Early Reactivation of Basement Faults in Central Zagros (SW Iran): Evidence from Pre-folding Fracture Populations in Asmari Formation and Lower Tertiary Paleogeography

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Abstract. Early reactivation of basement faults and related development of flexures/forced-folds in the Central Zagros are discussed based on fracture populations observed in outcrops and aerial photographs/satellite images and paleogeographic maps. The presence of pre-folding joint sets slightly oblique to anticline axes and observed even within synclines or the occurrence of N-S (and E-W) trending fracture sets near N-S trending basement faults and strongly oblique to cover folds are not compatible with simple fold-related fracture models in this region. These early fractures are proposed to have formed within the cover above deep-seated basement faults in response to the formation of flexures/forced folds whose geometries and orientations may be different from the present-day folds in the Central Zagros. This early stage of intraplate reactivation of the NW-SE and N-S trending basement faults likely marks the onset of collisional deformation and stress build-up in the Zagros basin. This reactivation led to facies variations and development of different sub-basins in the Central Zagros during the sedimentation of the Oligocene-Miocene Asmari Formation. The evaporitic series of the Kalhur Member within the Asmari Formation resulted from the development during Aquitanian times of a long and narrow restricted lagoon environment, between two main basement faults (i.e., DEF and MFF), and provide one of the main key constraints on the beginning of deformation in the region. Finally, based on observed fracture populations and proposed geodynamic evolution in the Central Zagros basin, it is suggested that partitioning of N-S Arabia-Eurasia convergence into a belt-perpendicular NE-SW shortening and a belt-parallel right-lateral strike-slip motion (as currently along the Main Recent Fault) in the Central Zagros may have started as early as Oligocene (?)-Lower Miocene times.

Keywords. Zagros, Asmari, tectonics, fold, fracture, basement

1 Introduction

Reactivation of basement faults occurs during orogenic evolution of collided passive margins, and this structural process is known to exert a strong control on the evolution of orogens (Dewey et al., 1986). Basement fault reactivation may induce localization of thrusts and folds in the developing shallow thrust wedge, reversal of extensional faults and development of crystalline thrust sheets, out-of-sequence thrusting and refolding of shallow nappes, development of accommodation structures such as lateral ramps, and development of basement uplifts (Wiltschko and Eastman, 1983; Glen, 1985; Cooper and Williams, 1989; Roure et al., 1990; Narr and Suppe, 1994; Butler et al., 1997).

A number of regional studies have demonstrated the compressional reactivation of preexisting structures within both the cover and the basement of foreland thrust belts worldwide (e.g., Alps: Roure et al., 1990; Lacombe and Mouthereau, 2002; Urals: Brown et al., 1999; Andes: Winslow, 1981; Kley et al., 1999; Cristallini and Ramos, 2000; Rockies: Dechesne and Mountjoy, 1992; Taiwan: Mouthereau et al., 2002; Lacombe et al., 2003; see also Letouzey, 1990; Mitra and Mount, 1998). Moreover, reactivation of intraplate basement faults and structural inversion of sedimentary basins have also been documented in the foreland far from the orogens (e.g., Tapponnier et al., 1986; Ziegler, 1987; Ziegler et al., 1995; Lacombe and Mouthereau, 1999; Marschak et al., 2000).

The Zagros belt results from the still active collision of the Arabian plate with the continental blocks of Central Iran (e.g. Stocklin, 1968; Jackson and McKenzie, 1984) (Fig.1). The Main Zagros Thrust (MZT) is considered as the suture, currently inactive, between the Arabian and Central Iran plates. GPS studies suggest that about one third of the active Arabia–Eurasia shortening (ca. 7 mm yr-1) is taken up in central Zagros (Vernant et al., 2004). Folding (and thrusting) of the Zagros sedimentary cover occurred mainly during the Mio-Pliocene by the end of deposition of the syntectonic upper Agha Jari Formation, about 7–3 Ma ago (Falcon, 1960; Stoneley, 1981; Berberian and King, 1981; Homke et al., 2004), while the Arabia-Eurasia continental collision culminated. The timing of the onset of this continental collision is, however, poorly constrained (estimates range from Late Cretaceous to Pliocene times, e.g., Berberian and King, 1981; Alavi, 1994; Agard et al., 2005; Sherkati et al., 2006) and has remained a matter of debate.

In the Zagros foredeep, although the geometry of the deformed cover is relatively well-known thanks to

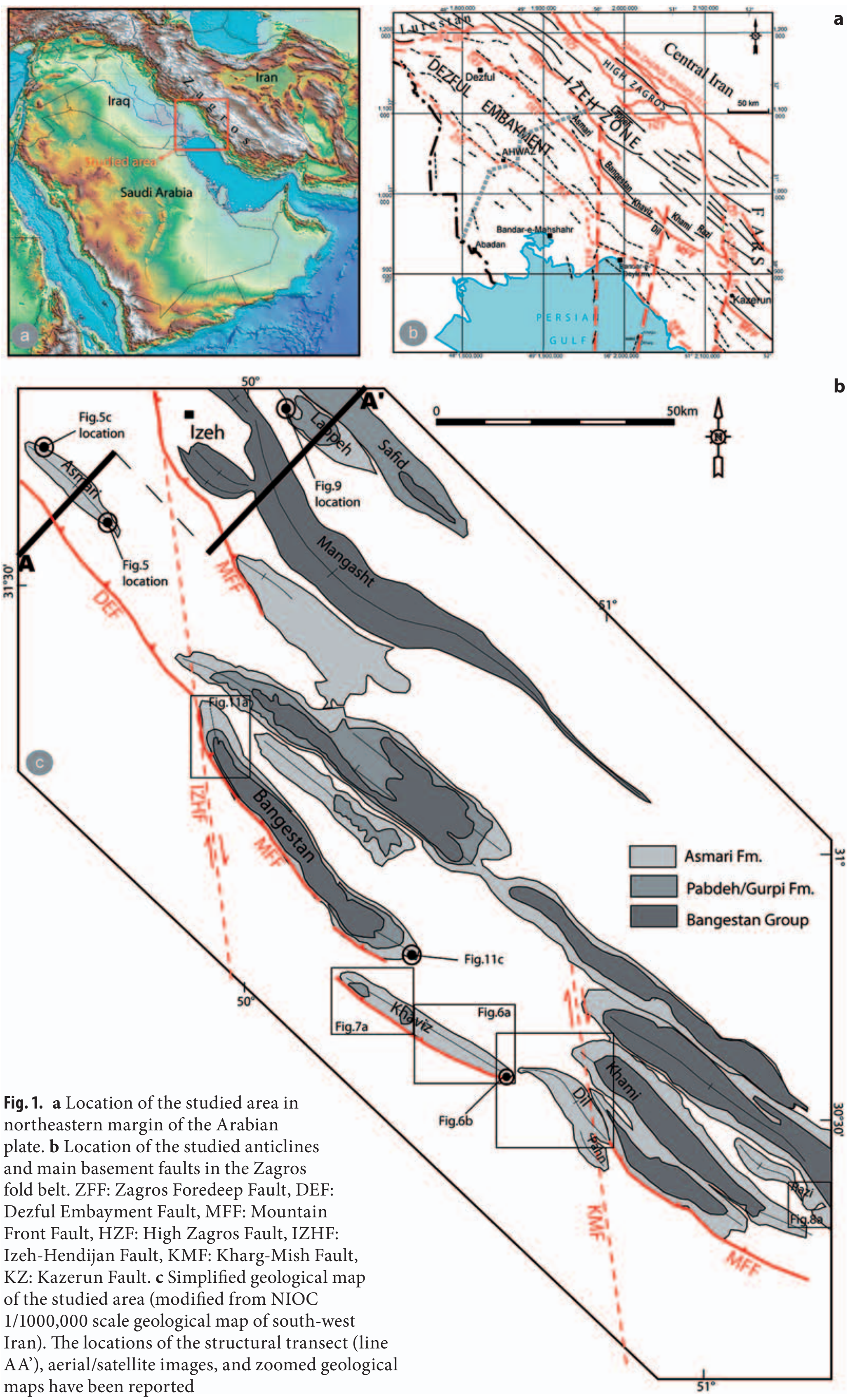

Fig. 1. **a** Location of the studied area in northeastern margin of the Arabian plate. **b** Location of the studied anticlines and main basement faults in the Zagros fold belt. ZFF: Zagros Foredeep Fault, DEF: Dezful Embayment Fault, MFF: Mountain Front Fault, HZF: High Zagros Fault, IZHF: Izeh-Hendijan Fault, KMF: Kharg-Mish Fault, KZ: Kazerun Fault. **c** Simplified geological map of the studied area (modified from NIOC 1/1000,000 scale geological map of south-west Iran). The locations of the structural transect (line AA'), aerial/satellite images, and zoomed geological maps have been reported

few seismic reflection lines, drilled-wells and excellent quality exposures (Fig. 2), information on the underlying basement is poor. The depth to basement can be estimated at 10–12 km on the basis of the results of aeromagnetic surveys (Morris, 1977) and from balanced cross-section (Blanc et al., 2003; McQuarrie, 2004; Sherkati et al., 2006). However, there is no clear image of basement fault pattern and defining their role in the structural evolution of the Zagros fold belt remains difficult. Reactivated basement normal faults inherited from the Tethyan rifting at a depth between 10 and 20 km have been thought for a long time to be responsible for the major earthquakes along the Zagros belt (Berberian, 1981, 1995; Jackson, 1980; Jackson et al, 1981; Jackson and McKenzie, 1984). Moreover, basement structures likely played a role in the deformation of the Zagros by localizing some topographic steps and major (often active) thrust faults in the cover (Berberian, 1995; Letouzey et al., 2002; Mouthereau et al., 2006). Recent balanced cross-sections in the Zagros emphasize that the basement is involved in shortening (Fig. 2) (Blanc et al., 2003; Letouzey and Sherkati, 2004; Sherkati et al., 2006). The generalized involvement of the basement in shortening is thought either to have followed (Molinaro et al., 2005; Lacombe et al., 2006) or to have been roughly coeval with (Mouthereau et al., this issue) folding of the sedimentary cover which occurred in late Miocene-Pliocene times. Oveisi et al. (this issue) provide evidence that both the sedimentary cover and the basement are currently deforming coevally but in a decoupled way at the Central Zagros front. In the Fars, Mouthereau et al. (2006) documented localized basement fault reactivation as early as during the middle Miocene.

