



Geometry and kinematics of the SE Zagros Mountains (Iran) : structural geology and geophysical modelling in a young collisional fold-thrust belt

Matteo Molinaro

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Dynamique et physico-chimie de la Terre et des planètes (ED 143)

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Spécialité Sciences de la Terre - Géologie

Geometry and kinematics of the SE Zagros Mountains (Iran) : structural geology and geophysical modelling in a young collisional fold-thrust belt

Géométrie et cinématique du Zagros Oriental (Iran) : géologie structurale et modélisation géophysique dans une chaîne récente de chevauchement – plissement

Par

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INTRODUCTION

General introduction to the Zagros Mountains and unsolved questions

Situated within the Alpine-Himalayan orogenic system, the Zagros Mountains extend along the Eastern Arabian margin for approximately 2000 km from Eastern Turkey in the north to the Hormuz Strait and Makran Mountains in the south-east. They constitute a morphological barrier separating the Arabian Platform and the Persian Gulf to the south-west from the large plateaux of Central Iran to the north-east and are almost entirely comprised within the country of Iran (Fig. 1). Compared to the neighbouring Himalayan Mountains, the Zagros Mountains present a relatively moderate topography with a mean elevation of ~1200 m and very few peaks exceeding 4000 m.

The Zagros Mountains result from the collision between the Arabian and Eurasian plates. Recent propagation of the deformation front over the Arabian margin has generated a fold-thrust-belt of exceptional width, the so-called Zagros fold-thrust belt (ZFTB). The extreme youth of the Zagros collisional belt, together with its arid climate and sparse vegetation, have allowed for an exceptionally good preservation and exposure of its fold-and-thrust structures and collisional geometry. In particular, the ZFTB has been often cited as one of the regions in the world displaying the finest examples of detachment folding. Therefore the Zagros Mountains constitute an ideal natural laboratory for studying the early stages of deformation within a colliding passive margin. This kind of study appears all the more opportune in the light of the considerable economic importance of the Zagros fold-thrust belt as a major hydrocarbon province of the Middle East. Despite these particularly favourable conditions, and compared to other mountain chains throughout the world, relatively little work has been done to understand the basic architectural elements and sequence of deformation in this orogen. Few studies exist based upon the classical concepts of fold-and-thrust belt geometry and mechanics as were first identified by workers such as Bally et al. (1966) and Dahlstrom (1970) in the Canadian Rocky Mountains and exposed in classical work such as Boyer & Elliott (1982). It is therefore imperative that the purely geometric facts, unbiased by genetic assumptions, be thoroughly explored in the Zagros Mountains before one can move forward to a stage of interpretation:

- Which factors (depth and nature of decollements, level of erosion, basement faulting, structural inheritance) control the present-day surface geometry of the Zagros fold-and-thrust structures?

- What is the sequence of development of these structures, i.e. do we have a purely forward propagation of the fold-thrust belt or is there any significant out-of-sequence reactivation within the deforming zone, and what is the timing of these events?
- What is the deeper (crustal and lithospheric) geometry of the Zagros Mountains and how does this affect their evolution?



Fig. 1. Physical and geographical position of the Zagros Mountains of Iran. ZFTB: Zagros Fold-Thrust Belt

The aim of this PhD dissertation is to apply these questions to the south-eastern part of the Zagros Mountains and in the structurally complex Zagros-Makran transitional zone known as the Bandar Abbas syntaxis. The work presented here is based upon a combination of field data – gathered during extensive fieldwork carried out in the region – and geophysical modelling of the Zagros lithospheric structure based upon gravity, topography and geoid data sets.

This work was carried out at the Department of Earth Sciences of the Université de Cergy Pontoise. The fieldwork was effectuated during three successive trips to Iran within the framework of a collaboration with the Geological Survey of Iran (GSI). Other institutions

involved in this work were the Université de Paris-Sud (UPS) and the Institut Français du Pétrole (IFP).

Plan of thesis

This thesis is presented in the form of a series of papers, which have been published or submitted for publication. These will form the core of the chapters.

Chapter I introduces the tectonic and geodynamic evolution and the inherited structural framework of the Eastern Arabian margin. The overall structure of the Zagros Mountains and a detailed review of previous work on the structural geology and crustal/lithospheric structure are presented in a separate paragraph.

Chapter II focuses on the eastern-most Zagros fold-thrust belt and the transitional zone with the Makran Mountains known as the Bandar Abbas syntaxis. It starts with a general introduction to the surface geology and lithostratigraphy of this area. The geometric facts of this structurally complex area as observed in the field, necessary for any further extrapolation of genetic aspects, are then presented in paper n.1 « **The origin of changes in structural style across the Bandar Abbas syntaxis, SE Zagros (Iran)** », published in *Marine and Petroleum Geology*. In this paper, having described the changes in structural style across the Bandar Abbas syntaxis, I go on to discuss the possible factors underlying these changes and the role of the facing Oman Mountains in the structural evolution of the syntaxis. At the end of the chapter a selection of additional photographs and field sketches are presented as a complement of paper n.1.

Chapter III focuses on a regional structural section through the eastern ZFTB. The description and discussion of this section are presented in paper n.2 « **The structure and kinematics of the south-eastern Zagros fold-thrust belt, Iran: from thin-skinned to thick-skinned tectonics** », submitted to *Tectonics*. Having first defined the geometry of the ZFTB in this area, I then propose a kinematic scenario for the development of the eastern ZFTB. Incremental restoration of the balanced cross-section allows us to discuss the sequence of deformation in the ZFTB and in particular the role of the basement in the deformation.

Chapter IV starts by reviewing current geometric and kinematic models of detachment folding. The results from the eastern ZFTB are then integrated in a discussion on the modes of folding in several areas of the ZFTB. This work, carried out in collaboration with S. Sherkati (NIOC), D. Frizon de Lamotte (UCP) and J.Letouzey (IFP), is presented in paper n.3 « **Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility,**

multiple detachments and final basement control », submitted to *Journal of Structural Geology*.

Finally, chapter V presents the results of geophysical modelling of the lithospheric structure in Zagros based upon the combined interpretation of different sets of geophysical data. The results of the modelling provide feedback to explain some of the results derived from the structural analysis of the eastern ZFTB in chapter III. This work, done in collaboration with Hermann Zeyen (UPS), is presented in paper n.4 « **Lithospheric structure underneath the south-eastern Zagros Mountains, Iran: recent slab break-off?** » submitted to *Terranova*.

CHAPTER I

TECTONIC AND GEODYNAMIC SETTING OF THE EASTERN ZAGROS MOUNTAINS

1. INTRODUCTION AND PLATE TECTONIC CONTEXT

The Eastern Zagros Mountains, geographically located in southern Iran, are situated within the general context of the convergence between the Arabian and Eurasian plates (Fig. I—1). For the most part this convergence zone is of a collisional type and coincides with the formation of the Zagros Mountains. In southern Iran, however, the collision transforms laterally into a subduction through the Bandar Abbas syntaxis and Zendan Fault transfer zone.

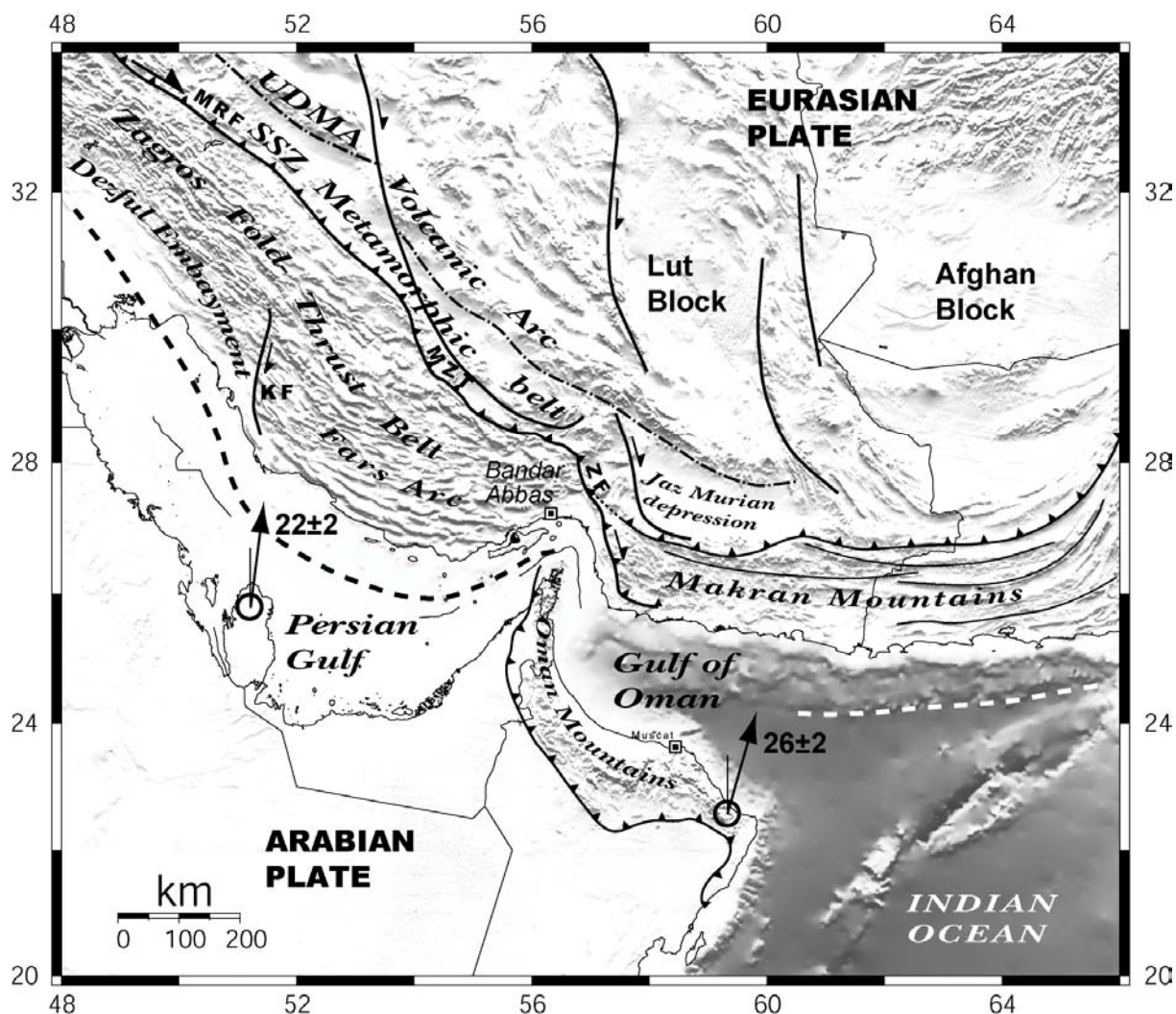


Fig. I—1 Structural map of the south-eastern Zagros Mountains and the Zagros-Makran transition zone. KF, Kazerun Fault; ZF, Zendan Fault; SSZ, Sanandaj Sirjan Zone; UDMA, Urumieh Dokhtar Magmatic Arc. GPS convergence vectors after Vernant et al. (2003).

This is due to the fact that the Arabian continental plate becomes oceanic with the Gulf of Oman and subducts beneath the facing Makran Mountains. The overriding plate in Makran is itself formed by two blocks (Lut and Afghan), which were accreted to Eurasia in Eocene times (Tirrul et al, 1982). The geometry and history of the south-eastern corner of the Arabian

plate are further complicated by the presence of the Oman Mountains resulting from the Late-Cretaceous obduction of Neo-Tethys ophiolites over the Arabian margin. The NNE-trend defined by the Oman Peninsula has been often cited as an important structural trend visible throughout the Arabian Plate and extending up to the Ural Mountains (O'Brien 1957), and is commonly referred to as the "Oman Line" (Gansser 1955, Hessami et al. 2001, Kadinski-Cade & Barazangi 1982, O'Brien 1957, Talebian & Jackson 2004).

2. PALEOGEOGRAPHIC EVOLUTION AND INHERITED GEOMETRY OF THE EASTERN ARABIAN PLATE MARGIN

2.1. Paleogeographic evolution

The Zagros Mountains are the surface expression of the uplift and deformation of the eastern margin of the Arabian Plate since Oligo-Miocene times. The long history of this margin is crucial to understanding the present-day inherited geometry of the Eastern Arabian margin and its control on the Neogene development of the Zagros orogen.

Prior to the formation of the eastern Arabian margin, the Arabian Plate had occupied an intra-cratonic setting since at least Eo-Cambrian times. At that time, regional strike-slip and associated extensional faulting (the Najd fault system), possibly connected to Palaeo-Tethys opening further north, affected the Arabian Plate (Fig. I—2). Whatever its origin, this extensional phase is relevant for the future history of the Arabian margin since it established a structural framework, which controlled the distribution and geometry of the sedimentary basins, and in particular of the Infracambrian salt basins (Edgell 1996, Sharland et al. 2001).

In Carboniferous times (315-295 Ma) the Arabian Plate was affected by "Hercynian" uplift and inversion of the former basins: this event resulted in a regional unconformity within the mid-Carboniferous sediments (Sharland et al. 2001). Onset of subduction of Palaeo-Tethys further north (Berberian & King 1981) may be related to this compressive event (Fig. I—3a). In Iran, Palaeo-Tethys was later sutured during the so-called Eo-Cimmerian tectonic event of Middle Triassic age. This suture zone is located roughly on the northern side of the current Alborz chain (Ricou et al. 1977, Stampfli 2000).

Neo-Tethys rifting commenced in Early Permian times (Ricou 1994) and continued through to Early Triassic (275-250 Ma) (Fig. I—3b-c), by which time a stable spreading oceanic ridge had formed. This led to separation and northward drift of the blocks that now form the Central Iran plate. The Eastern Arabian margin formed with a segmented geometry

controlled by transform faults, the most prominent of which can be seen separating the SE Zagros from the Oman Mountains and corresponding to the present day Dibba Fault line (Fig. I—2). Neo-Tethys opening continued uninterrupted until mid-Cretaceous times (Fig. I—3d,e). The appearance of an intraoceanic subduction zone (Fig. I—3f) and increased rates of subduction beneath Eurasia mark the beginning of the closure of Neo-Tethys. During this time the Arabian passive margin accumulated a thick and continuous sequence of platform carbonate rocks.

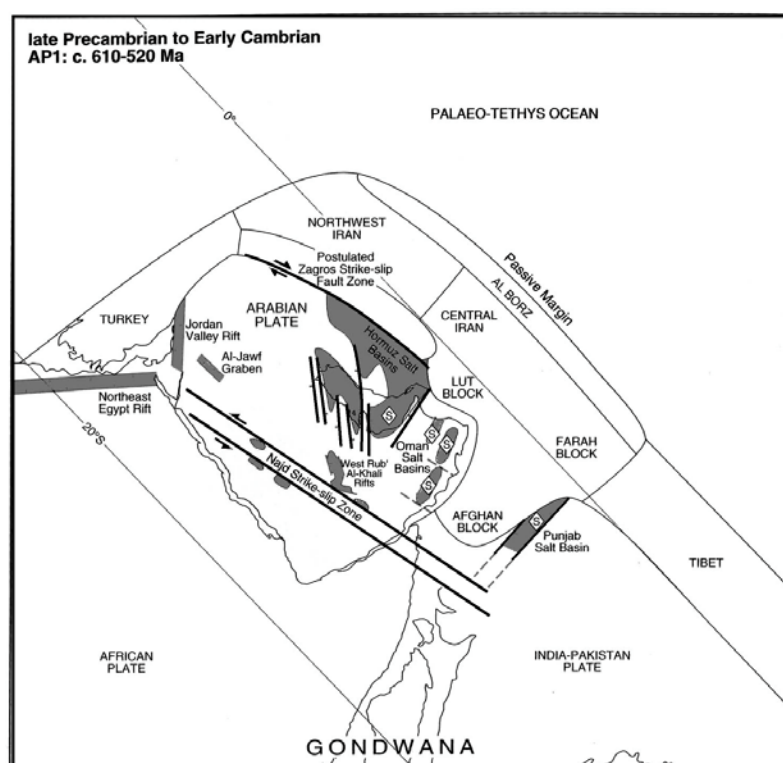


Fig. I—2 Paleogeographic setting of the Arabian Plate and surrounding blocks in Eo-Cambrian times. Modified after Sharland et al. (2001).

Approximately 130 Ma of relative tectonic stability were abruptly terminated when an intraoceanic offspring of Neo-Tethys, the Semail ocean (Stampfli 2000), obducted over the Arabian margin towards the end of Turonian (Béchennecc 1990, Breton 2004). Ophiolites and pelagic sediments were then thrust towards the SW along the entire length of the eastern Arabian margin, from the Oman Mountains in the south to southern Turkey and Syria in the north (Ricou et al. 1977) (Fig. I—3g).

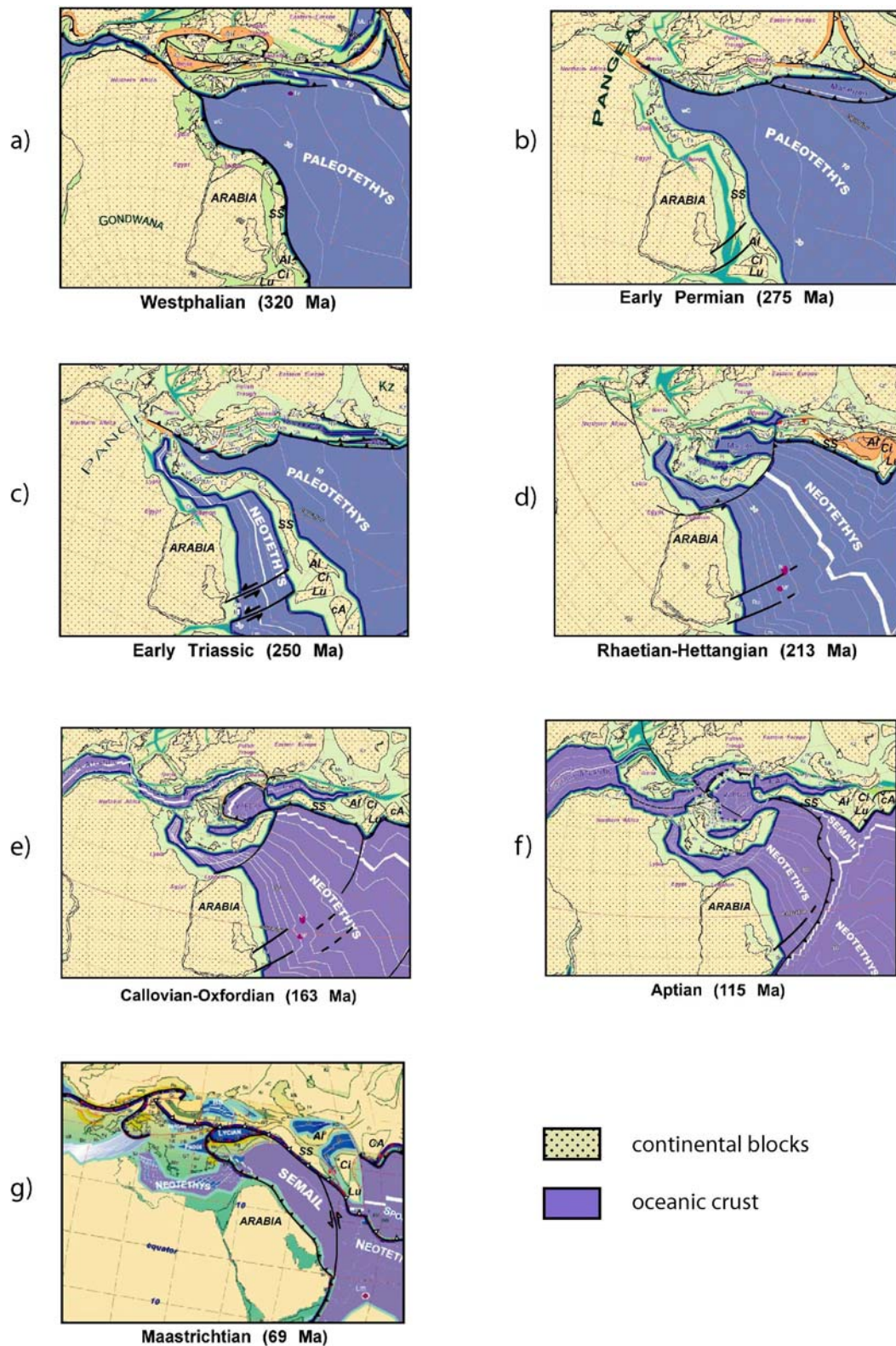


Fig. I—3 Paleogeographic evolution of the Arabian Plate (modified after Stampfli & Borel 2002) from Upper Carboniferous times to Maastrichtian. (a) Paleo-Tethys opening. (b) Initial Neo-Tethys rifting. Transform faults dissect the margins of incipient Neo-Tethys (c) Neo-Tethys opening, Paleo-Tethys converges. (d) Paleo-Tethys sutures in northern Iran. (e) Neo-Tethys subducts towards the north beneath Central Iran. (f) Semail ocean forms over an intra-oceanic subduction zone. (g) Semail ocean obducts over the eastern Arabian margin. SS: Sanandaj Sirjan. Al: Alborz. Ci: Central Iran. Lu: Lut. CA: Central Afghanistan.

Following the end of the obduction process in Maastrichtian times, the remaining Neo-Tethys (the “residual Tethys” of Braud, 1987) continued to subduct towards the NE beneath Central Iran (Fig. I—4) until the onset of collision in Zagros. The first signs of the collision from updated isopach maps in Central Zagros appear in Oligocene-Miocene times (Sherkati & Letouzey 2004). However the inception of collision is thought to have been diachronous along-strike Zagros, commencing in the north and propagating like a zip fastener towards the south. The main pulse of deformation, recognised throughout the whole of Zagros, occurred in Plio-Pleistocene times with the south-westward propagation of the deformation front and the development of the ZFTB.

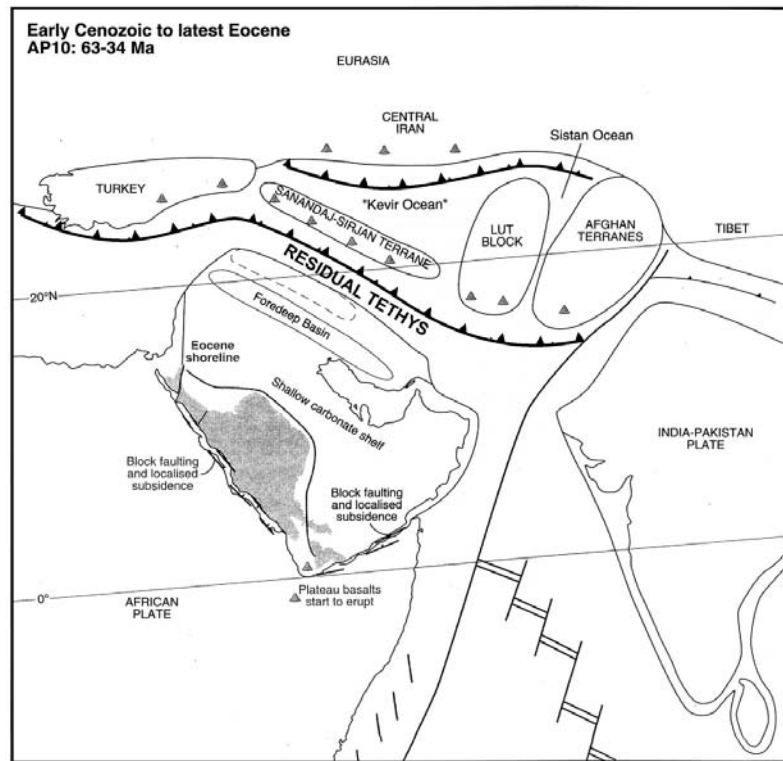


Fig. I—4 Cenozoic paleogeography of the Arabian Plate and surrounding regions. The “residual Tethys” subducts towards the north beneath the Central Iran blocks. Modified after Sharland et al. (2001).

2.2. Present-day kinematics.

The Arabian plate is presently moving towards Eurasia on a N 13° direction at a rate of 22 ± 2 mm/yr, increasing to 26 ± 2 mm/yr in eastern Oman (Fig. I—1), according to recent estimations based upon GPS measurements (Vernant et al. 2003). This is considerably lower than the velocity of 31 mm/yr which had been inferred from the NUVEL-1A plate motion model (DeMets et al. 1994). The pole of rotation determined for the Arabian Plate motion is

situated at $\sim 28^{\circ}\text{N}$ - 20°E (approximately central Lybia) by Vernant et al. (2003), in agreement with results from other authors. GPS measurements indicate that less than half of the Arabia-Eurasia convergence is taken up by Zagros (from 9 ± 2 mm/yr in the south decreasing to 4.5 ± 2 mm/yr in the north). The rest is transferred to northern Iran in the Alborz Mountains and the Caspian Sea, while the Sanandaj-Sirjan and Central Iranian blocks show little internal deformation (Jackson et al. 1995). Because of the obliquity of the convergence, deformation in north-western Zagros is presently partitioned into right-lateral strike-slip on the Main Recent Fault (MRF) (Talebian & Jackson 2002, Tchalenko & Braud 1974) and orthogonal shortening within the NW-trending folds of the ZFTB. In central and southern Zagros, on the other hand, no partitioning is reported and convergence is accommodated by orthogonal shortening within the roughly E-W folds of the Fars Arc.

2.3. Geometry of the Zagros-Makran transform margin

The Arabian margin in the transitional zone between Zagros and Makran is characterised by a segmented geometry, changing from the average NW-trend of Zagros to a NNE-trend in the Oman peninsula. This particular geometry of the margin is inherited from the initial phases of Neo-Tethys rifting and presumably resulted from the activation of a left-lateral transform fault. The geometry of this transform margin is constrained by published drilling data from the area north of the city of Bandar Abbas, which according to Stampfli et al. (2001), suggests location over a rift shoulder zone (Fig. I—5).

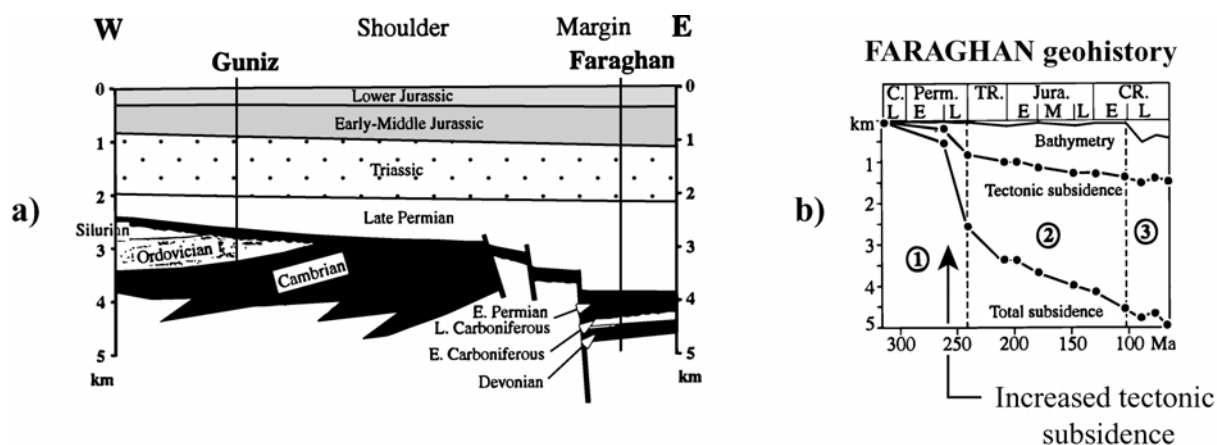


Fig. I—5 a) Stratigraphic correlation section based on two drillings in the Bandar Abbas area showing evidence for location over a rift shoulder. b) Subsidence curve based upon the Faraghan drilling showing increased subsidence rates in Permian-Triassic times. Modified after Stampfli et al. (2001).

Subsidence curves for this region show an unusually high tectonic subsidence at the transition between Permian and Triassic, interpreted by Stampfli et al. (2001) as evidence for localised block faulting and collapse of the margin. This transform margin was likely to have been controlled by older weaknesses within the Arabian basement. The pattern of distribution of the Eo-Cambrian salt basins suggests the presence of a fault-controlled high in this area separating the Zagros Hormuz basin in the north from the southern Oman salt basins (Fig. I—2). These N to NNE-trending alignments are known from elsewhere in the Arabian Plate and form the so-called “old grain of Arabia” (Henson 1951), thought to be the surface manifestation of ancient Pan-African structures (Fig. I—6). These structures influenced the later paleofacies patterns throughout the Eastern Arabian margin and were therefore of great importance to the final structural behaviour of the stratigraphic pile during shortening in Zagros and Oman.

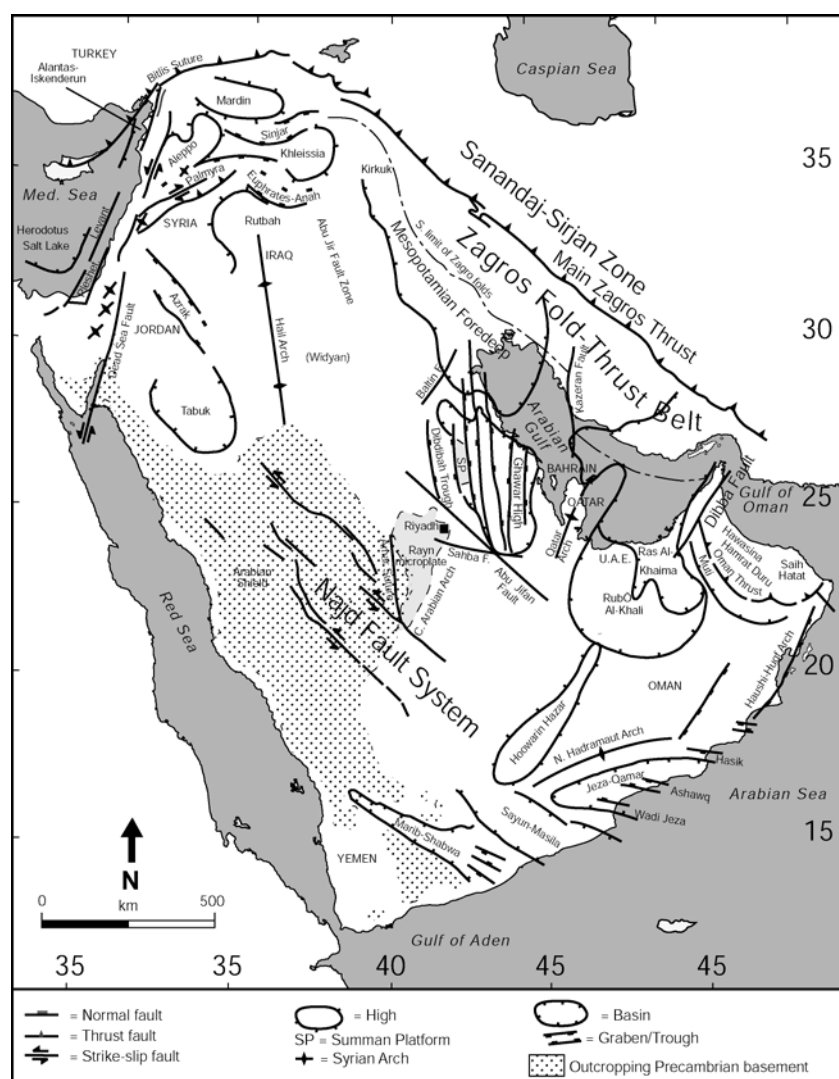


Fig. I—6 Major structural trends within the Arabian Plate. Modified after Ziegler (2001).

3. STRUCTURE OF THE ZAGROS FOLD-THRUST BELT

3.1. Structural subdivisions of the Zagros Mountains

The Zagros Fold-Thrust Belt (ZFTB) corresponds to the Arabian paleomargin inverted during collisional deformation. With widths varying between 250 and 350 km, the ZFTB is one of the largest fold-thrust belts in the world (Fig. I—7)

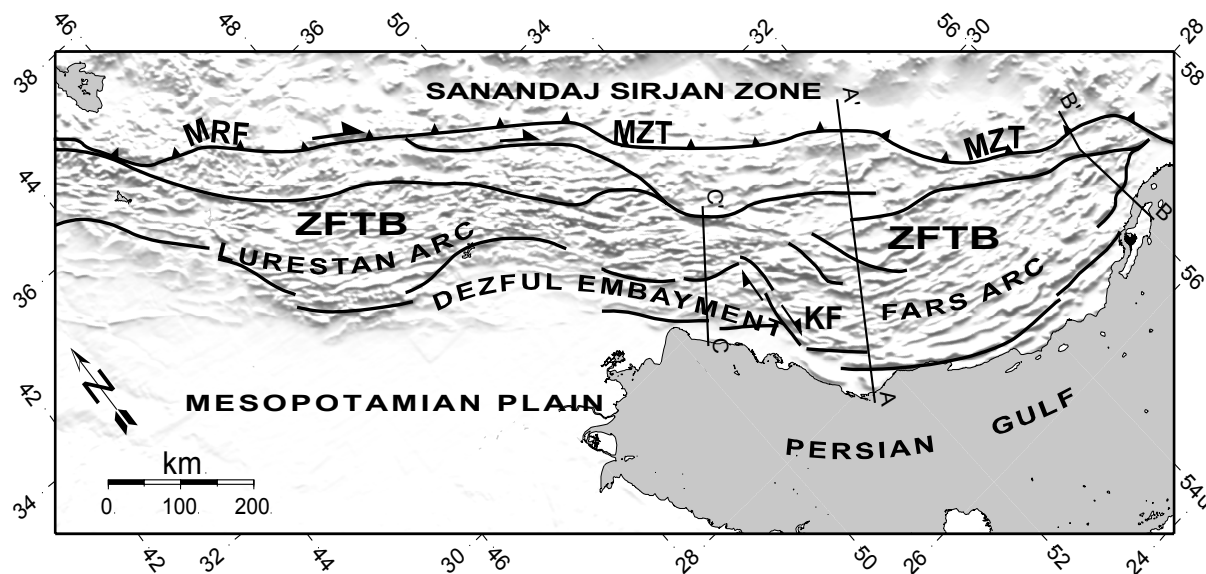


Fig. I—7 Map of the Zagros Fold-Thrust Belt (ZFTB) showing the principal tectonic subdivisions and fault lines. Sections A-A' and B-B' in figure I—14, section C-C' in figure I—15. Abbreviations as in figure I—1.

In the ZFTB, the Proterozoic-to-Recent sedimentary cover has been detached from the Pan-African basement and folded into a succession of huge cylindrical folds. It is flanked to the SW by the Persian Gulf and Mesopotamian Plain – representing the foredeep basin at the front of the orogen – and to the NE by a 150 to 250 km-wide belt of sedimentary-metamorphic rocks (the Sanandaj-Sirjan Zone, SSZ) (Ricou et al. 1977, Stocklin 1968). These latter are thrust over the ZFTB along the so-called Main Zagros Thrust (MZT), which is marked at the surface by a discontinuous belt of ophiolitic rocks and melange running along the entire length of the orogen (Ricou 1971). Another alignment of ophiolites is found north-east of the SSZ, marking the limit between the SSZ and a volcanic magmatic arc (the Urumieh-Dokhtar magmatic arc, UDMA, (Fig. I—1). Some debate exists on the origin of the SSZ and whether it should be considered as part of the Iranian continental block or of the Arabian Plate. It has been a tradition among workers on Iranian geology to connect the SSZ to the Central Iran domain (Haynes & McQuillan 1974, McCall 1997, Stampfli 2000, Stocklin 1968), based essentially upon stratigraphic correlations.

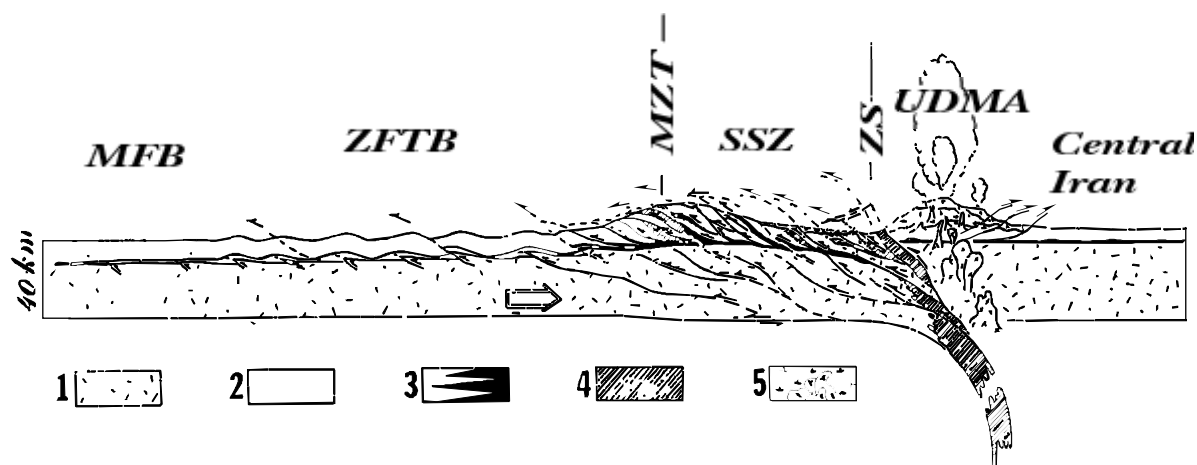


Fig. I—8 Generalised schematic model of the Zagros orogen slightly modified after Alavi (1994). 1 = continental crust; 2 = Phanerozoic sedimentary cover; 3 = evaporites (blank) and dolomites (black) at the base of the cover; 4 = oceanic crust; 5 = magmatic rocks of the UDMA zone. MFB: Mesopotamian Foredeep Basin, ZS: Zagros Suture. Other abbreviations as in figure I—1.

Therefore the suture between the Arabian and Iranian plates was usually placed SW of the SSZ along the MZT. However, Alavi (1994) argued, based upon structural observations, that the real suture zone should be situated on the north-eastern side of the SSZ next to the magmatic arc. In his interpretation, the ophiolites thrusting over the ZFTB are structurally connected to the ophiolites on the north-eastern side of the SSZ, which thus constitute the real “root” zone of the Late Cretaceous obduction (Fig. I—8).

3.2. Seismicity in Zagros: evidence for basement faulting

Within the Zagros orogen, the overwhelming majority of the seismicity is presently concentrated south-west of the MZT, within the ZFTB (Fig. I—9). The SSZ, by contrast, appears to be almost devoid of seismicity. The seismic activity within Zagros has long been considered to extend to depths as great as 80 km, with a greater concentration in the 30-15 km depth interval (Harvard CMT catalogue, 2002). However, recent studies based upon teleseismic waveform modelling (Maggi et al. 2000, Talebian & Jackson 2004) have reassessed these figures and it now appears that nearly all earthquakes in Zagros are confined to depths shallower than 20 km (Fig. I—10). The sole exception to this is seen in the Zagros-Makran transition zone, where depths of 28 km (Fig. I—11b) (Maggi et al. 2000, Talebian & Jackson 2004) occur in a NE-trending zone of greater seismicity extending north of the city of Bandar Abbas (Kadinski-Cade & Barazangi 1982).

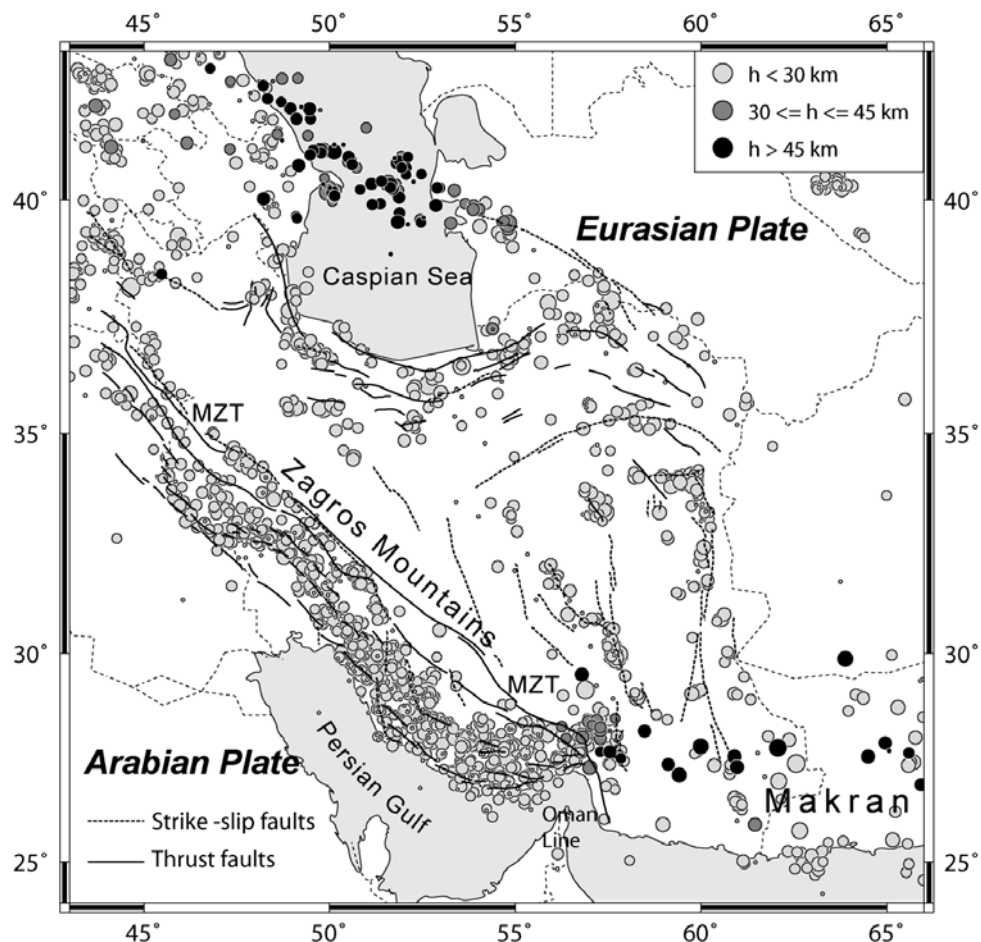


Fig. I—9 Seismicity of the Iranian region (1909-2004), modified after Engdahl & Bergman (2004), showing the location at depth of seismic events and the major structural trends in Iran

This, according to Talebian & Jackson (2004) is consistent with underthrusting of the Arabian basement beneath Central Iran in this area. Moving further east across the Oman Line and within the Makran subduction prism, the seismicity decreases abruptly in intensity but increases in depth (Fig. I—9) (Byrne & Sykes 1992), defining a 26° north-dipping subduction plane with a cluster of seismicity at a depth of ~60 km (Fig. I—10) (Engdahl & Bergman 2004, Maggi et al. 2000).

The focal mechanisms determined for seismic events in Zagros are predominantly of a reverse type. This seismic activity is currently the strongest line of evidence put forward by authors to prove the involvement of basement in the Zagros Neogene deformation (Fig. I—9) (Berberian 1995, Talebian & Jackson 2004). Another argument which is invoked is the existence of lines of strong change in structural elevation throughout Zagros, particularly well expressed in Central Zagros in the area of the Dezful Embayment (Sherkati & Letouzey 2004).

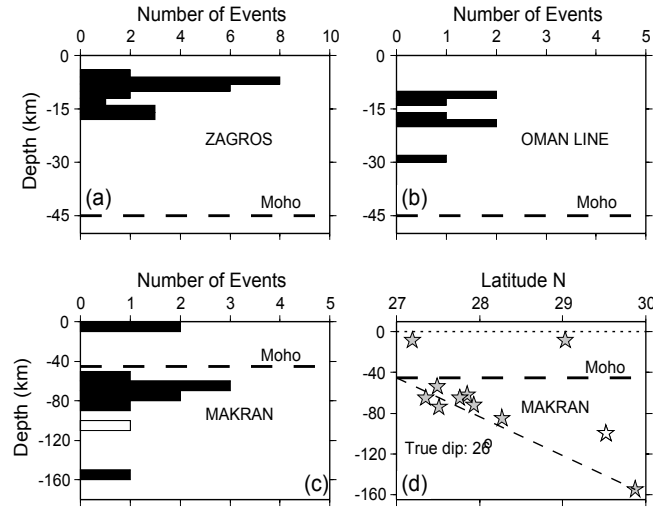


Fig. I—10 Histograms showing the focal depth distributions in (a) the Zagros, (b) the Oman Line and (c) the Makran regions. (d) N-S section of Makran showing inferred subduction plane. After Maggi et al. (2000).

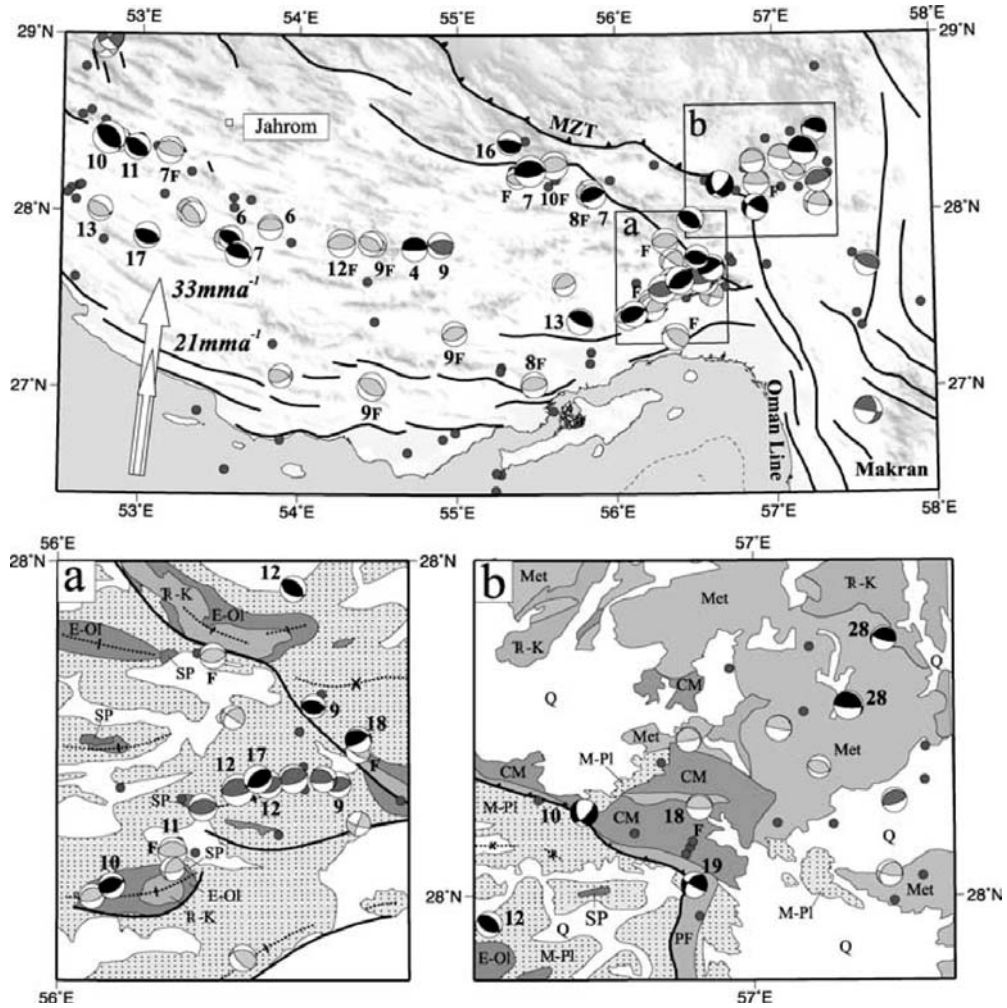


Fig. I—11 Fault plane solutions in the south-eastern Zagros and Oman Line regions, after Talebian & Jackson (2004), with centroid depths marked alongside where available. Light grey and dark grey spheres are Harvard CMT solutions. Black solutions are the results of Talebian & Jackson (2004). Note in (b) upper right hand corner the two high angle fault plane solutions at 28 km depth

Strike-slip solutions are much less frequent and are mainly associated with right-lateral movement along the Kazerun fault in Central Zagros (Baker et al. 1993) and to a lesser degree to strike-slip movement along the Main Recent Fault (MRF) (Fig. I—7) (Talebian & Jackson 2004, Tchalenko & Braud 1974). In the area of the Zagros-Makran transition, the focal mechanisms are predominantly of reverse type, although some isolated strike-slip events and one normal event are reported as well (Fig. I—11). The earthquakes in this region define clear alignments which are matched at surface by alignments of giant structures exhuming rocks as old as Palaeozoic, considered by Berberian (1995) as evidence for major basement faulting in this area.

3.3. Previous work on the structure of the ZFTB

3.3.1. Structural geology

Owing to the great amounts of trapped hydrocarbon accumulations in the Zagros foothills, for a long time studies on their structural geology were mainly undertaken by workers directly or indirectly connected to oil companies operating in the region. Early studies on the Zagros mountains focused mainly on the numerous spectacular salt diapirs piercing both the structures of the fold-thrust belt and the undisturbed cover in the Persian Gulf (De Bockh et al. 1929, Harrison 1930, 1931). Catalogues of the salt plugs were established and the salt was dated as Infra-Cambrian, based upon the presence of trilobites. However, some early work also focused on other structures unrelated to salt diapirism.

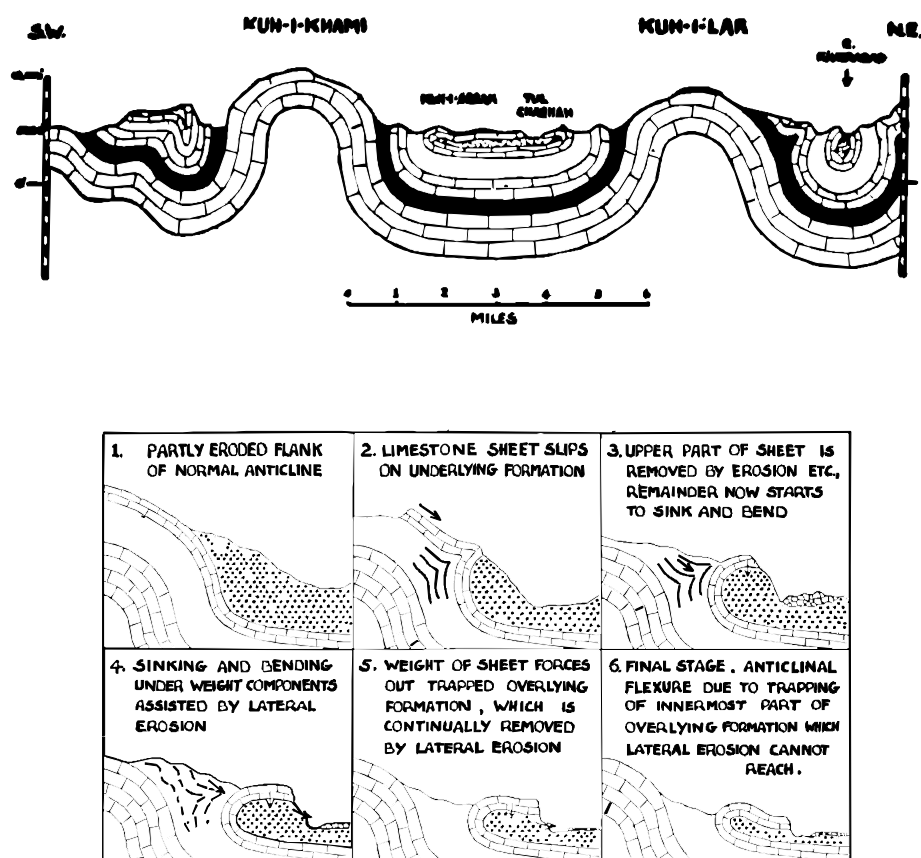


Fig. I—12 Collapse structures within Oligo-Miocene Asmari beds on the flanks of two Zagros anticlines in the Fars Arc (Fig. I— 7) (top) and conceptual model for their formation (bottom), after Harrison & Falcon (1935)

Harrison & Falcon (1934) and Harrison & Falcon (1935) investigated some enigmatic collapse structures disrupting Oligo-Miocene limestone beds on the flanks of some of the larger anticlines in Central Zagros. The most remarkable of these structures, named by the authors “flaps”, display entire panels of Oligo-Miocene limestone beds bent backwards to a completely overturned position in the synclinal valleys adjacent to the large anticlines (Fig. I—12). The authors attributed the formation of these structures to a combination of gravity and erosional processes and proposed a conceptual model for their development (Fig. I—12).

Subsequent work by O'Brien (1957) highlighted new aspects of the structure of Zagros in the Dezful Embayment area and in particular the role of the Lower Miocene evaporitic layers (Gachsaran Fm) as a major intermediate decollement horizon responsible for spectacular disharmonic folding within the cover. His sections, since reproduced by numerous authors, display the singular characteristic of synclines wedged against anticlines at depth (Fig. I—13a). The Gachsaran Fm is thus squeezed from areas of almost zero thickness to areas of huge accumulations of salt (salt bulges). The author presents the first example of kinematic reconstruction of a section in Zagros (Fig. I—13b). He also proposes a subdivision of the Zagros stratigraphic section into a series of structural units defined by their mechanical characteristics.

The first geological maps and a series of complete cross-sections of the ZFTB were established in the 50's and 60's by the BP Company (1956), later completed by the National Iranian Oil Company (NIOC 1975, 1976) (Fig. I—14). Two features in these cross-sections are here worth mentioning: (1) the visibly active role given to the basal salt layers in piercing the cover and in promoting the development of thrusts and folds and (2) the presence of basement faults cutting through the sedimentary cover.

The role of the basal salt layers in the development of the ZFTB was later discussed in detail by Colman-Sadd (1978), based essentially upon field observations. In particular, this author recognised for the first time the importance of the extreme mobility of the Hormuz salt layers at the base of the cover in generating pure buckle folds in Zagros. He did not however consider the basement to be involved in the deformation or to exert any influence on the development of folds, except in areas of unquestionable strike-slip faulting.

During the following 20 years or so work in Zagros came to a virtual standstill, mainly due to difficult conditions of access to the region. Folding in Zagros was again discussed briefly by Sattarzadeh et al. (2000), who acknowledged the coexistence of pure buckle folding and basement-induced folding in the ZFTB, based upon the map view pattern of the folds.

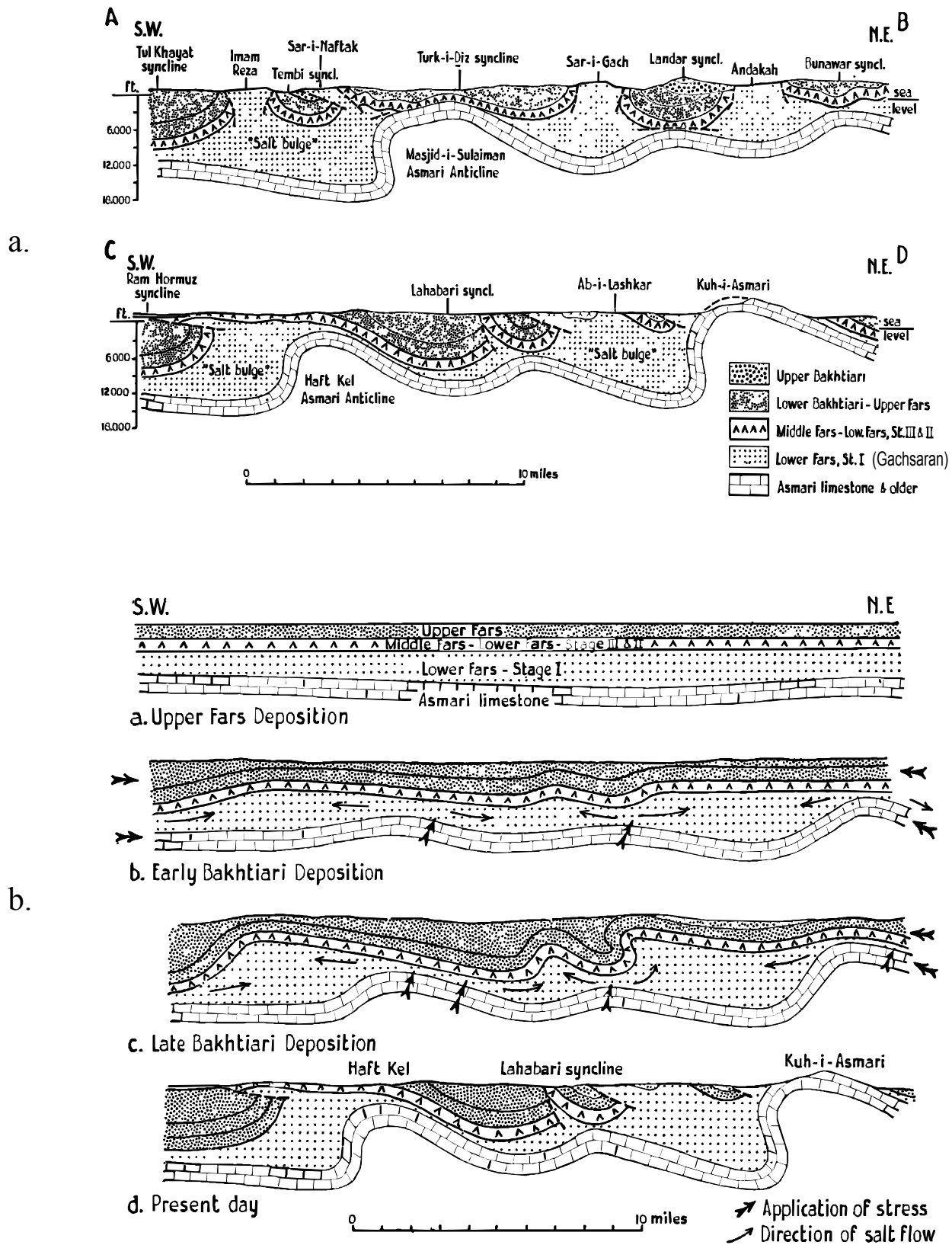
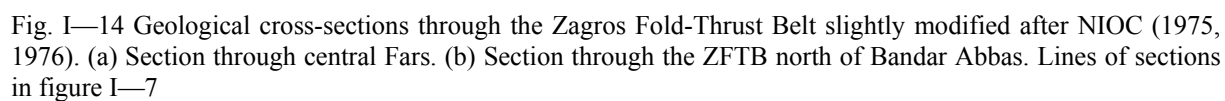
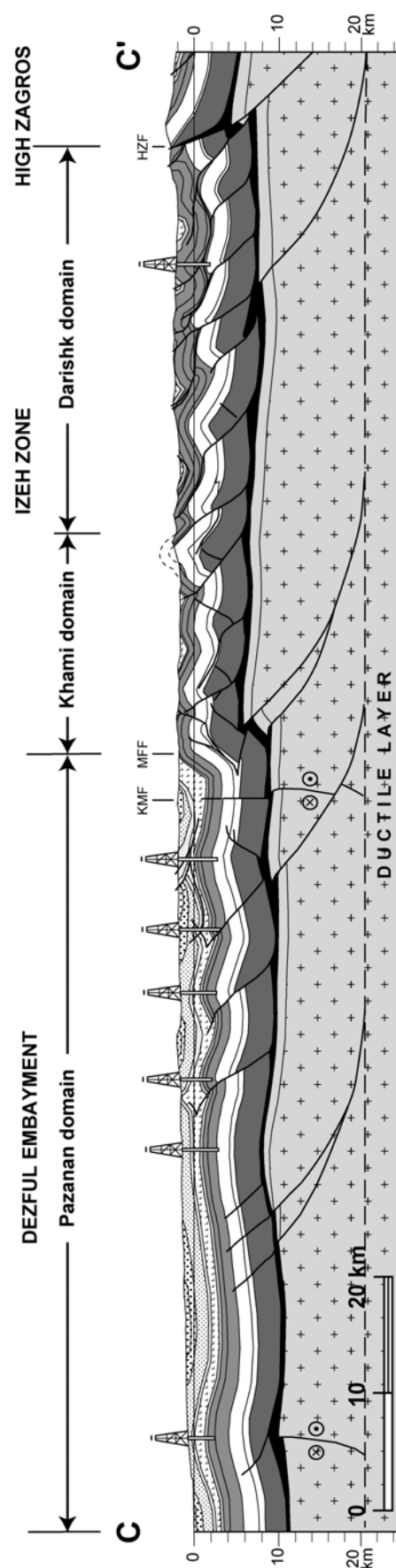


Fig. I—13 (a) Geological cross-sections through the Dezful embayment area (Fig. I—7). (b) Structural evolution proposed for section A-B. After O'Brien (1957).



Recent renewed interest in the ZFTB has resulted in a series of new papers illustrating some general sections through the ZFTB (Blanc et al. 2003, McQuarrie 2004, Sherkati & Letouzey 2004). These sections highlight the importance of the mechanical stratigraphy and the influence of multiple intermediate decollement levels on the structure of the ZFTB. This is particularly evident in central and northern Zagros where the surface wavelengths of the structures clearly cannot be explained alone by decoupling at the base of the cover (Fig. I—15) (Sherkati & Letouzey 2004). In the Fars region, on the other hand, the presence of numerous salt diapirs and the large wavelength of the folds strongly suggest that these are controlled by efficient decoupling of the entire cover over the basal salt layers. However, other decollement levels can be inferred in this region as well, as will be discussed in chapters II. The estimates of shortening reported from Zagros are as a rule very low when compared to other fold-thrust belts, with shortening ratios varying between 13 and 25 %.

Fig. I—15 Structural transect of the Central ZFTB in the area of the Dezful Embayment, modified after Sherkati & Letouzey (2004). HZF, High Zagros Fault; MFF, Mountain Front Fault; KMF, Kharg-Mish fault. Line of cross-section in figure I—7



3.3.2. The problem of the origin of the Fars Arc

This is a recurrent question in studies on the ZFTB and concerns essentially the origin of the curvature of the Fars Arc (Fig. I—7). The problem was first raised by Ricou (1976), who suggested that the curvature of the Fars Arc originated from two non-coaxial shortening events. However, this proposition implies that a significant change occurred at some time in the direction of convergence between the Arabian and Eurasian plates. Since most authors agree that this is not the case, this interpretation was rapidly abandoned. The discussion was revived by Bakhtari et al. (1998) based upon magnetic fabric measurements in the western branch of the Fars Arc. Having observed that the pre-folding magnetic lineations present a systematic clockwise obliquity with the fold axes, these authors suggest that the arcuate fold pattern of the Fars Arc results from post-folding vertical axis rotations. However, they do not explore any further the possible mechanisms controlling the rotation. Hessami et al. (2001) later presented a model for Zagros in which the rotation of fault-bound basement blocks controlled the development of the folds in the Fars Arc. Talebian & Jackson (2004) similarly suggest that the strike-slip faults in Central Zagros (e.g. the Kazerun Fault) underwent anticlockwise rotations to accommodate the transition from perpendicular convergence in the SE to partitioned convergence in the NW of the ZFTB. The main problem with these “basement-involved” interpretations is that it is never discussed upon which horizon these rotated blocks should be decoupled. Furthermore, the nature of the basement-cover interaction and the role of the intervening Hormuz salt decollement horizon remain unclear. Finally, in a recent paper (Aubourg et al. 2004, in press) suggest, based upon magnetic fabrics, that the folds in the eastern part of the Fars arc were rotated to their present position by interference with an indenting Oman Peninsula.

3.3.3. Crustal and lithospheric structure

Few geophysical studies have been carried out to investigate the crustal or lithospheric geometry of the Zagros Mountains. It has long been surmised that the Zagros Mountains are underlain by a crustal root, and this was confirmed by gravity data (Dehghani & Makris 1984, Snyder & Barazangi 1986), seismological information (Hatzfeld et al. 2003) and mantle tomography (Paysanos & Walter 2002), with maximum depths to Moho in the order of 45 – 50 km. The depth to Moho underneath the Persian gulf is reported at 40 km according to

results from the spectral analysis of P-wave amplitude ratios (Al-Amri & Gharib 2000) and from gravity modelling (Snyder & Barazangi 1986).

Much less is known about the structure of the lithosphere. Bird (1978), based upon finite element modelling, tested several lithospheric geometries beneath Zagros and concluded that only a model with a detached lithosphere could satisfactorily explain the distribution of seismicity underneath Zagros (Fig. I—16). Snyder & Barazangi (1986), in their final model based upon gravity modelling, chose a subducting lithosphere decoupled from the lowermost crust (Fig. I—17). The only other information existing on the lithospheric structure in this region comes from global tomographic models (Bijwaard & Spakman 2000, Bijwaard et al. 1998). These show a pronounced negative velocity anomaly beneath Central Iran and extending into Zagros (Fig. I—18), suggesting a warmer and thinner lithosphere.

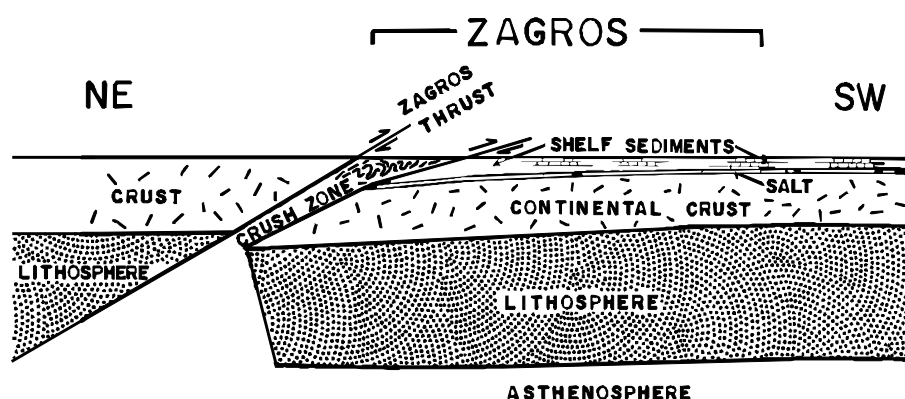


Fig. I—16 Lithospheric scale model of the Zagros Mountains based on finite element modelling, showing a possible lithospheric detachment beneath the Zagros suture zone. After Bird (1978).

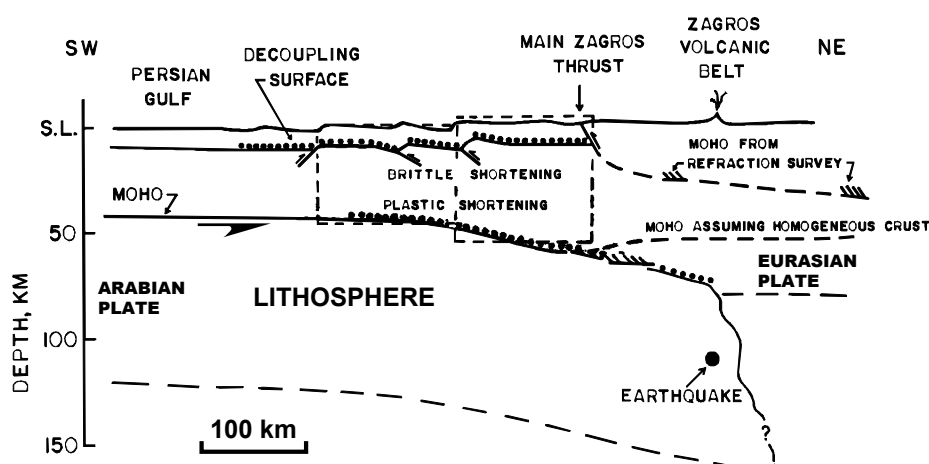


Fig. I—17 Crustal-lithospheric model of the Zagros Mountains based on gravity modelling after Snyder & Barazangi (1986)

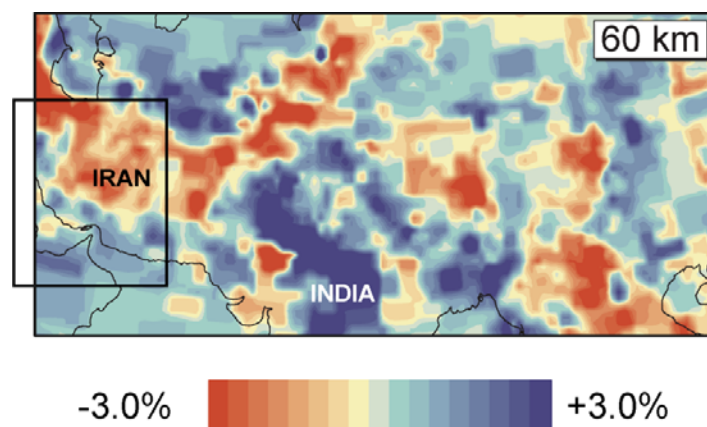


Fig. I—18 Tomography layer section of the Indian and Iranian regions at 60 km depth, modified after Bijwaard & Spakman (2000).

4. STRATIGRAPHY OF THE SOUTH-EASTERN ZFTB

The stratigraphy of the Zagros foothills was formally established by James & Wynd (1965) and this work still remains the basic reference for workers on Zagros. However, there is still some confusion on the stratigraphic nomenclature and in particular on the correlations with sedimentary systems in other regions of the Arabian Plate such as the neighbouring Oman Mountains.

The stratigraphic pile of the Eastern Arabian margin consists of a very thick (up to 10 km) and remarkably continuous Eo-Cambrian to Recent sequence resting on a Precambrian crystalline basement of Pan-African affinity. The sequence is not continuous throughout Zagros (Fig. I—19), but displays numerous lateral variations in facies reflecting changing paleogeographic conditions along-strike the Arabian margin. In this section we will limit our description to the stratigraphic sequence as observed on the field in the south-eastern Zagros and Bandar Abbas area.

4.1. Palaeozoic-Mesozoic sequence

- **Hormuz Salt.** The base of the sequence is represented by the evaporitic layers of the Eocambrian Hormuz formation. This formation, of uncertain thickness (1000-1500 m according to Kent, 1979), consists of an alternation of pure salt and dark massive dolomitic layers. During Neogene orogeny, the salt pierced through the overlying cover and buoyantly rose to the surface generating spectacular salt diapirs and glaciers visible throughout the south-eastern Zagros. On the field, the soluble salt is often absent because

of rapid weathering and in its place remains the insoluble material transported with the salt, including blocks of dolomite and “exotic blocks” of volcanic-magmatic rocks. As a result the diapirs typically present a strongly carstified and chaotic morphology (Fig. I—20a). The Hormuz salt is the main basal decollement horizon for the ZFTB. This is particularly evident in the Fars region, where the presence of this very thick ductile horizon has permitted the development of some of the finest examples of detachment anticlines in the world. In the Dezful Embayment the presence of the Hormuz salt is not verified and it is not precisely clear where the basal decollement for structures in this area is situated (Sherkati & Letouzey 2004).

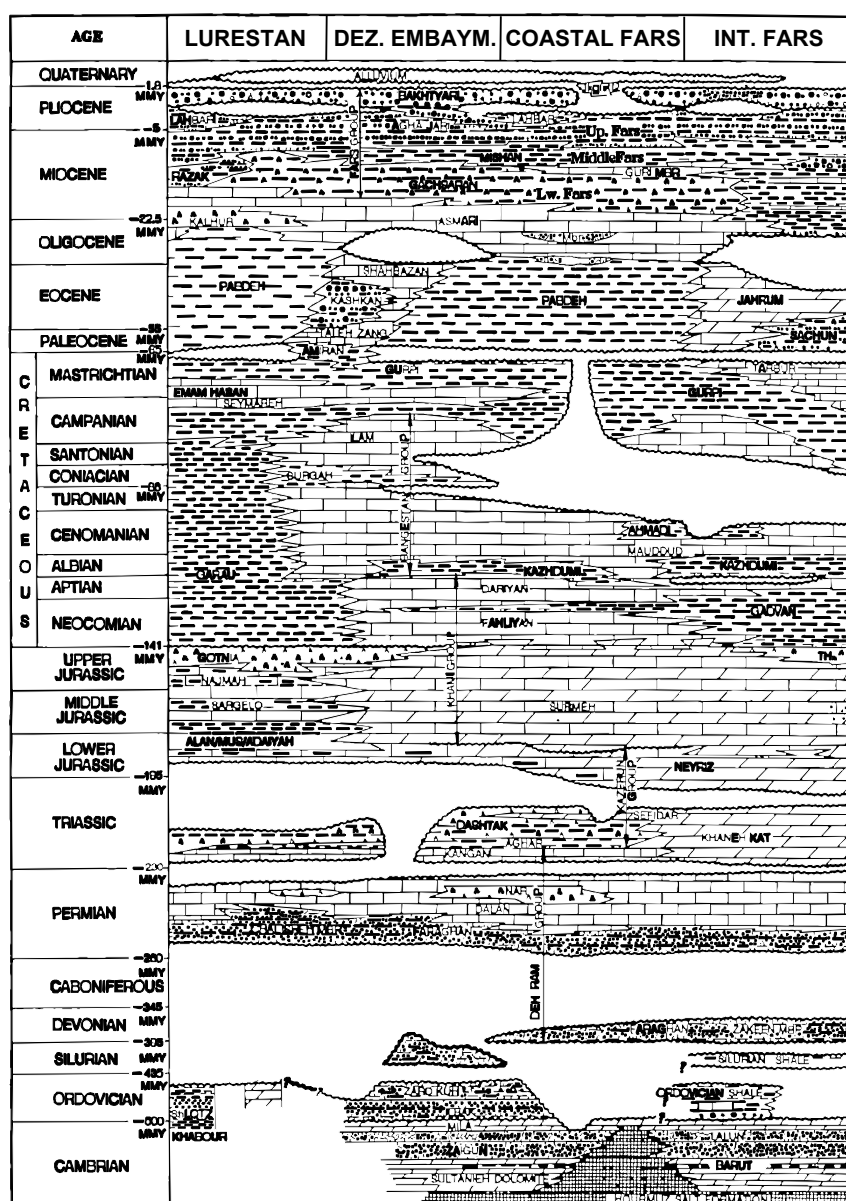


Fig. I—19 Approximately NW-SE stratigraphic correlation chart of the Zagros area, after Moitiei (1993). For location of Zagros domains indicated at top see Fig. I—7.

