



HAL
open science

The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics

M. Molinaro, Pascale Leturmy, Jean-Claude Guezou, Dominique Frizon de Lamotte

► To cite this version:

M. Molinaro, Pascale Leturmy, Jean-Claude Guezou, Dominique Frizon de Lamotte. The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics. *Tectonics*, 2005, 24 (3), pp.TC3007. 10.1029/2004TC001633 . hal-00022420

HAL Id: hal-00022420

<https://hal.science/hal-00022420>

Submitted on 20 May 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics

M. Molinaro, P. Leturmy, J.-C. Guezou, and D. Frizon de Lamotte

Département des Sciences de la Terre et de l'Environnement, UMR 7072, CNRS, Université de Cergy-Pontoise, Cergy, France

S. A. Eshraghi

Geological Survey of Iran, Tehran, Iran

Received 17 February 2004; revised 14 February 2005; accepted 11 March 2005; published 15 June 2005.

[1] We present the first complete balanced cross section across the southeastern Zagros fold-thrust belt (ZFTB). The following main structural features emerge from this section: (1) In the south of the ZFTB, the Proterozoic-to-Recent sedimentary sequence has been decoupled from its Panafrican basement along the ductile basal evaporites and folded into a series of large detachment anticlines. Ongoing shortening of these structures has resulted in migration of the basal salt layers into the cores of the anticlines and propagation of forelimb thrusts. (2) In the north of the ZFTB, deep-seated ramps have folded the hanging wall rocks and produced imbrications and duplex structures within the higher levels of the sedimentary sequence. (3) Out-of-sequence thrusts, linked to major seismogenic basement faults, have cut through the structures in the cover of the ZFTB. A three-step incremental restoration of the section shows that two main phases of deformation can be separated in the tectonic evolution of the ZFTB: a Mio-Pliocene thin-skinned phase, in the course of which most of the structures in the cover were generated, followed by a Pliocene to Recent thick-skinned phase, expressed as out-of-sequence faulting in the cover, which is currently underlined by the seismicity within the basement. In plan view, the initial structures of the southeastern ZFTB developed with a curved shape essentially controlled by the shape and thickness of the underlying Proterozoic salt basin (i.e., the “Jura style”). In the following basement-involved phase, out-of-sequence thrusts cut at oblique angles through the preexisting structures of the cover. The total shortening absorbed in the cover amounts to at least 45 km, corresponding to a ratio of ~22%. **Citation:** Molinaro, M., P. Leturmy, J.-C. Guezou, D. Frizon de Lamotte, and S. A. Eshraghi (2005), The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran:

From thin-skinned to thick-skinned tectonics, *Tectonics*, 24, TC3007, doi:10.1029/2004TC001633.

1. Introduction

[2] In the general context of the Alpine-Himalayan orogenic system, the Zagros fold-thrust belt (ZFTB) is the most recent result of the convergence and closure of the Neo-Tethys oceanic domain between Arabia and Eurasia [Takin, 1972; Haynes and McQuillan, 1974; Ricou *et al.*, 1977; Alavi, 1994; Stampfli *et al.*, 2001] (Figure 1). In the ZFTB, the Arabian passive margin sequence has been decoupled from its basement and deformed by large-scale folding and thrusting. A strong seismicity record indicates that within the underlying Panafrican basement shortening is presently accommodated by reverse faulting [Jackson and Fitch, 1981; Berberian, 1995]. Despite its evident interest as a major petroleum province, and compared to other mountain chains around the world, relatively little is known of the architecture and kinematics of deformation in Zagros. Although some general sections of the ZFTB have been proposed in recent papers [Blanc *et al.*, 2003; McQuarrie, 2004; Sherkati and Letouzey, 2004], aspects such as the kinematics of individual folds, the sequence of fold-and-thrust development and the relationship between deformation within the cover and basement structures remain yet to be defined.

[3] In this paper, we discuss new data and interpretations based upon field and map observations from the southeastern extremity of the Zagros ranges, close to the transition with the Makran accretionary prism. We present the first complete balanced cross section through this part of the ZFTB. The cross section constitutes the centerpiece of our paper and will allow us (1) to precisely define the main architectural elements of the ZFTB in this area, (2) to propose a kinematic model for the development of the ZFTB since Miocene times as well as discuss the kinematics of individual structures and (3) to propose a tentative reconstruction of the map view evolution of structures in the southeastern segment of the ZFTB. In particular we will show that two major and discrete phases can be separated in the tectonic evolution of the ZFTB: an initial thin-skinned phase of deformation

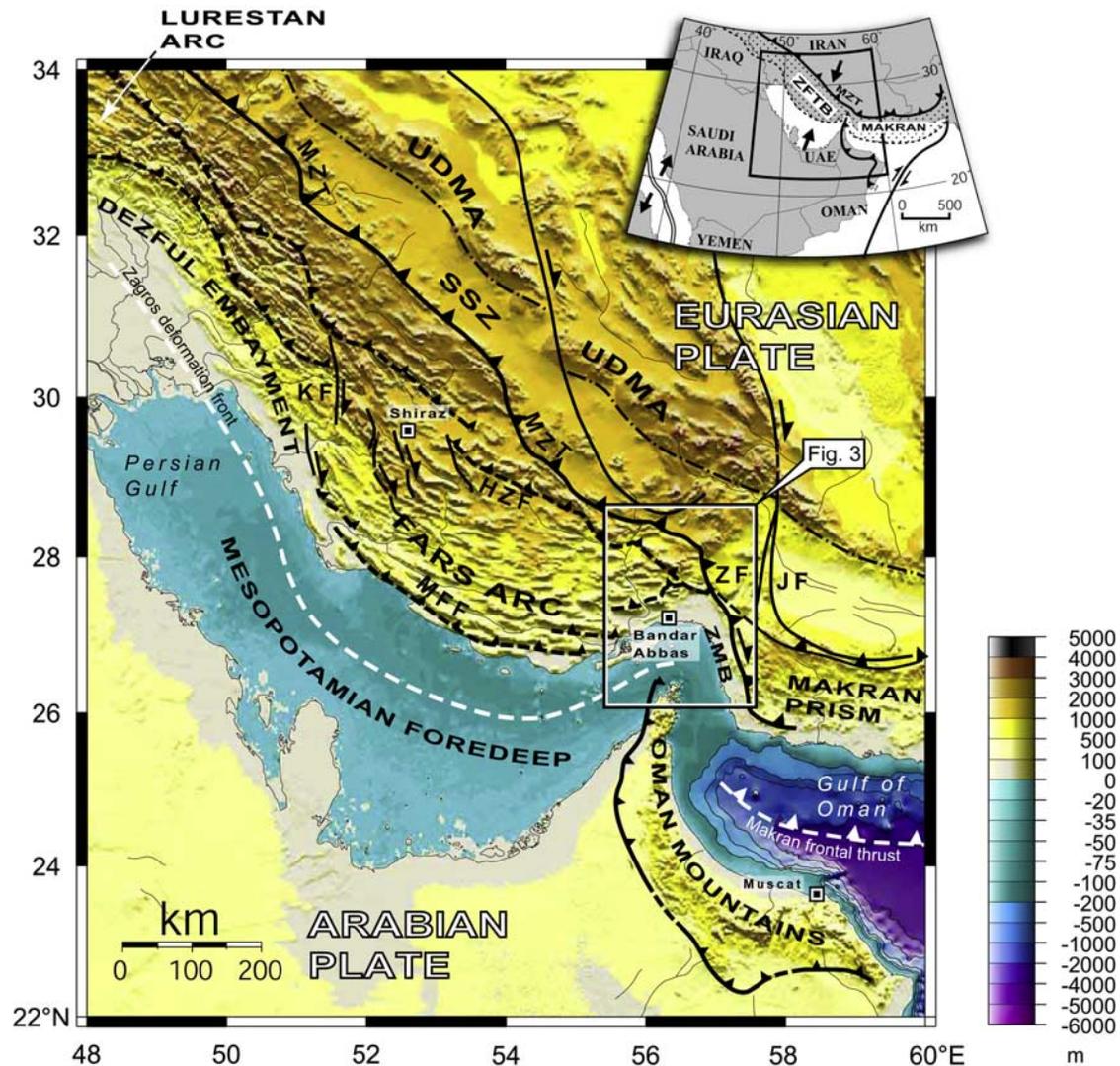


Figure 1. Physical map (source GEBCO data) and main structural features of the southeastern active Zagros Fold-Thrust Belt (ZFTB). SSZ, Sanandaj Sirjan Zone; UDMA, Urumieh Dokhtar Magmatic Arc; MZT, Main Zagros Thrust; ZF, Zendan Fault; KF, Kazerun Fault; JF, Jiroft Fault; MFF, Mountain Front Fault; HZF, High Zagros Fault. Inset is a location map showing the principal tectonic features of the Arabian-Iranian convergent margin.

followed and partly overprinted by a thick-skinned phase of deformation.

2. Methods and Geological Setting

2.1. Location and Methods

[4] The study area is located in the southeastern part of the orogen, close to the transition to the Makran subduction prism (Figure 1). In this region, the tectonic structures of the ZFTB describe a large festoon-shaped arc known as the Fars arc. Farther east, the transition to the Makran prism is marked by a pronounced reentrant underlined by the Oman peninsula jutting out into the Strait of Hormuz. In this area, known as the Bandar Abbas syntaxis, the structures of the ZFTB are connected by a narrow fold-and-thrust belt (the

Zendan-Minab belt [Molinaro *et al.*, 2004; Regard *et al.*, 2004]) to the western branch of the Makran arc.

[5] The work presented here is based in part on fieldwork carried out in the area directly north of the city of Bandar Abbas up to the town of Hadjiabad (Figure 1). Existing 1:100,000 and 1:250,000 scale geological maps of this region were modified and completed by satellite SPOT image analysis and mapping based upon our fieldwork. Compared to previous maps, this work allowed us to complete and better define the structural framework at various locations around the Bandar Abbas syntaxis. In particular detailed mapping was performed in the Minab and Hadjiabad areas [see also Molinaro *et al.*, 2004], on the structures aligned on the High Zagros Fault (HZF) (Jain, Faragun, and Kuh-e-Khush) and in the area around the junction between the Main Zagros Fault (MZT) and Zendan

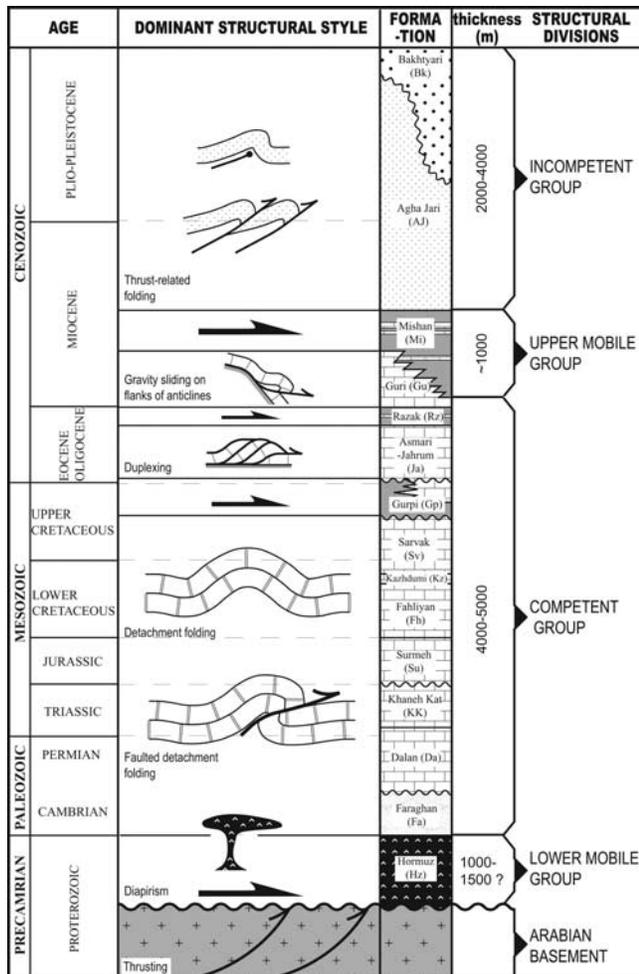


Figure 2. Mechanical stratigraphy of the southeastern ZFTB illustrating the dominant structural styles and detachment horizons as observed on the field for the various lithostratigraphic units. Structural divisions are slightly modified after O'Brien's [1957] classification. Stratigraphy and thickness of units are based on a compilation of authors' fieldwork and data from James and Wynd [1965], Szabo and Kheradpir [1978], and Sharland et al. [2001].

Fault (ZF). We constructed a 160-km-long line length balanced cross section starting from the city of Bandar Abbas and ending just north of the MZT. The section is based primarily upon surface data, with additional constraints from published focal mechanisms of seismic events and aeromagnetic surveys. Recent paleomagnetic and magnetic fabric studies provide support for a discussion on a final model attempting to explain the map view evolution of structures in the southeastern segment of the ZFTB.

