The Central Zagros fold-thrust bemt (Iran) : New insights from seismic data field observation and sandbox modelling

S. Sherkati, J. Letouzey, Dominique Frizon de Lamotte

To cite this version:

S. Sherkati, J. Letouzey, Dominique Frizon de Lamotte. The Central Zagros fold-thrust bemt (Iran) : New insights from seismic data field observation and sandbox modelling. Tectonics, American Geophysical Union (AGU), 2006, 25 (4), pp.TC4007. 10.1029/2004TC001766 . hal-00069591

TECTONICS, VOL. 25, TC4007, doi:10.1029/2004TC001766, 2006

Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modeling

S. Sherkati,[1] J. Letouzey,[2] and D. Frizon de Lamotte[3]

Received 10 November 2004; revised 27 January 2006; accepted 29 March 2006; published 20 July 2006.

[1] We present five generalized cross sections across the central Zagros fold-and-thrust belt (Iran). These sections show that the fold geometry varies significantly both horizontally and vertically. The style is closely related to the changes in the mechanical behavior of the lithostratigraphic horizons and, in particular, to the presence of intermediate décollements within the sedimentary pile. Restoration of the sections shows amounts of shortening of the same order from one section to the other. However, it appears to be unequally distributed, suggesting variations in basal décollement shear strength. Analogue modeling has been performed to systematically investigate the effect of an intermediate décollement level at different depths on the style of folding. The models demonstrate that the position of intermediate décollements is an important factor controlling both structural style and fold wavelength. Models with shallow intermediate décollement show regularly and widely spaced anticlines. In these models, the fold wavelength depends directly on the thickness of the dominant competent layer and short-wavelength superficial structures mask broad anticlines at depth. Models with deep intermediate décollement are characterized by the rapid propagation of deformation (with small rate of shortening) along this décollement influencing localization of forthcoming anticlines in the upper levels. Such propagation favors the development of duplexes and multiwavelength folds. On this basis, fold kinematics in central Zagros is discussed using the variation of structural style along different folds as an indicator of the sequence of deformation. Detachment folding is the main folding style at least for the initial stages of deformation and thrust faults developed only at later stages. Some of these faults, branched on décollement levels, express the progression of folding, whereas others are linked to late basement faults cutting through early structures. In general, the décollement levels are activated sequentially from deeper horizons to shallower ones. However, in one case (Gachsaran décollement) a shallow décollement is activated during the early stages of folding and then abandoned during the subsequent evolution. **Citation:** Sherkati, S., J. Letouzey, and D. Frizon de Lamotte (2006), Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modeling, *Tectonics*, *25*, TC4007, doi:10.1029/2004TC001766.

1. Introduction

[2] The Zagros fold-and-thrust (ZFTB) is currently the site of intense geological studies, which led to the publication of generalized balanced cross sections across the whole chain [*Letouzey et al.*, 2002; *Blanc et al.*, 2003; *McQuarrie*, 2004; *Letouzey and Sherkati*, 2004; *Sherkati and Letouzey*, 2004; *Molinaro et al.*, 2005a]. Following *Colman-Sadd* [1978], all these studies agree with a structural style dominated by detachment folding over a ductile lower décollement.

[3] Within the folded sedimentary pile, the presence of multiple secondary décollement levels complicates the fold geometry and explains the great difficulty to extrapolate a geometry at depth when subsurface data are lacking. As a matter of fact, *Falcon* [1969] mentioned the role of gravity tectonics in limestones and marls of the ZFTB in creating structural complexity at surface in places where the underlying structure is simple. Conversely, *O'Brien* [1957], *Edgell* [1996], and *Sherkati et al.* [2005] show through subsurface data, that simple surface geometries can mask complexity at depth.

[4] The role of basement faults during the building of the ZFTB remains a matter of debate. The seismic activity [*Berberian*, 1995; *Talebian and Jackson*, 2004] shows that the basement is currently involved in the deformation. However, *Molinaro et al.* [2005a] and *Sherkati et al.* [2005] demonstrate that the basement control on the surface structures only occurred at a late stage in the tectonic history. In other words, the current thick skinned style of Zagros folding succeeded a more general thin-skinned evolution.

[5] In this general frame, the aims of the present study can be summarized as follows: (1) to establish a comprehensive structural (mechanical) classification of the sedimentary pile in central Zagros; (2) to present new balanced cross sections across the central Zagros; (3) to describe the influence of intermediate décollement levels on structural style (for this purpose, we have obtain new insights from

---

[1] National Iranian Oil Company, Tehran, Iran.
[2] Institut Français du Pétrole, Rueil-Malmaison, France.
[3] Département des science de la Terre et Environnement, CNRS UMR 7072, Université de Cergy-Pontoise, Cergy, France.

0278-7407/06/2004TC001766

some analogue modeling experiments); and (4) to present kinematic hypotheses for fold development in Zagros.

2. Geologic Setting

[6] The Zagros fold-and-thrust (ZFTB) is a NW-SE trending orogenic belt, which extends over about 2000 km from Turkey through southwest Iran down to the strait of Hormuz. It is bound to the north by the Main Zagros Fault, interpreted as the suture zone of the Neo-Tethys ocean [*Ricou*, 1971] (Figure 1). Mainly on the basis of morphology, the ZFTB is divided in two adjacent belts: the High Zagros Belt (HZB) and the Zagros Simply Folded Belt (ZSFB) separated by the High Zagros Fault (HZF) (Figure 1) [*Stocklin*, 1968; *Falcon*, 1974; *Berberian and King*, 1981; *Alavi*, 1991]. On the basis of lateral facies variations, the Iranian ZSFB is divided into different tectonostratigraphic domains that are from SE to NW: The Fars province or eastern Zagros, the Izeh zone and Dezful Embayment or central Zagros and finally the Lurestan province or western Zagros [*Motiei*, 1994, 1995] (Figure 1).

[7] In the ZFTB, compressive deformation began in the Late Cretaceous by ophiolite obduction [*Ricou*, 1971]. Subsequent folding and thrusting are related to the ongoing collision of the Arabian plate with central Iran, which began by Oligocene–early Miocene along the Main Zagros Fault (Figure 1) [*Stocklin*, 1968; *Falcon*, 1969; *Berberian and King*, 1981]. The deformation front propagated progressively southwestward [*Hessami et al.*, 2001] and attained its current position along the shore of the Persian Gulf in Plio-Pleistocene times. The thick (6 to 12 km) sedimentary sequence involved in the Zagros folds has recorded the complex tectonic history of this area. It presents all the stages of evolution of a basin from a platform or a passive continental shelf to a rift and various stages of deformation associated with ophiolite obduction and plate collision.

2.1. Preobduction Sedimentary Sequence

[8] The sedimentary cover is supported by a Panafrican basement, which is exposed in the western part of the Arabian shield [*Falcon*, 1969; *Husseini*, 1988; *Konert et al.*, 2001]. There is no exposure of the basement in Iranian Zagros. Information about its depth and composition are gained from seismic, gravity and aeromagnetic surveys and fragments brought to the surface by salt diapirs [*Kent*, 1970].

[9] It is generally considered that the evaporites of the Hormuz Formation (latest Proterozoic–Early Cambrian) were deposited directly on the basement. However, as in Oman [*Peters et al.*, 2003], seismic evidence from northern Fars suggests the existence of pre-Hormuz sediments in some parts of the Iranian Zagros [*Letouzey and Sherkati*, 2004]. Unfortunately, the nature and precise age of them remain unknown. The Hormuz Formation is only known from diapirs and salt plugs in the Fars province and High Zagros Belt. It was originally deposited in evaporitic basins related to the north trending rifting, which developed at that time in the Arabian plate [*Edgell*, 1996]. It consists of salt, anhydrite, dolomite, shale and volcanic rocks [*Harrison*, 1930; *Kent*, 1970, 1986; *Haynes and McQuillan*, 1974; *Ala*, 1974].

[10] Epicontinental deposits of Paleozoic age contain some sedimentary gaps and show thickness and facies changes (see review by *Berberian and King* [1981]) linked to salt and epeirogenic movements, basement faulting and eustatic sea level changes. Deposition of Permian clastics and carbonates on a truncated Silurian to Cambrian surface underlines a Hercynian unconformity, which is the most important sedimentary gap in the Zagros belt [*Szabo and Kheradpir*, 1978].

[11] Permian and Triassic subsidence and facies patterns are parallel to the Main Zagros Fault (Figure 1). Crust thinning along this line is taken as evidence of thermal arching, rifting and opening of the Neo-Tethys ocean [*Koop and Stoneley*, 1982; *Stampfli and Borel*, 2004]. Throughout most of the Upper Triassic to Lower Cretaceous, the Arabian platform remained a broad, stable shallow shelf dominated by carbonate and some evaporite deposition (Figure 2). Numerous transgressions and regressions during the Mesozoic explain the lateral variations in facies of carbonates from southeastern Zagros to the Lurestan province in the northwest of the Zagros belt [*Setudehnia*, 1978; *Van Buchem et al.*, 2003; *Taati et al.*, 2003].

[12] Sedimentation on the Arabian and Zagros platform during the Mesozoic (Figure 2) was also strongly influenced by the presence of deep-seated basement faults. *Murris* [1980] pointed out that the basement faults influenced the Early Mesozoic sedimentation in the Arabian plate and central part of the Persian Gulf. These structures had periods of important activity alternating with intervals of relative quiescence. In particular, they were most active from the late Turonian to the early Campanian [*Sherkati and Letouzey*, 2004]. These periods correspond to major changes in basin configuration marking the early stages of regional compressive activity [*Murris*, 1980; *Koop and Stoneley*, 1982; *Sherkati and Letouzey*, 2004].

2.2. Synobduction and Postobduction Sedimentary Sequence

[13] The configuration of the NE margin of the Arabian platform changed abruptly with the early Coniacian–late Santonian ophiolite obduction [*Ricou*, 1971; *Falcon*, 1974; *Berberian and King*, 1981; *Sherkati and Letouzey*, 2004; *Agard et al.*, 2005]. Field surveys especially in the inner part of the belt provide information allowing a better understanding of this long period of convergence. Figure 3 presents the main sedimentary events from late Cretaceous till Pleistocene time in northwest of central Zagros.

[14] Northeast of the Arabian plate, a flexural basin has been formed due to the overloading of continental crust by ophiolite obduction in the late Cretaceous. This basin is marked by accumulation of Campanian flysch supporting radiolaritic nappes (Figure 3, events A and B). The nappes emplacement was followed by an uplift, which provoked Paleocene erosion in the High Zagros Belt (Figure 3, event C). The origin of this uplift is uncertain. It could correspond to a lithospheric response to the Paleogene breakoff of the Neo-Tethys slab put forward by *Agard et al.* [2005]. It is

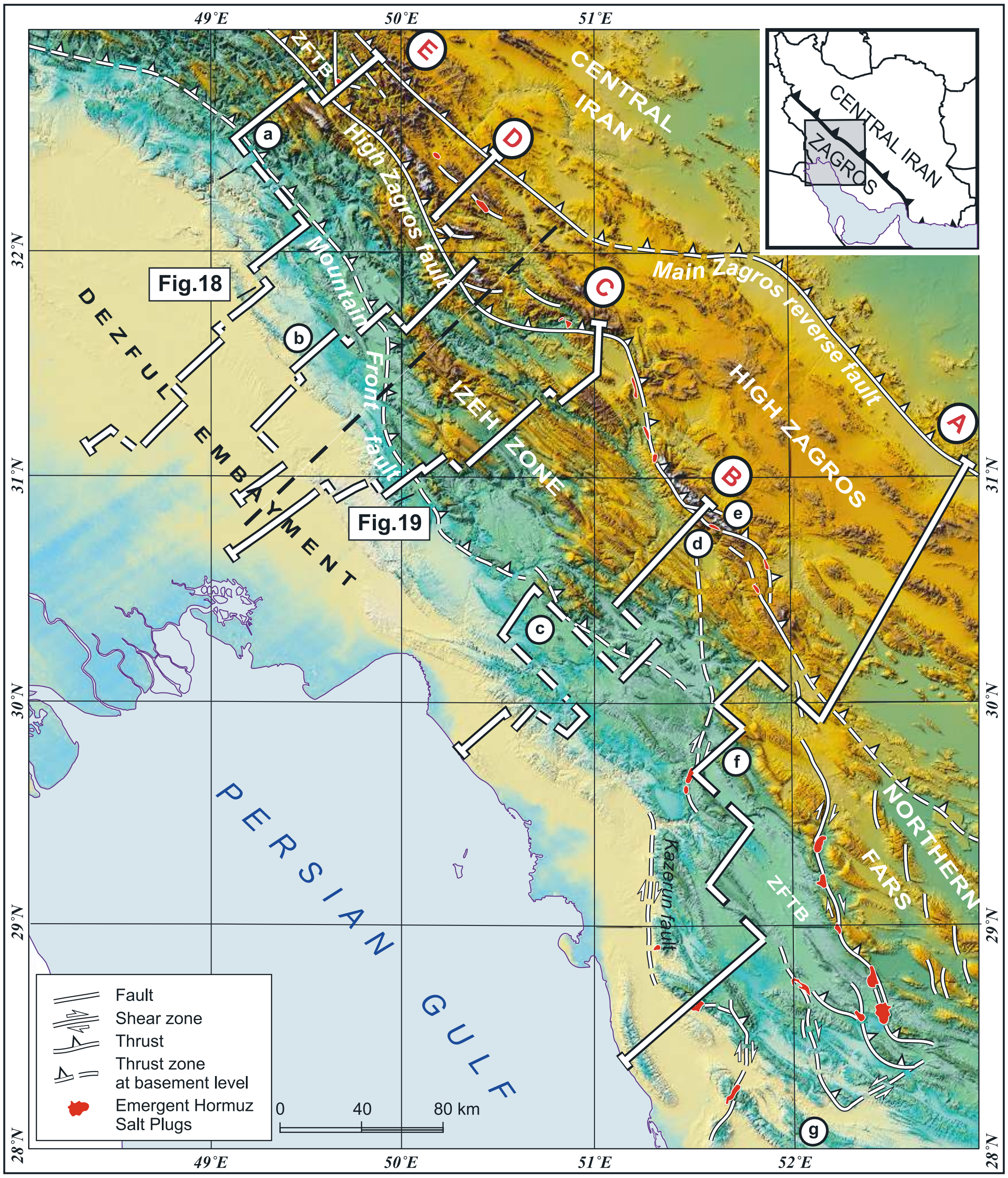

Figure 1. Topographic map and index map of the central Zagros showing the locations of the five structural transects A, B, C, D, and E (Figure 4) (white solid lines) and the location of the stratigraphic correlation chart (Figure 3) (black dashed line). The synthetic stratigraphic columns (a to g) of Figures 2, 16, and 17 are also located.

followed by a relatively calm period during the late Eocene (deposition of the Jahrom carbonate). During the late Oligocene–early Miocene, basinal facies (turbidite) developed in the northeast of the High Zagros area whereas elsewhere the limestones of the Asmari Formation were deposited (Figure 3, event D). This reveals the presence of a second flexural basin associated with the onset of continent-continent collision during the late Oligocene–lower Miocene (see review by *Agard et al.* [2005]). Erosion of the Oligocene and upper Eocene in some parts of the belt (Figure 3, events E and F) could be related to the development of a collision-related lithospheric flexure (bulge geometry) and linked activation of deep-seated basement faults.

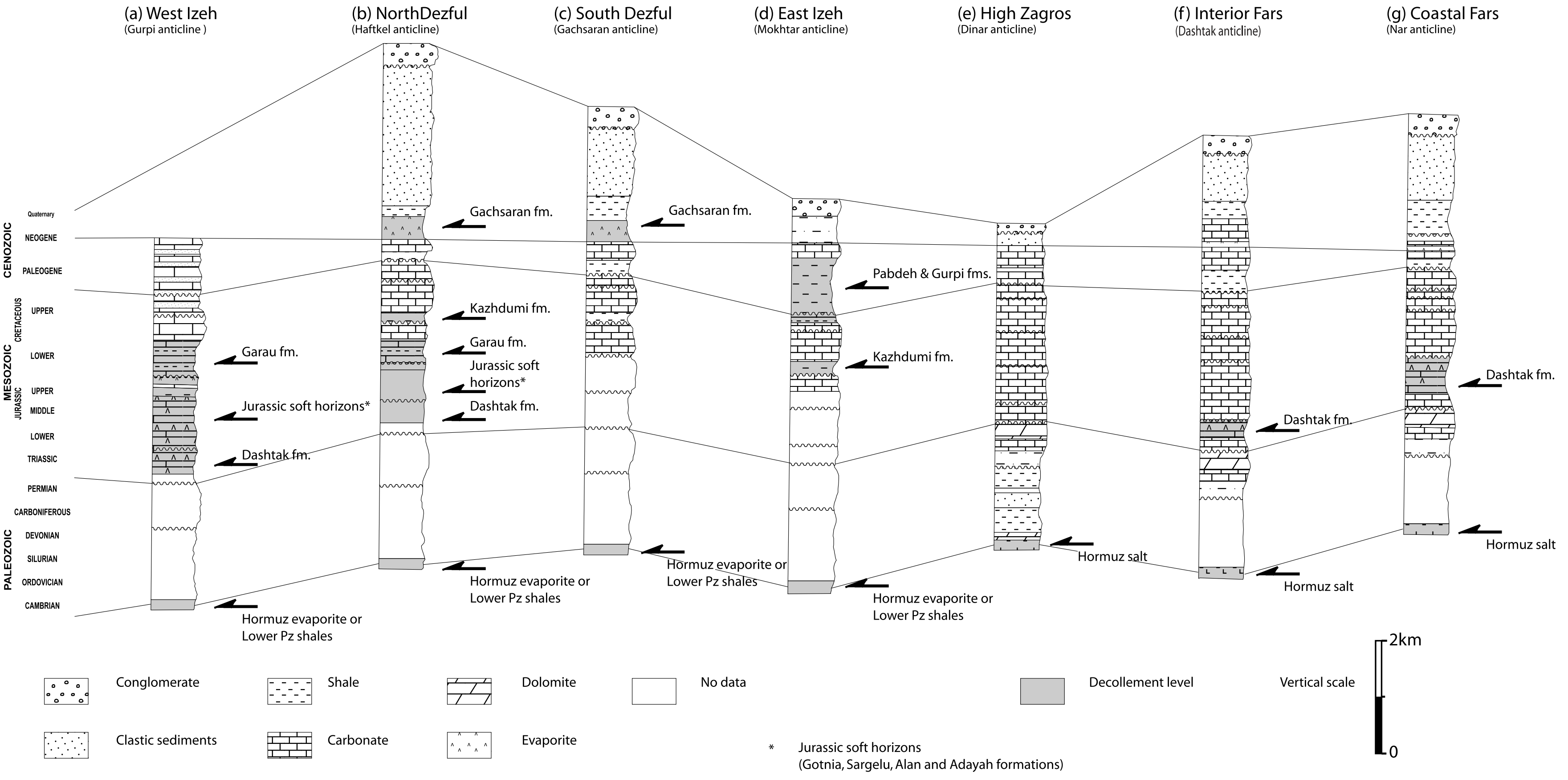

Figure 2. Generalized stratigraphic columns of the central Zagros fold-and-thrust belt. The sedimentary columns consist of several stiff layers that are separated by décollement levels (see Figure 1 for the location of each column).