- **Palaeozoic sequence.** Some of the best exposures of Palaeozoic rocks in Zagros are found in the Bandar Abbas area, where rocks as old as Silurian are brought to the surface by large thrust faults cutting through the entire cover. It is in this area that the type section for the Faraghan formation (Fig. I—20) was first defined (Szabo & Kheradpir 1978). It consists of a well-bedded coarse-grained quartz-arenite varying in colour between dark brown and white (Fig. I—20b). The absence of a large part of the Palaeozoic sequence, together with the observation of a regional angular unconformity indicates that the Zagros basin was affected by uplift and inversion in Carboniferous times (Szabo & Kheradpir 1978) (Fig. I—20), possibly in connection with Hercynian or Variscan orogeny
- **Mesozoic platform sequence.** The entire Permo-Triassic to Upper Cretaceous sequence consists of a thick and uninterrupted sequence of competent platform carbonates deposited in a passive margin setting. In central and northern Zagros the sequence is less uniform, with the presence of intermediary levels of evaporites (Triassic Dashtak fm) and shales (Middle Cretaceous Kazhdumi fm) (James & Wynd 1965). In the Bandar Abbas area these rocks are exposed as huge cliffs in the cores of the larger tectonic structures (Fig. I—20c). The Mesozoic sequence is interrupted by a regional unconformity dated as Post-Cenomanian-Turonian (Koop & Stoneley 1982), visible on the field as a weathered “hard ground” surface (Fig. I—20d) and considered to be the first sign of obduction-related tectonic instability along the Arabian margin. This was followed by deposition of the low weathering grey marls and marly limestone of the Gurpi Fm (Fig. I—20e) from Turonian to Maastrichtian times. From a structural point of view, the Mesozoic sequence, together with the underlying Palaeozoics, constitutes the main supporting frame for the very broad folds of the Fars Arc. The Gurpi horizon is an intermediate decollement horizon which has allowed imbrications and duplexing within the overlying Jahrom Fm (Fig. I—21).

4.2. Cenozoic sequence

- **Paleocene to Lower Miocene sequence.** The tectonic instability represented by the Gurpi marls ended with the re-establishment of carbonate platform conditions throughout Zagros (Jahrom/Asmari Fms) (James & Wynd 1965). The well-bedded light-coloured Asmari limestone is a major reservoir rock in central and northern Zagros. In the Bandar Abbas area it is replaced by the laterally equivalent Jahrom massive brown dolomite (Fig. I—21a). In the northern part of the Bandar Abbas area, this formation is frequently deformed by imbrications and duplexing. Renewed instability of the margin in Lower Miocene times

- possibly the first signs of collision – is marked by a regional unconformity and the appearance in eastern Zagros of the Razak Fm (lateral equivalent of the Gachsaran Fm), a distinctive layer of gypsiferous red marl containing lenses of conglomerates (Fig. I—21b).
- **Middle Miocene to Recent molasse sequence.** Starting from Middle Miocene the sedimentation in Zagros is increasingly controlled by the initial phases of the Arabian-Eurasian collision and the establishment of foredeep conditions on the Arabian margin (Koop & Stoneley 1982). The base of the Mishan Fm is marked in the Bandar Abbas area by a layer of reefal limestone (Guri Fm) of extremely variable thickness ranging from almost zero to several hundreds of meters (Fig. I—21b). This formation is often disrupted by gravity collapse on the flanks of the major anticlines. The Mishan formation, particularly developed in the south-eastern Zagros, consists of low weathering grey marls and thin-bedded marly limestone (Fig. I—21c) and constitutes another important regional decollement horizon. From Mishan upwards the molasse deposits become progressively more coarse-grained with the Agha Jari sandstone (Fig. I—21d) and the Bakhtyari conglomerate at the top (Fig. I—21e). A pronounced angular unconformity, widely observed throughout Zagros, marks the transition between the Agha Jari Fm and Bakhtyari Fm.

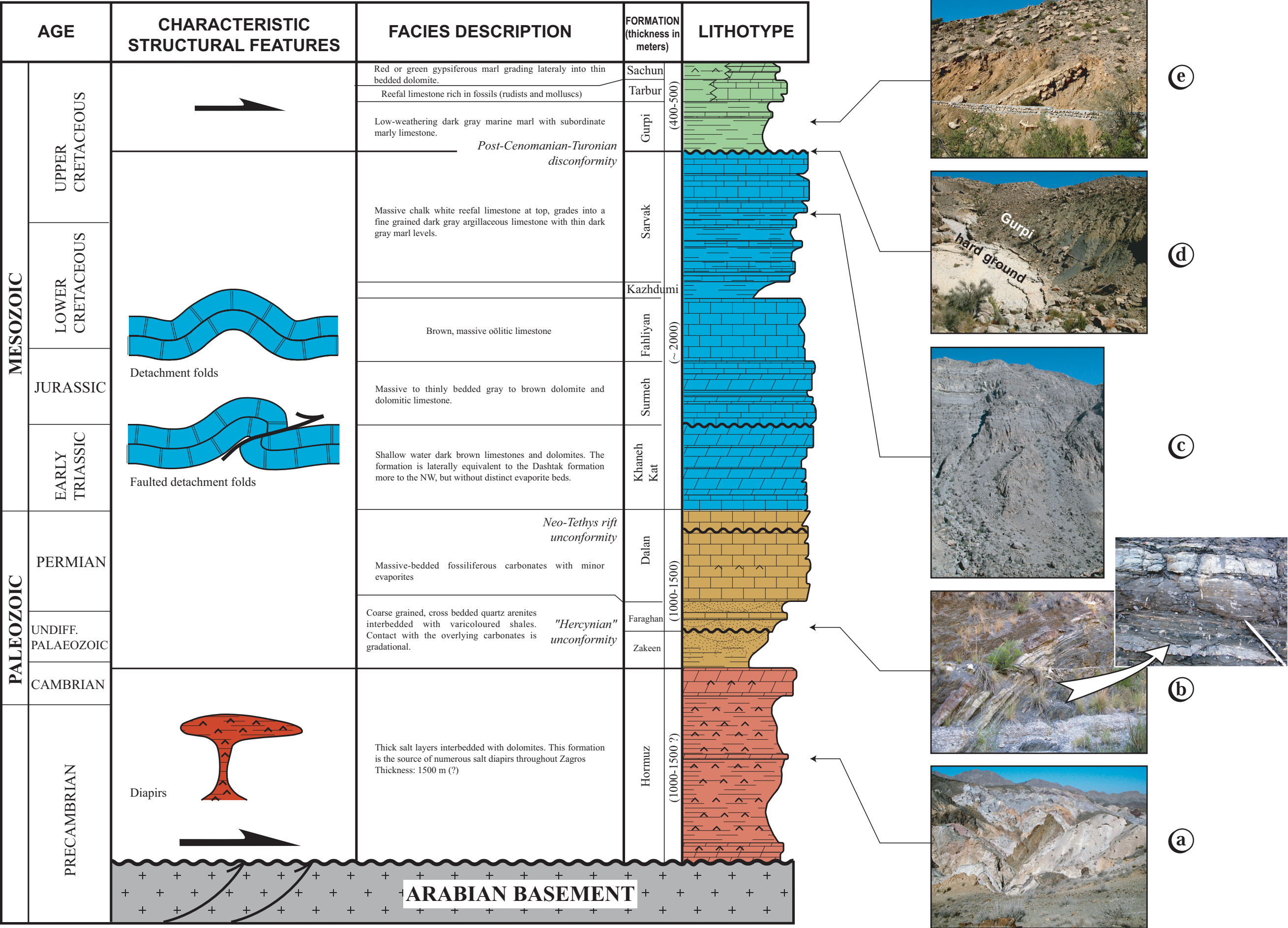


Fig. I-20 Mesozoic stratigraphy of the ZFTB in the Bandar Abbas area, showing descriptions of facies and dominant structural style of separate units

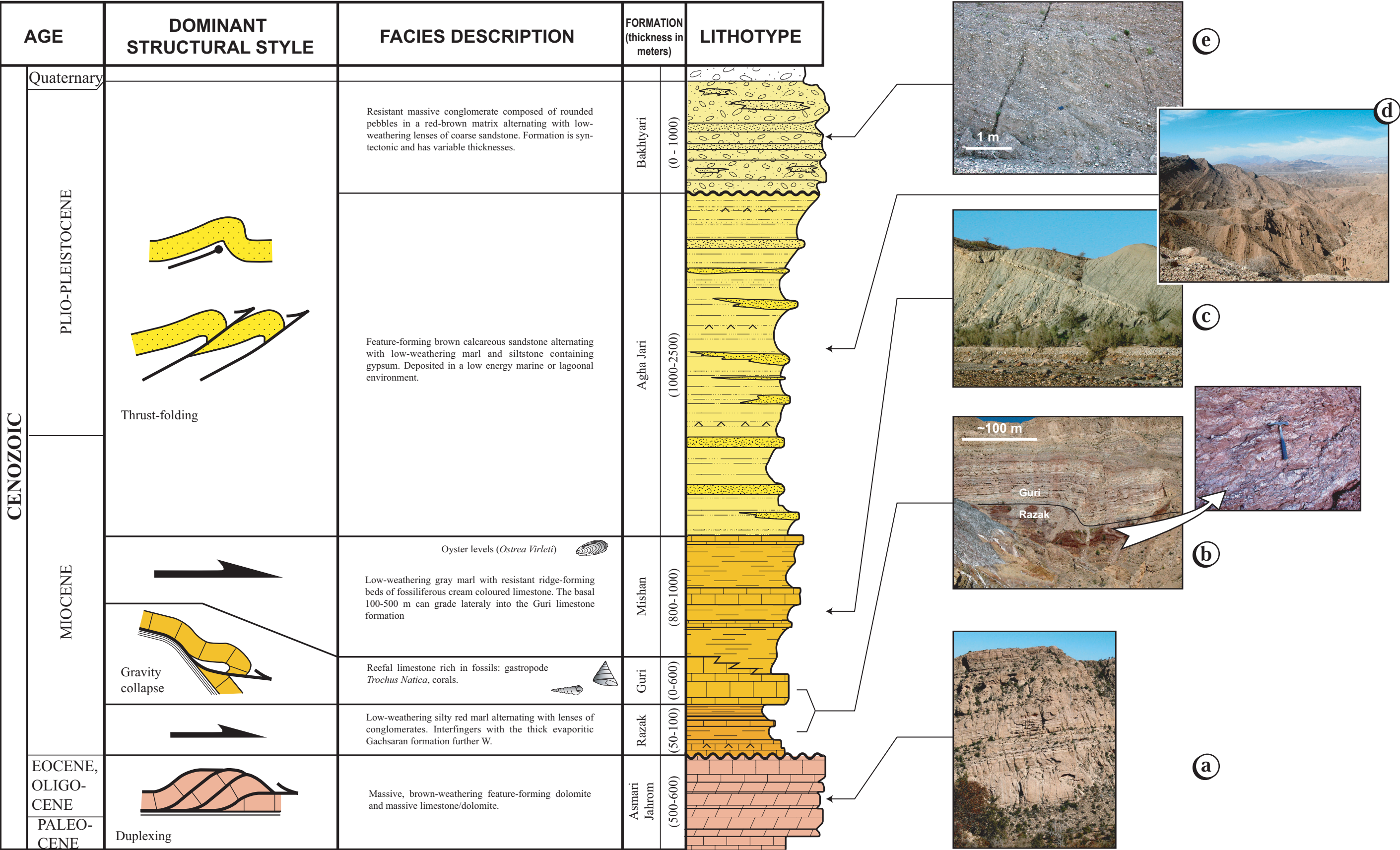


Fig. I-21 Cenozoic stratigraphy of the ZFTB in the Bandar Abbas area, showing descriptions of facies and dominant structural style of separate units

CHAPTER II

GEOLOGICAL ASPECTS OF THE BANDAR ABBAS SYNTAXIS

1 INTRODUCTION

Viewed on a satellite image, one of the most striking features of the transition between the Eastern Zagros Mountains and the Makran accretionary prism is the pronounced loop, or “syntaxis”, defined by the tectonic structures surrounding the city of Bandar Abbas. Such tectonic reentrants are not an uncommon feature in mountain belts. The Alpine-Himalayan orogen is punctuated by many syntaxes visible as bends and tucks disrupting the linearity of the mountain belts (Talbot & Alavi 1996) (Fig. II—1).

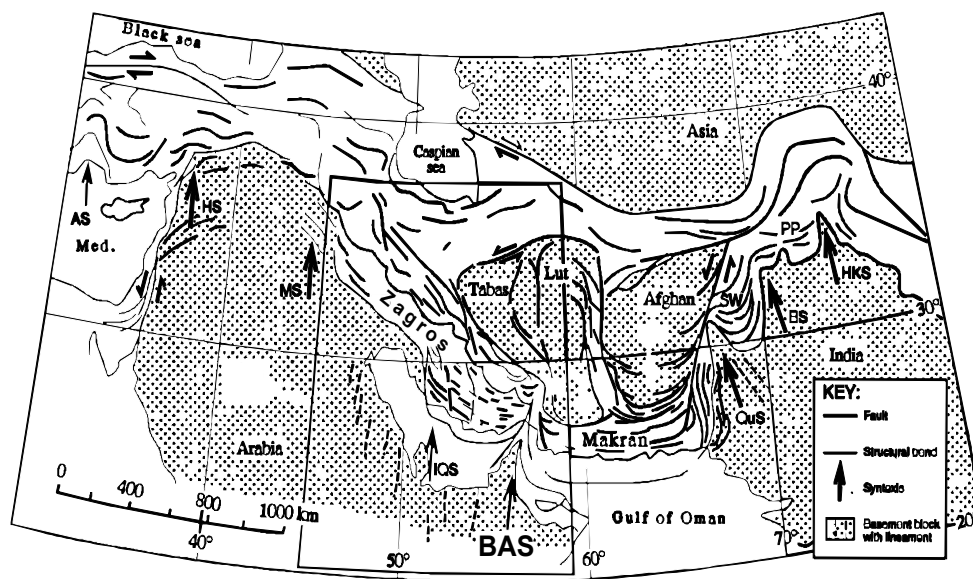


Fig. II—1 Map of the Alpine-Himalayan orogen indicating the various syntaxes (black arrows) defining separate orogenic compartments. AS : Antalya Syntaxis, HS : Halab Syntaxis, MS : Mosul Syntaxis, IQS : Incipient Qatar Syntaxis, BAS : Bandar Abbas Syntaxis, QuS : Quetta Syntaxis, BS : Bannu Syntaxis, HKS : Hazara-Kashmir Syntaxis. Modified after Talbot & Alavi (1996).

These syntaxes do not always coincide, as in our case, with a transition between different geodynamic contexts. Within a same mountain belt, they may separate orogenic compartments characterised by different stratigraphic sequences and consequently different mechanisms of development (e.g. Cotton & Koyi (2000)). In particular, the lateral continuity and efficiency of the decollement levels within and at the base of the stratigraphic pile will strongly affect the style of deformation of the various fold-and-thrust belts. The efficiency of a given detachment level is mainly determined by its lateral variations in geometry and facies, which are in turn often controlled within a sedimentary basin by inherited basement structures. So the fundamental reasons for such changes must ultimately be looked for in the

paleogeographic and tectono-sedimentary history of the area of interest. These, as will be shown, are also the main factors which controlled the evolution of the Bandar Abbas syntaxis.

The transition between the two limbs of the Bandar Abbas syntaxis, in addition to the change in structural trends, is also marked by a change in the structural style, a disappearance from west to east of salt diapirism and a drop in seismicity. In order to elucidate the causes of these changes and thus clarify the meaning of the Bandar Abbas syntaxis, in this chapter we proceed to a systematic and detailed description of the structural features of the syntaxis as observed on the field and on satellite images. The core of this study is presented in the following paper “**The origin of changes in structural style across the Bandar Abbas syntaxis, SE Zagros (Iran)**”, published in the journal *Marine and Petroleum Geology*. Detailed geological maps and balanced cross-sections from key structures across the syntaxis support our discussion in this paper. We conclude the chapter by adding further descriptions and photographs of structures throughout the Bandar Abbas syntaxis, with the aim of complementing the descriptions given in the paper.

<p><u>Ref.</u> Molinaro, M., Guezou, J. C., Leturmy, P., Eshraghi, S. A. & de Lamotte, D. F. 2004. The origin of changes in structural style across the Bandar Abbas syntaxis, SE Zagros (Iran). <i>Mar. Pet. Geol.</i> 21(6), 735-752. doi:10.1016/j.marpetgeo.2004.04.001</p>
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L'ORIGINE DES VARIATIONS DE STYLE STRUCTURAL DANS LA SYNTAXE DE BANDAR ABBAS, ZAGROS ORIENTAL (IRAN) (PAPIER N° 1)

Resumé : La syntaxe de Bandar Abbas marque la transition entre la chaîne de collision du Zagros et le prisme de subduction du Makran et constitue un trait structural majeur du système orogénique Alpes – Himalaya. Dans la partie externe du Zagros (le Zagros Fold Thrust Belt, ZFTB), cette transition est marquée par un changement soudain de direction et style structural et une diminution rapide de la sismicité et du diapirisme d'ouest en est de la syntaxe. La profondeur du niveau de décollement ainsi que la lithologie contrôlent le mode de plissement de chaque côté de la syntaxe, tandis que le couplage différent dans le niveau de décollement affecte le degré de déformation interne de la roche. Les plis larges et courts situés à l'ouest de la syntaxe sont décollés sur une puissante série évaporitique située à 8-9 km de profondeur, visible en surface à la faveur de nombreux diapirs de sel. Une forte sismicité suggère l'implication du socle dans la déformation. D'autre part, les plis longs et étroits situés à l'est de la syntaxe semblent être contrôlés par un niveau de décollement à 6 km de profondeur. L'absence de sismicité suggère que le socle n'est pas impliqué dans la déformation de cette région. On propose que le décollement basal pour ces structures corresponde au sommet érodé des nappes mésozoïques Omanaises mises en place lors de l'obduction à la fin du Crétacé de la Tethys sur la marge arabe. Ces structures de direction NNE-SSW observées dans la péninsule d'Oman sont visibles dans des profils sismiques en mer, se poursuivant vers le nord sous le détroit d'Hormuz. Enfin, cette étude montre que le Main Zagros Thrust et la faille de Zendan – qui marquent la limite entre le ZFTB et les zones internes de l'orogène – sont des contacts à faible pendage et non pas des failles verticales.

Mots clefs : *Zagros, Oman, syntaxe, plis de décollement, plis de propagation sur rampe, accident de socle, héritage structural*

2 THE ORIGIN OF CHANGES IN STRUCTURAL STYLE ACROSS THE BANDAR ABBAS SYNTAXIS, SE ZAGROS (IRAN) (PAPER N° 1)

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Abstract: The Bandar Abbas syntaxis marks the transition between the Zagros collisional belt and the Makran subduction-related prism and constitutes a major structural feature within the Alpine – Himalayan mountain belt. Within the foreland part of the Zagros (the Zagros Fold Thrust Belt, ZFTB), the transition is marked by a sudden change in structural trends and style and a rapid decrease in seismicity and salt diapirism from west to east of the syntaxis. The depth to decollement and lithology affect the geometry and size of the folds on each side of the syntaxis, while different mechanical coupling along the basal decollement affects the degree of internal rock deformation. Thus the short and broad folds of the western side of the syntaxis are decoupled along the 8-km deep Hormuz evaporites, visible at surface in numerous salt diapirs. Strong seismicity in this area suggests that the basement is involved in the deformation. By contrast, the long and narrow folds of the eastern side of the syntaxis appear to be controlled by frictional slip along a 6-km deep detachment. The absence of seismicity suggests that the basement is not involved in the deformation in this area. We propose that the basal decollement for these structures corresponds to the eroded top of the NNE-SSW trending Oman Mesozoic nappes resulting from Late Cretaceous obduction of Tethys on the Arabian margin. These structures are visible onshore in the northern tip of the Oman peninsula and seen in offshore seismic profiles continuing northward beneath the Strait of Hormuz. Finally, map view observations show that the Main Zagros Thrust and the Zendan Fault – separating the ZFTB from the internal zones of the orogen – are shallow low angle thrust faults rather than steeply-dipping faults.

Keywords: Zagros, Oman, syntaxis, detachment folding, fault-propagation folding, basement faulting, structural inheritance

2.1 Introduction

The Bandar Abbas syntaxis constitutes a major structural feature within the Alpine-Himalayan orogen, marking the transition between the Zagros collision belt to the W and the Makran accretionary prism and Oman Mountains to the E (Figure 1). It is marked by a sharp change in trend and style of the tectonic structures. The structures in this region describe a tight re-entrant underlined by the arched shape of the Oman peninsula jutting out into the Strait of Hormuz from the Arabian Peninsula (Figure 1). The transition is also characterised by a sharp drop in seismicity around 57.5°E (Byrne & Sykes 1992) in contrast with the active seismicity in the western sector of the syntaxis (Jackson et al. 1995, Kadinski-Cade & Barazangi 1982) (Figure 1a).

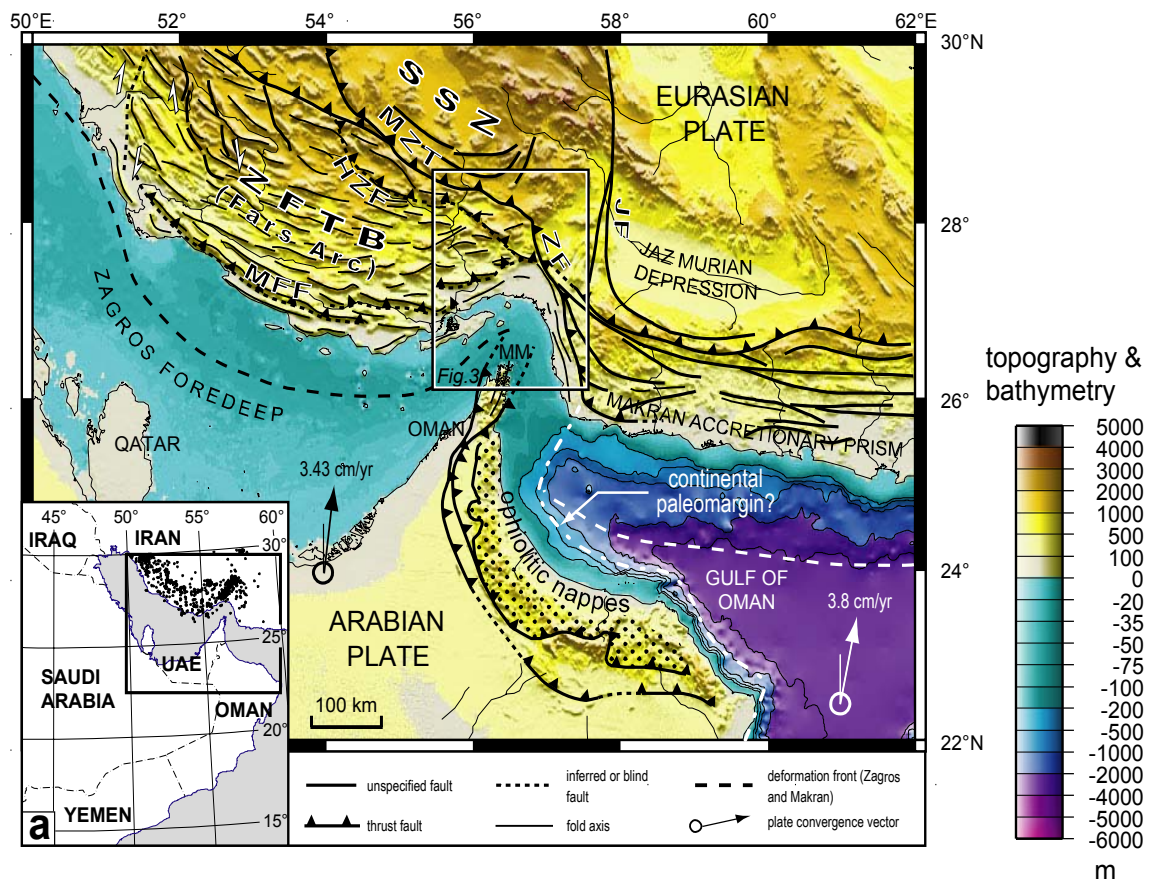


Figure 1. Physical map (source: GEBCO data) and main structural features of the transition between the active Zagros fold-thrust belt and Makran accretionary prism; structural trends of the Oman Mountains are shown too. ZFTB: Zagros Fold Thrust Belt, SSZ: Sanandaj Sirjan Zone, MZT: Main Zagros Thrust, ZF: Zendan Fault, MFF: Mountain Front Fault, HZF: High Zagros Fault, JF: Jiroft Fault, MM: Musandam Mountains. Heavy black dots: Semail ophiolite. Convergence rates after NUVEL-1A Plate II—motion model (DeMets et al. 1994). Inset (a): location map and earthquake epicentres (1964-1998, $M_s > 4.5$) in Zagros and Makran (from Harvard CMT catalogue)

Few authors have attempted to investigate the nature and causes of the peculiar geometry of the Bandar Abbas syntaxis. Sattarzadeh *et al.* (2000) suggest – based upon map observations – that the folds in the eastern branch of the syntaxis were originated by transpressive motion along the Zendan Fault (Figure 1). Studies based upon magnetic fabrics measurements on folds west (Bakhtari *et al.* 1998) and on both sides (Aubourg *et al.* 2004, in press) of the syntaxis highlighted possible vertical axis rotations. However, the causes of this sudden variation in structural style are poorly understood and no detailed field investigations have been carried out in order to describe precisely the nature and origin of the syntaxis.

The main objective of this paper is to provide a general overview on the structural style around the syntaxis. We analyse the general structural features of the Bandar Abbas syntaxis and present detailed surface mapping of a certain number of key structures within the east and west limbs of the syntaxis, completed by the construction of balanced cross-sections. This work allows us finally (1) to propose a conceptual model explaining the variations in structural style across the syntaxis and (2) to define more precisely the significance of two major faults in the region, namely the Zendan fault and the Main Zagros Thrust.

2.2 *Geological setting: the Arabian paleomargin in Zagros and Oman*

2.2.1 Structure of the Arabian paleomargin

The frontier between the Makran accretionary prism and Zagros Fold Thrust Belt (ZFTB) is classically placed along the “Oman Line” (Bushara 1995, Edgell 1996, Falcon 1974, Farhoudi 1978, Gansser 1955, Haynes & McQuillan 1974, Hessami *et al.* 2001a). Even if the definition of the Oman Line remains rather vague, it is usually associated with the NNE structural trend of the northern Oman Mountains (Musandam Mountains) (Figure 1). This NNE trend should correspond to the approximate trend of the Arabian palaeomargin in the western part of the Gulf of Oman, which should contrast the regular NW-SE trend of the Arabian palaeomargin elsewhere (i.e. Zagros and Oman). Activation of this trend supposedly occurred in the form of right-lateral transform faulting during the initial phases of Neo-Tethys rifting in Permian times (Sharland *et al.* 2001) and resulted in segmentation of the Eastern Arabian margin. Late Cretaceous Neo-Tethys obduction partly camouflaged the original Arabian paleomargin, so the present-day geometry reflects only partially the original syn-rift segmented geometry. Several authors have speculated on the geometry and position of this

margin based upon geophysical data (Bushara 1995, Khattab 1995, Ravaut et al. 1998). Offshore seismic reflection data and gravity profiles show a change corresponding to the approximate position of the sea floor slope-break between 57° and 58° E (Ravaut et al. 1997, Ravaut et al. 1998) (Figure 1). However, data are inconclusive and the exact geometry of this margin, especially in its north-eastward continuation onshore, remains largely unknown.

2.2.2 Tectonostratigraphy of the Arabian paleomargin in Zagros and Oman

The main stratigraphic and paleogeographic features of the Arabian margin in eastern Zagros and Oman are known (Clarke 1988, James & Wynd 1965, Sharland et al. 2001, Szabo & Kheradpir 1978, Ziegler 2001) and allow us to outline the main steps in the evolution of the eastern Arabian margin in these two regions (Figure 2).

The base of the sequence is represented by sediments of late Precambrian age deposited directly upon the Panafrican crystalline basement in an environment of rifted intrashelf basins, possibly related to the opening of Paleo-Tethys further north (Sharland et al. 2001). In Zagros, these sediments correspond to the mobile Hormuz evaporites. In Oman, the equivalent of Hormuz is found in isolated salt basins of the southern Oman Mountains (Ara formation) but seemingly not in the northern Oman Mountains (Clarke 1988). Most of the Paleozoic sequence is made up of epicontinental siliciclastics deposited in an intra-cratonic setting. The Tethyan rifting (Permian and Triassic in age) was succeeded by essentially carbonate deposition along the entire paleomargin of the expanding Neo-Tethys ocean (Sharland et al. 2001).

The first evidence of obduction of the Semail ocean (an intraoceanic offspring of Neo-Tethys according to Stampfli, (2000)) over the Arabian margin dates from the end of Turonian (the 'Senonian' phase according to Ricou *et al.*, (1977)) and is marked by a rapid shift of sedimentation towards more terrigenous facies and a regional unconformity within the Arabian shelf (Koop & Stoneley 1982, Ziegler 2001). Oceanic crust and sediments were thrust towards the SW over the Arabian margin during Campanian-Maastrichtian times (Alavi 1994). In Oman, this event resulted in imbrications within the autochthonous Mesozoic-Paleozoic shelf sequence and the emplacement of two main units, the Hawasina nappes – a tectono-stratigraphic unit representing the former Arabian margin – and the Semail

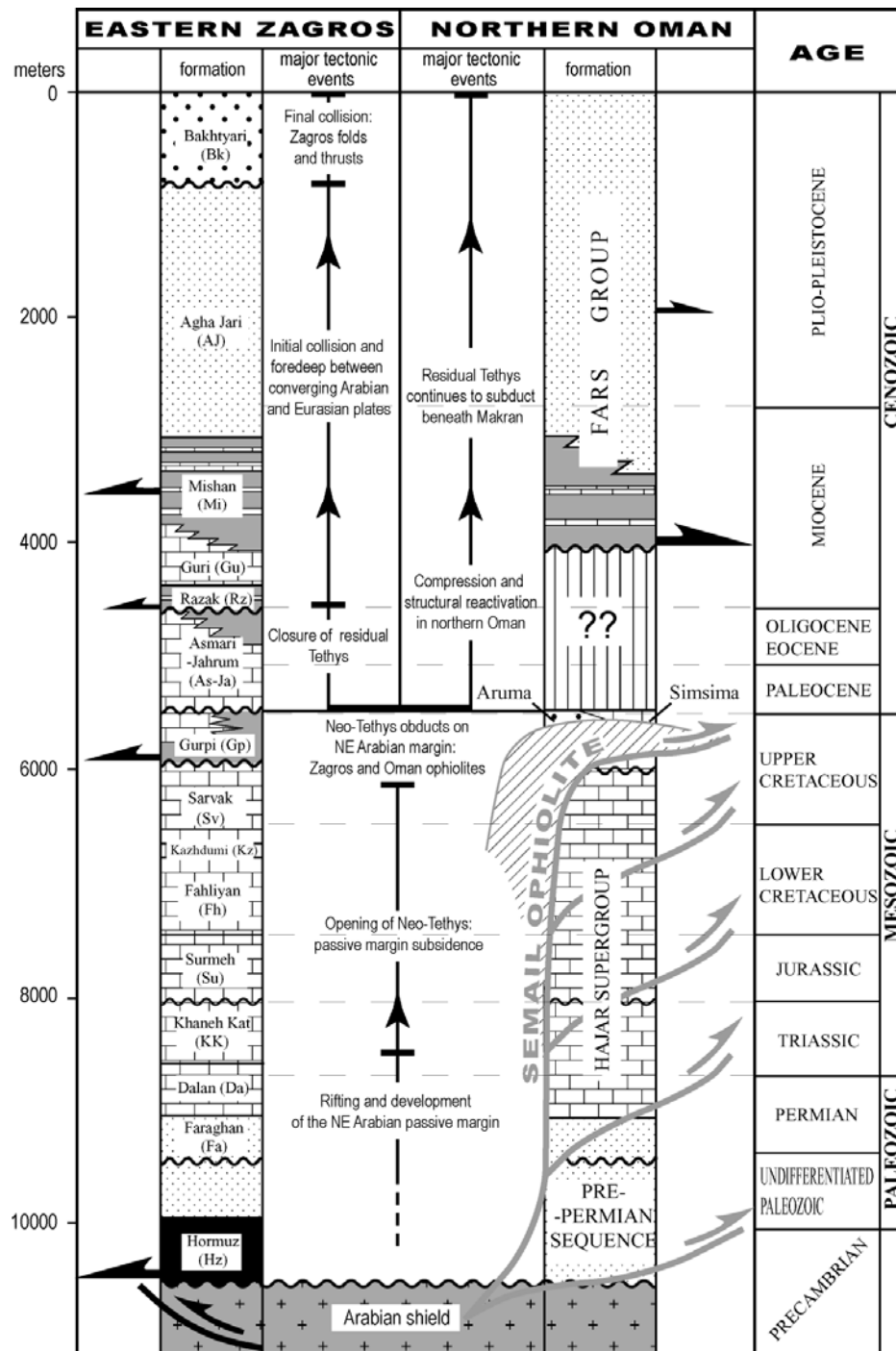


Figure 2. Stratigraphic chart showing the main tectonic events in south-eastern Zagros and northern Oman and inferred potential decollement horizons for these two areas. For northern Oman we give a schematic representation of the Semail ophiolite and structures within the margin related to Late Cretaceous obduction of Neo-Tethys. The implications of this scheme for Neogene deformation are discussed in paragraph 6.2. Vertical scale is approximate. Data compiled mainly from Clarke (1988), James & Wynd (1965), Szabo & Kheradpir (1978)

ophiolitic nappes (Figure 1). These two units form the essential structural framework of the Oman Mountains (Dunne et al. 1990 44, Searle et al. 1983 70). The structures describe an arc

in front of the Gulf of Oman, passing from E-W frontal trends at the eastern extremity of the Arabian Peninsula to NNE-SSW lateral trends at the tip of the Oman peninsula. In Zagros, the emplacement of the ophiolites is marked by a regional unconformity within the Arabian margin sequence (Sherkati & Letouzey 2004). These ophiolites are presently carried over the foreland Zagros by the so-called Main Zagros Thrust (MZT).

Obduction effectively ceased towards the end of Campanian while the remaining Neo-Tethys oceanic crust (the “residual Tethys” according to Braud, (1987)) continued to subduct beneath the Central Iran domain. Starting from Eocene times, the ensuing histories of the Zagros and Oman regions separate. In Oman, the “residual Tethys” represented by the Gulf of Oman is still closing and being subducted beneath the facing Makran mountains (Searle et al. 1983). Post-obduction sediments in this area include (1) Eocene shale and cyclic shelf carbonates of the Hadhramaut group deposited unconformably onto the allochthonous Semail ophiolite (Al-Lazki et al. 2002) and (2) lower Miocene to Recent clastic sediments of the Fars group. There is little evidence of post-Eocene tectonic activity – except for minor structural reactivation in the Musandam Mountains at the tip of the Oman Peninsula (Figure 1) (Searle et al. 1983) – and presumably the Oman structures have since been passively carried upon the northward migrating Arabian plate. In Zagros the “residual Tethys” was entirely closed by Oligocene-Miocene times. A rapid shift in sedimentation towards more detritic facies (the Mishan and Agha Jari formations) marks the passage from passive margin to foreland basin conditions on this part of the Arabian margin and the onset of collision between the Arabian and Eurasian plates (Hessami et al. 2001b, Sherkati & Letouzey 2004). Thick molasse sediments accumulated conformably in the newly established Zagros foredeep while its depocentre migrated over time from NE to SW to its present position, the Persian Gulf (Edgell 1996) (Figure 1). The widespread occurrence throughout the ZFTB of Plio-Pleistocene Bakhtyari conglomerates marks the most recent and vigorous phase in the collisional process (James & Wynd 1965).

To summarise, the present day picture is essentially one of a paleomargin preserved at two different stages of its inversion. In Zagros Neo-Tethys was already sutured by Oligocene-Miocene times with the initial phases of Arabia-Eurasia collision, while in Oman Neo-Tethys, represented by the Gulf of Oman, has yet to be sutured.

2.3 The Bandar Abbas syntaxis: general structural framework

The western part of the study area (Figure 3) exhibits the eastern-most folds of the Zagros Fold Thrust Belt (ZFTB). In this zone, the outcropping anticlines are capped most often by the competent limestone rocks of Eocene (Jahrum Fm) and lower-middle Miocene (Guri Fm) age while the synclines are composed mainly of Miocene sandstone and marls (Agha Jari and Mishan formations) and Plio-Pleistocene conglomerates (Bakhtyari Fm). These ENE-trending folds are crosscut by a NW-trending alignment of three “giant” antiforms (Kuh-e-Khush, Faraghun and Jain) extending between the northern tip of the Minab fold and the Main Zagros Thrust close to the town of Hadjiabad (Figure 3). These structures represent major topographic features in the region, reaching elevations around 3000m and exhuming rocks as old as Silurian (Ordovician?). The “en echelon” alignment of these three structures had been already remarked by Ricou (1974) and coincides with an alignment of seismic events, which Berberian (1995) attributed to movement along a basement fault, the High Zagros Fault (HZF).

Numerous salt diapirs are visible in the ZFTB and the western branch of the syntaxis (Ala 1974, Edgell 1996, Kent 1958, 1979, Talbot 1979, Talbot & Alavi 1996) and seem to be located preferentially towards the periclinal terminations of folds (see for example Namak, Suru, Finu, Baz, Muran folds) or at junctions between faults (Figure 3). This suggests the existence of an intimate relationship between Neogene structures and salt diapirs in Zagros. A recurrent question on this matter is whether or not the salt diapirism predates Zagros shortening, or in other words whether Zagros shortening occurred in a sedimentary cover already affected by mechanically weak points such as salt diapirs (Kent 1979). On the basis of our observations, we share the generally accepted view (Kent 1979, Koyi 1988, Talbot & Alavi 1996) that the diapirs predate Zagros shortening.

To the east, the structures of the ZFTB suddenly give way to the NNW-trending folds and thrusts of the so-called Zendan-Minab Belt (ZMB) (Fig.3). This change in structural direction is accompanied by a marked change in the style of folding (Figure 4). Folds in the eastern branch of the syntaxis (the ZMB between 57°30' and 57°00' E longitude) have very low aspect ratios (half wavelength / axial length ratio) (Figure 4a) and small amplitudes. Sattarzadeh *et al* (2000) suggested that the map pattern and geometry of these latter folds reflect a transpressive nature associated with the right-lateral strike-slip movement traditionally attributed to the Zendan Fault (Regard *et al.* 2003). However, such strike-slip movement has not been observed by the authors in the field and may take place further east

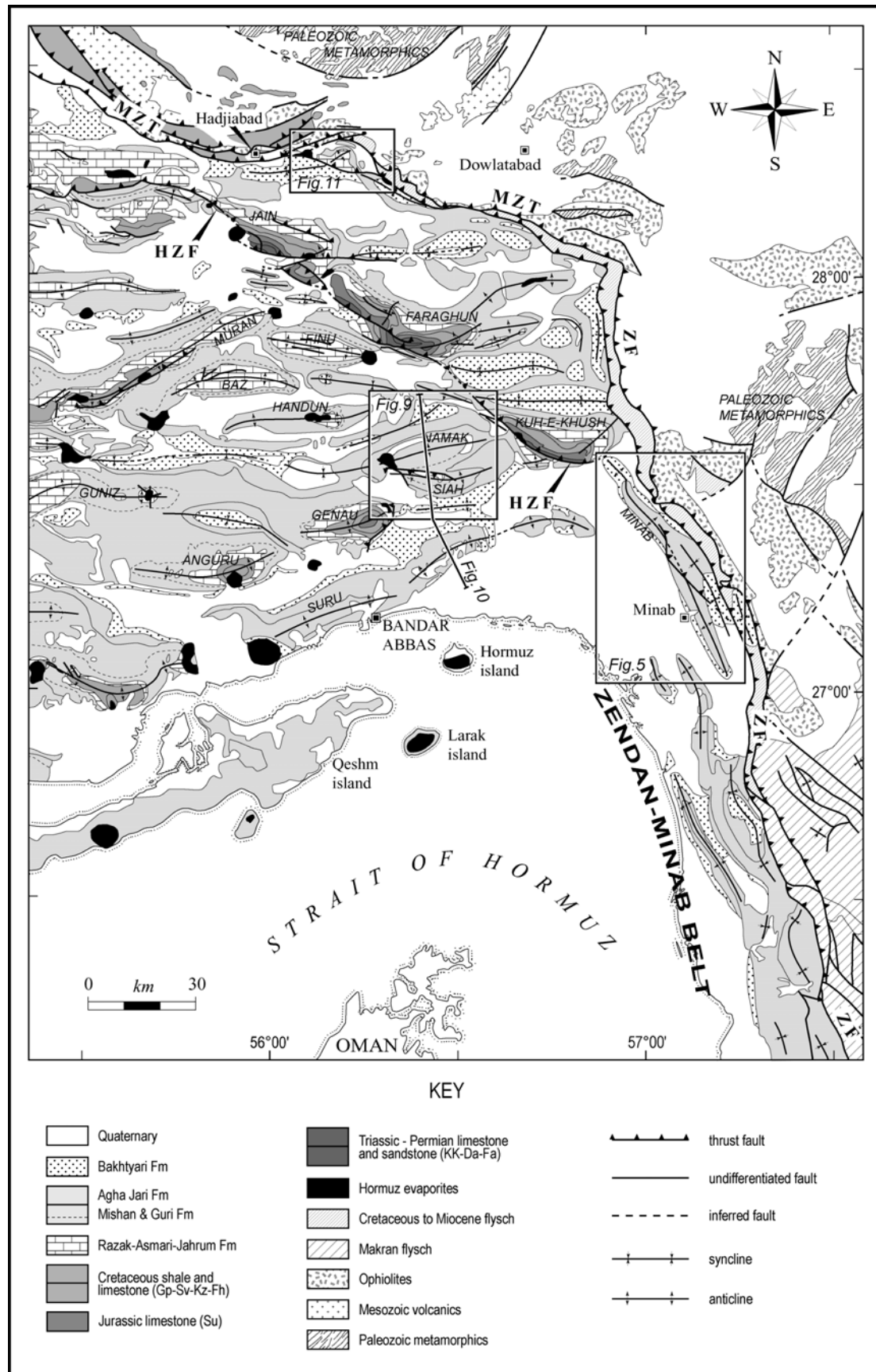


Figure 3. Geological map of the Bandar Abbas syntaxis compiled from geological maps (NIOC, 1977a,b, 1999) and author's fieldwork. The names of the major anticlines are indicated as well as the location of detailed geological maps examined in this paper.

along other faults such as the Jiroft fault (Figure 1). Folds in the western branch of the syntaxis, by contrast, (between $57^{\circ}00'$ and $55^{\circ}30'$ E longitude) have much higher aspect ratios (Figure 4b). West of the syntaxis, in the Fars Arc, the aspect ratios of folds tend to decrease (Figure 4c). The transition between the two branches of the syntaxis is also marked by the sudden disappearance of the salt diapirism. Some indications of salt extrusion are still visible on the southern flank of the Kuh-e-Khush antiform, and several blind salt diapirs have been inferred from seismic profiles crossing the coastal plain between Bandar Abbas and Minab (NIOC 1988). In the Zendan-Minab Belt salt diapirs are completely absent and offshore seismic profiles from the eastern side of the Strait of Hormuz show no indications of subsurface movement of salt in this sector.

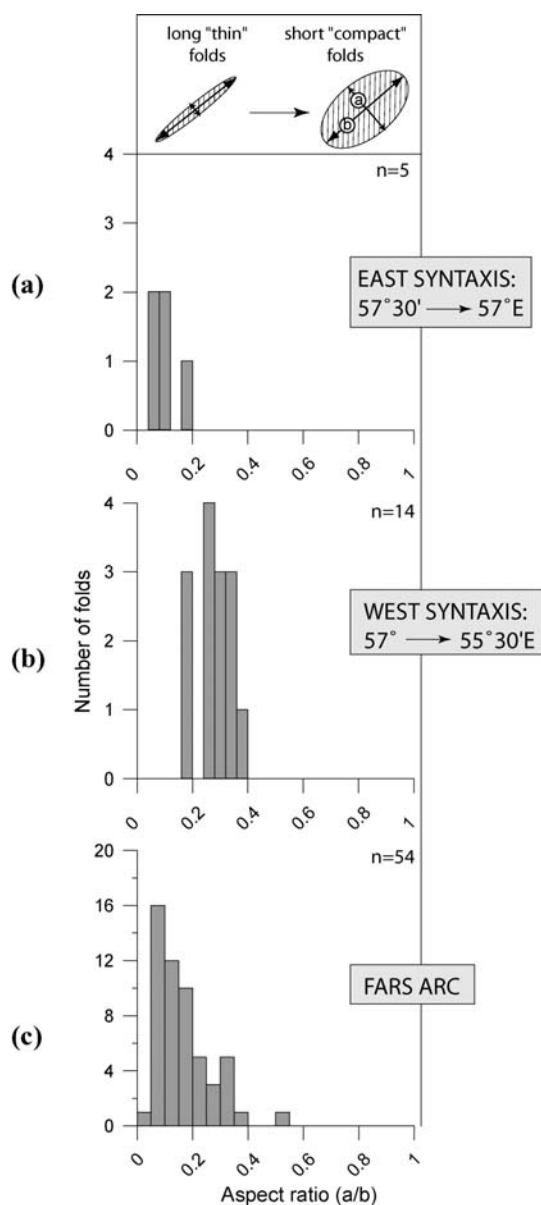


Figure 4. Frequency histograms showing variations of aspect ratios (half wavelength (a) / axial length ratio (b)) of folds throughout the Bandar Abbas syntaxis and the ZFTB. Based upon geological maps (NIOC 1977a, b)

Finally, the two branches of the syntaxis are distinguished by a sharp west to east decrease in seismicity (Figure 1a) (Kadinski-Cade & Barazangi 1982). The western branch of the syntaxis is characterised by one of the highest seismicity records in Zagros, and some of the largest earthquakes in the orogen have been recorded in this region (Khurgu event, $M_s=7.0$, Berberian, 1995). Focal mechanisms determined for these events indicate that north-directed convergence is accommodated within the basement by reverse faulting. Berberian (1995) interpreted these faults as the SE termination of the Mountain Front Fault (MFF) and the High Zagros Fault (HZF), two major reverse basement faults running along the entire length of the Zagros and defined by their seismicity and topographic expression (Figure 1). Moving towards the east the seismicity ends abruptly with a north-east trending zone of denser activity (Kadinski-Cade and Barazangi, 1982; Talebian and Jackson, 2004) (Figure 1a).

The folded structures of the syntaxis are separated from a continuous belt of Cretaceous-to-Miocene “flysch” and ophiolites of the internal zones (the Sanandaj Sirjan Zone, SSZ) by a major structural boundary to the north (Main Zagros Thrust, MZT) and east (Zendan Fault) (Figure 3). Much debate exists over the nature of the MZT, especially since its crustal significance as the suture between the Arabian and Iranian plates, hitherto unconditionally accepted by most authors, was put into doubt by Alavi (1994).

2.4 *Structural geology in the eastern limb of the syntaxis*

2.4.1 Minab fold and thrust

We first analyse the Minab fold and thrust in the eastern sector of the syntaxis (Figure 5). This fold is an approximately 60 km-long and average 10 km-wide structure composed essentially of a poorly consolidated alternation of Mio-Pliocene pebbly sandstone and marls (Agha Jari and Mishan formations). More recent synorogenic conglomerates, of Plio-Pleistocene age, can be observed in the forelimb of the fold as well as in the Palami and Baghe-Sisi synclines. The fold is cut by the so-called Minab thrust fault. Erosion has removed most of the topographic relief associated to the fold, except where the Minab thrust is most developed, where elevations reach a maximum of 600 m. Approximately parallel to these structures is the Zendan Fault, which carries Cretaceous-to-Miocene “flysch” and ophiolites towards the SW over the Minab fold.

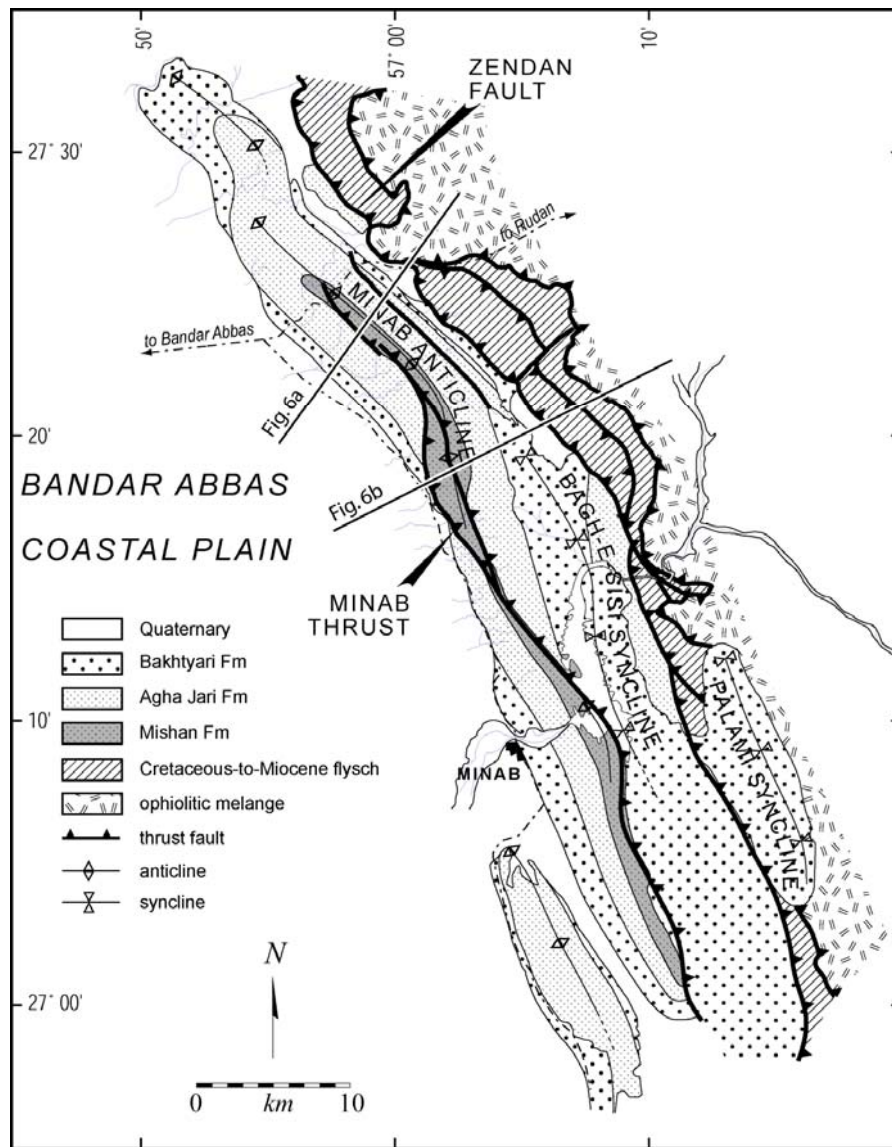


Figure 5. Detailed geological map of the Zendan-Minab fold and thrust area. Derived from geological maps (GSI 1980), SPOT satellite image and author's fieldwork. For sections a and b see Figure 6. For location see Figure 3

Two balanced cross-sections (Figure 6a and 6b) illustrate the geometry of the Minab fold and its along strike variation's. In both cases, interpretation at depth is only constrained by surface data.

The first section (Figure 6a) is situated close to the northern periclinal termination of the Minab fold, where the Minab thrust dies out; dip control is provided by excellent exposures along the Bandar Abbas to Rudan road. The Minab fold appears as a tightly folded and slightly asymmetric structure with steep limbs (70-80°) decreasing to about 35° in the backlimb towards the NE. The transition between the two limbs is abrupt and marked by a

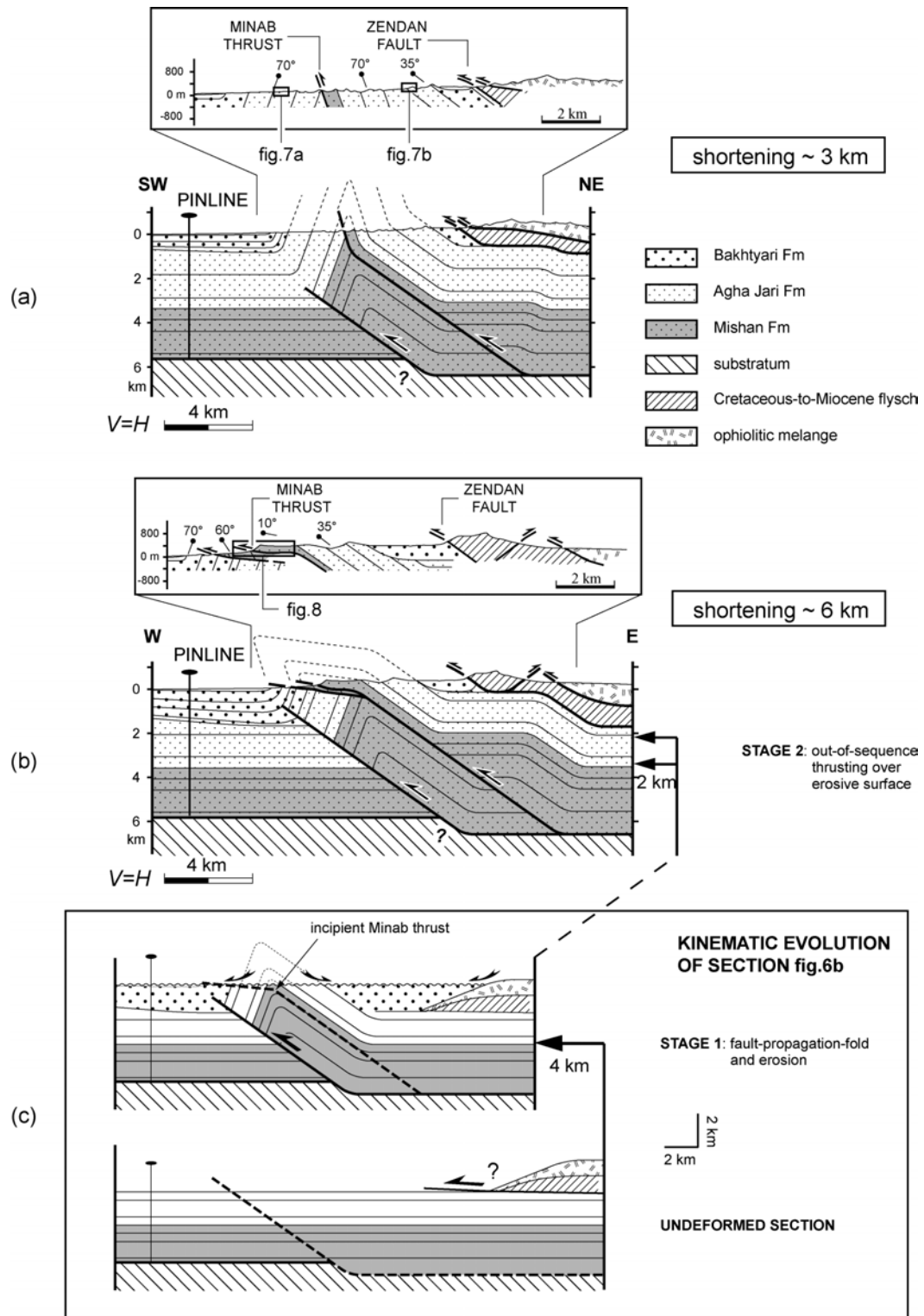


Figure 6. Balanced cross-sections through the Zendan-Minab fold-and-thrust belt. For location of sections see Figure 5. (c) Kinematic reconstruction of cross-section in Figure 6b

narrow zone of repeated folds and small-scale thrusting corresponding to the emergence of the Minab thrust. The Minab fold displays several kinds of mesoscale deformational structures

that can be distinguished as follows. (1) Well developed sets of joints perpendicular to bedding interpreted as resulting from pre-folding deformation (Layer Parallel Shortening, LPS) (Fig.7a). (2) Structures related to syn- or post-folding strain, specifically meter-scale forelimb thrusts associated with asymmetric kink folds (Figure 7a), and sets of low-angle thrusts reusing kink planes and deforming pre-folding joints (Figure 7b).

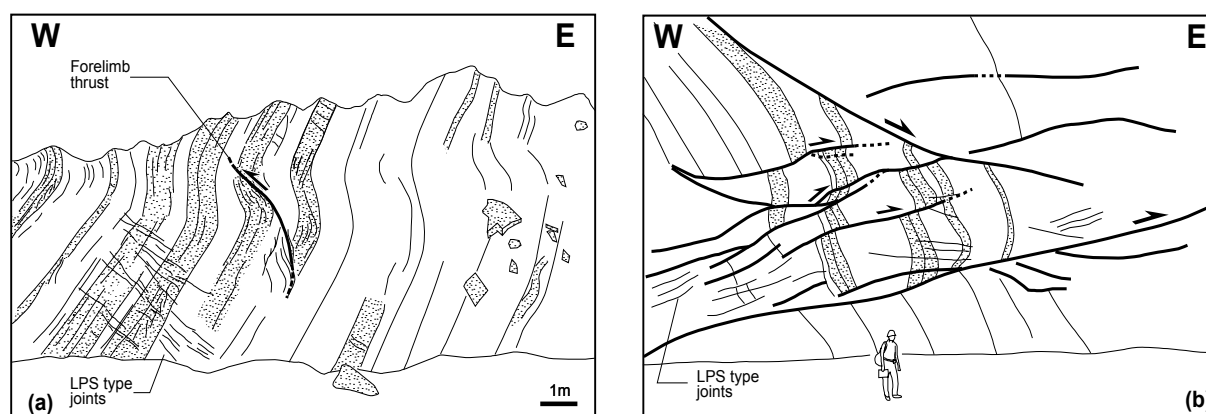


Figure 7. Line drawings from photographs showing mesoscale deformational features within Agha Jari sandstone of the Minab fold. (a) Metric scale kink fold and LPS type joints within the forelimb of the Minab fold (b) Example of small-scale thrusting in the backlimb of the Minab fold. For location of sites see Figure 6b

This first section of the Minab fold (Figure 6a) conforms to the fault-propagation-fold model (Suppe & Medwedeff 1990). The relatively strong internal strain encountered in the Minab fold (i.e. kink folds and jointing) is a commonly observed feature in folds developing in front of a propagating fault (Cooper & Trayner 1986 and references therein, Grelaud 2001, Thorbjørnsen & Dunne 1996). Cross-section balancing indicates that the fold soles out into a decollement level at a depth of about 6 km, with an associated slip of approximately 2.8 km. The position of the ramp at the base of the Minab fold could be controlled by a step in the substratum (Figure 6), as suggested by the map-view linearity of the structure.

The Minab fault appears as a secondary out-of-sequence thrust ramping up from the basal decollement at 6 km depth, passing into bedding-parallel slip within a ~ 4-km deep level, and cutting through the forelimb of the Minab fold.

About 10 km south of this section, the Minab thrust separates into two segments that cut through the forelimb of the Minab fold (Figure 6b). The precise geometry of the thrust is illustrated by a field section (Figure 8). Several smaller faults splaying upwards from the basal thrust segment are cut by the higher segment of the Minab thrust, a geometry that resembles closely structures described elsewhere by Morley (1988). The hanging wall cut-off of the

Minab thrust is not exposed due to erosion, allowing only an estimation of a minimum amount of displacement of approximately 2 km. Cross-section balancing indicates that shortening associated with the Minab fold has increased to an estimated 4 km.

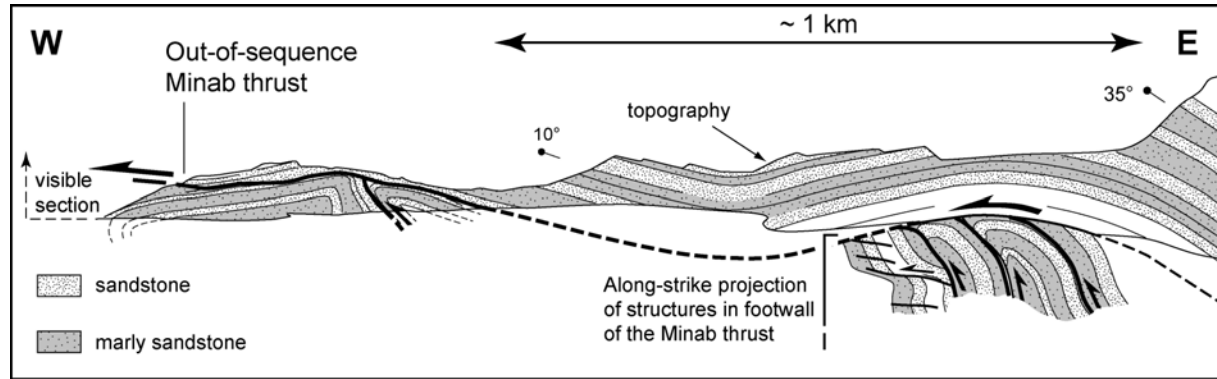


Figure 8. Schematic field section showing the geometric features of the out-of-sequence Minab thrust. Location of section in Figure 6b

A two-stage kinematic modelling of this second section (Figure 6b) has been performed (Figure 6c). In stage 1 the development of the Minab fold is accompanied by strong erosion and deposit of syn-folding conglomerates. In stage 2 growth of the Minab fold is blocked and the Minab thrust propagates over the former erosive surface, as indicated by the fact that the Minab thrust is seen thrusting over Quaternary alluvial fans (J. Mercier, *pers. comm.*, Regard, (2003)). Compared to the strongly eroded topography of the northern part of the fold, the higher relief along the central Minab fold is well correlated to the presence of the Minab thrust. This suggests that the most recent activity is concentrated on this latter thrust and that propagation of the Minab fold on the basal decollement is completely blocked at its front.

2.4.2 Geometry of the Zendan Fault

The Zendan Fault carries “flysch” of Oligo-Miocene age and ophiolitic melange nappes over the Mio-Pliocene sandstone and conglomerate of the Minab fold. These allochthonous units appear as dismembered nappe sheets that have been passively transported and deformed by folding of the foreland Tertiary succession (Figure 5). Since little is known about the initial paleogeographic relationships and the subsequent timing of tectonic emplacement, the question of the relation between the hanging wall allochthon and the Zagros folds is difficult to solve. Nevertheless, it seems unlikely that the Zendan fault can be simply interpreted as a

vertical strike-slip fault as has been often suggested, and this for two reasons. Firstly, cross-section restoration (Figure 6c) implies a minimum of 6 km of horizontal displacement, which would be geometrically incompatible with a vertical Zendan fault in the immediate rear of the Minab fold and thrust. Secondly, it would necessitate the presence of a cut-off in the footwall of the fault, thus implying that the “flysch” and ophiolites underlie the folded molasse succession. Clearly this is not the case, since the “flysch” – in part deposited at the same time as the molasse deposits – and the ophiolites are related to a different paleogeographic environment with respect to the Zagros molasse. Recent out-of-sequence reactivation of the Zendan fault may explain the fact that the “flysch” is presently seen thrusting over Quaternary deposits.

This interpretation does not exclude the strike-slip component suggested by Regard *et al* (2003), only that the Zendan fault cannot be simply interpreted as a crustal boundary accommodating pure strike-slip movement between the Zagros foredeep and the internal zones. Alternatively, the Zendan Fault could follow a staircase trajectory and root to depth further to the east, for instance where Palaeozoic metamorphic rocks (Bajgan metamorphic complex in McCall, (1997)) are exposed (Figure 3). This could represent the true boundary between the Zagros and Makran domains, as suggested too by the seismicity drop around 57.5° E (Figure 1) (Byrne & Sykes 1992).

2.5 Structural geology in the western limb of the syntaxis

2.5.1 Namak fold and Siah backthrust

In the western sector of the syntaxis, we analyse the relatively simple Namak fold and Siah backthrust situated directly north of Bandar Abbas (Figure 3, Figure 9 & Figure 10a). The main feature in this area is the Namak detachment fold. This anticline, in contrast with the Minab fold, is a symmetrical structure characterised by gently dipping limbs and a relatively large wavelength (18 km) compared to its axial length (33 km). It is capped by the competent Guri limestone of lower-middle Miocene age. Directly south of this fold, another fold (Siah) with a strongly north-verging geometry is cut by the Siah backthrust, which has carried Eocene limestone (Jahrum Fm) northwards over Miocene sandstone and marls (Agha Jari and Mishan formations). To the W, this backthrust intercepts the Namak fold at its termination, at which point an active salt diapir is visible (Figure 9).

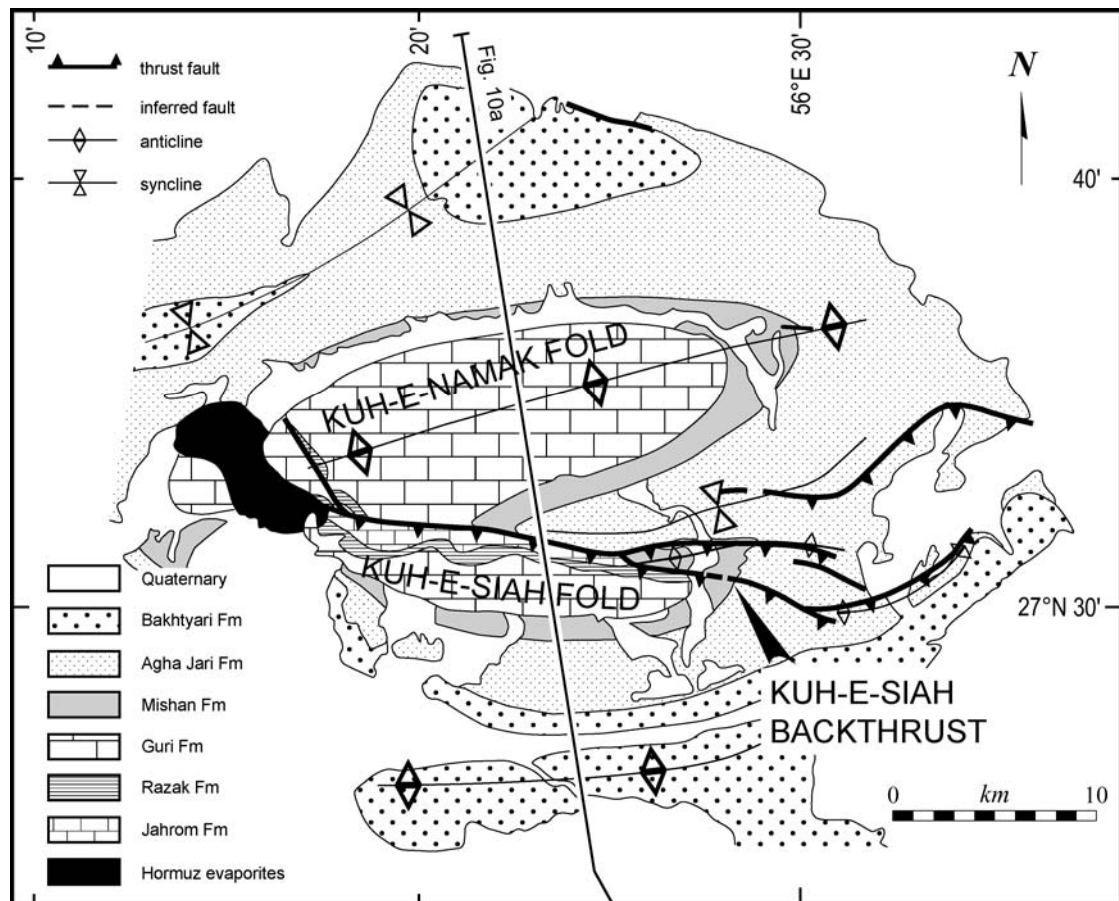


Figure 9. Detailed geological map of the Namak fold and Siah backthrust north of Bandar Abbas. Derived from geological maps (NIOC, 1999), SPOT satellite image and author's fieldwork. For location see Figure 3

The geometric features of the Siah anticline suggest that this fold is forced by an underlying basement fault. Basement faulting for this section is suggested by dip-slip seismic events occurring within the basement at a depth of 10 ± 4 km (Talebian & Jackson 2004), which Berberian (1995) attributed to movement on the Mountain Front Fault (Figure 1). Further evidence for the presence of a basement step is inferred from the uplift above regional datum of ~ 1 km of the syncline at the back of the Namak anticline (Figure 10).

The clear structural relationship between the position of the Siah backthrust and fold indicates that the thrust developed at a late stage. We tentatively relate this backthrust to the development of a north-verging fault-bend-fold (Suppe 1983) to the south, with an upper flat within the upper Cretaceous Gurpi marls. Restoration of the cross section to its undeformed state indicates ~ 6.5 km of shortening, which is about 12% of initial bed length (Figure 10b).