Our aim in this paper is to demonstrate that in the Central Zagros basement faults were reactivated during a (late Oligocene ?)-Lower Miocene early stage of collisional stress build-up and that this early basement fault reactivation (1) strongly controlled the paleogeography in the Paleogene and Lower Neogene, (2), presumably produced a phase of early large-scale flexure/forced-folding in the cover and (3) likely played a significant role during the early stage of fracturing within the Asmari Formation before the main Mio-Pliocene phase of cover folding (Stocklin, 1968; Berberian, 1981). For these purposes, we have looked at the fracture populations observed in the Asmari Formation cropping out in several anticlines in the Izeh Zone and Dezful Embayment and have carefully examined facies variations in the central part of the Zagros fold belt from Paleocene to Lower Miocene. Finally, the implications for the timing of the onset of collisional deformation and stress build-up in the Zagros belt are discussed.

2 Geological Setting and Tectonic Evolution of the Zagros Fold Belt

2.1 Main Lithological Units

The Zagros fold belt is located along the north-eastern margin of the Arabian plate (Fig. 1a). It forms a 200–300 km-wide series of remarkable folds extending for about 1200 km from eastern Turkey to the Strait of Hormuz. The sedimentary column in the Zagros is estimated to be up to 12 km (James and Wynd, 1965; Falcon, 1974; Huber, 1977) and comprises the Cenozoic foreland sequence and the underlying Paleozoic-Mesozoic deposits of the Arabian margin and platform. The sedimentary column, ranging from Cambrian to Plio-Quaternary, is embedded between two main detachment levels (mobile group), namely the Hormuz Salt Formation (Infra-Cambrian) at the base and the Gachsaran Formation (Lower Miocene) at the top (Lees, 1950; Falcon, 1969; Colman-Sadd, 1978). Since

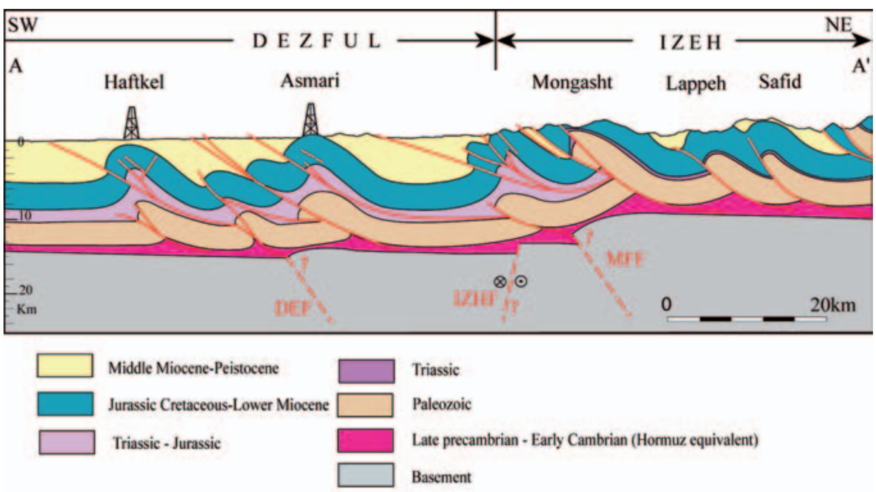

Fig. 2. Regional transect through the studied area showing regional deformation style in the Izeh zone and the north of Dezful Embayment (line AA' in Fig. 1**c**). Important basement features, Mountain Front Fault (MFF), Dezful Embayment Fault (DEF), and dextral strike-slip Izeh-Hendijan Fault (IZHF) are seen in this transect (modified from Sherkati et al., 2006)

the main stratigraphic units exposed in the studied area correspond to the Cretaceous to Pliocene-Quaternary time interval during which the main tectonic movements took place, we briefly describe hereafter the lithological series of this period (Fig. 3a). The Lower Cretaceous shows almost uniform carbonate platform sediments including the Khami and lower part of the Bangestan Group. The Upper Cretaceous is characterized by the neritic carbonate series of the Sarvak and Ilam formations, and terminates with the basinal facies (deep water marls and shales) of the Gurpi Formation. The Tertiary sedimentary series are less uniform and show a variety of facies from neritic to deep basinal (Pabdeh Formation) to shallow marine carbonates of the Jahrum and Asmari formations (Fig. 3b-c) during the Lower Tertiary. Spanning the Middle Miocene to Pliocene are the Gachsaran evaporites, the marls of the Mishan Formation, then the deltaic/estuarine shales and sandstones of the Agha-Jari Formation which reflect a first-order basin-scale regressive sequence and which marks the progressive infilling of the Zagros foreland basin. The Tertiary sedimentary history ended with deposition of the diachronous coarse fluvial conglomerates of the Pleistocene Bakhtiary Formation.

2.2 Geodynamics and Deformation, Previous Work

The present morphology of the Zagros is the result of the structural evolution and depositional history of the northern part of the Arabian plate including a platform phase during the Paleozoic; a Tethyan rifting phase in the Permian-Triassic; a passive continental margin phase (with sea-floor spreading to the north-east) in the Jurassic-Early Cretaceous; subduction to the north-east and ophiolite-radiolarite obduction in the Late Cretaceous; and collision-shortening during the Neogene (Falcon, 1974; Berberian and King, 1981; Berberian et al., 1982; Berberian, 1983).

From a geodynamic point of view, different models for the evolution of the Zagros mountain system in southern Iran have been proposed (e.g., Falcon, 1967; Stocklin, 1968; Wells, 1969; Ricou, 1970; Nowroozi, 1972; Haynes and McQuillan, 1974; Alavi, 1980, 1994, 2004; Berberian and King, 1981; Jackson et al., 1981; Ni and Barazangi, 1986). In almost all of them, northward movement of the Arabian plate relative to the Central Iran during Tertiary times resulted in thrust faulting and overfolding in the Imbricated Belt adjoining the trench zone and gentler folding in the Simply Folded Belt to the southwest. Despite this, the beginning of compression in the Zagros fold belt is poorly dated. The initial Arabian-Central Iran continental collision is considered to be Late Cretaceous (Hayenes and McQuillan, 1974; Berberian and King, 1981; Alavi, 1994), Eocene-Oligocene (Hooper, 1994), Oligocene-Miocene (Berberian et al., 1982) or late Miocene in age (Stoneley, 1981; McQuarrie et al., 2003). Berberian and King (1981) proposed that folding in the Zagros foldbelt started around 5 Ma and coincides with the second phase of extension in the Red Sea and Gulf of Aden. Based on the unconformity between the Agha-Jari and Bakhtyari formations, Falcon (1961) suggested that the deformation was initiated in the Early Pliocene. On the basis of several unconformities at different stratigraphic levels, Hessami et al. (2001) proposed that deformation has occurred by pulses since the end of the Eocene, and reached the front of the folded belt during an end-Pliocene phase. All these estimations are based on ages of unconformities and sediment formations mostly defined by James and Wynd (1965). Documented Holocene anticline growth (Mann and Vita-Finzi, 1988; Vita-Finzi, 2001; Oveisi et al., this issue) and recent seismicity (Jackson and McKenzie, 1984) indicate that deformation in the Zagros belt is still active, especially at deep crustal levels. Homke et al. (2004) defined the beginning of the deformation in part of the Zagros foreland basin (Push-e Kush Arc) at 8.1 to 7.2 Ma based on magnetostratigraphical study of Miocene-Pliocene sediments. Allen et al. (2004) stated that extrapolating present-day deformation rates for 3–7 million years produces displacements that equal or exceed the total deformation on many of fault systems that are currently active in the Arabia-Eurasia collision zone including the Zagros Simple Folded Zone. This age range is much shorter than the overall age of the collision which began in the early Miocene (16–23 Ma) or even earlier (Hempton, 1987; Yilmaz, 1993; Robertson, 2000) with an early Miocene flexure before folding (Sherkati et al., 2006). Agard et al. (2005) documented several major tectonic events that took place at the end of the Cretaceous, during the Late Eocene, and from the Mid-Miocene onwards (ca. <20–15 Ma) and concluded that collision must have started before ca. 23–25 Ma in the northern Zagros.