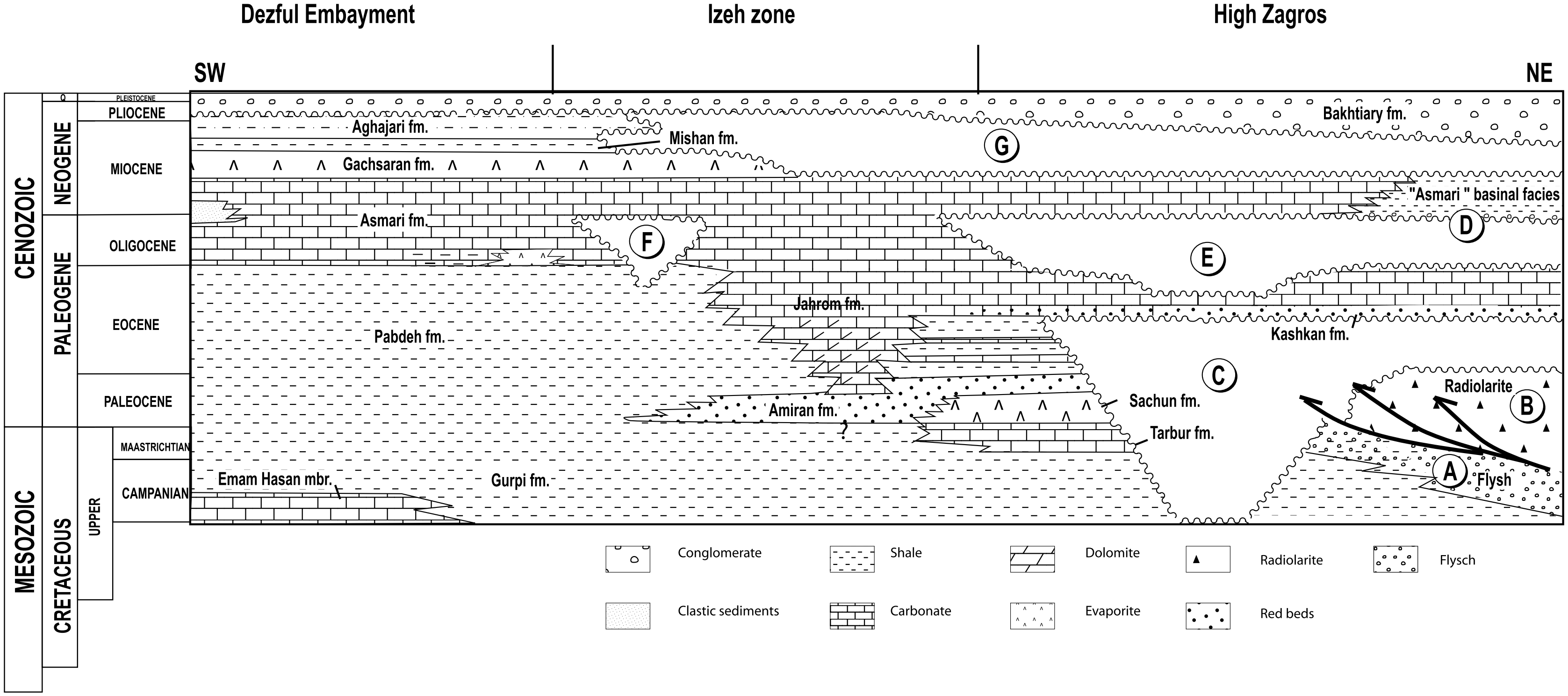

Figure 3. Correlation chart for the late Cretaceous and Tertiary (see Figure 1 for location) showing the main structural events that followed the ophiolite obduction. These events could be summarized as follows: Event A, deposition of Campanian flyschs in a flexural basin related to the ophiolite obduction over the northeastern margin of the Arabian plate; event B, emplacement of radiolaritic nappes coming from the Arabian margin and tectonically superimposed on the Campanian sediments; event C, erosion linked to a postobduction uplift; event D, northward change of Oligocene−early Miocene Asmari Formation (limestone) to basinal facies (turbidites) resting unconformably on Eocene limestones (this formation has been dated by C. Muller (oral communication, 2004) as Aquitanian-Burdigalian); event E, erosion interpreted as the result of an uplift of the continental lithosphere (bulge effect) related to the continent-continent collision that initiated likely during the late Oligocene−early Miocene; event F, erosion related to uplift along the Mountain Front Fault (basement fault reactivation?); event G, erosion related to the synfolding Zagros uplift.

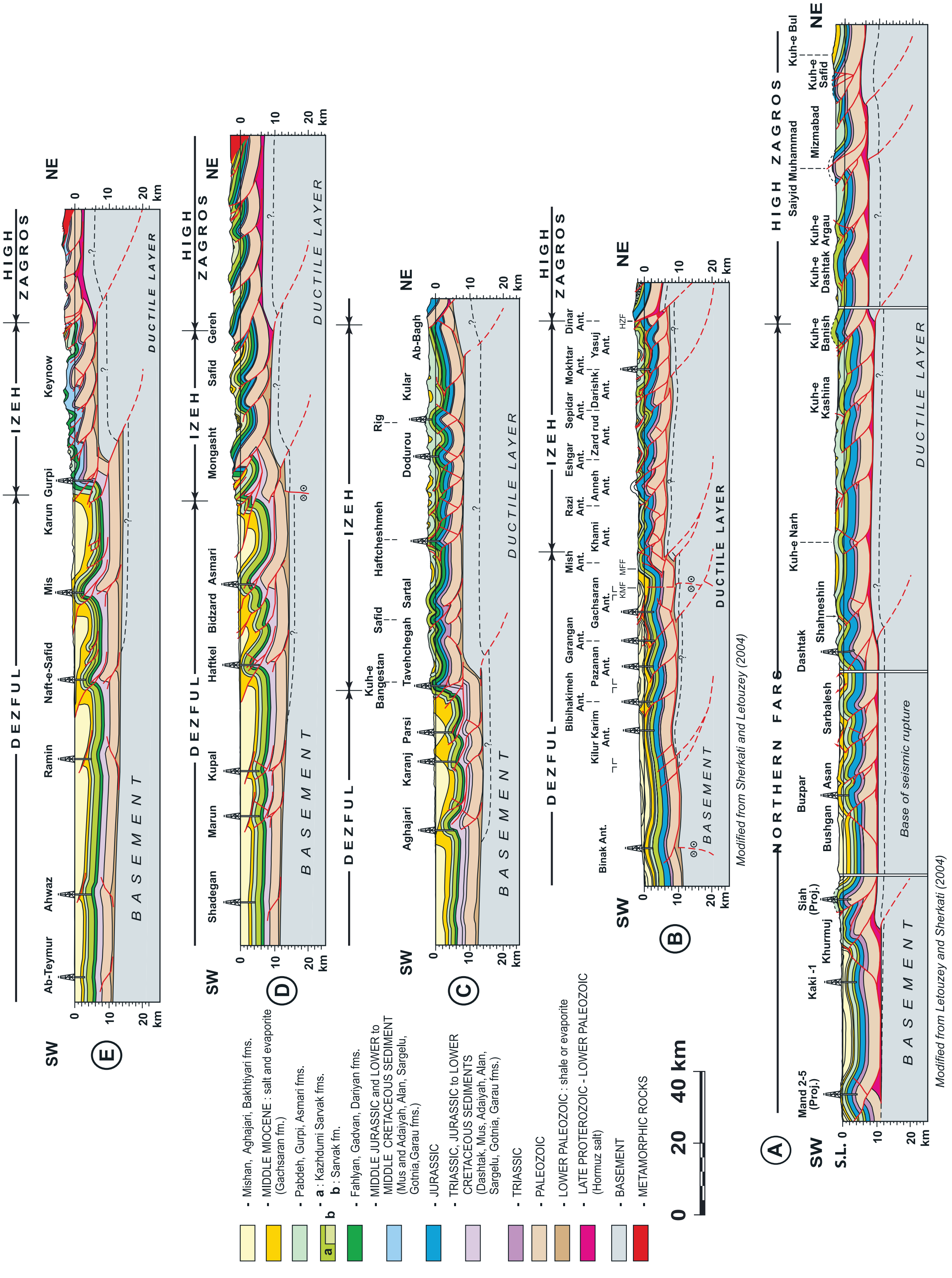
E
SW
NE
DEZFUL
IZEH
HIGH ZAGROS
Ab-Teymur
Ahwaz
Ramin
Naft-e-Safid
Mis
Karun
Gurpi
Keynow
BASEMENT
DUCTILE LAYER
0
10
20
km
D
Shadegan
Marun
Kupal
Haftkel
Bidzard
Asmari
Mongasht
Safid
Gereh
C
Aghajari
Karanj
Parsi
Kuh-e Bangestan
Tavehchegah
Safid
Sartal
Haftcheshmeh
Dodurou
Rig
Kular
Ab-Bagh
B
Binak Ant.
Kilur Karim Ant.
Bibihakimeh Ant.
Pazanan Ant.
Garangan Ant.
Gachsaran Ant.
Mish Ant.
Khami Ant.
Razi Ant.
Anneh Ant.
Eshgar Ant.
Zard rud Ant.
Sepidar Ant.
Darishk Ant.
Mokhtar Ant.
Yasuj Ant.
Dinar Ant.
KMF
MFF
HZF
Modified from Sherkati and Letouzey (2004)
A
S.L.
NORTHERN FARS
Mand 2-5 (Proj.)
Kaki -1
Khurmuj
Siah (Proj.)
Bushgan
Buzpar
Asan
Sarbalesh
Dashtak
Shahneshin
Kuh-e Narh
Kuh-e Kashina
Kuh-e Banish
Kuh-e Dashtak
Kuh-e Argau
Saiyid Muhammad
Mizmabad
Kuh-e Safid
Kuh-e Bul
Base of seismic rupture
Modified from Letouzey and Sherkati (2004)
- Mishan, Aghajari, Bakhtiyari fms.
- MIDDLE MIOCENE : salt and evaporite (Gachsaran fm.)
- Pabdeh, Gurpi, Asmari fms.
a b
- a : Kazhdumi Sarvak fms.
b : Sarvak fm.
- Fahliyan, Gadvan, Dariyan fms.
- MIDDLE JURASSIC and LOWER to MIDDLE CRETACEOUS SEDIMENT (Mus and Adaiyah, Alan, Sargelu, Gotnia,Garau fms.)
- JURASSIC
- TRIASSIC, JURASSIC to LOWER CRETACEOUS SEDIMENTS (Dashtak, Mus, Adaiyah, Alan, Sargelu, Gotnia, Garau fms.)
- TRIASSIC
- PALEOZOIC
- LOWER PALEOZOIC : shale or evaporite
- LATE PROTEROZOIC - LOWER PALEOZOIC (Hormuz salt)
- BASEMENT
- METAMORPHIC ROCKS
0 20 40 km

Figure 4

[15] The major regional angular unconformity between the Agha Jari and Bakhtyari formations is generally considered to have marked the late Pliocene climax of orogeny in the Zagros fold-and-thrust belt [*Haynes and McQuillan*, 1974; *Kashfi*, 1976]. However, growth strata within the upper part of the Agha Jari formation show earlier movements before this major unconformity as mentioned by previous workers [*Falcon*, 1974; *Motiei*, 1994; *Hessami et al.*, 2001; *Homke et al.*, 2004; *Sherkati et al.*, 2005]. The base of the growth strata is dated at 8.1–7.2 Ma by magnetostratigraphic correlation in northwest Zagros (Lurestan) [*Homke et al.*, 2004]. On the other hand, new seismic data show pinch out in the upper Gachsaran seismic reflectors along the forelimb of some anticlines, showing that folding began in middle Miocene time north of the Dezful Embayment [*Sherkati et al.*, 2005]. On the basis of these considerations, we acknowledge that the Zagros folding started in middle Miocene and covered the entire belt by the early Pliocene. The important uplift and erosion, which preceded the deposition of the Bakhtyari conglomerates (Figure 3, event G) could be related to the slab break off [*Molinaro et al.*, 2005b] of the “residual Tethys” (the ocean, which remained after the obduction [see *Agard et al.*, 2005]). A part of the salt extrusions is coeval with Zagros folding. Some of them remain active at the moment, but pinch outs and sedimentary gaps in southeastern Fars and High Zagros area show that important salt movements occurred prior to the Zagros orogeny [*Kent*, 1970; *Letouzey and Sherkati*, 2004].

2.3. Mechanical Stratigraphy of the ZFTB

[16] *O’Brien*’s [1957] mechanical stratigraphy of the ZFTB is not sufficiently detailed to explain the variations of structural style all over the Zagros. Figure 2 presents the mechanical stratigraphy of the sedimentary cover based on extensive geological study and subsurface data analysis [*Letouzey et al.*, 2002; *Sherkati and Letouzey*, 2004; *Sherkati et al.*, 2005]. It consists of several competent stiff layers that are separated by evaporitic or shale layers, involved in deformation as intermediate décollements.

[17] The Hormuz Formation is the basal décollement level in the Fars, Lurestan and High Zagros area. In the Izeh zone and Dezful Embayment, there is no surface occurrence of Hormuz salt plugs suggesting the absence of salt at depth, Eo-Cambrian evaporite horizons or Cambrian shale may be, in this case, the best alternative for basal décollement [*Sherkati and Letouzey*, 2004]. Whatever its nature, this basal décollement has been disrupted and cut by movement along late basement faults [*Sherkati and Letouzey*, 2004; *Molinaro et al.*, 2005a; *Sherkati et al.*, 2005].

[18] The Triassic evaporite (Dashtak Formation) is one of the major intermediate décollement levels in Coastal and subcoastal Fars as well as in the southwest Izeh zone. It is replaced northeastward by dolomite of the Khaneh Kat Formation, which is no longer a décollement horizon (Figure 2). Lower and Middle Jurassic evaporite and shales (Adayah and Sargelu formations), Upper Jurassic evaporites (Gotnia Formation), Lower and Middle Cretaceous shales (Garau and Kazhdumi formations), Eocene marls (Pabdeh Formation) and middle Miocene evaporites (Gachsaran Formation) are the other intermediate décollement levels within the sedimentary cover in different regions of the belt (Figure 2). The upper Miocene Mishan marl constitutes the main upper décollement in the Bandar Abbas area [*Molinaro et al.*, 2005a] but does not show the same mechanical behavior in central Zagros.

3. Presentation of the Regional Transects

[19] In order to study the lateral variation in structural style and shortening within the northern Fars and central Zagros, surface data, well information and seismic profiles were integrated to construct five cross sections from inner zone to foreland (Figure 4). Three of these cross sections are new (Figures 4c, 4d, and 4e), whereas two of them are modified from sections already published by *Sherkati and Letouzey* [2004] (Figure 4b) and *Letouzey and Sherkati* [2004] (Figure 4a). Surface data were obtained from 1:100,000 and 1:250,000 National Iranian Oil Company (NIOC) geological maps and also from several field surveys in the area. Unpublished seismic reflection and well data provided by NIOC were used to interpret the structures at depth. Seismic profiles exist in the Dezful Embayment, south of Izeh zone, all along transect B and along transect A from Dashtak anticline toward southwest (Figure 4).

3.1. Principles of Construction

[20] The cross sections were balanced, using LOCACE Software [*Moretti and Larrère*, 1989] on the basis of bed length and thickness conservation for stiff layers [*Dahlstrom*, 1969; *Woodward et al.*, 1985]. The orientation of the cross sections, drawn northeastward from the first NW-SE trending structures, is parallel to the inferred tectonic transport direction (i.e., perpendicular to the fold axis) (Figure 1). All sections are composite transects with several doglegs in order to include the best surface and subsurface data. As the folds are quite cylindrical at large scale and as the slip transmitted from one anticline to the other remains small everywhere, we assume that these jumps do not have significant consequences on sections balancing. In addition, none of our sections cross major strike-slip faults, so we minimize out-of-the-plane transport. Additionally, the transects are located away from the Hormuz salt plugs minimizing also lateral salt flow.