Our interpretation emphasises the role of the basal evaporite layer as a mechanically weak horizon, which allows rigid basement slices to underthrust the decoupled sedimentary

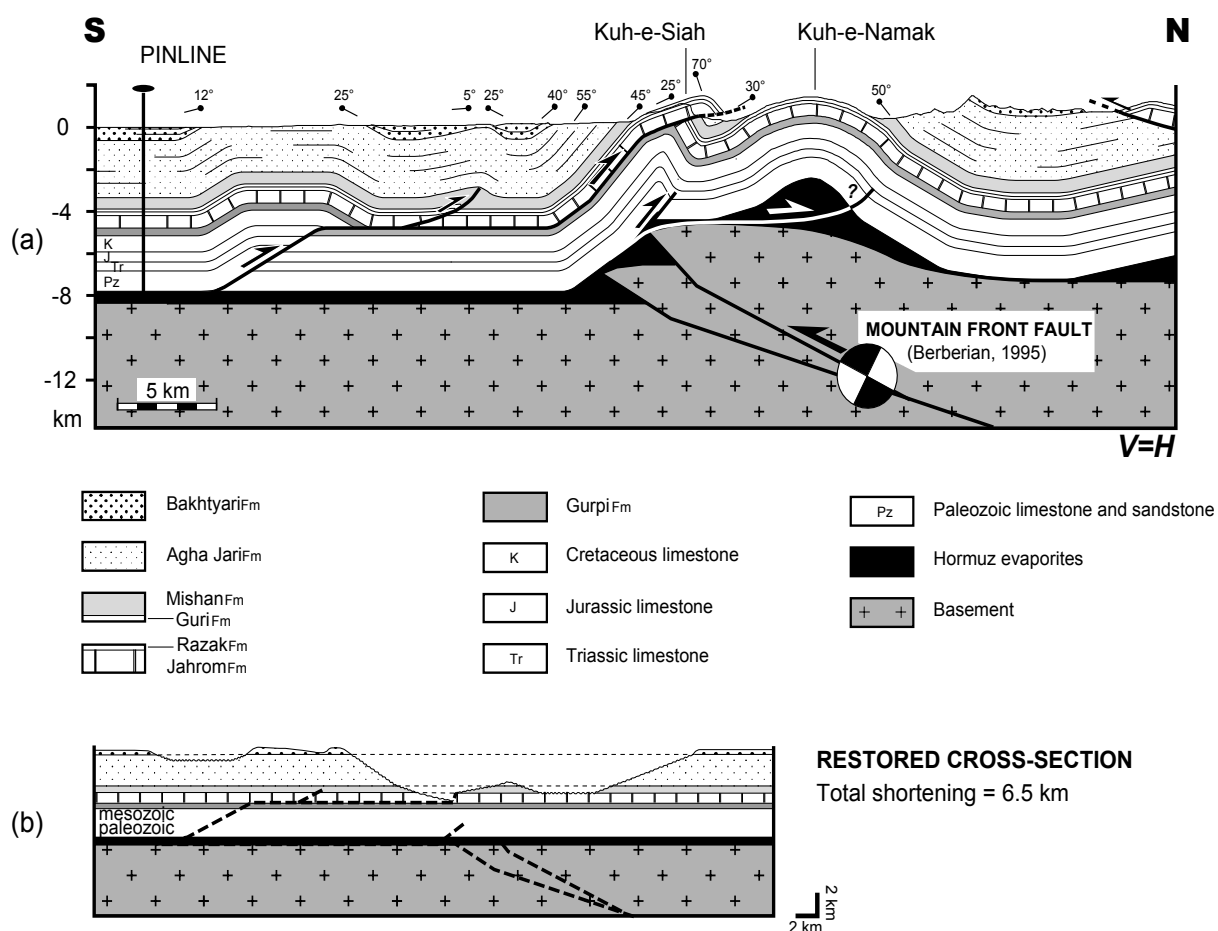


Figure 10. a) Balanced cross-section across Namak fold and Siah backthrust. For location of section see Figures 9 & 3. b) Restored section

cover. Additionally, it is likely that local flowage of the ductile Hormuz evaporites occurred towards the centre of the Namak anticline and contributed to its slightly accentuated shape.

2.5.2 Northern ZFTB and Main Zagros Thrust

To the north of the study area, the MZT represents a remarkably continuous lithological frontier separating a passive margin sequence to the south from ophiolitic-metamorphic-volcanic rocks of the Sanandaj Sirjan Zone (SSZ) to the north. However, from a structural point of view this frontier is much less well defined, essentially for two reasons:

- Rocks in the area around Hadjiabad (Figure 3), show complex imbrications and duplex structures that are more in common with the structural style within the SSZ than with the structures of the ZFTB.
- No sharp topographic feature can be associated with the MZT, as one would expect in the case of a major active crustal fault, indeed major topographic culminations in the region are

represented by the basement-involved structures such as Jain or Faraghun *south* of the MZT (Figure 3).

Two main trends can be distinguished within the structures S of the MZT (Figure 11): (1) N50-N60 trending faults corresponding to imbrications (duplex) of Eocene Jahrum limestone with a roof thrust at the base of the Mishan marls (Figs.11 and 12a) and (2) N110-N120 trending structures, such as the Abgarm thrust and syncline (Figure 11). Various inactive salt diapirs are visible in the area. Their position appears to coincide with the presence of faults, and in particular, junctions between faults (i.e. branch points).

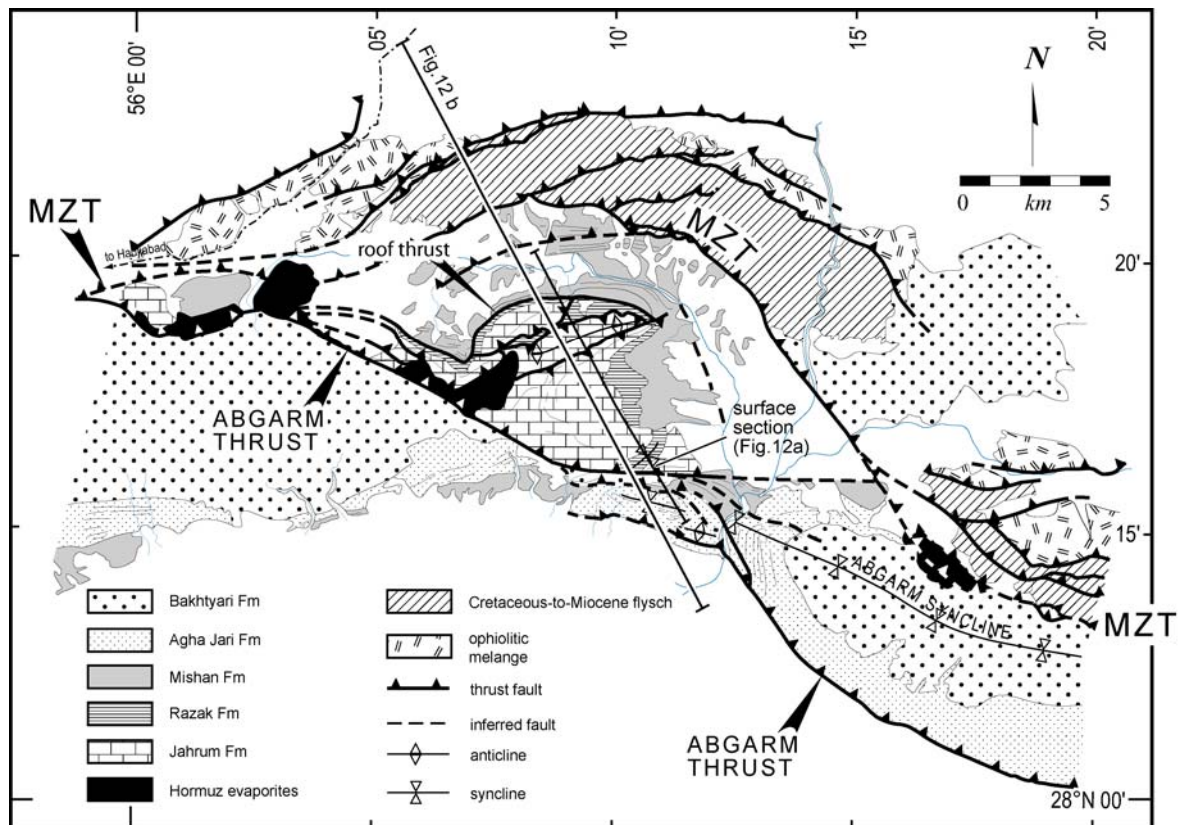


Figure 11. Detailed geological map of the MZT and associated structures in the area of Lardogarm, east of Hadjiabad. Derived from geological map (GSI 2002), SPOT satellite image and author's fieldwork. For location see Figure 3

To illustrate the structural style we have chosen a roughly NW-SE section cross-cutting the different structural trends mentioned above (Figure 12a & b) However, it must be kept in mind that the 2D section we present cannot fully represent a system that is in fact 3D. The interpretation at depth of these structures is poorly constrained. We favour an interpretation in

which duplexing of Jahrum limestone is limited to the back of the structure where the Jahrum slices are effectively visible, while the uplift of the frontal Jahrum monocline is related to the development of the deeper Abgarm thrust fault (Figure 12b).

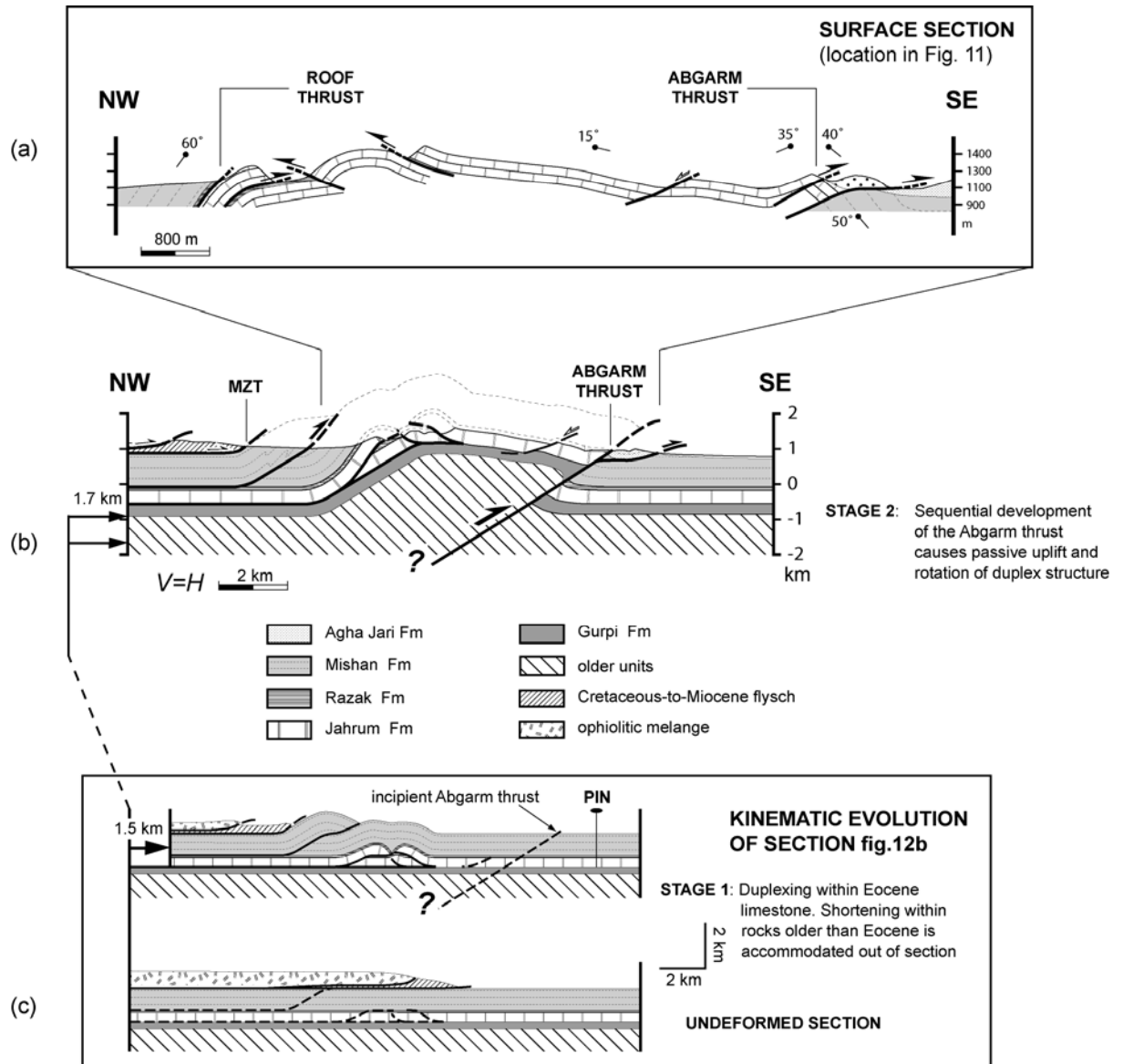


Figure 12. a) Surface section and b) balanced cross-section across the Lardogarm culmination. For location of sections see Figure 11. c) Kinematic reconstruction of cross-section in Figure 11b

A two-step kinematic modelling of the Lardogarm structure has been performed (Figure 12c). Stage 1 is marked by the development of the duplex within Jahrum limestone with a floor thrust within Gurpi marls and repetition within the roof sequence (Mishan marls). We assume that shortening within rocks older than Eocene is accommodated by other structures out of section. A minimum estimate of the shortening associated with this first step yields

approximately 1.5 km. In stage 2 the sequential development of the Abgarm thrust fault causes uplift and rotation of the duplex structure, with an associated shortening estimated at about 1.7 km. The presence of this latter fault is probably responsible for other major structural features in the area, such as the Abgarm syncline further east (Figure 11). Imbrication of Jahrum limestone is frequently observed in the region close to the MZT, especially to the W of Hadjiabad (Figure 3), and can be considered a typical feature of the Imbricate Zone.

The two-stage evolution of the Lardogarm section is well correlated with the two structural trends mentioned above (Figure 11). The trend of structures related to stage 1 (duplex within Eocene limestone) points to a NW to SE direction of tectonic transport, whereas the trend of structures related to stage 2 (the Abgarm thrust and fold) points to a NNE to SSW direction of transport. It is therefore likely that a change in the tectonic transport direction occurred between the two steps.

From our kinematic model (Figure 12c) and from the map pattern of fault traces (Figure 11), it appears that the “flysch” and ophiolitic melange thrust sheets have been transported passively along gently dipping décollements, in the same way as has been already described for the Zendan-Minab area. This is particularly evident when considering the map pattern of the MZT in relation with the footwall imbricate structures of the foreland, which is typical of what is known as a tectonic window through a culmination. Coeval emplacement of the duplex structure (stage 1 in Figure 12c) has produced localised structural relief and generated the conditions for differential erosion through the “flysch” and ophiolitic melange thrust sheets. This has resulted in the creation of a tectonic window into the underthrusting imbricated structures. This evidence points strongly to a shallow-dipping geometry for the MZT, such as has been proposed by Alavi (1994), and prompts us to reject the hypothesis of a steep crustal MZT in this area. In fact, as already stated by Alavi (1994), there is no “main” thrust fault in the area. However, we wish to emphasise that our interpretation has no implications for the position of the Neo-Tethys suture, but only for the geometry and style of the tectonic transition from the foreland Zagros to the Sanandaj-Sirjan Zone.

2.6 Discussion

The various cross-sections presented across some key structures have allowed us to separate the Bandar Abbas syntaxis into two regions distinguished by a change in direction and style of folding (Figure 4). The transition between the two branches is also accompanied by a sharp drop in seismicity (Figure 1a) and the disappearance of salt diapirs in the eastern sector of the syntaxis (Figure 3). In the following paragraphs, we will discuss the major factors that we believe can explain these various differences.

2.6.1 Different decollement horizons and their influence on the style of folding

As shown by the aspect ratio analysis (Figure 4), the majority of folds within the western limb of the syntaxis are characterised by short folds with large amplitudes. A few authors have already discussed the possible mechanisms of fold development within the ZFTB (Colman-Sadd 1978, Sattarzadeh et al. 2000). Their descriptions agree on the presence of forced folds (i.e. folds “forced” by slip on an underlying fault, (Cosgrove & Ameen 2000)), and pure buckle folds. The coexistence of these folding modes is well exemplified by the Namak section (Figure 10a). Basement faulting appears to have a control on the development of folds in the western limb of the syntaxis. The presence of a very efficient basal decollement (the Precambrian Hormuz evaporites) undoubtedly explains the considerable width and narrow cross-sectional taper of the ZFTB (Davis & Engelder 1985, Davis & Lillie 1994). However the activity of other important decollement horizons can be inferred too. This is illustrated by the Lardogarm section (Figure 12b), in which duplexing of Jahrum limestone is limited by a floor thrust within the Gurpi Fm and a roof thrust within the Mishan Fm. The role of the Gurpi marls as a decollement level had been already suggested for the Namak section (Figure 10a). The localised nature of the imbricate structures suggests that their position and size is controlled by along-strike changes in the facies – and thus efficiency – of the decollement horizons, although whether this can be tied to a secondary basement control (Woodward 1988) or early salt movements is difficult to affirm.

The eastern limb of the Bandar Abbas syntaxis is characterised by long and relatively narrow folds aligned within a narrow (30 km at most) NNW-SSE strip adjacent to the Zendan Fault. Previously, the problem of the origin of this peculiar geometry had been addressed by

Sattarzadeh *et al* (2000), who suggested that development of folds in this area is controlled by transpressive motion along underlying basement faults and along the Zendan fault. Work presented here shows that folding in this area can be explained by the fault-propagation-fold model (Figure 6) with secondary out-of-sequence thrusting, and a basal decollement at 6 km of depth. Similar aspect ratios of folds throughout the Zendan-Minab sector (Figure 4a) suggest the existence of a generalised decollement horizon at ~ 6 km. The narrow width of the fold belt, as well as the strong degree of internal rock deformation (Figure 7), indicate that mechanical coupling along this decollement is much stronger compared to the Hormuz decollement. This is typically expressed by the occurrence of out-of-sequence thrusting, which reflects the difficulty in this context of translating forward large panels of decolled sequence (Grelaud 2001, Morley 1988). Furthermore it is in agreement with recent results of an investigation into magnetic fabrics (Aubourg *et al.* 2004, *in press*), which shows that in this area they are of tectonic origin having erased the primary sedimentary fabrics. The deeper Hormuz evaporites would thus seem to be absent or in any case do not participate to folding in this area, an observation that is in agreement with the eastern limit of the Hormuz basin inferred from the absence of salt diapirs (Edgell 1996, Kent 1979). Also, the basement does not seem to be involved in the deformation in this area, as suggested by the low seismicity record compared to the western limb of the syntaxis (Figure 1a). Consequently, we think that there is no need to ascribe the peculiar geometry of folds in the Zendan-Minab area to a combination of transpression – of which there is no field evidence – and basement faulting, as suggested by Sattarzadeh *et al* (2000).

To sum up, it appears that the variation in geometry and spatial organisation of the folds across the syntaxis is strongly controlled by the depth and availability of decollement levels, (Figure 13). Additionally, the degree of internal rock deformation, as well as the width of the fold belts, suggests that coupling upon the main decollement levels within the two sectors of the syntaxis is noticeably different.

2.6.2 Influence of Omanese nappes

The question arises now as to the nature of the decollement horizon at 6 km in the Zendan-Minab area. This depth corresponds to no known decollement level in the ZSFB, and little is known of the important lateral variations of facies – and thus potential decollements – that must characterise this transitional zone between the Zagros and Makran domains.

However, we think that the answer may lie some 140 km further S, across the Strait of Hormuz, where the NNE trending structures of the Musandam Mountains, resulting from the Late Cretaceous obduction phase, suddenly dive into the sea off the northern tip of the Oman peninsula (Figure 1). The Musandam Mountains consist of stacked nappes of Mesozoic platform limestone that are separated from the Semail ophiolites to the south by the NE-SW trending Dibba fault zone (Searle et al. 1983). Offshore seismic reflection data and limited bore-hole data (Al-Lazki et al. 2002, Dunne et al. 1990, Michaelis & Pauken 1990) show that these structures are truncated by an erosive surface and covered by up to 6 km of syn-to-post obduction Tertiary sediments (Aruma-Simsima and Fars formations (Figure 2)). In particular, seismic lines published by Michaelis & Pauken (1990) show that the nappes can be followed beneath the Strait of Hormuz, truncated by a Middle Miocene unconformity and covered by a northward thickening wedge of Neogene sediments. The deepening of the Neogene basin is usually attributed to flexural loading of the margin following Zagros collision. However, seismic and well data show that the Neogene basin in the Strait of Hormuz deepens not only in the south-north direction, but also from west to east, reaching a maximum thickness along the Zendan-Minab coastline (Figure 13).

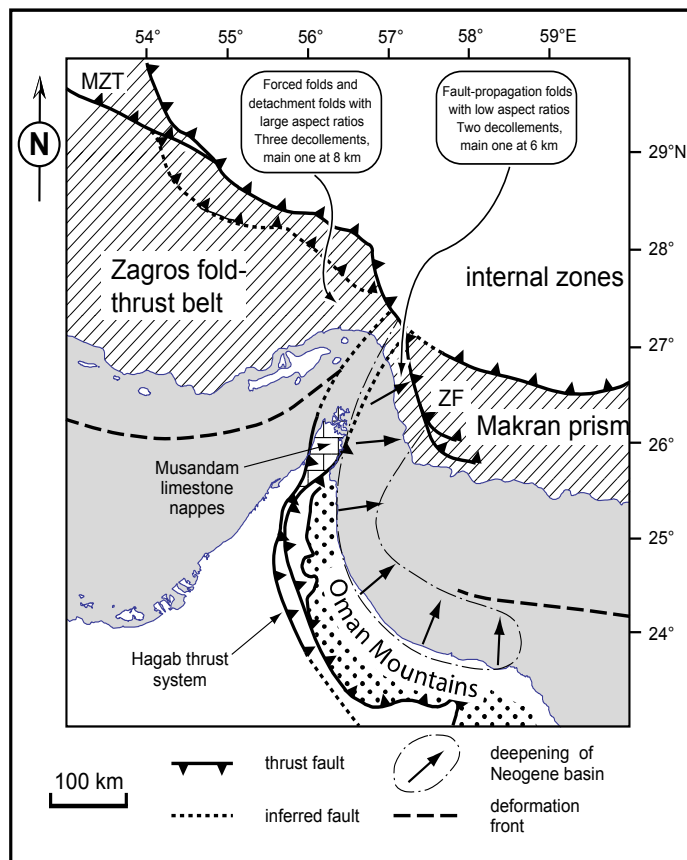


Figure 13. Schematic map illustrating the geometry of the Neogene basin according to Ravaut et al (1998). The Omanese nappes are suggested to underlie the eastern side of the syntaxis. The boundary between the two different folding styles in the syntaxis is proposed to coincide with the buried front-most omanese thrust faults (the Hagab thrust system). Heavy black dots: Semail ophiolite. MZT: Main Zagros Thrust, ZF: Zendan Fault

This particular shape of the basin is known from various studies done in the region based upon seismic and well data (Ravaut *et al* 1998; Al-Lazki *et al*, 2002) (Figure 13). Hence, one can reasonably admit that the Middle Miocene unconformity is in fact the decollement horizon that we were looking for, and that the eroded and buried Late Cretaceous Omanese structures underlie the whole of the eastern side of the syntaxis (Figure 13). This decollement level should thus approximately correspond to the base of the Fars group, while the imbricated and rigid Mesozoic-Paleozoic sequence can be considered as a “basement” for structures generated above this decollement level (Figure 2). The rapid deepening of the Neogene sediments from west to east of the syntaxis could be explained by the additional load represented by the ophiolites and the Makran prism. This would account for the abrupt transition between the two folding styles, which should thus coincide with the paleo-front of thrusting seen in the Musandam Mountains (the Hagab thrust system in Searle *et al.*, (1983)) (Figure 13). The sigmoidal deflections seen along the folds in the ZMB (e.g. close to the northern periclinal termination of the Minab fold (Figure 5)), could thus be directly related to interference with the NNE-SSW trending Oman structures and not, as suggested by Sattarzadeh *et al* (2000), to clockwise rotations caused by transpression along the Zendan fault.

2.7 Conclusion

Two main styles of deformation are recognised within the foreland folds around the Bandar Abbas syntaxis.

The western branch of the syntaxis is characterised by short and broad folds controlled by efficient slip within the Infra-Cambrian Hormuz evaporites at the basement-cover contact. The presence of the Hormuz evaporites in this area is testified by numerous salt diapirs piercing the cover. Farther north in the Imbricate Zone, deformation is more intense and slip along shallower horizons, notably the Gurpi and Mishan marls, allows the development of imbricate structures. Strong seismicity underlines the importance of active basement faulting in the western syntaxis. This is further supported by the cross-section through the Namak fold (Figure 10), which illustrates the control exerted by basement faulting on folding in this area.

By contrast, the eastern branch of the syntaxis is characterised by long and narrow folds governed by slip along a 6-km deep horizon, with a later reactivation within the upper stratigraphic section at ~ 4 km depth. The absence of salt diapirism suggests that the Hormuz

salt is absent in this sector. We propose that the basal decollement horizon to structures in this area corresponds to the eroded top of the northward converging Omanese Mesozoic nappes. This should situate the decollement level somewhere towards the base of the Fars Group (Figure 2), while the deeper stratigraphic horizons and basement do not appear to be involved in the Neogene deformation. Folds with similar geometries and detaching at ~ 4 km depth are observed deforming Tertiary molasse in the Oman Peninsula (Noweir 2000), suggesting that the same detachment is active in this area as well. The relative shallowness of the deformation in the ZMB probably explains the absence of seismicity in the eastern branch of the Bandar Abbas syntaxis.

The cross-sections across the MZT and the Zendan Fault suggest that these two faults have similar shallow low-angle geometries and accommodate essentially dip-slip movement. It appears clear that the MZT and Zendan Fault are in fact part of a single low-angle fault system separating the foreland folds from a structurally continuous and entirely allochthonous belt of “flysch” and ophiolitic melange extending from the western Makran zone to the Sanandaj Sirjan Zone in the north.

As testified by the different structural trends present around the syntaxis, the tectonic history of this area is not a simple one-step process. For instance, two different directions of tectonic transport have been inferred from the trend of structures in the area of Lardogarm close to the MZT (Figure 11), at N50-N60 and N110-N120 respectively. The suggested kinematic reconstruction (Figure 11c) shows that the coexistence of these two structural trends fits well with a two-step evolution for this area. Interestingly, it can be noted that the same trends are present elsewhere throughout the western branch of the syntaxis (Figure 3). The trends within this region are opposed by the constant NW-SE direction of structures that characterises the ZMB in the eastern side of the syntaxis. It is probable that these two major trends of the Bandar Abbas syntaxis did not result from a single continuous tectonic event. Rather we think that the particular position of the syntaxis, at the boundary between two evolving thrust-fold arcs – Zagros and Makran – could explain the interference between these different trends. The structures within the ZMB could thus be linked to recent westward propagation of the lateral branch of the Makran prism. Moreover, structures with the same trend are observed deforming Mio-Pliocene clastics in front of the Zendan Fault further north (Figure 3).

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3 FURTHER ILLUSTRATIONS AND REMARKS ON THE STRUCTURES PRESENTED IN PAPER N.1

3.1 *Some remarks on the balanced cross-sections*

The balanced cross-sections presented in paper n.1 were the first to be constructed during my thesis and are thus in a sense part of the initial “learning stage” of my doctoral thesis. During this time I assimilated the section balancing techniques, at the same time testing alternate solutions in order to obtain the most “reasonable” sections from a tectonic style and geometrical point of view.

The method used for the construction of the sections presented throughout this thesis is essentially the “kink” method as described by Suppe (1985), in which panels of constant dip (dip domains) are separated by narrow hinge lines, or kinks. The various dips measured at surface are thus projected to depth and the geometry of the structures reconstructed. The method has the advantage of being simply and readily applicable for obtaining information on the amount of shortening and depth-to-decollement of the fold-thrust structures.

The sections were restored using the principles of line-length section balancing according to which (Dahlstrom 1969) “in concentric regimes the cross-sectional length of a bed remains constant during deformation”. The implicit assumption is that shortening produces no significant internal deformation (i.e. change in rock volume) of the beds. The section is therefore considered balanced when it is (1) **geometrically viable** i.e. it can be restored to its original undeformed state without creating overlaps or gaps within the beds and (2) **admissible** i.e. it conforms to the tectonic style of the region of interest.

An important element for the construction of the sections were the photographs and sketches collected during the field trips to the Bandar Abbas area, which allowed the documentation of outcrop-scale structural features which could not be distinguished on satellite images or published geological maps. These are presented in the following paragraphs.

3.2 Minab anticline

Because of its accessibility and excellent exposure, the Minab anticline (Fig. II—2) presented particularly favourable conditions for studying the style of folding in the eastern sector of the Bandar Abbas syntaxis.

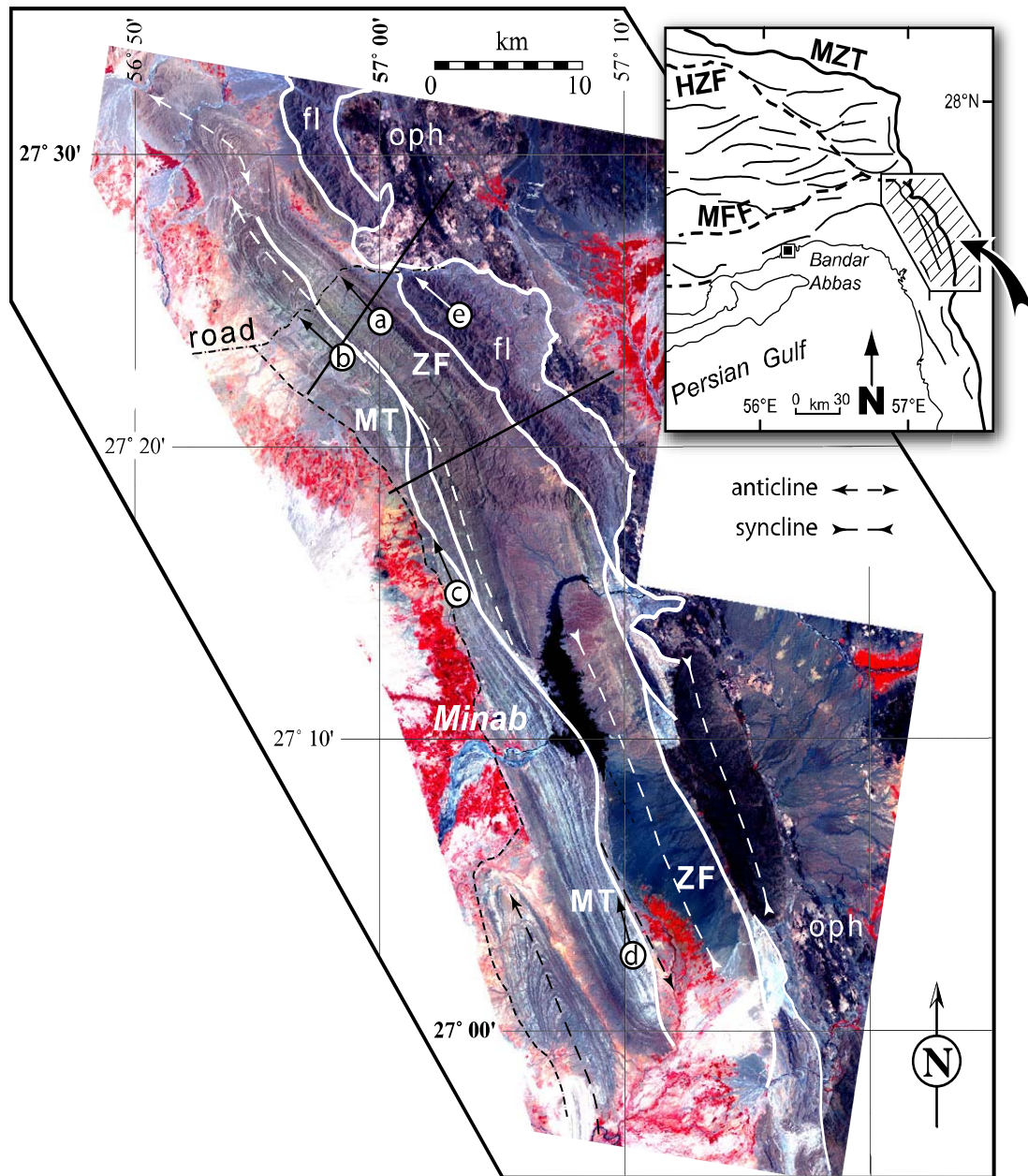


Fig. II—2 Interpreted SPOT satellite image of the Minab anticline and thrust east of Bandar Abbas. Dashed lines fold axes, heavy lines fault traces. MT, Minab Thrust; ZF, Zendan Fault; fl, Cretaceous to Miocene “flysch”; oph, ophiolitic melange. Labels a to e denote photographs in Fig. II—3, Fig. II—4 & Fig. II—5 Red patches correspond to areas of vegetation.

3.2.1 Kinks and small-scale thrusting

On the field, one of the most striking features of the Minab fold is the presence of meso-scale deformational features such as kinks, thrust faults and jointing, which are ubiquitous throughout the fold. These are well illustrated along the Bandar Abbas to Rudan road crossing the northern part of the fold (Fig. II—2). The kink folds are narrow zones of sudden change in bedding dip visible at several scales, varying from a few meters (Fig. II—3a) to several hundred meters (Fig. II—3b). They constitute zones of weakness, which are often reused by late joints or small thrusts (Fig. II—3a).

3.2.2 Minab and Zendan thrust faults

The Minab thrust (Fig. II—2, Fig. II—4) is best observed in the central part of the fold, slightly north of the town of Minab, where the throw on the fault is maximum and the Mishan marls in the hanging wall are carried well over the Agha Jari beds of the forelimb. The out-of-sequence character of this fault – discussed in paper n.1 – is clearly illustrated in Fig. II—4a where folds and thrusts in the foot wall are truncated by the subhorizontal out-of-sequence Minab thrust. The direction of thrusting, as evidenced by gypsum slickenfibres lineations within the fault zone (Fig. II—4a), is N235°. Further south close to the periclinal termination of the Minab fold, the Minab thrust changes in vergence since the Mishan marls are now observed back-thrusting towards the east. However, exactly how and where this change in vergence occurs is not yet clear.

Parallel to the Minab fold and overthrusting it, the Zendan fault carries “flysch” and ophiolitic melange rocks towards the west (Fig. II—5). This fault, as discussed in paper n.1, is a shallow passive contact resulting from a complex and probably multiphased history. Recent GPS measurements (Vernant 2003) show that the ensemble of the faults in this region, including the Zendan Fault, are presently accommodating a right-lateral shear of 11 ± 2 mm/yr. However, it should be pointed out that these movements concern only the present day kinematics of the region and cannot explain the history of the emplacement of the “flysch” and ophiolitic nappes, which probably involved thrusting of the nappes over large distances along the Eastern Arabian margin.

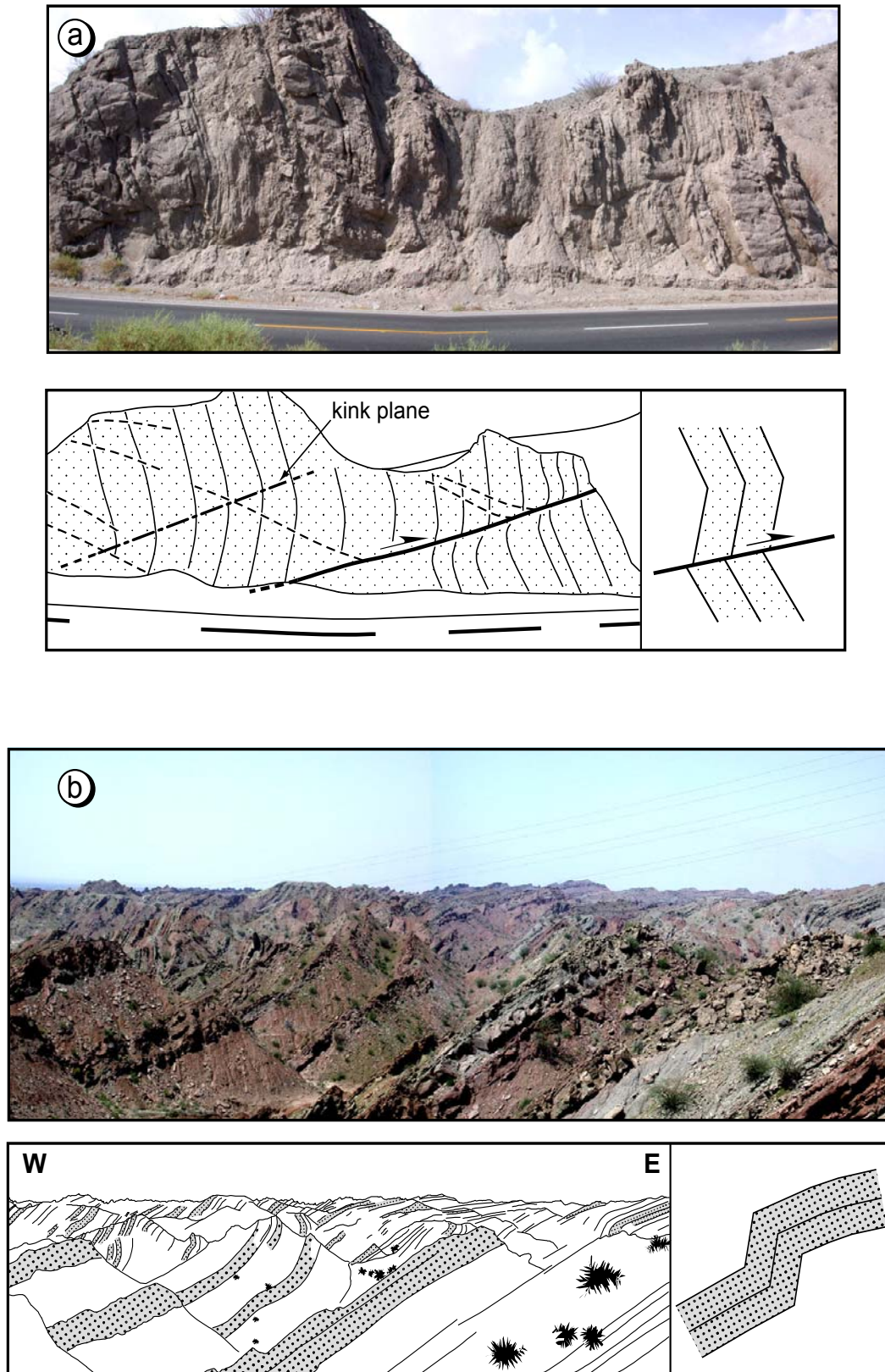


Fig. II—3 (a) Photograph and line drawing of small-scale kink folding of the Agha Jari beds in the northern part of the Minab Fold. Note the fault reusing a kink plane (interpretative sketch). (b) Photograph and line drawing with interpretative sketch of large-scale kink folding in the western flank of the Minab anticline. Viewpoints in Fig. II—2.

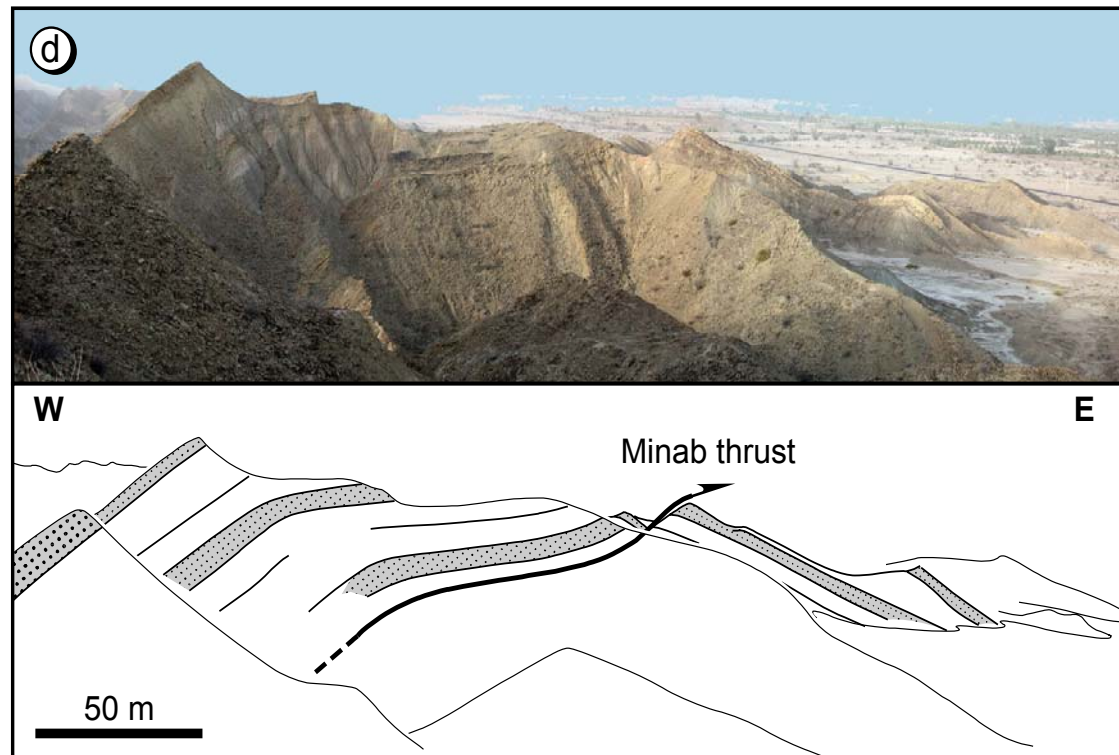
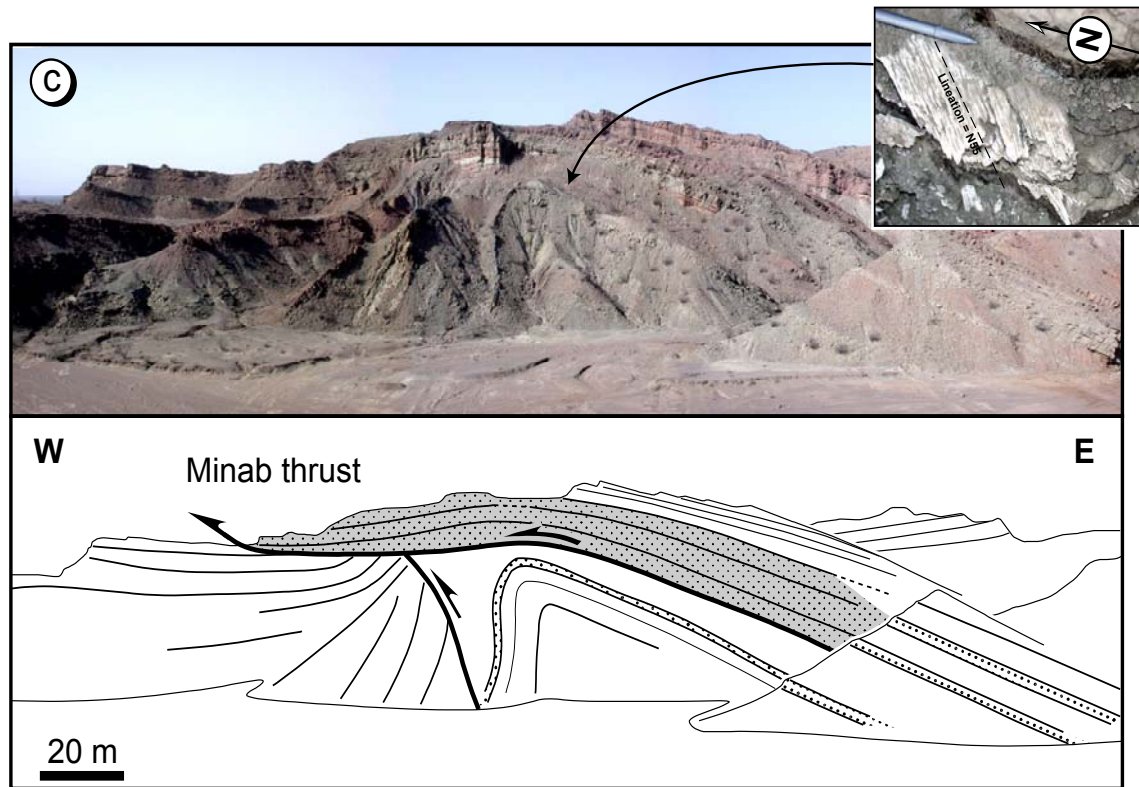


Fig. II—4 (c) Photograph and line drawing of the out-of-sequence Minab Thrust north of the town of Minab. Inset: detail on gypsum fibre lineations within the sub-horizontal Minab thrust plane, showing a transport direction of N235°. (d) Photograph and line drawing of the Minab Thrust further south. Note the change in direction of thrusting from Fig. II—4c. Viewpoints in Fig. II—2.

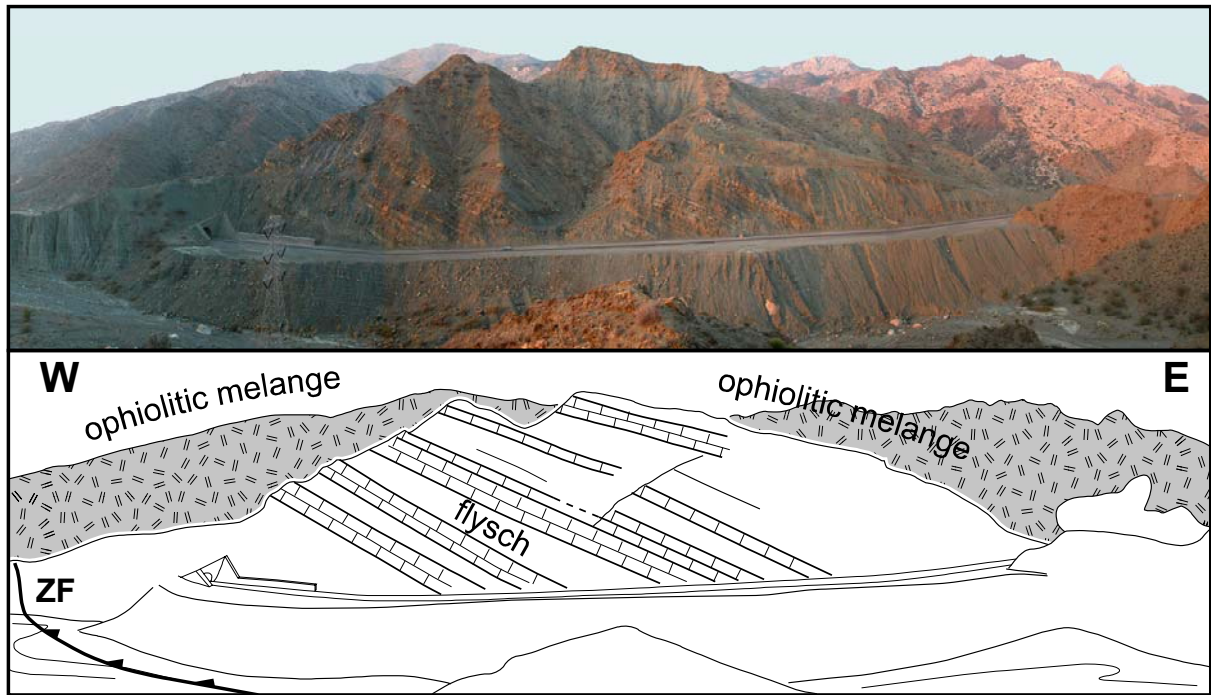


Fig. II—5 View of the “flysch” and ophiolitic melange nappes thrusting towards the west along the Zendan Fault (ZF) (approximate fault line in river bed at lower left hand corner). Viewpoint in Fig. II—2 (e).

3.3 Namak and Siah anticlines

The Namak anticline (Fig. II—6) is exemplary of the style of folding in the western side of the syntax. Its regular and well rounded geometry (Fig. II—7a, see also appendix 1) strongly suggests folding by buckling on a deep horizon, most probably the Hormuz Salt. Further north, a syncline cored by Bakhtyari conglomerates culminates at 1700 m, 600 m higher than the crest of the Namak anticline (Fig. II—7a).

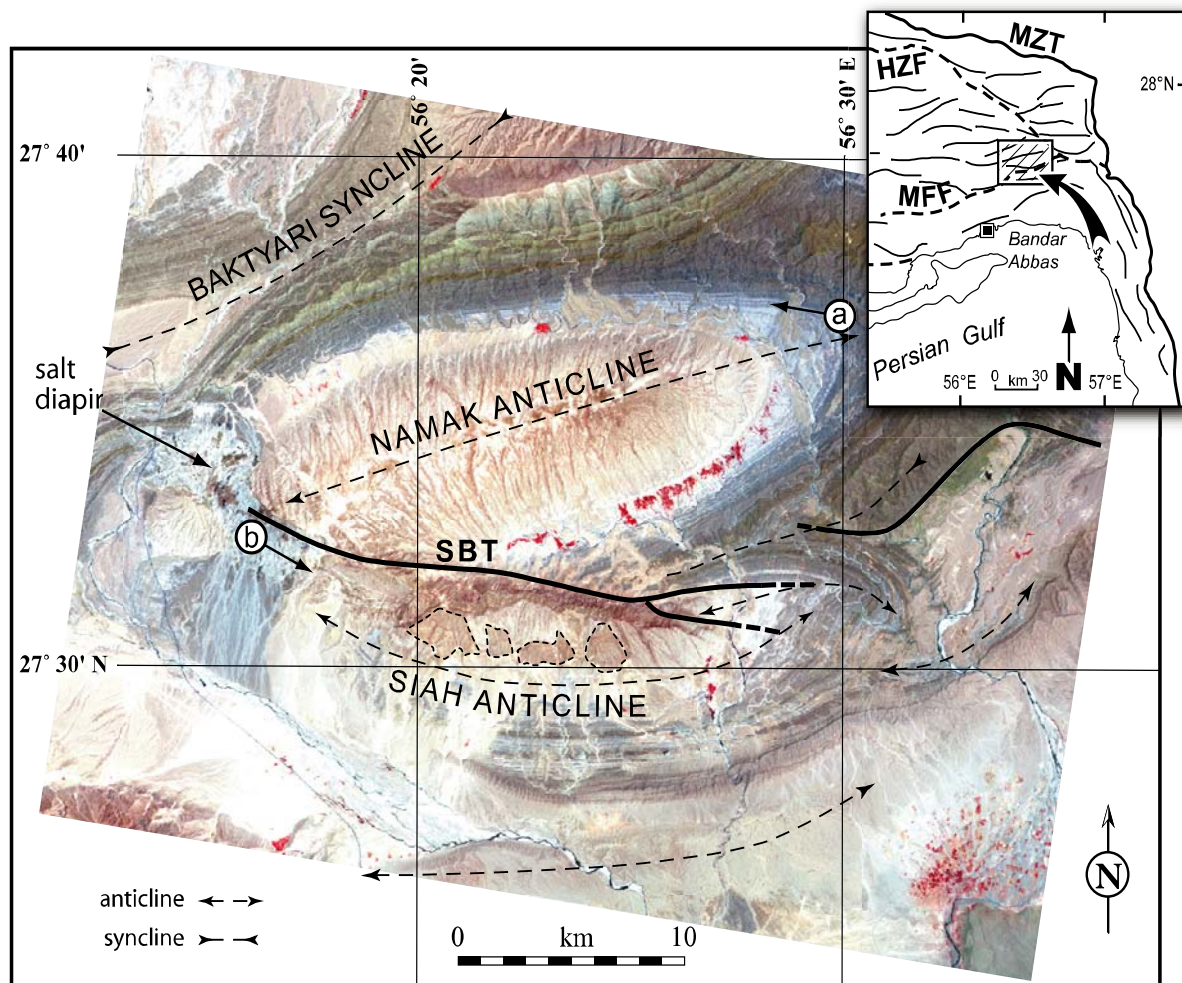


Fig. II—6 Interpreted SPOT satellite image of the Namak and Siah anticlines in the eastern ZFTB. Note the disrupted rafts of Guri limestone on the southern flank of the Siah anticline (dashed line contours). Dashed lines fold axes, heavy lines fault traces. SBT, Siah backthrust. Labels a and b denote photographs in Fig. II—7.

In contrast with the Namak anticline, the adjacent Siah anticline presents a strongly asymmetric north-verging geometry, accentuated by the emergence of the Siah backthrust along its crest. On its steep southern flank numerous gravity collapses are visible, disrupting

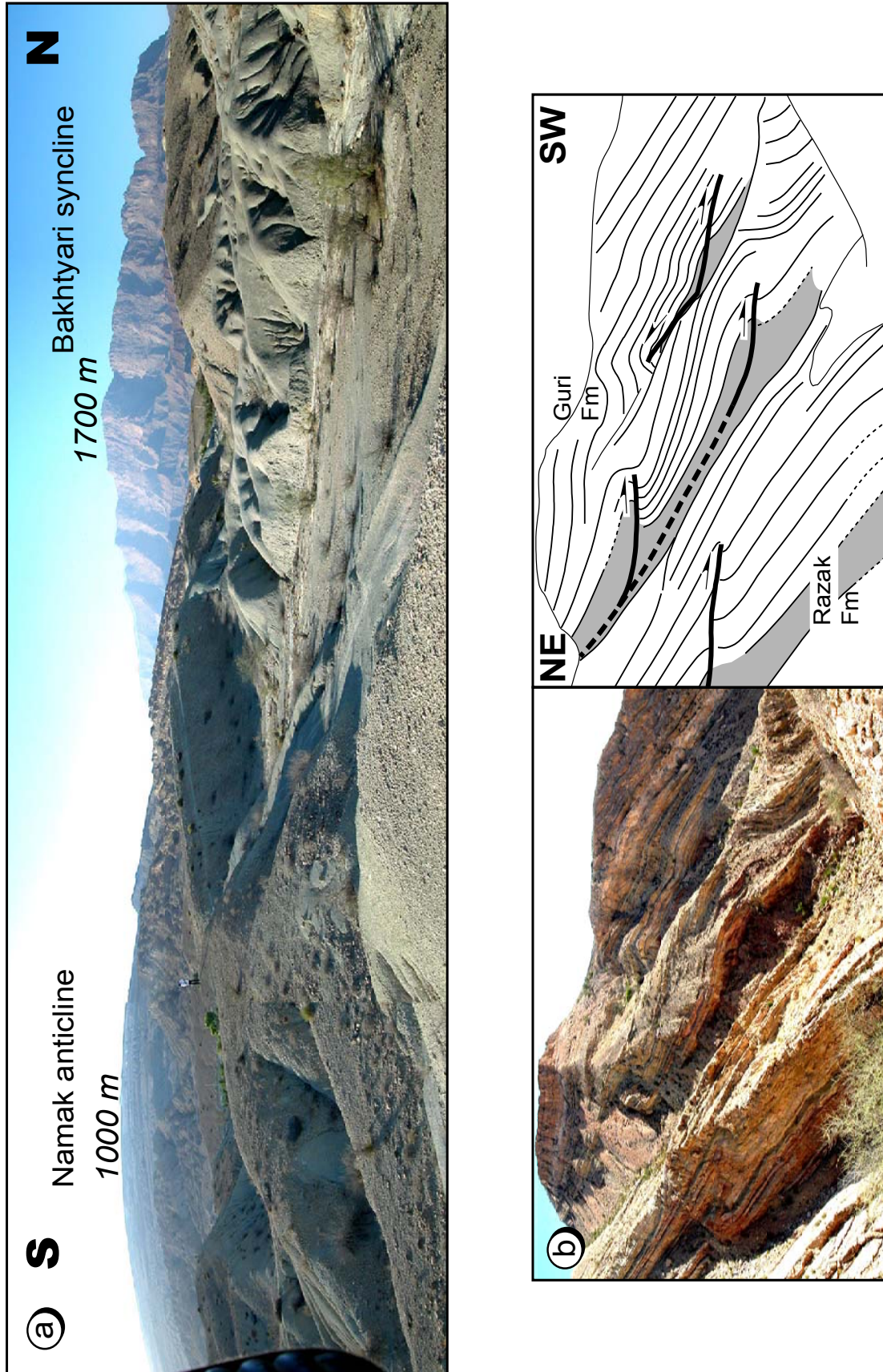


Figure II—7 (a) Panoramic view of the Namak anticline and the adjacent Bakhtyari syncline. (b) Photograph and interpretation of collapse structures within Guri limestone beds. Viewpoints in Fig. II—6.

beds of Guri limestone (Fig. II—6). These collapses occur by slip along the underlying Razak red marls and have produced diffuse folding and faulting within the Guri beds (Fig. II—7b) or, on a larger scale, sliding of entire panels of the Guri limestone (Fig. II—6).

3.4 Lardogarm culmination and MZT

The area of Lardogarm (Fig. II—8) is interesting since it provides a good illustration of both the structural style in the northern part of the Bandar Abbas syntaxis as well the geometry of the MZT. Also, as mentioned in paper n.1, this area displays several interesting examples of salt diapirism which can provide some clues on the timing of the diapirism in relation with Zagros deformation.

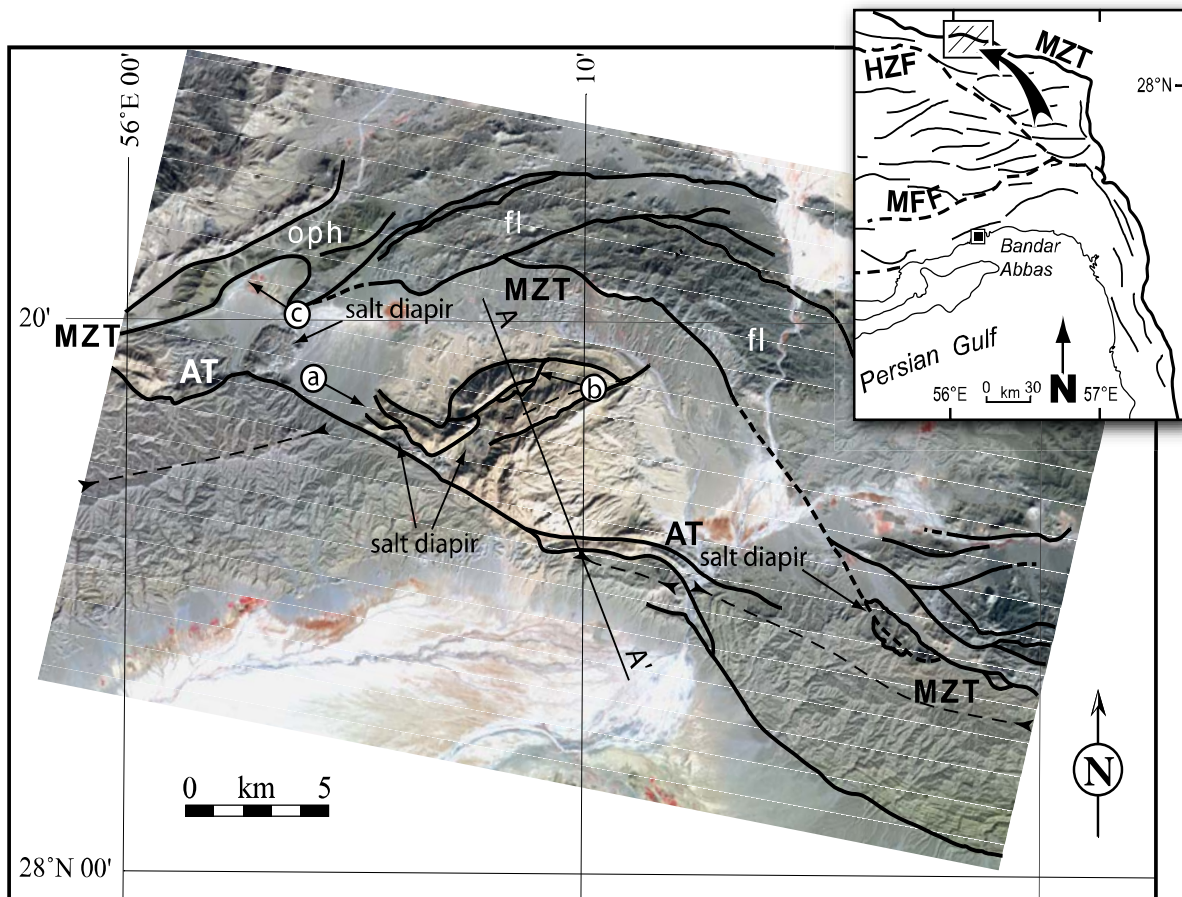


Fig. II—8 Interpreted SPOT satellite image of the Lardogarm culmination and Main Zagros Thrust (MZT) region. Dashed lines fold axes, heavy lines fault traces. AT, Abgarm Thrust; oph, ophiolites; fl, “flysch”. Labels a to c denote photographs in Figure II—9. Section A-A’ in Fig. II—10.

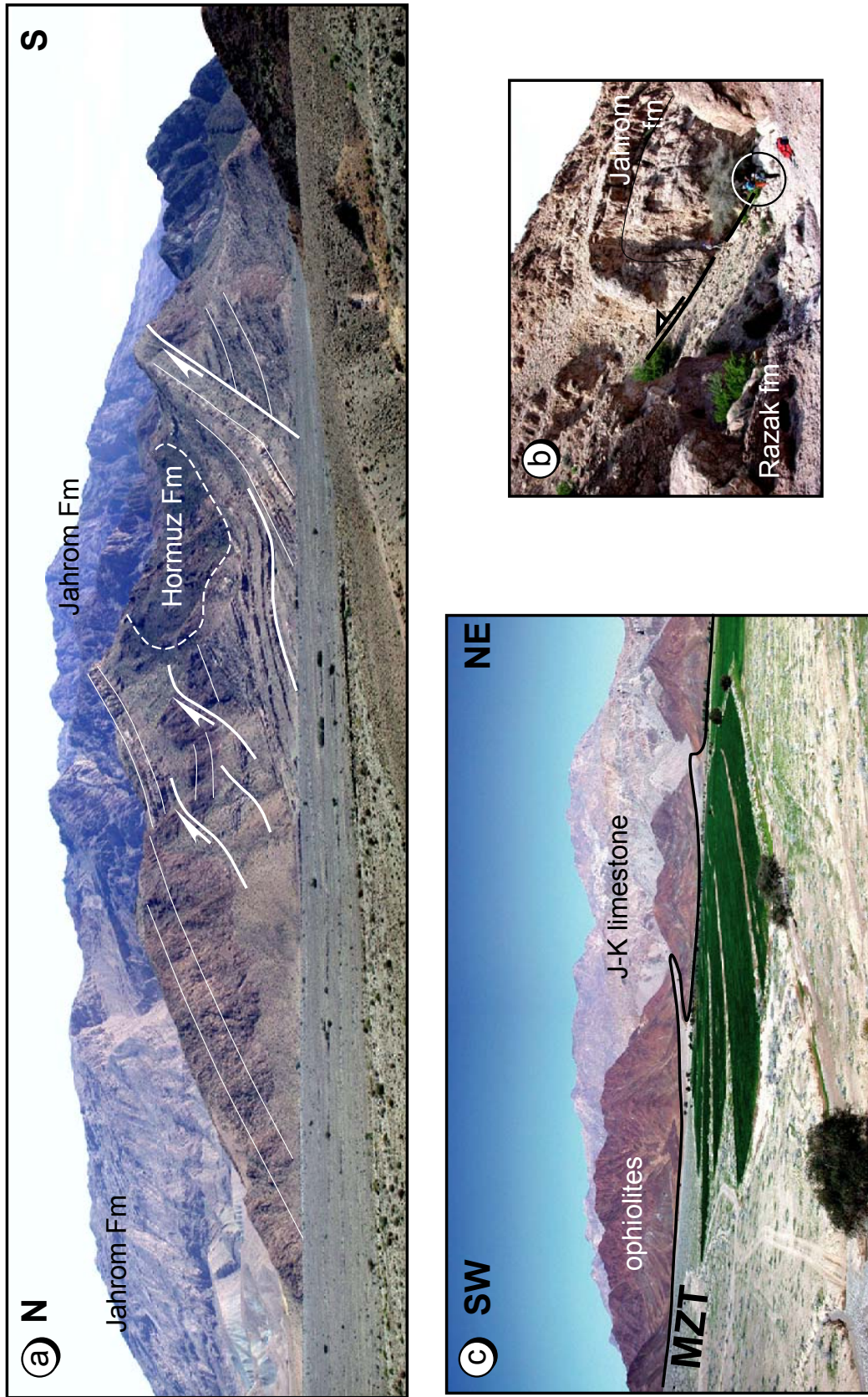


Figure II—9 (a) View on the Lardogarm culmination and Jahrom imbrications. Note the remains of a salt diapir within the thrust zone. (b) View on thrust fault on the northern side of the Lardogarm culmination carrying Jahrom limestone over Razak marls. (c) View on the MZT and ophiolitic nappes west of the Lardogarm culmination, looking towards the NW. Viewpoints in Fig. II—8.

At the centre of the satellite image the imbrications of Jahrom limestone are visible as a peculiar eye-shaped culmination rising above the surrounding flat plain of Mishan marls and the adjacent Agha Jari and Bakhtyari synclines. In the field they are visible as complex thrust faults cutting through the remains of a salt diapir (Fig. II—9a). These imbrications are related to slip within the underlying Gurpi Fm and involve thrusting of Jahrom limestone over the Razak red marls (Fig. II—9b). The overlying Mishan marls are not involved in the structure and must therefore act as a roof décollement for the imbrications (Fig. II—8). Further north, the MZT transports “flysch” and ophiolites towards the south, these latter visible as low isolated hills of a distinctive reddish brown colour (Fig. II—9c). The geometry of the MZT defined by these ophiolitic klippe is clearly that of a shallow and passive thrust plane, in agreement with the observations discussed in paper n°1 (paragraph 2.5.2).

3.4.1 Comment on the Lardogarm section

The cross-section of the Lardogarm culmination (paper n.1, Fig. 12) presented an interesting problem in terms of section balancing. The fact that only Jahrom limestone is observed at surface seemed to suggest that the culmination is produced by vertical stacking of Jahrom limestone imbricates with a floor thrust within the Gurpi marls and a roof thrust within the Mishan marls (Fig. II—10a). However, this extreme solution implies large amounts of horizontal shortening – in the order of 30 km – notably in the case of an interpretation of the south-dipping Jahrom monocline at the top of the structure as a foreland-dipping slice. This interpretation could not be justified in view of other structures observed along-strike in the area, so it was apparent that to reduce the amount of shortening it would be necessary to involve in the structure the deeper levels of the sedimentary sequence. So our preferred interpretation is one in which duplexing of Jahrom limestone is limited to the back of the structure where the Jahrom slices are effectively visible, while the uplift of the frontal Jahrom monocline is related to the development of the deeper Abgarm thrust fault (Fig. II—10b).

However, it is clear that the large-scale structure of this region is more complicated than this simple 2-dimensional interpretation. As can be seen on the satellite image (Fig. II—8), the structures in this area are characterised by a remarkable lack of lateral continuity. In other words the general structure of this area is a highly 3-dimensional one. Therefore an understanding of this structural framework – notably the relationship between the culmination and the adjacent synclines – necessarily requires the integration of information on a much larger, regional scale. This problem is dealt with in chapter III, where we present a regional

transect of the ZFTB extending from the Persian Gulf to the inner parts of the orogen and throwing new light on the geometry of this structurally complex area.

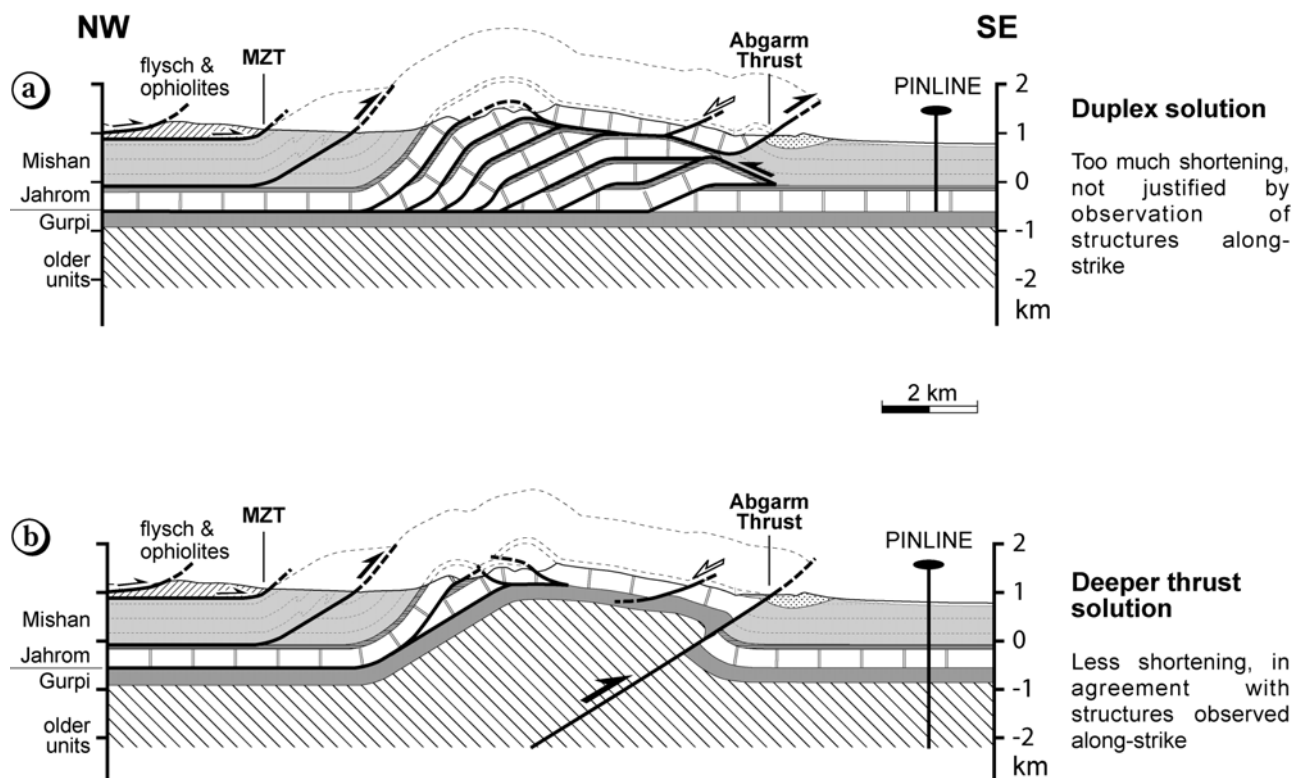


Fig. II—10 Two alternate cross-sections which can explain the surface data from the Lardogarm culmination. MZT, Main Zagros Thrust. Line of section in Fig. II—8.

3.5 Salt diapirism in relation to Zagros structures

We previously pointed out the fact that the distribution of salt diapirs in the ZFTB appears to be non-random when viewed against the Zagros structural framework. In trying to establish the nature of this relationship, one must address the following question: does salt diapirism predate the Zagros shortening? More specifically, does Zagros shortening occur in a sedimentary cover already affected by the mechanically weak points represented by salt diapirs (Kent 1979)? Two of the studied sites may provide the clues for answering this question.

I. In the area of Lardogarm the inactive salt diapirs appear to be located at the branch lines of the Jahrom imbricates (Fig. II—8). In this case the question of the relationship between structures and diapirs should be reformulated as follows: is the position of the branch

lines guided by pre-existing salt structures, or *viceversa* have the branch lines controlled the location of salt diapirs? In paragraph 2.5.2 it has been shown that duplexing in this area involves only Eocene limestone rocks with a probable floor thrust within Upper Cretaceous marls. This allows us to exclude the possibility that the salt has been drawn along thrust planes cutting the whole sedimentary cover, as would have been the case if the floor thrust to the duplex was situated in the Hormuz evaporites. Rather, we think that the salt structures initially pierced through a sedimentary cover not yet affected by Zagros shortening. In the course of the subsequent emplacement of the duplex structure, propagating thrust planes were guided by salt structures acting as mechanical discontinuities, which eventually ended up by localising the branch lines.

II. On the Namak fold and Siah backthrust (Fig. II—6), the point of interception between the backthrust and the Namak fold is marked by the presence of a salt diapir. It can be noticed that this point corresponds to the lateral terminations of both the backthrust and the Namak fold. The implications of the presence of the salt diapir for these structures are interpreted as follows:

- a) Withdrawal of salt at depth causes local touchdown of the sedimentary cover upon the basement, thereby blocking the lateral propagation of the Namak fold. This mechanism had been already suggested by Kent (1979) to explain the fact that salt diapirs often coincide with fold terminations, and could be extended to several other fold-diapir systems in the area of Bandar Abbas (Fig.3 in paper n.1).
- b) Breaching of the sedimentary cover by the diapir provides a mechanically weak spot that guides the lateral propagation of the backthrust.

The most obvious consequence of the observations discussed above is that the salt diapirs, probably triggered by the first gentle movements within the sedimentary cover, predate the development of the major Zagros structures. This proposition is in agreement with the generally accepted view that salt diapirs predate Zagros shortening (Kent 1979, Koyi 1988, Talbot & Alavi 1996). However, this does not mean to say that diapirism was initiated within a continuous and uniform salt layer. This would be to underplay the importance of the various tectonic episodes that punctuate the history of the Arabian margin, which must have influenced salt distribution in one way or another (Talbot & Alavi 1996). For instance “Hercynian” reactivation in mid-Carboniferous times or Neo-Tethys rifting – and associated extensional faulting – during Permo-Triassic times should be likely candidates for the remobilization of salt into various types of accumulations (salt pillows, salt walls, etc.). These

accumulations could then be the critical starting points from which the diapirs were generated during Zagros shortening.

4 CONCLUSION

Fig. II—11 summarises our main conclusions on the Bandar Abbas syntaxis. The ensemble of regional observables (fold patterns, distribution of diapirs, distribution of seismicity) suggested early on that the two limbs of the syntaxis are distinguished not only by a sharp change in structural trends, but also by different initial genetic conditions. This was later confirmed by the construction of balanced cross-sections, which showed that the style of folding is controlled by a change in mechanical stratigraphy across the syntaxis. So it became apparent that the geometry of the structures must be ultimately controlled by changing tectono-stratigraphic histories from one side to the other of the syntaxis. In particular, the inherited structural trends of the Arabian plate (Fig. II—11) appear as the fundamental factors which controlled the sedimentary and structural evolution of the margin in this area: firstly by controlling Hormuz deposition in Eo-Cambrian times (Fig. I—2); secondly by localising the transform faults which dissected the Arabian margin during Neo-Tethys rifting in Permo-Triassic times (Fig. I—3); and finally by guiding the emplacement and the structural trends of the obducted ophiolites and the imbrications within the Arabian shelf in Late Cretaceous times.