2.3 Basement Fault Pattern in the Studied Area

There is no published information about basement depth available from seismic refraction or reflection and without such knowledge it is difficult to have a clear image of basement faults patterns and their role in geodynamic evolution of the Zagros fold belt. Two dominant tectonic trends, respectively N-S and NW-SE, exist in the Arabian Shield (e.g., Stern, 1985). Moreover, there is evidence for the continuation of several structures known in the Arabian Shield northwards into the Zagros Basin, before these structures

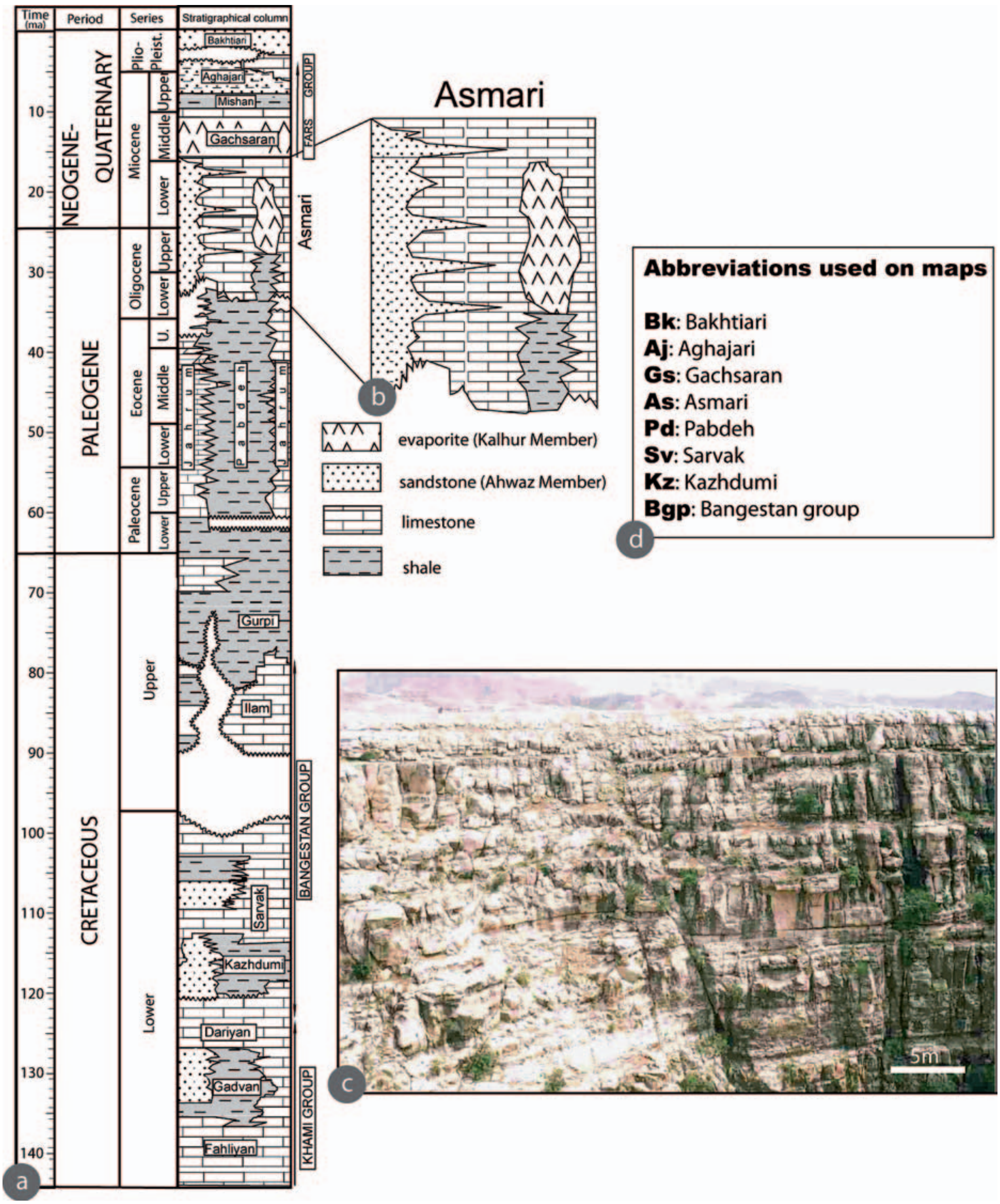

Fig. 3. **a** Lithostratigraphical chart showing the main stratigraphical units in the Central Zagros from Cretaceous to Pleistocene times. **b** Detail of the Asmari Formation. **c** Main exposed carbonate lithology of the Asmari Fm (e.g., Asmari anticline). **d** Abbreviations used in the following geological maps

were reactivated during the Cenozoic Zagros orogeny (Berberian, 1995; Talbot and Alavi, 1996; Hessami et al., 2001, Bahroudi and Talbot, 2003). In the Zagros belt, the approximate location and geometry of the basement Faults, despite the lack of detailed deep crustal knowledge, have been defined using a geodetic survey, more or less precise epicenter/hypocenter locations, as well as topographic and morphotectonic analyses (Berberian, 1995). The first group of basement faults includes the High Zagros Fault (HZF), the Mountain Front Fault (MFF), the Dezful Embayment fault (DEF), and the Zagros Foredeep Fault (ZFF) (Fig. 1b). Fault plane solutions for earthquakes along these faults indicate that they all dip about 60° NE (Bahroudi and Talbot, 2003), suggesting that they now act as reverse faults although they may have been activated as normal faults during the Permo-Triassic opening of Neo-Tethys (e.g., Jackson, 1980; Berberian, 1995).

Another group of basement faults are N-S trending faults which developed during the latest Proterozoic and early Cambrian in the Arabian basement (Beydoun, 1991). During the Mesozoic, and especially in the Triassic and Late Cretaceous, the N-S uplifts and basins related to this group of basement faults were intermittently reactivated (Edgell, 1992; Sherkati and Letouzey, 2004). These faults are steep to vertical and currently undergo right-lateral strike-slip motion (Baker et al., 1993; Berberian, 1995; Sepehr, 2001; Hessami et al., 2001). Some of these faults, located in the studied area, are the Izeh-Hendijan Fault (IZHF), the Kharg-Mish Fault (KMF), and the Kazerun Fault (KZ) (Fig. 1b). The Balarud Fault (BR) is an E-W left-lateral shear zone northwest of the Dezful Embayment.

The main morphotectonic regions in the Zagros fold belt are bordered by these major deep-seated basement faults (Fig. 1b). Figure 1c provides a simplified geological sketch map of the studied area.

3 Evidence for Pre-Folding Development of Joint/Vein Sets in the Asmari Formation

Fractures in folded sedimentary rocks are usually interpreted as the result of folding (Stearns, 1968; Stewarts and Wynn, 2000). Among different groups of so-called fold-related fractures, axial joints are supposed to be the result of local extension in the outer arc of the folds. Furthermore, based on consistent relations of the fractures with bedding attitude, even in the noses of folds, they are supposed to be in direct relation with fold geometry (Stearns and Friedman, 1972; Nelson, 2001). Fig. 4a shows, schematically, this symmetrical relationship between fold geometry and fold-related fracture pattern in map view; Fig. 4b presents the fracture pattern which can be expected to develop in a sedimentary cover undergoing flexure/forced-folding above dip-slip basement faults (Ameen, 1988; Cosgrove and Ameen, 2000).

The Asmari Formation (Fig. 3b-c) is one of the main reservoir rocks in SW Iran. This formation crops out along the Zagros fold belt where it forms the famous whaleback anticlines and is well-known as a carbonate fractured reservoir. Many studies dealing with the fracture pattern of the Asmari carbonates have been carried out and are still in progress. While McQuillan (1973, 1974, and 1985) stated that some fracture orientations bear no relation to the folds, Gholipour (1998) believes that the fractures within Asmari Formation are associated with vertical and axial growth of concentric folding (see also, Wennberg et al., 2006). The relative chronology of different fracture sets with folding in the Zagros is therefore still controversial.

In order to define the regional fracture pattern and its chronological relationship with folding, a careful analysis of fracture sets was carried out. To this pur-

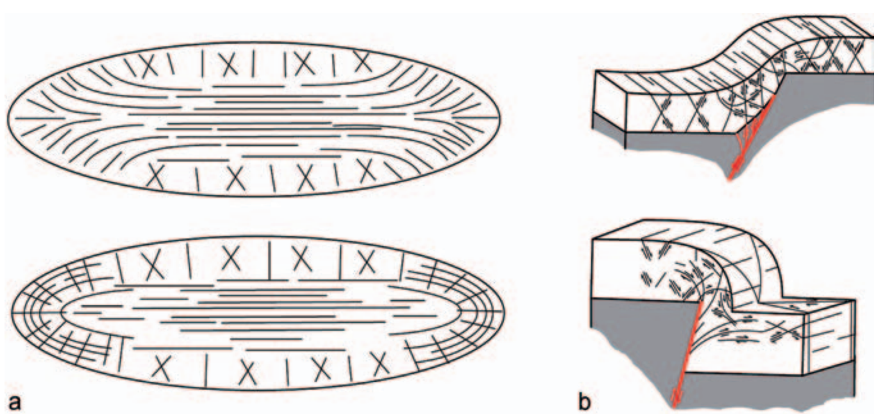

Fig. 4. Possible patterns of fold-related fracture sets. **a** Conceptual fracture models of Stearns (1968, 1978) in cylindrical and pericline parts of a simple buckle fold, in map view. Note the change in strike of fold-related fractures with changing bedding attitude in the pericline. **b** Fracture pattern in the cover above dip-slip normal (up) and reverse (down) basement faults (after Ameen, 1988, 1990)

pose, the orientations of sets of joints, veins and shear fractures/faults were measured in several anticlines located in the Izeh zone and in the northern part of the Dezful Embayment (Fig. 1c), within the uppermost part of the Asmari Formation which displays a lithology dominated by mudstones to wackstones (Fig. 3). Rather than focusing on fold-fracture relationships in a single anticline, data collection was thus organized to cover a large area in order to be able to differentiate regional fracture trends from fold-related fractures and local complexity. This allowed the relationships between fracture sets and regional structural trends to be discussed although all sets were not observed in all anticlines, especially those located away from underlying N-S basement faults.

At the outcrop scale, the most represented fractures are rectilinear with quite a regular spacing and a significant length (3 to a few tens of meters). These fractures can be confidently classified as joints because they do not show any evidence of offset across the fracture plane (mode-I opening); they are generally perpendicular to major bedding surfaces, and fracture walls often show plumose structures/hackle marks. These joints are frequently associated with parallel-mineralized veins. In contrast, some fractures were determined to have had a shearing mode of deformation where evidence of tail cracks or extensional jogs could be observed in the field.