[21] In the High Zagros Belt, the stratigraphic thicknesses of the various Phanerozoic units are determined from surface outcrops. In the Fars province, outcrops and bore hole data provide good thickness control on Permian to

Figure 4. Five regional balanced cross sections across the central Zagros from the inner parts of the belt to the deformation front (see Figure 1 for location map). The thin dashed line close to the top of the basement represents a suggested bottom for the pre-Hormuz sediments.

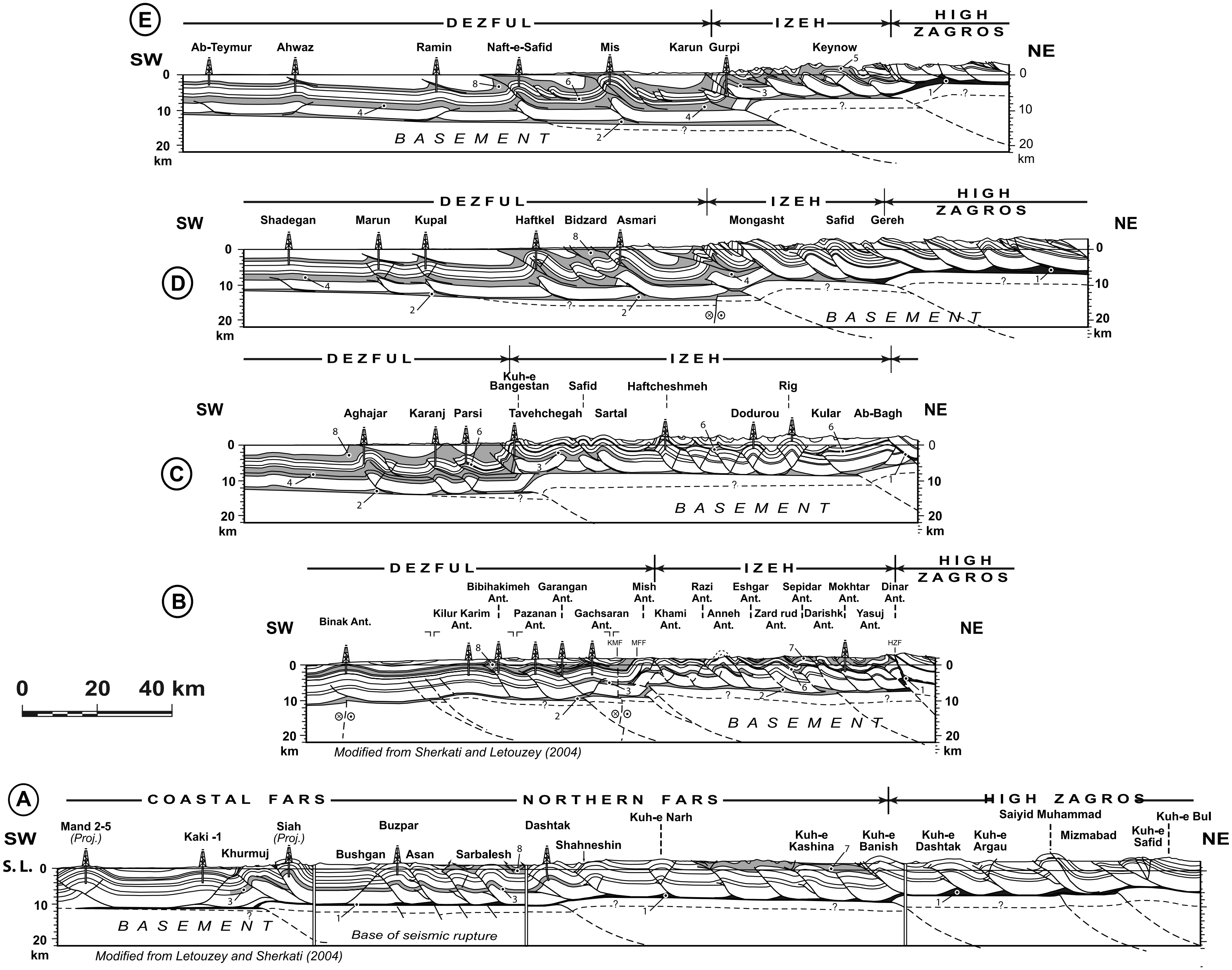
E
DEZFUL
IZEH
HIGH ZAGROS
SW
NE
Ab-Teymur
Ahwaz
Ramin
Naft-e-Safid
Mis
Karun
Gurpi
Keynow
BASEMENT
0
10
20
km
D
Shadegan
Marun
Kupal
Haftkel
Bidzard
Asmari
Mongasht
Safid
Gereh
C
Kuh-e Bangestan
Safid
Haftcheshmeh
Rig
Aghajar
Karanj
Parsi
Tavehchegah
Sartal
Dodurou
Kular
Ab-Bagh
B
Bibihakimeh Ant.
Garangan Ant.
Mish Ant.
Razi Ant.
Eshgar Ant.
Sepidar Ant.
Mokhtar Ant.
Dinar Ant.
Binak Ant.
Kilur Karim Ant.
Pazanan Ant.
Gachsaran Ant.
Khami Ant.
Anneh Ant.
Zard rud Ant.
Darishk Ant.
Yasuj Ant.
KMF
MFF
HZF
Modified from Sherkati and Letouzey (2004)
0
20
40 km
A
COASTAL FARS
NORTHERN FARS
HIGH ZAGROS
Mand 2-5 (Proj.)
Kaki -1
Khurmuj
Siah (Proj.)
Bushgan
Buzpar
Asan
Sarbalesh
Dashtak
Shahneshin
Kuh-e Narh
Kuh-e Kashina
Kuh-e Banish
Kuh-e Dashtak
Kuh-e Argau
Saiyid Muhammad
Mizmabad
Kuh-e Safid
Kuh-e Bul
S. L.
Base of seismic rupture
Modified from Letouzey and Sherkati (2004)
1
2
3
4
5
6
7
8
?

Figure 5

recent horizons. In the Izeh zone, outcrops and bore hole data provide control on Jurassic to recent units, whereas in the Dezful Embayment, well information is limited to the formations younger than Lower Cretaceous. The thicknesses of Jurassic and Triassic units were estimated from seismic data, and thicknesses for the Paleozoic formations were extrapolated from outcrop data in the High Zagros and seismic in the northern Fars.

[22] The depth to Hormuz or ''equivalent Hormuz'' décollement is deduced from an hypothesis of constant thickness of Paleozoic units except for Coastal Fars area, where a deep décollement level is visible on seismic lines allowing us to constrain the thickness of the phanerozoic sedimentary pile in this area [*Letouzey et al.*, 2002]. Such a hypothesis, is consistent with the stepwise uplift of the basement northeastward already discussed in recent papers [*Blanc et al.*, 2003; *Sherkati and Letouzey*, 2004; *Molinaro et al.*, 2005a; *Sherkati et al.*, 2005]. On our sections (Figure 4), the throw along these basement faults has been estimated by measuring the step in the elevation of the same Mesozoic formations at the bottom of the synclines from one side to the other of the faults. As noticed before in Coastal Fars [*Letouzey and Sherkati*, 2004], some pre-Hormuz Proterozoic basins may exist in different parts of the Zagros. Basement structures such as Mountain Front Fault and High Zagros Fault could have been induced by inversion of such Proterozoic basins, reactivation of Permian-Triassic normal faults [*Letouzey and Sherkati*, 2004; *Sepehr and Cosgrove*, 2004] related to the Neo-Tethys rifting or both (Figure 4). On the other hand, presence of infra-Hormuz Proterozoic basins could also explain some discrepancy between basement depth map deduced from gravity and magnetic data [*Motiei*, 1995].

[23] In the Dezful Embayment, *McQuarrie* [2004] restricted the deformation to superficial levels. However, good seismic lines in this zone demonstrate that Paleozoic seismic reflectors are involved in folding indicating that a basal décollement exists and is at least deeper than these Paleozoic seismic reflectors. In addition, the size and wavelength of the folds are consistent with a deep décollement. More generally, the southern segments of the cross sections cut through the ZSFB, where, according to the existence of an efficient basal décollement level, we assume that the structural style is dominated by large-scale detachment folding [*Davis and Engelder*, 1985; *Sattarzadeh et al.*, 2000; *Grelaud et al.*, 2002; *Mitra*, 2002; *Bonini*, 2003; *Sherkati et al.*, 2005]. When subsidiary décollement levels exist (Dezful Embayment, Izeh zone) disharmonic folding may develop [*O'Brien*, 1957; *Bonini*, 2003; *Sherkati et al.*, 2005]. The late stages of folding are marked by formation of faults connecting the different décollement levels. In the High Zagros Belt, the style is simpler and the anticlines may be interpreted as faulted detachment folds.

3.2. Description of the Transects

[24] Transects A, D, and E run from Main Zagros Fault (near the suture zone) to the deformation front, whereas transects B and C were constructed only from High Zagros Fault to the deformation front (Figures 1 and 4). The segments of the sections crossing the HZB are underconstrained by comparison to the ones crossing the ZSFB. Their geometry is only indicative, and the discussion will focus on the latter.

[25] Transect A (Figure 4) is a composite transect north of the Fars province and east of the Kazerun fault. It consists of asymmetric structures verging principally southwestward. Shortening is well distributed all along the transect: The shortening is 50 km for the whole section and 34 km for the ZSFB alone. Anticline wavelength is variable and shows close relationships with sedimentary thickness and mechanical stratigraphy (Figure 5). Average wavelength of the folds in High Zagros area is about 15–20 km in relation with the absence of décollement level (Dashtak Formation), which is represented here by carbonate and dolomite of the Khaneh-Kat Formation (Figure 5) [*Szabo and Kheradpir*, 1978]. In the ZSFB, the Kuh-e-Narh, Shahneshin, Kaki, and Mand anticlines also present the same style but with slightly larger wavelength due to a thickening of the sedimentary pile. In northern Fars, from Kuh-e-Banish to Kuh-e-Narh anticlines, 2–3 km wavelength anticlines in Oligo-Miocene carbonate mask underlying larger structures and suggest the implication of Eocene marl (Pabdeh Formation) as a superficial décollement level (Figure 5). Multiwavelength anticlines are characteristic features in the middle part of the northern Fars, where Triassic evaporite form a secondary décollement level. Anticline spacing varies from 7 to 15 km in this area.

[26] Transect B (Figure 4) is also a composite transect, which is drawn west of Kazerun fault [*Sherkati and Letouzey*, 2004]. The amount of shortening in ZSFB is 27 km, which is 7 km less than in transect A east of Kazerun fault. However, variation in structural characteristics of the anticlines from east to west of Kazerun fault remains unconnected to such a moderate decrease of the amount of shortening and seems to be mostly related to lateral change in sedimentary facies and basal friction value. Compared to transect A, anticline wavelength decreases (except Binak and Kilur Karim anticlines, which are larger) and structures are significantly tighter and more complex. Shortening seems to be mostly concentrated in the northern part of the section, where major thrust faults put Lower

Figure 5. Major décollement levels in central Zagros and north Fars province: 1, Late Proterozic–Lower Paleozoic (Hormuz salt); 2, Lower Paleozoic shales or evaporites; 3, Triassic evaporites (Dashtak Formation); 4, Triassic, Jurassic Lower Cretaceous soft sediments (Mus, Adaiyah, Alan, Sargelu, Gotnia, and Garau formations); 5, Jurassic to Lower Cretaceous soft sediments (Mus, Adaiyah, Alan, Sargelu, Gotnia, and Garau formations); 6, Albian shales (Kazhdumi Formation); 7, Campanian to Eocene marls (Gurpi and Pabdeh formations); 8, middle Miocene salt and evaporite (Gachsaran Formation).

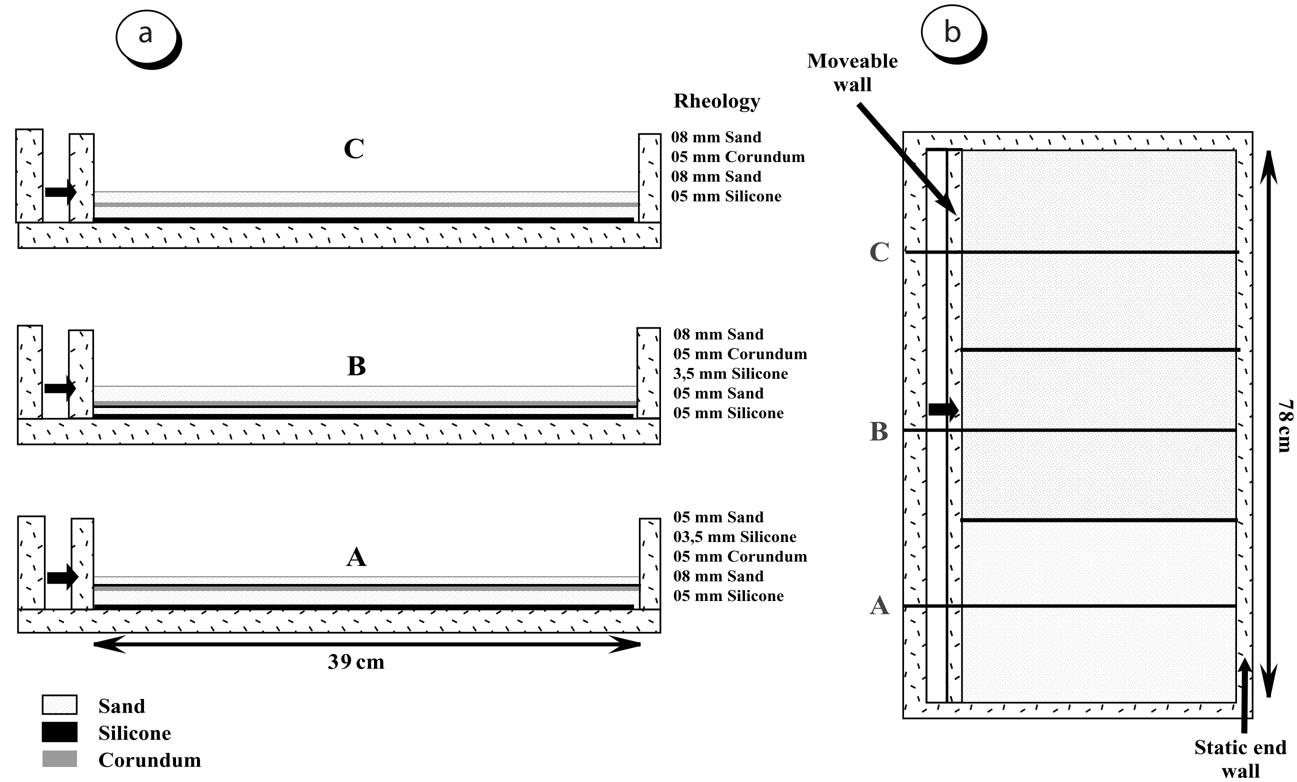

Figure 6. Modeling apparatus: (a) Schematic cross sections across the model setup and (b) schematic plan view of the sandbox. It is divided into three different models (A, B, and C) with different ductile and brittle material arrangement. The left wall is the pushing wall and the right wall remains stationary. Model A is for no intermediate décollement, model B is for deep intermediate décollement, and model C is for shallow intermediate décollement.

Paleozoic over the Middle Cretaceous. Absence of Hormuz salt west of Kazerun fault [*Edgell*, 1996] certainly caused variation in shear strength along the basal decollement [*Letouzey et al.*, 1995; *Cotton and Koyi*, 2000] and could explain the unequal strain distribution.

[27] The other key structural characteristic of transect B is the complete decoupling between deep and shallow levels. Shortening for each structure especially in Izeh zone is higher at shallow levels (for example, at Asmari Formation level) than in deep horizons (for example at Sarvak or Fahliyan levels). This difference shows that intermediate décollements (Pabdeh and Kazhdumi formations) efficiently transfer deformation from the anticlines to the adjacent synclines (Figure 5).

[28] Transect C (Figure 4) presents 33 km of shortening in the ZSFB. As in transect B, shortening is concentrated in the northern part of the transect, where Paleozoic rocks are exposed and thrust over Upper Cretaceous formations. Wavelength and style variation of folds are related to the active décollement levels. In the north of the section, 10–12 km wavelength anticlines (except Kular anticline) are observed. In the middle part of the section (i.e., between Haftcheshmeh and Dodurou anticlines) fold wavelength decreases to 3–4 km. Chevron type structures and "rabbit ears" folds in the Cenomanian carbonates of the Sarvak Formation are related to the existence of a secondary décollement level within Albian shale (Kazhdumi Formation) [*Sherkati et al.*, 2005] (Figure 5). These short-wavelength structures mask larger anticlines at depth in pre-Kazhdumi formations. South of Izeh zone, anticline wavelength increases again to 10–12 km. However, some shorter and tighter structures are also observed in the area (Safid anticline).

[29] Triassic evaporite (Dashtak formation) was drilled in the Bangestan well. More to the south in Dezful Embayment facies changes in the Lower Cretaceous from platform limestone (Fahliyan Formation) to deep marine shales and marly limestones (Garau Formation). Facies changes also in Jurassic from limestones (Surmeh Formation) to alternations of shales and anhydrite (Gotnia, Sargelu, Alan and Adayah formations) providing potential décollement levels. Middle Miocene evaporite (Gachsaran Formation) is a major décollement level in the Dezful Embayment [*O'Brien*, 1957; *Colman-Sadd*, 1978; *Bahroudi and Koyi*, 2003; *Sherkati et al.*, 2005]. As it is seen in the transects (Figure 5), mechanical behavior of Gachsaran formation as décollement is more efficient northwest of Dezful Embayment (transects C, D, and E) with respect to the southeast. This is probably related to increase of its thickness from SE to NW.