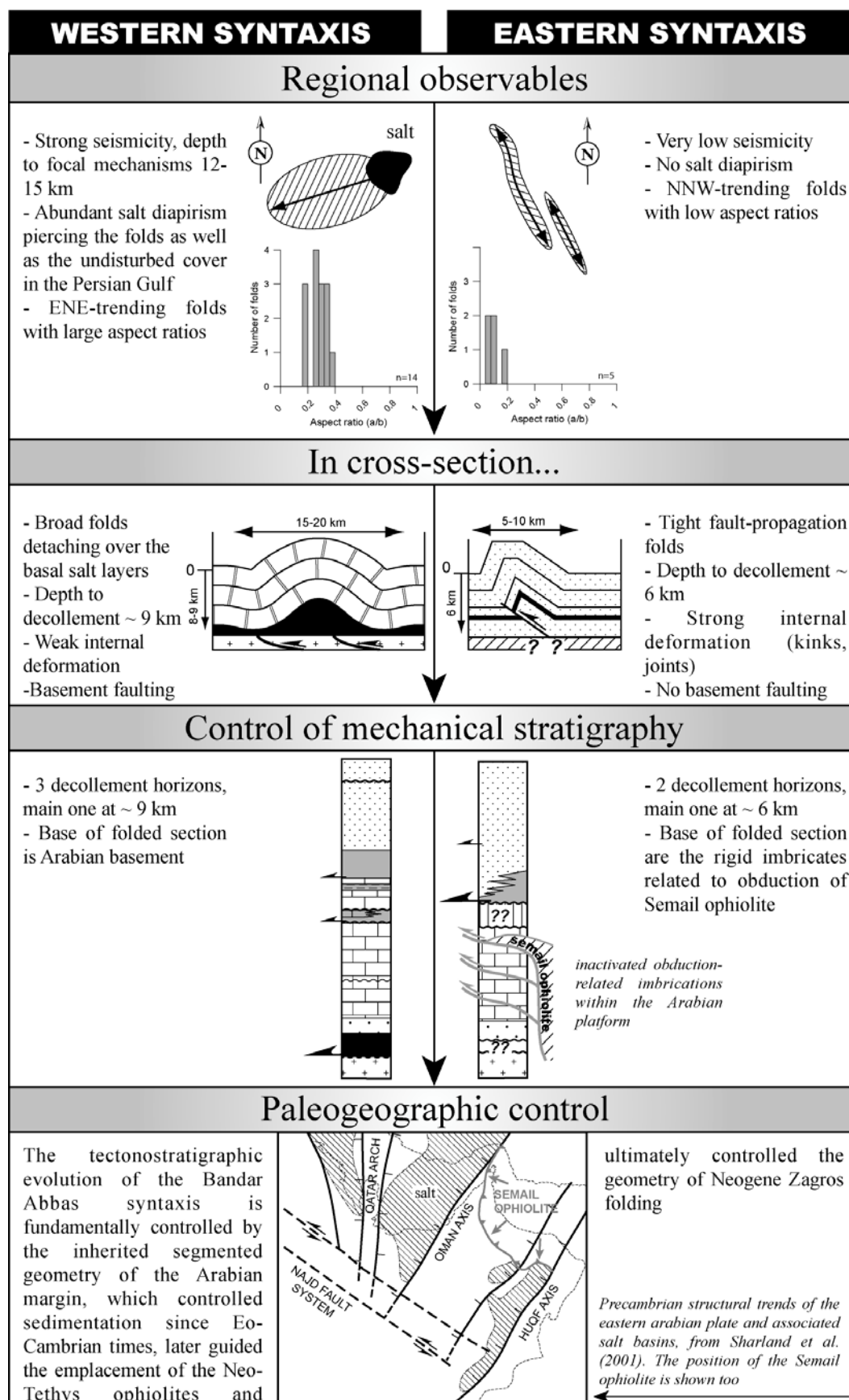


Fig. II—11 Summary diagram of the main features and controlling factors of the structure of the Bandar Abbas syntaxis

CHAPTER III

KINEMATICS OF THE EASTERN ZAGROS FOLD THRUST BELT

1 INTRODUCTION

In chapter II our discussion on the Bandar Abbas syntaxis focused exclusively on defining the general geometric characteristics of its fold-and-thrust structures. Our analysis permitted us to discuss some of the factors underlying the geometry of the syntaxis and notably the role of the inherited structural features of the Arabian paleomargin.

However, as mentioned at the end of paper n° 1, there still remains the important question of how the syntaxial loop was formed through time. Specifically, the following questions need to be addressed on this matter: what are the fold-and-thrust kinematics of the eastern Zagros Fold Thrust Belt? Did the structures in this area evolve through several distinct tectonic phases or through one single and continuous process? What is the meaning of the various tectonic trends present throughout the syntaxis in terms of its structural evolution?

The kinematics of orogenic belts have been discussed by authors in many different tectonic settings around the world (e.g. Perry 1978, Baker et al. 1988, Zoetemeijer & Sassi 1992, Grelaud et al. 2002). The basic principles upon which kinematic models are built are essentially the geometric criteria employed in section balancing (Bally et al. 1966, Dahlstrom 1969, Marshak & Woodward 1988, Woodward et al. 1989). In other words, the geometric features of a balanced cross-section can (and should) be directly interpretable in terms of kinematic concepts. Additionally, knowledge on the evolution of certain structures can be inferred by referring to well known models such as the fault-bend and fault-propagation folds (Suppe 1983, Suppe & Medwedeff, 1990). Many other tools exist to further constrain kinematic models, such as microtectonic analyses or magnetic fabric and paleomagnetic studies for the movement of rocks through space, or magnetostratigraphic sections for movement of rocks through time.

A long-standing axiom of the kinematic modelling of fold-and-thrust systems has been that deformation as a rule propagates in a hinterland-to-foreland progression (i.e. in “piggyback” fashion) (Dahlstrom 1970, Boyer & Elliott 1982). However, increasing evidence now suggests that in many mountain belts the picture is far from being so simple and that significant synchronous folding and thrusting (Boyer 1992) and out-of-sequence reactivation (Morley 1988) are bound to occur within the deforming zone.

In Zagros, little or no work has been done to understand its kinematic evolution, the sole possible exception being O'Brien's (1957) interpretation of the development of structures in the Dezful Embayment area (Fig. I—13b). The aim of this chapter is primarily to discuss the

kinematics of the eastern ZFTB by analysing in detail the structures along a transect throughout the whole of the eastern Zagros Fold Thrust Belt. I do this since I consider that only a regional-scale section can provide a sufficiently wide scope of analysis to discuss these matters. Having defined a kinematic scenario for this cross-section, I then extrapolate a possible scenario for the overall evolution of the eastern ZFTB and the Zagros-Makran transitional area.

This chapter is organised in a similar way to the preceding one. The core of the study is presented in a paper “**The structure and kinematics of the south-eastern Zagros fold-thrust belt, Iran: from thin-skinned to thick-skinned tectonics**”, submitted for publication in *Tectonics*. The rest of the chapter is intended to complement the results discussed in the paper. Firstly by presenting some additional illustrations and comments on the style of deformation in the eastern ZFTB. Then by discussing in more detail some aspects of the kinematics of the eastern ZFTB. Finally, by presenting some results from recent paleomagnetic and magnetic fabric studies performed on several folds in the Fars Arc and around the Bandar Abbas syntaxis in which I was partly involved. These studies highlighted vertical axis rotations which could be useful in constraining the kinematic evolution of this area.

<p>CURRENT STATUS OF PAPER N° 2: the paper has been accepted for publication (18th August 2004) in <i>Tectonics</i> pending moderate revision</p>

LA STRUCTURE ET LA CINEMATIQUE DU ZAGROS PLISSE ORIENTAL, IRAN : LA TRANSITION D'UNE TECTONIQUE DE COUVERTURE A UNE TECTONIQUE DE SOCLE (PAPIER N° 2)

Resumé : Nous présentons la première coupe équilibrée à travers le Zagros plissé oriental (le ZFTB, *Zagros Fold-Thrust Belt*). Cette coupe met en évidence les traits structuraux suivants : (1) Dans le sud du ZFTB, la série sédimentaire d'âge Protérozoïque à actuel a été décollée de son socle Panafricain sur une puissante série évaporitique et déformée en une série de grand plis de décollement. Au cours du plissement, les niveaux ductiles de sel ont migré au cœur des anticlinaux et des chevauchements se sont propagés dans les flancs avant des plis. (2) Dans le nord du ZFTB, des plis de cintrage sur rampe ont permis le transfert de raccourcissement dans les niveaux plus superficiels et produit des imbrications et des structures en duplex. (3) Des chevauchements hors-séquence, propagés à partir d'accidents de socle, ont recoupé tardivement les structures de couverture du ZFTB. La restauration en trois étapes de la coupe montre que le ZFTB a évolué en deux phases majeures de déformation : une phase d'âge Mio-Pliocène de tectonique de couverture, au cours de laquelle la plupart des structures dans la couverture se sont formées, suivie par une tectonique de socle du Pliocène à l'actuel. Celle-ci se traduit par les chevauchements hors-séquence dans la couverture et est soulignée à présent par l'intense activité sismique dans le socle. Vues en carte, les structures initiales du ZFTB se sont propagées avec une forme arquée contrôlée par la forme et l'épaisseur du bassin sous-jacent de sel Protérozoïque (i.e. le style du Jura). Au cours de la phase suivante de tectonique de socle, les chevauchements hors-séquence ont recoupé obliquement les structures préexistantes dans la couverture. Le raccourcissement calculé dans la couverture est d'au moins 45 km, soit un taux minimum de 22 %.

Mots clefs : *Zagros, ceinture de chevauchement-plissement, accident de socle, chevauchement hors-séquence, cinématique*

2 THE STRUCTURE AND KINEMATICS OF THE SOUTH-EASTERN ZAGROS FOLD-THRUST BELT, IRAN: FROM THIN-SKINNED TO THICK-SKINNED TECTONICS (PAPER N°2)

Paper submitted to *Tectonics* (February 2004)

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Abstract. We present the first complete balanced cross-section across the south-eastern 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 Panafrikan 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 south-eastern 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 pre-existing structures of the cover. The total shortening absorbed in the cover amounts to at least 45 km, corresponding to a ratio of ~22 %.

Keywords: *Zagros, fold-thrust belt, basement fault, detachment fold, out-of-sequence thrust, kinematic evolution*

2.1 Introduction

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] (Fig.1).

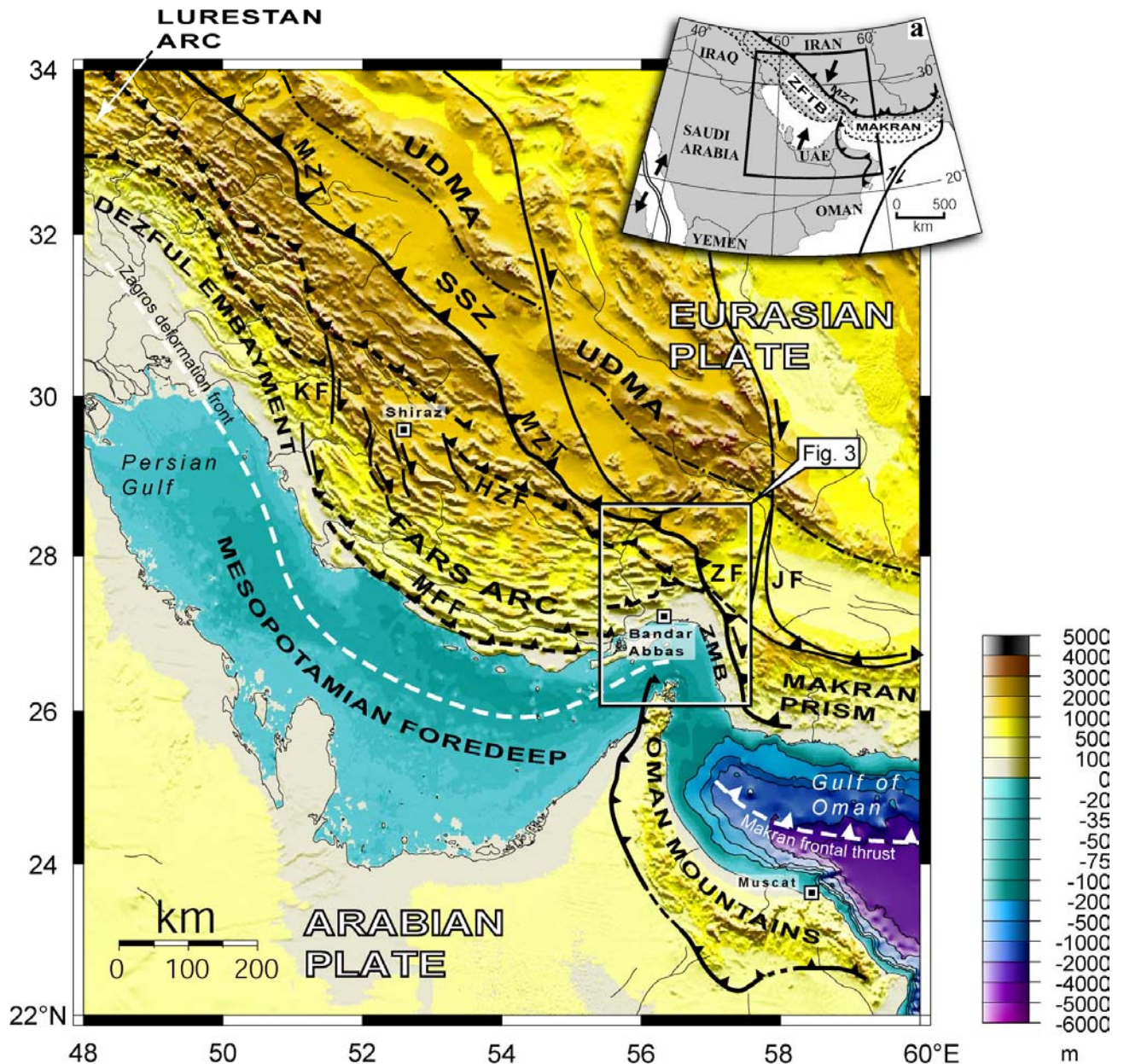


Fig. 1 Physical map (source: GEBCO data) and main structural features of the south-eastern active Zagros Fold-Thrust Belt (ZFTB). SSZ: Sanandaj Sirjan Zone, UDMA: Urumieh Dokhtar Magmatic Arc, MZT: Main Zagros Thrust, ZF: Zendan Fault, KF: Kazerun Fault, JF: Jiroft Fault, MFF: Mountain Front Fault, HZF: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

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.

In this paper, we discuss new data and interpretations based upon field and map observations from the south-eastern 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 centrepiece 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 south-eastern 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 followed and partly overprinted by a thick-skinned phase of deformation.

2.2 *Methods and geological setting*

2.2.1 Location and methods

The study area is located in the south-eastern part of the orogen, close to the transition to the Makran subduction prism (Fig.1). In this region, the tectonic structures of the ZFTB describe a large festoon-shaped arc known as the Fars arc. Further 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.

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 (Fig.3). Existing 1:100000 and 1:250000 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, Faraghun and Kuh-e-Khush) and in the area around the junction between the Main Zagros Fault (MZF) and Zendan 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 MZF (Fig.4). 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 south-eastern segment of the ZFTB.

2.2.2 Geodynamic context

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] (Fig.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 towards 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/y) of Arabia relative to Iran [Vernant *et al.*, 2003]. GPS data also suggests that about half of the convergence is taken up by Zagros. The direction of shortening is roughly N-S, with orientations ranging between N7° E (in south-eastern Zagros) and N 3° 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 $6,5 \pm 2$ mm/yr and $4,5 \pm 2$ mm/yr in central and northern Zagros respectively.

2.2.3 Mechanical stratigraphy of the Zagros Fold Thrust Belt in the Bandar Abbas area

The stratigraphic pile of the Arabian margin was first subdivided by *O'Brien*, [1950] into a number of tectono-stratigraphic units defined by contrasting mechanical behaviours. In this paper we adopt the principle of this scheme (Fig.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*, [1950]. 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.

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]. Due to 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 nineteen-seventies [Morris, 1977] and by other sources [*S. Sherkati*, pers. comm.].

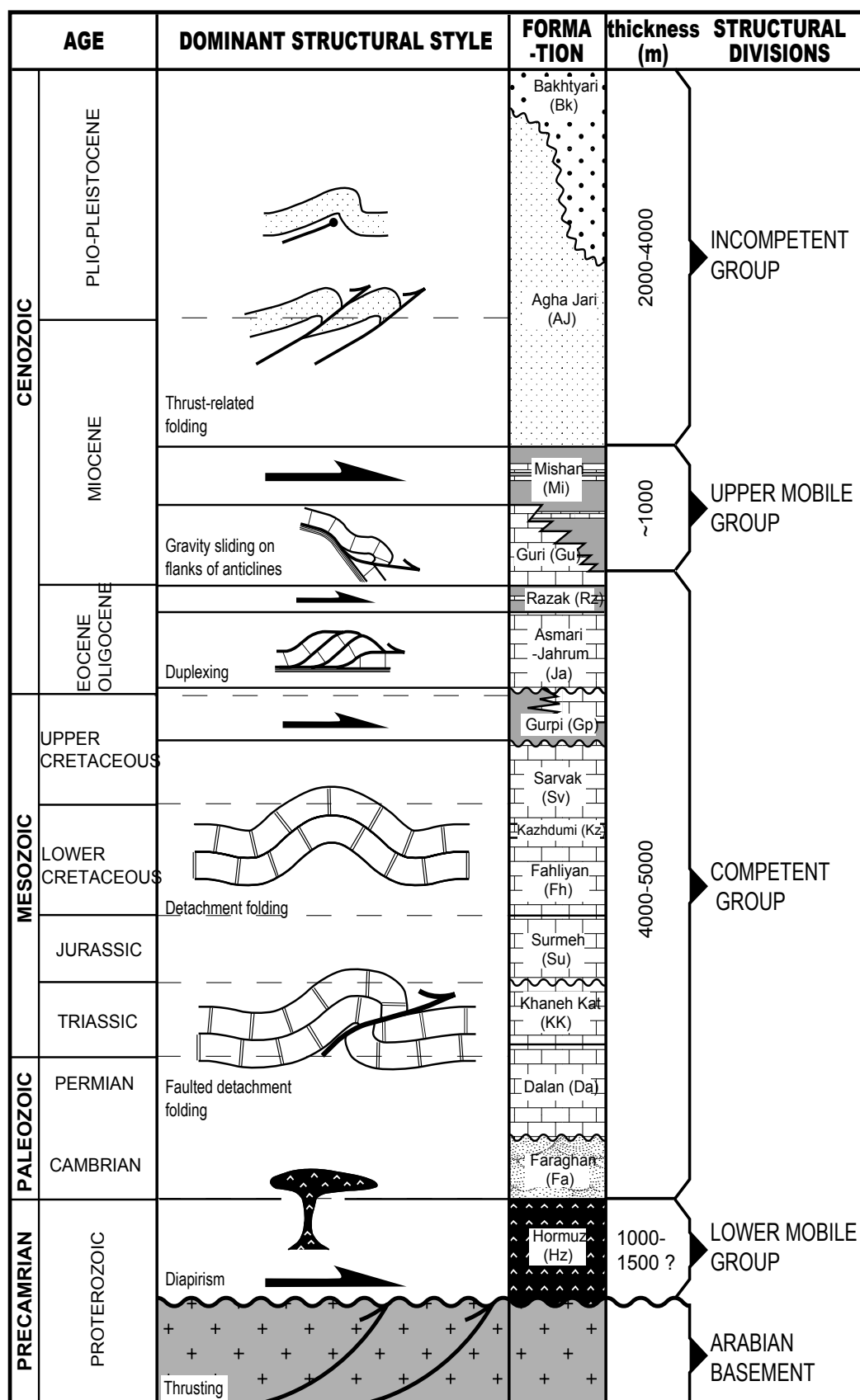


Fig. 2 Mechanical stratigraphy of the south-eastern ZFTB illustrating the dominant structural styles and detachment horizons as observed on the field for the various lithostratigraphic units. Structural divisions are slightly modified after O'Brien's [1950] classification. Stratigraphy and thickness of units based on a compilation of authors' fieldwork and data from James and Wynd [1965], Szabo and Kheradpir [1978] and Sharland et al. [2001].

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 towards 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].

A 4000-5000 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 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 recognisable layer of Guri reefal limestone, marking the base of the Mishan marls. Its thickness is extremely variable, ranging from several hundred meters of reefal build-up 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 responsible for frequently observed collapse structures within the overlying Guri limestone.

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 upwards through the main detachment folds tend to dissipate displacement within this upper incompetent horizon.

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-upwards evolution from marine-to-continental clastics (Agha Jari Fm) to coarse proximal conglomerates (Bakhtyari Fm) 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 meters. Structures observed within these formations include small-scale thrusting and thrust-related folds soling out into the Mishan marls.

2.2.4 General structure of the Zagros Fold Thrust Belt

The Zagros Fold-Thrust Belt (ZFTB) (Fig.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 (Figs. 1 & 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 (Fig.1).

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 centre of the Fars Arc) as well as its narrow cross-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.

The ZFTB is characterised 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 & 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 & 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 recognised 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 km (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 north-western Zagros, in the area of the Dezful Embayment (Fig.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 further to the southwest [Berberian, 1995].

2.2.5 Structure of the Bandar Abbas syntaxis

The Bandar Abbas syntaxis (Fig. 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 (Fig. 3a). 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].

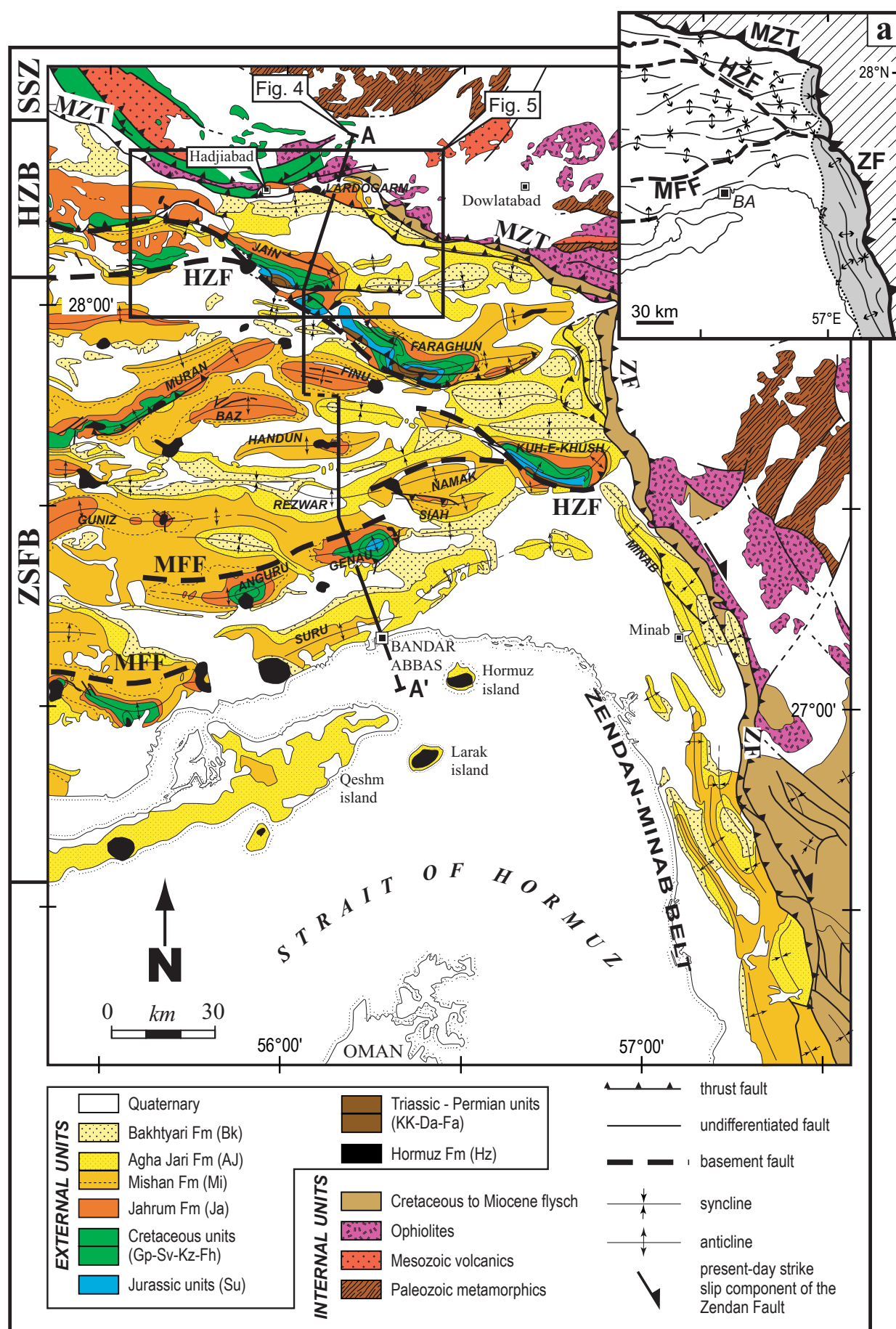


Fig. 3 Geological map of the ZFTB in the Bandar Abbas area compiled from geological maps [NIOC, 1977a; NIOC, 1977b; NIOC, 1999] and authors' fieldwork [Molinaro *et al.*, 2004]. **ZSFB**: Zagros Simple Fold Belt, **HZB**: High Zagros Belt. Other abbreviations as in Figure 1. The names on the map refer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

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 & 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 & 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) (Fig.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 towards 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 (Figs. 3 & 3a).

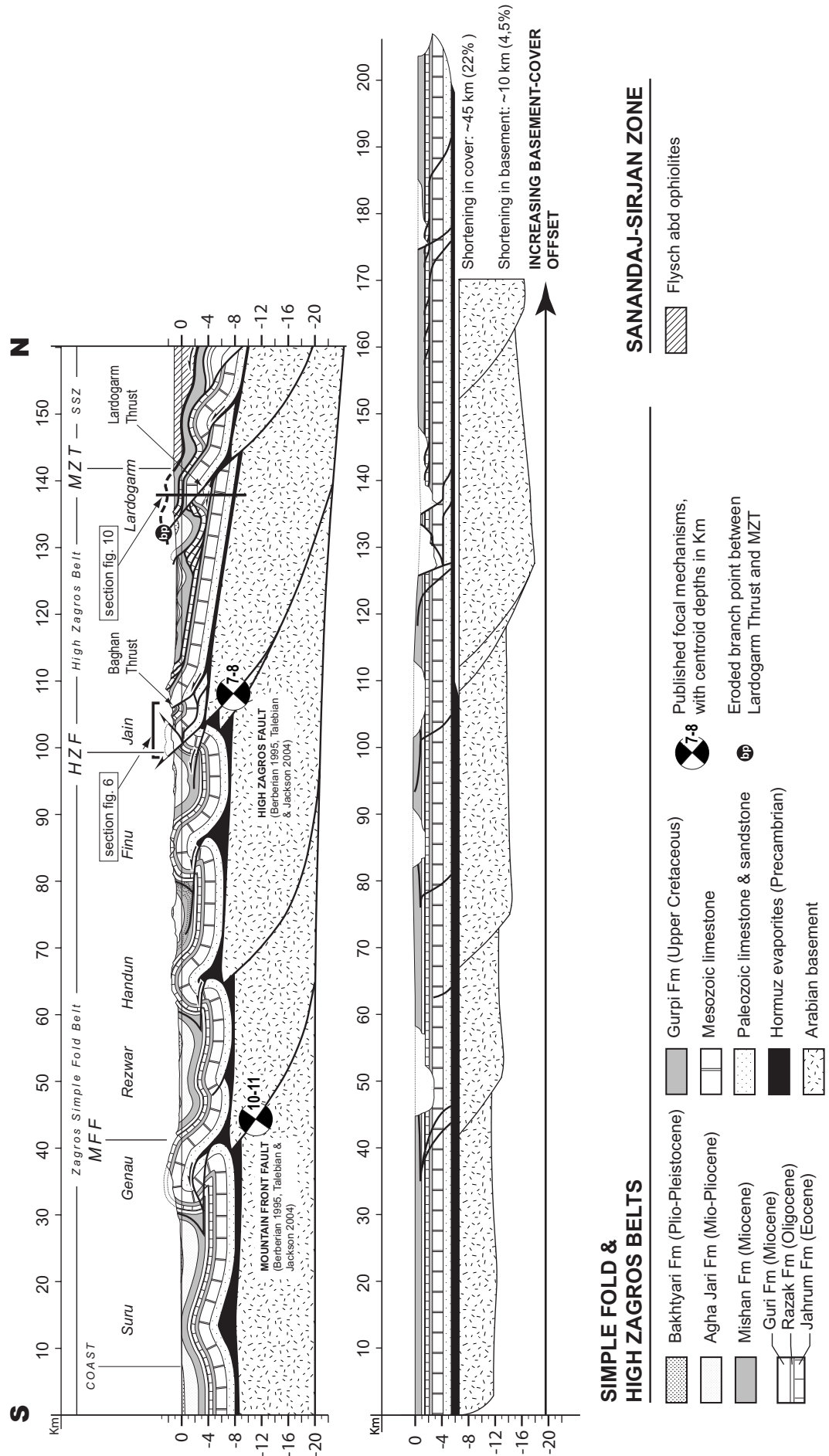
- The area south of the HZF and extending to the coastline is characterised by large regular anticlines, most often capped by the competent limestone rocks of the Jahrum and Guri formations, separated by wide synclines cored by Mio-Pliocene clastics of the Agha Jari and Bakhtyari formations. The wavelength 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 centre 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 towards a more E-W direction (Fig. 3a).
- The triangular-shaped area comprised between the HZF and MZT-ZF fault line (Fig. 3) is characterised by numerous topography-forming synclines cored by Agha Jari and Bakhtyari clastics separated by large flat plains of Quaternary deposits. Towards the west, in the

region of Hadjiabad, these synclines are replaced by close-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 N-trending faults and folds can be seen.

2.3 Regional structural cross-section

We have constructed a regional balanced cross-section extending from the Persian Gulf to the interior parts of the orogen (Fig.4). No seismic or well data were available to constrain our interpretations at depth. In order to cross-cut 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 (Fig.3). Because of the very slight obliquity (max 10°) between the plate convergence vector and the local trends of tectonic structures, we consider out-of-section transport to be negligible and the plane-strain assumption valid. The cross-section has been built using the classical 2D 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 minimisation 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 minimisation of shortening throughout the section. The section does not take into account any shortening that may derive from internal deformation or mesoscale 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.

Regional balanced and restored cross-section A-A' through the south-eastern 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 towards the hinterland and therefore a total decoupling between the two. Abbreviations as in Figure 1. Earthquake focal mechanisms from Berberian [1995] and Talebian and Jackson [2004]. Line of cross-section in Figure 3.



Since most of the Meso-Palaeozoic 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.

As discussed earlier on, 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 (Fig.3). The depths of the hypocentres considered in our section (10-11 km for the MFF, 7-8 km for the HZF, Fig. 4) are those reported by Talebian & Jackson, [2004], based upon seismic waveform modelling. An additional constraint held to localise 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 (Fig.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 sub-domains, the ZSFB to the south and the HZB to the north, separated by the HZF.

2.3.1 ZSFB sub-domain: faulted detachment folds

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 backlimbs. 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 (Fig. 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 backlimbs 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.

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 towards 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., submitted].

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; Mitra, 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 towards 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 and favours the progressive propagation of a fault through the forelimb.

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.

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 Rezwar fold – located at the centre 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.

2.3.2 HZB sub-domain: structure of the HZF and ramp-flat structures

The geological map (Fig.3) reveals a strong change in the style of deformation within the cover north of the HZF (the HZB sub-domain) from the ZSFB to the south.

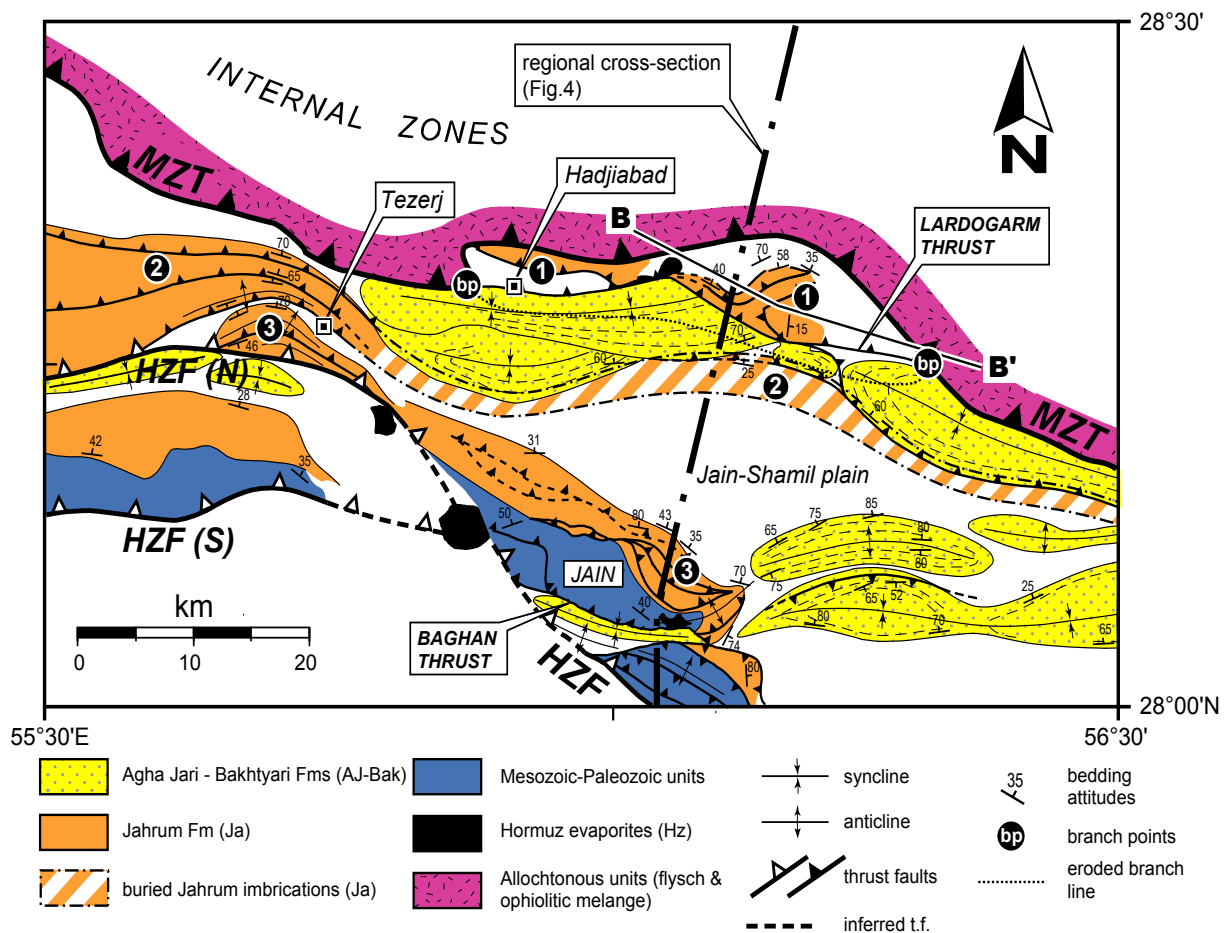


Fig. 5 Structural map of the High Zagros Fault and High Zagros Belt in the region of Hadjiabad. Derived from geological maps [NIOC, 1977a; GSI, 1994; GSI, 2002], SPOT satellite image and authors' fieldwork. Labels 1 to 3 denote structurally distinct duplexes. Duplex 2 is inferred to continue beneath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

On a detailed structural map of this area (Fig.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 (Figs. 3 & 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*, work in progress).

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 (Fig.6) illustrates the geometrical relationships and the tectonic style of the structures in the surroundings of the HZF and Jain area.

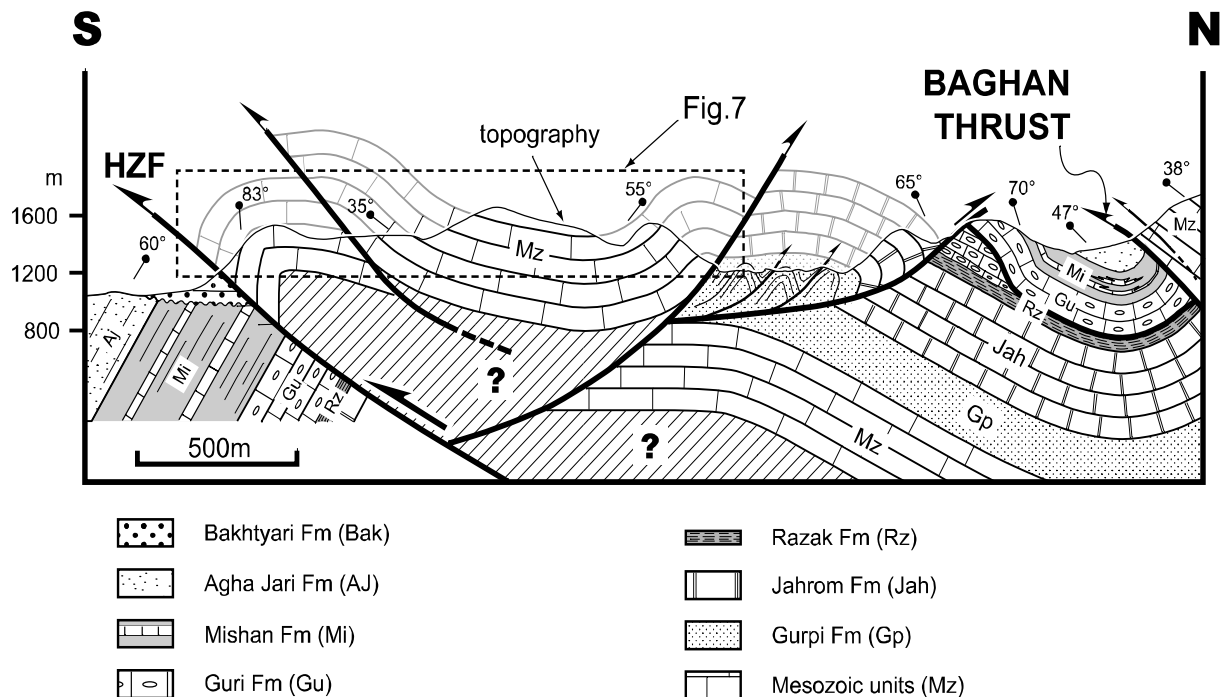


Fig. 6 Simplified field section through the HZF and associated structures in the area of the Jain antiform (Fig.3). Line of cross-section in Figure 4.

In the north, an important southverging 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 backthrust. These two faults thus delimit a “pop-up” structure composed of strongly folded and deformed rocks ranging in age from Cretaceous to Jurassic age (Fig.7).

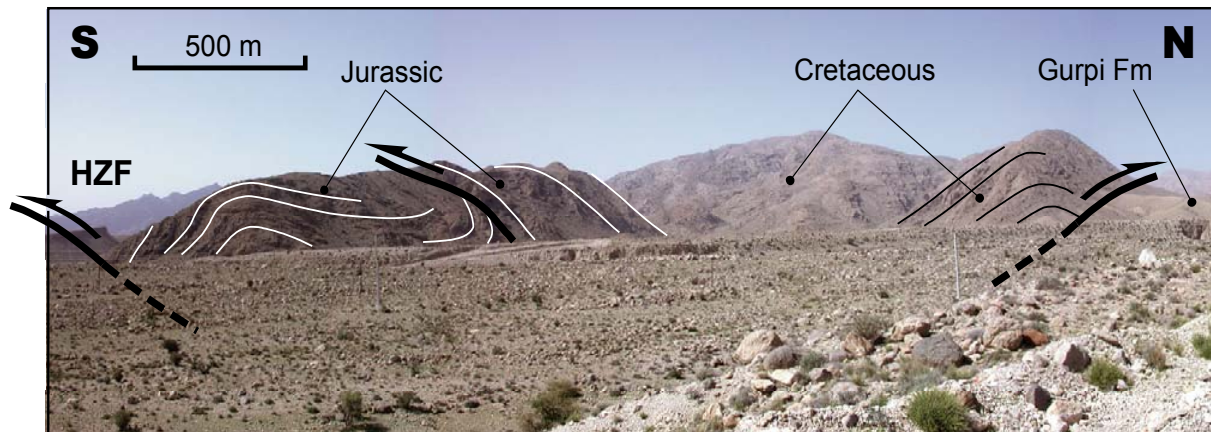


Fig. 7 View of the HZF and associated “pop-up” structure composed of highly deformed Jurassic to Cretaceous rocks. The photograph has been inverted to aid comparison with the section in Figure 6. The scale is relative to background. Location in Figure 6.

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 (Fig.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 Ma.

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) (Fig.5). In the area around the town of Hadjiabad and the village of Tezerj numerous close-spaced imbricate structures involving limestone of Eocene age (Jahrum Fm) are recognisable. These structures are inferred to continue towards the east beneath the Jain-Shamil plain (Fig.5). We have identified at least three structurally

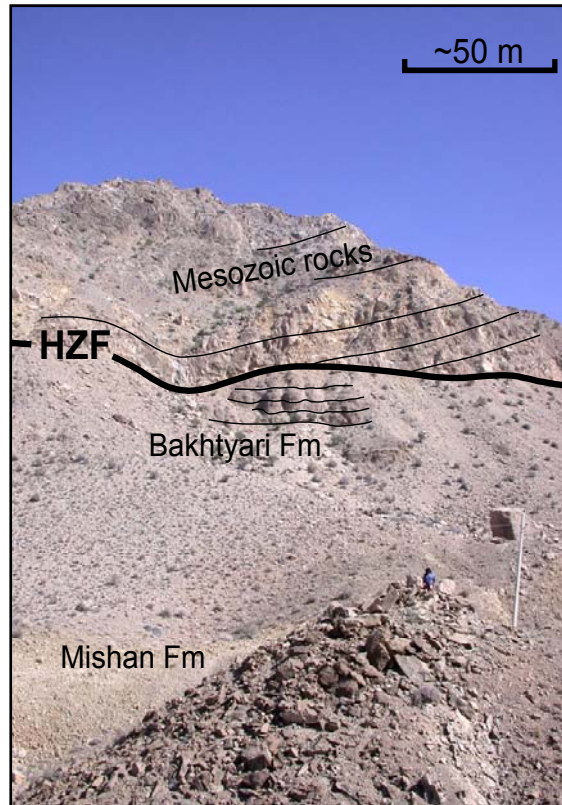


Fig. 8 Frontal view of the emergent HZF, looking towards the north. Rocks of Jurassic to Cretaceous age are carried towards the south over horizontal Plio-Pleistocene Bakhtyari conglomerates resting unconformably over south-dipping Mishan beds. This geometry gives evidence for two distinct tectonic phases. An initial pre-Bakhtyari folding phase tilted the Mishan beds. Erosion and deposit of the Bakhtyari marks 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.

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 (Fig. 9). The imbricate thrusts converge into the underlying Gurpi marls, thus proving that imbrication of Jahrum 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 transferring displacement from a lower flat probably situated within the Hormuz series (Fig.4). These deeper structures can be inferred in the area of Lardogarm (Fig.4) underneath the allochthonous units, the Mishan marls serving as a decoupling horizon between the two. In this framework the Lardogarm thrust (Figs. 4 & 5), carrying Jahrum limestone over Bakhtyari and Agha Jari clastics, is interpreted as an out-of-sequence structure – linked to a basement fault – cross-cutting an ENE-trending anticline and syncline.

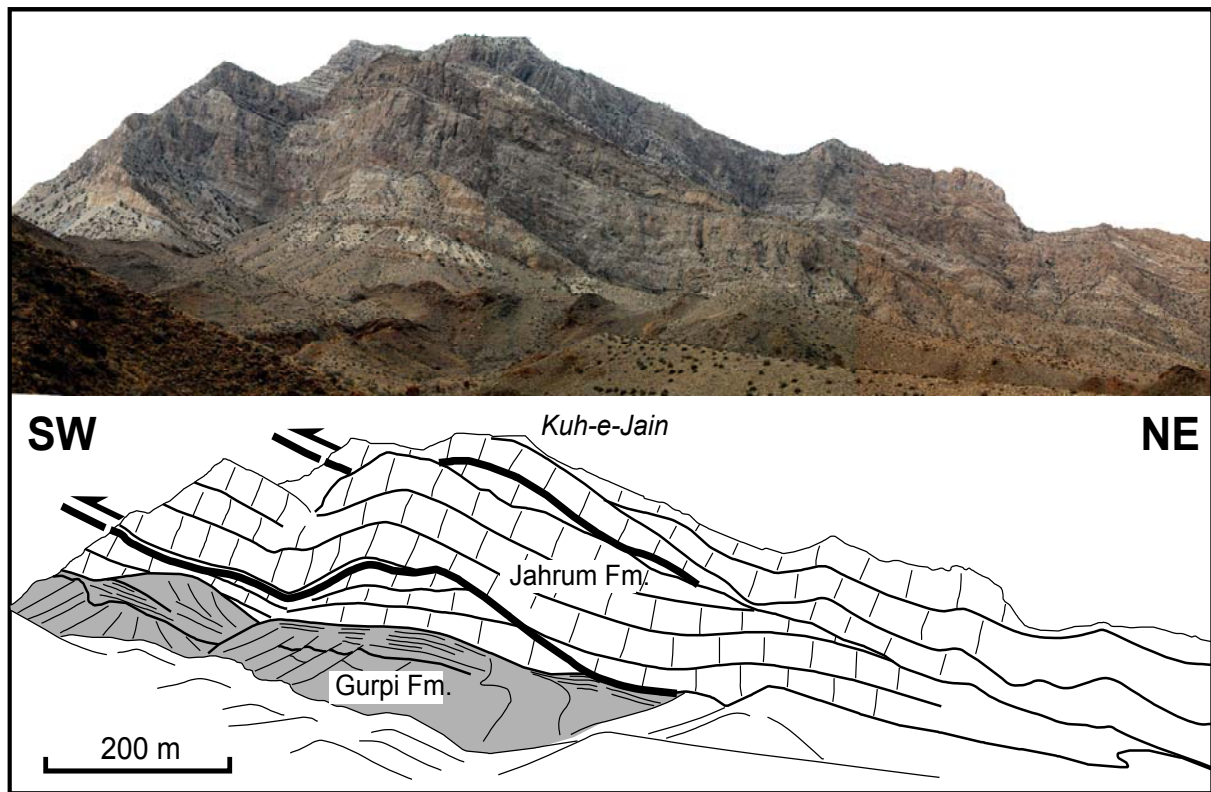


Fig. 9 Photograph and line drawing of imbrications of Eocene Jahrum limestone in the northern flank of the Jain antiform (see Figures 4 & 5 for location). The thrust planes are seen converging into the Upper Cretaceous Gurpi marls, thus proving the role of the Gurpi horizon as a decollement level.

The presence of the basement fault is confirmed by some seismic events – one of which located at 10 km depth – reported by *Talebian & Jackson*, [2004] from this area.

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 towards 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 Fm) or younger formations. This suggests that the present-day position of the allochthonous nappes is the result of repeated out-of-sequence reactivation.

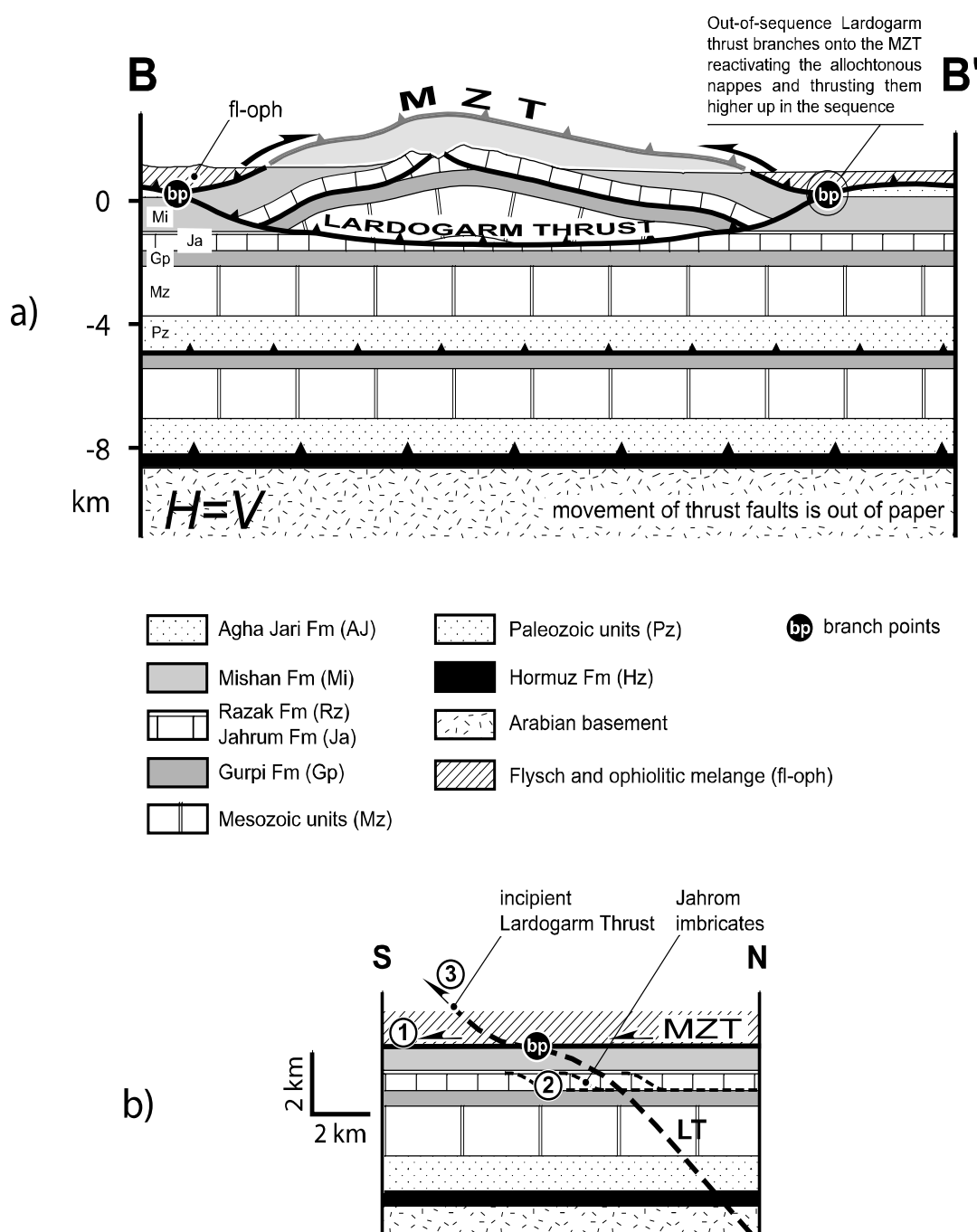


Fig. 10 a) Hanging-wall section (i.e. perpendicular to the transport direction), through the Lardogarm Thrust and MZT. The branch points shown in this figure and in Figs. 4 & 5 visualise the 3-dimensional geometry of the contact between the MZT and the Lardogarm Thrust. Location of section in Figs. 4 & 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.

The geometry of these contacts is illustrated with a hanging wall diagram (Fig.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 (Fig. 10b). The intersection between the MZT and the Lardogarm Thrust defines a leading branch line [e.g. *Boyer & Elliott*, 1982] represented in figures 4, 5, 10a and 10b by its corresponding branch points, which allows us to visualise the 3-dimensional geometry of this contact.

2.4 Discussion: shortening estimates and kinematics

2.4.1 Estimates of shortening

We have restored (Fig.4) the regional cross-section to its original pre-deformational 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 meso and micro-scale deformation. Also the reader should bear in mind that the hanging-wall cut-offs 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.

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 sub-surface 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.

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 a discrepancy (35 km) necessarily implies a complete decoupling between the sedimentary cover and the basement (Fig.4). The basement shortening lacking in our section must therefore occur somewhere further into the hinterland, probably in the form of thrust faults exhuming deep basement rocks. The 28 km-deep events reported by *Talebian & 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 5-10 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 contradicts the standard view on fold-thrust belts that shortening is first transmitted into the foreland within the sedimentary cover and is later recovered by younger thrusts within the basement.

2.4.2 Kinematics of the cross-section

Previous work done on Zagros rarely focused on the timing and kinematics of the orogenic processes. Lack of published seismic data visualising the detailed geometries of growth strata, as well as uncertainty on the ages of the syntectonic formations, make 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; *Sherkati 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.

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 (Fig.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.

The oldest part of the mountain belt, in a typical piggy-back sequence, is supposed to correspond to the structures situated north of the HZF. This is shown in step 1 (Fig. 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 (Fig. 6). *Sherkati and Letouzey* [2004], based upon tectono-stratigraphic 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 Fig.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., 2003]). It is therefore probable that the first structures in the HZB were initiated later, possibly in middle-late Miocene times in connection with the first appearance of the detritic sediments of the Agha Jari formation.

In step 2 (Fig. 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 *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

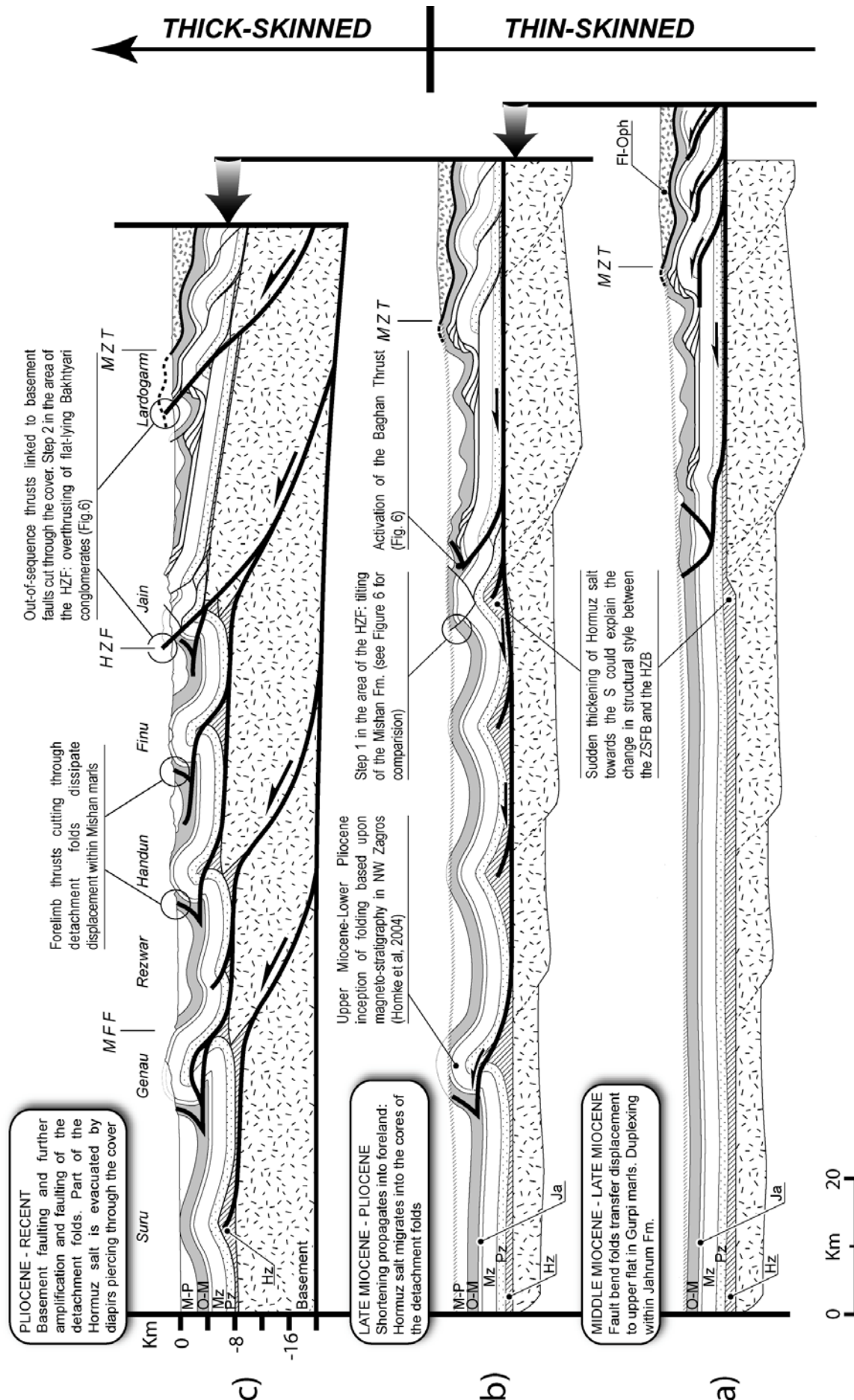


Fig. 11 Incremental three-step restoration of the cross-section through the south-eastern ZFTB (Fig.4). Hatched line (a & b) represents the approximate position of the mean topographical surface. **M-P**: Mio-Pliocene clastics (Agha Jari Fm and Bakhtyari Fm). **O-M**: Oligocene-Lower Miocene limestone and marls (Razak Fm, Guri Fm and Mishan Fm). **Ja**: Jahrum limestone. **Mz**: Mesozoic units. **Pz**: Paleozoic units. **Hz**: Hormuz evaporites. **Fl-Oph**: allochthonous "fluvial" and ophiolites. Other abbreviations as in Figure 1

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 (Fig.6). At the same time, activation of the Baghan Thrust (Fig.6) uplifts the duplex structure that is presently observed on the back of the Jain structure (Fig. 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 magneto-stratigraphic section through the Agha Jari molasse deposits in the north-west 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, towards 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.

Finally in step 3 (Fig. 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 pre-existing structures. Clear examples of out-of-sequence thrusting are given by the HZF and Lardogarm thrusts.

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 (Fig. 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 (Fig. 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 – based uniquely on 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 prefer to 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 (Fig.12).

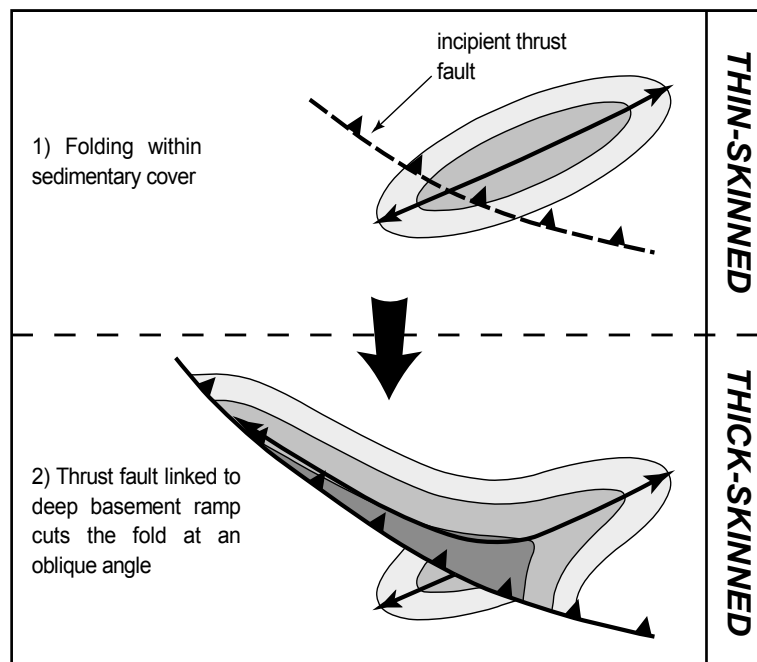


Fig. 12 Schematic model for the development of structures associated to the HZF in the Bandar Abbas area, illustrating the successive thin-skinned and thick-skinned tectonic styles. Compare with the Jain, Faraghun and Kuh-e-Khush structures in Figure 3.

The most clear example out of the three structures associated to the HZF is given by the Kuh-e-Khush antiform, north-east of the town of Bandar Abbas, where the remains of an ENE-trending anticline are recognisable both in the hanging wall and the footwall of the HZF.

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 (Fig. 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 (fig.4).

To summarise, 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 (Fig. 11a &

b). 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 (fig.11c).

2.4.3 Tentative reconstruction of the kinematic evolution of the south-eastern Zagros Fold-Thrust Belt

We complete our discussion on the tectonics in the Bandar Abbas area by proposing a tentative sketch of the kinematic evolution of the south-eastern 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.

In the first stage (Fig. 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.

In the second stage (late Miocene-Pliocene) (Figs. 11b & 13b) the deformation front propagated towards the south-west 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 (Fig. 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 non-coaxial directions of shortening related to changing kinematics of the Arabia-Eurasia convergence.

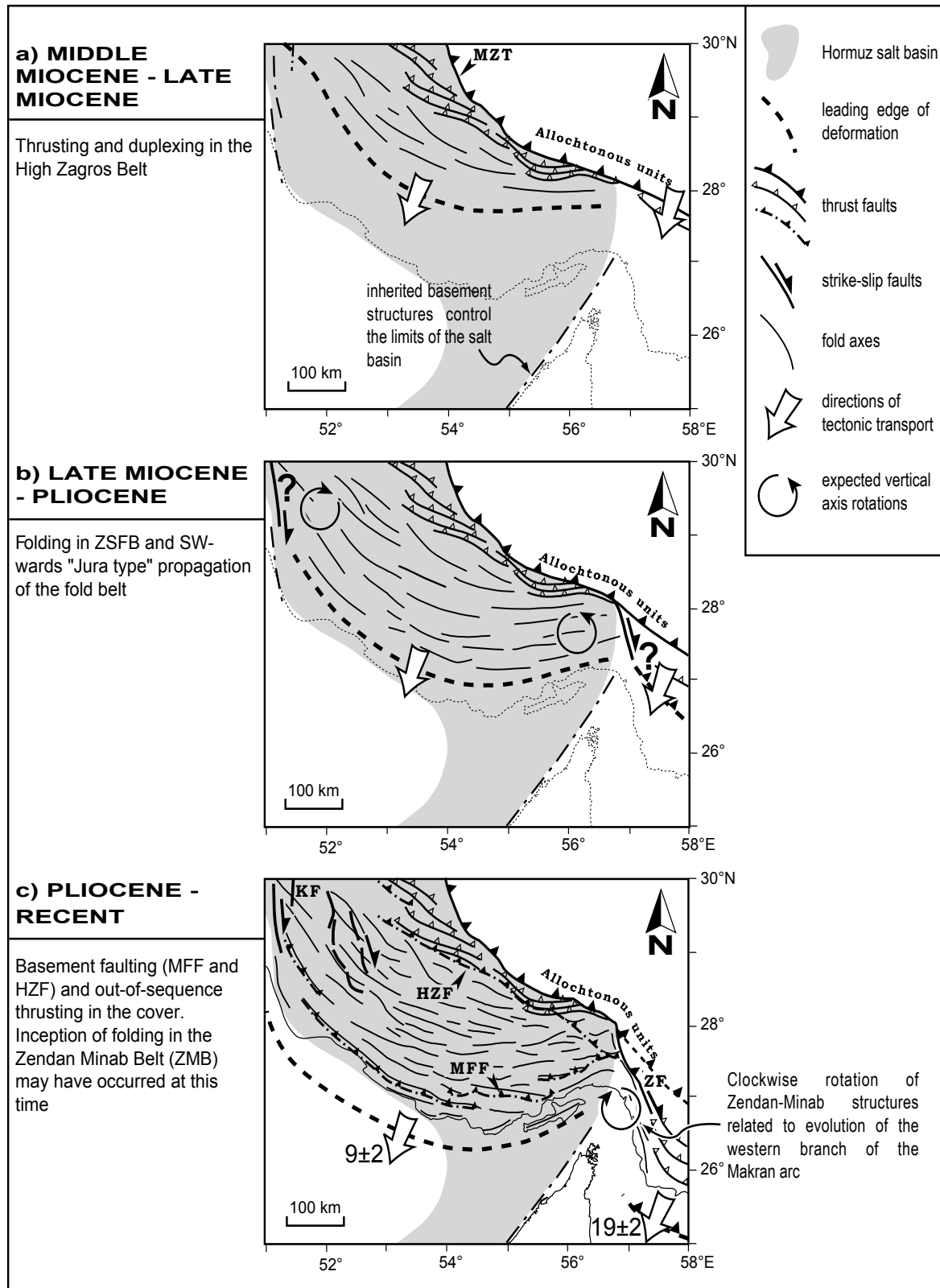


Fig. 13 Evolutionary model for the Fars Arc and Bandar Abbas syntaxis in south-eastern Zagros from middle Miocene to Recent times. Grey shading indicates the shape and extent of the underlying Hormuz salt basin, according to Kent [1979] and Sharland *et al.* [2001]. In (b), the geometry and thickness 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 palaeomagnetic data [Aubourg *et al.*, 2003] across the Fars Arc. GPS shortening rates ($\text{mm}\cdot\text{yr}^{-1}$) in Zagros and Makran (c) after Vernant *et al.* [2004] Abbreviations as in Figure 1.

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 (Fig.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 towards the east in the area of Bandar Abbas and towards the west in connection with the Kazerun Fault (Fig.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 (Fig. 13a) [Edgell, 1996; Sharland *et al.*, 2001]. As shown by analogue modelling [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 respectively in the western and eastern branches of the Fars arc (Fig. 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.*, in press] 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°.

Finally, in stage 3 (Figs. 11c & 13c) the structures of the ZFTB were cross-cut 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 Zendan-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 (Fig.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 Zendan Fault further north (Fig.3). These latter structures as well as those in the ZMB are likely to have resulted from interference with the south-westward propagation of the western branch of the Makran arc. Recent paleomagnetic data from the area of Minab [Smith *et al.*, 2003] (Fig.3) highlight clockwise vertical axis rotations of $\sim 20^\circ$ 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 Zendan Fault.

2.5 Conclusion

Two main stages of deformation are recognised within the south-eastern Zagros Fold Thrust Belt. In the first stage the deformation was thin-skinned in style. In the High Zagros Belt 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 Zagros Simple Fold Belt, 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 towards 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.

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 pre-existing folds and these new thrusts led to the

development of structures with characteristic map patterns (Fig.12), recognisable in the study area (Fig. 3).

The total decoupling between the cover and basement is highlighted by the difference in the calculated shortening ratios (Fig.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 towards the foreland. In other words, the late-stage involvement of the basement in foreland Zagros could be viewed as a step towards the re-establishment of the critical taper [in the sense of *Davis et al.*, 1983] throughout the entire mountain belt. The sudden and widespread occurrence of the Bakhtyari conglomerates in Plio-Pleistocene times could be interpreted as the sedimentary signature marking the onset of basement involvement throughout the ZFTB.

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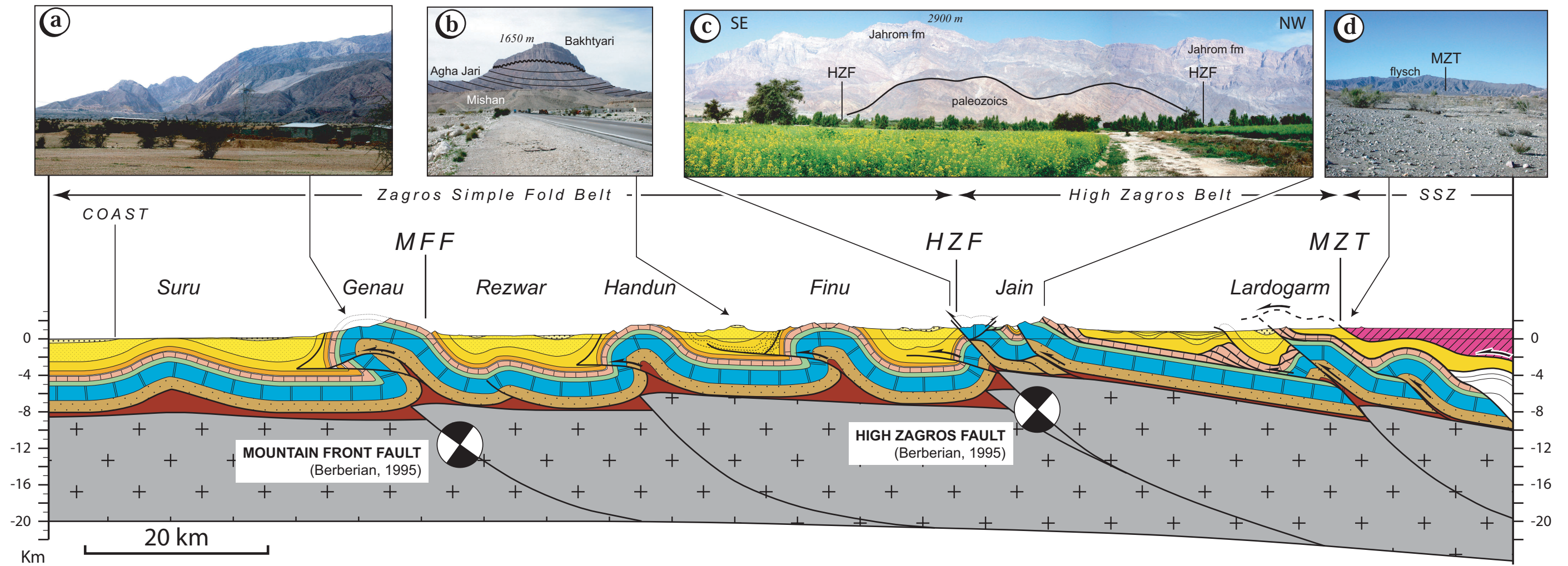
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S

N

**ZFTB**

- Bakhtyari Fm (Plio-Pleistocene)
- Agha Jari Fm (Mio-Pliocene)
- Mishan Fm (Miocene)
- Guri Fm (Miocene)
- Razak Fm (Oligocene)
- Jahrum Fm (Eocene)
- Gurpi Fm (Upper Cretaceous)
- Mesozoic limestone
- Paleozoic limestone & sandstone
- Hormuz evaporites (Precambrian)
- Arabian basement

SANANDAJ-SIRJAN ZONE

- Flysch and ophiolites

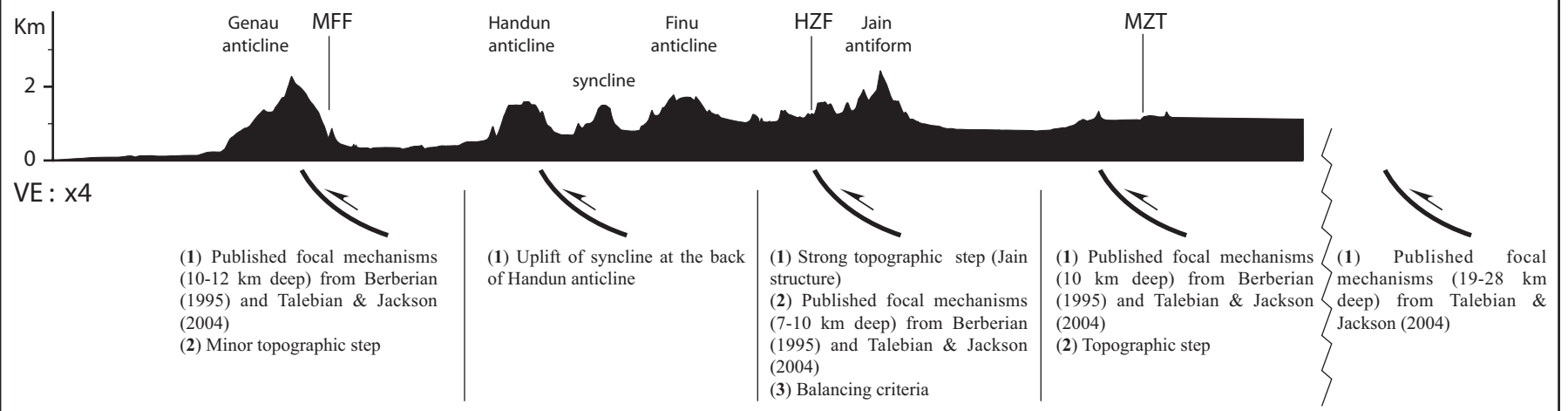
EVIDENCE FOR BASEMENT FAULTING

Fig. III-1 Regional transect through the eastern ZFTB in the Bandar Abbas area (location in Fig. 3 paper n.2)

3 FURTHER COMMENTS AND ILLUSTRATIONS OF THE GEOMETRY AND KINEMATICS OF THE EASTERN ZFTB

3.1 *Some details and comments on the balanced cross-section through the ZFTB*

3.1.1 The Jain and surrounding structures

Culminating at 2800 m and exposing Paleozoic rocks at its base (Fig. III—1c), this is undoubtedly the largest and one of the most complicated structural regions traversed by the cross-section presented in paper n°2, partly because of its inaccessibility and partly because of the complexity of its surface geology (Fig. III—2). It is an important element in our discussion since it forms part of three giant structures (Jain, Faraghun and Kuh-e-Khush) aligned on the HZF which proved particularly instructive for illustrating the interference between thin-skinned and thick-skinned tectonics in eastern Zagros. In the case of the Jain structure, the superposition of structural trends, though less evident than for the other two structures, can still be seen between the Jain monocline and the adjacent Bakhtyari-cored synclines. These synclines are topography forming structures (Fig. III—3) which can be observed to the east and south of the Jain structure (Figs. 3 & 6 in paper n°2).