2.2. Geodynamic Context

[6] The main structural features and the history of the Zagros Mountains are well known [Stocklin, 1968; Falcon, 1969; Ricou, 1974; Alavi, 1994]. In the course of the

collisional process, the Proterozoic-to-Recent sedimentary pile accumulated on the Arabian margin has been detached from its Panafrican crystalline basement and folded into a 2000-km-long mountain belt. The deformation front advanced into the foreland, generating a fold-thrust belt of exceptional width, the so-called Zagros fold-thrust belt (ZFTB). Flanking the ZFTB to the NE and parallel to it are the Sanandaj Sirjan Zone (SSZ), consisting of strongly deformed and imbricated metamorphic and sedimentary rocks, and the Urumieh-Dokhtar Magmatic Arc (UDMA), an Andean-type volcanic magmatic arc [Alavi, 1994] (Figure 1). The first major tectonic event in the development of the Zagros orogen was the late Cretaceous obduction of the Neo-Tethyan oceanic crust onto the Arabian margin [Stampfli et al., 2001]. This event effectively ceased toward the end of Campanian times, while the remnant Neo-Tethys oceanic crust continued to subduct beneath the Central Iran plate until the onset of the collision, presumably in Oligocene-Miocene times [Koop and Stoneley, 1982]. The collisional process is currently still active, with a N-S directed convergence rate of approximately 30 mm/yr according to the NUVEL-1A plate motion model [DeMets et al., 1994]. However, recent GPS data suggest a lower velocity ($\sim 20 \pm 2$ mm/yr) of Arabia relative to Iran [Vernant et al., 2004]. GPS data also suggest that about half of the convergence is taken up by Zagros. The direction of shortening is roughly N-S, with orientations ranging between $N7^\circ E$ (in southeastern Zagros) and $N3^\circ W$ (in the NW). The convergence rates are seen steadily increasing from NW to SE, from 9 ± 2 mm/yr in the southeastern ZFTB to 6.5 ± 2 mm/yr and 4.5 ± 2 mm/yr in central and northern Zagros, respectively.

2.3. Mechanical Stratigraphy of the Zagros Fold-Thrust Belt in the Bandar Abbas Area

[7] The stratigraphic pile of the Arabian margin was first subdivided by O'Brien [1957] into a number of tectono-stratigraphic units defined by contrasting mechanical behaviors. In this paper we adopt the principle of this scheme (Figure 2). However, we have added some modifications in the assignment of formations to the units, since the stratigraphic sequence in the Bandar Abbas area differs from the one considered by O'Brien [1957]. Also for some of the formations or groups of formations we have given a schematic representation of the dominant structural style as observed in the field.

[8] At the base of the sedimentary pile is the rigid Panafrican basement, corresponding to the Arabian metamorphic shield. Relatively little is known about these rocks, since in no place the basement is outcropping except as rare "exotic blocks" transported to the surface by salt diapirs [Haynes and McQuillan, 1974; Kent, 1979]. Because of the lack of published seismic and borehole data, the depth to the basement remains uncertain. Published focal mechanisms show that most of the seismic activity is concentrated at depths between 8 and 12 km [Jackson and Fitch, 1981; Berberian, 1995; Talebian and Jackson, 2004]. The earthquake hypocenters are interpreted as being located along reverse faults below the Hormuz salt, thus providing a

minimum estimate of depth to basement of ~ 8 km, a depth that is roughly confirmed by the results of aeromagnetic surveys carried out in the 1970s [Morris, 1977] and by other sources (S. Sherkati, personal communication, 2004).

[9] Resting directly upon the basement is the Lower Mobile Group, represented by the late Precambrian Hormuz evaporite layers. This level constitutes the main regional decollement level for most of the larger folds within the ZFTB. Given the large amounts of salt extruded by the diapirs, especially on the eastern side of the Fars arc, the initial thickness must have been considerable, around 1–1.5 km [Colman-Sadd, 1978; Kent, 1979]. However, subsequent Zagros folding has remobilized the salt, causing it to flow from the synclines toward the cores of the anticlines. Therefore its present-day thickness must be highly variable, ranging from almost zero beneath the synclines to perhaps thousands of meters in the cores of the anticlines [Edgell, 1996].

[10] A 4000- to 5000-m-thick Cambrian to lower Miocene sequence forms the so-called Competent Group. Apart from the initial Cambrian-Carboniferous clastic formations, the majority of this group until Upper Cretaceous consists of massive platform carbonate rocks [James and Wynd, 1965; Szabo and Kheradpir, 1978; Sharland et al., 2001]. The upper part of the group is lithologically more differentiated. Approximately 400 m of Upper Cretaceous marine marls (Gurpi formation) are overlain by 400–600 m of competent Eocene limestone-dolomite (Asmari-Jahrum formation) and 50–100 m of distinctive lower Miocene gypsiferous red marl (Razak formation). Polymictic conglomerates are visible within this latter formation, suggesting an important change in depositional environment possibly related to early regional tectonic movements. The Razak formation is the lateral equivalent of the Gachsaran formation, a thick evaporitic layer well known for its structural mobility in Central Zagros [e.g., O'Brien, 1957; Edgell, 1996]. At the top of the Competent Group is the easily recognizable layer of Guri reefal limestone, marking the base of the Mishan marls. Its thickness is extremely variable, ranging from several hundred meters of reefal buildup to zero [James and Wynd, 1965]. From a structural point of view, the Cambrian to Upper Cretaceous sequence is the main unit underlying the large wavelength anticlines of the region. Their geometry at depth, as will be further discussed, corresponds to that of detachment folds and faulted detachment folds. The overlying Gurpi formation is an important regional décollement horizon responsible for the development of imbrications and duplex structures within the Jahrum limestone. The Razak marls serve as a roof decollement for these imbrications. They are also respon-

sible for frequently observed collapse structures within the overlying Guri limestone.

[11] The Upper Mobile Group is usually associated to the lower Miocene Gachsaran formation [O'Brien, 1957]. The structural equivalent to this formation in the area of our study can be found in the incompetent Mishan marls. These consist of distal basin shale and marl alternating with layers of thin-bedded limestone. Although they do not display the same structural mobility as the Gachsaran formation, they constitute the major roof decollement for most of the underlying structures and more or less decouple deformation below and above them. Faults propagating upward through the main detachment folds tend to dissipate displacement within this upper incompetent horizon.

[12] The remainder of the stratigraphic sequence is represented by the Middle Miocene to Recent clastic sediments of the Incompetent Group. These molasse-type sediments, derived from the uplift and erosion of the Zagros Mountains, show a typical coarsening upward evolution from marine-to-continental clastics (Agha Jari Formation) to coarse proximal conglomerates (Bakhtyari Formation) at the top. The total thickness of the Incompetent Group varies considerably due to syntectonic sedimentation, especially in the higher members of the group [Hessami et al., 2001b]; estimates range between 2000 and 4000 m. Structures observed within these formations include small-scale thrusting and thrust-related folds soling out into the Mishan marls.

2.4. General Structure of the Zagros Fold-Thrust Belt

[13] The Zagros Fold-Thrust Belt (ZFTB) (Figure 1) is bordered to the SW by the Persian Gulf, representing the foredeep basin at the front of the orogen, and to the NE by the Main Zagros Thrust (MZT), considered by many as being the suture of the Neo-Tethys Ocean. Classically, the ZFTB is subdivided into two main structural zones distinguished by different topographies and styles of deformation. These are (Figures 1 and 3) the Zagros Simple Fold Belt (ZSFB) to the SW and the High Zagros Belt (HZB) to the NE. In between the two is the so-called High Zagros Fault (HZF). Additionally, the ZFTB can be laterally subdivided into three main segments of changing width and morphology, from NW to SE: the Lurestan Arc, the Dezful Embayment and the Fars Arc (Figure 1).

[14] In the Fars Arc, the Arabian Phanerozoic sequence has been decoupled from its Precambrian crystalline basement along the basal Hormuz salt layers and folded into a succession of huge cylindrical anticlines and synclines. The considerable width of the ZSFB in this area, (up to 250 km in the center of the Fars Arc) as well as its narrow cross-

Figure 3. Geological map of the ZFTB in the Bandar Abbas area compiled from geological maps [National Iranian Oil Company (NIOC), 1977a, 1977b, 1999] and authors' fieldwork [Molinaro et al., 2004]. ZSFB, Zagros Simple Fold Belt; HZB, High Zagros Belt. Other abbreviations are as in Figure 1. The names on the map refer to the major anticlines. A-A' is line of cross section in Figure 4. Boxed area indicates location of geological map in Figure 5. Inset is simplified structural map of the Bandar Abbas (BA) area, showing main fold axes and thrusts. Gray shading indicates NNW trending structures of the Zendan Minab belt.

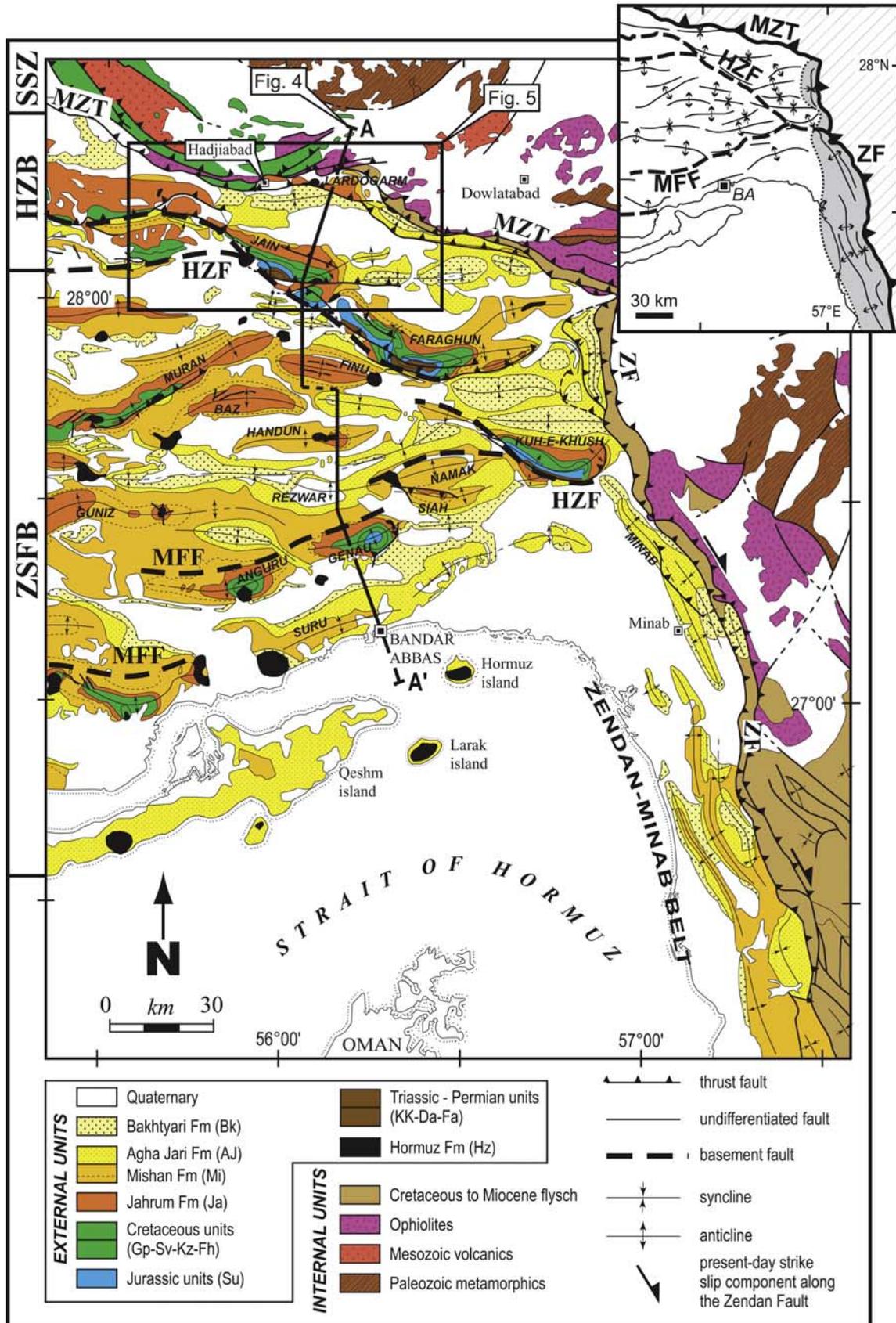


Figure 3

sectional taper ($\sim 1^\circ$ or less) are consistent with the presence of the Hormuz evaporites acting as an efficient basal decollement and permitting the deformation to propagate over large distances [Davis and Engelder, 1985]. The style of folding is typically that of detachment folding [e.g., Colman-Sadd, 1978; Molinaro *et al.*, 2004], although Sattarzadeh *et al.* [2000], based upon the variability of the observed aspect ratios, suggested that also forced folds (i.e., folds forced by slip on an underlying fault) are present in the ZSFB.