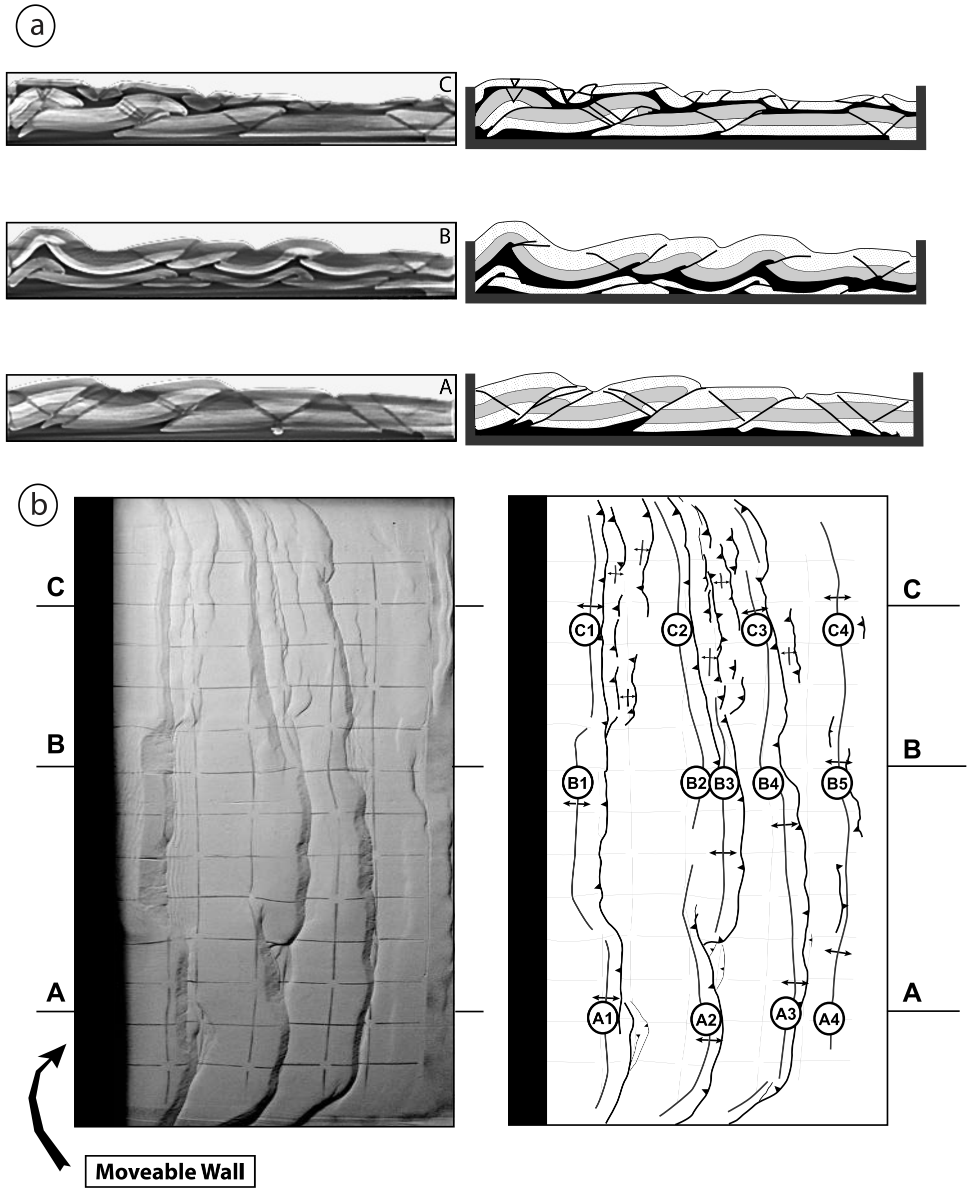

Figure 7. Map and cross sections through the models after 23% of shortening. (a) Cross sections through models A, B, and C. In model A, the structures are large, simple, and isopachly folded. There is less complexity at depth and in more shortened structures, thrust faults are seen at the surface with large displacement. In model B, multiwavelength folds are cored by complex compressional structures. In model C, upper brittle level contains small structures along the limbs or between the main anticlines, whereas below the intermediate décollement level, widely spaced ramp-related folds are characteristic features. The wavelengths of the main anticlines in the sections A and B are very different showing that the depth of the intermediate décollement level influences the spacing between the anticlines. (b) Plan view of the sandbox. Geometrical characteristics of the folds change across the box in relation with the different arrangements of weak and brittle materials. Model A is for no intermediate décollement, model B is for deep intermediate décollement, and model C is for shallow intermediate décollement.

[30] Transects D and E (Figure 4) present an identical shortening of 33 km in Izeh zone and Dezful Embayment and 65 km shortening through the entire belt. Along these transects, anticline wavelengths are about 15–20 km. In the southern part of the Dezful Embayment, shortening is considerably less than in the northern part. Structural complexity increases north of Dezful, as a result of the implication of intermediate décollement levels. Décollement levels are identified in Lower Cambrian, Triassic to Lower Cretaceous ductile units (Dashtak, Adayah, Sargelu, Gotnia

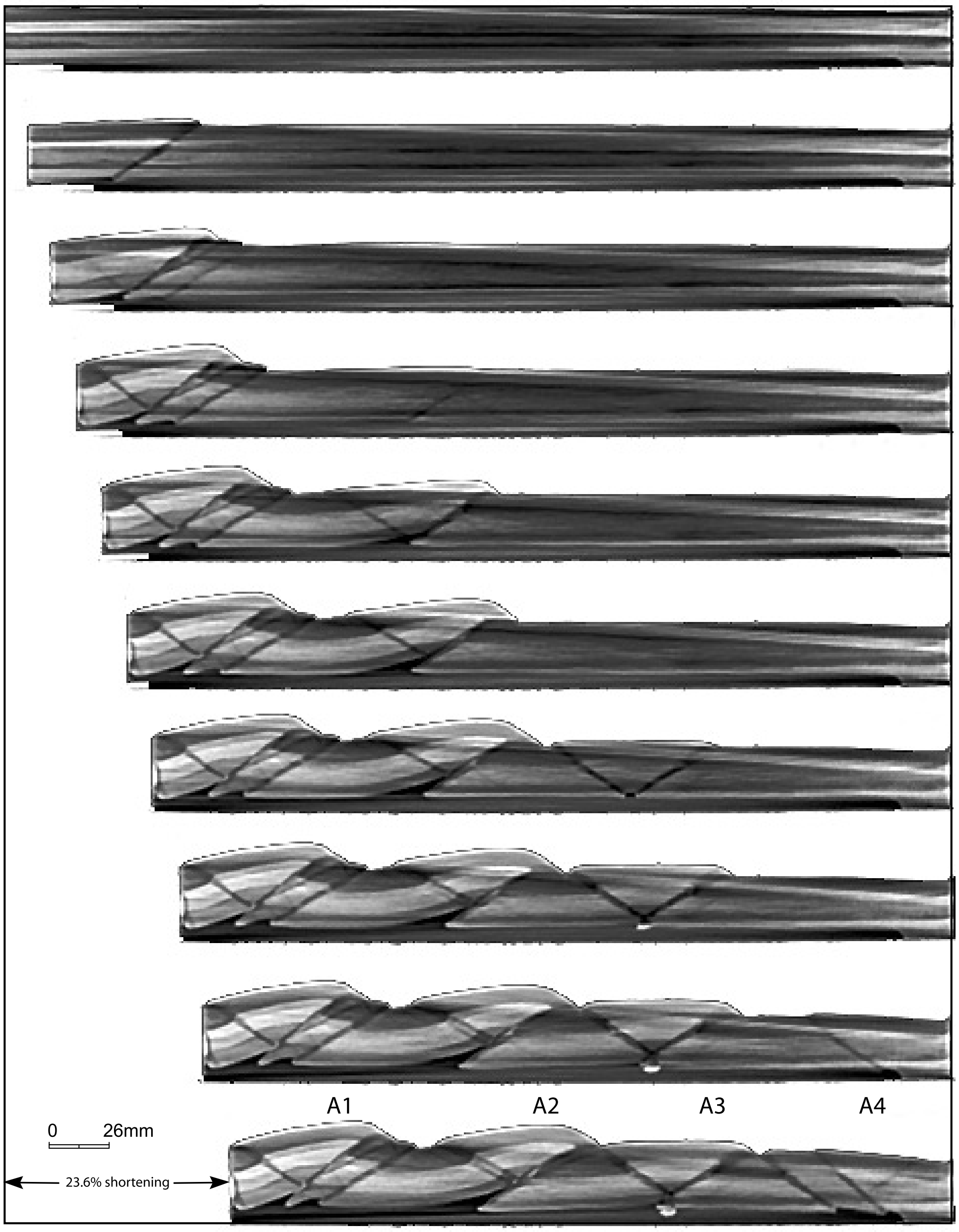

Figure 8. Successive cross sections during deformation of model A with one single basal décollement level. Anticlines form sequentially with the same spacing, which is controlled by the thickness of the competent unit. At high shortening rate, back thrusts form at the right side of the model because of the pinch out of the basal silicon layer. The same observation can be made in models B and C (see Figures 9 and 10).

and Garau formations) and Miocene evaporite (Gachsaran Formation) (Figure 5).

[31] It is known that disharmonic features formed in the middle Miocene (Gachsaran Formation) concurrently with folding [*Sherkati et al.*, 2005]. Such structures are observed in poorly developed structures like the Shadegan, Marun, and Kupal anticlines, which are the most external on section D and the Ahwaz and Ramin anticlines, which are in the same position on section E (Figure 4). So it appears that the Gachsaran Formation was activated as a décollement level in the early stage of folding concurrently with the basal décollement level [*Sherkati et al.*, 2005]. During further stages of deformation, it seems that the Gachsaran décollement was no more active and has been cut out by forelimb thrusts branched on the Dashtak décollement (see the Haftkel, Asmari, Naft-e-Safid and Mis anticlines, Figures 4d and 4e). As a consequence, the post middle Miocene clastics, which were trapped in the

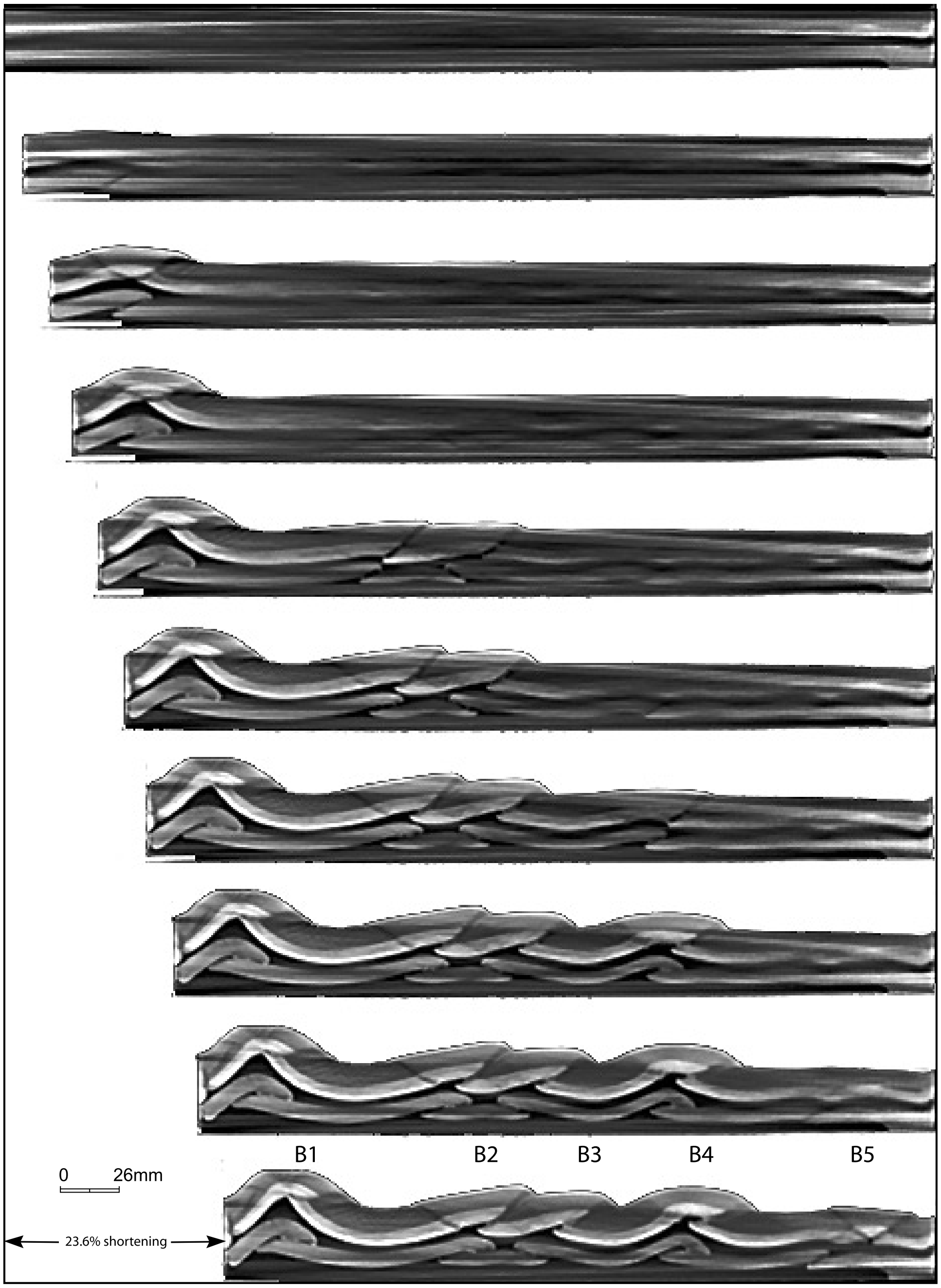

Figure 9. Successive cross sections during deformation of model B with a deep intermediate décollement level. Deformation of the lower sand layer before folding localizes forthcoming anticlines. The irregular anticlinal spacing results from the interaction between two factors: (1) the thickness of the pile and (2) the influence of the deep ductile unit.

synclines, were subject to steepening and overthrusting between the main anticlines. For instance, between Naft-e-Safid, Mis, and Gurpi anticlines (transect E) as well as between Haftkel and Asmari anticlines (transect D), the development of minor ramp-related folds in the intervening synclines show that a part of shortening has been transferred out of the anticlines.

4. Role of Intermediate Décollement Levels During Folding: An Analogue Modeling Approach

[32] Our sections through the ZFTB give an opportunity to address the question of the control exercised by the existence and depth of intermediate décollement levels on

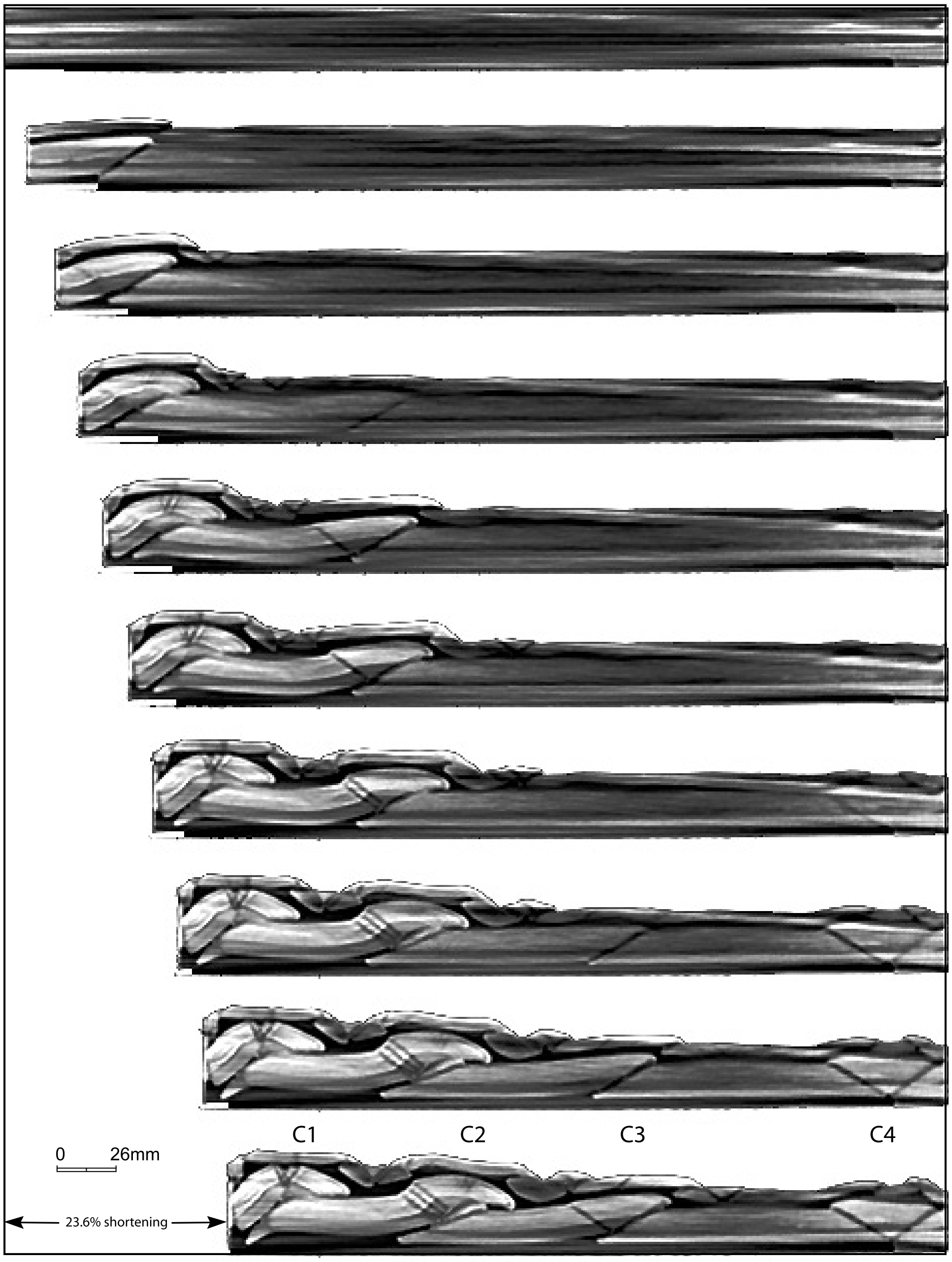

Figure 10. Successive cross sections during deformation of model C with shallow intermediate décollement level. Small structures mask main deep anticlines. Regularly spaced anticlines with wavelength close to the one observed on model A are seen at depth. Their wavelength is controlled by the thickness of the lower competent unit. Folds above the intermediate décollement level show high curvature and short wavelength. It is worth noting the development of some "rabbit ears" structures in upper competent unit in both flanks of the deep structures.

the geometry and kinematics of folding. For this purpose, we perform sandbox experiment visualized by X-ray tomography.