The structures in the Jain area can be separated in three classes according to their size:

- The first order structure is the Jain monocline developed over the HZF basement fault (Fig. III—2). In this class can be included the anticline and pop-up structure south of the monocline which are also linked to displacement along the HZF. These two main structures appear to relay each other, the lateral termination of the Jain monocline coinciding with the development of the thrust-anticline at its front, once again highlighting the extremely discontinuous and segmented geometry of the structures in this area. This peculiarity of structures in easternmost Zagros had been already discussed in paper n° 1 on the basis of aspect ratio measurements throughout the Fars Arc.
- Second order structures include imbrications disrupting the regularity of the Jain monocline, notably imbrications within the Jahrom Fm and some repetition visible within the deeper Paleozoic-Mesozoic section. These structures are also visible on the balanced cross-section (Fig. III—1).

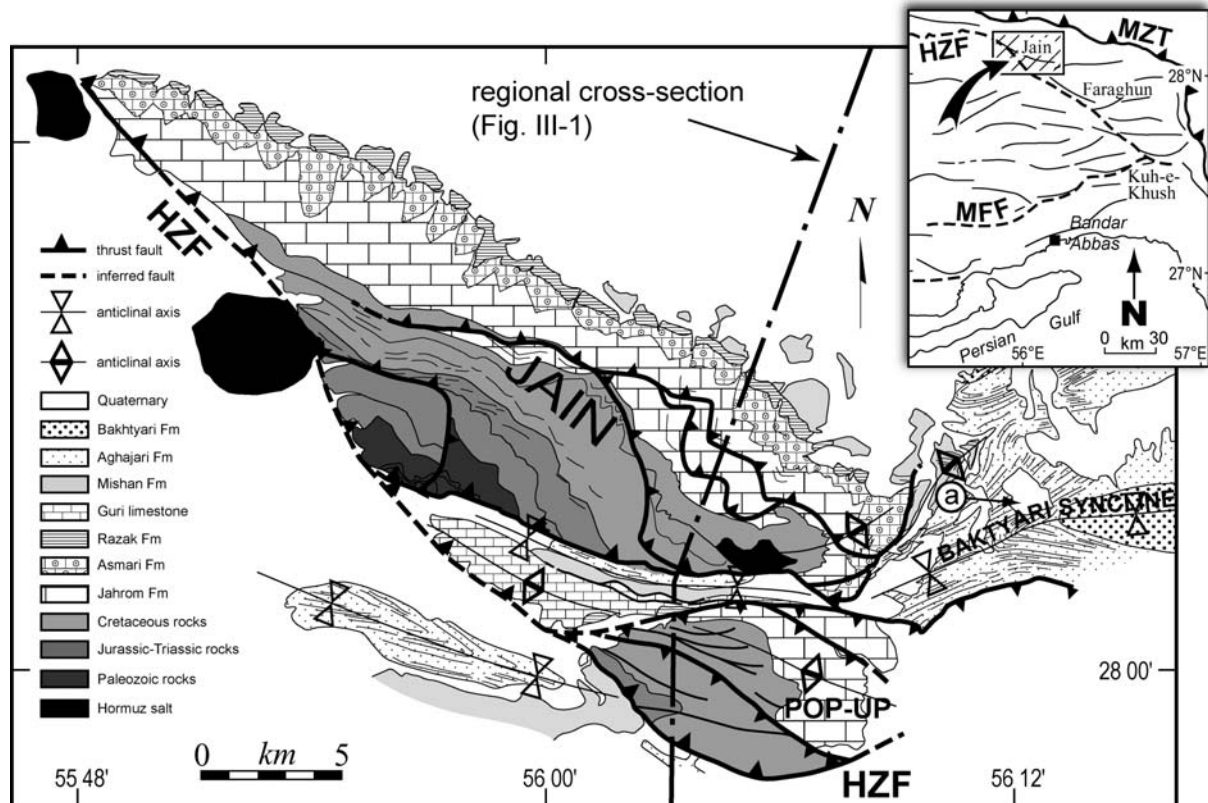


Fig. III—2 Geological map of the Jain monocline and surrounding structures directly north of Bandar Abbas (inset). Derived from geological map (GSI 2002), SPOT satellite image and author's fieldwork. Label a denotes viewpoint of photograph in Fig. III—3.

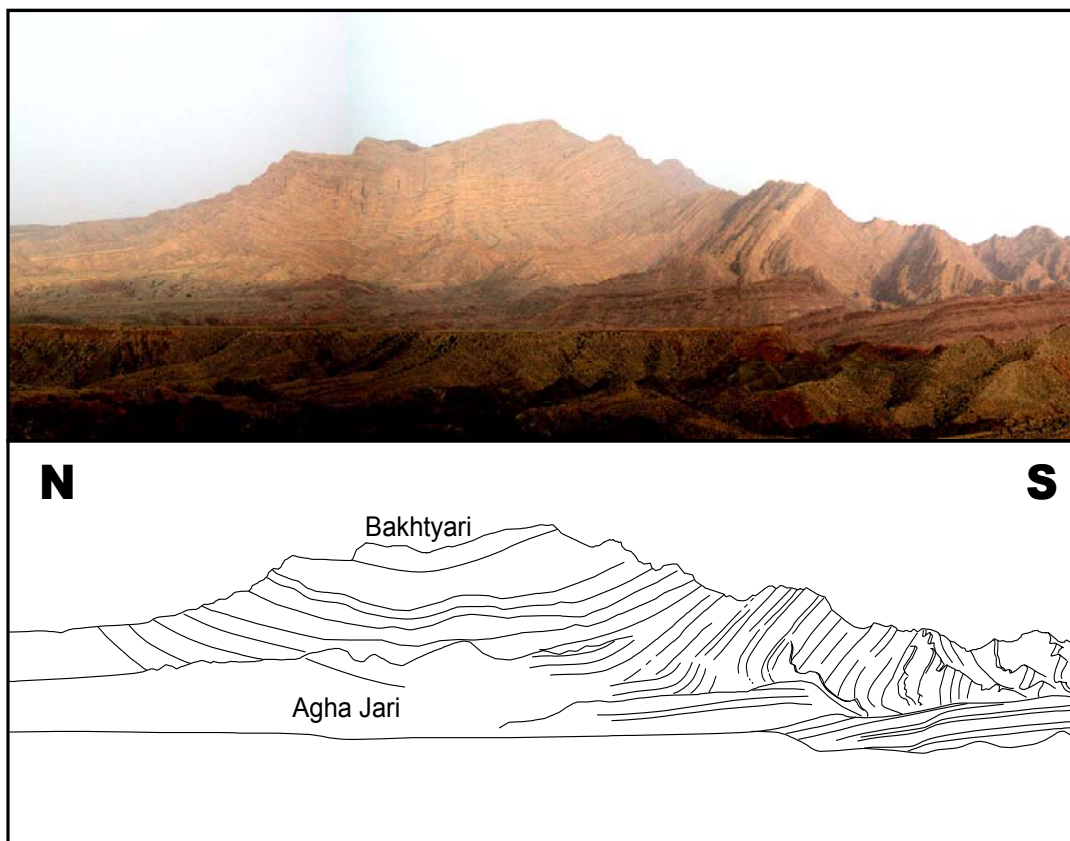


Fig. III—3 Photograph of a Bakhtyari-cored syncline east of the Jain structure. Viewpoint in Fig. III—2

- Finally, a third class of structures is represented by small-scale intra-formational deformation which could not be detailed on the cross-section. These include thrusts and folds visible within the Upper Cretaceous rocks of the pop-up zone, and small imbrications within the Guri limestone in front of the Jain monocline.

3.1.2 Evidence for basement faulting

In order to define the basement structures in the cross-section (Fig. III—1e), I considered several factors among which are published focal mechanisms and the general trends of the topography. Special attention was given to the elevation of the synclines and to steps in topography: simple folding over a horizontal decollement will not modify the elevation of a syncline. So an uplifted syncline can be explained in two ways: (1) repetitions by thrusting within the sedimentary cover and (2) basement faulting. Since it has already been shown (chapter II, paragraph 2.5.1) that the basement is involved in certain folds, I have considered that this is the main process controlling the uplift of the synclines and the generation of topographic steps in the area of our study. Moreover, several authors (Berberian 1995, Talebian & Jackson 2004) have already interpreted the strong seismicity of the study area as proof for basement involvement, in particular the HZF and MFF faults. Some deeper (18-28 km) seismic events recorded north of the MZT (Fig. I—11b) have also been interpreted as evidence for underthrusting of the Arabian basement in this area. Field images of the topographic features along the transect are particularly instructive, as in the comparison between the topography associated to the active HZF (Fig. III—1c) and that associated to the MZT (Fig. III—1d) a few kilometres north. As we already mentioned, the latter's negligible topography is strongly suggestive of an inactive and passively transported contact as depicted in the cross-section.

3.1.3 Growth strata

Growth strata have been reported by several authors in Zagros (Hessami et al. 2001b, Sherkati & Letouzey 2004, Homke et al. 2004, in press) based upon both subsurface data and field observations. They are mainly observed within the Miocene to Pleistocene clastics of the Agha Jari and Bakhtyari Fms preserved in the synclines and are of great importance in constraining the timing and the mechanisms of development of the fold-and-thrust structures (e.g. Ford et al. 1997, Suppe et al. 1997). In the absence of seismic data, the best way to

observe growth strata is from aerial views. Unfortunately these were not available in our study area, and due to the general shallowness of the erosion it is very difficult to observe them directly on the field. Only in one case have I been able to directly document growth strata (Fig. III—4), from a syncline directly south of the Faraghun structure (Fig. 3 in paper n°2). More often the transition between the Agha Jari and Bakhtyari Fms is expressed by a pronounced unconformity, frequently observed in the Bandar Abbas area (e.g. Fig. III—1b).

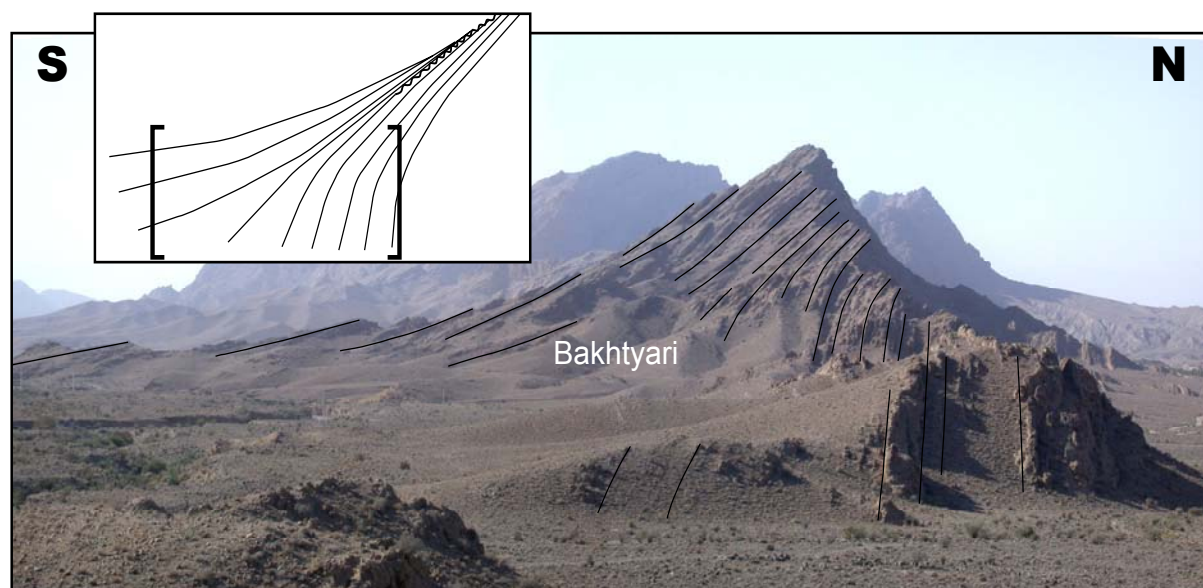


Fig. III—4 Growth strata within Agha Jari and Bakhtyari beds of a syncline in the Bandar Abbas region.

3.1.4 Style of deformation NE of the HZF: thrusting and folding within the molasse formations

The roughly triangular shaped area defined by the HZF and MZT-ZF faults (Fig. III—5), is curiously dominated by the presence of several large Bakhtyari-cored synclines. On the field these formations are seen deformed by diffuse small-scale folding and thrusting (Fig. III—6). The relatively small dimensions of these structures indicates that they detach at small depths, the Mishan marls probably serving as a decoupling horizon with the older underlying units. Structures of this kind are also observed in the northern part of the transect (Fig. III—1) and around the town of Ahmadi (Fig. III—5). It can be noticed that in this latter area the trends of the structures change to a NNW direction. This is related to the westward propagation into Zagros of the deformation associated to the so-called Zendan Fault and the lateral branch of the Makran system. The geometry of the Zendan Fault and the associated structures at its front clearly indicate the thrust component associated to this contact, as emphasised in paper

n°1. Whatever is the precise geometry and kinematics of the structures in this area, it is clear that they affect the molasse units independently and must be completely decoupled from the underlying units. The shortening they imply must therefore be recovered elsewhere within the older units by other structures not directly visible at surface.

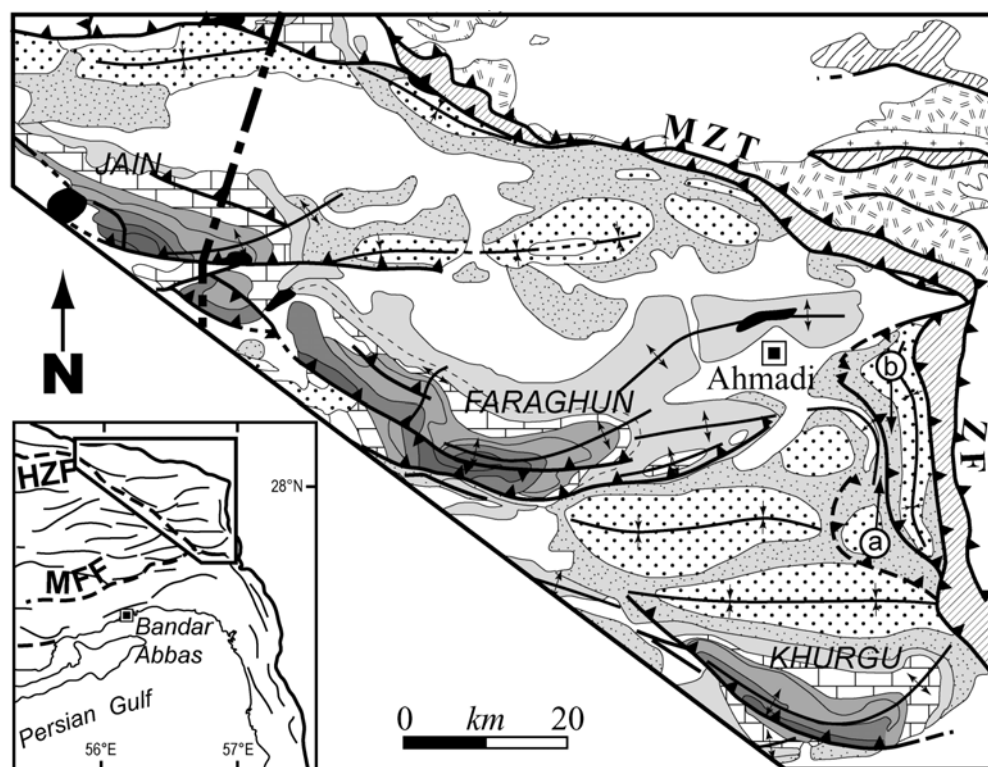


Fig. III—5 Geological map of the region comprised between the HZF, MZT and ZF faults. Map units and abbreviations as in Fig. 3 (paper n°2). Dash dot line : balanced cross-section in Fig. III—1. Labels a & b denote photographs in Fig. III—6.

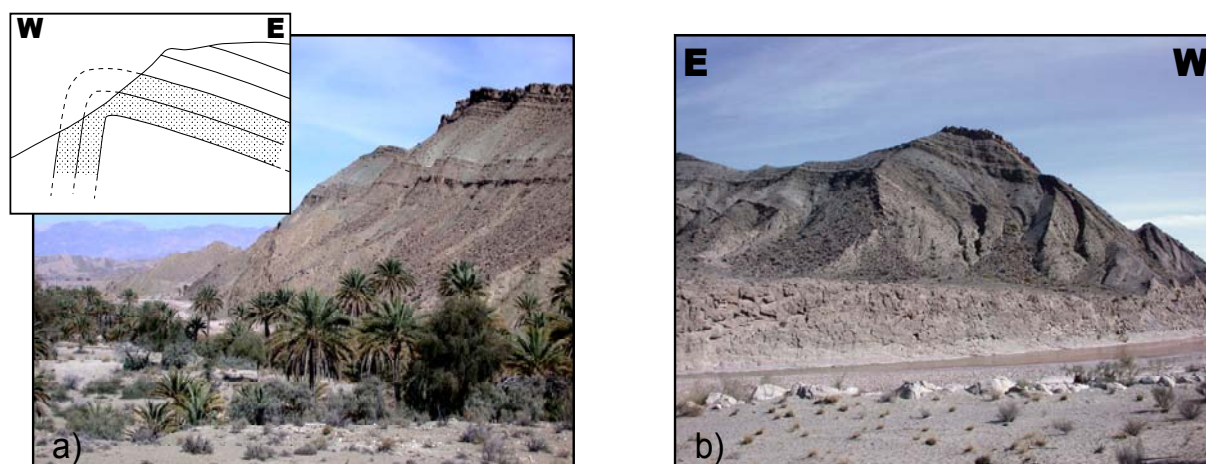


Fig. III—6 N-S trending folds within the Agha Jari Fm close to the Zendan Fault in the area of the town of Ahmadi (viewpoints in Fig. III—5).

This kind of tectonics, in which different structural units deform independently and are separated by a general decoupling horizon, corresponds to what Boyer & Elliott (1982), in discussing the deformation in the Appalachians, described as a “corrugated iron” pattern of deformation (Fig. III—7).

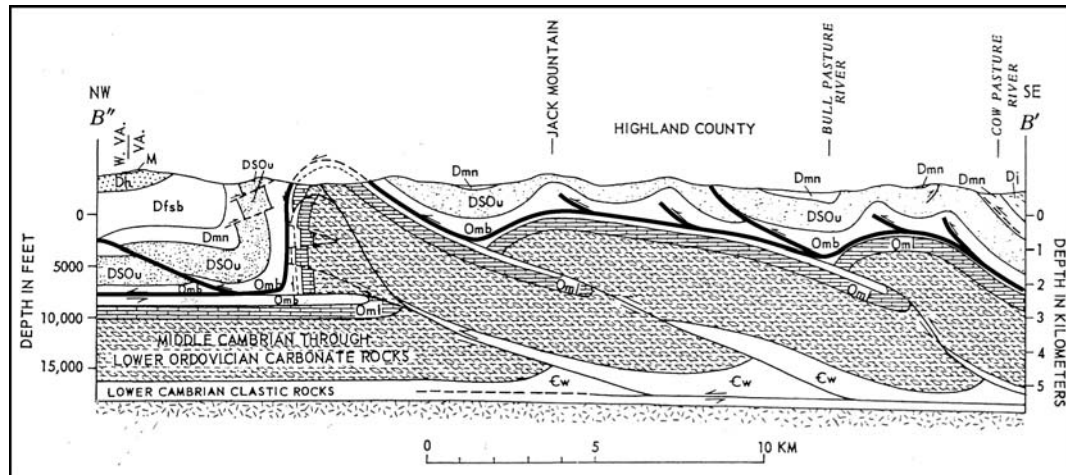


Fig. III—7 Cross-section through the Central Appalachian Valley and Ridge folds and thrusts, after Perry (1978).

3.2 Further insight on the kinematics of folding and thrusting in the ZFTB

It is suggested that the general progression of thin-skinned orogeny in the ZFTB, as I discussed in paper n°2 (steps a & b in Fig. 12), occurred in a piggy-back fashion, with imbrications and thrusting in the High Zagros Belt preceding folding in the Simple Fold Belt. However, there is some evidence suggesting that at a smaller scale the picture could be more complicated than simple sequential propagation of the fold-thrust structures.

3.2.1 Synchronous folding and thrusting in High Zagros

In the ZFTB it has been shown that in the early stage of propagation, shortening is accommodated in the High Zagros by imbrications and duplex structures. On the balanced cross-section (Fig. III—1), the imbricate stacks of Jahrom limestone seem to be located preferentially on the crests or forelimbs of structural culminations related to folding of the cover over deep-seated ramps. This apparent causative relationship between structures at different levels is observed in several other mountain chains and has been put forward by Boyer (1992) as geometric evidence for synchronous thrusting and folding. In his model (Fig.

III—8), to explain the locus of the imbricate stacks Boyer (1992) suggests that if at any one moment two thrusts (a & b) are activated simultaneously, then the imbricates accumulating above the upper flat (1 to 4) will be localised on the crest of the growing frontal fold by repeated break-back thrusting. The kinematic scenario within the HZB therefore appears to be more complicated than the classic piggy-back model and may involve synchronous folding and thrusting as in Boyer's model. Further work is required to accurately examine the stacks in relation to the culminations and understand the details of the kinematics. In particular, it should be checked whether their position is not also controlled by other factors, such as changes in facies – and thus efficiency – of the Gurpi decollement horizon (Fig. III—1).

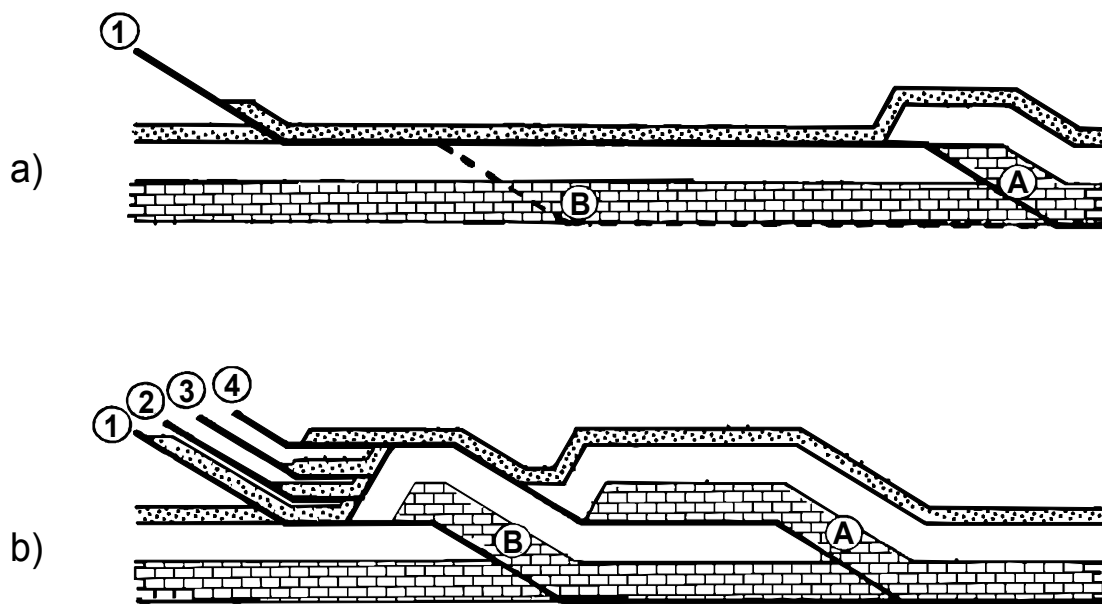


Fig. III—8 Model for synchronous folding and thrusting, after Boyer (1992). (a) Initial stage, in which only fault A is active. (b) Final stage: synchronous movement along faults A & B has caused the imbricates to accumulate on the forelimb of the growing frontal fold.

3.2.2 Sequence of folding in the Zagros Simple Fold Belt

In the ZSFB, it is interesting to notice that the largest and structurally most evolved of the detachment anticlines is the foremost one (Genau anticline) (Fig. III—1), suggesting that this fold was initiated earlier than the other ones. This would mean that in step b of Fig. 12, once the fold belt reached the area of greater salt thickness, it immediately propagated to the locus of the Genau anticline and subsequently deformed internally with the appearance of the other detachment folds, notably the Finu and Handun folds. This sequence of deformation is quite characteristic of fold belts developed on top of an efficient decollement horizon and is known from similar tectonic settings such as the Salt Range and Potwar Plateau (Grelaud et

al. 2002) and from analogue modelling (Costa & Vendeville 2002) (Fig. III—9). Both of these authors show that the location of the frontal structure is essentially controlled by the (fault-controlled) limits of the salt basin upon which the folds were detached. Precise dating of the synorogenic growth strata preserved in the synclines should allow one to verify whether a similar kinematic scenario could apply to Zagros as well. Also the role of inherited structures in the basement and their control on the geometry of the salt basin – and therefore on the fold belt – need to be clarified.

MOD. 1

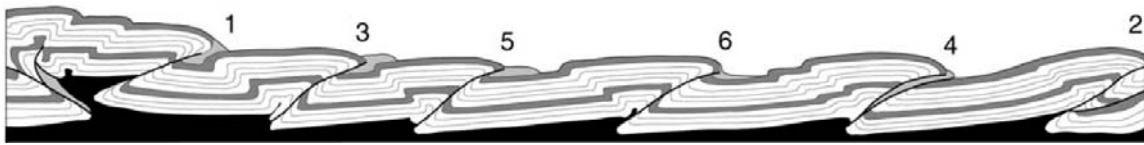


Fig. III—9 Analogue experiment illustrating the sequence of development (numbers 1 to 6) of fold-and-thrust structures above a ductile décollement horizon, after Costa & Vendeville (2002).

3.3 *Paleomagnetic and magnetic fabric data: constraints on the kinematics of the eastern ZFTB and the Bandar Abbas syntaxis.*

Paleomagnetic investigations are a useful tool of analysis in discussing the kinematics of fold-and-thrust belts since they can constrain the possible kinematic scenarios through the measurement of vertical axis rotations (Lowrie & Hirt 1986, Kissel et al. 1993, Allerton 1998). Also paleomagnetism should permit a precise identification of the relative chronology between the remnant magnetisation acquisition time and the folding process.

Magnetic fabrics, through the anisotropy of magnetic susceptibility (AMS), reflect the statistically preferred orientation of grains and/or crystal lattices of all the minerals which contribute to the magnetic susceptibility (see Rochette et al. 1992 & Borradaile & Henry 1997 for detailed reviews). In deformed areas, they are believed to record the early stages of pre-folding shortening imprinted in the rock; usually referred to as Layer Parallel Shortening (LPS) (Averbuch et al. 1992, Aubourg et al. 1997, Frizon de Lamotte et al. 2002)

Paleomagnetic and magnetic fabric studies on the Fars arc and the Bandar Abbas syntaxis have been carried out at the department of Earth Sciences of the University of Cergy Pontoise, with which I was partly associated during my thesis concerning structural aspects. In this paragraph, I will briefly present the main results of these studies and the inferences

which can be derived on the kinematics of the study area. I do not present the theoretical basis behind the techniques nor do I describe the experimental methodologies, for which the reader is referred to the above mentioned literature.

3.3.1 Magnetic fabrics across the Fars Arc and the Bandar Abbas syntaxis

Magnetic fabric studies were first carried out in Zagros, mainly in the western part of the Fars Arc, within the framework of a PhD thesis at the University of Cergy Pontoise (Bakhtari 1998). More recently an AMS study was carried out on the folds around the Bandar Abbas syntaxis (Aubourg et al. 2004, in press).

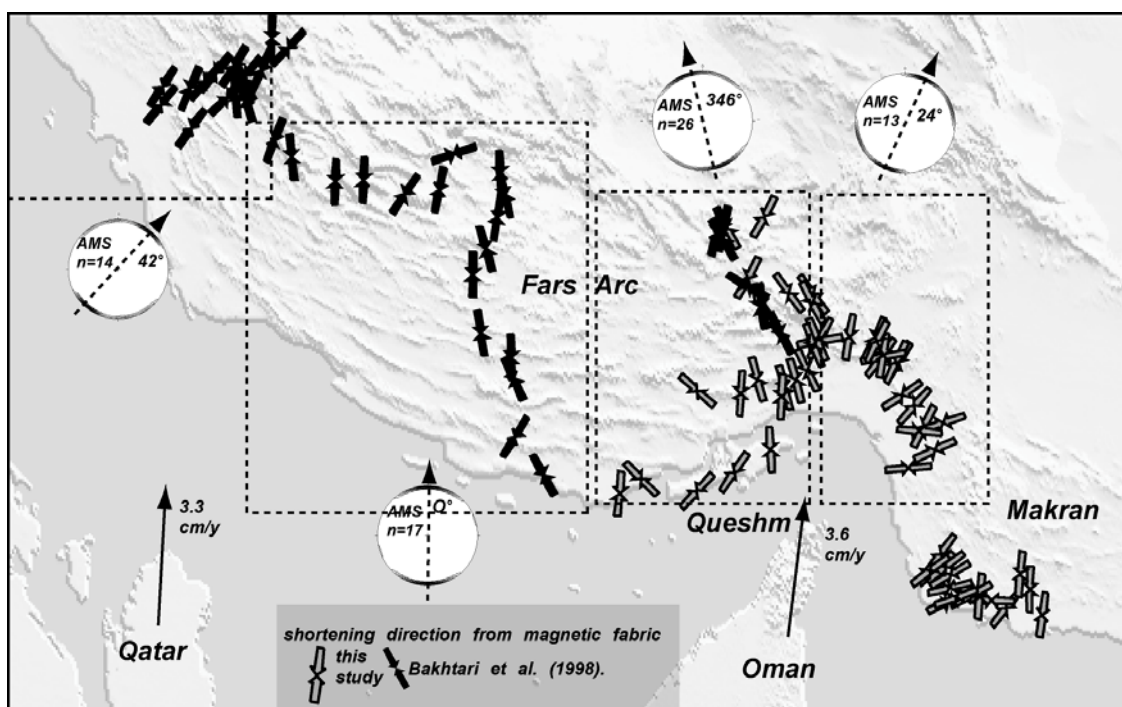


Fig. III—10 Map showing the shortening directions inferred from magnetic fabrics. Dashed boxes indicate measurements used to compute the average shortening directions shown in the density plots. Modified after Aubourg et al. 2004, (in press).

Figure III—10 summarizes the shortening directions derived from the magnetic fabric measurements across the eastern ZFTB and the Bandar Abbas syntaxis from this study. The pattern of magnetic lineations (considered normal to the shortening directions) displayed on the map reveals:

- In the western and central parts of the Fars Arc a fairly systematic obliquity with the local fold axes. This has been attributed by Bakhtari et al. (1998) to post-folding vertical axis clockwise rotation of the western branch of the Fars Arc.

- In the area of the Bandar Abbas syntaxis a fanning of the shortening directions roughly reproducing the arched shape described by folds in this area. Considering that convergence is supposed to have remained on a constant N10° direction since at least Miocene times, this pattern suggests that opposite vertical axis rotations occurred on either side of the syntaxis, anticlockwise on the western side and clockwise on the eastern side.

To sum up, the directions of magnetic lineations across the Fars arc could be explained by opposite vertical axis rotations of the two limbs of the arc, as was initially suggested by Bakhtari et al. (1998). These rotations should be related to the thin-skinned development of the salt-detached Zagros structures and not to hypothetical rotations of basement blocks as suggested by other workers in Zagros (Hessami et al. 2001a, Talebian & Jackson 2004). If these rotations were confirmed (for example by paleomagnetic measurements) they would lend support to the “Jura style” kinematic model suggested in paper n°2 for the development of the Fars arc. Work is currently being carried out by C. Aubourg at the Department of Earth Sciences (UCP) on paleomagnetic data across the entire Fars arc. Preliminary results from the area of Bandar Abbas suggest anticlockwise rotations of 15-20° on some folds, in agreement with the rotations suggested by magnetic fabric data.

3.3.2 Paleomagnetic and AMS study of the Minab Fold on the eastern side of the syntaxis

In the eastern part of the Bandar Abbas syntaxis, a detailed study based upon paleomagnetism, magnetic fabrics and microtectonics was carried out on the Minab fold in collaboration with B. Smith of the University of Montpellier. The aim of this work, which is summarised in a paper (Smith et al. 2004, in preparation), was twofold: firstly, to document possible vertical axis rotations in the eastern limb of the Bandar Abbas syntaxis and explain them in the context of the complex transition between the Zagros collisional belt and the Makran accretionary prism. Secondly, to understand the kinematics of a sigmoidal fold and in particular the mechanisms leading to the development of a curved fold.

Seven sites of sampling were selected in the Agha Jari fm in both limbs of the northern part of the Minab fold (Fig. III—11). For all of these sites AMS and paleomagnetic measurements were carried out. The following main results have been obtained from this study:

- a) All of the sites except one (site Z-51) record a pre-folding vertical axis clockwise rotation of $\sim 18^\circ$, indicating that the northern part of the Minab anticline underwent a post-Mio-Pliocene rigid clockwise rotation of approximately 18° . This rotation, as mentioned in paper n° 2, can be interpreted as the result of interference with the south-westward propagation of the western branch of the Makran prism arc.
- b) The fact that no differential rotation is measured between the sites indicates that the torsion of the fold is a primary feature coeval to fold growth and did not result from late bending of an already formed fold.

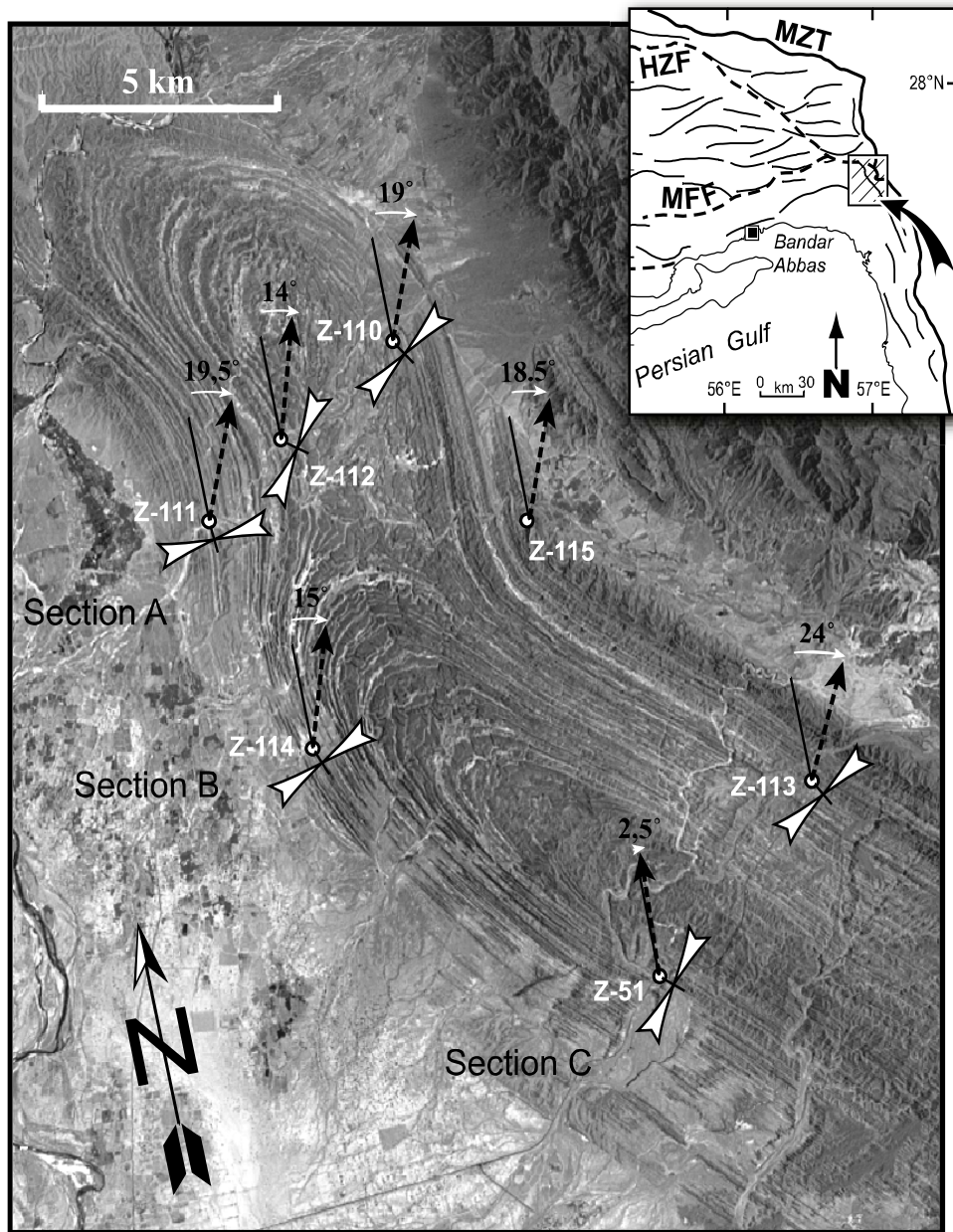


Fig. III—11 Results of AMS and paleomagnetic measurements in the northern part of the Minab fold (satellite SPOT image). Dashed arrows : declination of remnant magnetisation with angle measured relative to supposed Mio-Pliocene magnetic declination. White arrows: shortening directions inferred from AMS measurements. Modified after Smith et al. (2004, in preparation).

- c) The magnetic lineation is everywhere parallel to the local fold axis and probably records the Layer Parallel Shortening (LPS) imprinted in the early stage of the compression, before the onset of folding.

3.4 Microtectonic analyses

This is another useful tool of investigation when discussing the kinematics of a region: palaeo-states of stress can be reconstructed and different tectonic phases can be separated on the basis of measurements on meso-scale structures such as fault planes and striations. Microtectonic data (essentially fault-slip data) was collected in our study area during several field trips. Some of these data are presented in a series of maps of key structures included in the appendixes at the end of this manuscript. Though inconclusive, these fault-slip measurements show a scattering of directions which attests to the superposition of successive stress regimes. This is particularly evident in the area of Lardogarm (appendix 2). The structures in this area are organised in two main trends, at N50-N60 (corresponding to the Jahrum imbrications) and at N110-N120 (corresponding to the Abgarm thrust) which are well correlated with the general kinematic trends inferred from fault-slip measurements. A similar picture can be found on the Kuh-e-Khush antiform (appendix 3). The map pattern of this structure clearly gives evidence for two superimposed tectonic phases (compare with Fig. 13, paper n.° 3) and these can be found also in the general kinematic trends deduced from microtectonic measurements.

Measurements on the Minab fold (appendix 4) are scarce and need further work to be interpretable. An exhaustive study of fault slip measurements in the Zendan-Minab area has been carried out by Regard et al. (2004). In this study, Regard et al distinguish two main fault populations in this region, an older one giving evidence for E-W compression and a younger one indicating NE-SW compression. They suggest that this change in stress regime is related to the transition from a partitioned deformation regime – with faults bearing the E-W component and folds bearing the N-S component – to a non-partitioned one, under a constant N45° far-field stress regime (Fig. III—12). Regard et al conclude by proposing that this transition may have been triggered by changing geodynamic conditions in the general context of the Arabia-Eurasia convergence.

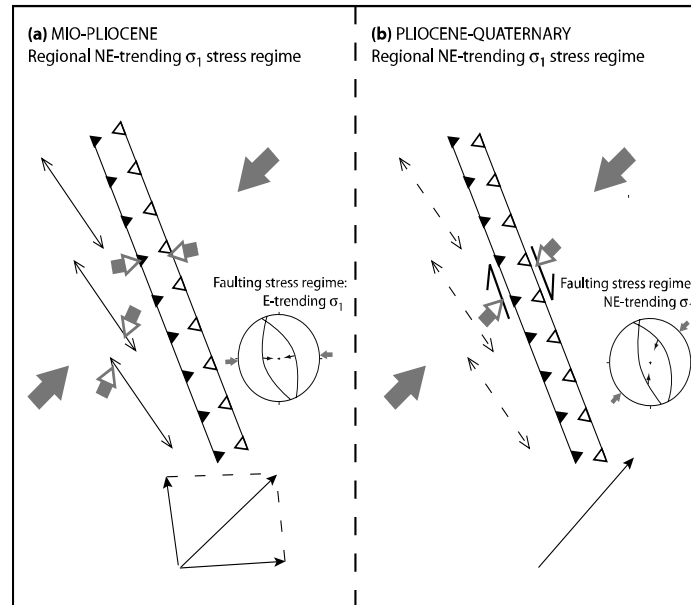


Fig. III—12 Model presented by Regard et al. (2004) to explain the two fault populations in the Zendan-Minab area. (a) NE-SW compression is partitioned between N-S convergence on folds and E-W convergence on NNW-trending faults. (b) NE-SW compression is now accommodated by transpression along parallel faults.

However, these two fault populations could be interpreted differently in the light of the 20° clockwise rotation of the Minab fold shown by paleomagnetic data (Smith et al. 2004, in preparation). The older E-W trending fault population could have been generated under a NE-SW compression regime and successively rotated to its present-day position. Continued NE-SW compression then resulted with the superposition of the younger fault population (Fig. III—13).

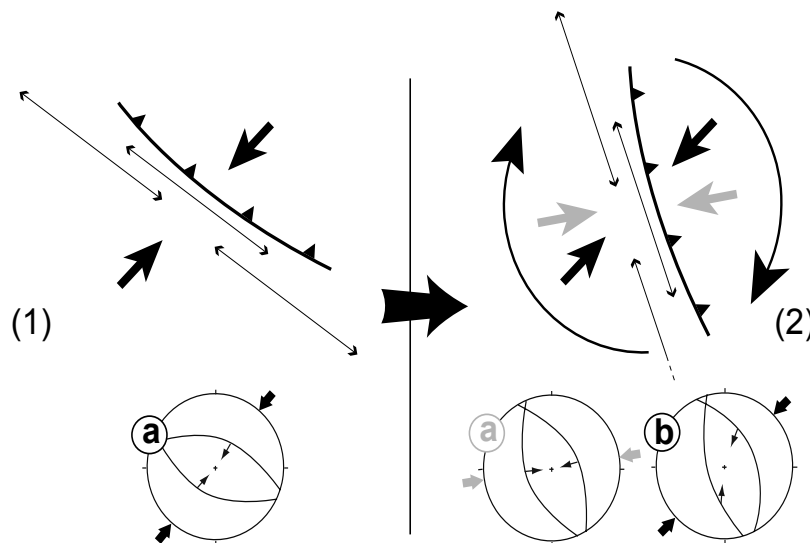


Fig. III—13 Alternative model to explain the two fault populations discussed by Regard et al. (2004). (1) Folds and an older set of faults (set a) form under a NE-SW compression and are then (2) rotated to their present-day trend and deactivated while a new fault population (set b) is generated under continued NE-SW compression.

Compared to Regard's (2004) hypothesis, this model has the advantage of being directly and simply interpretable in terms of the local dynamics of the lateral branch of the Makran fold thrust arc. In other words it does not need to be linked to changing far-field geodynamic conditions which are difficult to verify.

4 CONCLUSION

A general picture of how deformation progressed in the eastern ZFTB has been sketched in this chapter. Initial thin-skinned orogeny advanced sequentially towards the foreland. Deformation propagated in stepwise fashion from the hinterland where deep crustal faults probably absorbed shortening within the basement (Fig. III—14a). The style of deformation is strongly controlled by the geometry of the underlying salt basin: in the High Zagros Belt deformation propagated by thrusting and duplexing over a probably thin Hormuz decollement horizon. In the Zagros Simple Fold Belt, on the other hand, exceptionally large detachment folds developed over a thick and mobile Hormuz salt basin (Fig. III—14a). During the following thick-skinned orogeny, folds and thrusts within the cover became inactivated as younger and deeper ramps within the upper crust (basement) were activated and cut in out-of-sequence fashion through the cover structures (Fig. III—14b).

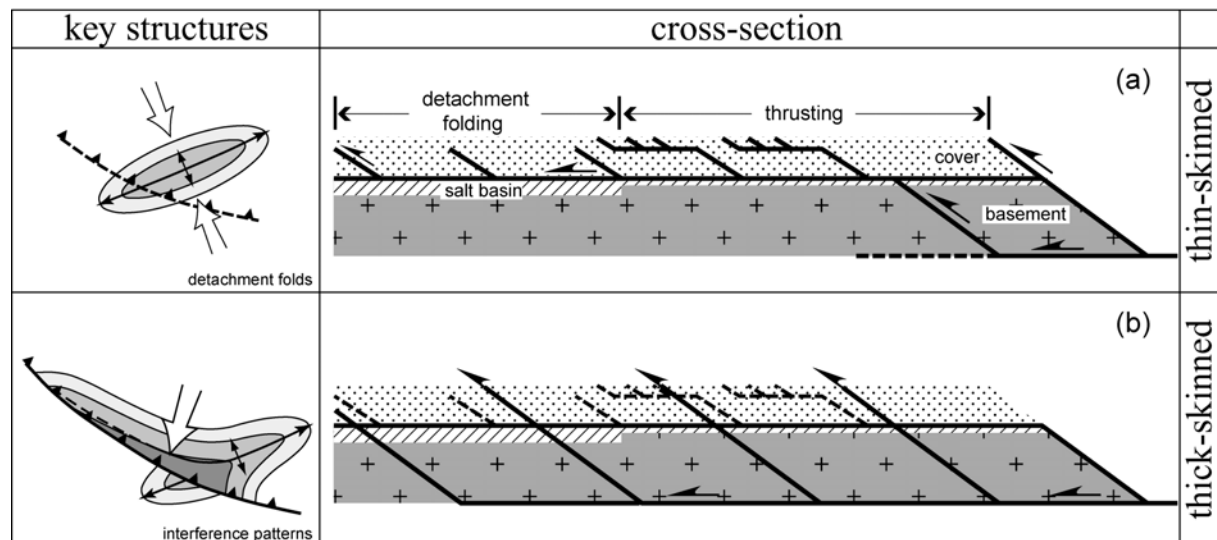


Fig. III—14 Schematic diagram illustrating the basic sequence of deformation in the ZFTB and associated key structures. (a) Thin-skinned detachment folding and thrusting is accounted for in the basement by thrusting in the hinterland. The style of deformation is controlled by the geometry of the underlying salt basin. (b) Structures in the cover become inactivated as out-of-sequence basement thrusts ramp up from a deeper crustal decollement and cut at oblique angles through detachment folds in cover.

Key to understanding this sequence of deformation is the observation of spectacular interference patterns which are attributed to the superposition at oblique angles of these two major tectonic phases. These particular geometries can be observed only in the easternmost ZFTB. Elsewhere in Zagros the basement faults strike parallel to the structures within the cover so the distinction between separate tectonic phases is less obvious.

Viewed at a crustal scale, this sequence of deformation appears to conform to the standard model in which deformation is initially transmitted into the foreland within the higher decollement levels and is later recovered by younger thrusts ramping up from deeper decollements (Perry 1978, Boyer & Elliott 1982).

The geometry of the Hormuz basin may be the main controlling factor, which determined the shape and extent of the Fars Arc. Therefore the solution to the “problem of the origin of the Fars Arc”, exposed in chapter I, may be a Jura style model in which the amount of propagation of the fold belt is controlled by the thickness and extent of the underlying salt basin. At any rate the fact that the basement was not involved during formation of these folds seems to invalidate previous models involving vertical axis rotations of basement blocks (Hessami et al. 2001a, Talebian & Jackson 2004).

As indicated in paragraph 3, the kinematics of folding and thrusting in the cover could be more complex in the details. Also the precise kinematics of individual structures remain yet to be discussed. This problem is dealt with in the following chapter, where the mechanisms of detachment folding and the role of various factors on the folding process are discussed, based upon examples from central and eastern Zagros. Finally, it still remains to be explained what factor triggered the abrupt transition from thin-skinned to thick-skinned deformation. This problem is discussed in chapter V.

CHAPTER IV

THE ZAGROS FOLD THRUST BELT: A NATURAL LABORATORY FOR DETACHMENT FOLDING

1. INTRODUCTION

In this chapter, I focus on the more general aspects of folding throughout Zagros. In the previous chapters it has been shown that folding in the eastern ZFTB and the Fars Arc is well explained by the detachment fold model, with a late stage interference caused by basement faulting. At the same time, geological sections from central Zagros, notably in the area of the Dezful Embayment (Sherkati & Letouzey 2004), show that folding in this area also conforms to the detachment fold model (Fig. I—15). However, the style and the spacing of the folds are considerably different and the picture appears to be complicated by the presence of multiple detachment horizons. So to obtain a more comprehensive view of the mechanisms of detachment folding throughout Zagros and the factors controlling the geometry and evolution of the folds, it appeared necessary to widen the scope of our investigation. I therefore decided together with D. Frizon de Lamotte to set up a collaboration with S. Sherkati of the National Iranian Oil Company (NIOC) and J. Letouzey of the Institut Français du Pétrole (IFP) who had been working on the geology of Central Zagros. The aim being to compare and combine our respective results from eastern Zagros and from central Zagros. The chapter starts with a review and discussion of previous work done on the geometry and kinematics of detachment folding. The core of the study is summarised in a paper « **Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and final basement control** », submitted to *Journal of Structural Geology*. The aim of this work is essentially to analyse the influence of various parameters on the style of folding in two separate but representative areas of Zagros, notably the influence of pre to syn-folding salt migration, the role of multiple detachment horizons and the effects of late stage basement faulting. This work is largely based on recent seismic profiles provided by NIOC and on field and aerial photographs of structures. We complete the chapter by further discussing some aspects of the folding in Central Zagros.

1.1. Short review of previous work on detachment folding

Among the three main classes of folds which are generally recognised, fault-bend folds, fault-propagation folds and detachment folds, these latter, though commonly observed, are the least understood in terms of kinematic evolution. This is due to the fact that there is no univocal relationship between a given geometry and a kinematic scenario. The concept of detachment folding was implicitly acknowledged at a very early stage under concepts such as

the “break thrust fold” of Willis (1893) (Fig. IV—1) or the “stretch thrust” of Heim (1921), in which the development of a thrust fault was considered to be the final stage in the fold evolution.

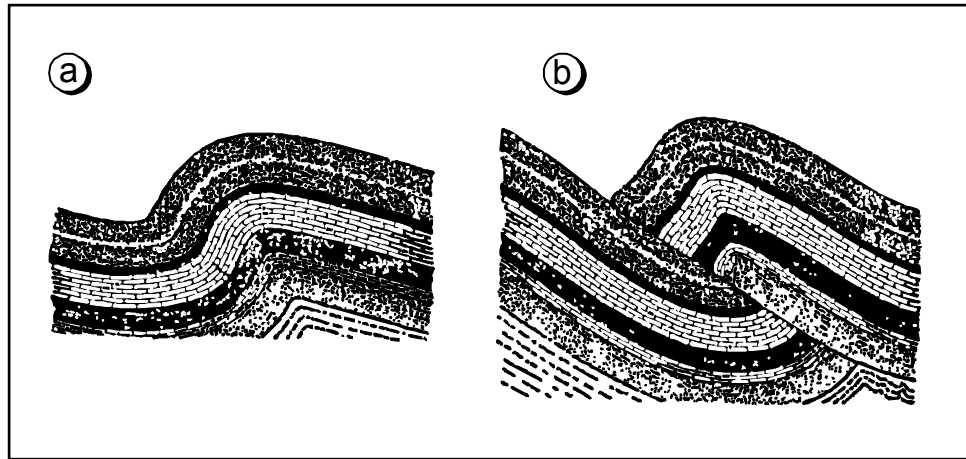


Fig. IV—1 Break-thrust fold of Willis (1893). Note that in stage (a) preceding the development of the fault, the fold is implicitly depicted as a detachment fold.

The first explicit recognition of detachment folding can probably be attributed to Buxtorf (1916), with his cross-sections through the Jura Mountains (Fig. IV—2). Detachment folds have since been documented from numerous other mountain belts around the world, notably the Parry Islands fold belt (Harrison & Bally 1988), the Zagros fold belt (Colman-Sadd 1978) and the Taiwan belt (Namson 1981), and have been studied based upon mechanical considerations and analogue modelling (Bonini 2003).

Detachment folds are characterised by a rounded and often symmetrical geometry at surface and usually display large wavelengths, even at low shortening ratios. De Sitter (1956) was the first to recognise that in concentric regimes of folding, implicit to detachment folds, the size of the structure is directly a function of the thickness of the folded panel. Mechanical analyses (Biot 1961) have demonstrated that the physical properties of the stronger dominant member in the stratigraphic succession will have a determining effect on the final size of the structures. Dahlstrom (1969) pointed out that in concentric regimes of folding, implicit to detachment folds, a fold train is necessarily bounded by an upper and a lower detachment (Fig. IV—3).

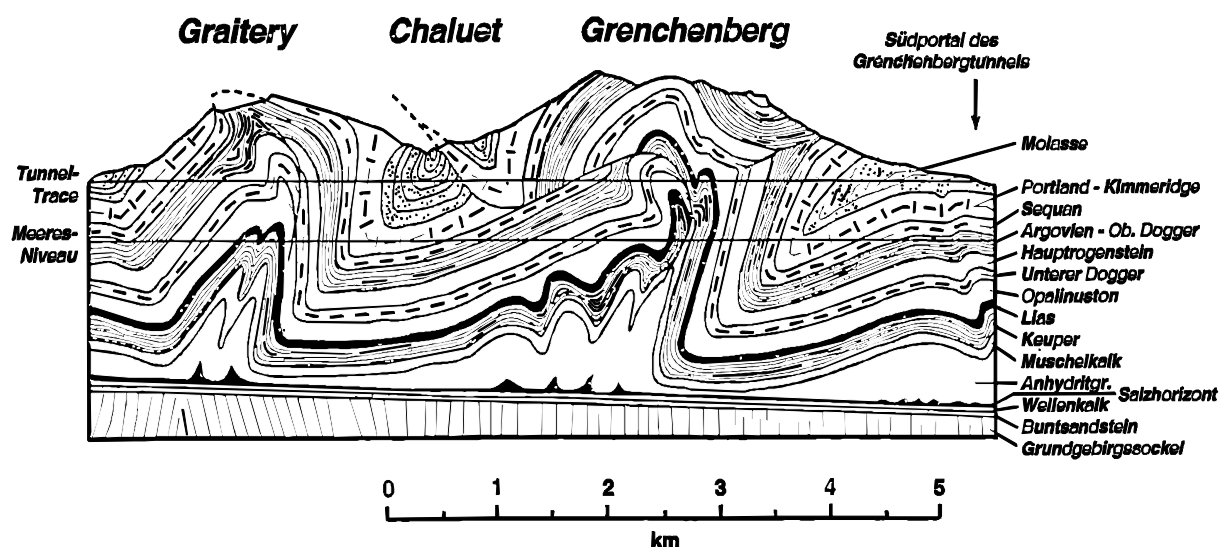


Fig. IV—2 Example of detachment anticlines in the Jura Mountains, Switzerland. Redrawn by Epard & Groshong (1993) from Buxtorf (1916). No vertical exaggeration.

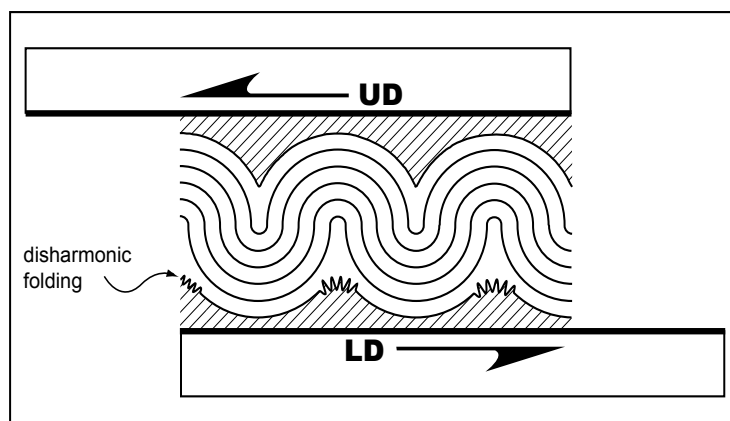


Fig. IV—3 Dahlstrom's (1969) conceptual model explaining why a concentrically folded panel is necessarily bound by an upper (UD) and a lower (LD) detachment zone.

While the lower detachment always exists, sometimes the upper detachment may not and never did exist and corresponds simply to the interface between rock and air/water (Dahlstrom 1969). From figure IV—3 one can remark that depending from the level of erosion, very different fold geometries will be observed at surface: close to the lower detachment one will observe tight anticlines, with possible internal disharmonic folding, separated by broad gentle synclines, while towards the upper detachment one will have the impression of tight synclines and broad anticlines.

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 therefore consists of a basal incompetent layer

acting as a detachment zone, such as 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 ductile material towards the core of the anticlines causing downwarp of the adjacent synclines. The structure will develop more or less symmetrically depending on the viscosity of the basal decollement: in areas such as Zagros characterised by ductile décollement horizons folds will originate as symmetric structures (Davis & Engelder 1985).

1.1.1. Kinematics of detachment folding

The first author to explicitly discuss the geometric evolution of buckle folds was De Sitter (1956), who proposed a model wherein the anticlines grow by increase in limb dip as the synclinal axes slide toward one another on the underlying detachment (Fig. IV—4). However, this model was later shown by Dahlstrom (1990) to violate the law of conservation of volume of Goguel (1952) since it implied a drastic variation in the location of the detachment horizon with the amount of shortening. With his paper, Dahlstrom (1990) set the foundations of the modern ideas on the kinematics of detachment folds by proposing, based upon balancing criteria, an evolution model “wherein the anticlinal fold limbs are short at the inception of folding and grow longer as dips increase and the fold grows”.

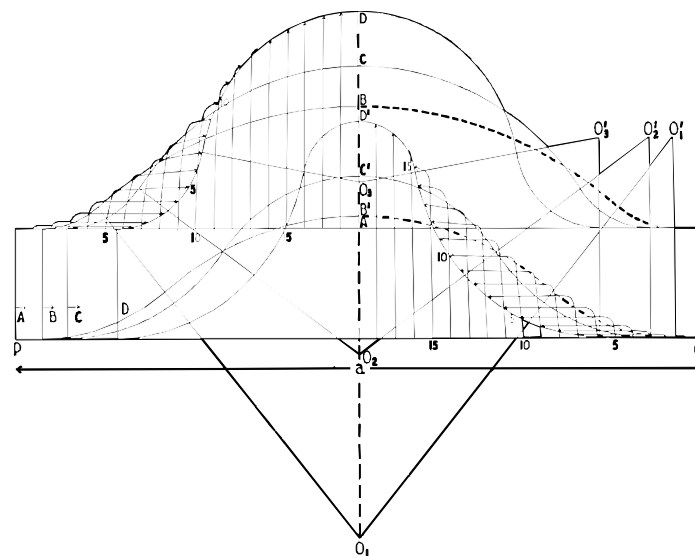


Fig. IV—4 De Sitter's (1956) model of geometric evolution of a concentric buckle fold, with illustration of particle trajectories on the flanks of the anticline.

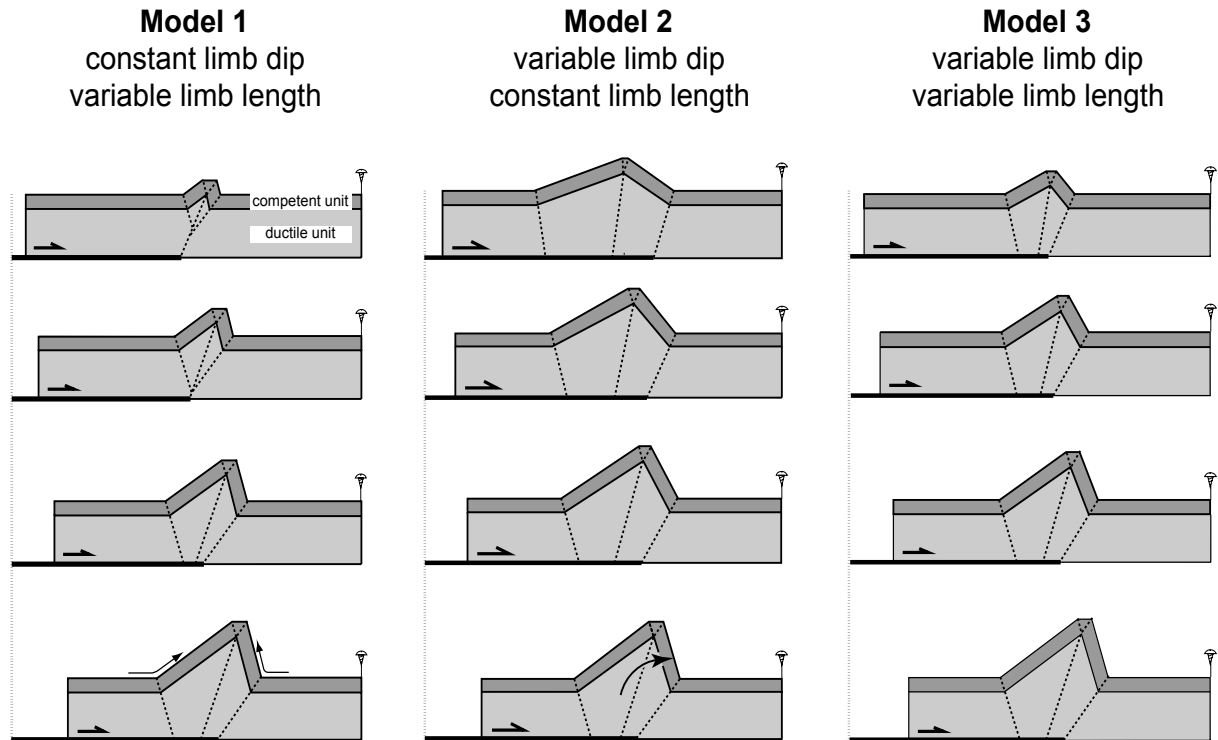


Fig. IV—5. Three possible models of growth of a detachment anticline. Model 1: growth by hinge migration; model 2: growth by limb rotation; model 3: growth by a combination of hinge migration and limb rotation. After Poblet & McClay (1996).

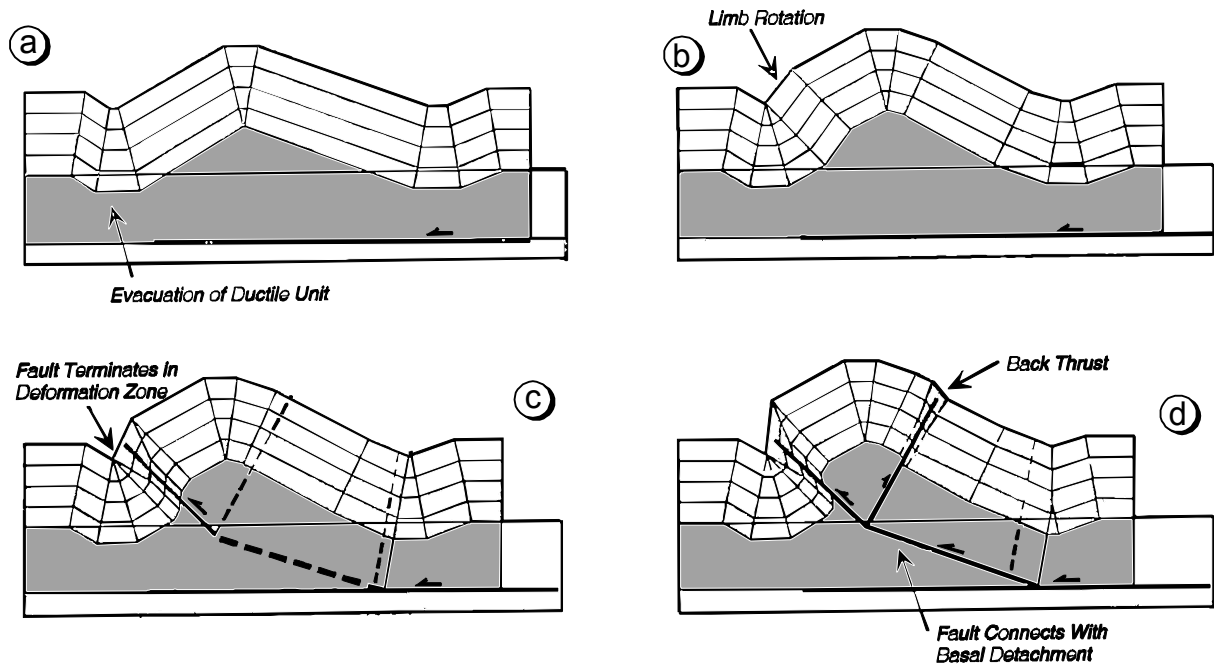


Fig. IV—6 Typical evolution sequence of a faulted detachment fold, after Mitra (2002). Note that the fold is initiated as a quasi-symmetric structure (a & b) and that the development of the asymmetry coincides with the propagation of a fault (c & d).

There are two main mechanisms which are now generally thought to contribute to the growth of a detachment fold: (1) limb lengthening by migration of beds through hinges and

(2) limb rotation. A whole series of papers followed in the next ten years or so dealing with the kinematics of detachment folds (Poblet & McClay 1996, Homza & Wallace 1997, Rowan 1997, Mitra 2002), the main debate being which of these two competing mechanisms is the most important in the early stages of fold development (Fig. IV—5).

The late stage evolution of detachment folds is generally considered to involve a transition from simple symmetric or asymmetric detachment folds to progressive propagation of a fault through the forelimb with increasing shortening (i.e. a faulted detachment fold, Mitra 2003) (Fig. IV—6). This is basically the concept which was already implicitly suggested by Willis's (1893) model (Fig. IV—1).

1.2. *Towards an unification of fold models?*

Folds are usually classified in one or the other of the three principal geometrical models mentioned at the beginning of the chapter (detachment, fault-propagation and fault-bend folds). However, in the light of our observations and the considerations exposed above, we believe that these models could be viewed as mere steps in a same continuous process of folding. In other words, it is suggested that in their late stages of evolution folds should necessarily pass through all three these steps, starting by simple buckling over a ductile layer and ending by connection of a forelimb thrust onto an upper flat (which may be the topographic surface) and folding over the ramp-flat transition (Fig. IV—7). A similar idea had already been proposed by Dixon & Liu (1992), based upon analogue modelling. The relative importance of each of these stages will primarily depend on the characteristics of the basal decollement. For a fold developed over a thin and relatively competent decollement horizon, the stage of buckling will probably be short lived and will be rapidly replaced by the propagation of a fault. On the other hand, a fold developed over a thick ductile decollement will likely develop over a long time by simple buckling. It is only when all the ductile material available to fill in the core of the anticline has been completely evacuated from the adjacent synclines, that the fault will start propagating through the forelimb.

Figure IV—8 shows an instructive field example within the Mishan formation (Fig. I—21) of a small fold deforming well-bedded limestone over a basal layer of incompetent shale. This example demonstrates unequivocally the transition from a simple detachment fold – with the complete evacuation of the basal shale layers from the adjacent synclines towards the core of the anticline – to a faulted detachment fold. Further shortening would probably result with

connection of the fault onto an upper flat, at which moment the fold would “become” a fault-bend fold.

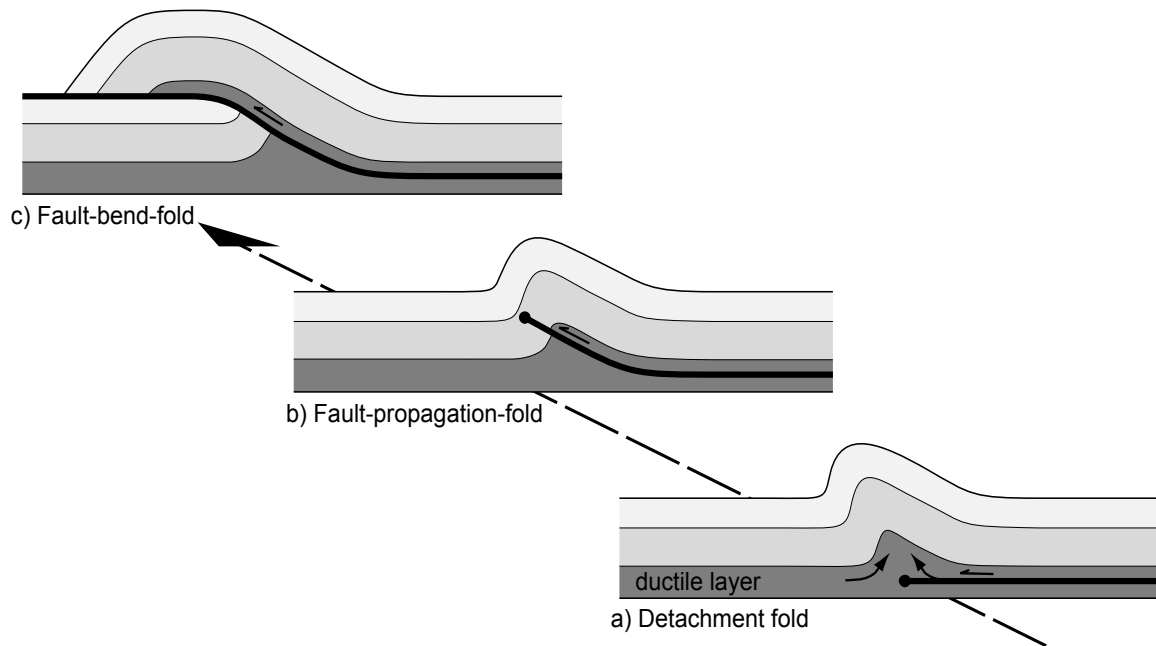


Figure IV—7 Typical evolution sequence of a fold. The fold is initiated by buckling, develops into a fault-propagation fold and ends as a fault-bend fold.

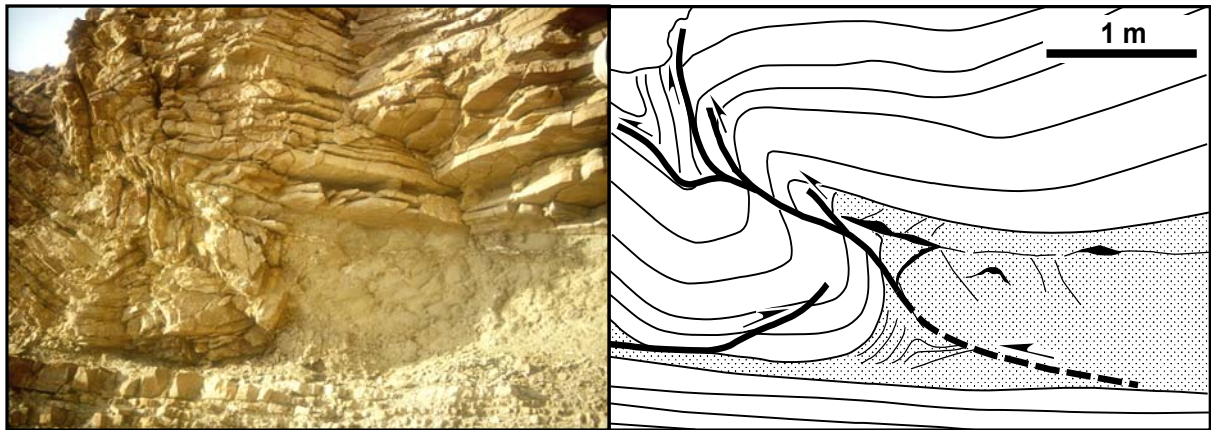


Fig. IV—8 Field example of a faulted detachment fold deforming the Mishan Fm in the area north of Bandar Abbas.

