponded to the development of large detachment folds over the Hormuz detachment. Immature examples of such detachment folds can be observed south of the Mountain Front Fault. The studied region forms the eastern 'limb' of the Fars Arc (Fig. 1), the shape of which is primarily controlled by the extent of the basal detachment (Molinaro et al., 2005a). In this context, the ENE–SSW trends of the folds result from a counter-clockwise rotation coeval with the propagation of this detachment. This first thin-skinned step is overprinted by E–W basement faults, which are currently active as defined by the strong seismicity (Talebian and Jackson, 2004).

A cross-section through the Kuh-e-Khush anticline (Fig. 19d) suggests that the basement fault (i.e. the High Zagros Fault) initially connected with the upper mobile group (Mishan marls), as indicated by the frontal triangle zone, but subsequently cut through the crest of the anticline at a high angle. This final stage resulted in a monoclinal structure culminating at 2400 m.

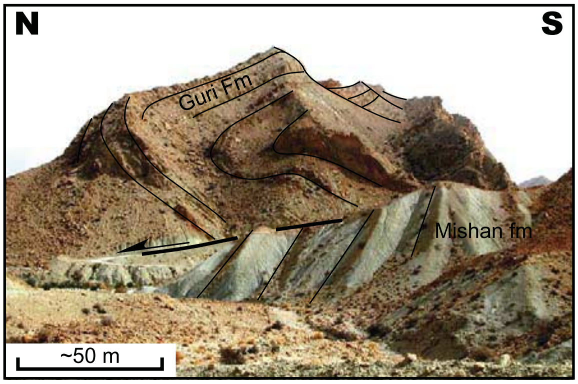


Fig. 18. Photograph of a gravity collapse structure on the northern limb of one of the larger anticlines in the Bandar Abbas area. Location in Fig. 1.

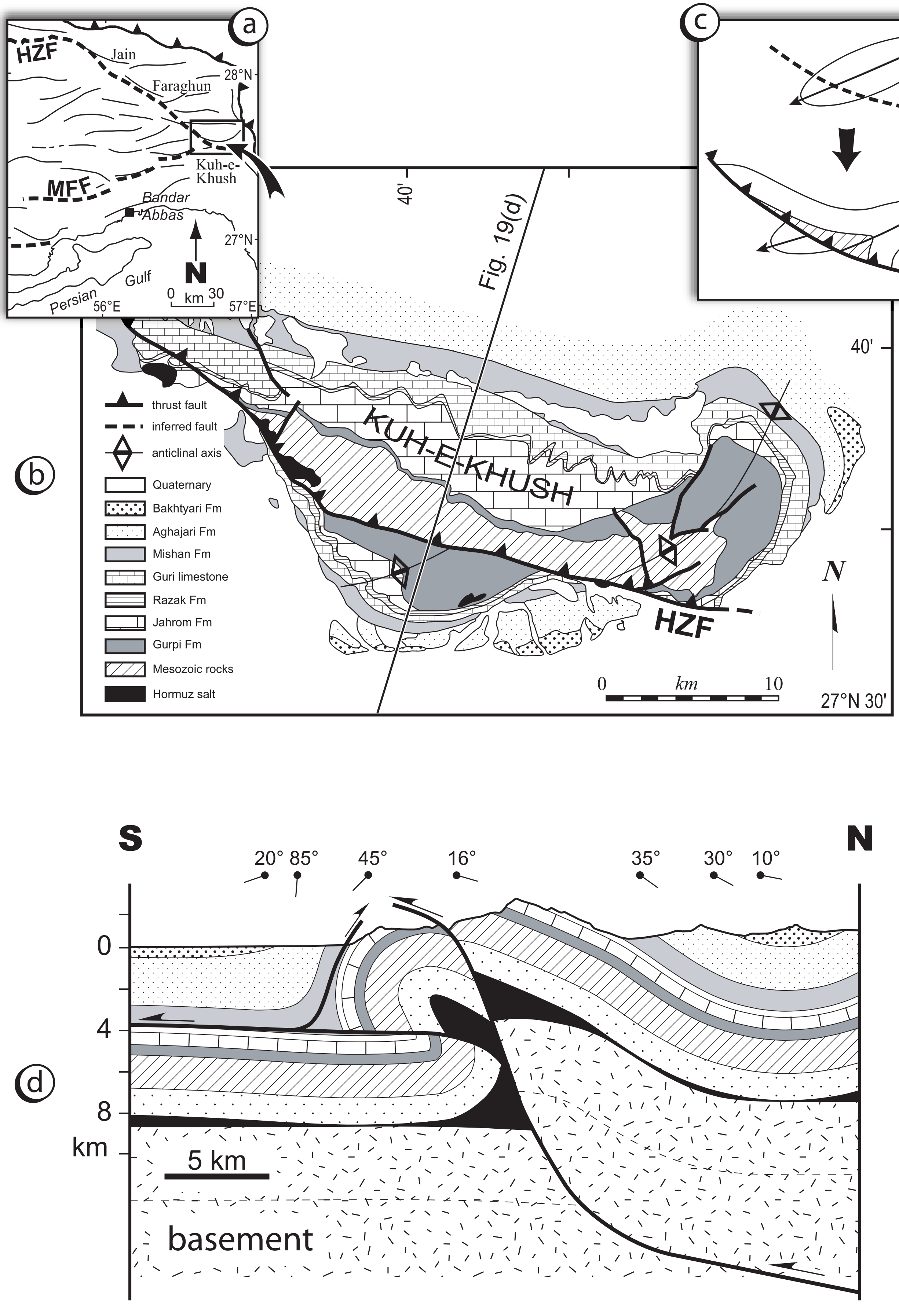
It is not certain that all of the thrust-faults are directly or indirectly linked to basement faulting. A possibility is that some of them represent an extreme evolution of detachment folding related to a complete depletion of the salt at the base of the synclines and their subsequent 'touchdown' upon the basement. At any rate, the observations establish that faulting occurred late in the Zagros deformation and commonly after the deposition of the Bakhtyari conglomerates.