[15] The ZFTB is characterized by a relatively intense seismic activity increasing from NW to SE and terminating abruptly at the transition between the eastern limb of the Fars Arc and the Makran prism. Recent studies have shown that nearly all earthquakes in Zagros are confined to depths shallower than 20 km [Maggi *et al.*, 2000; Talebian and Jackson, 2004]. This seismic activity is currently the strongest line of evidence put forward by authors to prove the involvement of the crystalline basement in the Zagros Neogene deformation [e.g., Jackson and Fitch, 1981; Kadinski-Cade and Barazangi, 1982; Baker *et al.*, 1993; Berberian, 1995; Talebian and Jackson, 2004]. Numerous blind faults are known to be active beneath the sedimentary cover. In particular the active Mountain Front Fault (MFF) and High Zagros Fault (HZF) are considered to be major segmented reverse faults, whose seismogenic and morphologic signature is recognized throughout the Zagros orogen [Berberian, 1995]. Movement accumulated by the ensemble of these faults has generated a total vertical displacement in the order of several kilometers (up to 6 km, according to Berberian [1995]). As a result, the level of exposure within the cover rocks changes considerably from one side to the other of the basement faults. This is particularly evident in northwestern Zagros, in the area of the Dezful Embayment (Figure 1), where the trace of the MFF is marked by an important step in the elevation of the same formations from one side to another of the fault [Sherkati and Letouzey, 2004]. Similarly, the Paleozoic rocks outcropping NE of the HZF (in the High Zagros Belt), are never exposed in the folded zone farther to the southwest [Berberian, 1995].

2.5. Structure of the Bandar Abbas Syntaxis

[16] The Bandar Abbas syntaxis (Figure 3) includes the easternmost folds and thrusts of the Fars Arc. To the east these structures abruptly give way to the NNW trending structures of the Zendan-Minab belt. This transition is marked by a noticeable change in the style of folding which has been shown to reflect the transition between changing decollement levels [Molinaro *et al.*, 2004].

[17] The seismicity in this area is among the strongest in the Zagros orogen. The focal mechanisms are predominantly of reverse type and occur at depths between 8 and 17 km [Talebian and Jackson, 2004]. They locally define clear alignments which have been attributed to the MFF and HZF basement faults [Berberian, 1995]. Some reverse focal mechanisms are also reported north of the MZT at depths increasing to a maximum of 28 km and have been attributed to underthrusting of the Arabian basement beneath

the metamorphic belt [Talebian and Jackson, 2004]. The HZF is matched at surface by a major NW trending alignment of three giant tectonic structures (Jain, Faraghun and Kuh-e-Khush structures) extending between the tip of the Minab fold (SE) and the MZT in the area of the town of Hadjiabad (NW) (Figure 3). These structures represent major topographic features in the region, reaching elevations of 3000 m and exposing at their base rocks as old as Silurian [Szabo and Kheradpir, 1978]. The dominant trend of these structures is NW-SE. However, it can be noticed that their eastern tips tend toward the ENE trend of other folds in the area. The HZF and its associated structures separate the region into two main structural zones roughly corresponding to the previously defined ZSFB and HZB zones (Figure 3 and inset).

[18] 1. The area south of the HZF and extending to the coastline is characterized by large regular anticlines, most often capped by the competent limestone rocks of the Jahrum and Guri formations, separated by wide synclines cored by Mio-Pliocene clastics of the Agha Jari and Bakhtyari formations. The wavelength of the folds, in the order of 15–20 km, is considerable, particularly when compared to their relatively short axial lengths (average 40 km). In comparison, folds of similar wavelength in the center of the Fars Arc can be traced for more than 200 km [Molinaro *et al.*, 2004]. Many of the anticlines are pierced by large active salt diapirs [e.g., Kent, 1979]. The average trend of the axial traces is ENE-WSW, roughly corresponding to the trend of the easternmost branch of the Fars Arc, although a few folds tend toward a more E-W direction (Figure 3 inset).

[19] 2. The triangular-shaped area comprised between the HZF and MZT-ZF fault line (Figure 3) is characterized by numerous topography-forming synclines cored by Agha Jari and Bakhtyari clastics separated by large flat plains of Quaternary deposits. Toward the west, in the region of Hadjiabad, these synclines are replaced by closely spaced, laterally discontinuous imbricate stacks of Jahrum limestone [Molinaro *et al.*, 2004]. Salt diapirism in this area is considerably less pronounced than south of the HZF and, according to Talbot and Alavi [1996], none of the diapirs in this area are currently active. Structural trends oscillate between ENE-WSW and E-W directions, except close to the Zendan Fault where north trending faults and folds can be seen.

3. Regional Structural Cross Section

[20] We have constructed a regional balanced cross section extending from the Persian Gulf to the interior parts of the orogen (Figure 4). No seismic or well data were available to constrain our interpretations at depth. In order to crosscut structures of interest and to maintain the section roughly parallel to the inferred directions of tectonic transport, the line of the section is composed of two segments and has variable azimuths (Figure 3). Because of the very slight obliquity (max 10°) between the plate convergence vectors [Vernant *et al.*, 2004] and the trends of tectonic structures in this area, we consider out-of-section transport

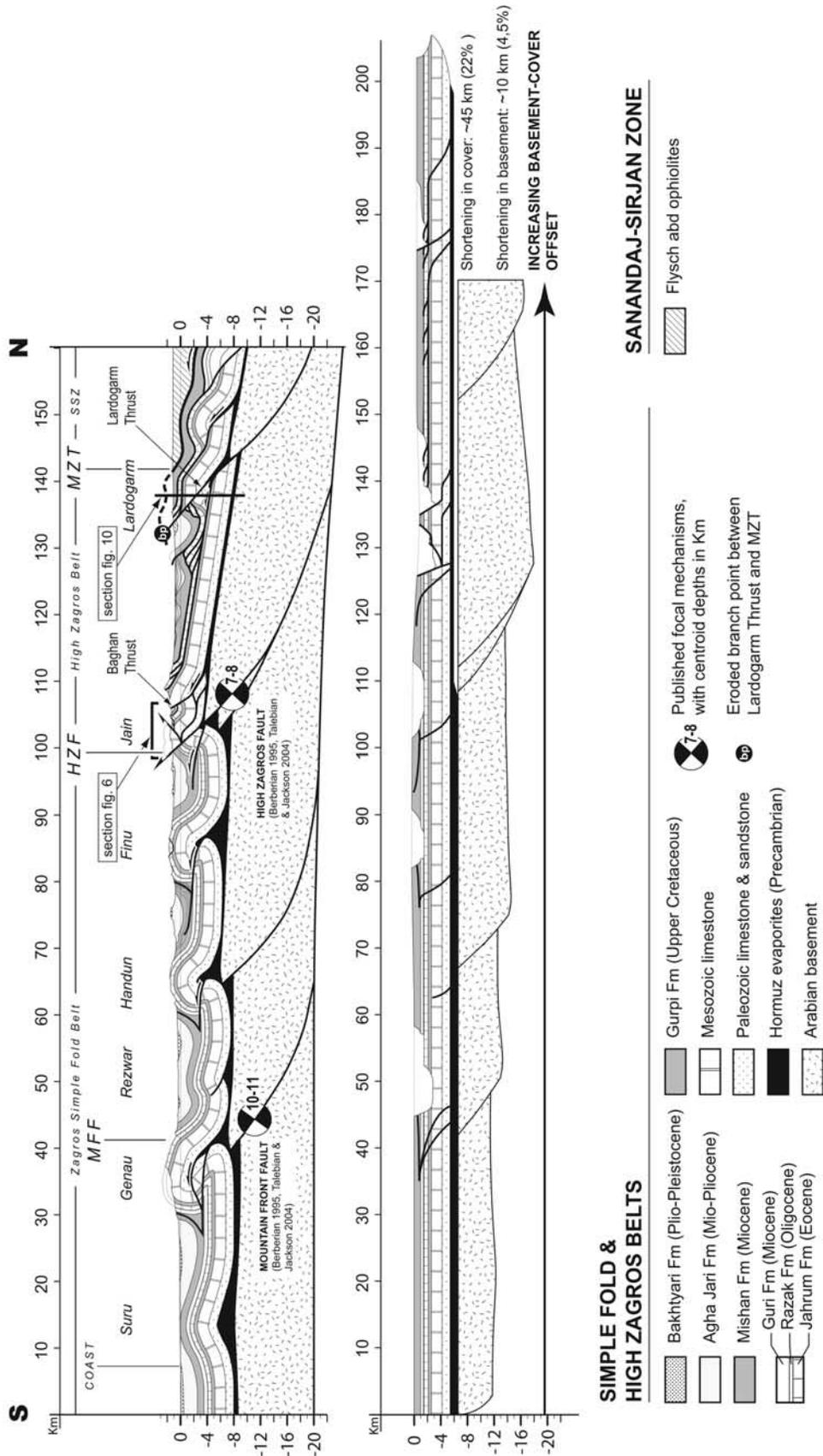


Figure 4

to be negligible and the plane-strain assumption valid. Strike-slip faulting, which could impair this assumption, has been speculatively suggested for this area based on satellite images [Hessami *et al.*, 2001a] but is not supported by any field data or by focal mechanisms. The cross section has been built using the classical two-dimensional line length balancing techniques and in accordance with the rules of geometrical acceptability as defined by *Dahlstrom* [1969] (i.e., preservation of bed lengths and consistency between adjacent structures). Two additional constraints were considered: (1) the minimization of the basal salt volumes involved in the cores of the larger anticlines, since we believe that there is a limit to the amount of salt one can reasonably admit, particularly in view of the large amounts that must already have been evacuated by the salt diapirs, and (2) the minimization of shortening throughout the section. The section does not take into account any shortening that may derive from internal deformation or meso-scale folding and thrusting, although in similar tectonic settings it has been shown that this may be of relevance to the total shortening budget [e.g., *Sans et al.*, 2003]. We have assumed a constant thickness of the Mesozoic-Paleozoic stratigraphic units throughout the section. Since most of the Meso-Paleozoic units correspond everywhere to platform sediments deposited in conditions of very low subsidence rates [*Sharland et al.*, 2001], we consider the “layer cake” assumption to be valid.

[21] As discussed earlier, the depth to the basal decollement considered in the section is of approximately 8–9 km. The strong seismicity throughout the study area proves that the basement is ruptured along several fault zones, which have been shown to roughly correspond to the MFF and the HZF [*Berberian*, 1995]. Their approximate position at depth is reported on the geological map (Figure 3). The depths of the hypocenters considered in our section (10–11 km for the MFF, 7–8 km for the HZF, Figure 4) are those reported by *Talebian and Jackson* [2004], based upon seismic waveform modeling. An additional constraint held to localize basement faults on the section was the depth to the base of synclines. This is clear in the case of the two synclines separated by the Handun anticline (Figure 4), where the uplift above regional datum of the northern syncline strongly suggests an intervening step in the basement. From a structural point of view, the section can be separated into two subdomains, the ZSFB to the south and the HZB to the north, separated by the HZF.

3.1. Zagros Simple Fold Belt: Faulted Detachment Folds

[22] The southern segment of the cross section cuts through the large and relatively simple folds of the ZSFB.

At surface, these folds present a regular and well-rounded geometry, with gently dipping limbs close to the hinge but rapidly increasing in the forelimb to values in the order of 70–80°. In the cases of the Genau and Finu anticlines, an increase in dip, albeit less severe, is observed also in the back limbs. In one case minor normal faulting is seen in the crest of an anticline (Finu anticline), probably related to the outer rim extension occurring during fold growth. A commonly observed feature on the limbs of these folds is gravity sliding and collapse of the Guri limestone beds on top of the Razak marls. This has resulted in disharmonic folding on the limbs of the major anticlines and toe thrusts carrying Guri limestone on top of the Mishan marls (Figure 2). These parasitic folds often show a strongly downdip asymmetric geometry in some cases approaching a style akin to recumbent folding. Structures of this kind can be observed indifferently on the forelimbs and back limbs of the major anticlines and presumably resulted from the gravitational instability incurred by oversteepening of the limbs. However, it is not clear at what stage in the growth of the anticlines the critical slope for sliding was reached.

[23] The geometry at depth of the larger anticlines is problematic. In view of the open and rounded surface geometry and the ascertained existence of large volumes of salt acting as a master detachment horizon, a condition that should enable ductile flow of material from the synclines toward the cores of the anticlines, we interpret them as detachment (buckle) folds. The Zagros folds were first interpreted as buckle folds by *Colman-Sadd* [1978] and have since been cited by many authors as one of finest examples of large-scale detachment folding [*Davis and Engelder*, 1985; *Sattarzadeh et al.*, 2000; *Mitra*, 2002; *Bonini*, 2003; *Sherkati et al.*, 2005].