[33] Through mechanical analyses [*Biot*, 1961] and experimental analyses [*Currie et al.*, 1962], it is known for a long time that the stronger dominant member within the lithostratigraphic pile have a determining effect on the size of the folds. Sandbox modeling shows that viscous layers at different depth and small overlaps could govern the propagation of deformation front [*Koyi et al.*, 2004]. In addition, the effects of lithological contrasts on the folding style has been studied in the field as well as experimentally [*Letouzey et al.*, 1995; *Sans and Vergés*, 1995; *Bonini*, 2003; *Couzens-Schultz et al.*, 2003; *Teixell and Koyi*, 2003; *Koyi et al.*,

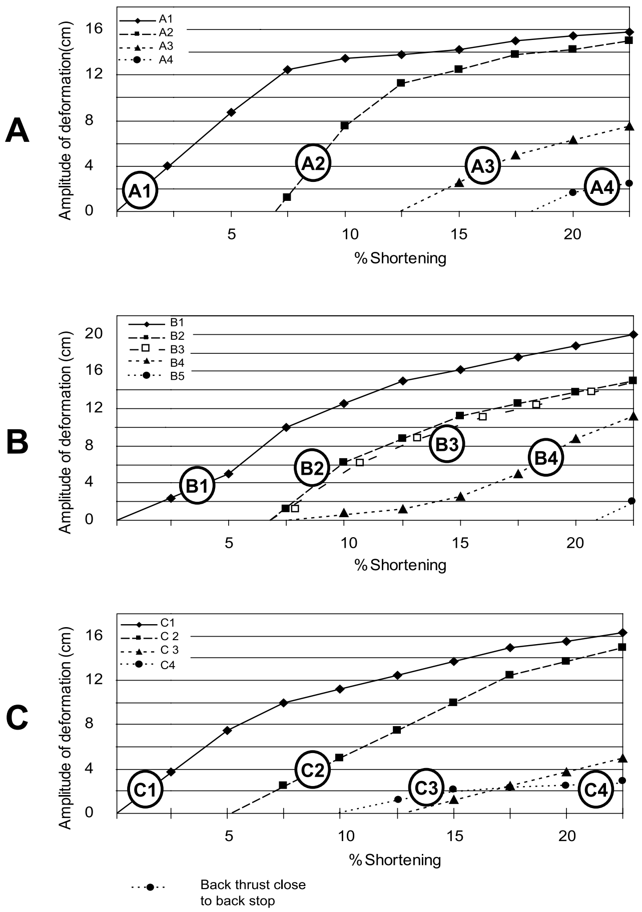

Figure 11. Plot illustrating the amplitude versus shortening in each part of the models. Amplitude is measured by the uplift of the crest of each anticline compare to the initial position. In model A (without intermediate décollement level) the rate of fold amplification decreases abruptly with the development of a new fold. By contrast, in models B and C (with an intermediate décollement) some folds (B2–B3 and C3–C4, respectively; see Figures 9 and 10) develop simultaneously.

2004; *Massoli et al.*, 2006]. In this paper we focus on the role of intermediate décollement level. In particular, we will show that the depth to this décollement level influences the anticlinal spacing and structural style both laterally and vertically.

4.1. Model Setup

[34] Two kinds of analogue materials were used: dry granular materials to simulate brittle sedimentary rocks, which obey a Mohr-Coulomb failure criterion, and viscous Newtonian material to simulate ductile rocks. Brittle analogues consist of dry sand and corundum with grain size of 100 μm. Their slight density contrast is large enough to be shown on the X-ray images. The ductile analogue consists of silicon putty (PDMS, variety SGM 36 of Dow Corning) with Newtonian behavior at low strain, a viscosity of 10^{-4} N s/m^2 and a density of 970 kg/m^3. Computerized X-ray tomography applied to analogue sandbox model allows us to analyze the kinematic evolution and the three-dimensional geometry without interrupting or destroying the model [*Colletta et al.*, 1991]. Distinct boundary conditions were used to simulate the distinct tectonic regimes discussed in this paper. When boundary conditions are perfectly repeated, the resulting structures obtained in the deformed models are also repeated, showing that structures are not developed at random but are strongly controlled by the rheology and boundary conditions [*Colletta et al.*, 1991]. All the models were deformed by moving the vertical wall at velocity of about 1.7 cm/h. The thickness of models represents about 8 km of sedimentary rocks. The box was initially 39 cm wide and 78 cm long. During each experiment, the box is divided laterally into three distinct models with dimensions of 26 cm wide and 39 cm long (Figure 6).

4.2. Model Results

[35] The result of analogue modeling shows that evolution of the model depends on the imposed arrangement of ductile and brittle layers (Figure 7). As indicated above, we will distinguish three different models: without intermediate décollement level (model A), with a deep intermediate décollement level (model B) and with a shallow décollement level (model C).

[36] In model A, without intermediate décollement level (Figures 7 and 8), the structures are large and simple. Fold wavelength is uniform and controlled by dominant competent unit. In more shortened structures, thrust faults with large displacement are seen at the surface. Back thrusts cut through the back limbs of the anticlines and terminate against the fore thrusts. Pop-up structures develop at early stages of deformation and are passively transported during the subsequent evolution. The development of such structures depends on the mechanical property of granular materials used in models. In the Zagros structures back thrusting is less frequently observed. This could be due to the rheology of carbonate rocks, which favors diffusive mass transfer (pressure solution) and folding rather than fracturing [*Gratier and Gamond*, 1990].

[37] In model B, with a deep intermediate décollement (Figures 7 and 9, folds are cored by duplex structures. Back thrusts are rarely seen on the back limb of the folds in the upper sand level. Within the deep brittle layer, folds and duplexes propagate rapidly during early stages of deformation localizing thrusts and folds in the upper level. Spacing between surface anticlines is not regular. However, the size of surface anticlines is controlled by the thickness of upper brittle layer and is influenced by deep structures. There is no direct connection between faults in lower and upper brittle units. However, Figure 9 shows that the lower and upper structures are related and formed simultaneously. In addition, we notice that each individual folds develop “fish tail” style similar to the one described by *Harrison and Bally* [1988] in Melville Island.

[38] In model C, with a shallow décollement (Figures 7 and 10), the shortening is also accommodated differently on

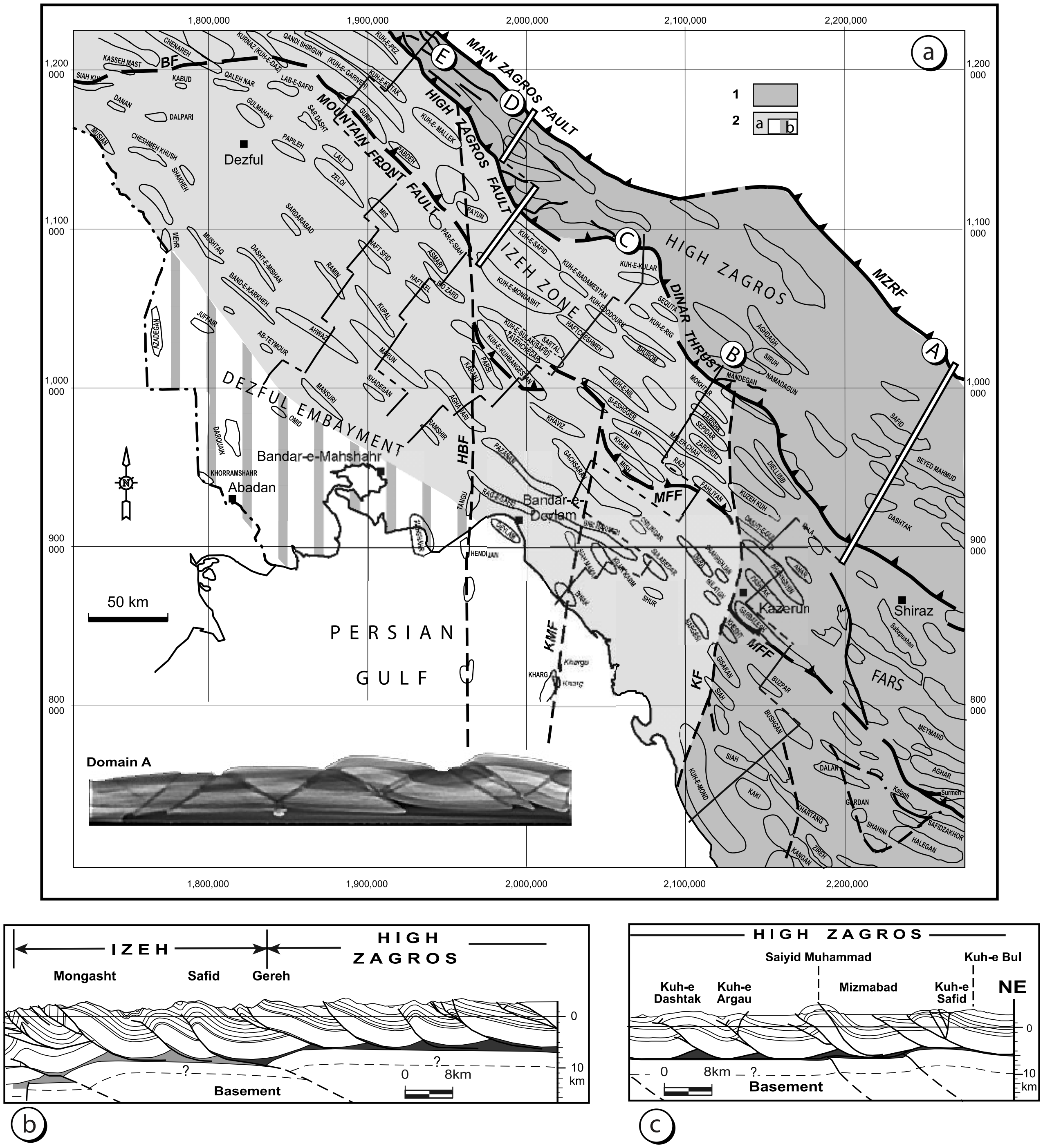

Figure 12. Typology of the basal décollement in central Zagros. (a) Structural map of the central Zagros and north Fars area showing the nature and probable extent of the basal décollement levels: Legend: 1, Late Proterozoic–Early Cambrian Hormuz décollement (proved by salt plugs in the Fars and High Zagros provinces); 2a, Lower Paleozoic shale or evaporite décollement; 2b, zone where the basal décollement is not activated. (b) Zoom into the northern half of the transect D (see Figure 4 for complete section and legend), showing widely spaced anticline cut by large thrust faults. The entire sedimentary pile is folded isopachly without important disharmonic features. Wavelengths of anticlines are about 10–15 km. Structural configuration along the northern part of the transect shows similarity with model A of analogue experiment (Figure 7). (c) Zoom into the northern part of the transect A (see Figure 4 for complete section). Because of the lack of major weak level within the stratigraphic column, large and simple structures isopachly folded above the basal décollement level (Hormuz salt).

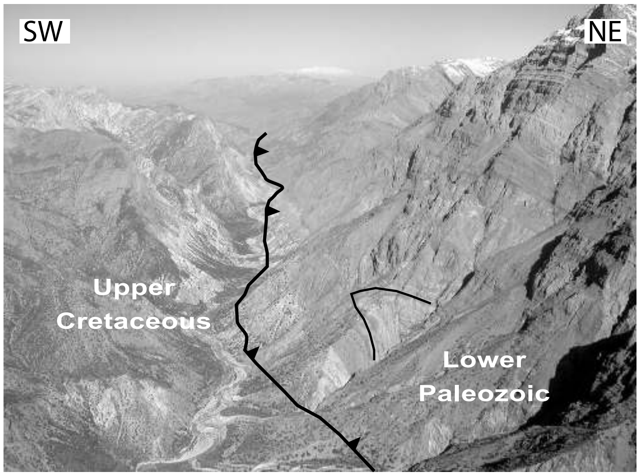

Figure 13. Ab-Bagh anticline along the High Zagros Fault. The fault cut all the sedimentary pile and put the Lower Cambrian over Upper Cretaceous sediments.

both sides of the intermediate décollement level. The upper level contains small structures along the flank of the main anticlines with minor displacement along numerous fore and back thrust faults whereas below the weak level, widely spaced fault-related folds with major faulting are the rule. Fold wavelength in lower competent unit is close to the spacing observed in model A and is proportional to the thickness of the lower brittle layer. The main faults in lower brittle unit curve upward into the upper décollement level. Further shortening is accommodated by triangle zone in deep section and minor thrusts in upper unit (rabbit ear folds). Our observations show similarity with results of analogue modeling, which was carried out by *Letouzey et al.* [1995] to illustrate structural style in the Atlas mountains of Algeria.

[39] As a general trend, we observe an increase of the amplitude of individual folds related to the shortening increase (Figure 11). According to *Cotton and Koyi* [2000] and in the absence of intermediate décollement, the rate of amplification of oldest folds decreases as shortening is transferred to a new imbricate ahead of the existing folds (Figure 11a). The general sequence of folds development is from the hinterland to the foreland (Figures 8, 9, and 10). However, modeling shows that in the presence of intermediate décollement, some folds develop synchronously (Figures 11b and 11c).

5. Discussion

[40] It is now possible to compare the model results with the central Zagros transects. As described above and compared to other areas in Zagros, this region is made up with a sedimentary pile presenting the highest competency contrasts. The different mechanical response of these nonuniform strata caused important changes in geometry of folds and the similarities with our analogue models suggest that their modes of formation are close to those observed in the field. We will first compare different subregions with the models; then we will address some specific problems dealing with the regional geology.

5.1. Comparison Between Cross Sections and Models

[41] The regions with a single basal décollement, represented by the Hormuz salt, are the High Zagros Belt and the northern part of the Fars province (Figure 12). These areas are characterized by widely spaced anticlines without important disharmonic features at depth (Figures 12b and 12c). Wavelength of anticlines are about 15 to 20 km and major thrust faults with large displacement cut through the folds and reach the surface in the more advanced stages of deformation. An example of such a structure is the Ab-Bagh anticline (Figure 13), the northernmost on transect C (Figure 4), which is cut out by a major thrust fault (the HZF) putting Lower Cambrian over the Upper Cretaceous. From a general point of view, the observed tectonic style shows strong similarity with the one observed in our model A (Figure 12).

[42] The regions presenting an additional deep décollement level are the coastal Fars province and the southeast of Izeh zone on the one hand and the north Dezful on the other hand (Figure 14). In the coastal Fars and southeast Izeh, the Triassic evaporites of the Dashtak Formation acted as a deep décollement (Figure 3, events F and G, and Figure 14). Transects A (between Dashtak and Khurmoj anticlines) and B (between Anneh and Gachsaran anticlines) illustrate that its influence on fold style remains inconspicuous with only some secondary faults branched on it (Figure 5). In the northern Dezful Embayment and northern Izeh zone, facies of Jurassic and Lower Cretaceous carbonate change to shale and anhydrite (Figure 3, events A and B) leading to the development of disharmonic features observed in the field (Figure 15). These ductile units, in addition to the Triassic evaporite, form a thick (almost 2000 m) interval acting as a major décollement level. The presence of this décollement zone considerably affects the folds style in the area (Figures 5c, 5d, 5e, and 14b). More precisely, it separates symmetric and tight folds with average wavelength of about 3–4 km in Cenomanian carbonates and younger sediments, from widely spaced asymmetric anticlines in Lower Jurassic and older rocks. Such a geometry with a major decoupling between upper and lower levels, corresponds to the one observed in the model B (Figures 9 and 14).

[43] The regions presenting an additional shallow décollement level are large and variegated. We will discuss first the role and extent of the Pabdeh-Gurpi (Campanian to Eocene) and Kazhdumi (Albian) décollements (Figure 16), and then we will address the particular case of the Gascharan (middle Miocene) salt (Figure 17).

[44] The extent of Pabdeh-Gurpi and Kazhdumi shallow intermediate décollement levels in central Zagros and north Fars area is shown on Figure 16. In the Izeh zone (Figure 4b, between High Zagros fault and Anneh anticline) and northern Fars (Figure 4a, between Kuh-e-Banish and Kuh-e-Purdah), the activation of Pabdeh and Gurpi marls led to the development of short-wavelength anticlines in the Oligo-Miocene carbonates of the Asmari Formation.