It is, however, out of the scope of this paper to describe all the fracture sets identified in the investigated area and their relative chronology, which is reported in detail elsewhere (Ahmadhadi et al., submitted). In this paper, we only focus on the fracture sets which illustrate pre-folding extensional fracture development. In the following, members of a fracture set share both a common range of strike and dip orientation and a common deformation mode. For most of the joint sets, common orientation could be identified only after removal of bedding dip by stereographic rotation. Commonality of fracture orientation after removal of bedding dip, where the fractures are subparallel and bed perpendicular, is taken as supportive of a pre-folding origin (Hancock, 1985). Fracture strikes either perpendicular or parallel to bedding strike are not affected by rotation of bedding to remove the dip and may be interpreted as occurring during any stage of fold growth. When the pre-folding origin of a fracture set is consistently deduced from several anticlines, a regional significance of this pre-folding fracture set can be confidently derived.

Most joint sets described hereinafter are either pseudo-axial (i.e., sub-parallel to fold axes) or oblique to fold axes; most of them were reactivated (re-opened and/or sheared) during later fold development.

3.1 Early N040–050° (and N020–030°) Joint/Vein Sets

Among the different fracture sets observed in the investigated anticlines, an early set of N040–050° trending joints has been identified in numerous outcrops. A good example of this set is provided by the Asmari anticline (location Fig.1c) where a population of straight, regularly-spaced N040–050° fracture sets is observed on the crest and near the SE termination of this anticline (Fig. 5 a and b). These fractures often display plumose structures (e.g., in the Safid anticline) and/or occur as parallel-mineralized vein systems (e.g., Bangestan anticline); the attitude of these fractures with respect to bedding in fold flanks indicates that they predate folding and should be interpreted in their unfolded attitude. The strike of this joint set is often slightly oblique to present-day fold axes or to the local bedding strike (e.g., in Asmari, Khaviz, and Bangestan anticlines). Development of this joint set could be synchronous with the formation of stylolitic peaks parallel to this direction (Ahmadhadi, 2006).

The aerial photograph of Fig. 5 (a, b), taken near the top of the Asmari anticline confirms that the N040–050° fracture set is not strictly perpendicular to the fold axis. It corresponds to a very regular pattern of systematic joints without any directional perturbation. At the same location, lineaments in form of N140° trending fracture swarms (Fig. 5a), slightly oblique to the fold axis, are identified (see Sect. 3.2). As some of these fractures abut on fractures belonging to the regular N040–050° fracture set, the latter developed first. Such a chronology is further compatible with the fact that the N040–050° fracture set forms a very regular fracture pattern compared to the N140° set. Finally, a minor N-S set is observed. It corresponds to relatively short rectilinear fractures which generally abut on the two previous fracture families (see Sect. 3.3).

A second minor group of fractures comprises N20° to N30° joints (e.g., in Asmari, Khaviz, Bangestan). In Bangestan anticlines, they postdate the development of the 040–050° joint set, but show conflicting chronological relationships with N140° fractures. They likely reflect a slight evolution of the compressional trend from N40°–50° to N20°–30°, also marked by the change in trends of stylolitic peaks (Ahmadhadi, 2006).

3.2 Pseudo-Axial N140° Joint/Vein Sets

The Khaviz anticline (Figs. 6 and 7, location Fig.1c) is remarkably rectilinear with a mean axial trend of about 110–120° and dip of the flanks of about 30°. The NE flank is more gently inclined than the SW flank. Fracture measurements were performed in the field

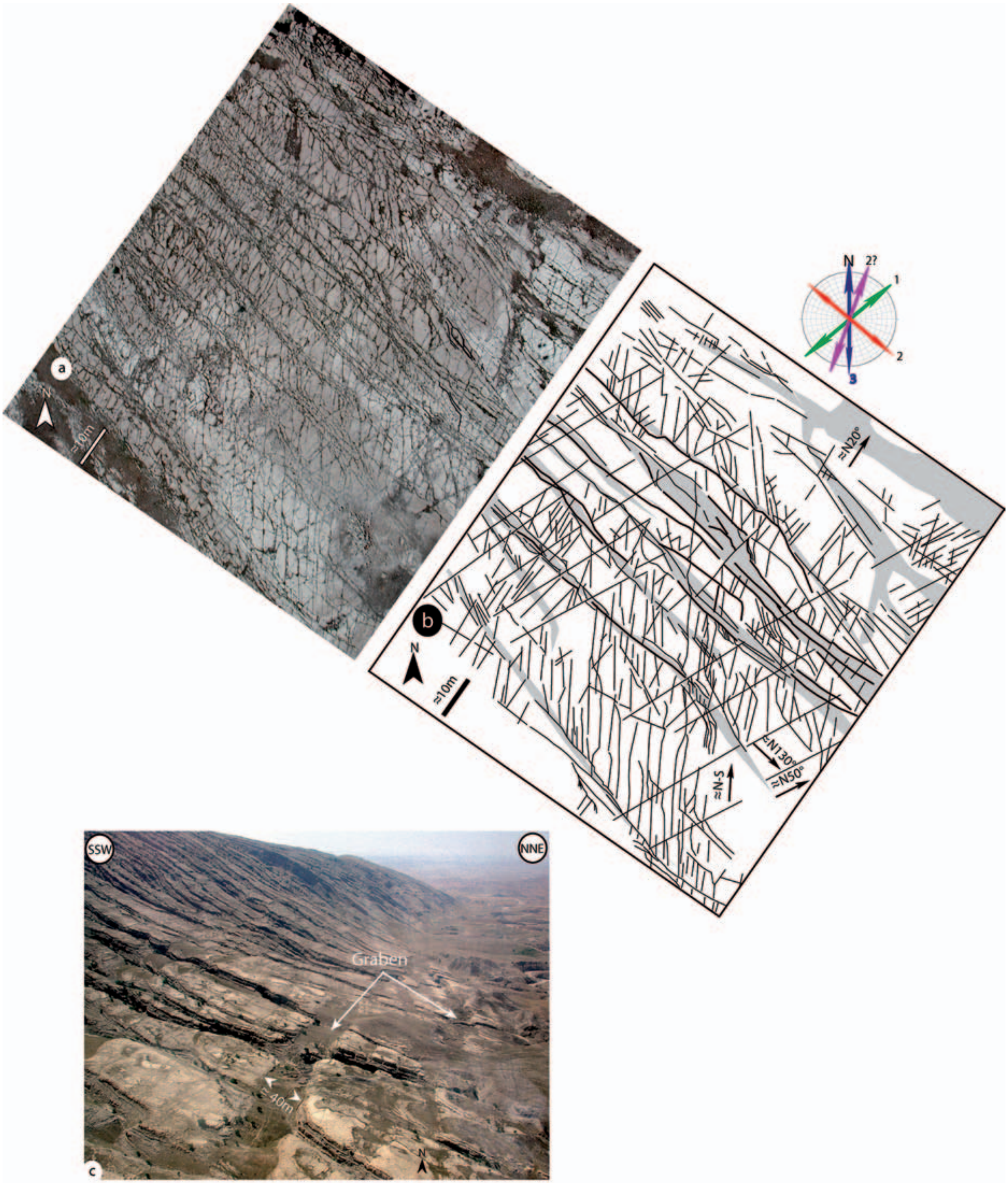

Fig. 5. Main fracture sets observed on the southern plunge of the Asmari anticline (see Fig. 1c for location): **a** aerial photographs and **b** Interpretation. The regular, non-disturbed fracture network with an azimuth of about N50° is considered as the first fracture set; N130-140° trending fractures formed a series of fracture swarms almost parallel to the fold axis; N-S fracture sets abut on the previous sets. **c** A series of ESE-WNW grabens near the NW termination of the fold on its northern flank

around the SE nose of the anticline (Fig. 6). It is noteworthy that the directions of large-scale lineaments observed on the satellite image from the NW part of the anticline (Fig. 7) are roughly similar to those of the small-scale fracture sets (Fig. 6b). This suggests again that the scale of observation has little influence on the identification and statistical measurements of these fracture sets.

As shown in Fig. 6a, a group of fractures which are perpendicular to bedding and have a mean strike of 130°–150° are observed around the SE nose of the anticline where the fold axis swings into an orientation of 120–130°. In most sites, these fractures mimic axial fractures, but are in fact slighty oblique to the local fold hinge : their strike always deviates clockwise from the anticline axis and in most sites this deviation ranges from 10° to 20°. In addition, the strike of these fractures in the pericline is not consistent with that predicted for axial, fold-related fractures (Figs.4a and 6). These characteristics support that the 130°–150° bed-perpendicular fractures rather predate folding. Unfortunately, the low bedding dip precludes unambiguous demonstration that these fractures have been actually folded (unfolding would have revealed a better commonality of fracture orientation than with the current bedding attitude, hence a pre-folding origin). Larger deviations of the trend of this joint set relative to the anticline axis can be seen in the stations K3, K9, and K10. These stations are located almost along an arbitrary N-S trending line, although no N-S fault was observed on the measurement location or on the geological map. After unfolding, the fractures (red on Fig.6a) become vertical, with a 155–170° trend. In these three sites, the strong obliquity of fracture strike with fold axis further confirms that these fractures are not fold-related (see Sect. 5).