[24] The geometry and kinematics of detachment folds were first discussed in detail by *Dahlstrom* [1990] and *Jamison* [1987]. Recent renewed interest has resulted in a whole new series of papers dealing with the various aspects of detachment folding [*Anastasio et al.*, 1997; *Homza and Wallace*, 1997; *Rowan*, 1997; *Mitra*, 2002, 2003]. According to most authors, a prerequisite condition for the generation of detachment folds is the existence of a high competency contrast between the sedimentary units involved in the folding process. The simplest model consists of a basal incompetent layer acting as a detachment zone, such as shale or salt, overlain by a thick competent unit such as carbonates or sandstones. The basal unit responds in a ductile manner to fold growth, with movement of material toward the core of the anticline and downwarping of the adjacent synclines. Depletion of the ductile layers at the base of the synclines, causing local “touchdowns” upon the basement, then blocks the development of the anticline

Figure 4. Regional balanced and restored cross section A-A' through the southeastern ZFTB. Restoration of the cross section yields 45 km of shortening in the cover versus 10 km in the basement. The discrepancy in the shortening ratios implies an increasing basement cover offset toward the hinterland and therefore a total decoupling between the two. Abbreviations are as in Figure 1. Earthquake focal mechanisms are from *Berberian* [1995] and *Talebian and Jackson* [2004]. Line indicates cross section in Figure 3.

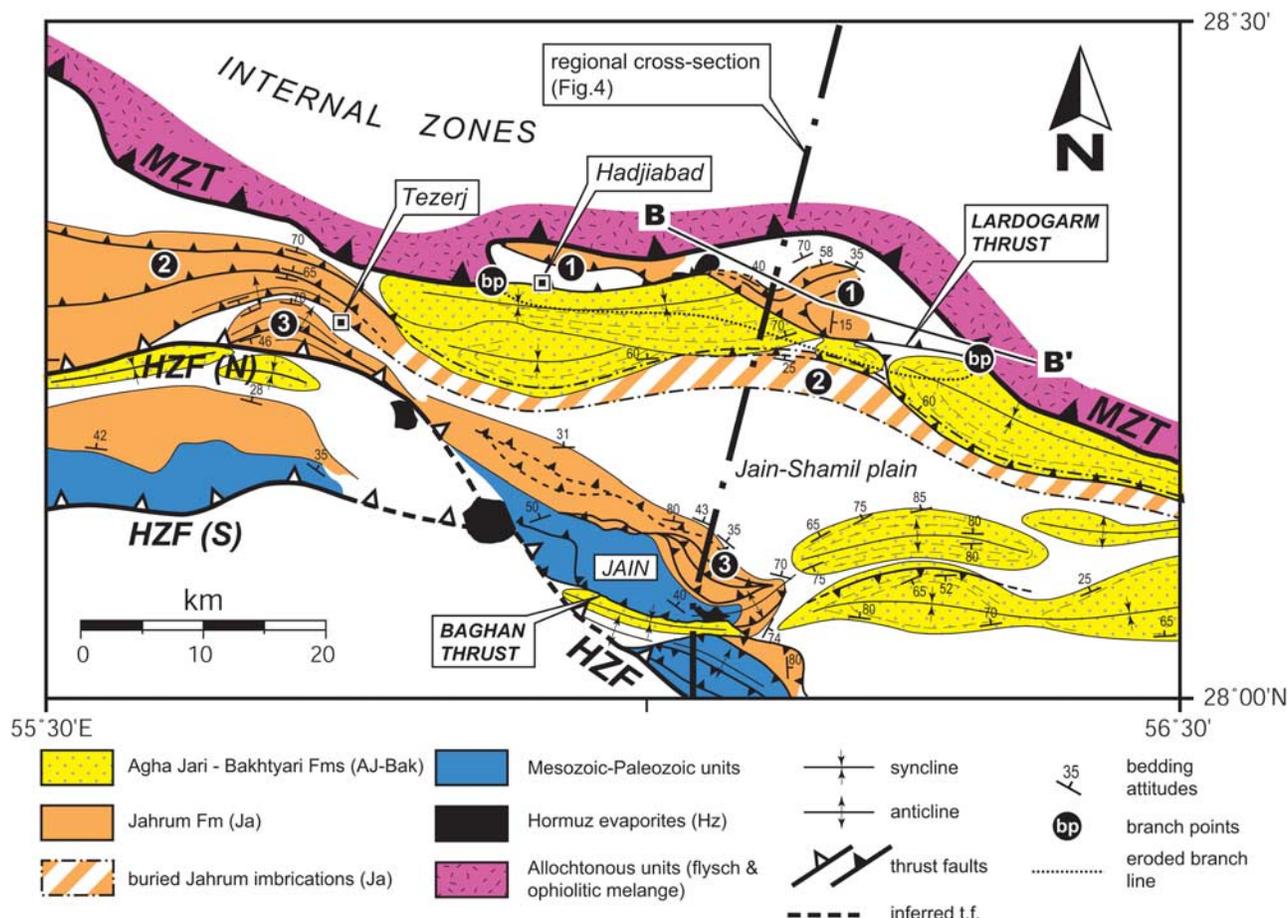


Figure 5. Structural map of the High Zagros Fault and High Zagros Belt in the region of Hadjiabad derived from geological maps [NIOC, 1977a; Geological Survey of Iran (GSI), 1994, 2002], SPOT satellite image, and authors' fieldwork. Labels 1 to 3 denote structurally distinct duplexes. Duplex 2 is inferred to continue beneath the Jain-Shamil plain in order to explain the north dipping beds in the southern flank of the adjacent synclines (see also Figure 4). The eroded branch line and branch points represent the contact between the Lardogarm Thrust and the MZT (see text and Figure 10 for further explanations). HZF (S)-(N), southern and northern segments, respectively, of the High Zagros Fault. Bedding attitudes were compiled from geological maps and authors' fieldwork. B-B' is line of hanging wall section in Figure 10. For location, see Figure 3.

and favors the progressive propagation of a fault through the forelimb.

[25] In our section, the steep limbs of the most developed folds would suggest that these have already reached the more mature stage involving faulting within the forelimb. This, according to Mitra [2002], occurs by formation of a fault within the competent unit which then propagates both up section and down section until eventually connecting to the upper and lower incompetent units (in our section the Mishan marls and the Hormuz evaporites, respectively). It can also be noted that the presence of a fault carrying the anticline over the footwall syncline allows a considerable reduction in the volume of salt involved in the cores of the structures. The displacement generated along the forelimb thrusts is dissipated within the incompetent Mishan marls. Further deformation of the structure may have resulted in overturning of the forelimb and imbrications

occurring within the footwall of the breakthrough fault, as in the case of the Genau anticline. Examples of this latter kind of structures were first reported by Perry [1978] from the West Virginia Valley and Ridge.

[26] Continuous migration of Hormuz salt into the cores of the anticlines probably resulted in grounding of the synclines upon the basement. We suggest that the smaller Rezwari fold, located at the center of the large synform separating the Genau and Handun anticlines, developed at this stage in response to the increased drag produced by welding between the basement and cover.

3.2. High Zagros Belt: Structure of the High Zagros Fault and Ramp Flat Structures

[27] The geological map (Figure 3) reveals a strong change in the style of deformation within the cover north

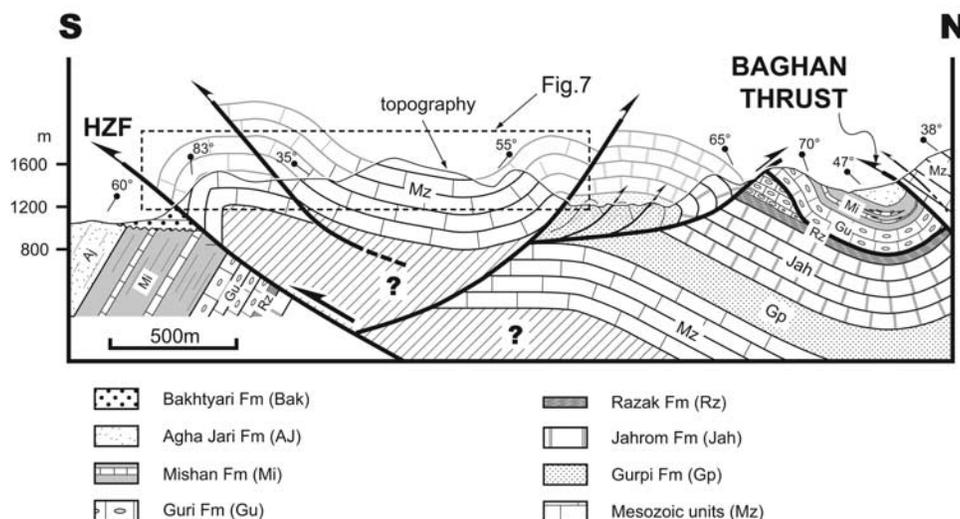


Figure 6. Simplified field section through the HZF and associated structures in the area of the Jain antiform (Figure 3). Line is cross section in Figure 4.

of the HZF (the HZB subdomain) from the ZSFB to the south. On a detailed structural map of this area (Figure 5), the NW trending HZF is marked at surface by an emerging stratigraphic section ranging in age from Oligocene to Devonian. At 2800 m, it also corresponds to the highest topographical relief of our section (the Jain structure). Based upon the observation of Mesozoic rocks outcropping south of the village of Tezerj and on the strike of the major structure related to the HZF, the Jain monocline, the western continuation of the HZF can be separated into two branches (Figures 3 and 5). This suggestion is also supported by a detailed analysis of the mean topographic elevations, which allowed the identification at a regional scale of two distinct topographic steps (P. Leturmy, manuscript in preparation, 2005).

[28] The actual surface emergence of the HZF is interpreted as corresponding to the frontal-most thrust fault of the Jain structure. A detailed field section (Figure 6) illustrates the geometrical relationships and the tectonic style of the structures in the surroundings of the HZF and Jain area. In the north, an important south verging thrust fault (Baghan Thrust) has carried rocks ranging from Eocene to Devonian age over a tight syncline cored by the Agha Jari and Mishan formations. Minor imbrications of Guri limestone affect the southern limb of this syncline, possibly related to fold tightening and/or transfer of displacement from the Baghan Thrust. In the south, Jurassic to Cretaceous platform limestone is brought to surface by a north dipping frontal thrust fault, interpreted to correspond to the emergence of the HZF, and a south dipping back-thrust. These two faults thus delimit a “pop-up” structure composed of strongly folded and deformed rocks ranging in age from Cretaceous to Jurassic age (Figure 7). Interestingly, the frontal fault is seen thrusting over near-flat lying beds of Bakhtyari conglomerates resting unconformably upon south dipping Mishan marls. This important geometric evidence suggests that the structural evolution

of this area involved at least two main tectonic events. In the first event the Mishan beds were tilted in connection with an early folding episode. This was followed by a period of relative tectonic quiescence marked by erosion of relief and widespread deposition of the Bakhtyari conglomerates. The tilted Mishan beds, together with the overlying horizontal Bakhtyari conglomerates, were subsequently overridden by Mesozoic rocks during a second tectonic event (Figure 8). In other words this means that the HZF was activated during or after deposit of the Bakhtyari conglomerates as an out-of-sequence structure at a late stage in the structural evolution of the area. Even if the Bakhtyari conglomerates are difficult to date and are probably diachronous throughout Zagros, this final phase of deformation must have occurred very recently, in the last 2–3 Myr.

[29] To the north and east of the HZF a series of E-W trending synclines and anticlines deforming the Agha Jari and Bakhtyari formations are visible, separated by a large flat Quaternary plain (the Jain-Shamil plain) (Figure 5). In the area around the town of Hadjiabad and the village of Tezerj numerous closely spaced imbricate structures involving limestone of Eocene age (Jahrom Formation) are recognizable. These structures are inferred to continue toward the east beneath the Jain-Shamil plain (Figure 5). We have identified at least three structurally distinct duplexes, indicated by the numbers in Figure 5, each duplex being composed of a minimum of two or three horses. A well-exposed example of the third duplex can be observed on the uplifted back of the Jain monocline (Figure 9). The imbricate thrusts converge into the underlying Gurpi marls, thus proving that imbrication of Jahrom limestone is related to bedding-parallel slip along the Gurpi marls. The Gurpi horizon must then correspond to an upper flat accommodating shortening that has ramped up in the hinterland from the deeper levels of the sedimentary sequence. We interpret this upper flat as being connected to fault-bend-folds



Figure 7. View of the HZF and associated “popup” structure composed of highly deformed Jurassic to Cretaceous rocks. The photograph has been inverted to aid comparison with the section in Figure 6. The scale is relative to background. Location is in Figure 6.

transferring displacement from a lower flat probably situated within the Hormuz series (Figure 4). These deeper structures can be inferred in the area of Lardogarm (Figure 4) underneath the allochthonous units, the Mishan marls serving as a decoupling horizon between the two. In this framework the Lardogarm thrust (Figures 4 and 5), carrying Jahrum limestone over Bakhtyari and Agha Jari clastics, is interpreted as an out-of-sequence structure, linked to a basement fault, crosscutting an ENE trending anticline and syncline. The presence of the basement fault is confirmed by some seismic events, one of which located at 10 km depth, reported by *Talebian and Jackson [2004]* from this area.