5. Discussion

The different examples presented above allow us to propose a general scenario for the development of the Zagros detachment folds.

First of all, we demonstrate that folding in the Zagros occurred in discrete steps rather than as a continuous process, in agreement with Hessami et al.'s (2001) conclusions. In the Dezful Embayment, a first step (pre-Upper Gachsaran) is shown by the early migration of the Gachsaran salt from the crests of incipient anticlines towards intervening synclines. The mechanisms responsible for this early migration of the Gachsaran salt are very different from the ones explaining the mobility of the Hormuz salt or the second step of Gachsaran salt migration. In the first case, we have to invoke flow by gravity along the structural surface of the growing anticline, whereas, in the second case, diapirism played an essential role in the process, as classically understood (Fig. 6). This difference is very important and is the key to understanding the particular geometry known in the Dezful Embayment since O'Brien's (1957) work and characterised by superficial synclines jammed against the crests of underlying anticlines (Fig. 8).

A second step in the development of folds in the studied areas is demonstrated by growth strata observed in the upper


a
HZF
Jain
Faraghun
28°N
Kuh-e-Khush
MFF
Bandar Abbas
27°N
N
Persian Gulf
56°E
0 km 30
57°E
c
b
40'
Fig. 19(d)
40'
thrust fault
inferred fault
anticlinal axis
Quaternary
Bakhtyari Fm
Aghajari Fm
Mishan Fm
Guri limestone
Razak Fm
Jahrom Fm
Gurpi Fm
Mesozoic rocks
Hormuz salt
KUH-E-KHUSH
HZF
N
0 km 10
27°N 30'
d
S
N
20° 85° 45° 16° 35° 30° 10°
0
4
8
km
5 km
basement

Aghajari Fm., which, according to recent magnetostratigraphic studies from the northwest Dezful, was deposited during the Upper Miocene (Homke et al., 2004). This step ended with the widespread deposition of the coarse conglomerates of the Bakhtyari Fm. The third and last step folded and faulted the Bakhtyari Fm.

In the Zagros, the control of the fold wavelength by the depth of the lower detachment (Eastern Zagros), by the thickness between the lower and upper detachments (Dezful Embayment and Khami domain of the Izeh zone) or by the thickness between the intermediate Kazhdumi and upper detachment (Darishk domain of the Izeh zone) is evident from the map (Fig. 1). Along cross-sections through the Dezful Embayment and the Izeh zone (Sherkati and Letouzey, 2004), the wavelength decreases from the foreland to the hinterland. Such a pattern is opposite to the one usually observed in fold-thrust belts, where the decrease in the wavelength toward the foreland results from a staircase geometry of the thrust-faults. The reason that Central Zagros is so different is that folds in the Izeh zone are detached on an intermediate décollement which is absent in the Dezful Embayment. In addition, the detachments are disconnected from each other or are only connected at a very late stage of evolution. In other words, the folds are not ramp related.

We have presented different arguments showing that both hinge migration and limb rotation occur during folding. This is in agreement with models of detachment folding proposed by former authors: Dahlstrom (1990), model 3 of Poblet and McClay (1996) and Mitra's (2003) unified kinematic model of detachment folds. A first line of evidence comes from the comparison between different sections showing that fold development is accompanied by increasing wavelength and limb dip of the folds. The development of second-order structures, such as flaps (Figs. 16 and 17), furnishes strong evidence for hinge migration. Finally, the late activation of secondary detachments (Figs. 7 and 12) and development of forelimb thrusts (Figs. 8, 15 and 17) suggest that limb rotation was mostly active during the final stages of folding. This could imply blockage of the folding process as a consequence of merging of the hinges of two adjacent synclines or, more drastically, 'touchdown' against the basement.

In the studied areas, basement faults only developed late in fold evolution (Sherkati and Letouzey, 2004; Molinaro et al., 2005a) corresponding to the third step of our scenario. This is clearly demonstrated in the Eastern Zagros, where out-of-sequence basement thrusts cut at oblique angles through earlier thin-skinned structures (Fig. 19). However, the reason for this abrupt change from thin-skinned to thick-skinned tectonic style remains a matter of debate. Molinaro et al. (2005b) suggest a possible relationship with slab break-off below the Zagros orogenic belt and correlative uplift. This hypothesis, which must be tested, gives a consistent explanation for the following processes: (1) regional uplift throughout the Zagros, (2) complete change in the sedimentary environment from fine-grained siliciclastic rocks to Bakhtyari conglomerates and (3) activation and propagation of basement faults into the folded cover.

Fig. 19. The Kuh-e-Khush anticline in the Bandar Abbas area. (a) Location map (see also Fig. 1); (b) detailed geological map based on existing maps (NIOC, 1999), SPOT satellite image and authors' fieldwork. Notice the obliquity between the HZF basement fault and the axial trace of the original detachment fold; (c) two-stage evolution for the Kuh-e-Khush anticline as suggested by its map pattern; (d) balanced cross-section through the Kuh-e-Khush anticline. Line of section in B.

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