LES PLIS DE DECOLLEMENT DU ZAGROS PLISSE CENTRAL ET ORIENTAL : LE ROLE DE LA MOBILITE DU SEL, LES DECOLLEMENTS MULTIPLES ET LA REACTIVATION TARDIVE DU SOCLE (PAPIER N° 3)

Resumé : Les plis de décollement sont étudiés sur la base d'exemples de terrain et de subsurface dans le Zagros Central et Oriental (Iran). Différents aspects du plissement discutés dans ce papier sont bien illustrés dans la région d'étude. En particulier, nous nous intéressons à : la mobilité du sel, les niveaux de décollement multiples et le rôle tardif des accidents de socle. La mobilité du sel concerne le décollement basal « Hormuz » et le décollement supérieur « Gachsaran ». Pour ce dernier, on montre que la mobilité résulte non seulement du diapirisme syn-plissement mais aussi d'une migration précoce sous l'influence de la gravité des anticlinaux en voie de formation vers les synclinaux. Le plissement concentrique entre deux niveaux de décollement est directement observable dans la zone d' Izeh (Zagros Central), où l'on montre que la longueur d'onde dépend de la distance entre les deux niveaux de décollement et le style de plissement du niveau d'érosion. A travers la chaîne du Zagros, les plis de décollement se sont formés au cours d'une première phase de tectonique de couverture, suivie par la phase actuelle de tectonique de socle. Cette séquence est particulièrement bien exprimée dans le Zagros Oriental où les accidents de socle recoupent obliquement les plis de décollement déjà formés.

Mots clefs : *Décollement, pli de décollement, mobilité du sel, tectonique de couverture, tectonique de socle, Zagros (Iran)*

2. DETACHMENT FOLDING IN THE CENTRAL AND EASTERN ZAGROS FOLD-BELT (IRAN): SALT MOBILITY, MULTIPLE DETACHMENTS AND FINAL BASEMENT CONTROL (PAPER N° 3)

Paper submitted to Journal of Structural Geology (May 2004)

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

Keywords : *detachment, detachment fold, salt mobility, thin-skinned tectonics, thick-skinned tectonics, Zagros Mountains (Iran).*

2.1. Introduction

Numerous fold-and-thrust belts are formed by detachment of sedimentary layers above an incompetent unit, such as shale or evaporite (Davis & Engelder 1985). Historically, a good example of control exerted by such a detachment horizon is the Jura at the front of the western alpine orogen where stiff Mesozoic layers (mainly carbonate) are folded upon weak Triassic evaporite (Buxtorf 1916, De Sitter 1956, Goguel 1952, Laubscher 1977). If the detachment horizon (or *décollement* level) is thick enough, the development of detachment folds (i.e. “an unfaulted fold train above a through-going detachment”, Dahlstrom 1990) is expected. The kinematics of detachment folds remain a matter of debate because of the absence of an univocal relationship with a given geometry (Homza & Wallace 1995, Mitra 2003, Poblet & McClay 1996). However the importance of the mechanical stratigraphy of the sedimentary pile involved in the folds is always put forward. In connection to this last aspect, a question of major importance in detachment folds is the role of diapirism and, more generally, of salt mobility.



Fig. 1 Physical map (source: GEBCO data) and main structural features of the Zagros fold-thrust belt with location of the figures. See also appendix 5. ZSFB: Zagros Simply Folded Belt.

The Zagros Mountains of Iran result from the opening and then the closure of the neo-Tethys ocean between the Central Iran domain and the Arabian plate (Alavi 1994, Berberian & King 1981, Ricou 1971). Within this orogenic belt, the external zones, the so-called « Zagros Simply Folded Belt » (ZSFB) (Falcon 1969, Stocklin 1968) (Fig. 1), represent the palaeo-margin of the Arabian plate folded during Cenozoic times. The ZSFB is often cited as one of the regions in the world displaying the best examples of large scale detachment folds

(Colman-Sadd 1978) as shown by their regular and well rounded geometry (Fig. 2). This is due to a very efficient décollement level (the Hormuz salt) located at the base of a thick (up to 10.000 m) sedimentary sequence. More precisely, O'Brien (1950, 1957) was the first to divide the stratigraphic pile into five structural/mechanical ensembles namely: (1) the basement group (Panafrican crystalline basement), (2) the lower mobile group (Hormuz salt), (3) the competent group (Cambrian to Lower Miocene platform sediments), (4) the upper mobile group (Miocene salt) and (5) the incompetent group (Miocene to recent molasses). However, this mechanical stratigraphy, defined originally in the Dezful Embayment, is not uniform throughout Zagros and depends strongly on the considered region (Fig. 3).



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

So, concerning the mechanisms active during folding in fold-thrust belts, the ZSFB allows to address different questions including: (1) the role of salt mobility, (2) the role of multiple décollements in the sedimentary cover (3) the interference between different phases of deformation and finally (4) the role of the basement during folding.

The aim of this paper is not to present new models of detachment folds but (1) to discuss the different aspects listed above on the basis of examples and (2) to give an overview of the geometry and kinematics of folds in the ZSFB. Data and interpretations were mainly derived from field observations and mapping but also from a comparison with seismic profiles kindly provided by the National Iranian Oil Company (NIOC). We will successively

focus on three particular regions where recent field work has been done (Molinaro et al. 2004, Molinaro et al. 2004, submitted, Sherkati & Letouzey 2004): the Dezful Embayment and Izeh zone, which are both situated in the central Zagros, and the south-eastern Zagros (Fig. 1).

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

The Dezful embayment is the region where, historically, O'Brien (1957) proposed a conceptual kinematic model to explain why in this region and “contrary to the accepted trends of diapiric movements” the Miocene salt has moved from anticlinal areas into synclinal areas. The sections of this author are now classical and have been reproduced recently by several workers such as Bonini (2003), Edgell (1996) and Sattarzadeh et al. (2002). It is worth noting that these authors do not discuss O'Brien's (1957) model in which the folding occurs very late (i.e. after the deposition of the Aghajari Fm.) and diaspirism plays a major role. New available data, presented here, show that folding occurred during at least two steps and that diaspirism is likely only one aspect of the salt mobility.

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

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

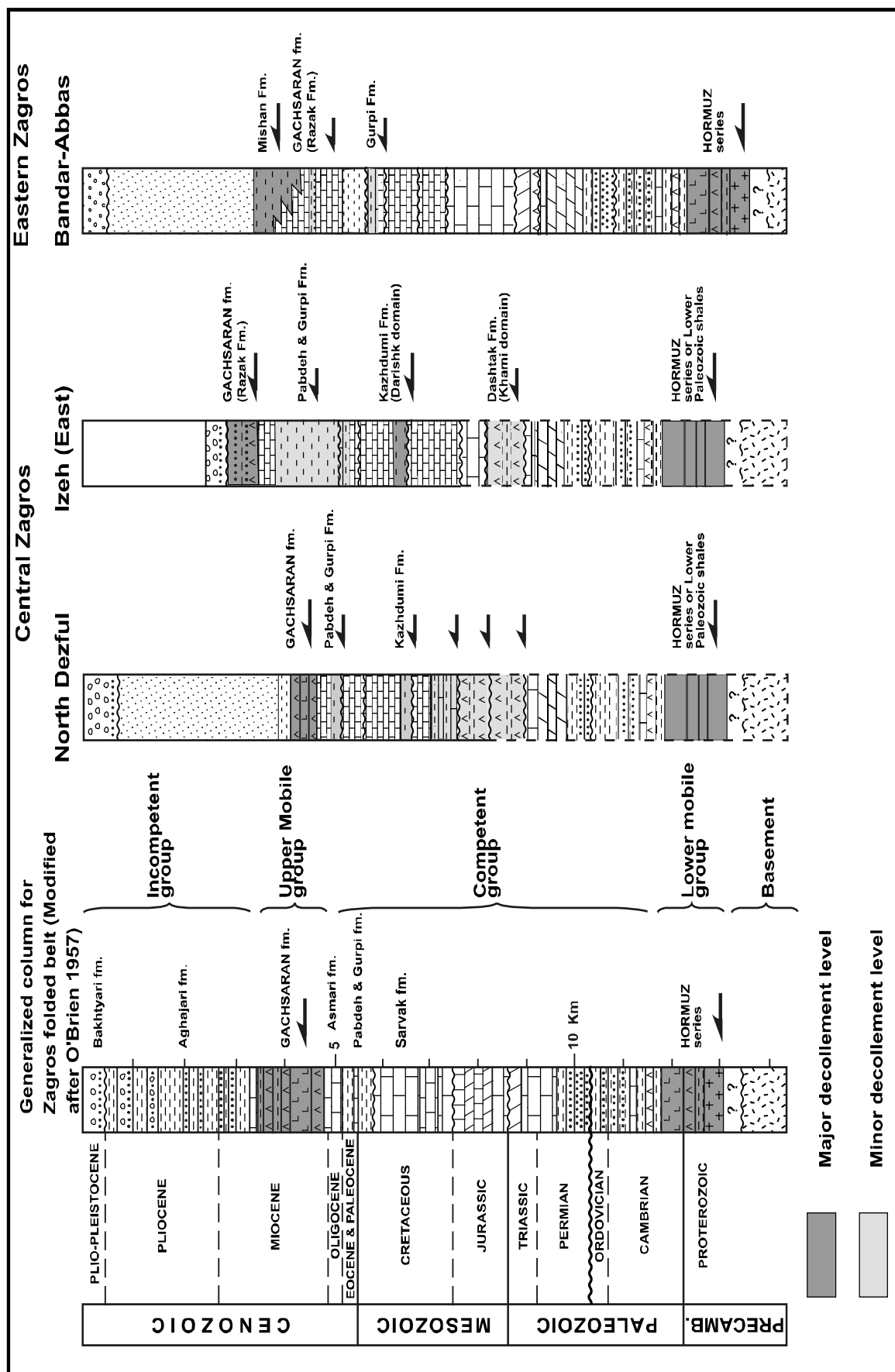


Fig. 3: Generalised stratigraphic column indicating the main detachment horizons in Central and Eastern Zagros. The mechanical properties are not uniform throughout the belt (the mechanical stratigraphy proposed by O'Brien (1957) is given for the record). Units with dashed outline (Izeh and Dezful zones)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

A seismic profile towards the periclinal termination (Fig. 4) and the central zone (Fig. 5) of the Ab Teymur anticline illustrates the fold geometry at a very early stage of development. On both sections a salt pillow (or salt bulge) formed by accumulation of salt from the lower Gachsaran Fm is visible along the southern limb of the fold. At the base of the Gachsaran Fm. some disturbance in the reflectors could represent drag folds (Fig. 4), indicative of salt migration. Unfolding of the Aghajari molasses situated above the Gachsaran Fm. leads to a pre-Aghajari geometry where the salt bulge already exists (Fig. 6b). This suggests that the “pinch-and-swell” geometry of the Gachsaran Fm. was developed before the deposition of the lower Aghajari. It could result from either a depositional accumulation or an early migration and in both cases, it is necessarily linked to a first step in the folding process (Fig. 6b). As the salt was at or near the surface during this folding process, we suppose that it was, at least partially, driven by gravity toward the depressions (i.e. toward the syncline). During the subsequent step of folding (recorded by growth strata visible in the upper Aghajari Fm., Fig. 5), the existence of the bulge induced the development of an arch in the above-lying sediments explaining why the positions of the fold axes at top-Asmari and above Gachsaran does not coincide (Fig. 4). During this second step a diapiric migration of the Gachsaran salt is likely (Fig. 6d). The main difference with O’Brien’s (1957) model is that in our view a first folding step occurred early during or just after the Gachsaran deposition allowing a downward migration and accumulation of salt within the synclines. In our model, the asymmetry in the distribution of the salt should be linked to an initial asymmetry of the syndepositional folds.

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

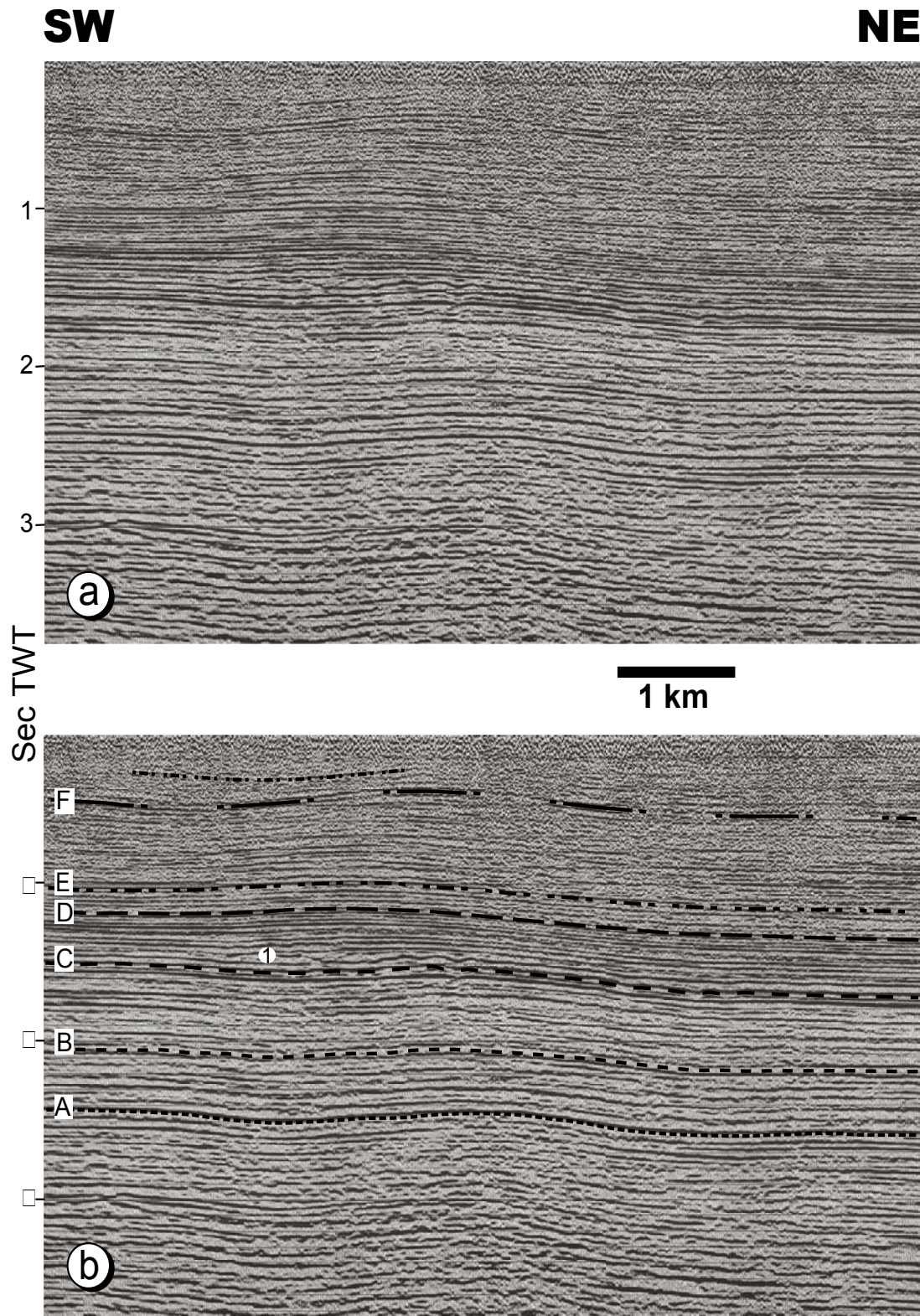


Fig. 4: Non interpreted (a) and interpreted (b) versions of a seismic profile cutting the periclinal termination of the Ab Teymur anticline (see location on Fig. 1). Vertical scale is in seconds of two-way travel time (TWT). The profile illustrates initial stage of folding. An incipient salt bulge is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

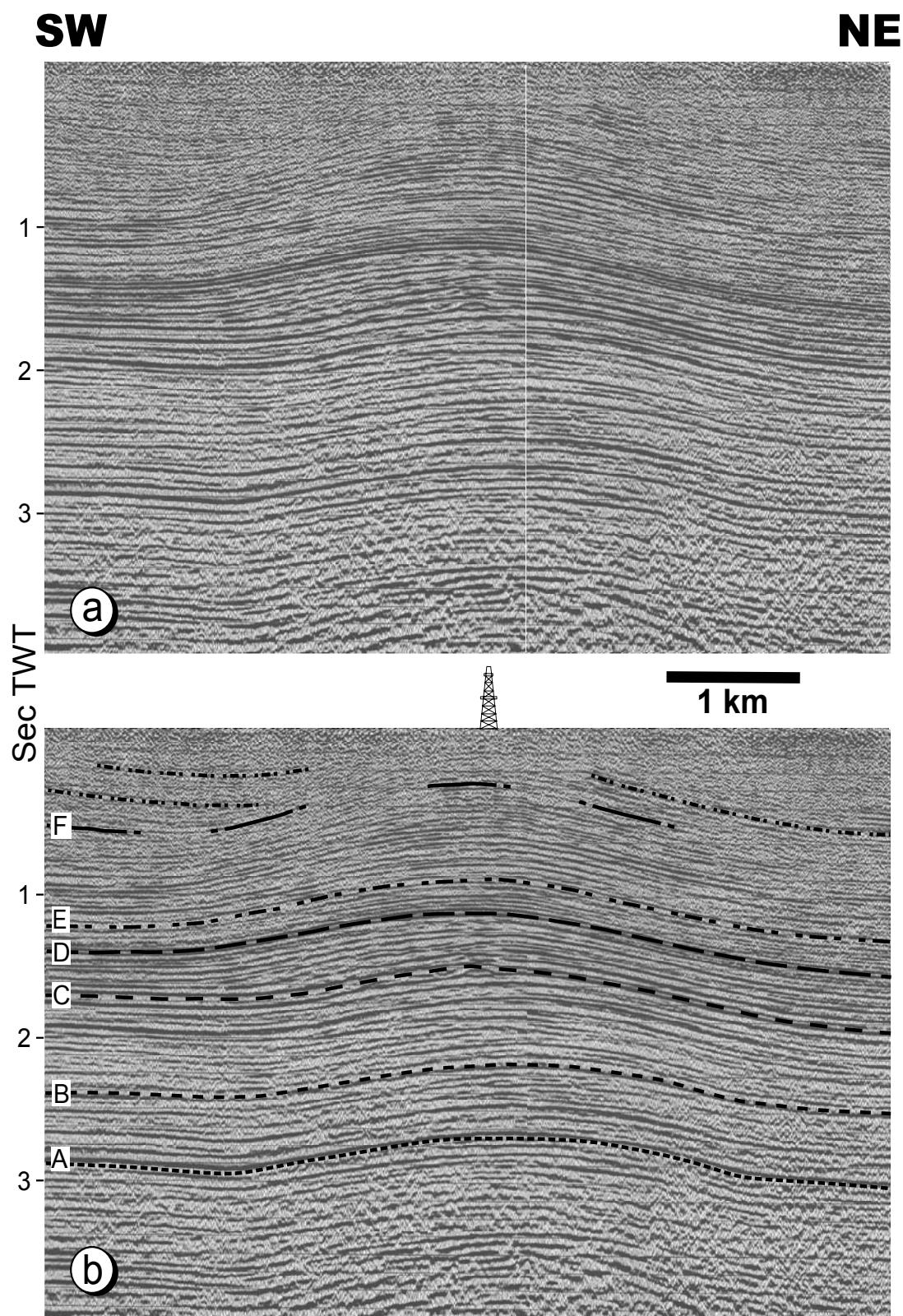


Fig. 5: Non interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Ab Teymur anticline (see location on Fig. 1). Vertical scale is in seconds of two-way travel time (TWT). By comparing with Fig. 4 and assuming that deformation increases from periclinal termination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

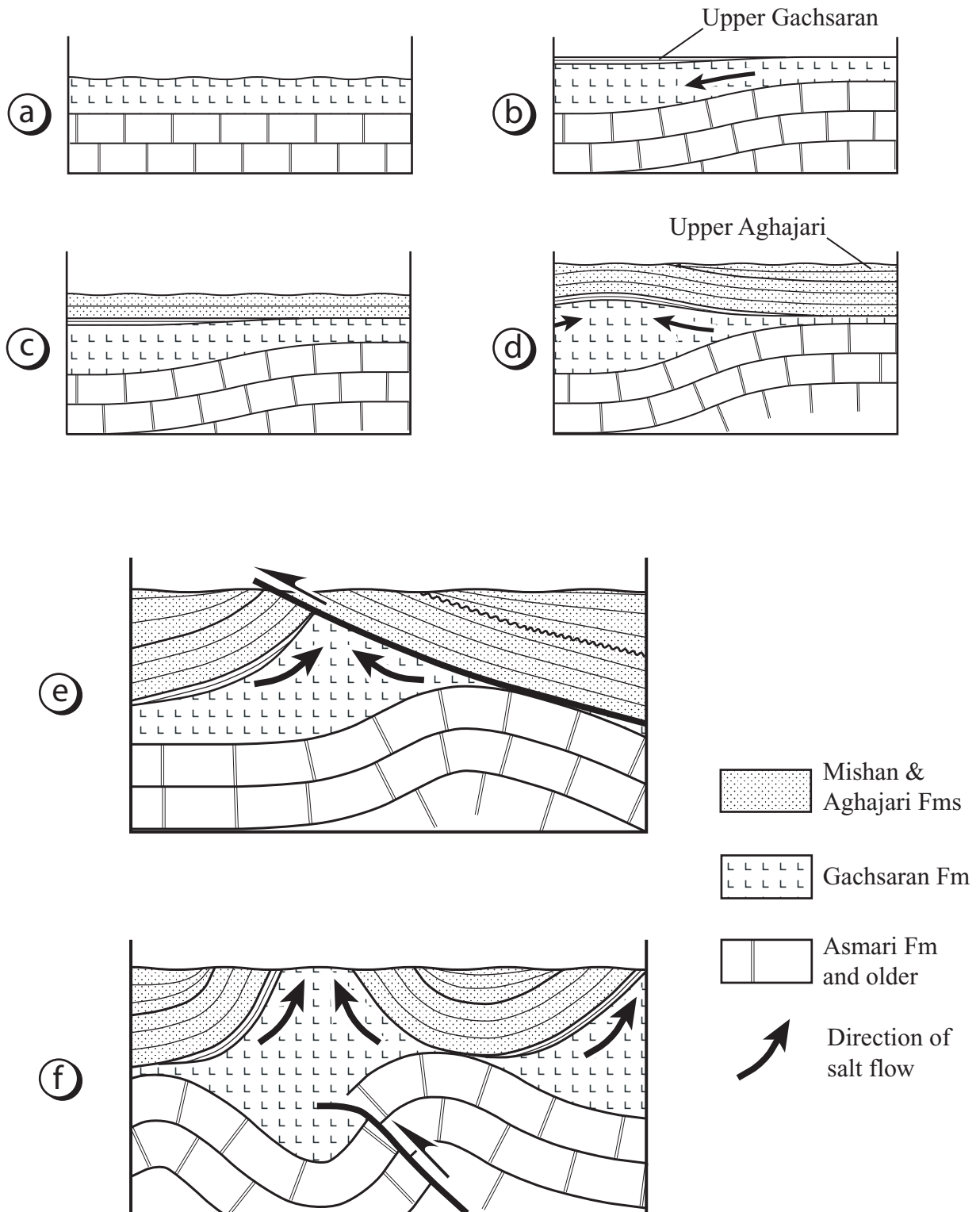


Fig. 6 Conceptual kinematic model explaining the two-step migration of the Gachsaran salt. A: initial stage, deposition of the Gachsaran salt; B: first folding step and coeval migration of the salt towards the intervening synclines during the deposition of the Upper Gachsaran; C: deposition of Mishan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

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

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

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

A very important observation is that the reflectors corresponding to the upper Gachsaran layers are pinched out along the crest and the northern limb of the southern anticline (Fig. 8).

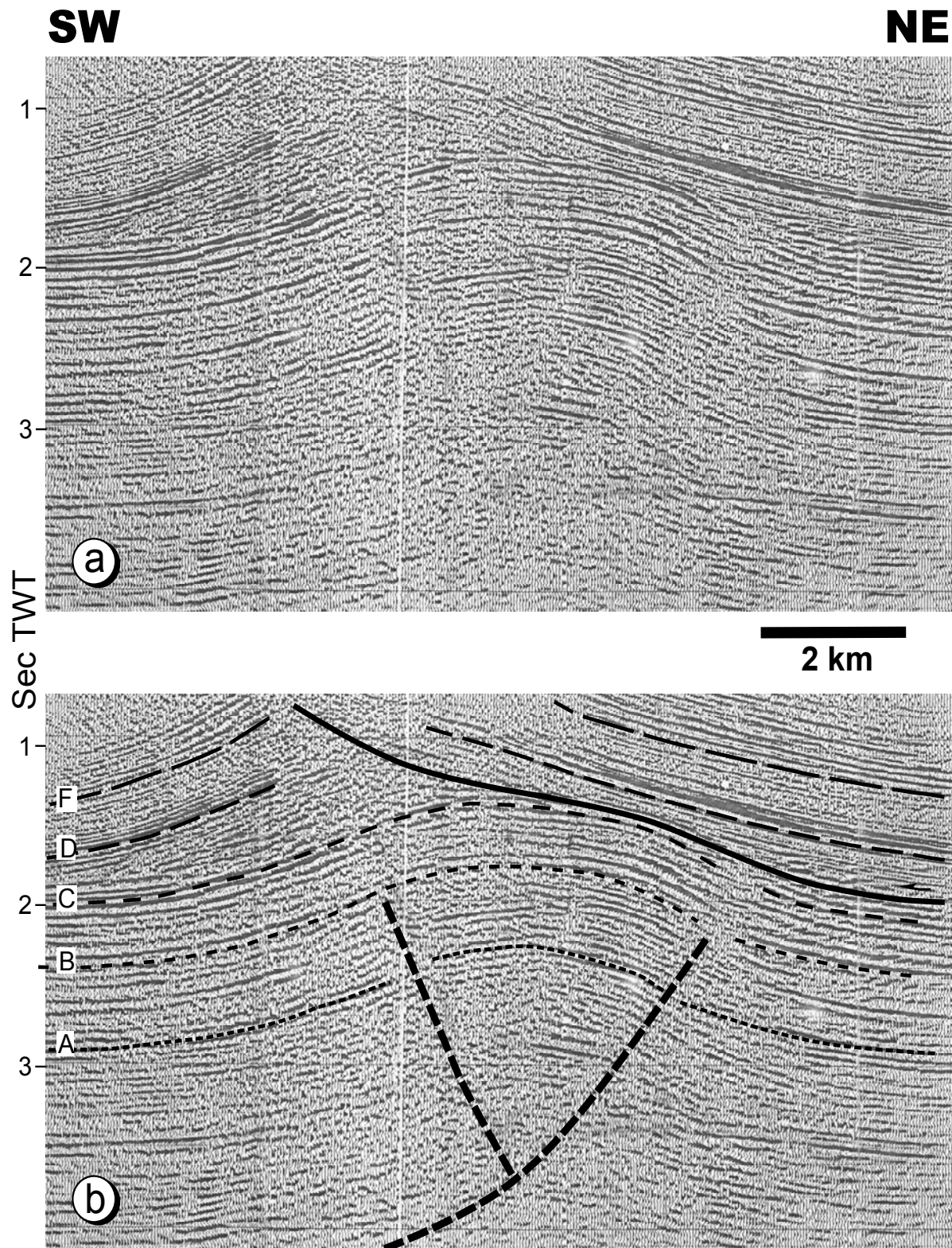


Fig. 7: Non interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Ahwaz anticline (see location on Fig. 1). Vertical scale is in seconds of two-way travel time (TWT). At this stage, a complete de-coupling between the incompetent and competent groups is observed. Note the development of the “salt bulge” along the forelimb of the anticline and, by contrast, the thinning (or even the absence) of the Gasharan Fm. along the backlimb and crest of the anticline. See 6E for the kinematic scenario. (Seismic horizons same as in Fig.4).

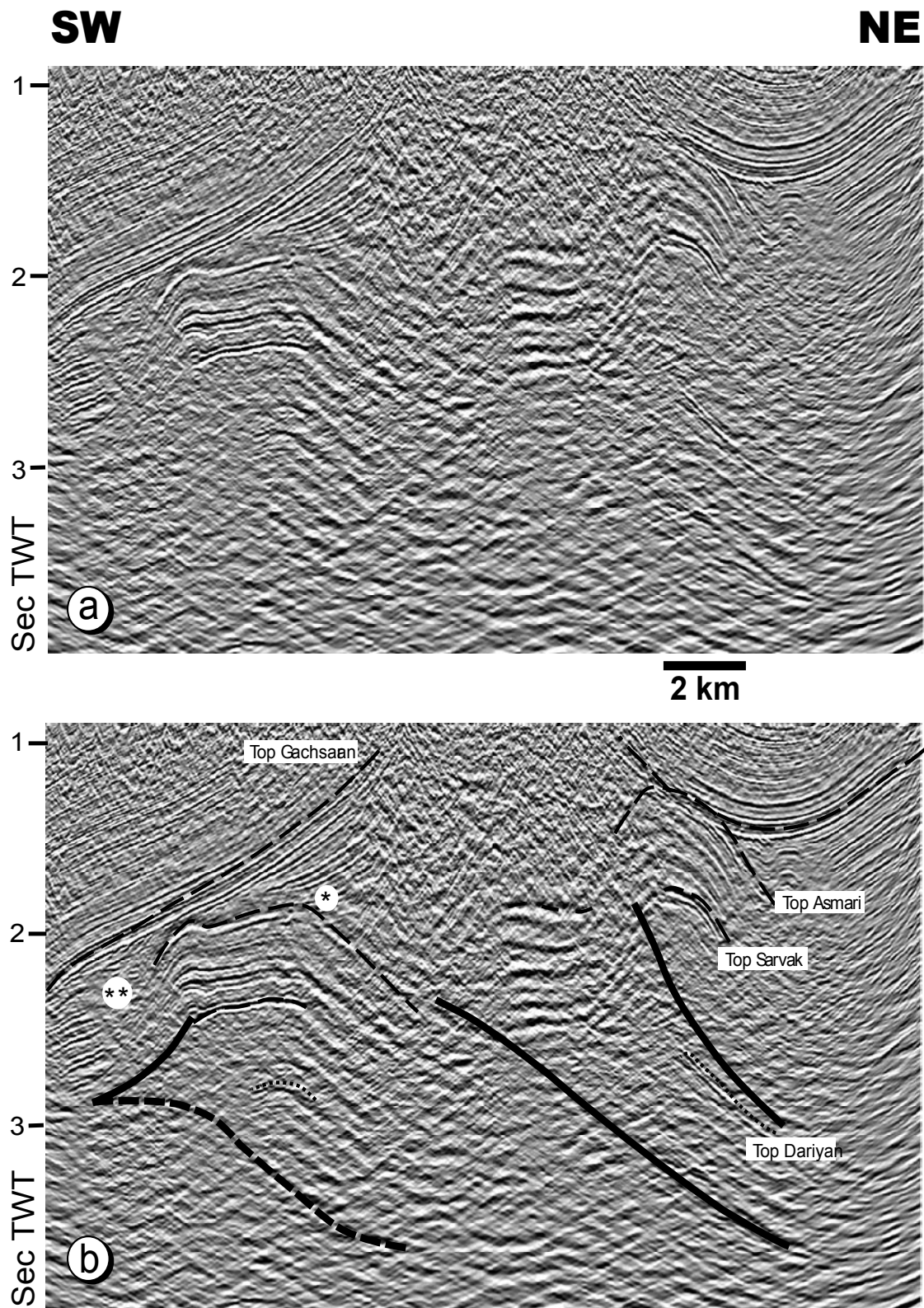


Fig. 8: Non interpreted (a) and interpreted (b) versions of a seismic profile cutting the central part of the Parsi and Karanj anticlines (see location on Fig. 1). Vertical scale is in seconds of two-way travel time (TWT). Note the considerable accumulation of salt within the salt bulge, leading to the development of an intervening surface anticline. Pinch out of the Upper Gachsaran seismic reflectors (labelled by a star) indicate that folding started in Middle Miocene times in this area. Small “rabbit ear” structure on the flank of the main anticline to the left show involvement of Gurpi marls as a secondary décollement level. At depth development of forelimb thrusts cutting through the Sarvak Fm. is observed. See Fig. 6 F for the proposed kinematic model.

This shows that, as suggested above, the salt, situated immediately below, had migrated before the deposition of the upper Gachsaran Fm in relation with a first folding event. Compared to the Gachsaran, the lower Aghajari Fm., situated immediately above, is more or less isopach suggesting that it deposited during a period of relative quiescence. Folding of the Aghajari Fm. accompanied by the extrusion of salt up to the surface (Fig. 6f) occurred only in a second step likely during the deposition of the upper Aghajari (not visible on the profile).

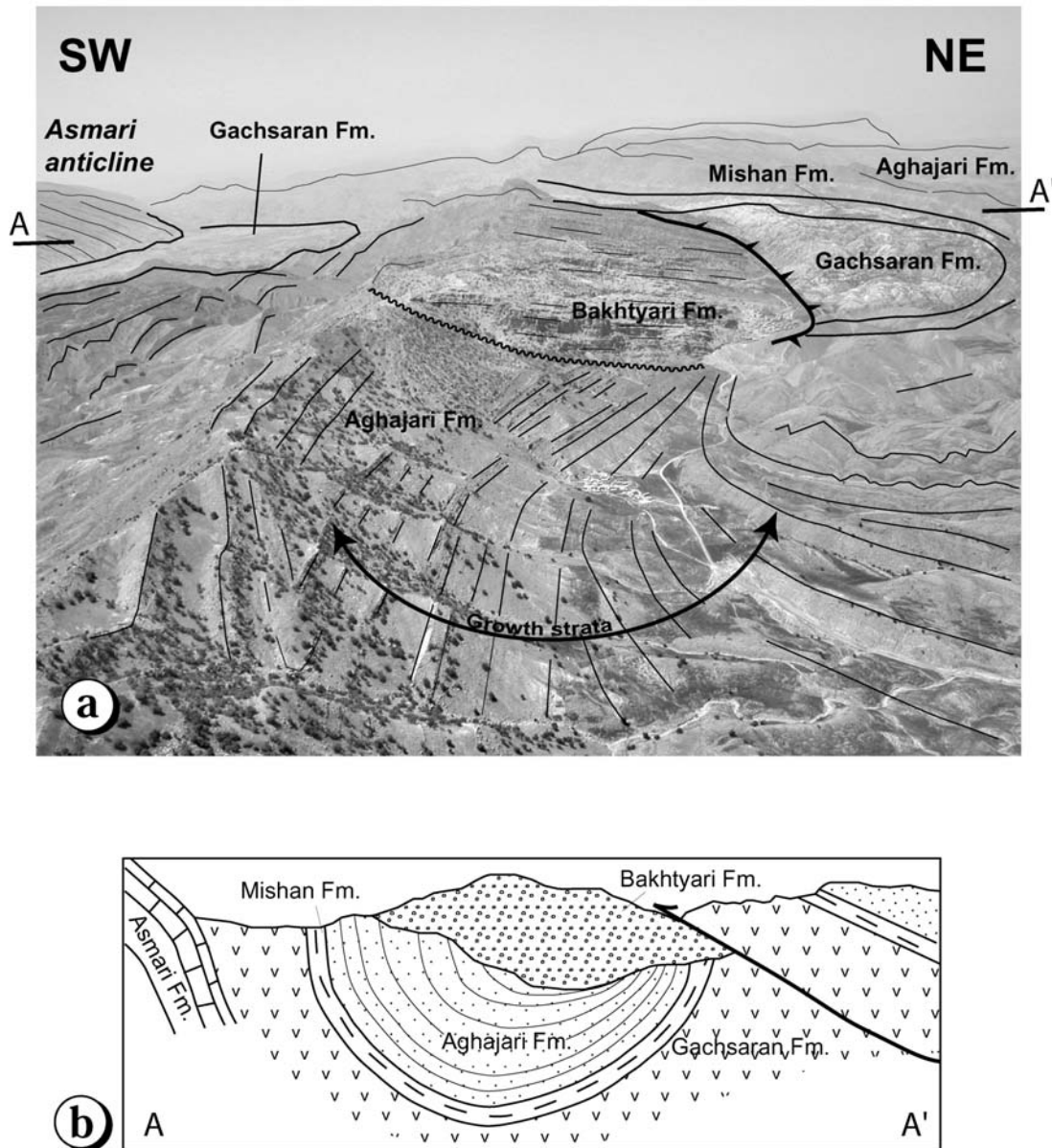


Fig. 9 (a) Photograph and (b) line drawing showing growth strata in upper Aghajari formation, which is unconformably overlain by Bakhtyari conglomerate and subsequently faulted. It shows that folding and faulting are not coeval. Some 20 Km south-west of Izeh city, north-east of Kuh-e-Asmari anticline (Looking NW, see Fig.1 for location map).

Field observation in the Dezful embayment permits us to illustrate and complete some of the topics discussed above. Growth strata in the upper Aghajari are exposed in numerous places (Fig. 9) confirming that, in this area, folding (in fact a second step of folding as shown above) occurred during the deposition of this formation. The conglomerates of the Bakhtyari Fm rest unconformably on already folded layers and are subsequently faulted (Fig. 9). This important geometric evidence, which has already been emphasised by Molinaro et al. (2004, submitted) and seems quite general at the scale of the Zagros, indicates that folding and faulting are not coeval but distinct processes separated by important erosion and widespread deposition of the Bakhtyari conglomerates. From this point of view, the folds of the Dezful, and more generally of the ZSFB, pertain to the category of “break-thrust” folds (Willis 1893) where folding precedes fault propagation.

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

Dahlstrom (1969) emphasises that concentric folding implies the existence of detachment levels separating concentrically folded structural units (Fig. 10). The necessity for a lower detachment is always evident but the role of an upper detachment is less frequently discussed (see Bonini (2003), Harrison & Bally (1988)). The Izeh zone provides surface structures allowing such a discussion.

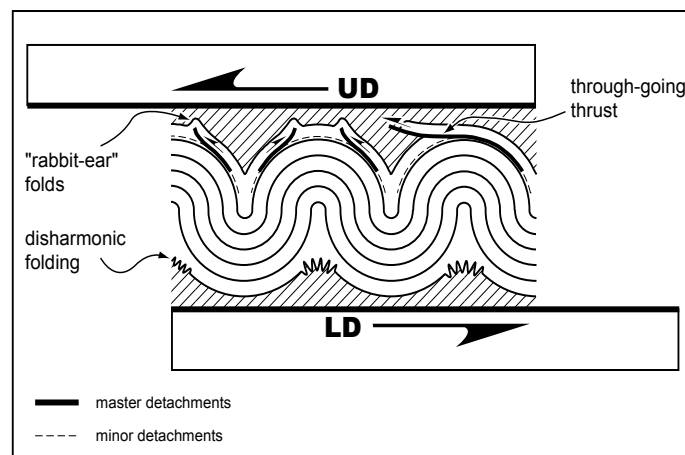


Fig. 10: Diagram illustrating why geometrically a train of concentric folds must be separated from the rocks above and below it by a detachment horizon (LD: lower detachment; UD: upper detachment) (modified from Dahlstrom (1969)). We have decorated Dahlstrom's ideal model with secondary features such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

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

Northeast of the town of Izeh, in the Darishk domain, the Kuh-e-Rig and Kuh-e-Dodurou structures (Fig. 11) form a pair of rounded anticlines underlined by the Asmari limestone and separated by a narrow syncline in which the lower Gachsaran Fm shows a tight but regular isoclinal geometry. For evident geometric reasons, the anticline pair was necessarily limited from the overlying rocks by a detachment horizon, which is the presently eroded upper mobile group. The concentric mode limits the thickness of the sedimentary sequence that can be folded together in the same structural unit (Colman-Sadd 1978, Dahlstrom 1969, Goguel 1952). So the Kuh-e-Rig and Kuh-e-Dudrou structures are also necessarily bounded by a lower detachment. Its precise location is difficult to assign. However, given the size of the anticlines, it is likely that the Hormuz salt, if present in the area, is too deep to constitute this lower limit.

The Balut-Boland anticline (Fig. 12) situated 25 km further south but already in the Darishk domain is a very tight chevron fold involving Sarvak limestone. Other similar anticlines have been observed in the area. Their shape requires that they are situated very close to the detachment active in this zone, which is most probably the Kazdhumī shales (Sherkati & Letouzey 2004). Interestingly, it can be noticed that the observation of broad anticlines with narrow synclines (Fig. 11) or, on the contrary, pinched anticlines (Fig. 12) and wide synclines is only dependent of the level of erosion above the Kazdhumī detachment.

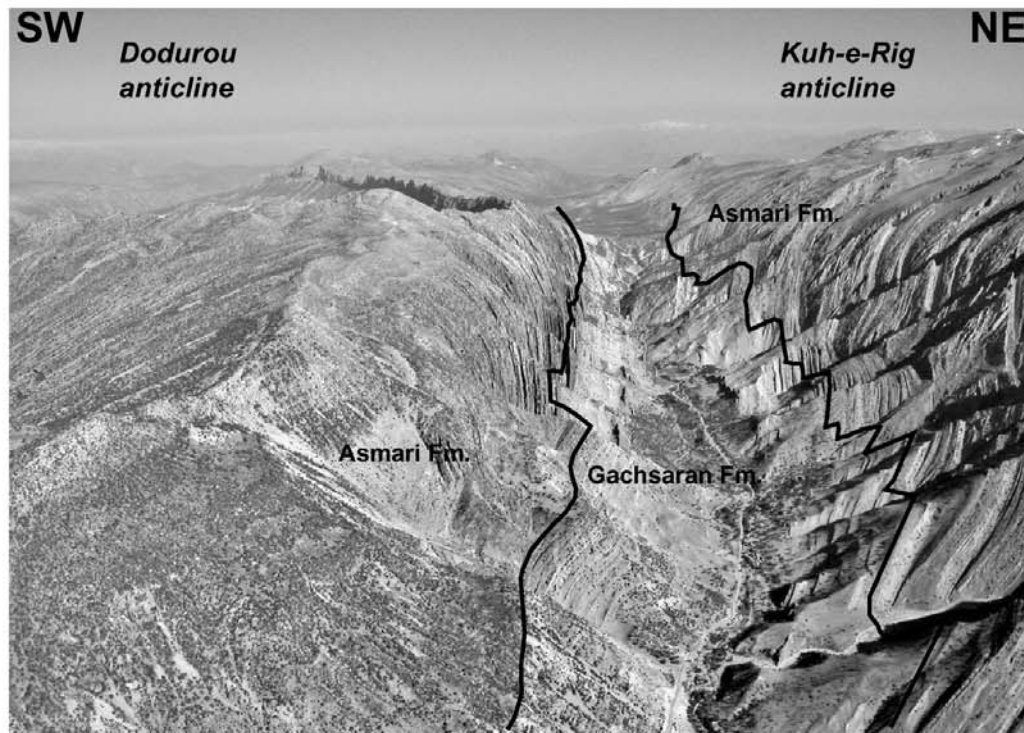


Fig. 11: (a) Photograph and (b) line drawing showing a tight and isoclinal syncline cored by the Gachsaran formation. Some 10 Km south of Lurdegan city (looking NW, see Fig.1 for location map).

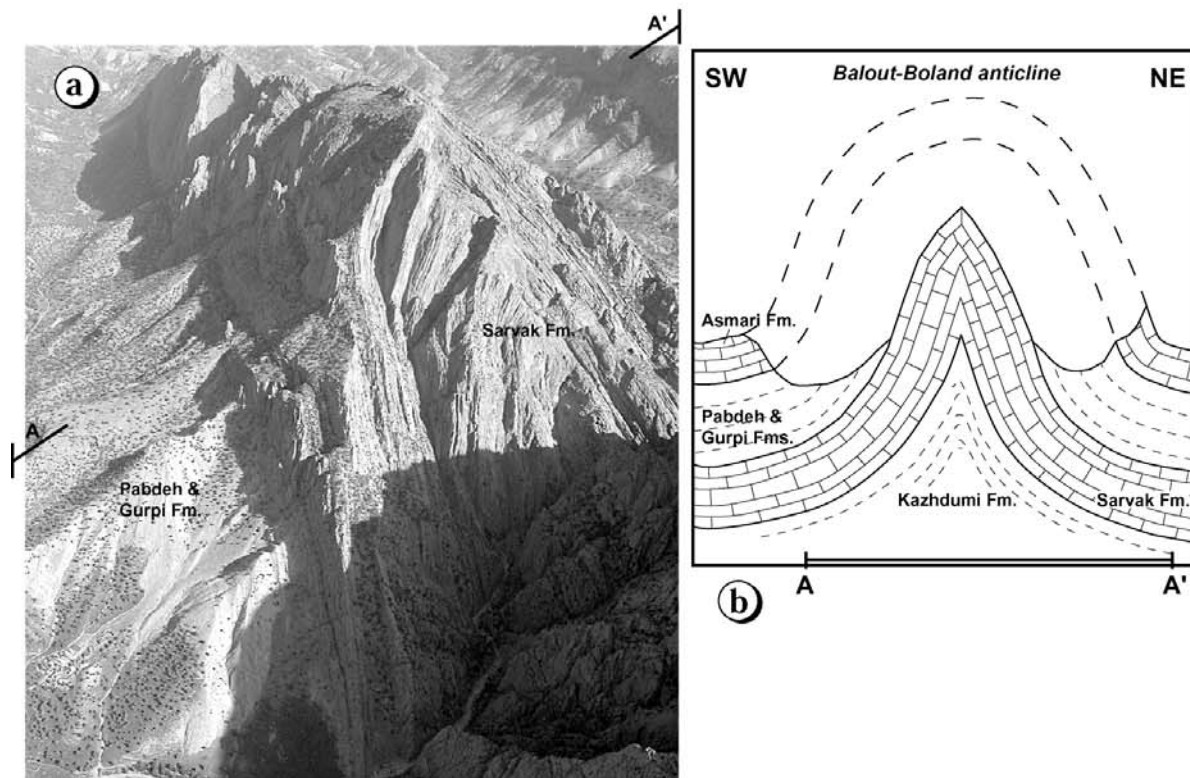


Fig.12: (a) Photograph and (b) line drawing showing a chevron type anticline in Cenomanian carbonate (Sarvak formation, 3.5 Km wavelength). Its shape indicates that the underlying Albian shales (Kazhdumi formation) should be acting as an efficient décollement level. Some 50 Km SE of Lurdegan city (looking NW, see Fig.1 for location map).

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

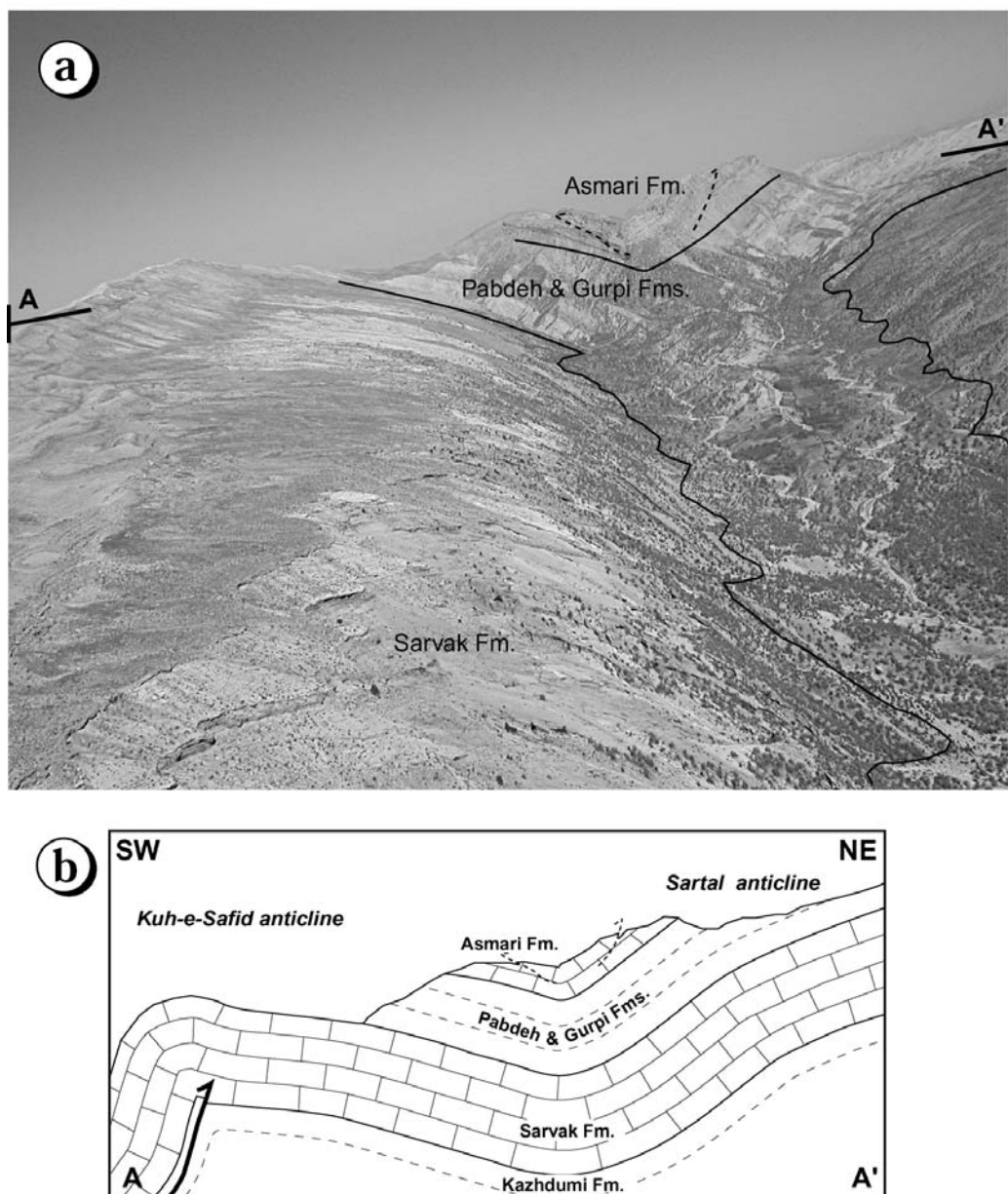


Fig.13- (a) Photograph and (b) line drawing showing very wide structures (6 to 10 Km wavelength) in Cenomanian carbonate (Sarvak formation) with minor effect of Albian shales as an intermediate decollement level (visible on the southern flank of Safid anticline). Their shape suggests a deeper intermediate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

In all these examples a striking characteristic is the absence or scarcity of thrust faults: not only major thrust faults controlling the geometry and kinematics of the folds but also subsidiary faults (the so-called “fold-accommodation faults”, (Mitra 2002)). Thus the folds presented above are “pure” detachment folds. As in the Dezful, continuing deformation resulted with the activation of secondary detachment levels. In particular, there are numerous field examples testifying the role of the Papdeh-Gurpi marls as a secondary detachment controlling the development of minor structures. Different cases can be separated:

- (1) In some examples, the sense of shear along the secondary detachment is toward the anticlinal hinge and, consequently, opposite in both limbs of the anticline. This leads to the development of convergent drag folds often associated with small thrusts (“rabbit ear” structures, (Dahlstrom 1970, Letouzey et al. 1995)) (Fig. 14).
- (2) In examples where the asymmetry of the anticlines is more accentuated, parallel-bed shearing along the backlimb is expressed by a flat thrust-fault propagating beyond the hinge and cutting through the steep forelimb (Fig. 15). Such structures mimic “forelimb thrusts” but are linked to the activation of a secondary detachment and not to forward shear of the whole front limb.

The activation of the Papdeh-Gurpi secondary detachment can also trigger the development of gravity collapse structures as long since recognised by Harrison & Falcon (1934, 1935). Among these structures the most spectacular and puzzling are certainly the so-called “flaps” defined by Harrison & Falcon (1934). Following these authors, a flap is “a part of limestone sheet, which has bent over backward without breaking” until a completely overturned position has been attained. We have observed such flaps in the Asmari limestone situated in front of the Tanowsh anticline (Fig. 16). For Harrison & Falcon (1934, 1935) flaps are purely gravitational structures resulting from the collapse of oversteepened flanks into eroded valleys. Following (De Sitter (1956), we think that they rather originated during folding. More precisely and following Saint Bézar et al. (1998), we consider that flaps are recumbent synclines born by collapse along the limbs of anticlines and accentuated during the migration of the synclinal hinges. In any case, the development of a flap structure requires the disruption by erosion of the Asmari layers involved in the structure (Fig. 17). This suggests that, in the Izeh zone, the folding process continued while the erosion process was already active.

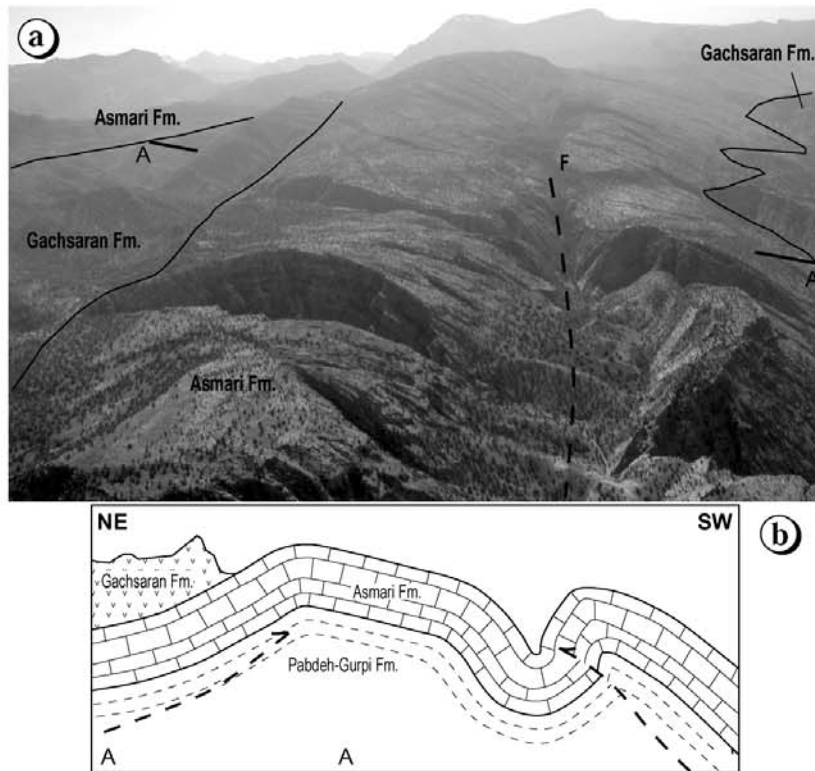


Fig.14: (a) Photograph and (b) line drawing showing an anticline in Oligo-Miocene carbonate (Asmari formation). Small rabbit ear structure in southern flank shows shearing along the intermediate décollement level (Eocene marls, Pabdeh formation) toward the hinge of the main anticline. Some 35 Km south-east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

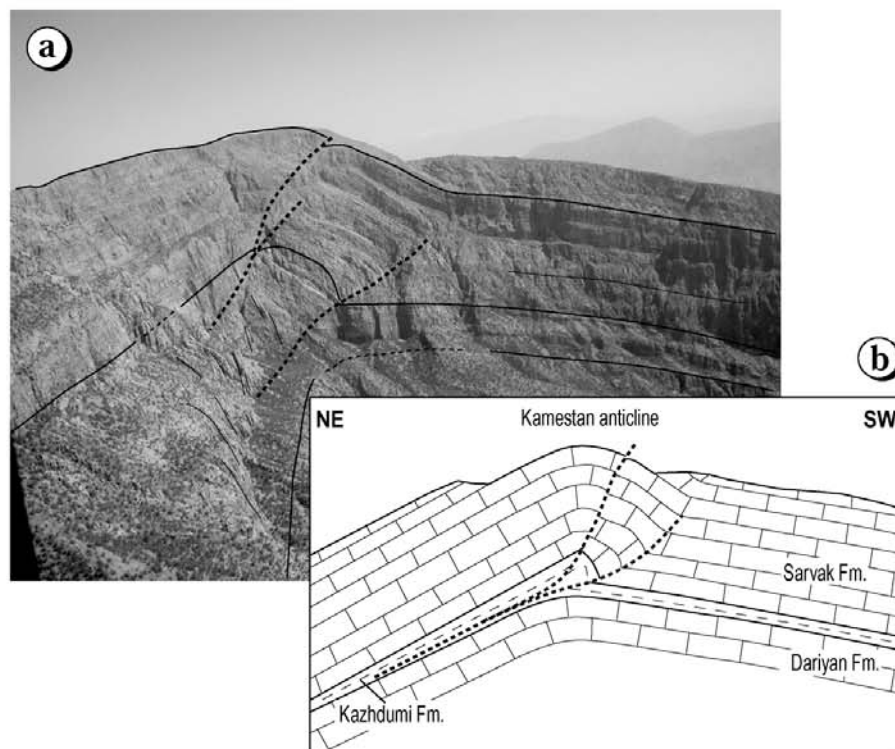


Fig.15: (a) Photograph and (b) line drawing of the Kamestan anticline in Cenomanian carbonate (Sarak Fm.). This structure illustrates forelimb thrust at an initial stage of development with activation of the Kazhdumi shales as an intermediate décollement level. See Fig. 10 for the conceptual model.

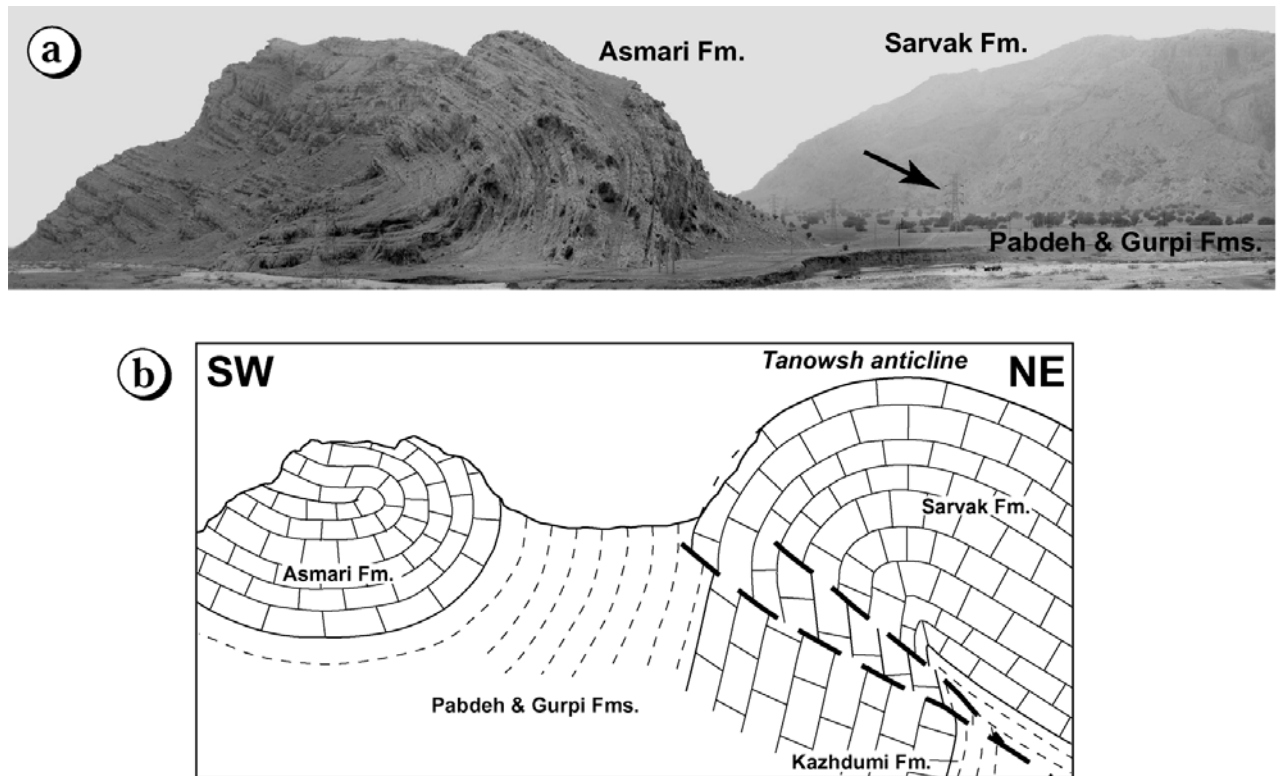


Fig.16: (a) Photograph and (b) line drawing showing a recumbent syncline in Oligo-Miocene carbonate (Asmari formation). Some 15 Km south-east of Izeh city (looking NW, see Fig. 1 for location map). Such structures had been already described as gravity collapse structures and named "flaps" by previous workers (Harrison & Falcon 1934). In our interpretation flaps are born by collapse along the limbs of anticlines and accentuated during migration of the synclinal hinge (see Fig. 17 for the proposed kinematic scenario). So its development requires disruption by erosion of the Asmari carbonate.

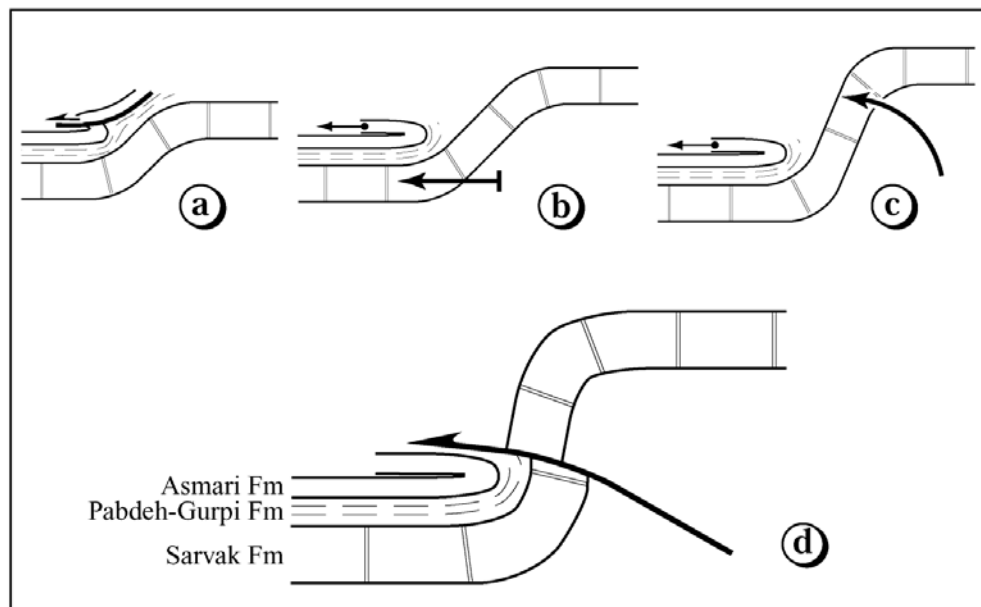


Fig. 17: Conceptual kinematic model explaining the development of a flap in front of a growing anticline. A: initial stage characterised by collapse along the front of the anticline; B: flap development by rolling up in front of a migrating hinge; C: limb rotation and progressive blockage of the forelimb;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

This situation contrasts with the one observed in the Dezful (see above) where onlaps observed on both sides of the anticlines (Fig 4; Fig. 6) suggest that fold uplift rate was slower than regional subsidence.

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

Due to its current seismic activity (Berberian 1995), it is generally acknowledged that the crystalline basement is involved in the ZSFB and, in particular, along the Mountain Front and High Zagros faults (Fig. 1). Another argument proving the involvement of the basement is the strong difference of the level of exposure of the sedimentary cover from one side to the other side of these major faults. This is particularly evident in the Central Zagros, between the Dezful Embayment and the Izeh zone, where the Mountain Front Fault is marked by a considerable step (about 3km) in the elevation of the same formation (Sherkati & Letouzey 2004). A similar step exists between the High Zagros, where Palaeozoic rocks are outcropping, and the Izeh zone where the older rocks are of Jurassic age (Sherkati & Letouzey 2004). However, as the basement faults are blind and strike parallel to the main surface structures, their timing and precise role in the deformation are very difficult to discuss in the Central Zagros. In the eastern Zagros, by contrast, the basement faults cut obliquely previous detachment folds (Molinaro et al. 2004, submitted) giving birth to spectacular interference structures, which are very informative.

Compared to O'Brien's (1950) general mechanical stratigraphy (Fig. 3), the Eastern Zagros presents the following characteristics: (1) a thick and very efficient lower mobile group (Hormuz salt), largely extruded by diapirs, (2) the absence of efficient intermediate detachments within the competent group and (3) an upper mobile group represented by the Mishan marls (absence of Gachsaran salt) (Fig. 3). This upper detachment seems to have acted as an upper flat connected through ramps to the Hormuz salt (Molinaro et al. 2004, submitted) but does not appear efficient enough to allow the deformation above and below it to be completely decoupled. In other words, in the Eastern Zagros, the competent group and the above-lying molasses are folded harmonically in very broad anticlines. Mesozoic or older rocks are exposed in the cores of the anticlines whereas molasses and Bakhtyari conglomerates are preserved in the synclines. Secondary detachments, located in the Razak

and Gurpi Fms, are responsible for spectacular collapses of the overlying Guri and Jahrum limestone respectively (Fig. 18). However, we never observe flaps as in the Izeh zone.

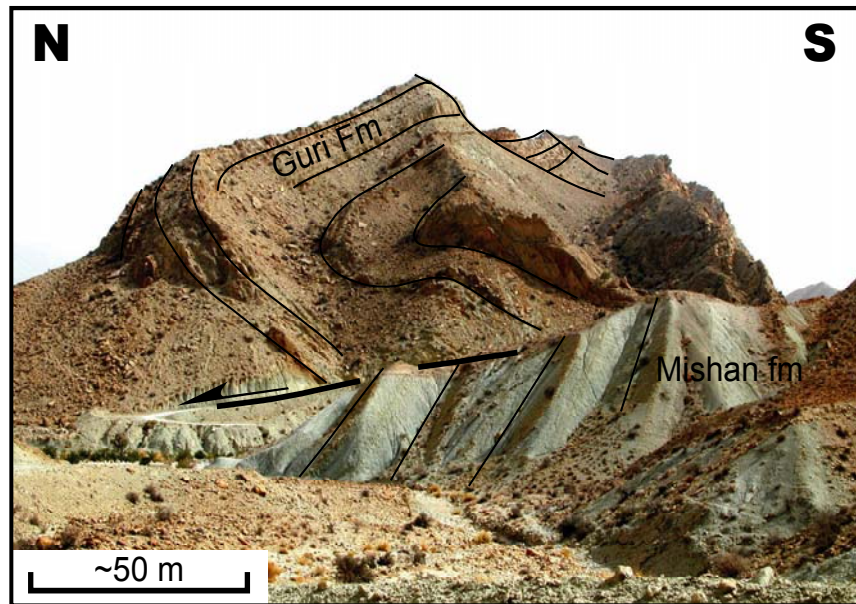


Fig. 18: Photograph of a gravity collapse structure on the northern limb of one of the larger anticlines in the Bandar Abbas area. Location in Fig. 1.

In order to discuss the role of the basement we will focus on one of the three giant en-échelon structures (Jain, Faragun and Kuh-e-Khush anticlines, Fig. 19 A) extending NW-SE from Hadjiabad to Minab (Molinaro et al. 2004, in press). These structures, which belong to the High Zagros belt, underline segments of the High Zagros Fault. In map view, the Kuh-e-Khush anticline exhibits a particular shape mimicking a butterfly (Fig. 19 B). This pattern results from a two-step evolution with a late basement fault cutting through an already formed detachment fold (Fig. 19 C) (Molinaro et al. 2004, submitted).

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

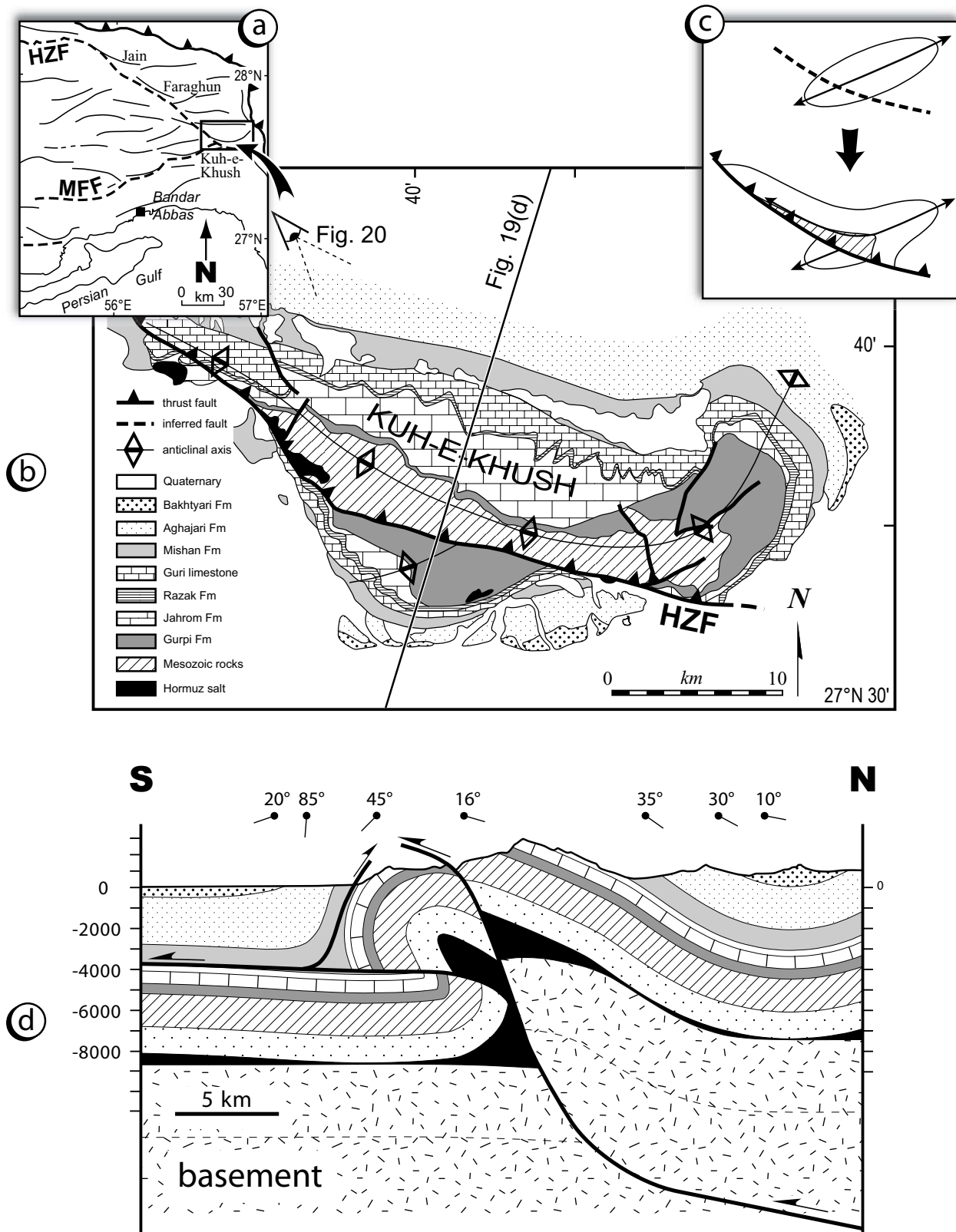


Fig. 19: The Kuh-e-Khush anticline in the Bandar Abbas area A : Location map (see also Fig. 1) ; B: Detailed geological map based on existing geological maps (NIOC 1999), SPOT satellite image and authors fieldwork. Note the obliquity between the HZF basement fault and the axis of the former detachment fold; C: The two-staged evolution of the Kuh-e-Khush structure as suggested by its map pattern; D: Balanced cross-section through the Kuh-e-Khush anticline. Line of section in Fig. 19 B.

A cross-section through the Kuh-e-Khush anticline (Fig. 19 D) suggests that the basement fault (i.e. the High Zagros Fault) initially connected with the upper mobile group (Mishan marls), as indicated by the triangle zone developed frontally, and subsequently cut through the crest of the anticline. This final stage resulted with a monoclinial structure culminating at 2400 m (Fig. 20).