[30] The HZB domain is structurally overlain by allochthonous nappes of ophiolitic melange and Eocene/Oligocene flysch. These thrust sheets, which strictly speaking pertain to the internal zones (Sanandaj Sirjan Zone), have been carried toward the SW along the Main Zagros Thrust. Previous work done in this area [*Molinaro et al., 2004*] has shown the MZT to be a rather shallow dipping thrust plane which has been passively folded by underthrusting and duplication of the foreland sequence. Evidence for this kind of geometry was provided by the recognition of tectonic windows (related to tectonic culminations within the underthrusting foreland structures) piercing through the overriding allochthonous thrust sheets. It therefore follows that the tectonic emplacement of the ophiolitic and flysch nappes must have occurred prior to any deformation within foreland Zagros. There is a general consensus that obduction of Neotethyan oceanic crust and its associated pelagic sediments occurred in Early Coniacian–Late Santonian times [*Falcon, 1974; Ricou, 1971*]. However, in the region of our study the ophiolitic and flysch nappes are systematically observed resting on top of lower Miocene (Mishan Formation) or younger formations. This suggests that the present-day position of the allochthonous nappes is the result of repeated out-of-sequence reactivation. The geometry of these contacts is illustrated with a hanging wall diagram (Figure 10a), where the allochthon thrusts over the Agha Jari sandstones and Mishan marls. We interpret this as being linked to the out-of-sequence Lardogarm thrust ramping up from the basement, branching onto the sole of the allochthonous nappes (i.e., the MZT) and thrusting them higher up into the stratigraphic sequence (Figure 10b).

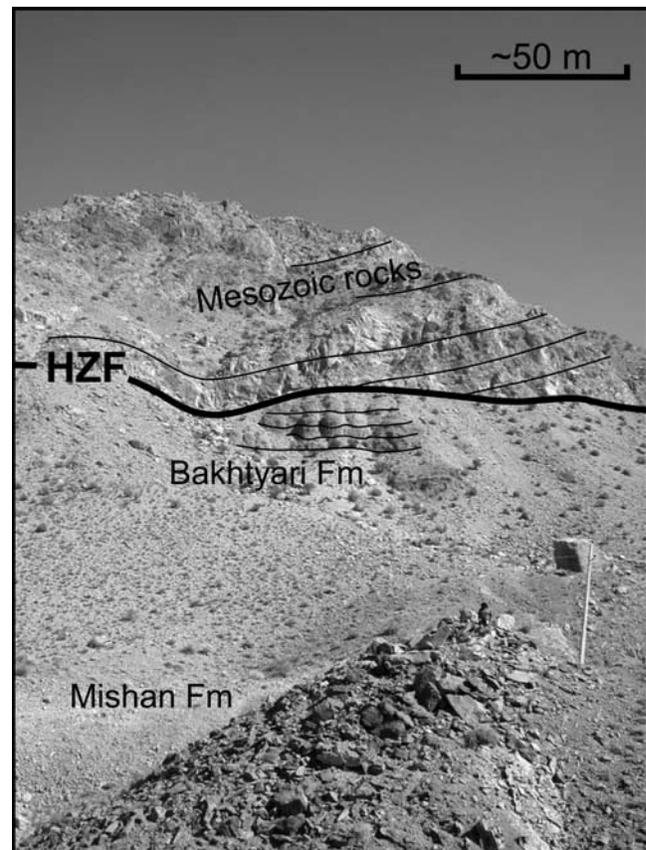


Figure 8. Frontal view of the emergent HZF, looking toward the north. Rocks of Jurassic to Cretaceous age are carried toward the south over horizontal Plio-Pleistocene Bakhtyari conglomerates resting unconformably over south dipping Mishan beds. This geometry gives evidence for two distinct tectonic phases. An initial pre-Bakhtyari folding phase tilted the Mishan beds. Erosion and deposit of the Bakhtyari mark a period of relative tectonic quiescence. This was followed by a syn- to post-Bakhtyari phase of thrusting along the HZF. The scale is relative to background. Compare with section in Figure 6.

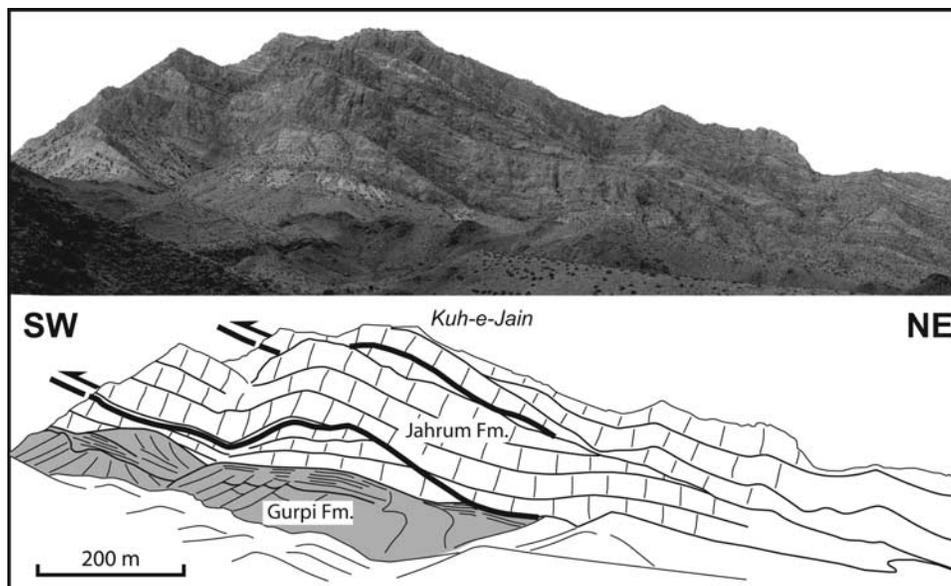


Figure 9. Photograph and line drawing of imbrications of Eocene Jahrum limestone in the northern flank of the Jain antiform (see Figures 4 and 5 for location). The thrust planes are seen converging into the Upper Cretaceous Gurpi marls, thus proving the role of the Gurpi horizon as a decollement level.

The intersection between the MZT and the Lardogarm Thrust defines a leading branch line [e.g., *Boyer and Elliott*, 1982] represented in Figures 4, 5, 10a, and 10b by its corresponding branch points, which allows us to visualize the three-dimensional geometry of this contact.

4. Discussion: Shortening Estimates and Kinematics

4.1. Estimates of Shortening

[31] We have restored (Figure 4) the regional cross section to its original predeformational length using the classical line length restoration techniques. As mentioned above, the section does not take into account any shortening that may derive from internal mesoscale and microscale deformation. Also the reader should bear in mind that the hanging wall cutoffs of the emerging faults are rarely preserved, meaning that the amount of displacement that can be attributed to a specific fault is always a minimum. Therefore the total shortening estimates given here should be regarded as minimum values.

[32] Restoration of the entire section yields approximately 45 km of shortening within the cover, which corresponds to a ratio of 22%. Of this, approximately 25–30 km (corresponding to a ratio of 32–38%) are accommodated by shortening within the HZB alone, while the remaining 15–20 km (12–16%) can be attributed to the folding in the ZSFB. These values are close to those proposed by *Blanc et al.* [2003] in a section through the Dezful Embayment (49 km = 25%) based on surface data but higher than the total 25 km (13%) indicated by *Sherkati and Letouzey* [2004] for their section in the Dezful Embayment based on surface and subsurface data. However, it should be noted that the

latter author's section crosses only the ZSFB, stopping south of the HZB which is where the highest amounts of shortening are expected. *McQuarrie* [2004], proposed a total 85 km (~26%) and 67 km (~18%) of shortening in the Dezful Embayment and in the Fars Arc, respectively. However, these relatively high values derive from her choice of an exclusively thin-skinned style of deformation.

[33] Restoration of the basement structures in our section yields approximately 10 km of shortening. This corresponds to a 4.5% ratio, which is much lower than in the cover, even considering the high uncertainties that must affect our calculation. Such discrepancies, implying a complete decoupling between shortening in the sedimentary cover and in the basement (Figure 4), are commonly observed in foothill regions and were first highlighted by *Dahlstrom* [1969] based upon his work in the Canadian Rockies belt. The necessary implication is that the basement shortening lacking in our section (~35 km) is recovered somewhere farther into the hinterland, probably in the form of thrust faults exhuming deep basement rocks. The 28-km-deep events reported by *Talebian and Jackson* [2004] about 60–70 km north of the MZT in this area could represent part of the basement shortening missing in our section. *Sherkati and Letouzey* [2004] observe a similar balancing problem in their cross section in the Dezful Embayment. As *McQuarrie* [2004] does not involve the basement in her sections across the ZFTB, she necessarily encounters the same problem. However, the solution proposed by this author, involving a 5- to 10-km-thick basal salt layer in the Fars Arc, is in our view unrealistic. *Blanc et al.* [2003], on the contrary, obtain a higher shortening ratio within the basement than in the cover, which appears unlikely in view of our results. Also it implicitly contradicts the standard view on fold-thrust belts that shortening is first transmitted

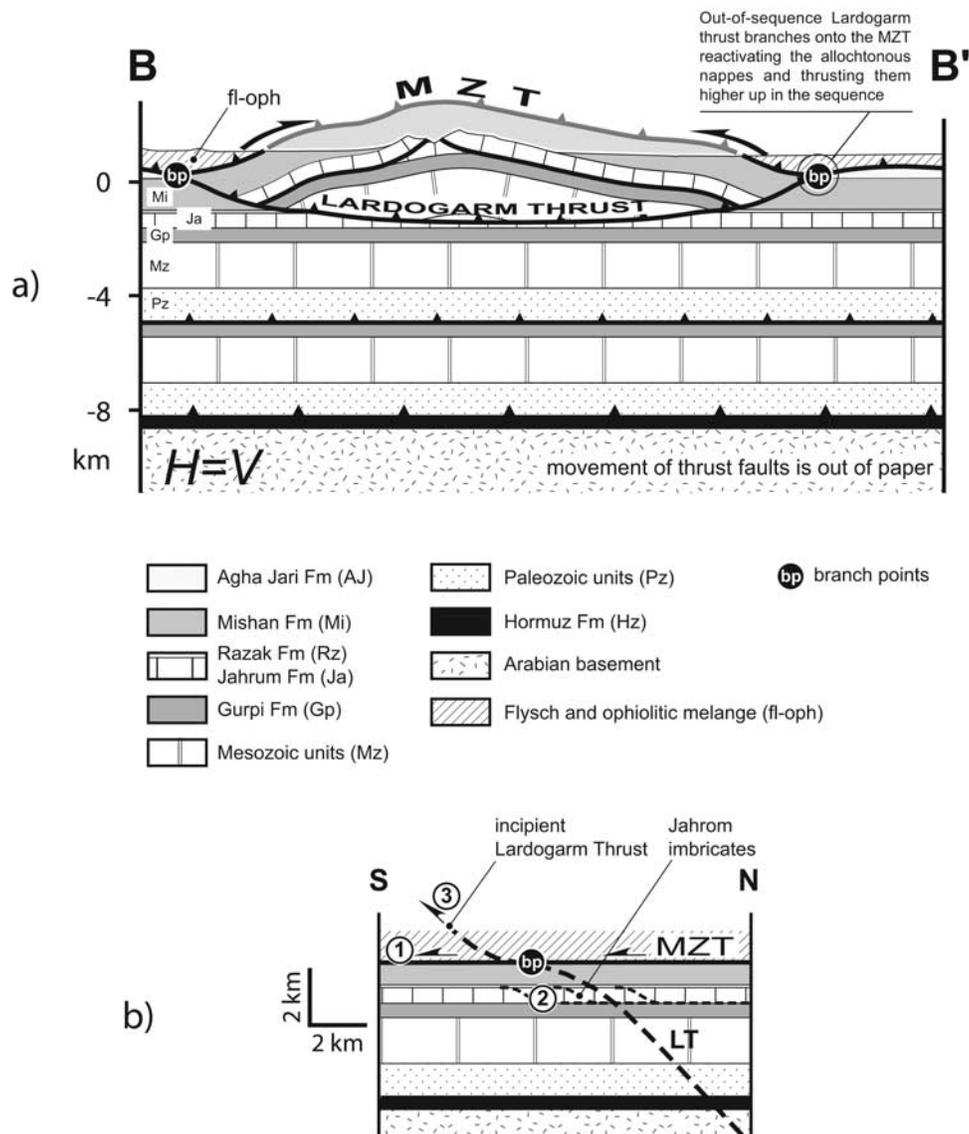


Figure 10. (a) Hanging wall section (i.e., perpendicular to the transport direction) through the Lardogarm Thrust and MZT. The branch points shown in this figure and in Figures 4 and 5 visualize the three-dimensional geometry of the contact between the MZT and the Lardogarm Thrust. Location of section in Figures 4 and 5. (b) Schematic diagram showing the relationship between the various structural units in the area of Lardogarm. The out-of-sequence Lardogarm Thrust cuts up section through the Jahrum imbricates and branches on the sole thrust of the allochthonous flysch and ophiolites (i.e., the MZT). The numbers indicate the order of activation of the different structures. LT, Lardogarm Thrust.

into the foreland within the sedimentary cover and is later recovered by younger thrusts within the basement.