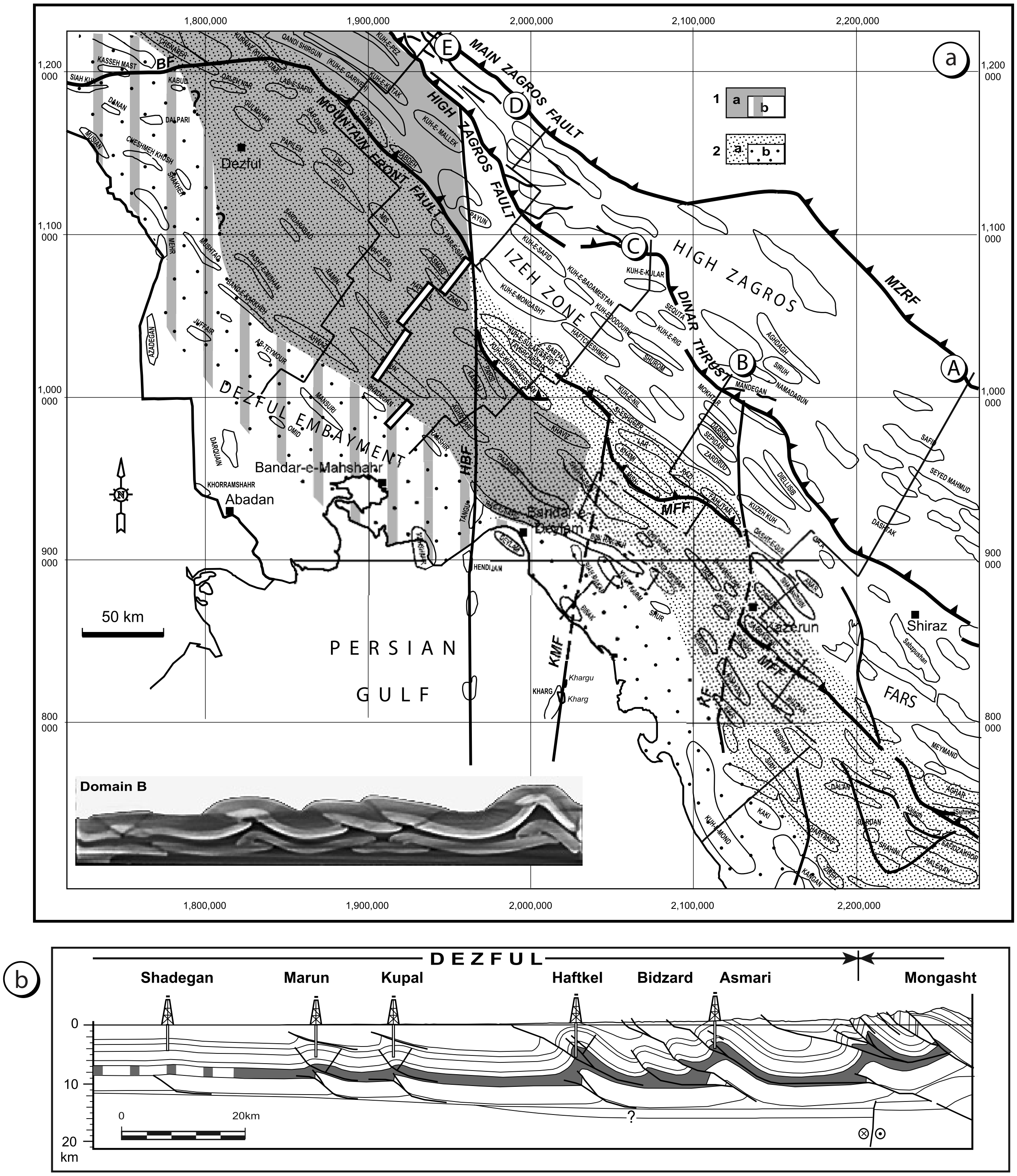

Figure 14. Typology of the deep intermediate décollements in central Zagros. (a) Structural map of central Zagros and north Fars area, showing 1a, extent of Triassic, Jurassic, and Lower Cretaceous intermediate décollement levels (Dashtak, Adayah, Sargelu, Gotnia, and Garau formations); 1b, zone where the facies of these formations remains unchanged but where they have not activated as intermediate décollement levels because of the low amount of deformation; 2a, Triassic evaporite décollement level (Dashtak formation); 2b, zone where the Triassic lost its mechanical behavior as an intermediate décollement level. (b) Zoom into the southern half of the transect D (see Figure 4 for complete section and legend). The Lower Cretaceous, Jurassic, and Triassic sediments (Garau, Gotnia, Sargelu, Alan, and Adayeh formations) are the main intermediate décollement levels in north Dezful. Note the irregular wavelength of the folds showing similarity with model B of analogue experiment.

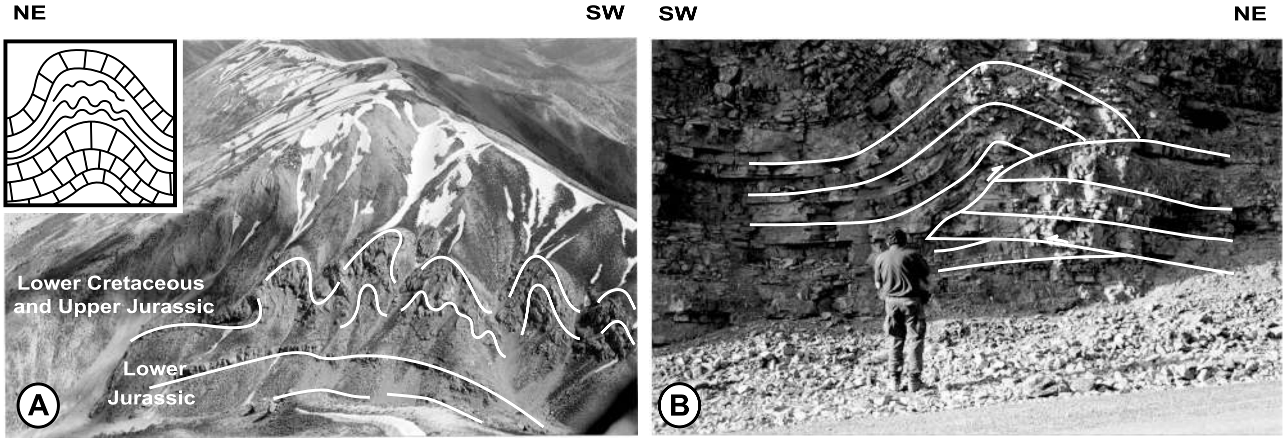

Figure 15. Field evidence of multiple décollements in the Jurassic and Cretaceous levels of the northwest Dezful embayment (close to transect E, Figure 4). (a) Disharmonic features along the Upper Jurassic–Lower Cretaceous boundary; (b) disharmonic features and thickening in the Garau Formation (Lower Cretaceous).

Because of a change in facies from marls to limestones, this formation is no longer a décollement in northwestern Izeh zone (Figures 5e and 16). In southeast Izeh zone and parts of northeast Dezful Embayment the Albian shales of the Kazhdumi Formation represent another shallow decollement level (Figure 16). Its influence on fold style is seen along transect B (between High Zagros Fault and Eshgar anticline) and transect C (north of Dezful Embayment and parts of north Izeh zone) (Figures 16b and 16c). The Kazhdumi formation does not exist in the Fars province east of Kazerun fault. In this area, the Albian is represented by carbonate and loses its role of décollement level (Figure 16). Concerning the sequence of activation of the two décollements, it seems that the basal décollement has been activated first and the shallow one later in order to accommodate the deformation in the upper levels of the folded sedimentary pile. Such an evolution is very close to the one observed in our model C (Figures 7 and 10).

[45] Middle Miocene salt (Gachsaran formation) is a shallow intermediate décollement level restricted to Dezful Embayment (Figures 17, 5c, 5d, and 5e). Compared to the pre-Asmari shallow décollements, the mechanism and timing of its activation are different from those discussed above. In particular, it seems that the decoupling along Gachsaran salt started in primary stage of folding [*Sherkati et al.*, 2005]. So, complexly folded and thrusted post-Gachsaran sediments have little relationships with the underlying structures, which are folded isopachly and conserved their style through the different stages of deformation (Figures 18 and 19). This particular chronology could be related to the low friction existing along the Gachsaran salt compared to the one applied along the basal décollement where, according to our reconstruction, there is no Hormuz salt (Figure 12). Then, at a late stage of deformation, major thrust faults develop and cut through the whole pile. Such a structural style is not really reproduce in our models probably because within these models the two décollement levels were made with the same material (silicone). From an exploration point of view, it is worth noting that structural traps in Dezful Embayment are in the crests of the major anticlines at Asmari and Sarvak levels and are sealed by Gachsaran or Gurpi formations, respectively. However, some structures can develop in back limb, forelimb or even in the intervening synclines. Related to the implication of intermediate décollement levels, some of these secondary structures have considerable size and may be considered as potential secondary traps (Figures 18 and 19).

5.2. About the Kazerun Fault Zone

[46] The Zagros belt becomes wider from NW to SE along the Kazerun Fault Zone (KFZ) as it is seen on structural map and transects (Figures 1 and 4). In map view (Figure 1) the KFZ consists of N-S en echelon segments of steep right-lateral strike-slip faults underlined by some Hormuz salt diapirs. It is known that the KFZ is trending parallel to Panafrican Proterozoic basement trend and constituted the western limit of an Hormuz salt rift basin [e.g., *Edgell*, 1996; *Sepehr and Cosgrove*, 2005]. It also controlled facies variation during the Albian from shales in the Dezful Embayment to mostly carbonates in the Fars province [*Sepehr and Cosgrove*, 2004; *Letouzey and Sherkati*, 2004; *Sepehr and Cosgrove*, 2005]. The KFZ must be consequently interpreted as an inherited structure. However, the sedimentary control is not localized along a linear structure but rather along a 20 km wide strip. During the Zagros folding, the current localization of Kazerun fault zone has been probably influenced by preexisting salt domes distributed along basement structures (Figure 1) [*Letouzey and Sherkati*, 2004]. At the moment, the Kazerun fault zone is an active right-lateral strike-slip system transferring deformation from the Main Zagros Fault to the

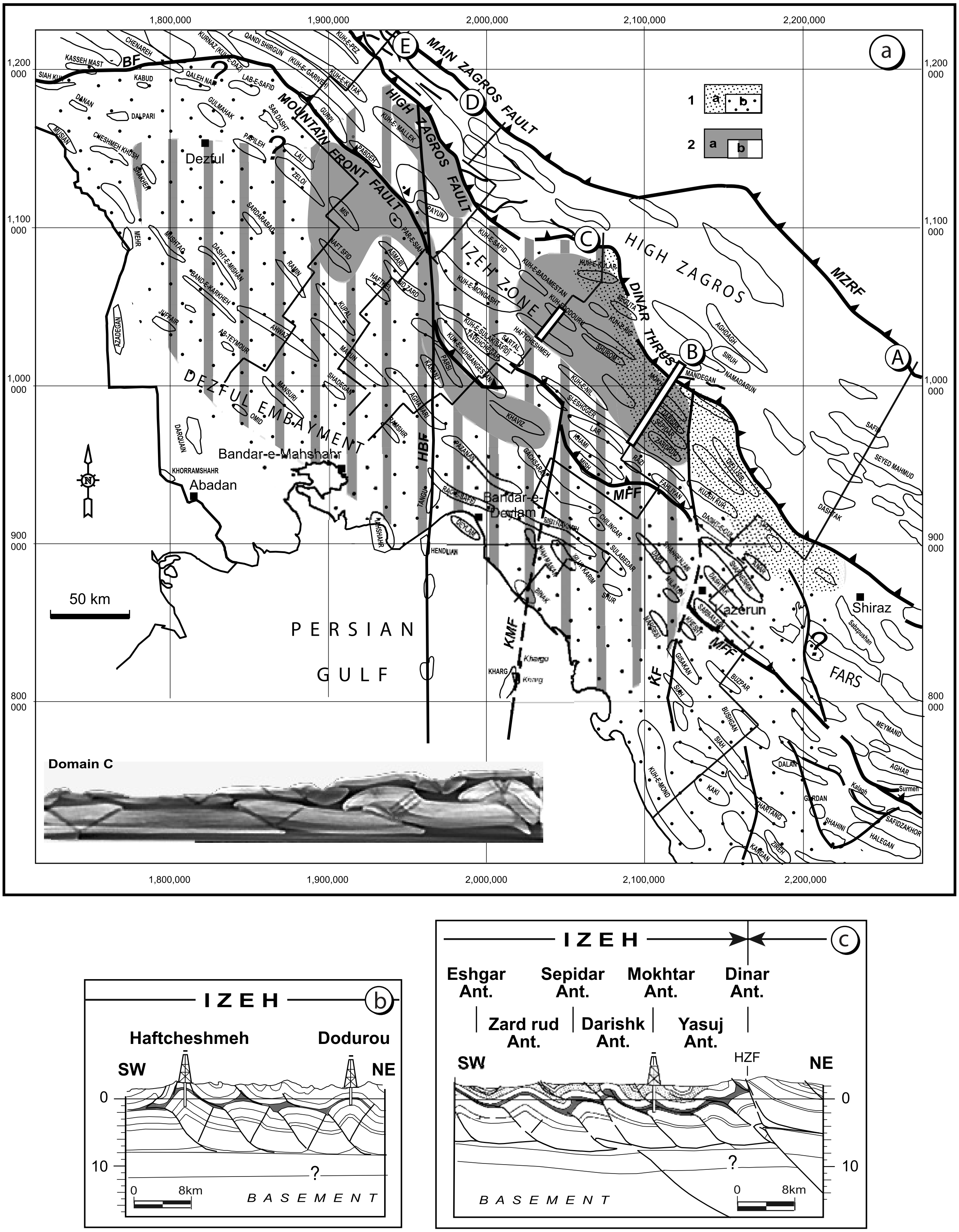
a
1 a b
2 a b
MAIN ZAGROS FAULT
HIGH ZAGROS FAULT
MOUNTAIN FRONT FAULT
DINAR THRUST
HIGH ZAGROS
MZRF
IZEH ZONE
DEZFUL EMBAYMENT
PERSIAN GULF
FARS
BF
HBF
KMF
KF
MFF
A
B
C
D
E
Dezful
Bandar-e-Mahshahr
Abadan
Bandar-e-Deylam
Kazerun
Shiraz
Kharg
50 km
N
Domain C
1,800,000
1,900,000
2,000,000
2,100,000
2,200,000
1,200 000
1,100 000
1,000 000
900 000
800 000
b
IZEH
Haftcheshmeh
Dodurou
SW
NE
0
10
0 8km
BASEMENT
?
c
IZEH
Eshgar Ant.
Sepidar Ant.
Mokhtar Ant.
Dinar Ant.
Zard rud Ant.
Darishk Ant.
Yasuj Ant.
SW
HZF
NE
0
10
0 8km
BASEMENT
?

Figure 16

active folds and thrusts distributed within the Fars province [*Authemayou et al.*, 2005; *Lacombe et al.*, 2006].

[47] The restoration of our sections indicate that difference in amount of shortening (maximum 15 km) cannot explain the abrupt longitudinal offset observed along the Zagros Frontal Fault. In fact, east of KFZ, the deformation is distributed over 312 km, whereas west of it the same amount of shortening is distributed over 232 km and even less northwestward. Structural style is also different from one side of the fault zone to the other. East of KFZ, where Hormuz salt is the basal décollement level, shortening is equally distributed across the belt whereas to the west, where the basal décollement changes to a different lithology, probably a Lower Paleozoic shale or evaporite, deformation mostly concentrated in the inner zone. This variation in nature of basal décollement and the comparison of shortening and structural style on both sides of the fault are in good agreement with widely accepted analytical models of fold-and-thrust belts, which pointed out the relationships between basal shear strength and propagation of deformation [*Letouzey et al.*, 1995; *Cotton and Koyi*, 2000; *Bahroudi and Koyi*, 2003]. So, according to *Blanc et al.* [2003], the large (at least 150 km) cumulative lateral displacement along this transfer zone proposed by some authors [*Berberian*, 1995; *Hessami et al.*, 2001; *Bahroudi and Koyi*, 2003] is not reasonable nor supported by field evidence.

5.3. About the Fold Development in the ZSFB

[48] The amount of shortening decreases considerably southwestward along the transects (Figure 4), providing an opportunity to observe different stages of deformation. Comparison of geometrical characteristics of the folds show that folds geometry could not be easily characterized by simple geometric models. Footwall synclines, high-angle thrust faults and flattening of propagated thrust fault into upper décollement levels resulted in a quite complex geometry of folds.

[49] On the basis of our structural analysis, we present a conceptual model for fold evolution in pre-Asmari formations (Figure 20). In the first stage of deformation symmetric buckling of sedimentary rocks situated above the basal décollement is responsible for the first seed of the fold and ductile flow of salt from the basal décollement toward the core of the anticlines. Wavelength at this stage is controlled by the thickness of the sedimentary cover. It could also be influenced by the presence of a deep intermediate décollement level in sedimentary pile as it was shown in the analogue models (Figure 9).