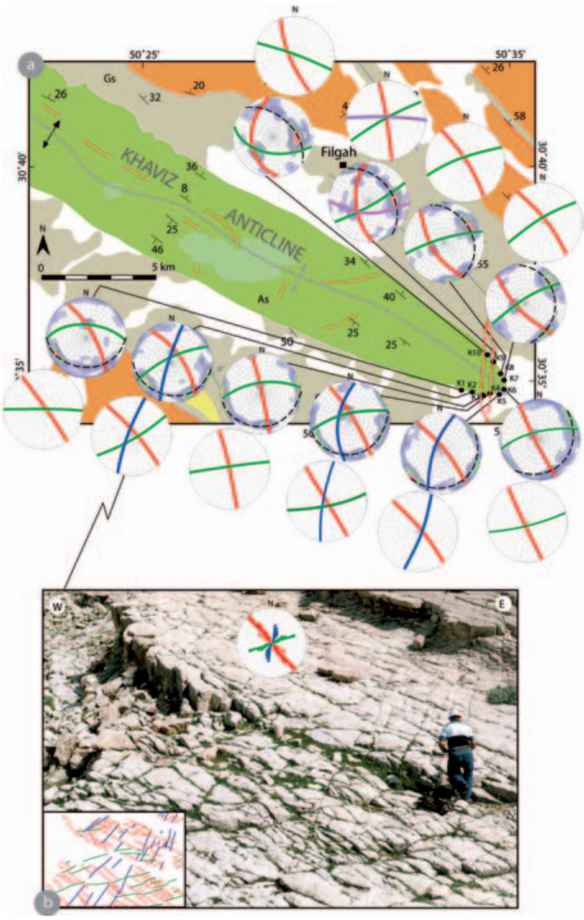

Fig. 6. **a** Geological map of the eastern part of the Khaviz anticline (see Fig. 1c for location) and fracture orientations around its NE termination. Diagrams: Schmidt lower hemisphere projection. Red, green, blue, purple: N140°, N050°, N-S-N020° and E-W trending fracture sets, respectively. Dashed lines are bedding planes. Fractures on diagrams with white background have been unfolded. The N140° fracture is persistently observed around anticline termination regardless of bedding attitude. The neraly N-S fracture trend, observed in the sites K3, K9, and K10, is likely related to an underlying N-S trending fault zone, indicated by a dashed line. **b** Main fracture sets observed in site K2

Fault slip-data were additionally collected in the NE flank of the Khaviz anticline (Fig.7). An important point at the first glance is that most of the fault-plane strikes slightly obliquely to the local bedding strike (N130°–N°140 vs. N110–120°) although the local fold axis is very rectilinear nearby the measurement site. Special attention was paid to the geometrical attitude of these faults with respect to tilted beds;

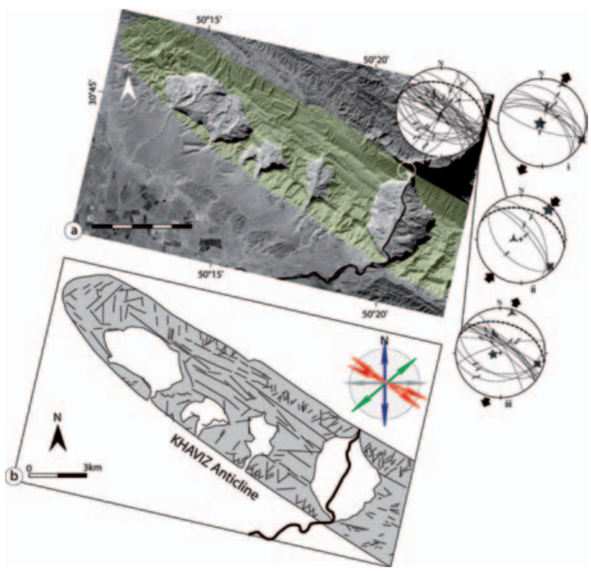

Fig. 7. **a** SPOT 5 satellite image on the western part of the Khaviz anticline. **b** Main sets of fractures observed on satellite image. Large photo-scale lineament show almost the same trends as those which were observed on the SE nose of this anticline at the outcrop scale. Fault slip data: Wulff lower hemisphere projection; five, four, and three corner stars correspond to the maximum ($\sigma1$), intermediate ($\sigma2$) and minimum ($\sigma3$) principal stress axes, respectively; Convergent/divergent solid arrows show the direction of compression and extension, respectively. Dashed lines are bedding planes

within a heterogeneous fault population, this geometrical reasoning allows separation of data subsets based on their age relative to fold development, even though no direct cross-cutting relationships between faults or superimposition of striations on fault planes are observed. These faults were further interpreted in terms of stress regimes using the method developed by Angelier (1990).

Among the data set, three populations of faults were identified and separated on the basis of their kinematics and their chronology relative to folding. The first set consists of steeply dipping normal faults with dip-slip slickenside lineations. The stress tensor computed from this set does not display a vertical σ1 axis; rather, the σ1 axis is perpendicular to bedding, while the other stress axes lie within the bedding plane. In such a case, the fault system has to be interpreted after back tilting to its initial position. After unfolding, the dip-slip normal faults indicate a pre-folding horizontal N30° extension (Fig. 7, diagram i), roughly consistent with the pre-folding N140° joint set identified in the SE nose of the anticline. Most of the remaining faults can be separated into a set of reverse faults and a set of oblique-slip normal faults, respectively related to a N40° compression and a N20° extension, both postdating folding (Fig. 7, diagrams ii and iii). The geometry of some of the post-folding faults suggests that they could result from the reactivation of the earlier normal faults despite the absence of evidence of superimposed striations on fault planes. The reverse faults likely mark the compressional state of stress responsible for folding. The significance of the late post-folding normal faults in terms of extension at fold hinge could seem questionable since the site of measurements is apparently located away from this hinge; however, since only the uppermost part of the fold is visible (most part remains buried) and taking into account the low dip of the flank, it is likely that at the scale of the fold, the site is still located in its outer rim, so we conclude that this normal fault set and the related N020° extension presumably reflects extension at the fold hinge.

The Razi anticline (Fig. 8, location Fig. 1c) is located in the northern part of the Mountain Front Fault (MFF) at about 56 km south-eastward of the Khaviz anticline. Fracture orientations were collected along a valley cutting the anticline axis and both flanks were accessible to measurements. This anticline has a quite gentle geometry and the structural dip is even less than 10°. Among fracture data, a group of fractures striking N130°–N140° and N040°–050° are consistently observed (Fig. 8a), as in the Khaviz anticline. The N140° fractures are everywhere perpendicular to the bedding plane. Furthermore, two of the measurement stations (R1 and R2, Fig. 8a) where this fracture group is observed are located in a gentle syncline next to the Razi anticline, in the concave-upward part of which fold-related axis-parallel extensional fractures are unlikely. These observations demonstrate that, as in the Khaviz anticline, the N140° fracture set (and probably the N040°–050° as well) predated folding (or were created at a very early stage of folding).

On the NE flank and near the NW termination of the Asmari anticline where the structural dip is low, some grabens can be observed (Fig. 5c). These grabens are trending ESE-WNW, oblique to the fold axis. Therefore, they presumably predated folding that led to the present-day Asmari anticline structure. Although likely, offset of the normal faults bounding these grabens due to bedding-parallel slip during folding, which could have unambiguously demonstrated that these grabens developed before folding, could unfortunately not be observed. However, offsets of early outcrop-

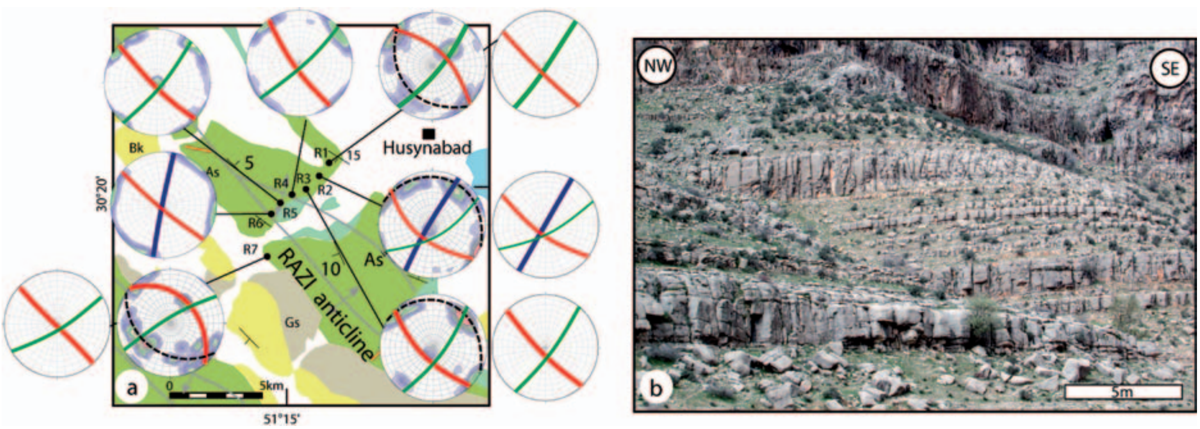

Fig. 8. **a** Geological map of the Razi anticline (see Fig. 1**c** for location) and fracture orientations on both flanks and fold crest. Note that the prominent joint sets are observed in the adjacent syncline (sites R1 and R2). **b** Intensive fracturing within horizontal beds in the Razi anticline. Colour code for fracture sets: same key as in Fig. 6. Fractures on diagrams with white background have been unfolded