4.2. Kinematics of the Cross Section

[34] Previous work done on Zagros rarely focused on the timing and kinematics of the orogenic processes. Lack of published seismic data visualizing the detailed geometries of growth strata, as well as uncertainty on the ages of the syntectonic formations, makes it difficult to establish the precise timing of the development of tectonic structures.

The widely observed angular unconformity between the Bakhtyari conglomerates and the Agha Jari sandstone had long been considered as indicating that the main pulse of deformation in the ZFTB occurred in Plio-Pleistocene times [James and Wynd, 1965]. However, recent studies based on field observations of unconformities [Hessami et al., 2001b] and isopach maps derived from industrial subsurface data [Koop and Stoneley, 1982; Sherkat and Letouzey, 2004] suggested that the first compressive movements started as early as late Eocene in the northeast of the ZFTB and propagated progressively southward.

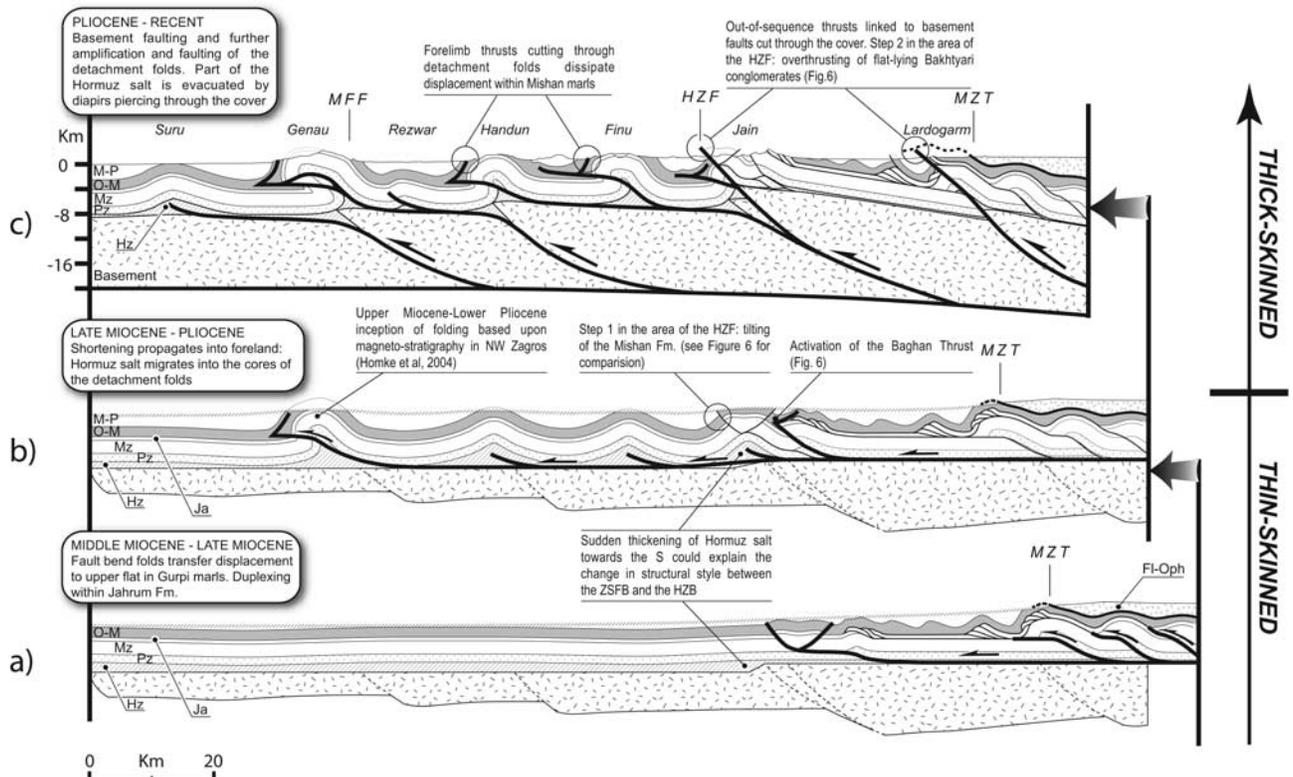


Figure 11. Incremental three-step restoration of the cross section through the southeastern ZFTB (Figure 4). Hatched line (Figures 11a and 11b) represents the approximate inferred position of the mean topographical surface. Abbreviations are M-P, Mio-Pliocene clastics (Agha Jari Formation and Bakhtyari Formation); O-M, Oligocene-lower Miocene limestone and marls (Razak Formation, Guri Formation and Mishan Formation); Ja, Jahrum limestone; Mz, Mesozoic units; Pz, Paleozoic units; Hz, Hormuz evaporites; Fl-Oph, allochthonous flysch and ophiolites. Other abbreviations are as in Figure 1.

[35] The structural analysis presented in this paper provides some geometric constraints that can help to unravel the main steps in the history of folding and thrusting of the studied area. A three-step kinematic scenario is proposed (Figure 11) for the outer part of the section, based on the unfolding of the balanced cross section. No attempt has been made to reconstruct the history of internal units. For each step the faults considered to be active are underlined in bold. We acknowledge that our scenario remains oversimplified: more refined models including accurate temporal bracketing of tectonic events will necessitate additional information on the age and sources of the molasse deposits.

[36] The oldest part of the mountain belt, in a typical piggyback sequence, is supposed to correspond to the structures situated north of the HZF. This is shown in step 1 (Figure 11a), where deep ramps in the hinterland have folded the hanging wall rocks (including previously emplaced flysch and ophiolitic melanges) and transferred displacement to the higher levels of the stratigraphic sequence. The front-most structure for this first step is supposed to correspond to the “pop-up” structure described above in the HZF area (Figure 6). *Sherkati and Letouzey* [2004], based upon tectonostratigraphic evidence derived from updated isopach maps in NW Zagros, suggested that

the first compressive movements in the area of the HZF (i.e., the end of step 1 in Figure 11a) occurred in upper Eocene–Oligocene times, and *Hessami et al.* [2001b] reached similar conclusions based upon field evidence. However, this timing would imply for our cross section a long-term shortening rate of ~1 mm/yr, which is an order of magnitude lower than the present-day shortening rates determined from geodetic data (9 ± 2 mm/yr, [*Vernant et al.*, 2004]). It is therefore probable that the first structures in the HZB were initiated later, more likely in middle-late Miocene times in connection with the first appearance of the detritic sediments of the Agha Jari formation.

[37] In step 2 (Figure 11b) the deformation front has extended into the foreland causing the sedimentary cover to fold into a succession of large detachment folds. We suggest that the sudden change in structural style between the HZB and the ZSFB is related to a decrease in thickness from south to north of the basal Hormuz series. This change in stratigraphic thickness, which is also suggested by the decrease of salt diapirism in the HZB, was seemingly controlled by a step in the basement, possibly normal faulting inherited from Eo-Cambrian extension [*Sharland et al.*, 2001]. We surmise that at this stage the folds grew as relatively symmetrical structures. This, as discussed by

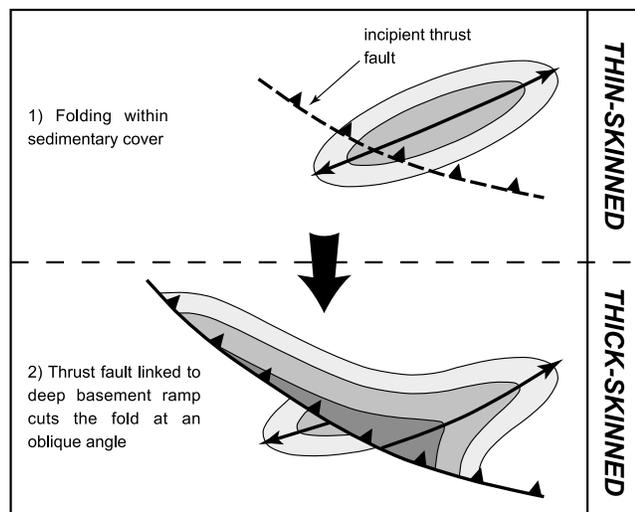


Figure 12. Schematic model for the development of structures associated to the HZF in the Bandar Abbas area, illustrating the successive thin-skinned and thick-skinned tectonic styles. Compare with the Jain, Faraghun, and Kuh-e-Khush structures in Figure 3.

Davis and Engelder [1985] and *Davis and Lillie* [1994] and as illustrated by scaled analogue models [e.g., *Letouzey et al.*, 1995; *Cotton and Koyi*, 2000], is a typical feature of structures developed on top a weak detachment zone such as the Hormuz series. In the area of the HZF, the development of an anticline uplifts the “pop-up” structure and rotates the Mishan marls to their presently observed dip. This corresponds to the first step in the two-phased evolution of early structures described for this area (Figure 6). At the same time, activation of the Baghan Thrust (Figure 6) uplifts the duplex structure that is presently observed on the back of the Jain structure (Figure 9). Scanty information derived from studies made elsewhere in Zagros can help us to roughly constrain the timing for the second step of our kinematic scenario. *Homke et al.* [2004], based upon a magnetostratigraphic section through the Agha Jari molasse deposits in the northwest of the Dezful Embayment, showed that initiation of folding at the height of the MFF occurred in late Miocene times between 8.7 and 8.2 Ma. In our section, the foremost fold of the ZSFB (the Genau fold) is located approximately over the MFF. However, in view of the NW-SE diachrony of the Zagros collision, we consider that the first movements on the Genau fold occurred slightly later than in NW Zagros, toward the end of Miocene–beginning of Pliocene. It is unclear whether folding in the ZSFB commenced everywhere at this time. However, analogue models of fold-thrust belts on top of weak detachment horizons such as the ZSFB [e.g., *Letouzey et al.*, 1995; *Cotton and Koyi*, 2000; *Costa and Vendeville*, 2002], as well as observations from similar tectonic contexts [e.g., *Grelaud et al.*, 2002], show that the propagation of deformation in these settings is usually very rapid. The most likely scenario is thus one in which the basal decollement horizon was simultaneously active over a wide area and the

folds developed at the same time. We consequently propose that the inception of folding in the north of the ZSFB occurred not long before the ages given by *Homke et al.* [2004], possibly already in late Miocene times.

[38] Finally in step 3 (Figure 11c), corresponding to the present-day section, the deformation becomes thick-skinned with the activation of major basement thrusts, notably the HZF and the MFF. The shortening in the basement is then taken up in the cover essentially in two ways: (1) further amplification and tightening of the folds in the ZSFB and (2) out-of-sequence break-back thrusting cutting through preexisting structures. Clear examples of out-of-sequence thrusting are given by the HZF and Lardogarm thrusts.

[39] In the area of the HZF, the previously tilted and eroded Mishan marls are now covered unconformably by beds of Bakhtyari conglomerates and overridden by rocks of Jurassic age, thus completing the two-step history described for this area (Figure 6). Further evidence for the out-of-sequence interpretation of the HZF can be inferred from the map pattern of its three major associated structures, Jain, Faraghun, and Kuh-e-Khush (Figure 3). As mentioned above, although their dominant trend is NW-SE, the eastern tips of these structures tend to align themselves on the average ENE trend of the folds in the eastern limb of the Fars Arc. This peculiar geometry had been already noted by *Ricou* [1974], who suggested, on the unique basis of satellite images, that it was originated by dextral transpression along the HZF. However, such dextral slip is not observed on the field and focal mechanisms determined for earthquakes along the HZF invariably show reverse faulting. Consequently we interpret these structures as resulting from the interference between a late NW trending thrust fault, linked to reverse basement faulting, and an ENE trending detachment fold (Figure 12). The clearest example of this kind of structure is given by the Kuh-e-Khush antiform, 60 km northeast of the town of Bandar Abbas (Figure 3), where the remains of an ENE trending anticline are recognizable both in the hanging wall and the footwall of the HZF.

[40] In the area of Lardogarm the fault-bend folds described in step 1 are crosscut by the ESE trending Lardogarm thrust. The map pattern of structures in this area (Figure 5) is indicative for an out-of-sequence interpretation of the Lardogarm thrust fault. We suggest that this was also due to the activation of a basement fault (Figure 4).

[41] To summarize, two main stages of deformation can be distinguished within the ZFTB. In an initial thin-skinned stage shortening is accommodated within the cover by thrusting in the HZB and large-scale folding in the ZSFB until at least upper Miocene times (Figures 11a and 11b). In a second thick-skinned stage starting in Pliocene times, and currently underlined by a strong seismicity record, major out-of-sequence basement thrusts cut through the overlying structures of the cover (Figure 11c).