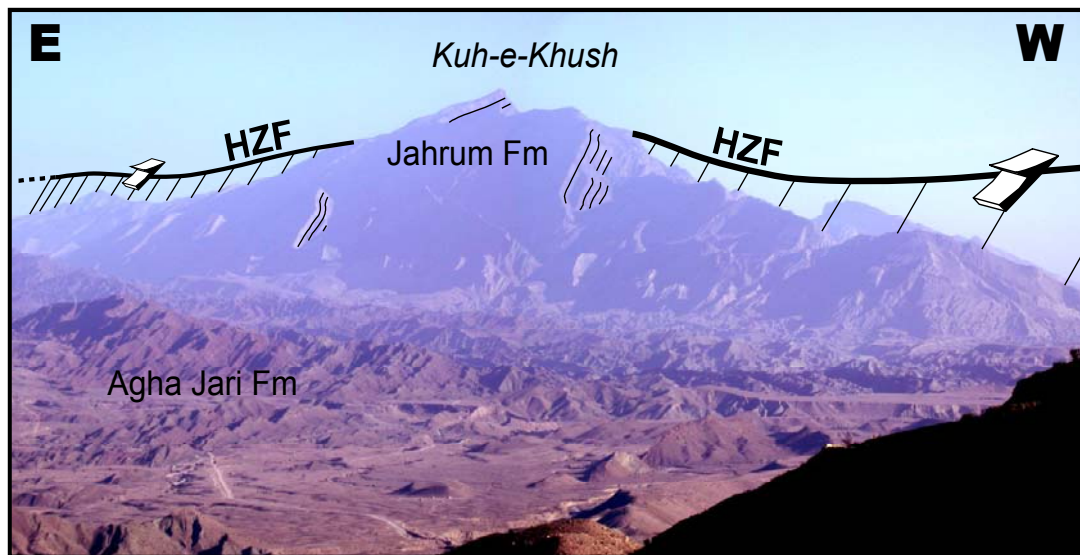


Fig. 20: Photograph of the northern limb of the Kuh-e-Khush anticline. Viewpoint in Fig. 19B

It is not sure that all thrust faults are directly or indirectly linked to basement faulting. A possibility is that some of them represent an ultimate evolution of detachment folding related to a complete depletion of the salt at the base of the synclines and their subsequent “touchdown” upon the basement. In any case, it is established that faulting occurred at late stages of the evolution and frequently after the deposition of the Bakhtiari conglomerates.

2.5. Discussion

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

First of all, we demonstrate that folding in the Zagros occurred by steps rather than a continuous process. In the Dezful Embayment, a first step (pre-Upper Gachsaran) is shown by the early migration of the Gachsaran salt from the crests of incipient anticlines towards intervening synclines. The mechanisms responsible for this early migration of the Gachsaran

salt are very different from the ones explaining the mobility of the Hormuz salt or the later Gachsaran salt migration. In the first case, we have to invoke flow by gravity along the topographic surface whereas, in the second case, diapirism is, as classically admitted, an active process (Fig. 6). This difference is very important and is the key to understand the particular geometry known in the Dezful since O'Brien's (1957) work and characterised by superficial synclines chocked at depth against crests of anticlines (Fig. 8).

A second step in the development of folds in the studied areas is demonstrated by growth strata observed in the Upper Aghajari Fm., which, according to recent magnetostratigraphic studies from the north-west Dezful, was deposited during the Upper Miocene (Vergés et al. 2003). This step is sealed by the widespread deposition of the coarse conglomerates of the Bakhtiari Fm. The third and last step corresponds to folding and faulting of the Bakhtiari Fm.

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

In agreement with Mitra's (2003) unified kinematic model of detachment folds, we have presented different arguments showing that both hinge migration and limb rotation are active during folding. A first line of evidence comes from the comparison between different sections showing that fold development is accompanied by increasing wavelength and limb dip of the folds. The development of second-order structures, such as flaps (Fig. 16; Fig. 17), furnishes strong evidence for hinge migration. Finally, the late activation of secondary detachments (Fig. 7; Fig. 12) and the development of forelimb thrusts (Fig. 8; Fig. 15; Fig. 17) suggest that limb rotation was mostly active during the final stages of folding as a consequence of merging

of the hinges of two adjacent synclines or, more drastically, “touchdown” against the basement

In the studied areas, basement faults only developed at a late stage of the fold evolution (Molinaro et al. 2004, submitted, Sherkati & Letouzey 2004) corresponding to the third step of our scenario. This is clearly demonstrated in the Eastern Zagros where out-of-sequence basement thrusts cut at oblique angles through earlier thin-skinned structures (Fig. 19). However, it is not yet completely understood why the basement faults cut preferentially the forelimb of pre-existing anticlines and not randomly as one would expect for out-of-sequence thrusts. More generally, the reason for this abrupt change from thin-skinned to thick-skinned tectonic style remains a matter of debate. Molinaro & Zeyen (2004, submitted) suggest a possible relationship with slab break-off, and correlative uplift, below the Zagros orogenic belt. This hypothesis must be confirmed, however it gives a consistent explanation for the following processes: (1) global uplift of the Zagros, (2) complete change in the sedimentary environment with transition from fine-grained silicilastics to Bakhtiari conglomerates and (3) development of basement faults.

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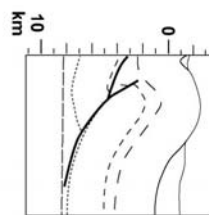
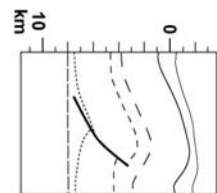
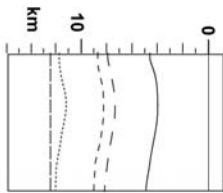
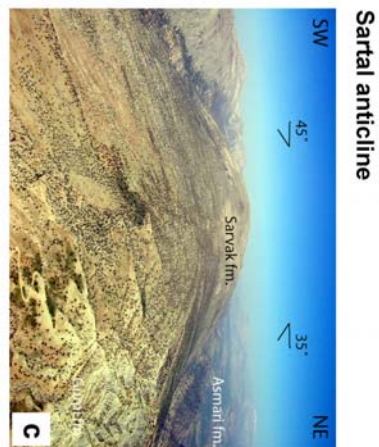
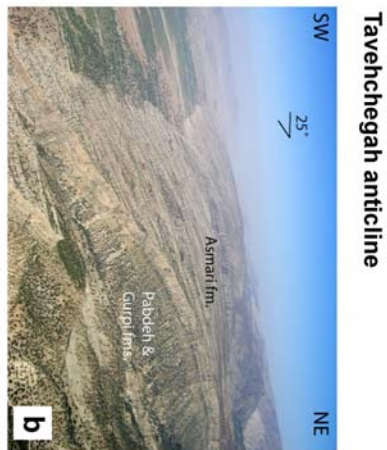
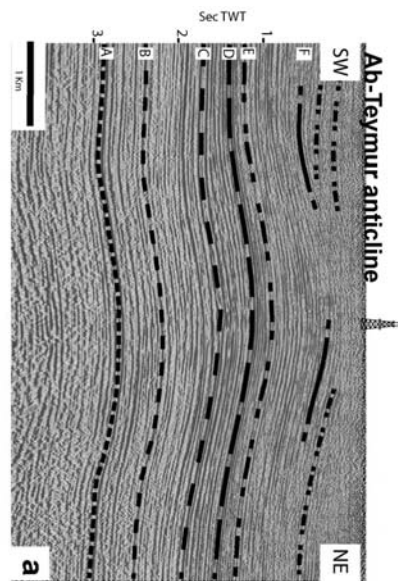
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3. COMPLEMENTARY REMARKS (paragraph in collaboration with S. Sherkati)

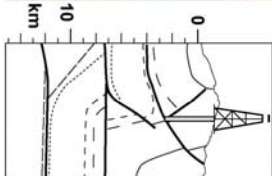
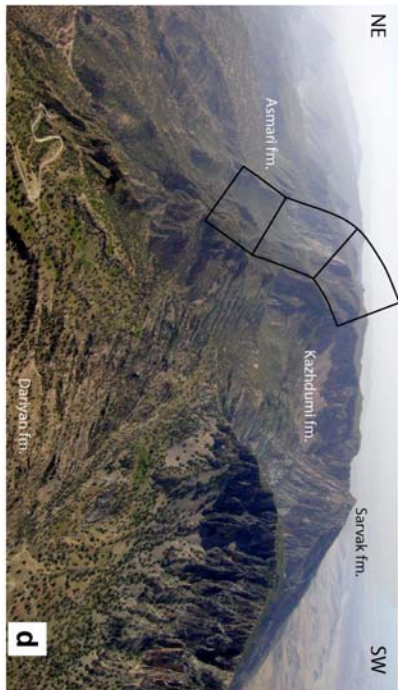
3.1. *Kinematics of Zagros detachment folds based on field examples*

Different stages of fold development in Zagros Mountains were explained in paper n° 3 based on seismic profiles. Here we illustrate these stages of development based on field examples from different parts of Zagros. Gentle detachment folds without any intervening thrust fault show the initial stage of folding (eg Ab-Teymur anticline, Fig. IV—9a). The fold wavelength at this stage is controlled by thickness of the competent units as already mentioned by Currie et al (1962). Folds with small amount of contraction in Zagros foreland show high wavelength-amplitude ratio on the order of 10:1 (eg Ab-Teymur see paper n° 3 and Fig. IV—9a). Increased shortening results in fold growth and decrease of the wavelength-amplitude ratio by hinge migration and fold tightening (eg Ahwaz, Tavehchegah and Sartal anticlines, Fig. IV—9b & c). The mechanism of fold growth seems to be very similar to the faulted detachment fold model discussed by Mitra (2002). Anticlines at the primary stage of contraction are almost symmetric but gradually become more asymmetric during fold development. Most of the limb rotation occurs on the front limb of the structures.

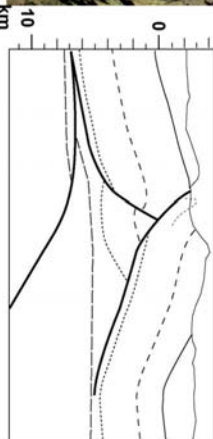
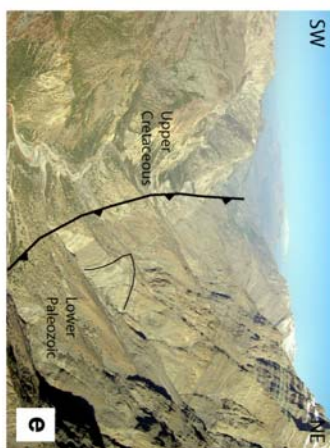
Progressive deformation causes shearing associated with fault propagation through the sedimentary pile to accommodate shortening specially in lower levels. Movement on the major fault controls subsequent evolution of the fold (Mitra 2002). The breakthrough of the major fault may take a variety of different paths (Fig. IV—9d & e). In a sedimentary pile without any intermediate ductile unit, the major thrust propagates through all the units and connects to the basal decollement level (Fig. IV—9e). In this case, thrust faults with major displacement are seen at the surface, and can place even Paleozoic rocks on the Tertiary sediments. Folds in this case present their maximum anticline size (15 to 20 Km wavelength). Involvement of intermediate ductile units could absorb fault propagation and block folds from increasing in size (Fig. IV—9d). Folds in this case are tighter and smaller in the superficial horizons and their size changes as a function of the depth of the intermediate decollement level. Back-limb steepening is a significant geometrical characteristic of the Zagros folds, which accelerates in the more progressed stages of deformation.



Kuh-e-Bangestan anticline

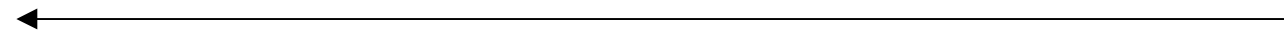


Kuh-e-Sabzu anticline



Top Sarvak formation
Top Triassic evaporite
Top Paleozoic
Top basal decollement level
Top Basement

Fig. IV—9 a) Seismic profile of Ab-Teymur anticline, showing an early stage of detachment folding in Zagros. b) Tavehchegah anticline presents a Zagros fold with small amounts of contraction. c) Sartal anticline with steeper flanks and larger anticlinal area shows a more progressed stage of deformation. Limb rotation and hinge migration seem to be essential mechanisms in fold development. d) Bangestan anticline shows more shortening and also steeper flanks. Flank steepening causes instability in the ductile units and favours activation of intermediate decollement levels and development of thrust faults. In this case the size of fold is a function of the thickness of competent units above intermediate decollement level. Limb segment rotation is seen in northern flank. e) Kuh-e-Sabzu anticline shows the ultimate stage of deformation. All sedimentary units are cut by a thrust fault and Lower Paleozoic series rest on Upper Cretaceous sediments. Absence of intermediate decollement levels allowed the fold to achieve its maximum size (15km wavelength).



3.2. *Timing of folding in Zagros orogenic belt*

The pinch out of the Upper Gachsaran seismic reflectors (Middle Miocene) towards the crest of the main anticline was taken as evidence for the initial stage of folding in Dezful Embayment (see paper in this chapter). Deposition of isopach younger horizons (Mishan and Lower Aghajari formations) continued until Upper Aghajari where growth strata shows onset of the main phase of the folding in Upper Miocene. Hessami et al (2002b) based on local older unconformities suggested that a first phase of folding (at least in part of the North Fars) started in Early Oligocene time. He mentioned also an Early Miocene phase of folding for the North Izeh zone but failed to present any evidence for this interpretation.

Field observations in North Izeh zone show some interesting sedimentological features (buildup and unconformity) at the top of structures in Upper Asmari formation (Fig. IV—10,11&12). These evidences support Hessami et al's (2002b) idea for the Early Miocene initiation of folding in the north of Izeh zone. Fig. IV—10 shows the central part of Lapeh anticline (NW of Izeh city, refer to appendix 5 for location map) close to the High Zagros fault. This anticline is cored by Pabdeh and Gurpi formations, exposed in deeply eroded valleys. Reefal facies of Upper Asmari carbonate at the top of the structure could be related to the probable early phase of structuring at Early Miocene time, which caused local water depth shallowing and favored development of reefs at top of the structure. A close up of this feature (Fig. IV—11) shows "onlap" of Upper Asmari carbonates toward the crest of the anticline.

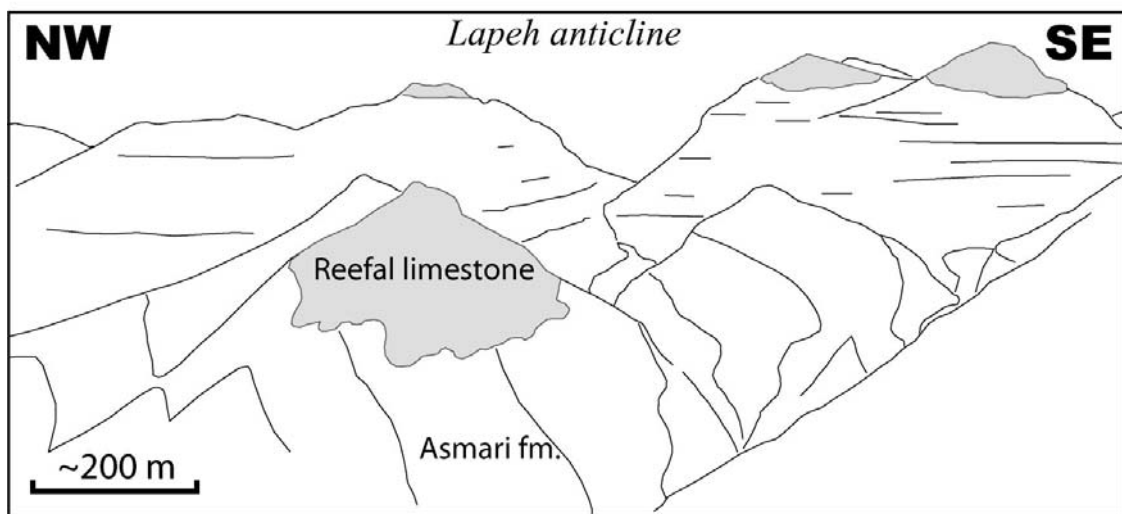


Fig. IV—10 Photograph and line drawing from Lapeh anticline, 50Km north of Izeh city (refer to appendix 5 for location map). It shows Upper part of Asmari carbonate change to reefal facies at the top structure. Such structure suggest that folding began as early as Early Miocene time in this area.

Fig. IV—12 presents a small structure north of Payun anticline, north of Izeh zone (refer to appendix 5 for location map). It also shows an unconformity in Upper Asmari carbonates towards the crest of the anticline. However it should be noticed that presented interpretations are not unique and one may relate these structures to simple sedimentological mechanisms. However their relationship with the anticlines strongly suggests a tectonic control.

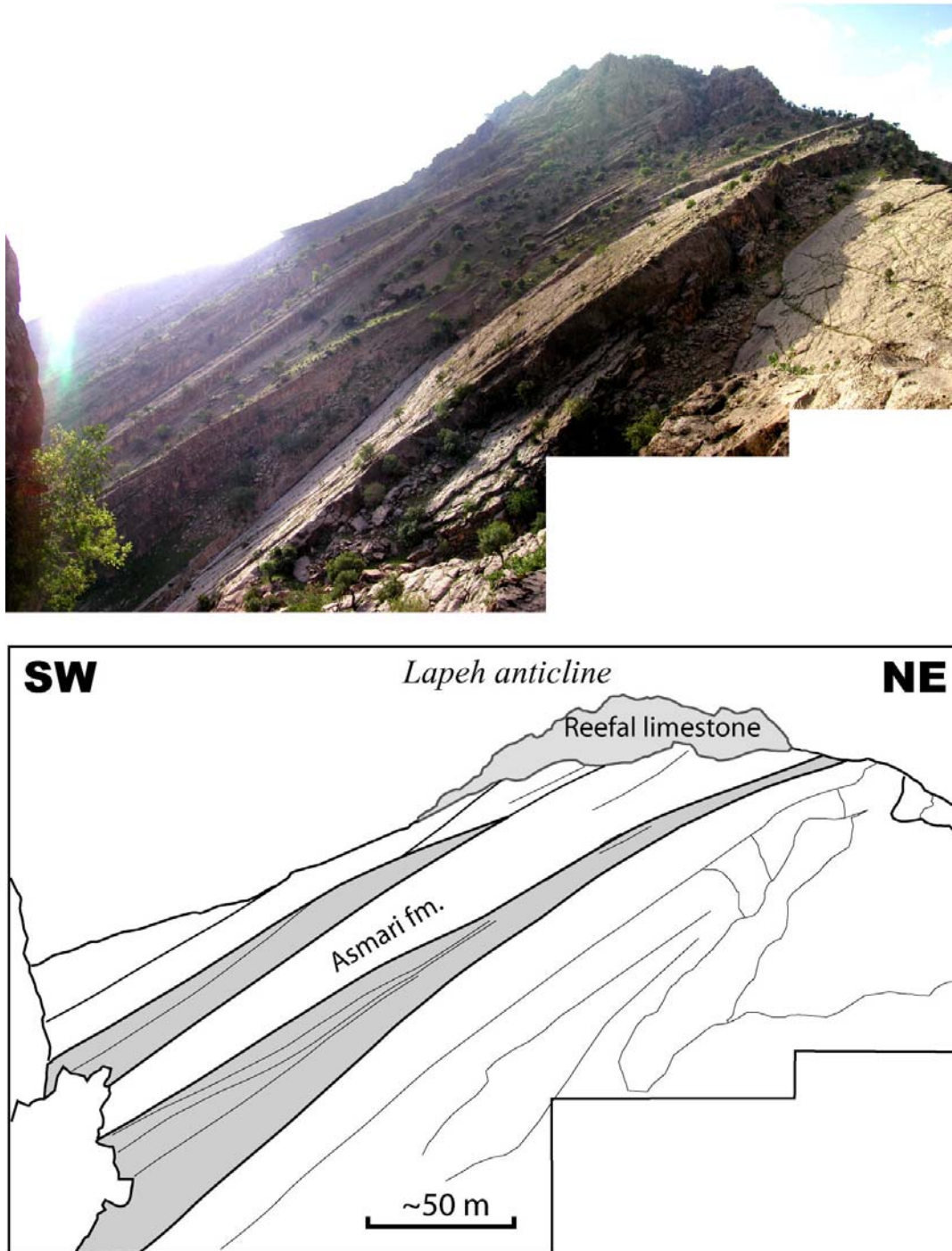


Fig. IV—11 Photograph and line drawing from southern flank of the Lapeh anticline, 50 Km north of Izeh city (refer to appendix 5 for location map) showing "on lap" of Upper Asmari carbonates towards the crest of the anticline.



Fig. IV—12 Photograph and line drawing from small structure north of Payun anticline (see appendix 5 for location map). It shows local unconformity in Upper Asmari carbonates towards the crest of the anticline. It could be related to the probable Early Miocene onset of folding. Shale layers above unconformity are dated as Burdigalian using Nanofossils (age determination by Carla Muller).

3.3. *Influence of intermediate decollement level on fold geometry*

This paragraph is completely dedicated to intermediate decollement levels and their influence on fold style. In this part we present some field observations and interpretations regarding ductile units within sedimentary pile, further illustrating the role of intermediate decollement levels on geometrical characteristics of the Zagros folds.

Most of Zagros folds are associated with a variety of primary and secondary geometrical features. These features are mostly related to the influence of intermediate decollement levels. Some of these features are seen in field or geological maps and some others are encountered in wells and seismic profiles. The most common variants in the geometry of these secondary structures associated with intermediate decollement levels are shown in Fig. IV—13. They are “rabbit ear” structures and axial shift from superficial crest to depth.

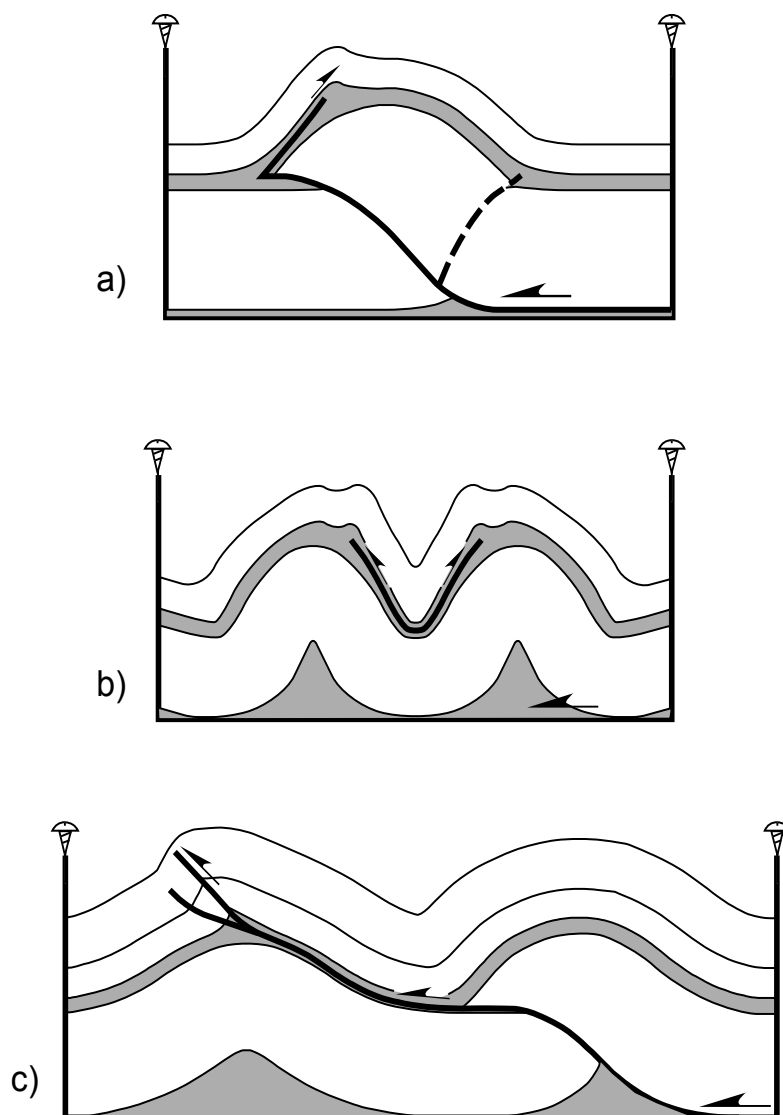


Fig. IV—13- Variation in structural styles of most common secondary structures associated with main folds and related to the occurrence of multiple décollements. a) Secondary décollement enables imbrication and under thrusting, which produced “rabbit ear” structures on forelimb of the main folds (Letouzey et al 1995). b) Space problem in tight synclines and sedimentary succession with differential layer parallel strain produce secondary small structures on both flanks of the main folds (Dahlstrom 1970 and Mitra 2002). c) Intermediate décollements allow the transfer of shortening from one structure to another. Tightening of the fold above secondary décollement and steepening of the forelimb cause axial shift from surface to depth.

“Rabbit ear” structures are a geometrical feature which has long been reported from Zagros mountains (Fig. IV—14). Mechanical and geometrical mechanisms to produce these kind of structures were also explained by several authors (Dahlstrom 1970, Letouzey et al 1995 and Mitra 2002).

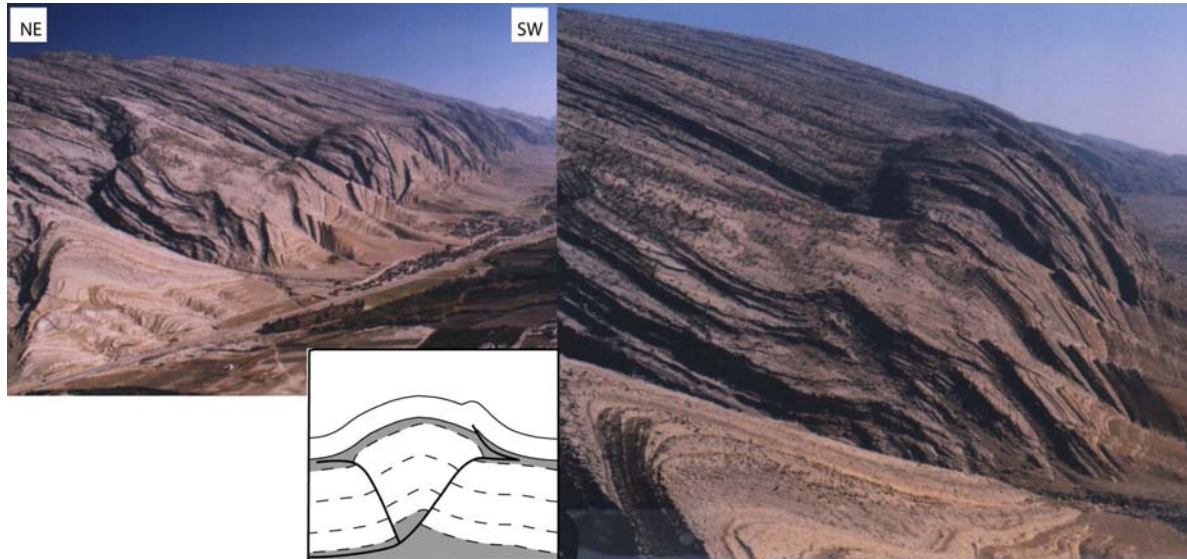


Fig. IV—14- Photographs from southern flank of Dashtak structure in Fars area, East of Kazerun fault. Small “rabbit ear” structure in Asmari carbonates could be related to backward shearing along Pabdeh marls. Schematic line drawing shows probable interpretation.

Axial shift from surface to depth is also one of significant effects of intermediate decollement levels on fold geometry. It was reported from seismic lines and wells (Fig. IV—15). Activation of an intermediate ductile unit and shearing along these levels were considered as the main reasons for this axial shift.

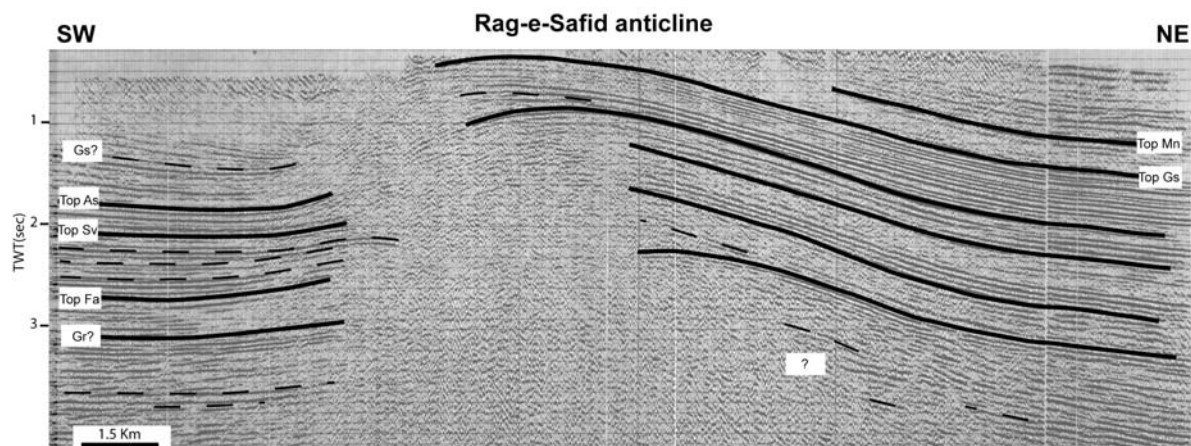


Fig. IV—15 Seismic line and interpretation from Rag-e-safid anticline (See appendix 5 for location map). Axial shift from surface to depth could be related to the implication of lower Cretaceous ductile unit in folding. Thickness variation to the left of the section should be related to the reactivation of deep seated N-S faults during sedimentation (Sherkati & Letouzey 2004).

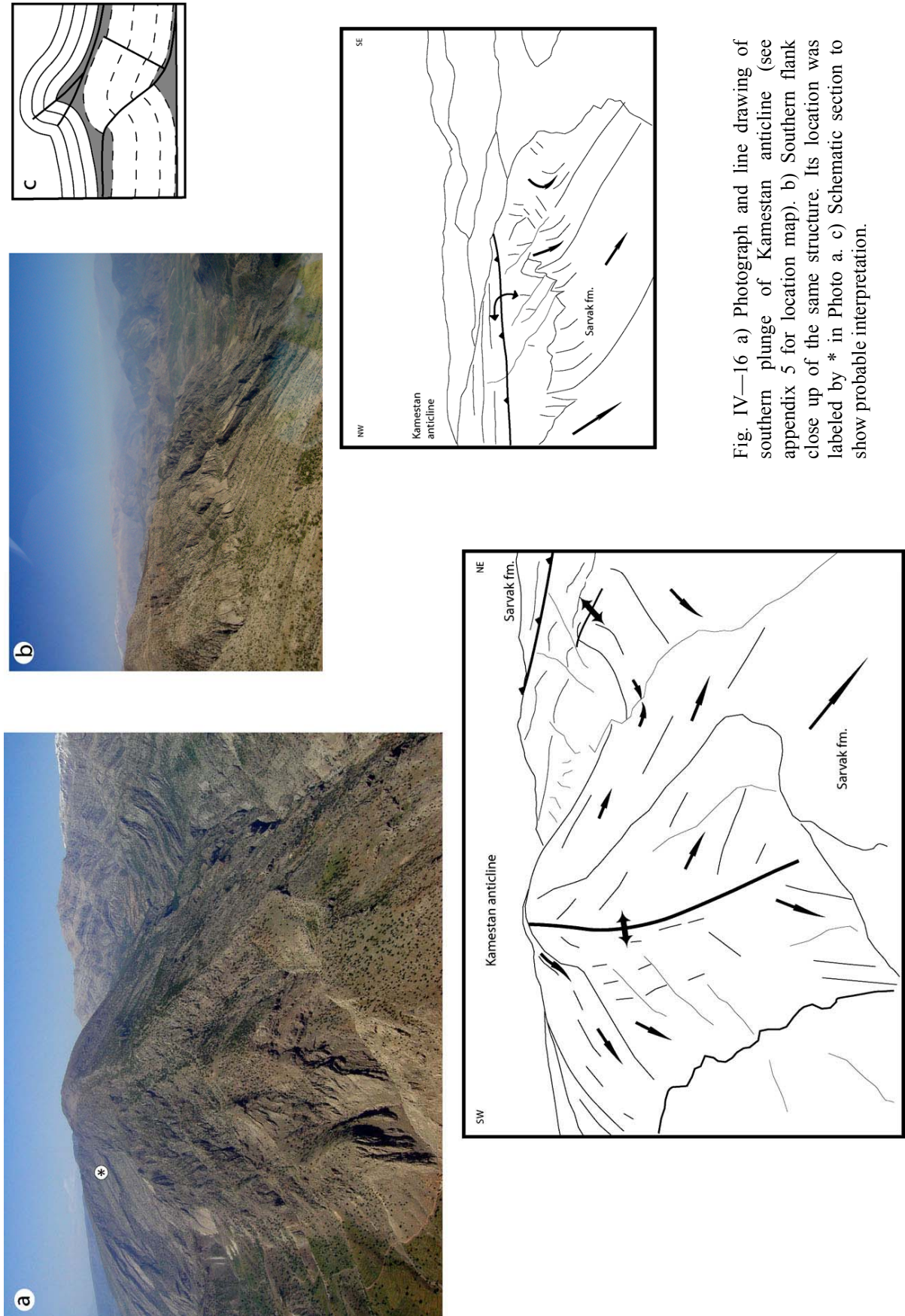


Fig. IV—16 a) Photograph and line drawing of southern plunge of Kamestan anticline (see appendix 5 for location map). b) Southern flank close up of the same structure. Its location was labeled by * in Photo a. c) Schematic section to show probable interpretation.

Poor quality of the old seismic images does not permit to interpret steeper flank of the structures in Zagros (Fig. IV—15). Recent developments in acquisition and processing in addition to more field observations permit a better interpretation of the geometry of these blank zones, especially when an intermediate decollement level is involved in folding (Fig. IV—16). Fig. IV—16 shows specific geometry associated with kink band in southern flank of Kamestan anticline. This geometry, which is often seen in Central Zagros anticlines, could be related to the activation of intermediate ductile units, which transfer a flat thrust fault from back limb to steeper flank. These faults, which are sometimes seen at the surface, do not cut all the sedimentary pile and detach at one of the intermediate decollement levels. The fault patterns seen on the forelimb of Kamestan and Parsi anticlines could be representative of fault geometry in most of the folds in Central Zagros, which form in sediments with high competency contrast. High angle thrust faults and vertical to overturned forelimbs in the beds above secondary decollement level are significant geometrical features in these folds. They could explain steepening of the beds at depth in wells located at the superficial crest of anticlines. These secondary features are important elements that define the geometry and size of the structural traps. So accurate mapping of these features could be critical in geometrical evaluation of anticlines.

CHAPTER V

LITHOSPHERIC STRUCTURE OF THE ZAGROS MOUNTAINS

1 INTRODUCTION

Lithospheric processes are known to affect the evolution of mountain chains (e.g. Dewey 1988, Davies & von Blanckenburg 1995, de Boorder et al. 1998, Buiter et al. 2002). In particular, major dynamic processes such as slab retreat or break-off, and the resulting surface uplift or sinking (Buiter et al. 2002) and changing thermal regimes (Davies & von Blanckenburg 1995) have a profound influence on the structural and sedimentary evolution of orogenic belts. Surface dynamics have been correlated to deep lithospheric processes in different geodynamic contexts such as the Taiwan collision (Teng et al. 2000), the Central Apennine foredeep in Italy (Van der Meulen et al. 2000) or the Aegean arc (Sorel et al. 1988).

In this chapter, I will attempt to establish in a similar manner a link between the deep lithospheric processes and the recent (post-collision) structural evolution of the Zagros Mountains. In the previous chapter a rough kinematic scenario was sketched for the evolution of the ZFTB from Miocene to Recent times. The main result is that at some stage of its history, orogeny in Zagros suddenly switched from a thin-skinned to a thick-skinned style of deformation. This change in tectonic regime was matched by an abrupt change in sedimentation throughout Zagros marked by the widespread appearance of the Bakhtyari conglomerates. So what factor triggered these sudden surface changes? Could there have existed a deeper, lithospheric-scale dynamic process which controlled the evolution of the entire orogen? In order to answer these questions, I had the opportunity to set up a collaboration with H. Zeyen of the Université de Paris Sud, Orsay, to perform lithospheric modelling of the Zagros Mountains and thus gain access to the very deep structure of the orogen. H. Zeyen had developed over several years an algorithm allowing the simple and direct construction of lithospheric models on the basis of multiple geophysical data sets – including topography, gravity and geoid data – available on the web. The initial idea was to construct two lithospheric-scale models on either side of the Bandar Abbas syntaxis. These would complete a series of transects based upon the same technique and designed to image the entire Arabian-Eurasian convergence zone (Fig. V—1), some of which were being implemented by M. Fernández of the Institute of Earth Sciences “Jaume Almera” in Barcelona.

The main result obtained at this stage is a complete lithospheric section through the south-eastern Zagros Mountains (line B, Fig. V—1) which is presented in a paper published in *Terra Nova* under the title **“Lithospheric structure underneath the south-eastern**

Zagros Mountains, Iran: recent slab break-off? As will be seen, the lithospheric structure imaged by this model – and the supposed dynamic processes behind it – could be one of the key factors which governed the recent history of Zagros.

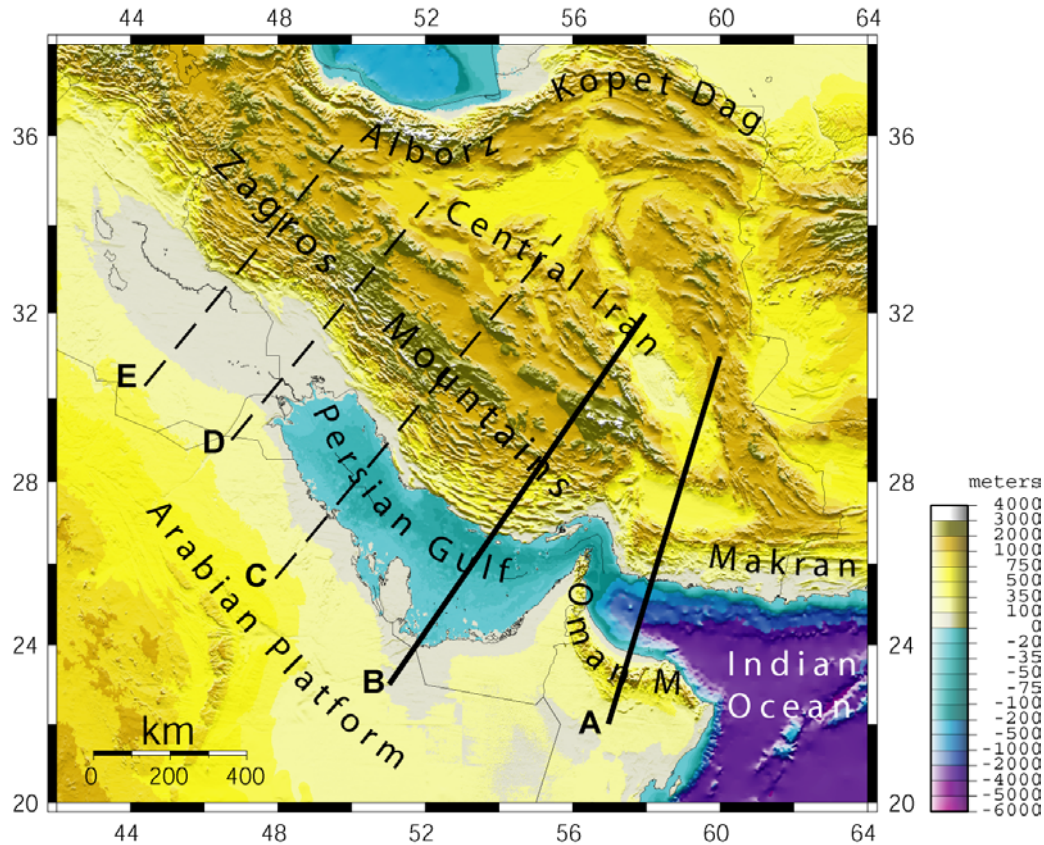


Fig. V—1 Lines of lithospheric transects planned or constructed across the Arabian-Eurasian convergence zone. Full line B, transect presented in this thesis, full line A, planned transect. Dashed lines C, D, E, transects implemented by M. Fernández at the Institute of Earth Sciences “Jaume Almera”, Barcelona

2 INTEGRATED LITHOSPHERIC MODELLING: METHOD AND DATA

The numerical method used to obtain the lithospheric models is based upon the combined interpretation of three coupled geophysical concepts: thermal field, local isostasy and gravity field. The algorithm uses a finite element technique which solves the various physical equations and allows us to obtain the density and temperature structure of the lithosphere by trial-and-error, comparing calculated surface heat flow, gravity, geoid and topography curves with available measured data. We will start by briefly describing the fundamental physical concepts behind the method. A full description of the technique used

can be found in Zeyen & Fernandez (1994), while details of the specific equations are described by different authors such as Talwani et al. (1959), Chapman (1979), Lachenbruch & Morgan (1990).

2.1 *Basic principles*

2.1.1 Thermal field

The first step taken by the program is the calculation of the thermal structure throughout the lithosphere. This is calculated in two dimensions under steady state conditions by the following equation (Turcotte & Schubert 1982):

$$\nabla(k \cdot \nabla T) + A(x, z) = 0 \quad (1)$$

where k is the coefficient of thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$), T is temperature ($^{\circ}\text{C}$), $\nabla = (\partial/\partial x, \partial/\partial z)$, and A is radiogenic heat production (W m^{-3}).

The resulting calculated surface heat flow will thus depend on the incoming heat flow from the asthenosphere – which is controlled by lithospheric thermal conductivity and temperature at the lithosphere/asthenosphere boundary – and radiogenic heat production within the model, essentially restricted to the crust. Unfortunately heat flow data were not available for our area of study so no comparison was possible with the calculated heat flow curve.

2.1.2 Topography under isostatic equilibrium and temperature-dependent density

Topography is calculated by assuming local isostatic compensation throughout the model. Absolute elevation is therefore determined for a given lithospheric column by calculating its buoyancy force and comparing it to that of a reference column. The reference column is taken from Lachenbruch & Morgan (1990) and corresponds to the one calculated for mid-oceanic ridges, where topography and lithospheric structure are well known. Isostatic balance is supposed to be achieved at the lowermost point of the lithosphere in the model. Elevation E is thus calculated using the following two equations (Lachenbruch & Morgan 1990):

$$E = \frac{\rho_a - \bar{\rho}_1}{\rho_a} H + E_0 \quad E \geq 0 \quad (2)$$

$$E = \frac{\rho_a}{\rho_a - \rho_w} \left[\frac{\rho_a - \bar{\rho}_1}{\rho_a} H + E_0 \right] \quad E < 0 \quad (3)$$

where ρ_a is density in the asthenosphere (kg m^{-3}), ρ_1 is average density in the lithosphere (kg m^{-3}), ρ_w is density of water (kg m^{-3}), H is thickness of the lithosphere and E_0 is the calibration elevation = -2400 m determined by Lachenbruch & Morgan (1990) for mid-oceanic ridges. In order to obtain ρ_1 , average density throughout the lithosphere, the following equation relating density to temperature is used:

$$\rho(T) = \rho_a \cdot (1 - \alpha(T - T_a)) \quad (4)$$

where α is the thermal expansion coefficient ($4 \cdot 10^{-5} \text{ K}^{-1}$) and T_a the temperature at the lithosphere-asthenosphere boundary (1300°C). This is a fundamental equation used by the algorithm which allows the coupling between the temperature structure of the lithosphere and the density distribution. Once this latter is determined, the corresponding gravity and geoid anomalies can be calculated.

2.1.3 Gravity and geoid potential anomalies

The gravity and geoid anomalies both reflect density inhomogeneities within the lithosphere, however with different depth dependence. Because gravity is inversely proportional to the square of the distance, its sensitivity to density anomalies decreases rapidly with depth. Gravity anomalies thus reflect mainly crustal density distribution. Gravity anomalies are calculated by applying the free-air correction. For this, the program uses a two-dimensional algorithm described in Talwani et al. (1959).

The reference geoid is defined as the gravitational equipotential surface corresponding to sea level, while a geoid anomaly is defined as the difference between the calculated reference geoid and the altimeter-measured geoid. An excess mass at depth will result in a positive anomalous potential and positive geoid height (Chapman 1979). Geoid anomalies are inversely proportional only to the distance and are therefore more sensitive to deep density

variations than gravity. They therefore tend to reflect variations within the lithospheric mantle.

2.2 Numerical method

The modelling is performed through a command window such as the one shown in Fig. V—5, in which the lowermost case corresponds to the actual lithospheric model and the four upper cases contain the measured data with error bars (black crosses) and the curves (in colour) calculated for the model. The model is split up into a number of bodies for which the following rock properties are defined: (1) thermal conductivity, (2) coefficients for density dependence on temperature and increasing pressure with depth, (3) body densities, (4) (radiogenic) heat production.

At each new run, the shapes and densities of the various bodies within the model are modified interactively through the command window. The algorithm solves equations (1) to (4) using a finite element technique and displays the corresponding topography, gravity, geoid and surface heat flow curves. Modelling thus proceeds by trial-and-error, until the measured and calculated data are reasonably well-matched.

2.2.1 Tests of the effect of density and depth variations on the model

In order to illustrate the sensitivity of the program to density and thickness variations at different depths, a series of tests were conducted on a synthetic 4-layer model composed of two simple columns. Table 1 summarises the parameters used in these models.

	Heat Production ($\mu\text{W m}^{-3}$)	Thermal conductivity [§] ($\text{W m}^{-1} \text{K}^{-1}$)	Density (Kg m^{-3})	Layer thickness (Km)
Sediments	1	3 (TCT=1.550E-03)	2400	7
Upper crust	1	3 (1.550E-03)	2750	15
Lower crust	0.2	2.5 (8.000E-04)	2950	15
Mantle	0.02	2.3 (8.700E-04)	3200*	123

* Mantle density is re-calculated everywhere using equation (4) based upon the temperature field

§ Thermal conductivity is re-calculated as a function of temperature, using $C=C_0/(1+TCT*T)$ for $T<800^\circ$ and $C=C_0*EXP(TCT*(T-800))$ for $T>800^\circ$. C_0 =initial values in table; TCT = temperature dependency factors

Table 1 Parameters considered in the synthetic models (Figs. V—2,3) and in the starting model (Fig. V—5).

In the first test (Fig. V—2), the densities of the various layers in the left hand side column were each decreased in turn by 3% to evaluate the effect of an equal density variation but at different depths. As expected, because the column is lighter, the gravity anomaly decreases and topography increases. Geoid, on the other hand, is little affected by shallow variations, and it is only when the density in the mantle is modified that a strong negative anomaly appears in the geoid curve.

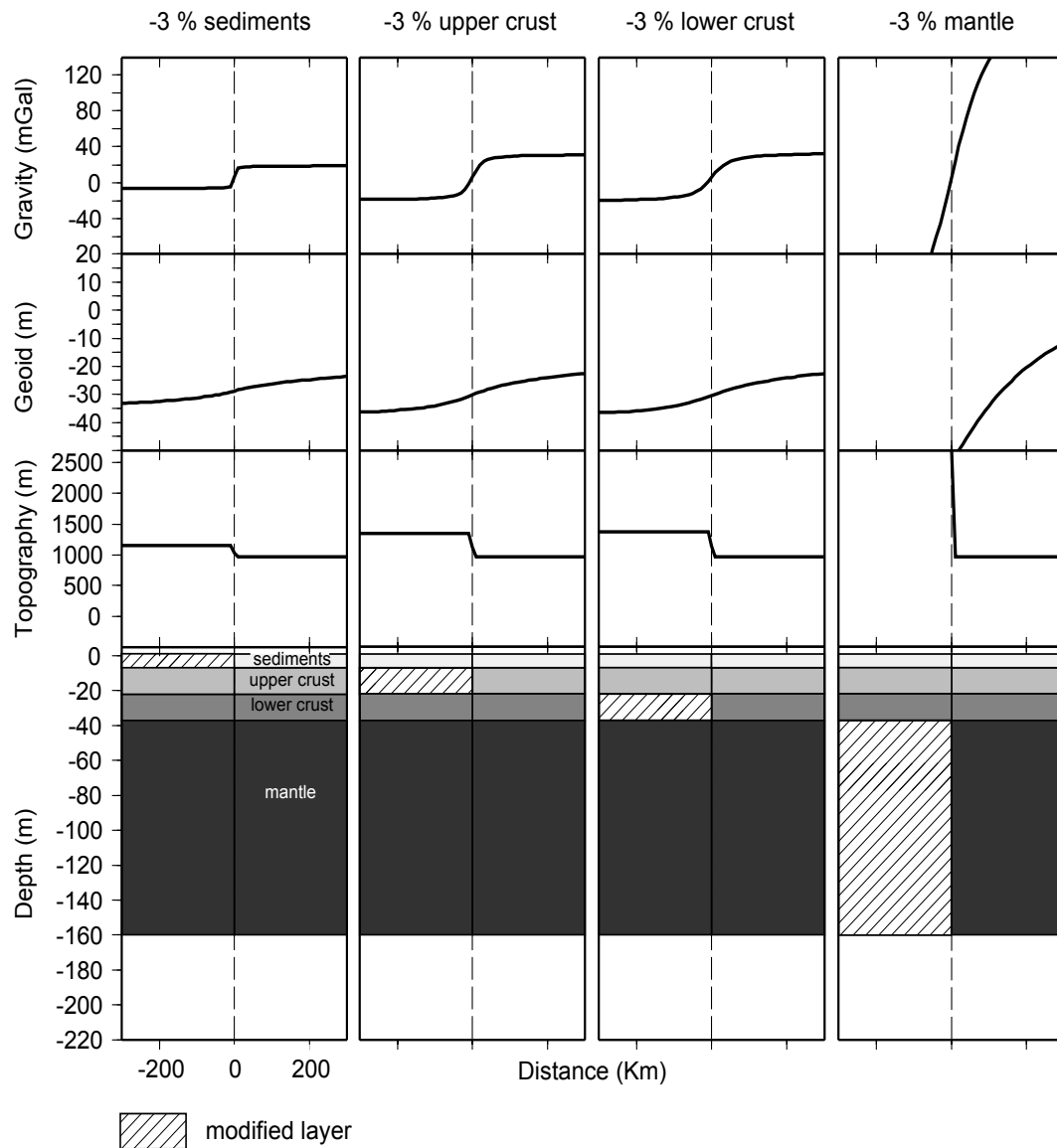


Fig. V—2 Synthetic 4-layer model illustrating the effect on calculated gravity, geoid and topography curves of a 3% density decrease in each layer.

In a second test (Fig. V—3), the thickness of each layer in the left-hand column was increased by 10%. Thickening of the sediments and upper and lower crust decreases the weight of the column and therefore results in a negative gravity anomaly matched by an

increase in topography. Thickening of the mantle, on the other hand, has the opposite effect. This is due to the fact that the lithosphere-asthenosphere boundary – that is the 1300°C isotherm – has been pushed deeper leading to overall cooling of the lithospheric column. The temperature-dependent density of the column is therefore increased leading to a positive gravity anomaly and sinking of the topography.

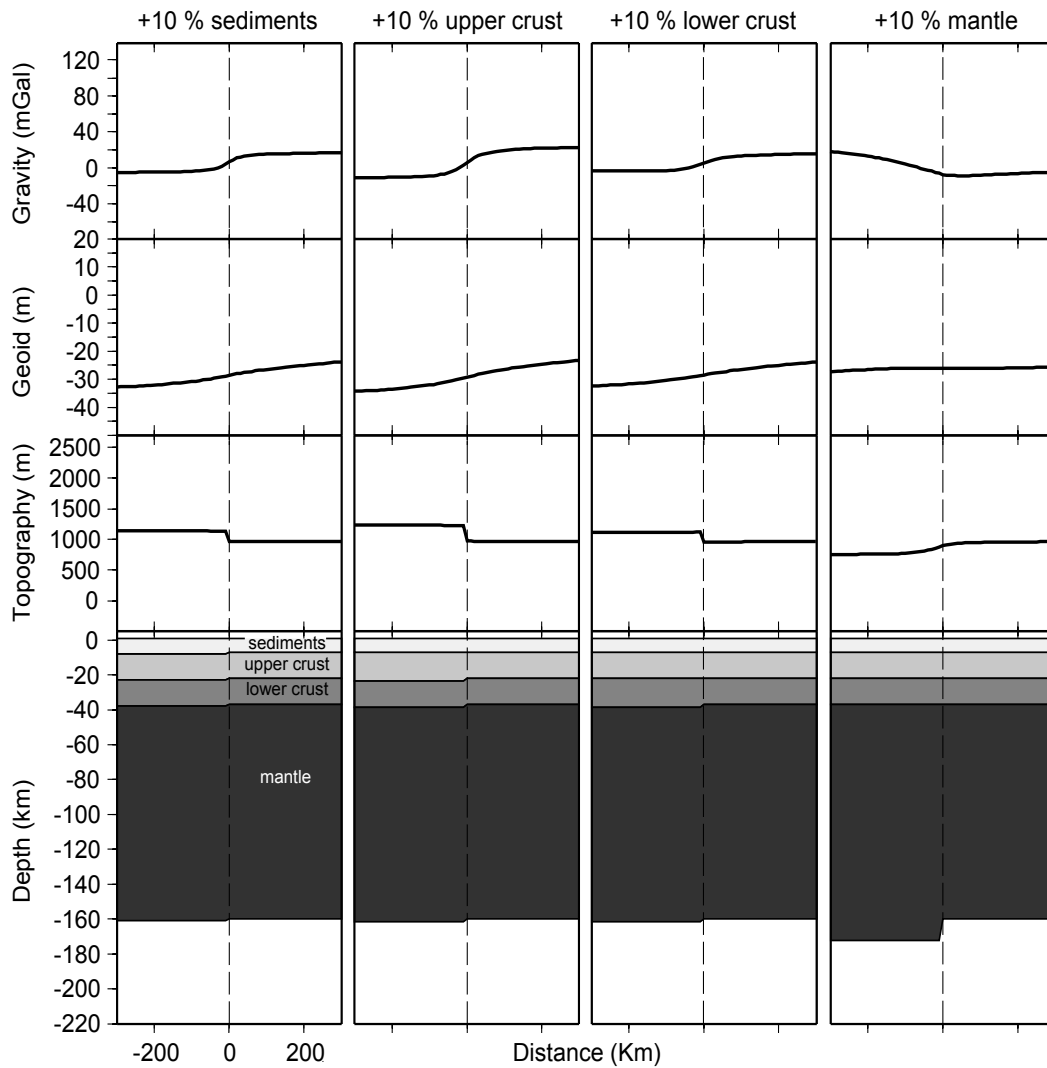


Fig. V—3 Synthetic 4-layer model illustrating the effect on calculated gravity, geoid and topography curves of a 10% thickness increase in each layer.

2.3 Data used for the model and preliminary interpretations

The data used in the modelling were all taken from the world-wide data sets available from the site <ftp://topex.ucsd.edu/pub> (Sandwell & Smith 1997). Topography is taken from

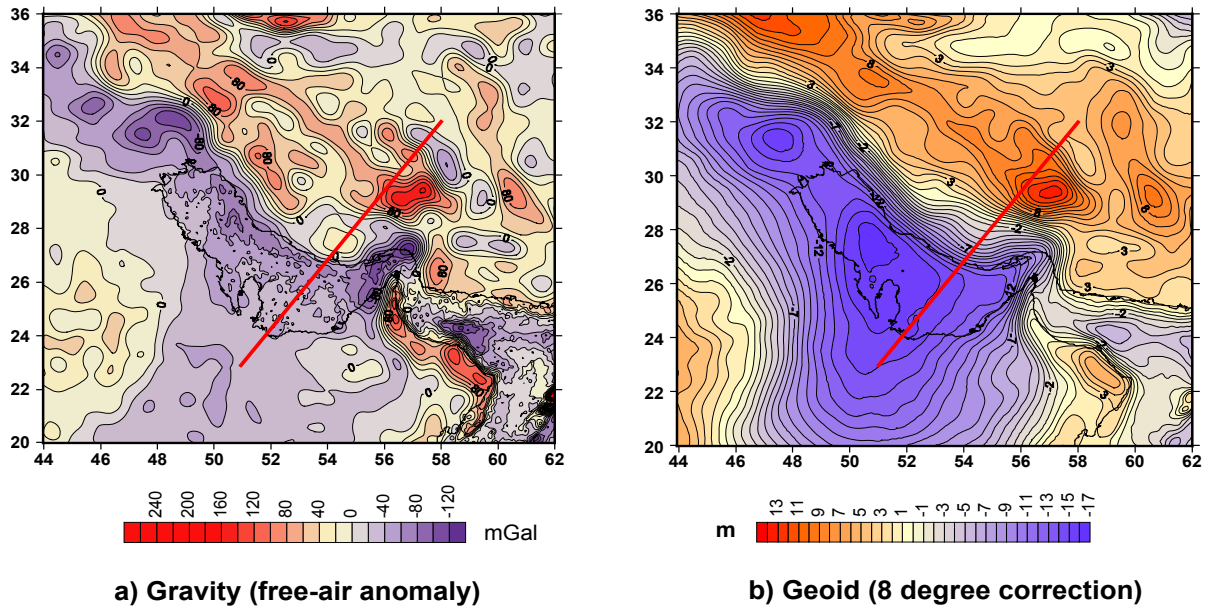


Fig. V—4 (a) Free air gravity anomaly map of the Persian Gulf and Zagros region. Contour interval 20 mGal. (b) EGM96-corrected geoid anomaly map. Contour interval 1 m. Red line modelled section.

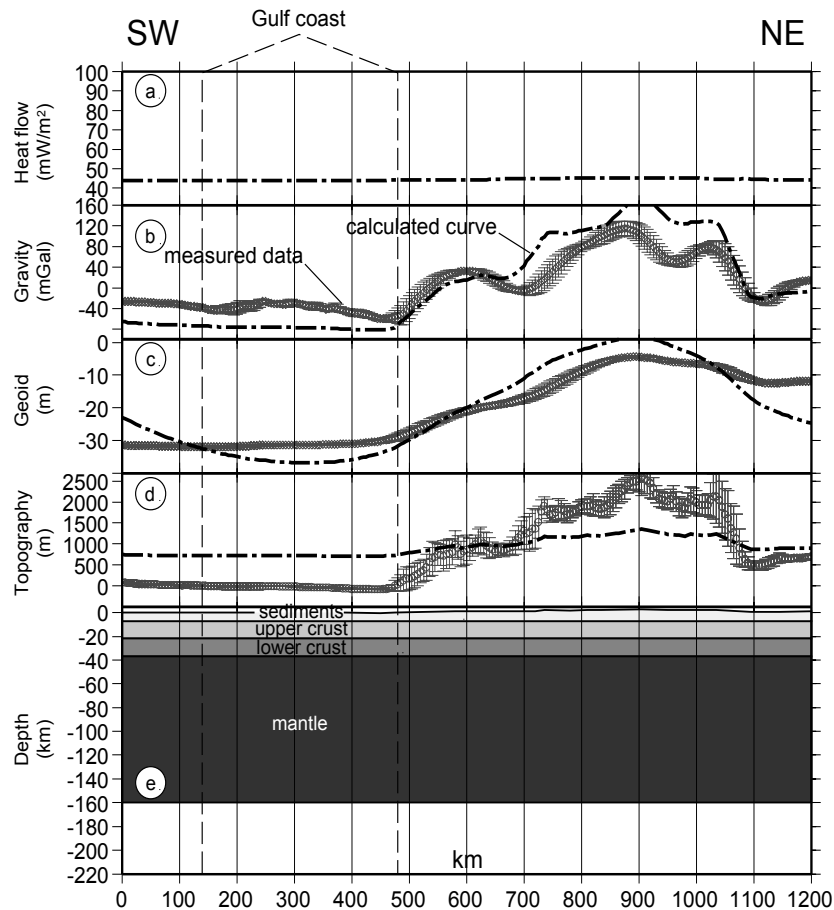


Fig. V—5 Initial four-layered model considered for the construction of the lithospheric transect presented in paper n° 4. Only the topography has been modelled. Layer parameters are those shown in table 1. The data sets are averaged every 5 km from a 50 km wide strip on both sides of the profile. Crosses correspond to measured data with error bars and dash-dot lines to calculated values. The model illustrates the influence of topography on the calculated gravity and geoid anomalies (dash dot lines). Note the difference between the measured and calculated geoid (discussion in text). Line of section in Fig. V—1(b) and Fig. V—4.

the TOPEX global 2-min data set. The Zagros Mountains are characterised by a very large wavelength topography (Figs. V—1, V—5d) with relatively few intermediate or small wavelengths. Topography rises steadily northeastwards from the Persian Gulf and levels out at about 2000 m in the metamorphic SSZ belt. Maximum elevations of about 4000 m are found in the UDMA volcanic arc.

The free air gravity anomaly data set (1-min TOPEX) is shown in Fig. V—4a. The intermediate wavelengths in the pattern of these anomalies essentially reflect non-compensated topographic features related to local structures such as thrust faults (Fig. V—5b). A very large orogen-scale positive anomaly is also discernible, suggesting that the Zagros Mountains either have yet to achieve crustal isostatic compensation, as could be supposed in a young and actively deforming orogen, or that compensation occurs at greater depths than in the crust.

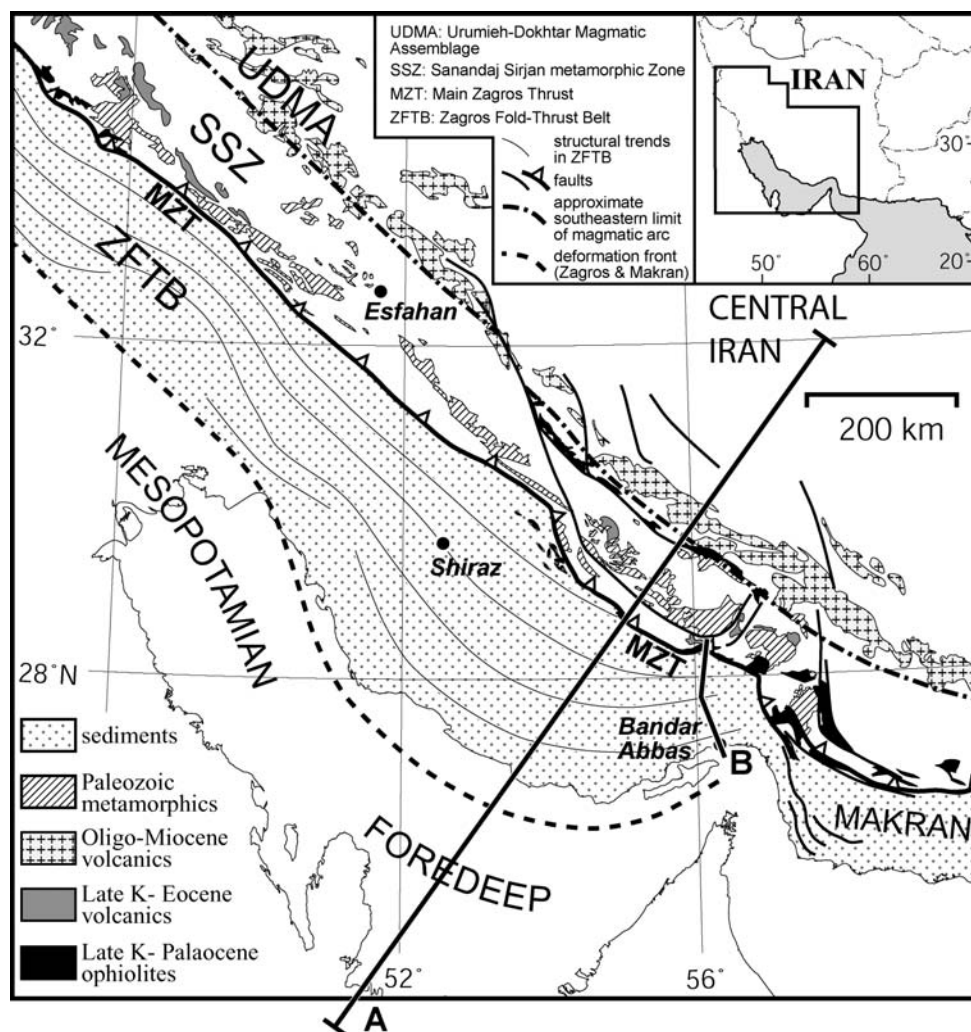


Fig. V—6 Main geological units of the Zagros Mountains in southern Iran, after existing geological maps (NIOC 1977). Ages of volcanic rocks after Berberian et al. (1982). Line A, location of lithospheric model, line B location of balanced cross-section through the ZFTB.

The geoid dataset (TOPEX 2-min, Fig. V—4b) used for the modelling was corrected for known global-scale anomalies attributed to very deep mantle sources. This was done by subtracting from the measured regional geoid a standard geopotential reference model (EGM96).

In the starting model (Fig. V—5c), the Zagros Mountains topography mass, without taking into consideration possible compensating masses, is clearly associated with a NW-SE positive geoid. However, the relatively weak amplitude and large wavelength of the measured anomaly (compared to the calculated one, Fig. V—5c) suggests that it may be partly compensated by some deeper, subcrustal, low density anomaly. So an initial qualitative interpretation suggests that the lithosphere may be thinned beneath Zagros.

Finally, an important element considered during the construction of the model was information provided by geological data. The intention was to produce a model based upon geophysical techniques but integrating “a priori” information based upon geological considerations, in order to propose a more realistic interpretation of the purely geophysical model. The map in Fig. V—6 shows the main lithological units and structural trends of the south-eastern Zagros Mountains, based upon 1:1000000-scale maps (NIOC 1977), which were considered to constrain the model. In the ZFTB, the depth and the geometry of the basement, as well as the geometry of the overthrusting SSZ metamorphics, were constrained with the balanced cross-section presented in paper n° 2.

<p>CURRENT STATUS OF PAPER N° 4: paper accepted for publication in <i>Terra Nova</i> on September the 7th</p>

STRUCTURE LITHOSPHERIQUE SOUS LE ZAGROS ORIENTAL, IRAN : DÉTACHEMENT LITHOSPHERIQUE RÉCENT ? (PAPIER N° 4)

Resumé : Une modélisation lithosphérique conjointe, basée sur l'interprétation simultanée de données de gravimétrie, du géoïde et de topographie, met en évidence un amincissement lithosphérique sous la chaîne de collision du Zagros (Iran). Nous proposons que ceci résulte d'un détachement récent au niveau de la transition entre la lithosphère continentale et océanique. Ceci est suggéré aussi par les données récentes de la distribution de sismicité en profondeur. En accord avec d'autres modèles publiés sur le Zagros, la croûte montre au contraire un épaissement atteignant un maximum de 52 km sous la zone métamorphique. On propose que le soulèvement thermique attendu d'un détachement lithosphérique, en modifiant l'angle critique du prisme orogénique, ait pu déclencher la transition récente dans le Zagros plissé d'une tectonique de couverture à une tectonique de socle.

Mots clefs : *Zagros, structure lithosphérique, détachement lithosphérique*

3 LITHOSPHERIC STRUCTURE UNDERNEATH THE SOUTH-EASTERN ZAGROS MOUNTAINS, IRAN: RECENT SLAB BREAK-OFF? (PAPER N° 4).

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Abstract. Integrated lithospheric modelling, based upon the combined interpretation of gravity, geoid and topography data sets, highlights a previously undocumented lithospheric thinning beneath the Zagros collisional belt (Iran), which we propose to relate to recent slab break-off at the continent-ocean transitional lithosphere. Recent published data on the distribution of seismicity at depth supports this interpretation. In agreement with other published models of Zagros the overlying crust exhibits on the contrary a noticeable thickening reaching a maximum of 52 km. It is suggested that the consequent thermal uplift expected from slab break-off modified the Zagros wedge taper and triggered the recently documented switch from thin-skinned to thick-skinned deformation in the Zagros Fold Thrust Belt.

Keywords: *Zagros, crustal structure, lithospheric structure, slab break-off*

INTRODUCTION

The Zagros Mountains are a young and active collisional belt developed at the frontier between the converging Arabian and Eurasian plates (Fig.1). Compared to other more evolved mountain chains, little is known about the deep lithospheric structure of Zagros. Finite element (Bird 1978) and gravity modelling (Dehghani & Makris 1984) provided the basis for early work on the gross crustal structure in Zagros. Further details were highlighted by Snyder & Barazangi (1986), based mainly upon gravity modelling. More recently Hatzfeld et al. (2003) investigated the crustal structure in Zagros based upon seismological information.

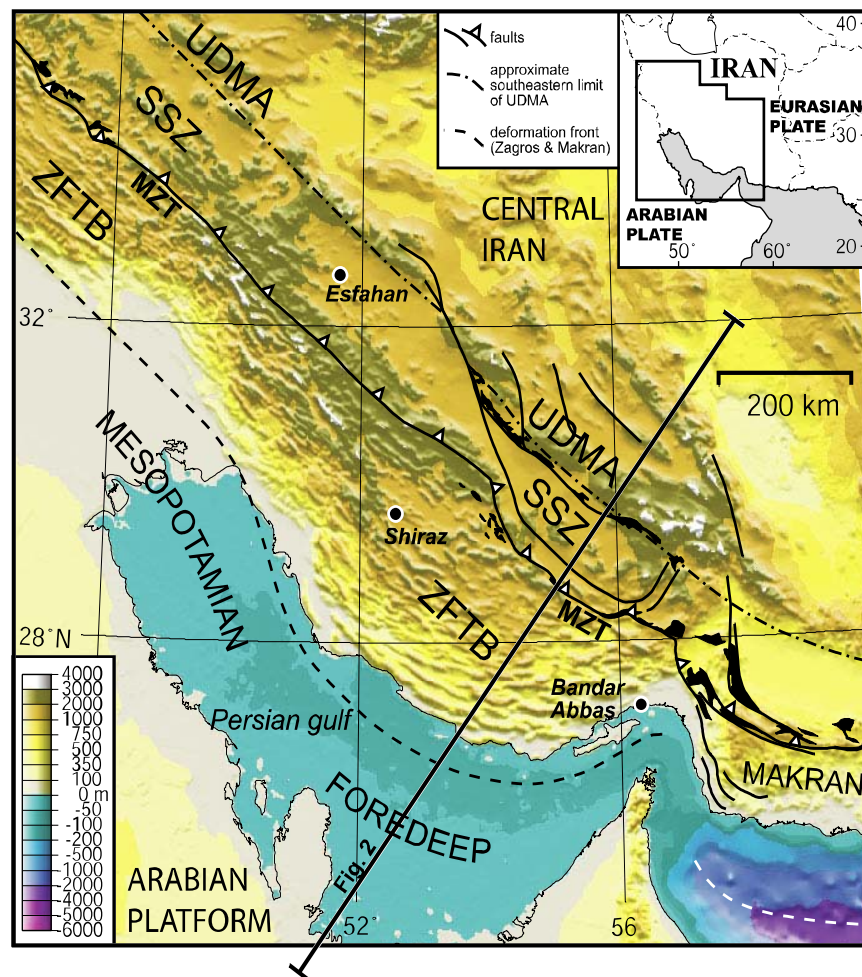


Fig. 1 Topography (source: GEBCO dataset) and main structural zones of the Zagros Mountains, Iran. ZFTB: Zagros Fold-Thrust Belt, SSZ: Sanandaj Sirjan Zone, UDMA: Urumieh-Dokhtar Magmatic Assemblage, MZT: Main Zagros Thrust. Black shading: Neo-Tethys ophiolites and ophiolitic melange.

In this paper, we present the results of numerical modelling of the lithospheric structure beneath south-eastern Zagros based upon the combined interpretation of gravity, geoid and topography (local isostasy) data. The trial-and-error algorithm we employ determines the two-dimensional thermal structure of the lithosphere and therefore allows us to take into account the dependence of body density on temperature (Zeyen & Fernandez 1994). Our method, though non-unique, has the advantage of greatly reducing the number of possible solutions through the combined use of different data sets. The main new result obtained by our model is a strong thinning of the lithosphere directly beneath the Zagros Mountains. We propose to interpret this as evidence for recent break-off of the subducted Arabian plate slab. We conclude with a conceptual model attempting to explain the recent evolution of the Zagros Mountains in relation to lithospheric slab break-off.