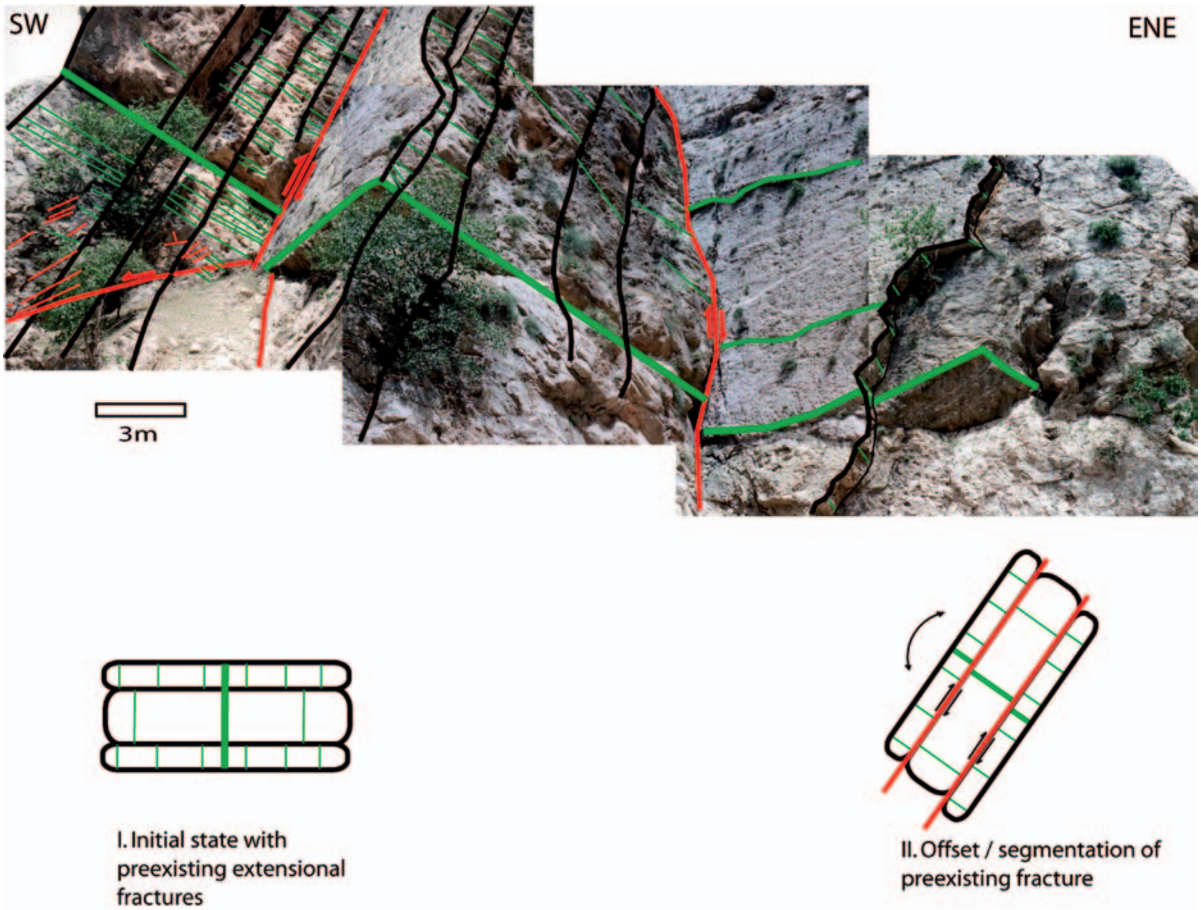

Fig. 9. Offset and segmentation of a large extensional N130°-140° trending fractures within Asmari carbonate beds by bedding-parallel slip in the SW limb of the Lappeh anticline (see Fig. 1c for location). This observation supports extensional fracture development before layer tilting (folding)

scale N130–140° trending extensional fractures (and even normal faults) by bedding-parallel slip have been observed in other outcrops (e.g., the Lappeh anticline, location Fig. 1c), which supports that early extensional fractures and normal faults formed in response to pre-folding extensional state of stress (Fig. 9).

As for the normal faults, the N140° trending joints and veins of this set were reopened and/or sheared during later folding (Ahmadhadi et al., submitted).

3.3 N-S (and Perpendicular E-W) Trending Joint/Vein Sets Oblique to Fold Axes

Another group of fractures which show no symmetrical relationship with fold geometry in the studied area include N-S fractures. These N-S fractures are commonly found associated with perpendicular E-W joints and mineralized veins (Fig. 10), the interpretation of which is still enigmatic (Ahmadhadi, 2006), so the reason of this association will not be dealt with hereinafter. It was mentioned previously that in the nose of the Khaviz anticline, nearly N-S trending fractures oblique to the fold axis were observed. The NW termination of the Khami anticline and the NE flank of the Dil anticline are two other examples in which N-S and E-W trending joint sets perpendicular to bedding bear no symmetrical relationship with fold geometry (Fig. 10). This strongly suggests that these sets are not fold-related and that they have to be interpreted as pre-folding joint sets. Their abutting relationships on the N050° and N140° sets further confirm that all three sets are likely pre-folding.

In the Asmari anticline the N-S set has been observed next to N-S trending faults in the eastern part of the fold (Fig. 5), which are likely underlain by a N-S trending basement fault. More generally, the sites where the N-S trending fractures were measured in these anticlines more or less coincide with the location of an underlying basement fault (Fig. 10).

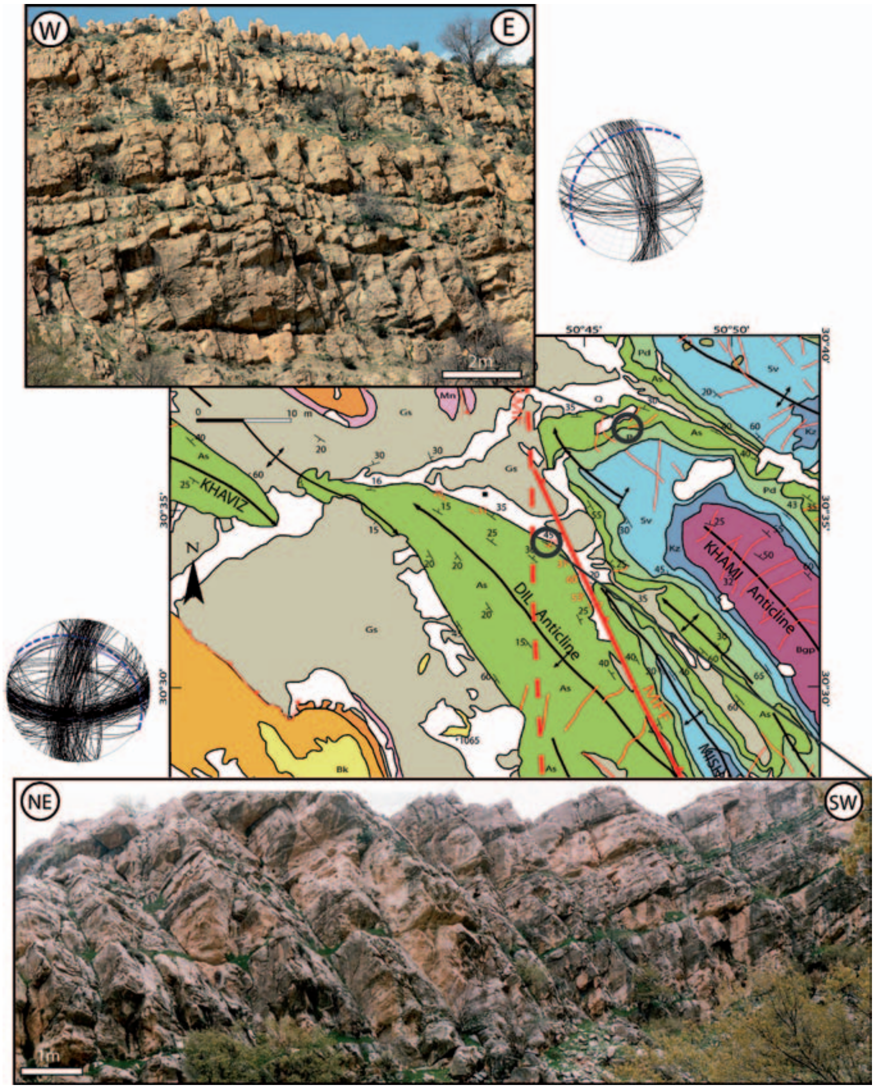

Fig. 10. N-S (and perpendicular E-W) striking joint sets in the northern flank of the Dil anticline and the northwestern termination of the Khami anticline (see Fig. 1**c** for location). These joint sets are strongly oblique to the general structural trend. This area is located near an underlying N-S trending basement fault (KMF)

In the very same way, interpretation of Spot images of the NW termination of the Bangestan anticline (Fig. 11) also shows N-S and E-W trending lineaments (i.e., large-scale fractures) which are strongly oblique to the fold axis. These fracture sets developed in the vicinity of the nearby underlying N-S trending Izeh fault (Fig. 11).

In summary, outcrop investigation and lineament interpretation on satellite photos indicate that N-S (and sometimes associated E-W) trending fracture sets predominantly occur in the outcrops located near N-S trending basement faults (e.g., IZHF and KMF, Fig. 1b and c); this suggests that the development of these fracture sets is not fold-related but is rather controlled by the reactivation of these N-S basement faults.