4.3. Tentative Reconstruction of the Kinematic Evolution of the Southeastern Zagros Fold-Thrust Belt

[42] We complete our discussion on the tectonics in the Bandar Abbas area by proposing a tentative sketch of the

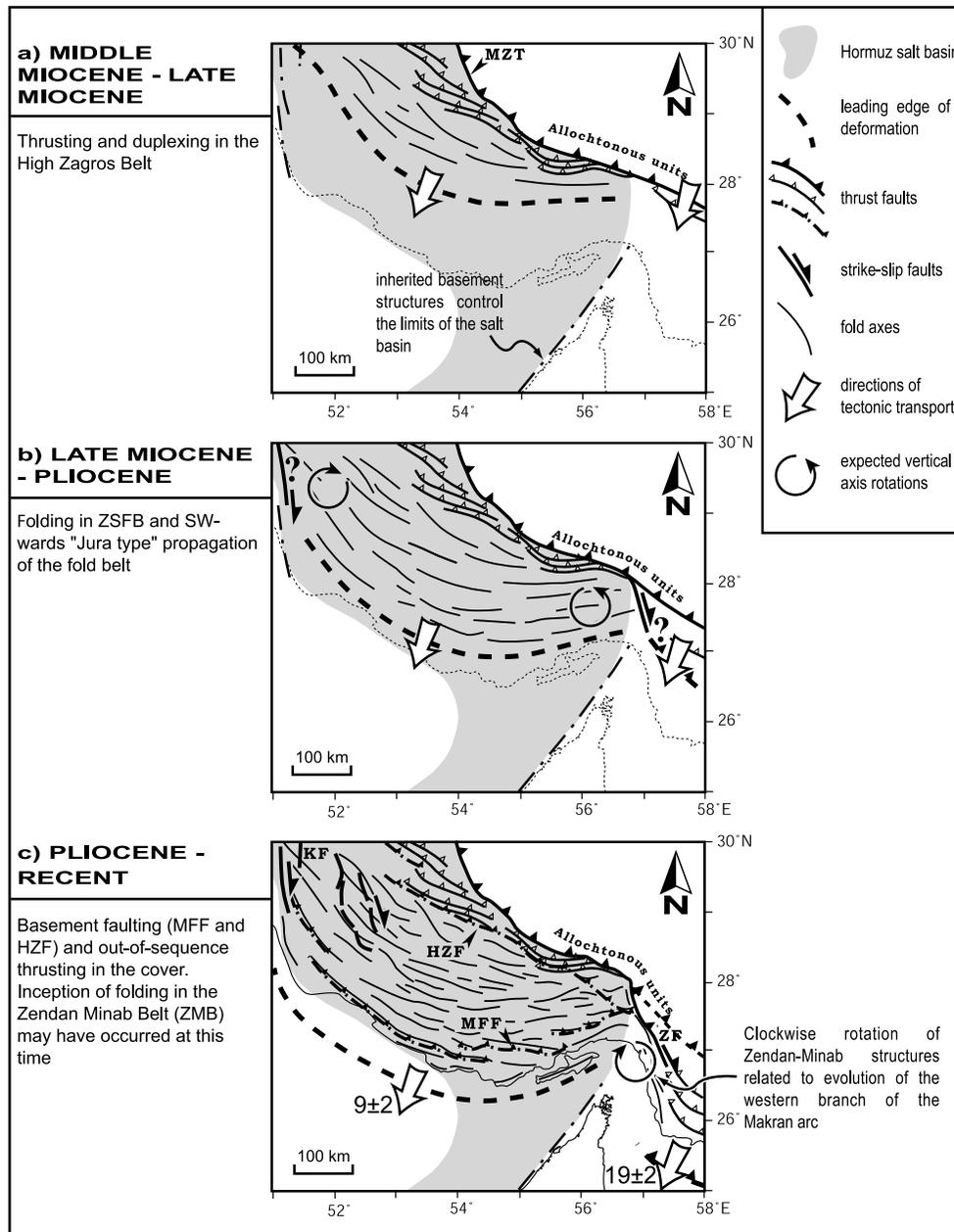


Figure 13. Evolutionary model for the Fars Arc and Bandar Abbas syntaxis in southeastern Zagros from middle Miocene to Recent times. Gray shading indicates the shape and extent of the underlying Hormuz salt basin, according to Kent [1979] and Sharland *et al.* [2001]. In Figure 13b, the geometry and thickness of the salt basin is interpreted to control the curved shape of the Fars Arc (see text for further explanations). The vertical axis rotations expected in this model are supported by recent paleomagnetic data [Aubourg *et al.*, 2003] across the Fars Arc. GPS shortening rates (mm/yr) in Zagros and Makran (Figure 13c) are after Vernant *et al.* [2004] Abbreviations are as in Figure 1.

kinematic evolution of the southeastern ZFTB. The problems discussed below are classical in structural geology and refer to the development of arcs in fold-thrust belts as described by Marshak *et al.* [1992] or Macedo and Marshak [1999]. The area of our study is located precisely at the boundary between two arcs (i.e., Zagros and Makran), each one being related to a different tectonic setting.

Consequently one can expect complex patterns to arise due to the interaction and overprint between the two arcs.

[43] In the first stage (Figure 13a), the structures of the HZB develop by sequential addition of imbricates with a general SSW-ward direction of tectonic transport. The overall trend of these first structures is supposed to be NW-SE. As discussed in the previous section and as indicated in

Figure 11a, this first stage probably started in middle Miocene times and continued until the end of Miocene.

[44] In the second stage (late Miocene-Pliocene) (Figures 11b and 13b) the deformation front propagated toward the southwest by large-scale folding of the sedimentary cover above the ductile Hormuz evaporites. The axial traces of the folds developed with a festoon-shaped curvature corresponding to the present-day curve of the Fars Arc (Figure 13b). Such curvatures are a commonly observed feature in fold-and-thrust belts and have been the subject of debate, one of the main questions being whether these curves are primary (i.e., were born with their present shape) or secondary (i.e., resulted from late vertical axis rotations) [Marshak *et al.*, 1992]. According to Ricou [1976], the present curvature of the Fars Arc resulted from the superposition of two noncoaxial directions of shortening related to changing kinematics of the Arabia-Eurasia convergence. However, there is no evidence to support a major change in the direction of the plate convergence vector since at least Miocene times [Jestin and Huchon, 1992]. Hessami *et al.* [2001a], on the other hand, attributed the deviations of the trends of fold axes in the Fars Arc to the effect on the cover of vertical axis rotations of basement blocks bounded by strike-slip faults. By contrast, in our reconstruction (Figure 11) most of the folds in the ZSFB were already formed prior to any involvement of the basement in the deformation. Consequently the factor controlling the curvature of the Fars arc must be looked for in the cover itself. We suggest that the main controlling factor was the extent and thickness of the basal Hormuz detachment horizon. The Hormuz salt basin pinches out toward the east in the area of Bandar Abbas and toward the west in connection with the Kazerun Fault (Figure 1) [Kent, 1979]. The geometry of this basin is largely controlled by inherited structural features within the Arabian paleomargin, dating back to Eo-Cambrian times (Figure 13a) [Edgell, 1996; Sharland *et al.*, 2001]. As shown by analogue modeling [Macedo and Marshak, 1999], a lateral pinch-out of the evaporite layers will affect the strength of the detachment horizon and therefore the amount of propagation of the deformation front into the foreland. The lateral branches of the fold-thrust belt will thus become “pinned” by the stronger coupling along the thinner basal detachment. A similar explanation has been proposed for the Jura Mountains, at the front of the western alpine orogen. The arcuate shape of this fold-and-thrust belt has been attributed to the progressive lateral pinch-out of the Triassic evaporite horizons upon which the Jura folds and thrusts detach [Vann *et al.*, 1986; Philippe, 1994]. In this case one can expect vertical axis clockwise and anticlockwise rotations to occur in the western and eastern branches, respectively, of the Fars arc (Figure 13b). Results from magnetic fabrics and paleomagnetism studies are encouraging in this sense. Clockwise rotations have been suggested in western Fars from studies on magnetic fabrics [Bakhtari *et al.*, 1998; Aubourg *et al.*, 2004] to explain a systematic anticlockwise obliquity between the pre-folding magnetic lineation [e.g., Kligfield *et al.*, 1981; Averbuch *et al.*, 1992] and the

fold axes. Also, recent paleomagnetic data from the area of Bandar Abbas [Aubourg *et al.*, 2003] indicate anticlockwise rotations of 15–20°.

[45] Finally, in stage 3 (Figures 11c and 13c) the structures of the ZFTB were crosscut by out-of-sequence thrusts originating from basement faults. Shortening transmitted into the cover advanced the deformation front to its present-day position in the Persian Gulf. We surmise that the structures of the Zandan-Minab Belt, with an orientation close to that of the HZF, developed at the same time. Recent folding in this area is supported by the observation of growth strata within Plio-Pleistocene conglomerates of the forelimb of the Minab fold (Figure 3) [Molinaro *et al.*, 2004] and is in agreement with observations by Regard *et al.* [2004]. Folds and thrusts with the same trend are observed deforming Mio-Pliocene clastics in front of the Zandan Fault farther north (Figure 3). These latter structures as well as those in the ZMB are likely to have resulted from interference with the southwestward propagation of the western branch of the Makran arc. Recent paleomagnetic data from the area of Minab [Smith *et al.*, 2003] (Figure 3) highlight clockwise vertical axis rotations of ~20° in the ZMB, these rotations being related to the evolution of the western branch of the Makran thrust-arc system. The faster propagation of the Makran system relative to Zagros (more than twice as much) inferred by GPS measurements [Vernant *et al.*, 2004] would account for the present-day right-lateral shear [Regard *et al.*, 2004] accommodated by the shallow aseismic Zandan Fault.

5. Conclusion

[46] Two main stages of deformation are recognized within the southeastern ZFTB. In the first stage the deformation was thin-skinned in style. In the HZB deep ramps transferred displacement to an upper flat situated within the Upper Cretaceous Gurpi marls and produced discontinuous imbrications within the Eocene Jahrum limestone and folding of the previously emplaced allochthonous units (flysch and ophiolites). In the ZSFB, by contrast, the sedimentary cover was detached along the basal Hormuz evaporites and folded into a series of large symmetrical detachment folds. Ongoing shortening and migration of salt toward the cores of the anticlines resulted in the propagation of forelimb thrusts dissipating displacement within the lower Miocene Mishan marls. Oversteepening of the limbs of the anticlines resulted in gravity collapse structures within the Guri limestone beds. In plan view, the folds developed with an arched shape corresponding to the present-day Fars Arc. We suggest that this shape was primarily controlled by the original extent and thickness of the basal Hormuz detachment horizon. The vertical axis rotations expected in this “Jura-type” model of propagation of the fold belt, clockwise in western Fars and anticlockwise in eastern Fars, are confirmed by paleomagnetic and magnetic fabric studies of the region.

[47] This first stage was followed and overprinted by a thick-skinned stage of deformation, which is currently underlined by a strong seismicity record. Out-of-sequence thrusts, linked to deep-seated basement faults, cut through

the overlying cover structures. In plan view, the intersection at oblique angles between preexisting folds and these new thrusts led to the development of structures with characteristic map patterns (Figure 12), recognizable in the study area (Figure 3).

[48] The total decoupling between the cover and basement is highlighted by the difference in the calculated shortening ratios (Figure 4). While the deformation in the cover propagated into the foreland along the ductile Hormuz evaporites, shortening was probably recovered within the basement by thrusting in the hinterland. In a subsequent “readjustment” of the mountain belt as a whole, the basement-involved deformation also shifted toward the foreland. In other words, the late stage involvement of the basement in foreland Zagros could be viewed as a step toward the reestablishment of the critical taper (in the sense of Davis *et al.* [1983]) throughout the entire mountain belt. This fundamental change in the mechanism of deformation

in Zagros could be related to the major reorganization of the Arabia-Eurasia collision reported by several authors at about 3–5 Ma [Westaway, 1994; Allen *et al.*, 2004; Regard *et al.*, 2004]. This is also the time of the sudden and widespread occurrence throughout Zagros of the Bakhtyari conglomerates, which could be interpreted as the sedimentary signature marking the onset of basement involvement in the orogen. However, precise dating of these probably diachronous deposits is required to confirm this hypothesis.

[49] **Acknowledgments.** This research was funded by the MEBE (Middle East Basin Evolution) program. We are grateful to the Geological Survey of Iran (GSI), Tehran, Iran, for willing assistance on the field. We also wish to thank C. Aubourg, H. Koyi, S. Lallemand, J. Letouzey, and S. Sherkaty for useful and informative discussions on Zagros tectonics. We thank J. Vergés and O. Bellier for their detailed reviews, which helped to improve the manuscript. M. Molinaro acknowledges a Ph.D. grant from the French Ministry of Research.