GEOLOGICAL BACKGROUND

A number of structural subdivisions are classically recognised in the Zagros Mountains (Alavi 1994, Falcon 1974, Ricou et al. 1977)) (Fig. 1). Starting from the south-west, the Persian Gulf and Mesopotamian Plain represent the foredeep developed at the front of the orogen and thinning out progressively towards the south-west in the Arabian Platform. To the north-east, the Zagros Fold Thrust Belt (ZFTB) consists of large parallel concentric folds related to Neogene inversion of the Arabian margin. Parallel to the ZFTB are the Sanandaj Sirjan Zone (SSZ), consisting of mainly Precambrian metamorphic rocks, and the Urumieh-Dokhtar Magmatic Arc (UDMA), an Andean type volcanic magmatic arc including rocks ranging in age from Upper Jurassic to Quaternary. These two zones are separated from the ZFTB by the Main Zagros Thrust (MZT), considered by many as being the suture between the Arabian and Eurasian plates. A narrow belt of strongly tectonised ophiolitic melange marks the MZT, and more ophiolites are found aligned in a belt separating the UDMA and SSZ zones (Fig.1).

The main steps in the development of the Zagros Mountains are well known. The first major tectonic event was the late Cretaceous obduction of Neo-Tethyan oceanic crust along the entire length of the north-eastern Arabian margin (Koop & Stoneley 1982, Ricou 1971, Ziegler 2001). This event ceased towards the end of Campanian, while the remnant Neo-Tethys oceanic crust continued to subduct beneath the Central Iran plate until the onset of

continental collision in Oligocene-Miocene times (Koop & Stoneley 1982). The collisional process is currently still active, with a N-S directed convergence rate of approximately 20 ± 2 mm/y, according to recent GPS data (Vernant et al. 2003).

METHOD AND DATA

The modelling algorithm utilises the fact that gravity, geoid and topography all depend on the density distribution, but with different distance dependence (Zeyen & Fernandez 1994). Topography variations reflect variations in average density of the lithosphere. The effect of density variations on gravity anomalies decreases proportionally to r^{-2} , imaging mainly crustal structures whereas geoid undulations diminish proportionally to r^{-1} , reflecting also deep lithospheric density variations. Gravity and geoid anomalies are calculated in 2D (Chapman 1979, Talwani et al. 1959, respectively). Topography is calculated under isostatic equilibrium, meaning that it does not take into account any mechanical rigidity in the lithosphere, an assumption that may be too restrictive for the Arabian plate, but is acceptable for the 5km elastic thickness under the Zagros estimated by Snyder & Barazangi (1986).

Variations of topography may be induced by density variations in the crust, variations of crustal thickness or temperature variations in the lithospheric mantle, i.e. thickness of the lithosphere. The densities in the mantle are related linearly to temperatures through the thermal expansion coefficient ($4 \cdot 10^{-5} \text{ K}^{-1}$). Since we defined the base of the lithosphere as the 1300°C isotherm, it would certainly have been advantageous to also control lithospheric thickness through surface heat flow data, however no data were available for our area.

All data used are taken from the world-wide data sets available from the site <ftp://topex.ucsd.edu/pub> (Sandwell & Smith 1997). In order to avoid small-scale local extrema, the different data sets were averaged every 5 km from a 50 km wide stripe on both sides of the profile. In figure 2, the data are represented by dots with error bars that correspond to the standard deviation of the data within the stripe and represent the lateral variability of the data.

LITHOSPHERIC MODEL: DESCRIPTION

The transect we modelled starts within the Arabian platform, crosses the Persian Gulf, continues across the ZFTB, SSZ and UDMA structural zones and ends in Central Iran (Fig.1). The line of the section has been chosen perpendicular to the strike of the main structural domains, thus ensuring the minimisation of undesired three-dimensional effects. Also to this purpose the section has been placed at a suitable distance from the structurally complex Zagros-Makran transition zone, where three-dimensional effects are most likely to occur (Molinaro et al. 2004).

The resulting model (Fig.2(I)) displays a noticeable thickening of the crust, from an average 35-40 km beneath the Arabian shield to a maximum of approximately 52 km beneath the Zagros metamorphic and magmatic belts (SSZ and UDMA). The 35 to 45 km crustal thickness beneath the ZFTB is in the range of values obtained by Hatzfeld et al. (2003) and Snyder & Barazangi (1986). By contrast, our maximum of 52 km underneath the SSZ differs from the results of Snyder & Barazangi (1986) in that they located their maximum (~ 60 km) further south, beneath the MZT. However, it could roughly correspond to the ~ 60 km reflector reported by Hatzfeld et al. (2003) from Giese et al. (1983) underneath the UDMA. Most of the crustal thickening occurs NE of the MZT, suggesting that it is achieved mainly by thrusting within the Zagros metamorphic belt (SSZ) (Fig.2(II)). Also a perceptible thickening is visible within the upper crust in the area of the ZFTB. This is compatible with basement-involved deformation in this area, as suggested by the strong seismicity within the upper crust (Berberian 1995, Talebian & Jackson 2004) and as shown by the balanced cross-sections of the ZFTB (Molinaro et al. 2004, submitted).

The deep structure of the Arabian platform and Persian Gulf is, generally speaking, poorly constrained. Results from the spectral analysis of P-wave amplitude ratios (Al-Amri & Gharib 2000) show a depth to Moho of ~ 50 km underneath the southern Persian Gulf coast, while Al-Lazki et al. (2002), based upon gravity modelling along a transect across the Oman Mountains, obtain 40-45 km of crustal thickness within the Arabian platform. Similar values are also proposed by Snyder & Barazangi (1986) (~ 40 km). We find that our data is best explained by a 42 km-thick crust beneath the Arabian Platform decreasing to 37 km beneath the Persian Gulf.

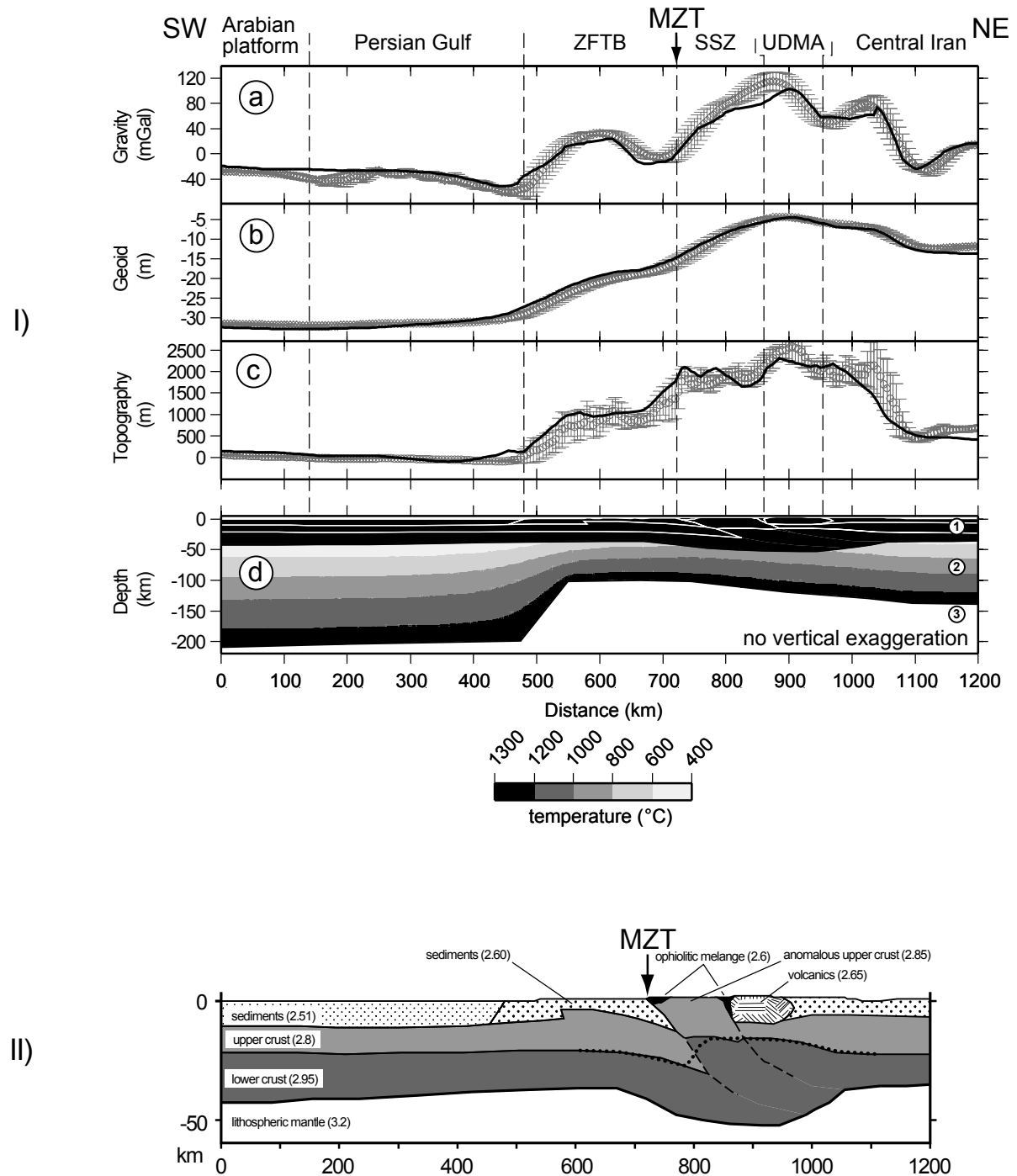


Fig. 2 **I)** Lithospheric model across the Zagros Mountains. (a) free-air gravity anomaly, (b) geoid anomaly and (c) topography. Crosses correspond to measured data with error bars and solid lines to calculated values. (d) Resulting model at scale 1:1. (1) crust, (2) lithospheric mantle with temperature distribution, (3) asthenosphere.

II) Crustal structure (vertical exaggeration) and body densities implemented in the model. Dotted line shows an alternative model explaining the geophysical data as well without, however, taking into account geological considerations. Dashed lines: geological interpretation of thickening in lower crust.

This crustal thinning could be linked to the rifting episode that affected the Arabian margin in Permo-Triassic times. The upper 10 km of the crust are made up of platform sediments. The

density we chose for this body (2510 kg/m^3) is close to that used by Snyder & Barazangi (1986) in their gravity models across Zagros.

Clearly the data used for our modelling is not sufficient alone to justify the crustal model. For example a smooth limit between upper and lower crust (dotted line in Fig.2 (II)) would fit the data as well. However, as shown with the test model (Fig. 3(d), continuous lines), without a thickening of the lower crust (or an increase of crustal density) the data cannot be fitted.

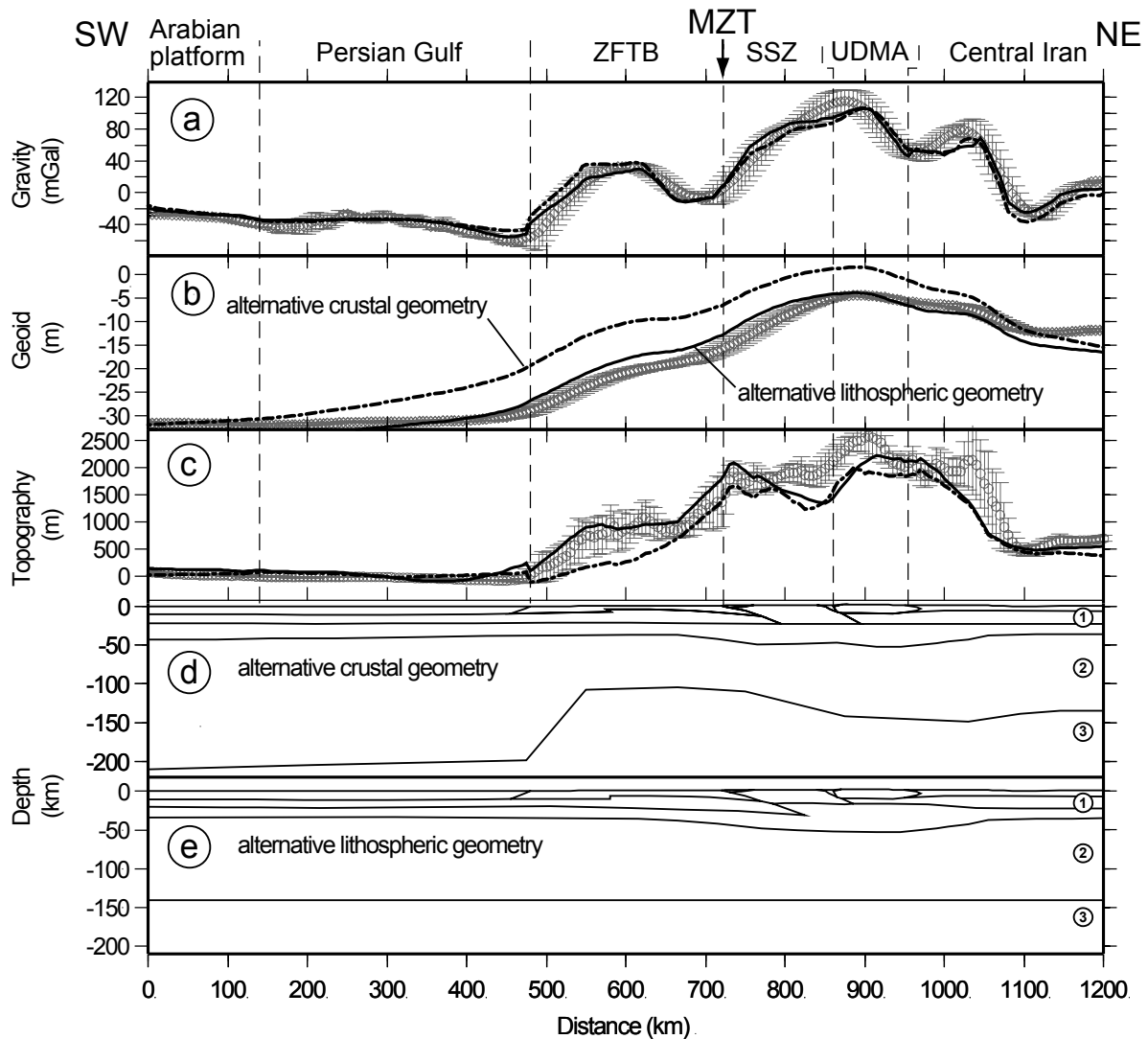


Fig. 3 Examples of alternative models tested. Continuous lines (a, b & c) correspond to an alternative crustal model (d) in which the upper limit of the lower crust beneath the SSZ is flat. The lithospheric thickness has been increased and the crustal thickness decreased with respect to model in Fig.2 (I) in order to compensate the density decrease so that the gravity data are well explained (a). However geoid (b) as well as topography (c) cannot be fully explained with such a model, showing that the lower crust has to thicken beneath the SSZ or the crustal density has to increase.

Dash-dot lines (a, b & c) are calculated for an alternative lithospheric geometry (e). Note the pronounced misfit between the calculated and measured geoid for this new model. (1), (2) & (3) as in Fig. 2.

The details of the crustal model in Fig.2 (II) are based essentially on geological maps of the region (NIOC 1977a, b) and on geological considerations presented elsewhere (Molinaro et al. 2004, submitted). In particular, the construction of balanced cross-sections provided constraints for the geometry and depth of the basement in the ZFTB as well as the overthrusting SSZ belt (Molinaro et al. 2004, submitted).

The most striking feature in our model is the marked thinning of the lithospheric mantle directly beneath Zagros. The base of the lithosphere (defined as the 1300°C isotherm) is seen rising abruptly from an average depth of 200 km beneath the Arabian platform to a minimum of 100 km underneath the SSZ and UDMA structural zones. The strongest constraint for this result is given by the positive geoid anomaly, which reflects a topography that is partly compensated by deeper density variations in the lower lithosphere. To show the sensitivity of our calculations to the depth localisation of density variations, we have tested an alternative model with a 140 km deep horizontal lithosphere-asthenosphere boundary (Fig. 3(e), dash-dot lines). By reducing the thickness of the Arabian crust to 33 km and increasing the densities in the Arabian sediments we managed to recover a good fit with the gravity data but not with the topography and geoid data. In particular, the pronounced discrepancy between the measured and calculated geoid curves confirms the sensitivity of this calculation to deep-seated density variations. Based on further tests, we estimate the uncertainty of lithospheric thickness to about 10% and that of crustal thickness to ± 2 km.

Recent global tomographic models (Bijwaard & Spakman 2000, Bijwaard et al. 1998) show a marked negative velocity anomaly beneath Central Iran and extending towards the Persian Gulf, also suggesting a thinned lithosphere. We propose to interpret this as evidence for break-off of the continental-oceanic lithosphere underneath Zagros. Slab break-off has been suggested before in settings such as Taiwan (Teng et al. 2000) or the Mediterranean (Wortel & Spakman 2000) and is increasingly recognised as a viable mechanism for consumption of lithospheric mantle in continent-continent collision zones (e.g. Pysklywec 2001). Information on the distribution of seismicity at depth is encouraging in this sense. A recent reappraisal of earthquake focal mechanisms in Zagros (Talebian & Jackson 2004) has shown seismicity in the mantle to be virtually non-existent. The hypothesis of slab break-off underneath Zagros had been already proposed by Bird (1978). Also, recent studies using the same method as the one described here along a series of transects in northern Zagros have produced similar results (Fernandez et al. 2003), raising the possibility of a generalised slab break-off throughout the whole of Zagros.

EFFECTS OF SLAB BREAK-OFF ON THE STRUCTURAL EVOLUTION OF ZAGROS

The possibility that the Arabian plate lithosphere may have undergone break-off at some stage during the Zagros collision leads to the important question on how the orogen responded to this event. To this purpose, it is useful to recall briefly the main consequences expected from a hypothetical slab break-off (Davies & von Blanckenburg 1995):

- A modification of the thermal – and thus magmatic – regime within the crust due to the replacement of cold lithospheric mantle with hot asthenospheric material against the base of the overriding plate.
- Buoyant ascent of crustal sheets leading to rapid exhumation of ultra-high-pressure facies rocks.
- A generalised uplift of the orogen due to an increase in the regional geothermal gradient.

Due to the lack of information on the values of heat flow and the nature of magmatic and metamorphic rocks in Zagros the first two points are difficult to verify and cannot be discussed here. However, we think that the third expected consequence of slab break-off can be indirectly verified by the recent dynamics of Zagros.

Molinaro et al. (2004, in press) showed, based upon geological interpretations, that the ZFTB recently underwent two major stages of tectonic deformation (Fig.4). In an initial middle Miocene to Pliocene thin-skinned phase (Fig.4a), the cover was folded into a series of large folds detaching along a thick basal layer of salt. The shortening implied by this phase of deformation was probably recovered within the basement by thrusting in the SSZ. Starting in Pliocene times, the deformation became thick-skinned with the activation of major out-of-sequence basement thrusts (Fig.4b) (Molinaro et al. 2004, in press). These two phases of deformation were separated by a period of widespread erosion and deposit of Plio-Pleistocene conglomerates throughout the ZFTB (Bakhtyari Fm, James & Wynd, 1965). We propose that this important change in tectonic style in Zagros was directly related to the uplift generated by the slab break-off. If we consider the orogen in terms of a critically deforming taper (Davis et al. 1983), it is clear that uplift and consequent erosion in the hinterland will reduce the overall orogenic wedge taper (Fig.5a). A way for the wedge to maintain critical taper would then be

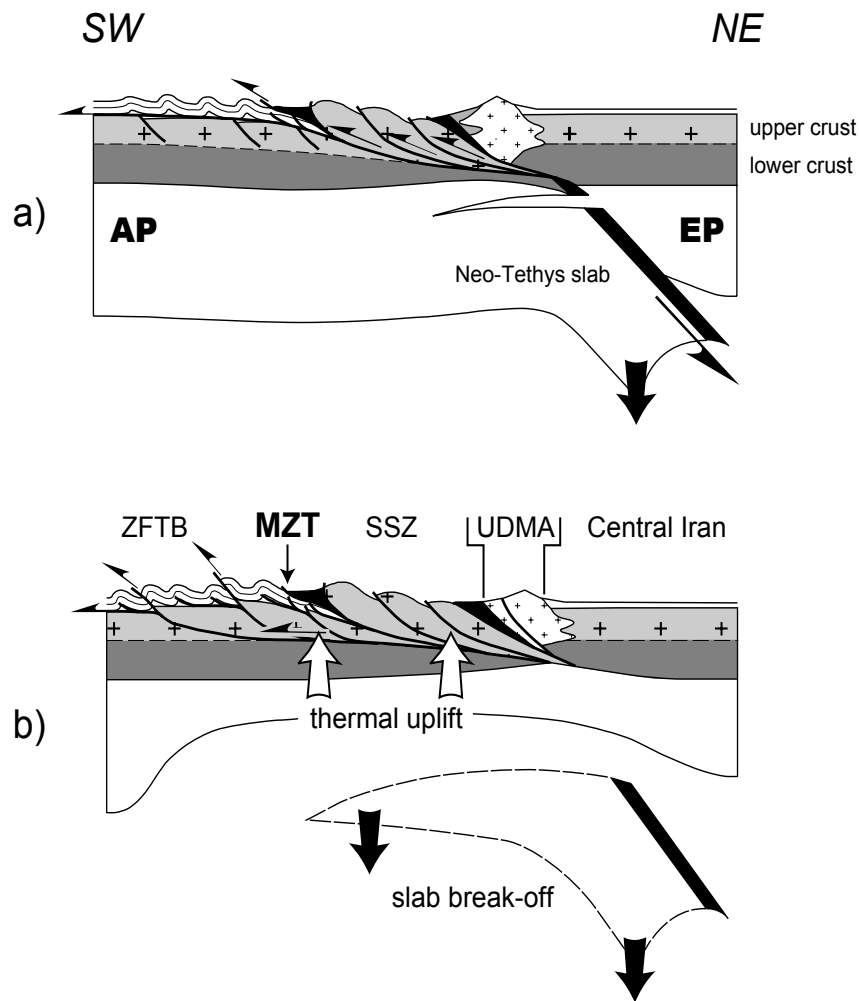


Fig. 4 Conceptual model illustrating the two main stages of recent deformation in Zagros and their possible relation with lithospheric slab break-off. Black shading: ophiolites. **AP**: Arabian Plate. **EP**: Eurasian Plate. Other abbreviations as in Figure 1. **a)** Miocene to Pliocene thin-skinned deformation in the ZFTB. **b)** Pliocene to Recent thick-skinned deformation in the ZFTB. Lithospheric slab is detached underneath Zagros, leading to thermal uplift of the orogen. Basement faults within the ZFTB are interpreted to re-use syn-rift structures of the passive margin.

to increase the angle of the basal detachment by involving deeper levels in the deformation, i.e. to switch to a thick-skinned style of deformation (Fig.5c). The increased erosion generated by uplift of the orogen could provide an explanation for the sudden and widespread occurrence of the Bakhtyari conglomerates throughout the ZFTB (Fig.5b). Yoshioka & Wortel (1995) suggest that the detachment of the Hellenic subduction migrated laterally at a rate of ~20 cm/yr. If we consider a similar rate for Zagros, this would mean that break-off would take ~10 Ma to propagate from one end of Zagros to the other. So it may have commenced as early as 15 Ma ago in northern Zagros. Precise dating of the Bakhtyari conglomerates throughout Zagros could enable checking of the existence of an along-strike diachrony correlating with lateral migration of the break-off.

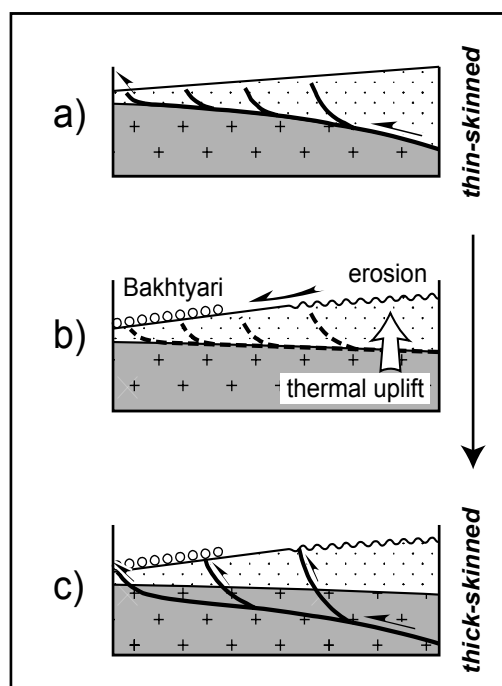


Fig. 5 Schematic cartoon illustrating the effect of wedge taper on the mode of deformation in Zagros. **a)** Folding and thrusting within the cover. **b)** Orogenic uplift linked to slab break-off reduces wedge taper and triggers erosion and deposit of Bakhtyari conglomerates. **c)** Activation of a deep detachment within the basement increases wedge taper.

Slab break-off would also eliminate the main driving force powering the Arabian – Eurasian convergence, i.e. slab pull. However, present-day convergence in Zagros could still be explained by the effects of ridge push and mantle plume activity in the Red Sea/Afar region (Zeyen et al. 1997) and by slab pull towards the north underneath Turkey.

Finally, we point out that for such a recent slab break-off the lithosphere would not yet be heated up to thermal equilibrium. This means that our model gives a maximum thickness estimate of the lithosphere beneath Zagros.

CONCLUSION

Several studies of the Zagros collisional belt, based upon different geophysical techniques, have investigated the crustal structure underneath Zagros, but few have discussed the deeper geometry of the lithosphere. Our modelling based upon the combined interpretation of gravity, geoid and topography data sets, yields a crustal geometry similar to those proposed by previous authors with a maximum depth to Moho of 52 km beneath Zagros. In addition, our model highlights a thinned lithospheric mantle below the crustal root

which we propose to relate to recent slab break-off. Information on earthquake distribution at depth and global tomographic models supports this hypothesis. The recent transition from thin-skinned to thick-skinned deformation in foreland Zagros, documented by geological studies, can be linked to the effects of slab break-off. Thermal uplift and surface erosion generated by this event probably modified the orogenic wedge taper in Zagros and triggered the involvement of deeper levels of the crust in the deformation. The sudden and widespread occurrence of Plio-Pleistocene Bakhtyari conglomerates could be the sedimentary marker of this major change of tectonic regime.

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3.1 Comparison with lithospheric models in northern Zagros

As mentioned in the introduction of this chapter, analogous lithospheric modelling has been carried out by the team at the Institute of Earth Sciences of Barcelona on a series of transects through northern Zagros (lines C, D, E, Fig. V—1). We will here briefly present the results obtained with these models with the aim of comparing them to our model.

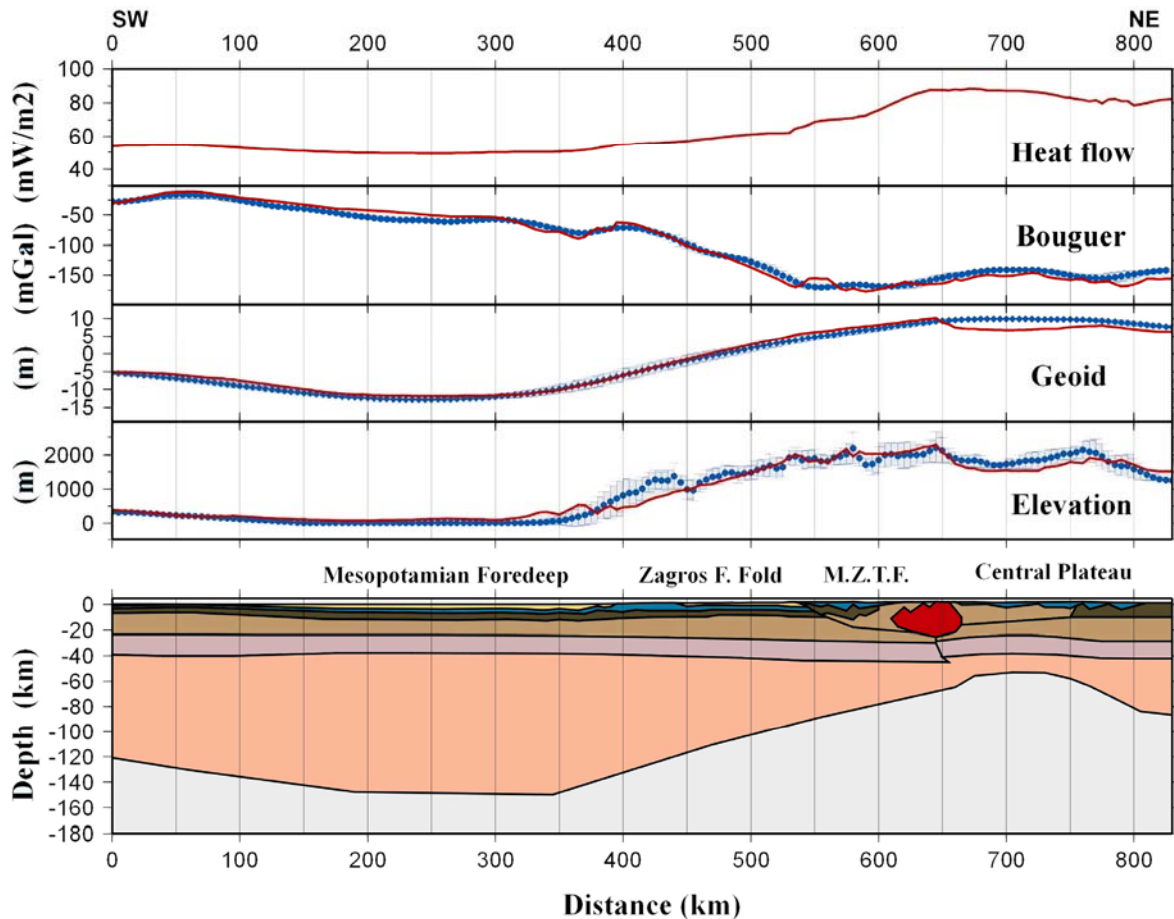


Fig. V—7 Lithospheric transect through the northern Zagros Mountains, after Fernandez et al. (2003b)

Figure V—7 shows a lithospheric transect crossing northern Zagros in the Lurestan area (Fig. V—1, section E), after Fernandez et al. (2003b). The technique used for its construction is in every respect analogous to the one described at the beginning of this chapter. The data sets are also the same except for the gravity anomaly data which were obtained from a private consortium. Also the densities at surface are constrained by available industrial data. The model displays a marked thinning of the lithosphere underneath Zagros, reaching a maximum of ~60 km beneath the magmatic-metamorphic belt. This is in agreement with our results except that the maximum thinning in our model is less (100 km) and shifted more towards the Zagros fold belt (Fig. 2, paper n° 4). Unlike our model, the crust displays little to no thickening beneath Zagros.

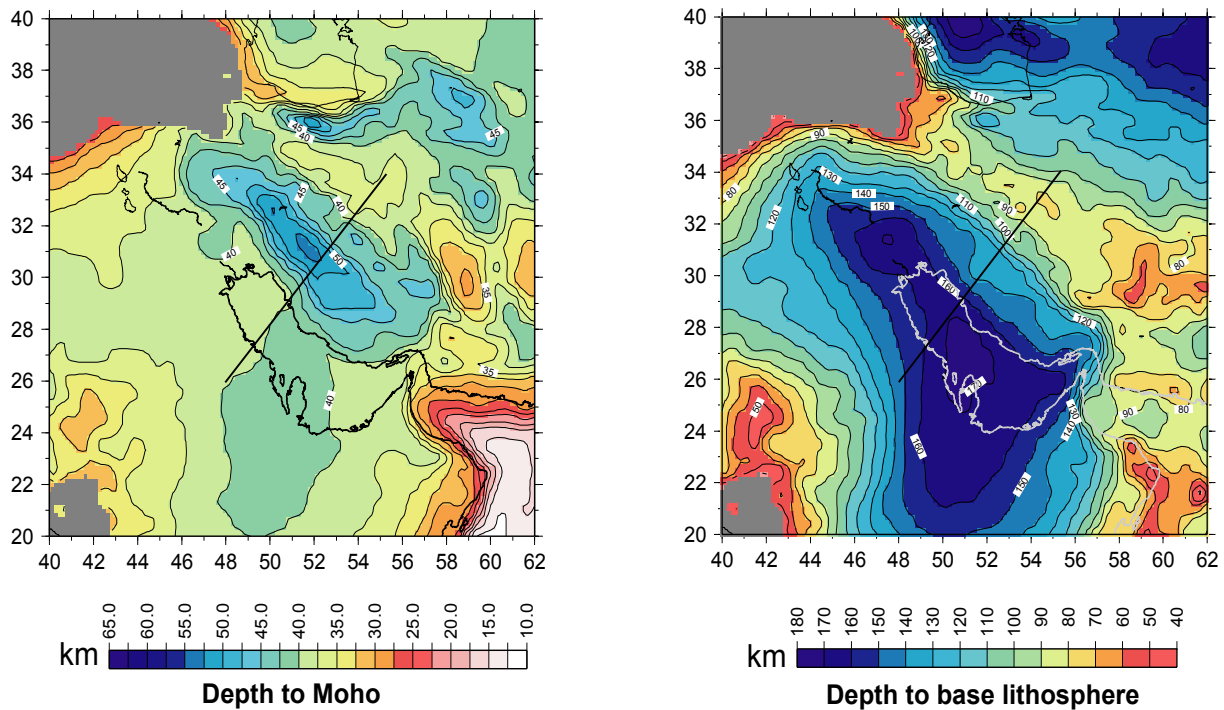


Fig. V—8 Contour maps showing calculated depth to MOHO and depth to base lithosphere for the Persian Gulf and Iranian region, after Fernandez et al. (2003a).

In a more recent development of the modelling algorithm, Fernandez et al. (2003a) have calculated the 3D crustal and lithospheric structure of the Persian Gulf and Iranian region (Fig. V—8). This model suggests that the lithospheric thinning beneath Zagros could be generalised to the entire orogen. Also it shows a crustal root beneath Zagros reaching a maximum depth of ~55 km.

3.2 The problem of dynamic effects on the modelling

A problem that was pointed out during refereeing of paper n° 4 is that the model is a static one and therefore cannot take into account the effects of a highly dynamic process such as slab break-off. What would be the result if these effects were taken into consideration? One of the possible effects is the suction generated by the sinking detached slab (Gvirtzman & Nur 1999), which should in theory depress the topography. Also if slab detachment is supposed to be very recent, as in our case, the lithosphere would not yet have reached the thermal equilibrium which is assumed by the modelling. In other words, the model obtained with our assumptions does not necessarily correspond to the one that would be obtained by considering

these effects. However, taking these effects into consideration should in theory favour the hypothesis of a thinned (detached) lithosphere. On the one hand, because suction causes topography to descend and thus counteracts thermal uplift, to explain the topography in Zagros we would need an even greater lithospheric thinning (and thermal heating). On the other hand, if as we suppose, slab break-off is very recent, the lithosphere should still be relatively cold and dense. So again to explain our data we would need an even greater lithospheric thinning in the model.

4 CONCLUSION

To summarise, in this chapter we propose to explain the recent dynamics of the Zagros Mountains by studying the very deep structure of the orogen. There are several examples described in the literature where surface (upper crustal) processes have been linked to very deep lithospheric processes. In this study, geophysical modelling highlights an unexpectedly thin lithosphere beneath Zagros which is matched by an (expected) crustal thickening, or root, centred upon the metamorphic (SSZ) and volcanic (UDMA) belts. Among the possible various interpretations, the thinned lithosphere can be explained by post-collision slab break-off. The dynamic consequences expected from this major event (essentially thermal uplift) could be the key factor which controlled the recent structural and sedimentary evolution of the ZFTB, notably the sudden switch from thin-skinned to thick-skinned deformation discussed in chapter III and the sudden change in sedimentary regime with the appearance of the Bakhtyari conglomerates. However, since very little is known about this formation (age of deposit, sources), more work is needed in order to understand its meaning.

GENERAL CONCLUSIONS

This final section is a summary, chapter by chapter, of the main objectives and results discussed in this thesis. In conclusion there is a short paragraph on the main possibilities opened up by the continuation of work presented here.

1 Structural style across the Bandar Abbas syntax and its implications in terms of the tectono-sedimentary history of the south-eastern Arabian margin

This thesis focuses on the southeastern segment of the Zagros Mountains, Iran, and the transitional structures with the adjacent Makran subduction prism commonly referred to as the Bandar Abbas syntax. Although some work had already been done on this region, in particular by the team of the University of Cergy Pontoise using magnetic fabric studies and paleomagnetism (Bakhtari 1998, Aubourg et al. 2003, Aubourg et al. 2004, in press), the basic architectural framework of this structurally complex area remained largely unknown. The first part of this thesis (chapter 2) is dedicated to understanding this framework.

Because it is situated at the boundary between two geodynamically distinct contexts – recent collision in Zagros and subduction in Makran – the tectono-stratigraphic history of this area can be expected to be more complex than elsewhere along the Arabian margin. The presence of the Late Cretaceous obduction-related thrust nappes of the Oman peninsula bisecting the Bandar Abbas syntax adds to this complexity. Using the traditional tools of investigation of the field geologist, I have analysed the geometry of the fold-and-thrust structures in this region, both in map and in cross-sectional view. Generally speaking, simple map observations of structures can be very revealing concerning the depth to decollement (through the wavelengths) and the existence of multiple tectonic phases (through cross-cutting or interference relationships). However, it is only with balanced cross-sections that these qualitative observations can be confirmed and that a true geometrical understanding can be achieved for a specific area.

Once the geometrical characteristics of the two limbs of the Bandar Abbas syntax had been clearly defined, a chain of underlying linked factors could be established to explain the change in style of folding and thrusting from one side to the other of the syntax (Fig. II–11):

- Control of mechanical stratigraphy on fold development: folds in the western limb are detached from the Arabian basement along the 8-9 km deep Hormuz salt, while in the eastern limb they sole out into a 6 km deep decollement horizon.

- Contrasting tectono-sedimentary histories from one side to the other of the syntaxis. On the eastern side the Arabian margin was affected by Late Cretaceous obduction of Neo-Tethys ophiolites (Oman) and has not yet started colliding with Central Iran. The rigid ophiolitic nappes and related imbrications of the Oman peninsula are inferred to continue beneath the molasse units of the Zagros domain, and form the “basement” upon which folds in the eastern limb of the syntaxis detach. The western side, by contrast, has been involved in the collision since early Miocene times and the Late Cretaceous ophiolites are seen passively overriding the Zagros folds and imbrications along the MZT.
- Primary control of the inherited segmented morphology of the south-eastern Arabian paleomargin (Molinaro et al. 2004), which has strongly influenced sedimentary patterns since at least Eo-Cambrian times and later guided the emplacement of the Oman ophiolites.

The relationship between the various structurally distinct ophiolitic nappes surrounding the syntaxis remains problematic. Should the ophiolites in the Oman peninsula be connected to the ophiolites presently thrusting over Zagros along the Zendan Fault? What is the relationship between the ophiolites found within the Makran prism and those in the facing Oman Mountains? Understanding the meaning of these various ophiolitic bodies could be one of the keys to further deciphering the complex geodynamic history of this region.

2 Overall mountain belt kinematics and individual fold development in the Zagros foothills.

While from a kinematic point of view the development of fold-thrust structures in the eastern limb of the syntaxis appeared relatively simple, the western limb of the syntaxis presented a more complicated picture. Firstly, the observation of different interfering tectonic trends and the apparent involvement of the basement in the deformation suggest a complex kinematic scenario clearly involving distinct tectonic phases. Secondly, the predominant mode of folding in this area, detachment folding, remains the least understood in terms of kinematics compared to the other main fold models (fault-propagation and fault-bend folds).

Concerning the first point, only a regional balanced cross-section through the fold-thrust structures of this area was able to provide a sufficiently wide scope of analysis to tackle the problem (chapter 3). Incremental restoration of this cross-section confirmed the hypothesised multi-phased tectonic history of this area and shed new light on the relationship between basement and cover deformation in Zagros. In fact, a fairly standard picture emerged of the

progression of deformation through Zagros. In the initial thin-skinned phase of deformation, thrusts and folds ramped up from the hinterland in stepwise fashion while progressively migrating through time towards the foreland (Fig. III—14a). The fold belt evolved with a plan view curvature controlled by the thickness and geometry of the underlying Hormuz salt basin (the “Jura style”). The crystalline basement being the deepest and accordingly last level to be involved in the deformation, faults originating from it then cut in out-of-sequence fashion through the cover during a late thick-skinned phase of deformation (Fig. III—14b). At the same time, propagation of the western branch of the Makran arc resulted in superimposition of NNW-trending structures such as the Minab fold on the Zagros framework. Restoration of the balanced cross-section yields ~ 45 km of shortening, corresponding to a ratio of 22%, close to values calculated by other authors (Blanc et al. 2003, McQuarrie 2004, Sherkati & Letouzey 2004) elsewhere in Zagros.

Some problems still need clarification concerning the relation between deformation in the basement and in the cover. If the basement thrusts in the balanced cross-section (Fig. III—1) are supposed to be decoupled and independent from deformation in the overlying cover, then one would expect them to cut through any part of the deformed cover. Instead, the late basement thrusts appear to coincide almost everywhere with the already formed anticlines, giving the impression that the structures in the cover “influence” the location of the basement thrusts. This is a major problem in the kinematic model for which a solution has yet to be found.

Probably the most distinguishing feature of the Eastern Zagros foothills is the exceptionally thick ductile salt horizon underlying its folded cover, which offered particularly favourable conditions for the generation of pure buckle folds. Therefore the Zagros Mountains represent the ideal setting for investigating the second problematic point mentioned above, i.e. the kinematics of individual detachment folds. By combining field observations from my area of study with field and seismic observations from the Dezful Embayment area we have given an outline of how detachment folds developed in Zagros (chapter 4). We have shown that hinge migration and limb rotation both occurred in the early stages of development of the folds, in agreement with Dahlstrom’s (1990) model of fold growth. The former mechanism is suggested by spectacular “flap structures” observed on the forelimbs of some of the anticlines, while the latter can be inferred from parallel seismic lines across given anticlines and from field examples of folds at different stages of evolution. In the

later stages of folding, thrusts originating from basement faults cut through the forelimbs of the anticlines. In eastern Zagros the obliquity between folds and these late thrusts resulted in distinctive butterfly-shaped interference structures. Salt mobility was an important factor throughout the folding process: at the base of the sedimentary column, because it constitutes the prerequisite condition necessary for the very existence of large detachment folds. Within the sedimentary column, because it can lead to spectacular disharmony within the folded section – notably in the Dezful Embayment region – which had long been observed (O'Brien 1957) but hitherto misunderstood.

3 Lithospheric structure underneath the Zagros Mountains: possible controlling factor of the recent orogenic dynamics

In the final section of this thesis (chapter 5) I have attempted to understand some of the fundamental factors controlling the orogenic process in the Zagros Mountains. Having defined in the previous chapters their geometry and identified two main steps in their evolution, I decided to approach the question from a new angle by investigating the very deep (lithospheric) structure of the orogen. To this end, I employed a geophysical technique allowing the simultaneous interpretation of potential anomalies (geoid and gravity) and topography. The advantage of this technique is that the models can be obtained by imposing an initial geological model and then proceeding by trial and error until the calculated curves match the data. In other words, a “geologist’s view” can be integrated with the results of the geophysical computation. Using this double approach, a complete image of the crustal and lithospheric structure in Zagros was obtained, as shown with the transect in figure VI—1 combining the lithospheric model with the balanced cross-section discussed in chapter 3.

The main result obtained from this general model is a strong lithospheric thinning (reaching a minimum of 100 km) directly underneath the Zagros orogen which it is suggested results from recent lithospheric slab break-off. It is argued that such a major dynamic process could have influenced the structural evolution of the orogen by modifying its wedge taper. This would provide the link between the deep lithospheric processes and the upper crustal evolution of Zagros: uplift generated by break-off would have modified the wedge taper in Zagros, triggering the transition from thin-skinned to thick-skinned tectonics. It could also explain the sudden change in sedimentary regime with the orogen-wide appearance of the Bakhtyari conglomerates.

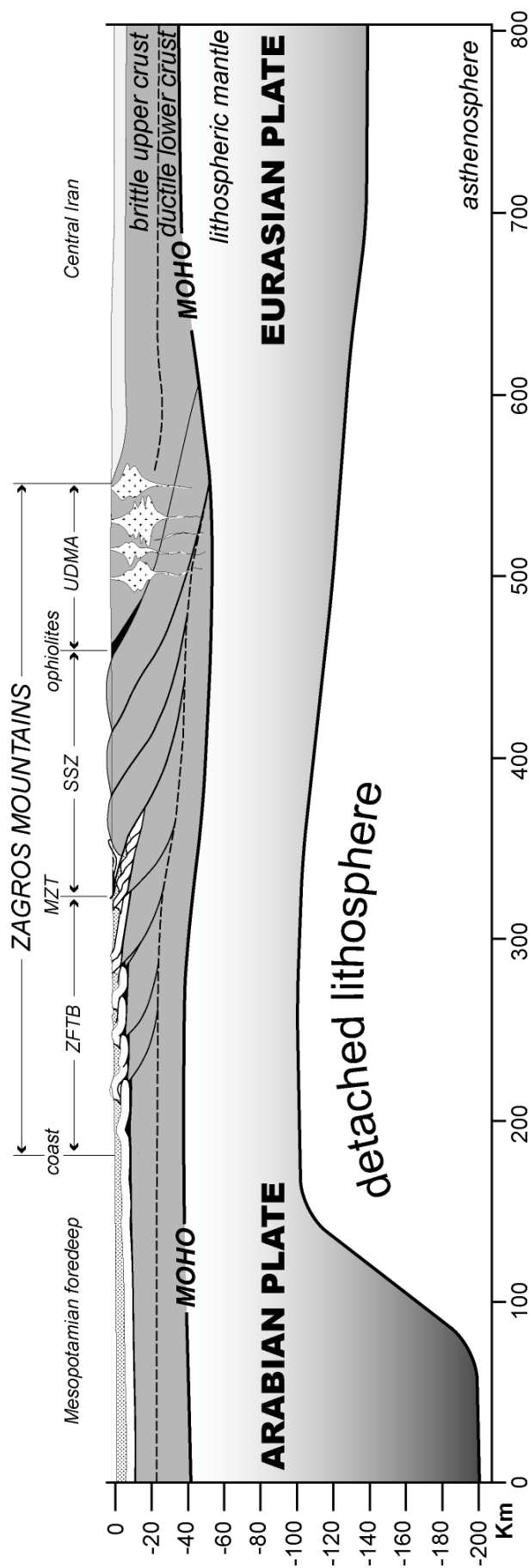


Fig. VI—1 Final crustal and lithospheric structure of the Zagros Mountains (no vertical exaggeration). The image has been obtained by projecting the balanced cross-section (chapter III) through the ZFTB (line of section in Fig. V—6) on the lithospheric model (chapter V) (line of transect Fig. V—6), using the MZT as fixed reference. In ZFTB, stippled units: Cenozoic rocks, blank units: Mesozoic-Paleozoic rocks.

4 Future prospects

The work presented in this thesis opens up new possibilities for the research and understanding of the Zagros Mountains. The first step which should precede any investigation on a specific area is to achieve a good understanding of the fundamental structural framework and the geometry of its structures. Accordingly, the first part of this dissertation concentrated on this objective, after which I felt justified in examining in greater depth the chain of causes and factors underlying what we observe. It was then possible to sketch a rough kinematic scenario from the observed geometry and deduce the factors controlling this kinematic scenario from the deep lithospheric geometry.

Further work should aim at elaborating these preliminary results. The kinematic model of evolution of the ZFTB could be better constrained by (a) constructing other balanced cross-sections and integrating existing sections from elsewhere in Zagros (e.g. Sherkati & Letouzey 2004) and (b) by providing accurate temporal brackets for the ages of tectonic events with detailed analyses of the ages and sources of the molasse deposits (i.e. magnetostratigraphic sections). Also it would be interesting to couple the horizontal kinematics inferred from balanced cross-sections with vertical movements deduced from other techniques such as source rock burial histories and fission track measurements: dating these vertical movements would provide powerful constraints on the possible kinematic scenarios.

On the other hand, due to the exceptionally good preservation and exposure of its structures, the Zagros foothills constitute a natural laboratory for understanding the kinematics and mechanics of detachment folding. In particular the analysis of the growth strata preserved in the synclines and the study of meso and micro-scale structures associated with the folding process would help to improve current models of folding.

Finally, further developments of the results would improve the understanding of the deep structure of the Zagros orogen and confirm the proposed lithospheric detachment. Firstly, by integrating the results of the lithospheric model with work carried out by the Institute of Earth Sciences “Jaume Almera” in Barcelona on northern and central Zagros and ultimately obtaining an image of the complete 3-D structure of the orogen. In the longer term, by improving and further constraining the models with new gravimetric data and with heat flow data. A decisive help for future studies would be the implementation of wide-angle seismic reflection profiles, such as the ECORS programme in the Pyrenees, imaging the deep crustal structure of the orogen.

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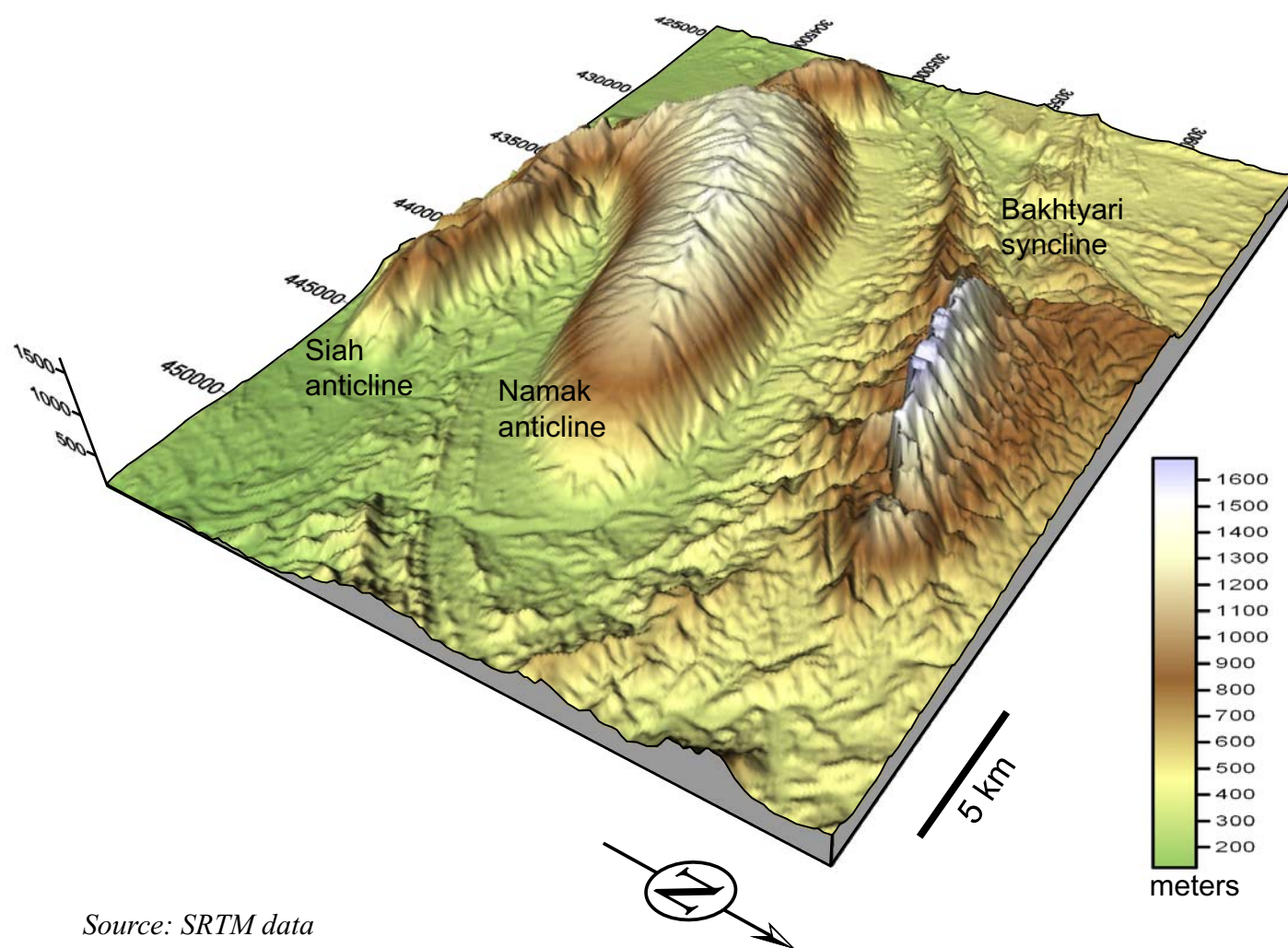
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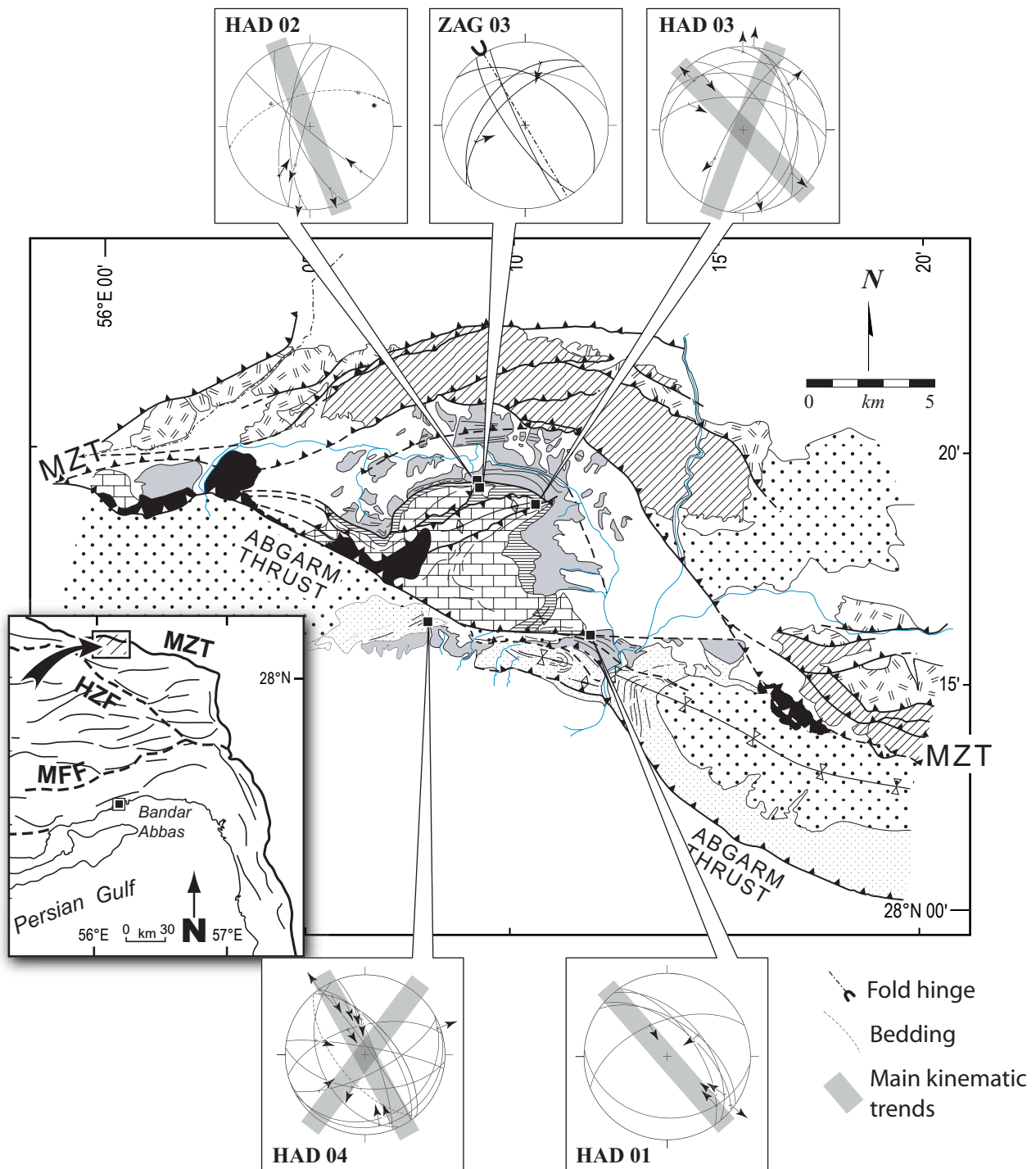
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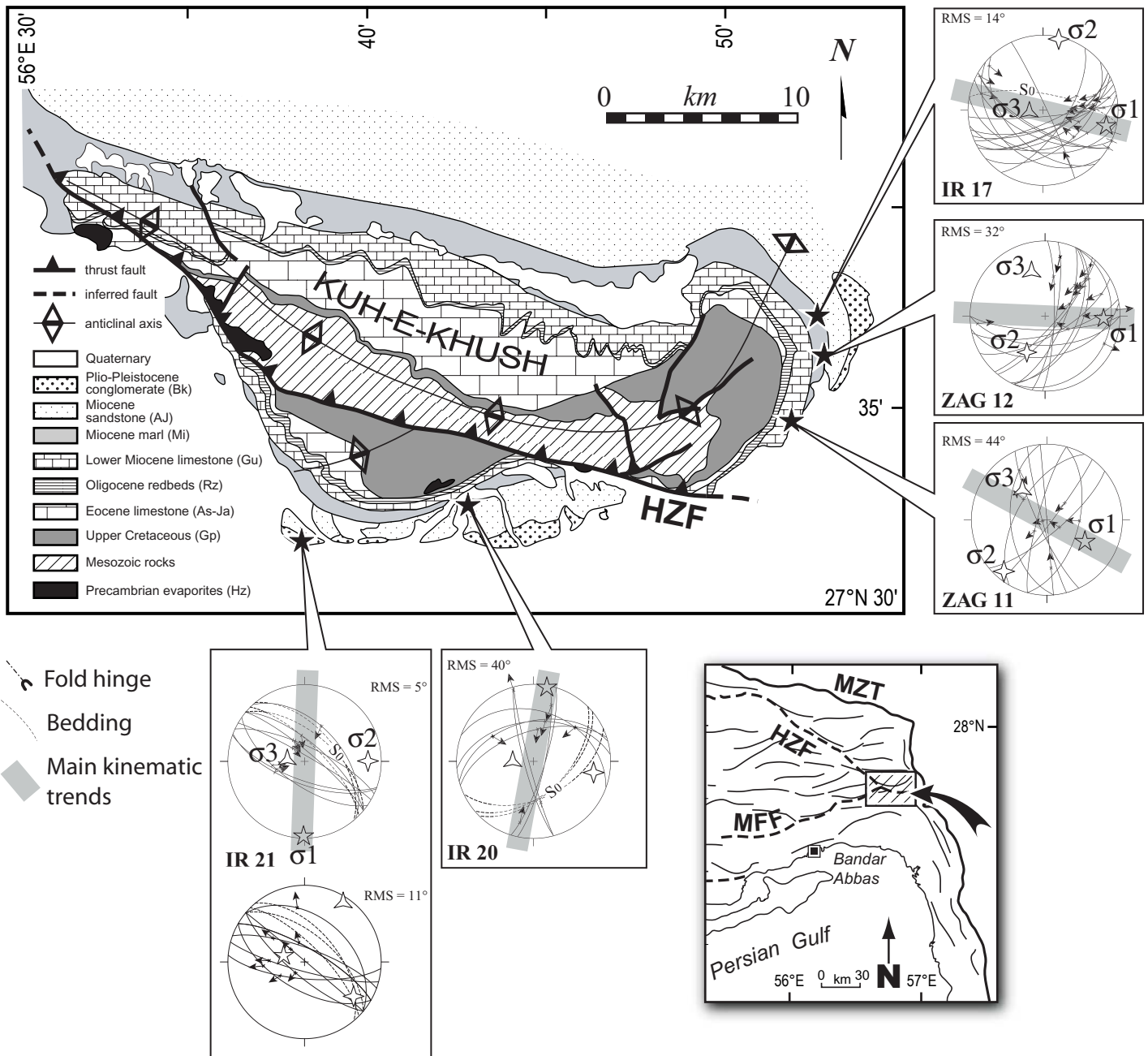
Some of the maps and figures in this dissertation were elaborated using open source Generic Mapping Tools software (GMT, Wessel and Smith, 1995) (<http://gmt.soest.hawaii.edu/>).

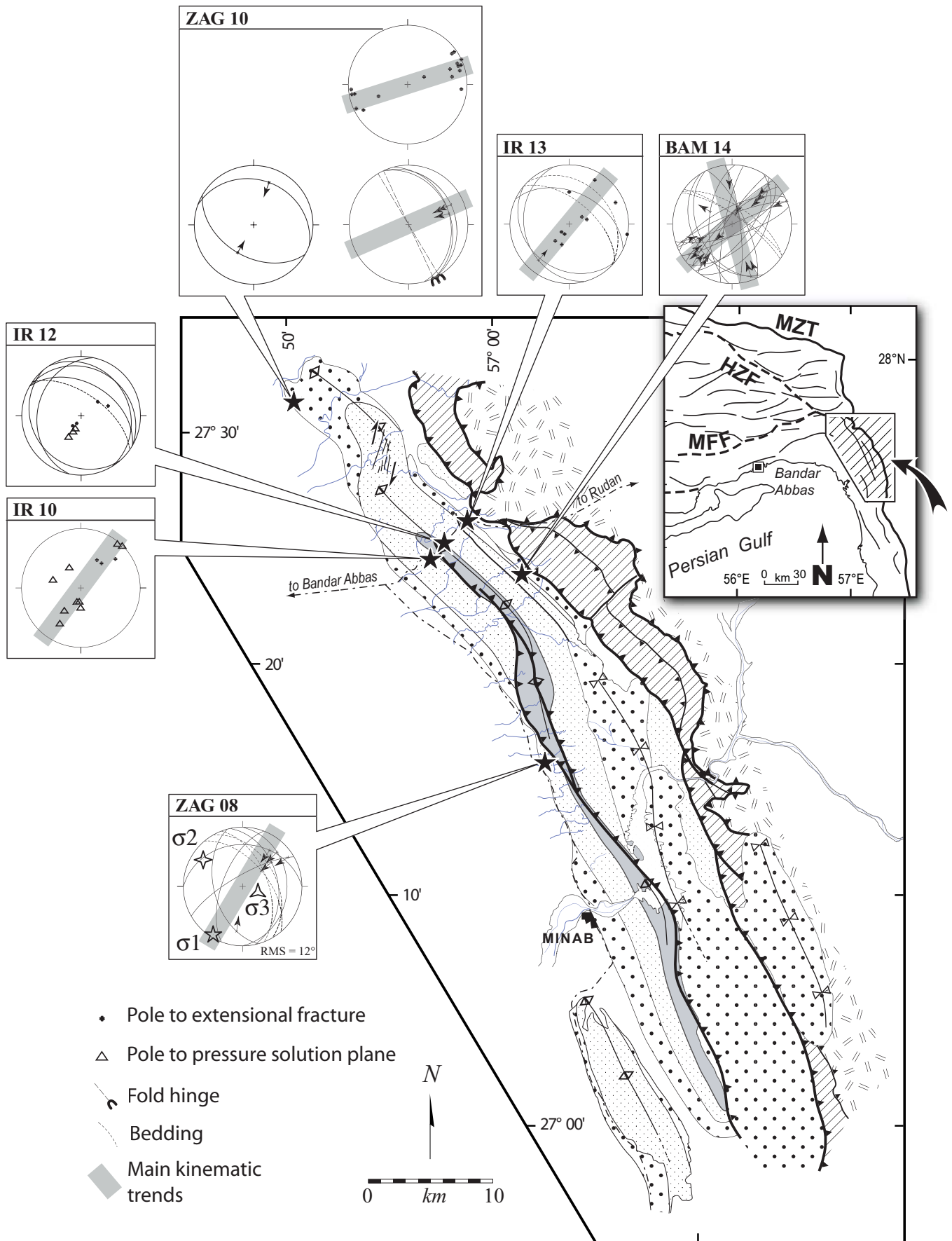
APPENDIXES

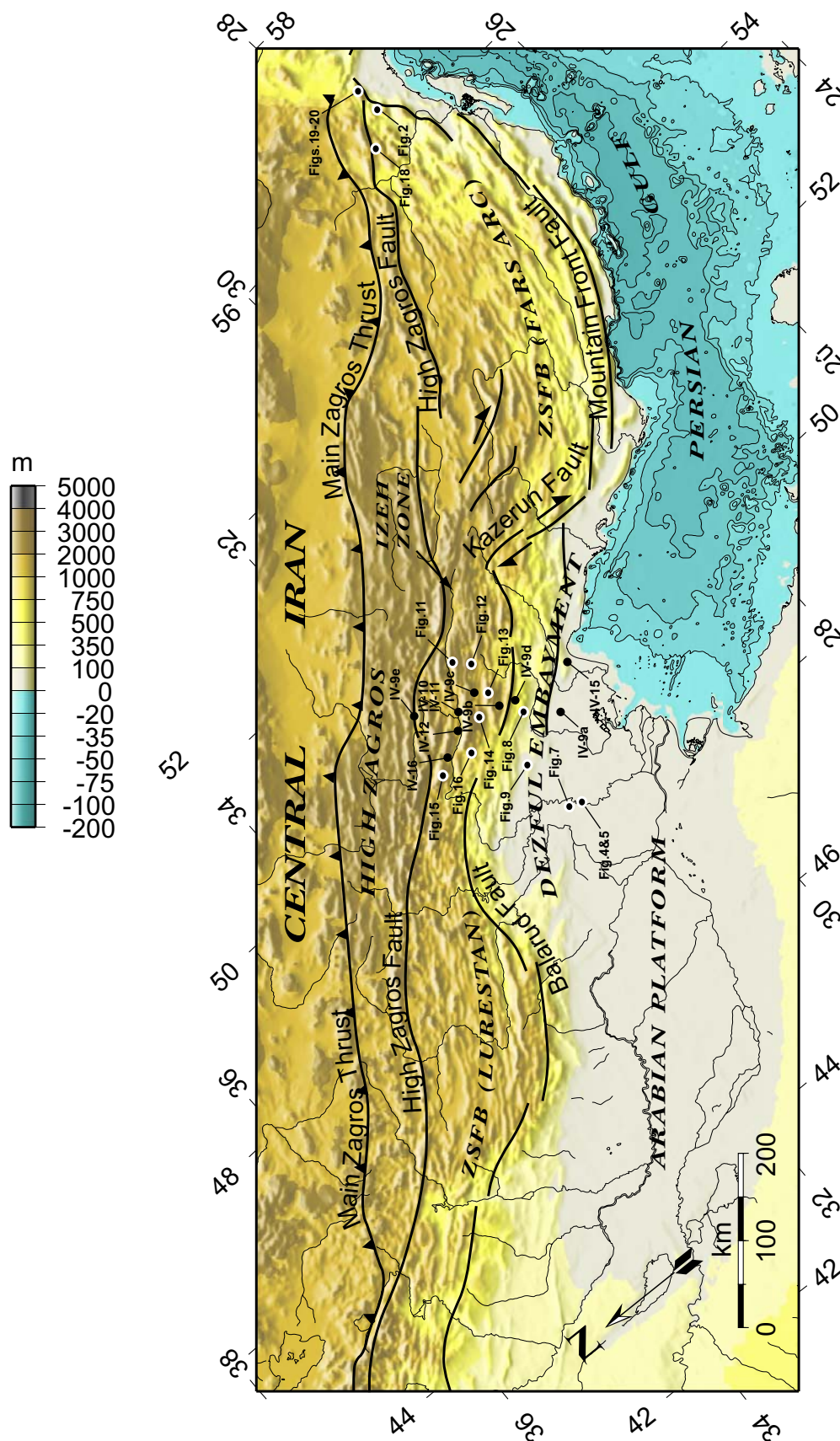


All the stereoplots presented in appendixes 2,3,4, as well as calculations of stress tensors, were generated using Daisy 3.0 software by F. Salvini (Università degli Studi "Roma 3"). Data was collected during several field trips. HAD, ZAG: data collected personally; BAM: data from S. Lallemand; IR: data from X. Braud









Location map for figures discussed in chapter IV. Black & white circles (Fig. 1 to 20) indicate location of figures discussed in chapter 4, paragraph 2 (paper n.º3). Black circles (IV-9 to IV-16) indicate location of figures discussed in chapter 4, paragraph 3 (complementary remarks).

ABSTRACT

This thesis focuses on the structure and kinematics of the south-eastern Zagros Mountains (Iran) and the transitional structures with the adjacent Makran accretionary prism, known as the Bandar Abbas syntaxis. The structural framework of this complex region, as evidenced by detailed field-based mapping and balanced cross-sections through some key structures, is strongly controlled by changing mechanical stratigraphy from one side to the other of the syntaxis. Large folds detaching over a thick 8-9 km deep salt layer on the western side suddenly give way to narrow folds controlled by frictional slip along a 6-km deep horizon in the east. This is explained by changing paleogeographic conditions from one side to the other of the syntaxis ultimately related to inherited (Precambrian) structural features of the eastern Arabian margin.

Restoration of the first complete balanced cross-section through the south-eastern Zagros fold-thrust belt shows that the external part of the orogen (a) underwent two main phases of deformation, i.e. a Mio-Pliocene thin-skinned phase of deformation followed and partly overprinted by a Pliocene to recent thick-skinned phase currently underlined by intense mid-crustal seismic activity throughout Zagros, and (b) absorbed at least 45 km of shortening since middle Miocene times.

The presence of an exceptionally thick layer of salt at the base of the cover allowed the development of huge detachment anticlines. Field examples from our study area and seismic profiles from Central Zagros allow us to discuss the still poorly understood kinematics of these folds as well as examine the various factors controlling the style of folding, essentially salt mobility, multiple decollement levels and late basement faulting.

Finally, geophysical modelling of the deep lithospheric structure of Zagros brings new insight on the fundamental factors controlling the recent orogenic dynamics. In particular, a previously undocumented thinning of the lithosphere beneath Zagros could be attributed to recent slab break-off. It is argued that such a major dynamic event could have modified the orogenic wedge taper and triggered the previously discussed switch from thin-skinned to thick-skinned tectonics.

Keywords: *Zagros, syntaxis, structural inheritance, detachment fold, basement fault, kinematics, salt mobility, lithospheric structure*

RESUME

L'objectif de cette thèse est l'étude de la structure et la cinématique du Zagros oriental (Iran) et de la zone de transition avec le prisme du Makran appelée syntaxe de Bandar Abbas. Une étude structurale de terrain a été menée pour tenter de comprendre l'architecture de cette région complexe. L'analyse détaillée en carte et en coupe d'un certain nombre de structures typiques montre le contrôle exercé par la stratigraphie mécanique sur le mode de plissement de chaque côté de la syntaxe. Les grands plis dans l'ouest de la syntaxe sont décollés sur une puissante série évaporitique située à 8-9 km de profondeur, tandis que les plis étroits situés à l'est sont décollés sur un niveau à 6 km. Ceci est expliqué par un changement des conditions paleogéographiques d'un côté à l'autre de la syntaxe lié à l'influence de structures (Précambriennes) héritées dans la marge arabe orientale.

La restauration de la première coupe équilibrée à travers le sud-est de la ceinture du Zagros permet de montrer que le Zagros plissé a subi deux phases tectoniques majeures, une première, d'âge Mio-Pliocène, impliquant la couverture suivie par une deuxième, d'âge Pliocène, impliquant le socle - couverture. Celle-ci se poursuit jusqu'à l'actuel et est soulignée partout dans le Zagros par une sismicité intense dans la croûte supérieure. Le raccourcissement accommodé dans la section depuis le Miocène moyen est d'au moins 45 km.

La présence d'une puissante série évaporitique à la base de la couverture a favorisé le développement de grands plis de décollement. L'analyse d'exemples de terrain dans la région d'étude ainsi que de profils sismiques dans le Zagros Central permet de discuter la cinématique de ces plis ainsi que les facteurs contrôlant leur style, notamment la mobilité du sel, l'existence de multiples décollements et le rôle tardif des failles de socle.

Enfin, une modélisation géophysique de la structure lithosphérique du Zagros permet de discuter les facteurs fondamentaux qui ont guidé l'évolution récente de l'orogène. On met en évidence un amincissement lithosphérique qui pourrait être lié à un détachement récent du slab plongeant. On propose que ce processus, en modifiant l'angle critique du prisme orogénique, est le facteur fondamental qui a déclenché la transition d'une tectonique de couverture à une tectonique de socle - couverture

Mots-clefs : *Zagros, syntaxe, héritage structural, pli de décollement, accident de socle, cinématique, mobilité du sel, structure lithosphérique*