4 Paleogeographic Evidence for a Basement Fault Control on Sub-Basin Geometries and Lateral Facies Variations During Oligocene-Lower Miocene Times

The main objective of this section of the paper is to study whether the basement faults affected basin architecture and facies distribution during lower Tertiary times. Such information can be used to date the inception of deformation in the foredeep and therefore to test models where fracturing predates folding. With this aim, we examined paleofacies evolution in the region located between the Bala-Rud (BR) Fault to the north-west and the Kazerun Fault to the east (Fig. 1b)

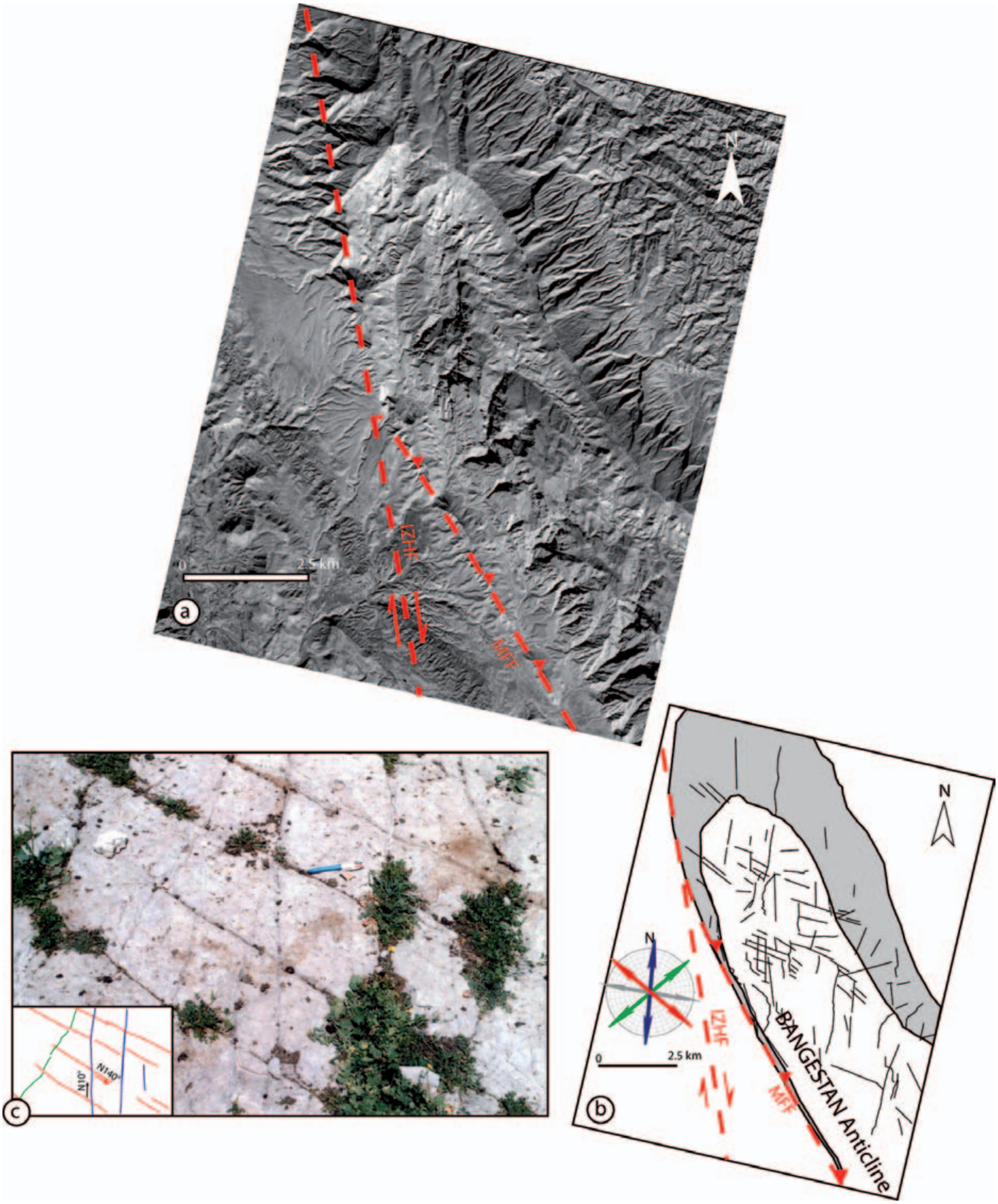

Fig. 11. **a** SPOT 5 satellite image on the SE termination of the Bangestan anticline (see Fig. 1c for location) and **b** interpretation of large-scale fractures on the NW termination of the Bangestan anticline close to a N-S trending basement fault (IZHF). Note that the main interpreted lineaments strike N-S and E-W, i.e., oblique to the local structural trend. **c** Main joint sets observed in the field in the SE nose of the Bangestan anticline

during the Lower Tertiary. Our study is mainly based on both previous works (James and Wynd, 1965; Berberian and King, 1981; Motiei, 1993) and a new analysis of well data from the Dezful Embayment. We especially focus on Oligocene to Lower Miocene paleofacies, which is the period of the Asmari sedimentation.

The Zagros basin with marine carbonate platform sedimentation became established in the early Jurassic and continued until Miocene times with the greatest subsidence being located in the northeast, possibly along several faults (Berberian and King, 1981). During the Palaeocene and Eocene the Pabdeh (neritic to basinal marls and argillaceous limestones) and the Jahrum (massive shallow marine carbonates) Formations were deposited in the middle and on both sides of the Zagros basinal axis, respectively (Fig. 12a). This basin was gradually narrowed and in Lower Oligocene times the Lower Asmari Formation, including carbonates, deeper marine marls, and sandy limestone (Ahwaz Member) were deposited (Fig. 12b). Different intra-basins and facies including clastic facies (Ahwaz/Ghar sandstone Member), carbonates and evaporites (Kalhur Member) were well developed during the Upper Oligocene-Early Miocene time (Fig. 12b to d). The important feature at this time is the rough co-

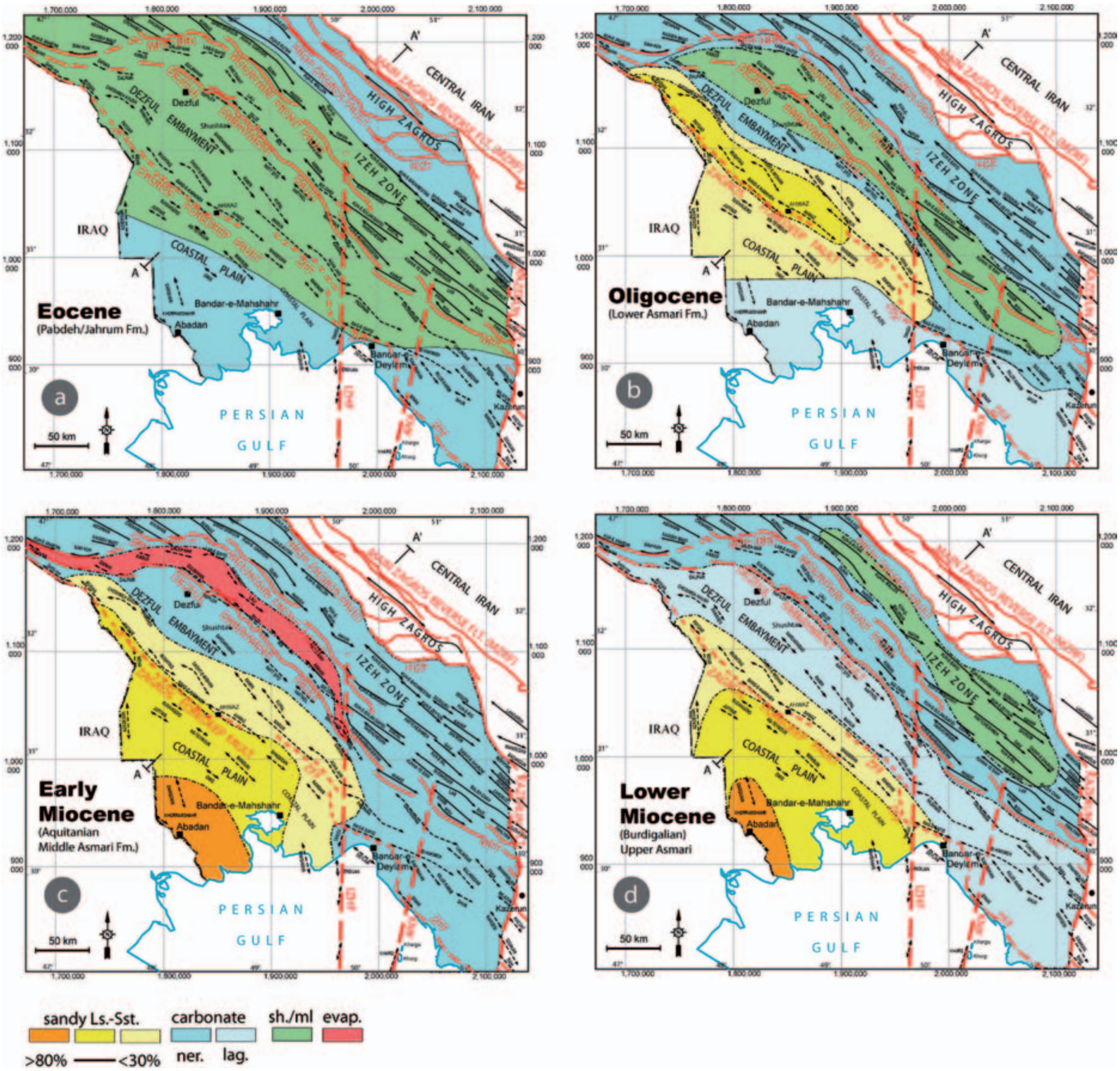

Fig. 12. Paleogeographical maps in the Central Zagros based on previous work (James and Wynd, 1965; Berberian and King, 1981; Motiei, 1993) and information from unpublished paleologs of drilled wells and surface sections in the Central Zagros: **a** Eocene; **b** Oligocene; **c** Lower Miocene (Aquitanian); **d** Lower Miocene (Burdigalian); see text for details

incidence of these intra-basins with the main NW-SE trending basement faults (i.e. MFF and DEF). Just in the center of the basin, basinal facies (marls and shales) changed to an evaporitic facies (Fig. 1c). No intermediate facies variation and transition from marls and shales to evaporites has been reported in the literature. This narrow basin is limited to the north and northeast by the MFF and BF and to the south and to the east by the DEF and IZHF, respectively. Farther south, the Ahwaz/Ghar Member delta front, indicated by more than 30% of the sand content of the Asmari carbonate, formed just and parallel to the south of the ZFF. This sand content gradually increases southward (Fig. 12c and d). During Burdigalian times, the Upper Asmari carbonates covered the entire basin with a hemipelagic facies toward the northern part of the Mountain Front Fault (Fig. 12d).