References

- Alavi, M. (1994), Tectonics of the Zagros orogenic belt of Iran: New data and interpretations, *Tectonophysics*, **229**, 211–238.
- Allen, M., J. Jackson, and R. Walker (2004), Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates, *Tectonics*, **23**, TC2008, doi:10.1029/2003TC001530.
- Anastasio, D. J., D. M. Fisher, T. A. Messina, and J. E. Holl (1997), Kinematics of décollement folding, *J. Struct. Geol.*, **19**, 355–368.
- Aubourg, C., B. Smith, H. Bakhtari, N. Guya, S. A. Eshraghi, and S. Delaunay (2003), Vertical axis rotations pictured by paleomagnetic data across the Zagros-Makran syntaxis (Iran), paper presented at EGS-AGU-EUG Joint Assembly, Eur. Geophys. Soc., Nice, France.
- Aubourg, C., B. Smith, H. Bakhtari, N. Guya, S. A. Eshraghi, S. Lallemand, M. Molinaro, X. Braud, and S. Delaunay (2004), Post Miocene shortening pictured by magnetic fabric across the Zagros-Makran Syntaxis (Iran), in *Orogenic Curvature: Integrating Paleomagnetic and Structural Analyses*, edited by A. J. Sussman and A. B. Weil, *Spec. Pap. Geol. Soc. Am.*, **383**, 17–40.
- Averbuch, O., D. Frizon de Lamotte, and C. Kissel (1992), Magnetic fabric as a structural indicator of the deformation path within a fold-thrust structure: A test case from the Corbières (NE Pyrenees, France), *J. Struct. Geol.*, **14**, 461–474.
- Baker, C., J. Jackson, and K. Priestley (1993), Earthquakes on the Kazerun Line in the Zagros Mountains of Iran: Strike-slip faulting within a fold-thrust belt, *Geophys. J. Int.*, **115**, 41–61.
- Bakhtari, H., D. Frizon de Lamotte, C. Aubourg, and J. Hassanzadeh (1998), Magnetic fabric of Tertiary sandstones from the Arc of Fars (eastern Zagros, Iran), *Tectonophysics*, **284**, 299–316.
- Berberian, M. (1995), Master “blind” thrust faults hidden under the Zagros folds: Active basement tectonics and surface morphotectonics, *Tectonophysics*, **241**, 193–224.
- 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.
- Boyer, S. E., and D. Elliott (1982), Thrust systems, *AAPG Bull.*, **66**, 1196–1230.
- Colman-Sadd, S. P. (1978), Fold development in Zagros simply folded belt, southwest Iran, *AAPG Bull.*, **62**, 984–1003.
- Costa, E., and B. C. Vendeville (2002), Experimental insights on the geometry and kinematics of fold-thrust belts above weak, viscous evaporitic décollement, *J. Struct. Geol.*, **24**, 1729–1739.
- Cotton, J. T., and H. A. Koyi (2000), Modelling of thrust fronts above ductile and frictional detachments: Application to structures in the Salt Range and Potwar Plateau, Pakistan, *Geol. Soc. Am. Bull.*, **112**, 351–363.
- Dahlstrom, C. D. A. (1969), Balanced cross sections, *Can. J. Earth Sci.*, **6**, 743–757.
- Dahlstrom, C. D. A. (1990), Geometric constraints derived from the law of conservation of volume and applied to evolutionary models for detachment folding, *AAPG Bull.*, **74**, 339–344.
- Davis, D. M., and T. Engelder (1985), The role of salt in fold-and-thrust belts, *Tectonophysics*, **119**, 67–88.
- Davis, D. M., and R. J. Lillie (1994), Changing mechanical response during continental collision: Active examples from the foreland thrust belts of Pakistan, *J. Struct. Geol.*, **16**, 21–34.
- Davis, D. M., J. Suppe, and F. A. Dahlen (1983), Mechanics of fold-thrust belts and accretionary wedges, *J. Geophys. Res.*, **88**, 1153–1172.
- DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effects of recent revisions to the geomagnetic time scale on estimates of current plate motions, *Geophys. Res. Lett.*, **21**, 2191–2194.
- 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 the Zagros Range, in *Time and Place in Orogeny*, *Geol. Soc. Spec. Publ.*, **3**, 9–22.
- Falcon, N. L. (1974), Southern Iran: Zagros Mountains, in *Mesozoic-Cenozoic Orogenic Belts*, *Geol. Soc. Spec. Publ.*, **4**, 199–211.
- Geological Survey of Iran (GSI) (1994), Geological map of Iran quadrangle 112 Hadjiabad, scale 1:250000, Tehran.
- Geological Survey of Iran (GSI) (2002), Geological map of Iran, sheet 7246, Orzuieh, scale 1:100,000, Tehran.
- 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. Pet. Geol.*, **19**, 1127–1139.
- 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, and C. J. Talbot (2001a), The significance of strike-slip faulting in the basement of the Zagros fold and thrust belt, *J. Pet. Geol.*, **24**, 5–28.
- Hessami, K., H. A. Koyi, C. J. Talbot, H. Tabasi, and E. Shabanian (2001b), Progressive unconformities within an evolving foreland fold-thrust belt, Zagros Mountains, *J. Geol. Soc. London*, **158**, 969–981.
- Homke, S., J. Verges, M. Garces, 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.
- Homza, T. X., and W. K. Wallace (1997), Detachment folds with fixed hinges and variable detachment depth, northeastern Brooks Range, Alaska, *J. Struct. Geol.*, **19**, 337–354.
- Jackson, J. A., and T. Fitch (1981), Basement faulting and the focal depths of the larger earthquakes in the Zagros mountains (Iran), *Geophys. J. R. Astron. Soc.*, **64**, 561–586.
- James, G. A., and J. G. Wynd (1965), Stratigraphic nomenclature of Iranian oil consortium agreement area, *AAPG Bull.*, **49**, 2162–2245.
- Jamison, W. R. (1987), Geometric analysis of fold development in overthrust terranes, *J. Struct. Geol.*, **9**, 207–219.
- Jestin, F., and P. Huchon (1992), Cinématique et déformation de la jonction triple mer Rouge-golfe d’Aden-Rift éthiopien depuis l’Oligocène, *Bull. Soc. Geol. Fr.*, **163**, 125–133.
- Kadinski-Cade, K., and M. Barazangi (1982), Seismotectonics of southern Iran: The Oman line, *Tectonics*, **1**, 389–412.
- Kent, P. E. (1979), The emergent Hormuz salt plugs of southern Iran, *J. Pet. Geol.*, **2**, 117–144.
- Kligfield, R., W. H. Owens, and W. Lowrie (1981), Magnetic susceptibility anisotropy, strain and progressive deformation in Permian sediments from the Maritime Alps (France), *Earth Planet. Sci. Lett.*, **55**, 181–189.
- 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.

- Letouzey, J., B. Colletta, R. Vially, and J. C. Chermette (1995), Evolution of salt-related structures in compressional settings, in *Salt Tectonics: A Global Perspective*, edited by M. P. A. Jackson, D. G. Roberts, and S. Snellson, *AAPG Mem.*, 65, 41–60.
- Macedo, J., and S. Marshak (1999), Controls on the geometry of fold-thrust belt salients, *Geol. Soc. Am. Bull.*, 111, 1808–1822.
- Maggi, A., J. Jackson, K. Priestley, and C. Baker (2000), A re-assessment of focal depth distributions in southern Iran, the Tien Shan and northern India: Do earthquakes really occur in the continental mantle?, *Geophys. J. Int.*, 143, 629–661.
- Marshak, S., M. S. Wilkerson, and A. T. Hsui (1992), Generation of fold-thrust belts: Insight from simple physical and analytical models, in *Thrust Tectonics*, edited by K. R. McClay, pp. 83–92, CRC Press, Boca Raton, Fla.
- 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, 1673–1694.
- Mitra, S. (2003), A unified kinematic model for the evolution of detachment folds, *J. Struct. Geol.*, 25, 1659–1673.
- Molinaro, M., J. C. Guezou, P. Leturmy, S. A. Eshraghi, and D. F. de Lamotte (2004), The origin of changes in structural style across the Bandar Abbas syntaxis, SE Zagros (Iran), *Mar. Pet. Geol.*, 21, 735–752.
- Morris, P. (1977), Basement structure as suggested by aeromagnetic surveys in southwest Iran, paper presented at Second Geological Symposium of Iran, Iranian Pet. Inst., Tehran.
- National Iranian Oil Company (NIOC) (1977a), Geological map of Iran, sheet 5, South-central Iran, scale 1:100,000, Tehran.
- National Iranian Oil Company (NIOC) (1977b), Geological map of Iran, sheet 5, South-east Iran, scale 1:100,000, Tehran.
- National Iranian Oil Company (NIOC) (1999), Geological map of Iran quadrangle, I-13, Bandar Abbas, scale 1:250,000, Tehran.
- O'Brien, C. A. E. (1957), Salt diapirism in south Persia, *Geol. Mjnb.*, 19, 357–376.
- Perry, W. J. (1978), Sequential deformation in the Central Appalachians, *Am. J. Sci.*, 278, 518–542.
- Philippe, Y. (1994), Transfer zone in the southern Jura thrust belt, (eastern France): Geometry, development and comparison with analogue modeling experiments, in *Exploration and Petroleum Geology of France, EAPG Memoir*, vol. 4, edited by A. Mascle, pp. 327–346, Springer, New York.
- Regard, V., O. Bellier, J.-C. Thomas, M. R. Abbassi, J. Mercier, E. Shabanian, K. Feghhi, and S. Soleymani (2004), Accommodation of Arabia-Eurasia convergence in the Zagros-Makran transfer zone, SE Iran: A transition between collision and subduction through a young deforming system, *Tectonics*, 23, TC4007, doi:10.1029/2003TC001599.
- Ricou, L. E. (1971), Le croissant ophiolitique péri-arabe: Une ceinture de nappes mises en place au Crétacé supérieur, *Rev. Geogr. Phys. Geol. Dyn.*, 13, 327–350.
- Ricou, L. E. (1974), L'étude géologique de la région de Neyriz (Zagros iranien) et l'évolution structurale des Zagrides, Ph.D. thesis, Univ. Paris-Sud, Orsay, France.
- Ricou, L. E. (1976), Évolution structurale des Zagrides: La région clef de Neyriz (Zagros iranien), *Mem. Soc. Geol. Fr.*, 125, 140.
- Ricou, L., J. Braud, and J. H. Brun (1977), Le Zagros, *Mem. Soc. Geol. Fr.*, 8, 33–52.
- Rowan, M. G. (1997), Three-dimensional geometry and evolution of a segmented detachment fold, Mississippi Fan foldbelt, Gulf of Mexico, *J. Struct. Geol.*, 19, 463–480.
- Sans, M., J. Vergés, E. Gomis, J. M. Parés, M. Schiattarella, A. Travé, D. Calvet, P. Santanach, and A. Doucet (2003), Layer parallel shortening in salt-detached folds: Constraint on cross-section restoration, *Tectonophysics*, 372, 85–104.
- 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.
- Sharland, P. R., R. Archer, D. M. Casey, R. B. Davies, S. H. Hall, A. P. Hewerd, A. D. Horbury, and M. D. Simmons (2001), Arabian plate sequence stratigraphy, *GeoArabia Spec. Publ.* 2, Gulf. PetroLink, Bahrain.
- 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): Salt mobility, multiple detachments and final basement control, *J. Struct. Geol.*, in press.
- Smith, B., C. Aubourg, J.-C. Guezou, H. Nazari, X. Braud, and N. Guya (2003), Palcomagnetic investigation of a sigmoidal fold in the Zagros-Makran syntaxis (Southern Iran) and kinematic implication, paper presented at EGS-AGU-EUG Joint Assembly, Eur. Geophys. Soc., Nice, France.
- Stampfli, G., J. Mosar, P. Favre, A. Pillevuit, and J.-C. Vannay (2001), Permo-Mesozoic evolution of the western Tethys realm: The Neo-Tethys East Mediterranean Basin connection, in *Peri-Tethyan Rift/Wrench Basins and Passive Margins, Peri-Tethys Mem.*, vol. 6, edited by P. A. Ziegler et al., *Mem. Mus. Natl. Hist. Nat.* 186, 51–108.
- 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.
- Takin, M. (1972), Iranian geology and continental drift in the Middle East, *Nature*, 235, 147–150.
- Talbot, C. J., and M. Alavi (1996), The past of a future syntaxis across the Zagros, in *Salt Tectonics*, edited by J. L. Alsop, D. J. Blundell, and I. Davison, *Geol. Soc. Spec. Publ.*, 100, 89–109.
- 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.
- Vann, I. R., R. H. Graham, and A. B. Hayward (1986), The structure of mountain fronts, *J. Struct. Geol.*, 8, 215–227.
- Vernant, P., et al. (2004), Present-day crustal deformation and plate kinematics in the Middle East constrained by GPS measurements in Iran and northern Oman, *Geophys. J. Int.*, 157, 381–398.
- Westaway, R. (1994), Present-day kinematics of the Middle East and eastern Mediterranean, *J. Geophys. Res.*, 99, 12,071–12,090.

S. A. Eshraghi, Geological Survey of Iran, P.O. box 13/85, 1494 Tehran, Iran.

D. Frizon de Lamotte, J.-C. Guezou, P. Leturmy, and M. Molinaro, Département des Sciences de la Terre et de l'Environnement, UMR 7072, CNRS, Université de Cergy-Pontoise, 5 mail Gay-Lussac, Neuville-sur-Oise, F-95031 Cergy, France. (matteo.molinaro@geol.u-cergy.fr)