[50] As deformation increased, the structures continue to buckle by hinge migration and limb rotation, which allowed fold to grow with transfer of material from synclines toward the anticlines [*Sherkati et al.*, 2005] (Figures 20b and 20e). At this stage, thrust faults develop from deeper levels. Passage from buckle fold to faulted detachment fold [*Mitra*, 2002] is probably a function of efficiency and thickness of the basal décollement [*Ramberg*, 1970]. Without intermediate ductile units, growth of the fold can continue to achieve the maximum anticlinal size seen today in the Zagros (20 km wavelength anticlines) (Figure 20c). The path of fold development is different when intermediate décollements exist (Figure 20g). As a function of competency contrast between ductile units and competent rocks, at certain stage of fold growth, activation of shearing in ductile units triggered new thrust faults along shallow décollements. The superficial levels accommodate shortening in different ways with respect to the lower competent rocks by formation of duplex, ‘‘fishtail’’ and/or ‘‘rabbit ears’’ structures (Figure 20g).

[51] It is worth noting that our conceptual model does not take into account the role of basement reverse faults as the High Zagros Fault or the Mountain Front Fault (Figures 1 and 4). As discussed by *Sherkati and Letouzey* [2004], *Molinaro et al.* [2005a], and *Sherkati et al.* [2005], these faults, which are currently active, developed at a late stage of the tectonic evolution and cut through already formed structures. These basement faults were certainly inherited from the long and complex geodynamic history of the Zagros. However, as already explained above, the considerable difference in the level of exposure of the bottom of synclines from the southern side of these faults to the northern one (i.e., 3 km for the Mountain Front Fault, Figure 4) strongly supports that their main period of activity postdates the development of detachment folds.

6. Conclusion

[52] Experimental modeling with two décollement levels, show that the position of intermediate décollements is an important factor controlling structural style and fold wavelength. Models with shallow intermediate décollement show regularly and widely spaced anticlines with major thrust faults at depth, the fold wavelength depends directly on the

Figure 16. Typology of the shallow intermediate décollements in central Zagros: the Kazhdumi and Gurpi-Papdeh décollements. (a) Structural map of the central Zagros and north Fars area showing the extent of the Albian shales (Kazhdumi Formation) and Upper Cretaceous to Eocene marls (Gurpi and Pabdeh formations) for 1a, extent of the Gurpi-Papdeh décollement level; 1b, zone where this interval is not a décollement level; 2a, extent of the Kazdhumi décollement level; 2b, zone where this interval is not a décollement level. (b) Zoom into the middle part of the transect C (see Figure 4 for complete section and legend) showing anticlines cored by the Lower Cretaceous carbonates. Superficial folds are almost symmetric and tight with average wavelength of about 3–4 km. Albian shales (Kazhdumi formation) is the main intermediate décollement level in this area. Regional transect shows similarity with model C of the analogue experiments. (c) Zoom into the northern part of transect B (see Figure 4 for complete section and legend), where Gurpi-Pabdeh formations and Albian and Kazhdumi formations were activated as superficial intermediate décollement levels.

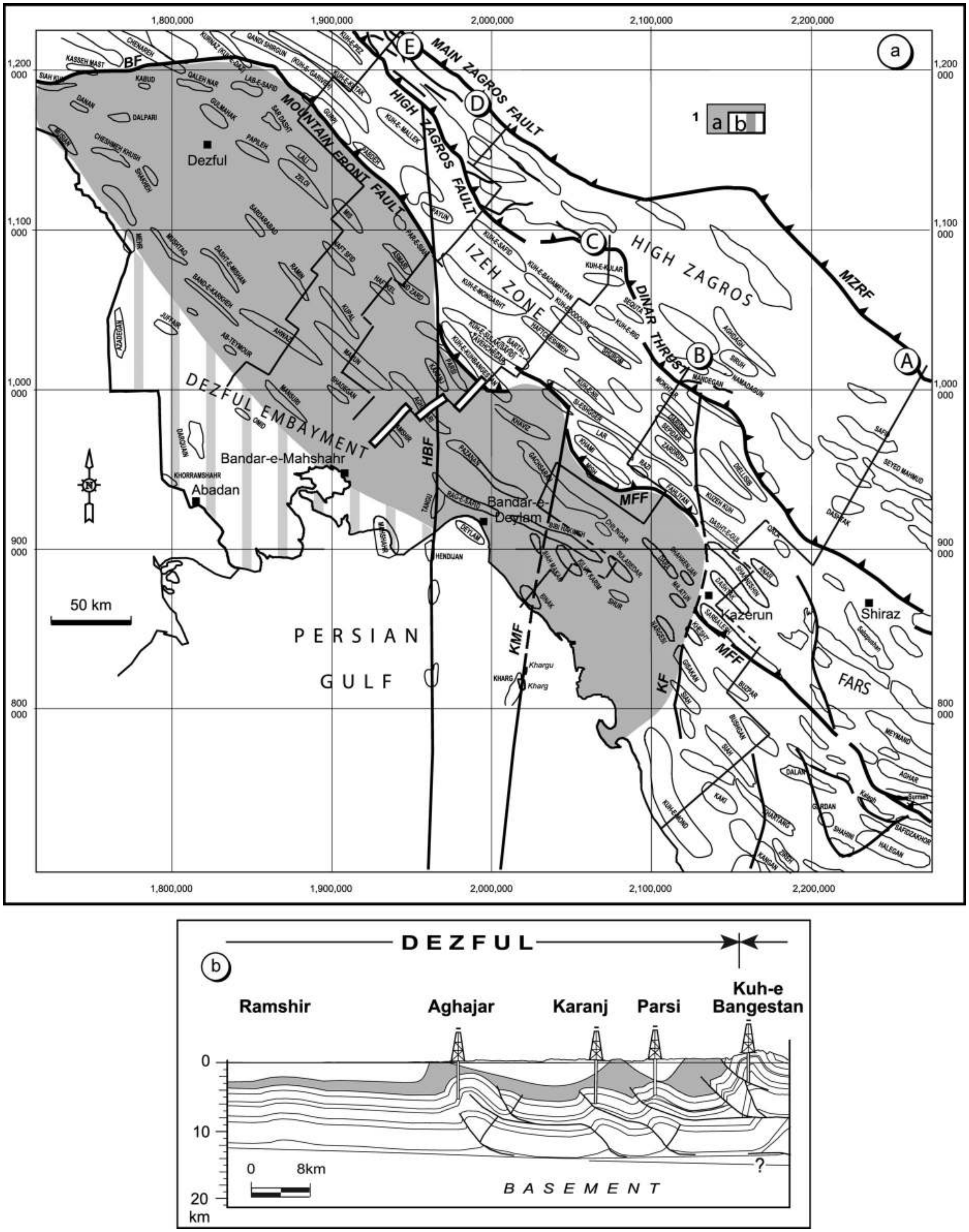

Figure 17. Typology of shallow intermediate décollements in central Zagros: the Gachsaran décollement. (a) Structural map of central Zagros and north Fars area showing the extent of middle Miocene evaporite (Gachsaran Formation). Note that Gachsaran Formation remains an active décollement even in the more external Zagros folds southwest of Dezful Embayment. (b) Example from southern part of transect C (see Figure 4 for complete section and legend), where Gachsaran salt is intermediate décollement level. Notice that post-Gachsaran sediments are completely decoupled from the lower levels.

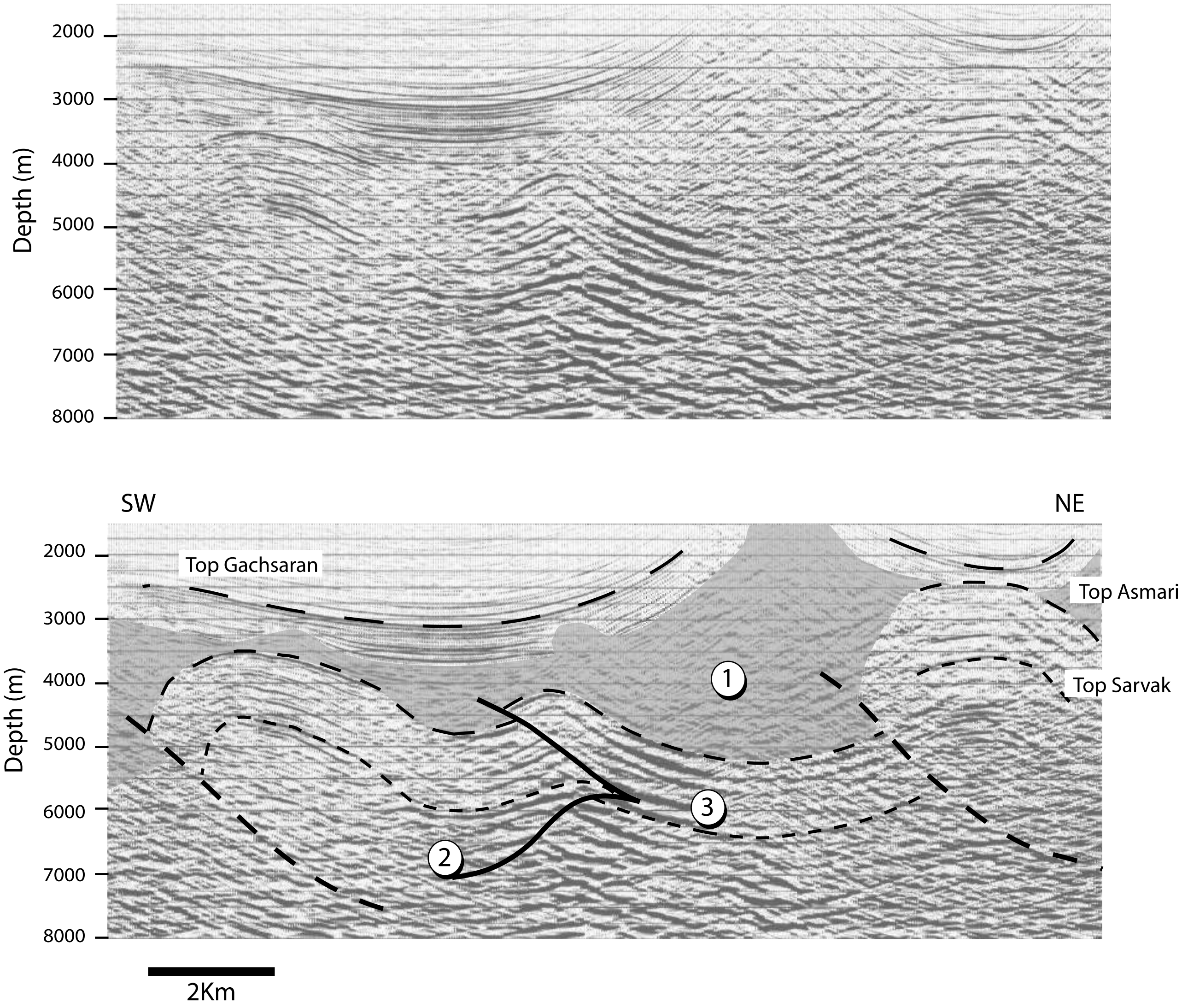

Figure 18. Seismic example of folded structures in the Dezful Embayment, south of the Mountain Front Fault (see location on Figure 1). The lower part of the middle Miocene Gachsaran formation is a major weak zone, which separates two completely different folded domains. Multiple décollement levels at (1) middle Miocene (Gachsaran Formation), (2) Albian (Kazhdumi Formation), and (3) Campanian to Eocene levels (Gurpi and Pabdeh formations) increase the complexity of the fold geometry. They favor development of triangle zones and nonisopach folding.

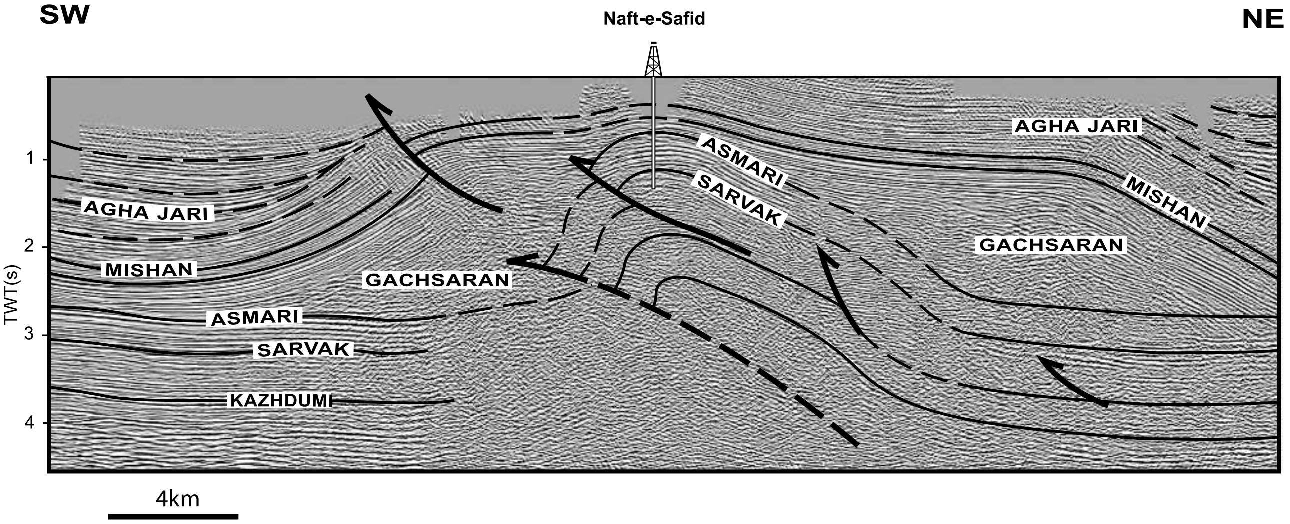

Figure 19. Seismic section through the Naft-e-Safid anticline in the Dezful embayment (see location on Figure 1). The southern flank of the Naft-e-Safid anticline is not imaged by the seismic. However, the difference in elevation from the crest of this anticline to the adjacent syncline is about 4000 m suggesting a steep and faulted southern flank. Seismic horizons within upper Gachsaran Formation correspond to alternation of anhydrite and shale, whereas transparent lower Gachsaran corresponds to mobile salt. Some horizon pinch outs at the bottom and top of Gachsaran formation suggest early tectonic movements in this zone (see *Sherkati et al.* [2005] for a discussion). Small buckling within Asmari Formation likely results from the activation of the Kazhdumi décollement.

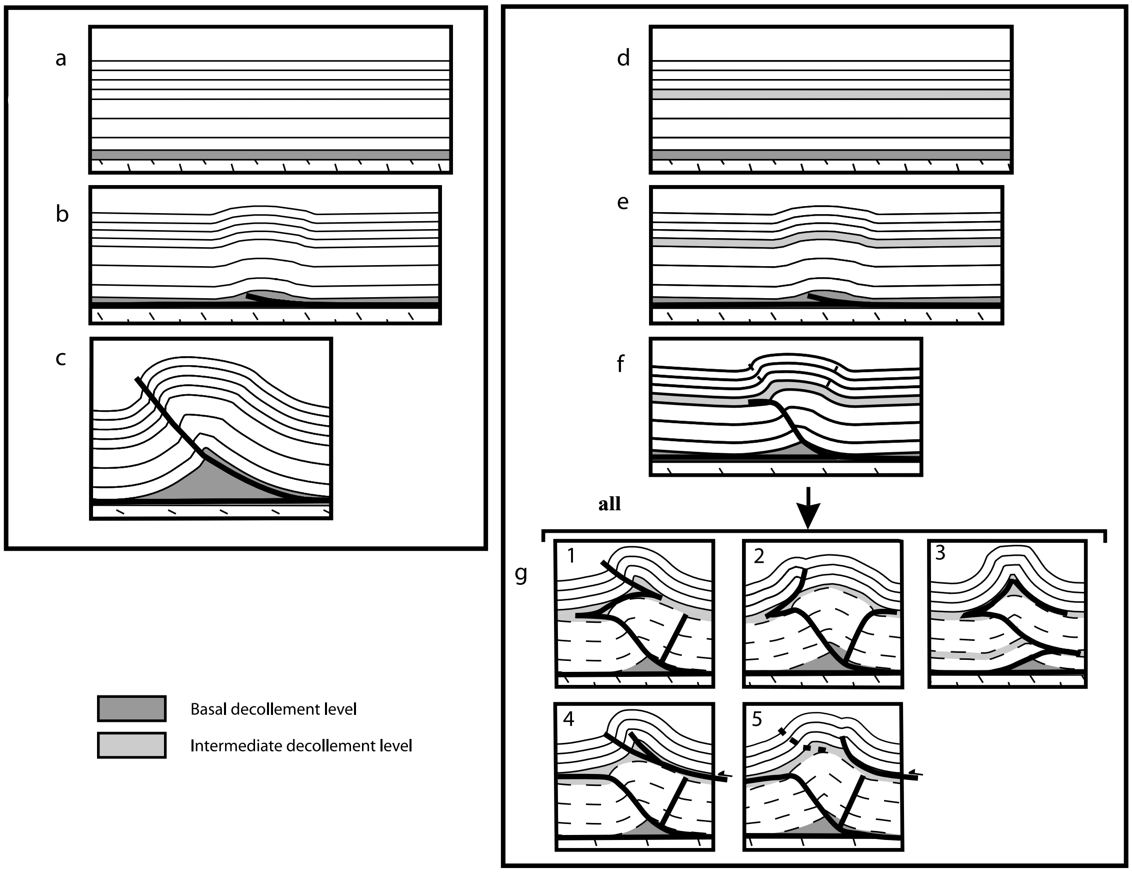

Figure 20. Conceptual kinematic scenario for folding in central Zagros. (a–c) Model without intermediate décollement level, a- state before deformation; b- buckling and migration of the basal ductile unit toward the core of the detachment fold; c- development of the fold with migration of material from synclines toward the anticline and limb rotation. At this stage a major thrust fault develops in deeper the horizons. (d–g) Model with intermediate décollement level, a- state before deformation; b- buckling of the sedimentary pile and slip along the basal décollement level; c- a thrust fault develops in the lower competent unit and a box-fold forms in the upper stiff layer; d- development of secondary structures such as “fishtail” (d1 and d3) or “rabbit ears” folds (d2). The excess of shortening in the upper levels is transferred to an adjacent structure (d4 and d5).

thickness of the dominant competent unit. Short wavelength superficial structures mask broad underlying anticlines. Models with deep intermediate décollement show rapid propagation of deformation (with small rate of shortening) along this décollement influencing localization of forthcoming anticlines in upper levels. Such a propagation favors the development of duplexes at depth and multiwavelength folds, which are controlled by the thickness of the dominant competent unit.

[53] Analysis of field and subsurface data in the central Zagros show that response to deformation in the sedimentary cover varies both laterally and vertically in the sedimentary pile as a function of the distribution of décollement levels and the relative competence of the different formations. On the basis of our analysis of the structures in study area (Figure 4), the distribution of these décollement levels were mapped. Except Gachsaran décollement (see above), which was activated at early stage of folding the other décollement seems to be sequentially activated from basal level upward (Figures 20d–20g). The surface configuration of some folds does not always reflect subsurface structural conditions. So modern seismic acquisition and processing are necessary to image deep structures.

[54] The restoration of the transects in north Fars and central Zagros shows that shortening is of the same order across the study area. It changes from 50 km in north Fars province to 65 km in northwest of central Zagros. However, the same amount of shortening is unequally distributed from one side to the other of the Kazerun transfer zone. In the Fars area, the distribution of deformation is almost homogeneous from inner zone to foreland whereas west of the Kazerun fault zone it is mostly concentrated in inner zones. The absence of Hormuz salt west of Kazerun fault could explain the difficulty in the propagation of deformation in central Zagros as suggested by previous workers [*Cotton and Koyi*, 2000; *Bahroudi and Koyi*, 2003; *Sepehr and Cosgrove*, 2004, 2005].

[55] The observed final geometries resulted from implication of intermediate décollement levels in folding and thrusting. Activation of these ductile units within the sedimentary cover during continuous folding triggered new thrust faults in shallower levels and favored the development of fishtail and a variety of small-scale structures, which are not easily characterized by existing geometrical models.

[56] **Acknowledgments.** The authors thank the National Iranian Oil Company (NIOC) exploration staff for permission to publish this paper and particularly M. Mohaddes, M. Zadeh Mohammadi, and A. Ahmadnia for their continuing support over many years. We acknowledge our colleagues from Institut Français du Pétrole (IFP) and Université de Cergy-Pontoise and in particular C. Aubourg, J. M. Daniel, J. C. Guézou, P. Leturmy, M. Molinaro, and J. L. Rudkiewicz, for helpful discussions during this study. S.S. acknowledges a Ph.D. grant from the NIOC and TOTAL. Special thanks are due to Eric Blanc, Hemin Koyi, and Jaume Vergés for their helpful reviews.

References

Agard, P., J. Omrani, L. Jolivet, and F. Mouthereau (2005), Convergence history across Zagros (Iran): Constraints from collisional an earlier deformation, *Int. J. Earth Sci.*, *94*, 401–419.

Ala, M. A. (1974), Salt diapirism in southern Iran, *AAPG Bull.*, *58*, 758–770.

Alavi, M. (1991), Sedimentary and structural characteristics of the Paleo-Tethys remnant in NE Iran, *Geol. Soc. Am. Bull.*, *103*, 983–992.

Authemayou, C., O. Bellier, D. Chardon, Z. Malekzade, and M. Abassi (2005), Role of the Kazerun fault system in active deformation of the Zagros fold-and-thrust belt (Iran), *C. R. Geosci.*, *337*, 539–545.

Bahroudi, A., and H. A. Koyi (2003), Effect of spatial distribution of Hormuz salt and deformation style in the Zagros fold and thrust belt: An analogue modeling approach, *J. Geol. Soc. London*, *160*, 719–733.

Berberian, M. (1995), Master "blind" thrust faults hidden under the Zagros folds: Active basement tectonics and surface morphotectonics, *Tectonophysics*, *241*, 193–224.

Berberian, M., and G. C. P. King (1981), Towards a paleogeography and tectonic evolution of Iran, *Can. J. Earth Sci.*, *18*, 210–265.

Biot, M. A. (1961), Theory of folding of stratified viscoelastic media and its implications in tectonics and orogenesis, *Geol. Soc. Am. Bull.*, *72*, 1595–1620.

Blanc, E. J. P., M. B. Allen, S. Inger, and H. Hassani (2003), Structural styles in the Zagros simple folded zone, Iran, *J. Geol Soc. London*, *160*, 401–412.

Bonini, M. (2003), Detachment folding, fold amplification, and diapirism in thrust wedge experiments, *Tectonics*, *22*(6), 1065, doi:10.1029/2002TC001458.

Colletta, B., J. Letouzey, R. Pinedo, J. F. Ballard, and P. Bale (1991), Computerised X-ray tomography analysis of sand-box models: Examples of thin-skinned thrust systems, *Geology*, *19*, 1063–1067.

Colman-Sadd, S. P. (1978), Fold development in Zagros Simply Folded Belt, southwest Iran, *AAPG Bull.*, *62*, 984–1003.

Cotton, J. T., and H. A. Koyi (2000), Modeling of thrust fronts above ductile and frictional detachments: Application to structures in the Salt Range and Potwar Plateau, Pakistan, *Geol. Soc. Am.a Bull.*, *112*, 351–363.

Couzens-Schultz, B. A., B. C. Vendeville, and D. V. Wiltschko (2003), Duplex style and triangle zone formation: Insights from physical modeling, *J. Struct. Geol.*, *25*, 1623–1644.

Currie, J. B., H. W. Patnode, and R. P. Trump (1962), Development of folds in sedimentary strata, *Geol. Soc. Am. Bull.*, *73*, 655–674.

Dahlstrom, C. D. A. (1969), Balanced cross sections, *Can. J. Earth Sci.*, *6*, 743–757.

Davis, D. M., and T. Engelder (1985), The role of salt in fold-and-thrust belts, *Tectonophysics*, *19*, 67–88.

Edgell, H. S. (1996), Salt tectonism in the Persian Gulf Basin, in *Salt Tectonics*, edited by J. L. Alsop, D. J. Blundell, and I. Davison, *Geol. Soc. Spec. Publ.*, *100*, 129–151.

Falcon, N. (1969), Problems of the relationship between surface structure and deep displacements illustrated by Zagros range, in *Time and Place in Orogeny*, edited by P. E. Kent, G. E. Satterthwaite, and A. M. Spencer, *Geol. Soc. Spec. Publ.*, *3*, 9–22.

Falcon, N. (1974), Southern Iran: Zagros mountains, in *Mesozoic-Cenozoic Orogenic Belts*, edited by A. Spencer, *Geol. Soc. Spec. Publ.*, *4*, 199–211.

Gratier, J. P., and J. F. Gamond (1990), Transition between seismic and aseismic deformation in the upper crust, *Geol. Soc. Spec. Public.*, *54*, 461–473.

Grelaud, S., W. Sassi, D. Frizon de Lamotte, T. Jaswal, and F. Roure (2002), Kinematics of eastern Salt Range and south Potwar Basin (Pakistan): A new scenario, *Mar. Petrol. Geol.*, *19*, 1127–1139.

Harrison, J. C., and A. W. Bally (1988), Cross sections of the Parry Islands fold belt on Melville Island, Canadian arctic islands: Implications for the timing and kinematic history of some thin-skinned decollement systems, *Bull. Can. Petl. Geol.*, *36*, 311–332.

Harrison, J. V. (1930), The geology of some salt plugs in Laristan (southern Persia), *Q. J. Geol. Soc. London.*, *86*, 463–522.

Haynes, S. J., and H. McQuillan (1974), Evolution of the Zagros suture zone, southern Iran, *Geol. Soc. Am. Bull.*, *85*, 739–744.

Hessami, K., H. A. Koyi, C. J. Talbot, H. Tabasi, and E. Shabanian (2001), Progressive unconformities within an evolving foreland fold-thrust belt, Zagros mountains, *J. Geol. Soc. London*, *158*, 969–981.

Homke, S., J. Vergés, M. Garcés, H. Emami, and R. Karpuz (2004), Magnetostratigraphy of Miocene-Pliocene Zagros foreland deposits in the front of the Push-e-Kush arc (Lurestan province, Iran), *Earth Planet. Sci. Lett.*, *225*, 397–410.

Husseini, M. I. (1988), The Arabian Infracambrian extensional system, *Tectonophysics*, *148*, 93–103.

Kashfi, M. S. (1976), A source bed study of the Oligo-Miocene Asmari limestone in SW Iran, *J. Pet. Geol.*, *7*, 419–428.

Kent, P. E. (1970), The salt plugs of the Persian Gulf region, *Leicester Lit. Philos. Soc. Trans.*, *64*, 56–88.

Kent, P. E. (1986), Island salt plugs in the Middle East and their tectonic implications, in *Dynamical Geology of Salt and Related Structures*, edited by I. Leiche and J. J. O'Brien, pp. 3–37, Elsevier, New York.

Konert, G., A. M. Afifi, S. A. Al-Hajri, K. De Groot, A. A. Al Naim, and H. J. Droste (2001), Palaeozoic stratigraphy and hydrocarbon habitat of the Arabian plate, in *Petroleum Provinces of the Twenty-First Century*, edited by M. W. Downey, J. C. Threet, and W. A. Morgan, *AAPG Mem.*, *74*, 483–515.

Koop, W. J., and R. Stoneley (1982), Subsidence history of the Middle East Zagros Basin, Permian to Recent, *Philos. Trans. R. Soc. London, Ser. A*, *305*, 149–168.

Koyi, H. A., M. Sans, and A. Bahroudi (2004), Modelling the deformation front of fold-thrust belts containing multiple weak horizons, *Bull. Geofis. Teorica Appl.*, *45*, 101–103.

Lacombe, O., F. Mouthereau, S. Kargar, and B. Meyer (2006), Late Cenozoic and modern stress fields in the western Fars (Iran): Implications for the tectonic and kinematic evolution of central Zagros, *Tectonics*, *25*, TC1003, doi:10.1029/2005TC001831.

Letouzey, J., and S. Sherkati (2004), Salt movement, tectonic events and structural style in the central Zagros fold and thrust belt (Iran), in *24th Annual GCSSEPM Foundation, Salt-Sediments Interactions and Hydrocarbon Prospectivity, Concepts, Applications and Case Studies for the 21st Century* [CD-ROM], Soc. of Econ. Paleontol. and Mineral. Found., Houston, Tex.

Letouzey, J., B. Colletta, R. Vially, and J. C. Chermette (1995), Evolution of salt related structures in compressional setting, in *Salt Tectonics: A Global Perspective*, edited by M. P. A. Jackson, D. G. Roberts, and S. Snelson, *AAPG Mem.*, *65*, 41–60.

Letouzey, J., S. Sherkati, J. M. Mengus, H. Motiei, M. Ehsani, A. Ahmadnia, and J. L. Rudkiewicz (2002), A regional structural interpretation of the Zagros Mountain Belt in northern Fars and High Zagros (SW Iran), paper presented at AAPG Annual Meeting, Houston, Tex.

Massoli, D., H. A. Koyi, and M. R. Barchi (2006), Structural evolution of a fold and thrust belt generated by multiple décollements: Analogue models and natural examples from the northern Apennines (Italy), *J. Struct. Geol.*, *28*, 185–190.

McQuarrie, N. (2004), Crustal scale geometry of the Zagros fold-thrust belt, Iran, *J. Struct. Geol.*, *26*, 519–535.

Mitra, S. (2002), Structural models of faulted detachment folds, *AAPG Bull.*, *86*, 671–693.

Molinaro, M., P. Leturmy, J. C. Guezou, D. Frizon de Lamotte, and S. A. Eshragi (2005a), The structure and kinematics of the south-eastern Zagros fold - thrust belt, Iran: From thin-skinned to thick-skinned tectonics, *Tectonics*, *24*, TC3007, doi:10.1029/2004TC001633.

Molinaro, M., H. Zeyen, and X. Laurencin (2005b), Lithospheric structure beneath the south-eastern Zagros Mountains, Iran: Recent slab break-off?, *Terra Nova*, *17*, 1–6.

Moretti, I., and M. Larrère (1989), Computer-aided construction of balanced geological cross sections, *Geobyte*, *Oct. 1989*, 2–24.

Motiei, H. (1994), Stratigraphy of Zagros (in Farsi), report, Geol. Surv. of Iran, Tehran.

Motiei, H. (1995), Petroleum geology of Zagros (in Farsi), vols. 1 and 2, Geol. Surv. of Iran, Tehran.

Murris, R. J. (1980), Middle East: Stratigraphic evolution and oil habitat, *AAPG Bull.*, *64*, 597–618.

O'Brien, C. A. E. (1957), Salt diapirism in south Persia, *Geol. Mijnbouw*, *19*, 357–376.

Peters, J. M., J. Filbrandt, J. Grotzinger, M. Newall, M. Shuster, and H. Al-Siyabi (2003), Surface-piercing Salt Domes of interior north Oman, and their significance of the Ara Carbonate "Stinger" hydrocarbon play, *Geoarabia*, *8*, 231–270.

Ramberg, H. (1970), Folding of laterally compressed multilayers in the field of gravity, *Phys. Earth Planet. Inter.*, *2*, 203–232.

Ricou, L. E. (1971), Le croissant ophiolitique périarabe. Une ceinture de nappes mises en place au Crétacé supérieur, *Rev. Geogr. Phys. Geol. Dyn.*, *13*, 327–350.

Sans, M., and J. Vergés (1995), Fold development related to continental salt tectonic: Southeastern Pyrenean thrust front, Spain, in *Salt Tectonics: A Global Prospective*, edited by M. P. A. Jackson, D. G. Roberts, and S. Snelson, *AAPG Mem.*, *65*, 369–378.

Sattarzadeh, Y., J. W. Cosgrove, and C. Vita-Finzi (2000), The interplay of faulting and folding during the evolution of the Zagros deformation belt, in *Forced Folds and Fractures*, edited by J. W. Cosgrove and M. S. Ameen, *Geol. Soc. Spec. Publ.*, *169*, 187–196.

Sepehr, M., and J. W. Cosgrove (2004), Structural framework of the Zagros fold-thrust belt, Iran, *Mar. Pet. Geol.*, *21*, 829–843.

Sepehr, M., and J. W. Cosgrove (2005), Role of the Kazerun Fault Zone in the formation and deformation of the Zagros fold-thrust belt, Iran, *Tectonics*, *24*, TC5005, doi:10.1029/2004TC001725.

Setudehnia, A. (1978), The Mesozoic sequence in south-west Iran and adjacent areas, *J. Petrol. Geol.*, *1*, 3–42.

Sherkati, S., and J. Letouzey (2004), Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), *Iran, Mar. Pet. Geol.*, *21*, 535–554.

Sherkati, S., M. Molinaro, D. Frizon de Lamotte, and J. Letouzey (2005), Detachment folding in the central and eastern Zagros fold-belt (Iran), *J. Struct. Geol.*, *27*, 1680–1696.

Stampfli, G. M., and G. D. Borel (2004), The TRANSMED transects in space and time: Constraints on the paleotectonic evolution of the Mediterranean domain, in *The TRANSMED Atlas, The Mediterranean Region From Crust to Mantle*, edited by W. Cavazza et al., pp. 53–80, Springer, New York.

Stocklin, J. (1968), Structural history and tectonics of Iran: A review, *AAPG Bull.*, *52*, 1229–1258.

Szabo, F., and A. Kheradpir (1978), Permian and Triassic stratigraphy, Zagros basin, south-west Iran, *J. Pet. Geol.*, *1*, 57–82.

Taati, F., F. Van-Buchem, and P. Razin (2003), High resolution sequence stratigraphy of the Bangestan group in a tectonically active setting (Dezful- Izeh) Zagros-Iran, paper presented at AAPG International Conference, Barcelona, Spain.

Talebian, M., and J. Jackson (2004), A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran, *Geophys. J. Int.*, *156*, 506–526.

Teixell, A., and H. A. Koyi (2003), Experimental and field study of the effects of lithological contrasts on thrust-related deformation, *Tectonics*, *22*(5), 1054, doi:10.1029/2002TC001407.

Van Buchem, F., F. Gaumet, D. Baghbani, R. Ashrafzadeh, and F. Keyvani (2003), The relative impact of inherited tectonic features and eustatic sea level variations on the Jurassic/Cretaceous evolution of the Dezful Embayment, central Zagros, Iran, paper presented at AAPG International Conference, Barcelona, Spain.

Woodward, N. B., S. E. Boyer, and J. Suppe (1985), An outline of balanced cross sections, in *Studies in Geology II*, 170 pp., Dep. of Geol. Sci., Univ. of Tenn., Knoxville.

D. Frizon de Lamotte, Département des science de la Terre et Environnement (CNRS UMR 7072), Université de Cergy-Pontoise, F-95031 Cergy Cedex, France. (dfrizon@u-cergy.fr)

J. Letouzey, Institut Français du Pétrole, BP 311, F-92852 Rueil-Malmaison Cedex, France. (jean.letouzey@ifp.fr)

S. Sherkati, National Iranian Oil Company, Yaghma allay, Jomhouri avenue, Tehran, Iran. (ssherkati@niocexp.org)