The present-day approximate coincidence of facies changes and the elongated shape of the confined, evaporitic sub-basin with basement faults is noteworthy. However, one has to take into account the influence of Mio-Pliocene deformation on the distribution of paleofacies in the Oligocene-Lower Miocene times. The amount of shortening estimated on the basis of balanced cross-sections in the Central Zagros, including the High Zagros and extending to the southwest of the Dezful Embayment, was reported to be about 50 km (Sherkati et al., 2006). Shortening in the Dezful Embayment is lower than in the High Zagros and the Izeh zone where a large amount of shortening is accommodated by imbricated thrust nappes. This means that the amount of southwest-ward differential displacement of the cover above the basement, somewhere between MFF and DEF can be considered negligible for our concerns. Nevertheless, there is always some discrepancies concerning the (projected) location of basement faults in the present-day cover but in any case, this intra-basin could not be displaced from the Izeh zone, northeast of the MFF, into the Dezful Embayment.

As a result, we conclude that during lower Tertiary times, both the geographic distribution of the facies and the location of the basement faults appear remarkably consistent. During Eocene times, the Pabdeh basin covered a wide area from the south of the High Zagros fault toward the Zagros Foredeep Fault (Fig. 12a). The depocenter of this basin gradually narrowed and migrated toward somewhere between the MFF to the north and the ZFF to the south following the progradation of the carbonate platform and clastic facies of the Lower Asmari Formation during the Lower Oligocene (Rupelian) (Fig. 12b). The development of a long narrow evaporitic intra-basin (Kalhur Member) during the latest Oligocene-early Lower Miocene (Chattian-Aquitanian, Fig. 12c) likely indicate an abrupt facies change (both laterally and vertically), which seems to be difficult to interpret simply by eustasy or any sedimentological process alone, without any tectonic control. Rather, the localization of this intra-basin somewhere between the MFF which borders its northern margin and the DEF which borders its southern margin (Fig. 12c) and also an abrupt facies change from marls to evaporites, suggests a direct relation between this restricted lagoon intra-basin and deep-seated basement faults. So, even though an eustatic control cannot be ruled out, we suggest that the genesis of this sub-basin has been, at least partly, tectonically controlled.

If the above-mentioned basement faults were reactivated during lower Tertiary times with a component of vertical motion, causing large wavelength flexure or forced-folds in the overlying cover and therefore local topographic uplifts, they should have influenced accommodation space for the sedimentation especially for those areas located above them. To test this idea, a simplified transect based on the thickness variations of the main lithostratigraphical units (formations) with definite time lines (top and bottom) and data accessibility in the region was built (Fig. 13). The direction of this transect was chosen to cut the main NW-SE trending basement faults in the studied area (Fig. 1b). The Sarvak formation does not seem to be affected by the NW-SE trending basement faults (Fig. 13a). This formation shows almost a uniform variation in their thickness between ZFF and MFF, while the important fluctuations appear within Pabdeh/Jahrum and Asmari formations (Fig. 13b). Both thickness and main facies variations coincide with the location of the main basement faults; this strongly suggests that these faults were reactivated during Pabdeh/Jahrum and Asmari deposition.

5 Discussion: Early Fracture Development in the Asmari Formation Related to Flexure/Forced-Folding above Reactivated Basement Faults

Based on the field observations in the Central Zagros (Sect. 3), some prominent fracture sets cannot be interpreted by a conventional fold-related fracture model, and therefore explained by a single episode of fracturing during the Mio-Pliocene cover folding. There are several lines of evidence supporting that they are not fold-related fracture sets: (i) most of identified fracture sets are made of joints/veins lying perpendicular to bedding whatever their position in the fold (Figs.6 and 8) (ii) the N140° trending joints and normal faults (Figs.5 to 8), which mimic axial fractures, are in fact slightly oblique to the anticline axes and are sometimes observed in the adjacent synclines (e.g., Razi anticline); (iii) these N140°–160° fracture sets display a relatively consistent trend even in the nose of anticlines

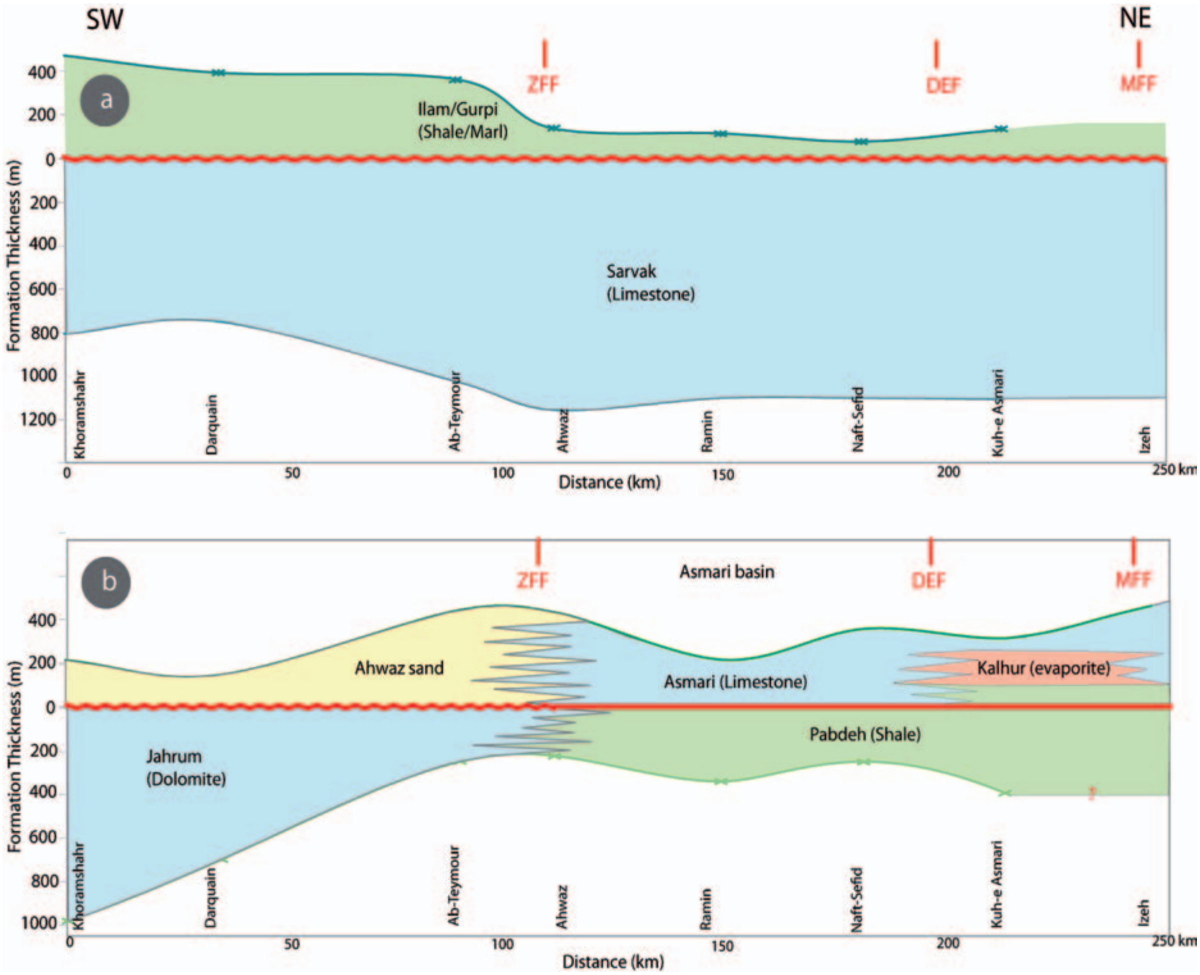

Fig. 13. Simplified transect perpendicular to the general trends of the folds in the Central Zagros (see transect location on Fig. 1b, and text for details). The Sarvak Formation does not show any thickness variations across NW-SE-trending basement faults **a**, while important fluctuations appear within the Pabdeh/Jahrum and Asmari Formations (Paleogene to Lower Miocene) **b**

(e.g., the Khaviz anticline), in contrast with common predictions of axial, fold-related fractures; (iv) the N-S trending outcrop-scale fractures and photo-scale lineaments are strongly oblique to the general fold axial trend in the sites close to N-S trending underlying basement faults (e.g., Dil, Khami, and Bangestan anticlines). On the other hand, the orientations of the main fracture group (~N140°–160°), despite the lack of their direct relations with the folds, are nearly similar in the Khaviz, Razi, Asmari and Bangestan anticlines (Figs.5 to 8, 11) and in the other anticlines investigated within the Central Zagros (Ahmadhadi et al., submitted). These observations strengthen the idea that this prominent fracture group developed under an extensional stress field (either local or regional) which affected the Asmari Formation before the main Mio-Pliocene phase of cover folding (Ahmadhadi et al., 2005).

We have suggested that basin architecture and facies variations and distribution during the Asmari sedimentation could have been controlled by the reactivation of deep-seated basement faults. We propose that at that time, the reactivation of the N140° and N-S basement faults included a component of vertical motion, which caused large wavelength flexure or forced-folds in the overlying cover (Fig. 14). Flexures/forced-folds could have induced an extensional state of stress above NW-SE trending basement faults (e.g. MFF, ZFF) within the uppermost part of the sedimentary cover (e.g. the Asmari limestones, which were likely rapidly lithified after deposition). The observed N-S trending fracture set (e.g., Khaviz anticline) and the location of measurement sites containing this fracture group near underlying N-S trending basement faults (e.g. IZHF and KMF) suggest that they should have also initiat-

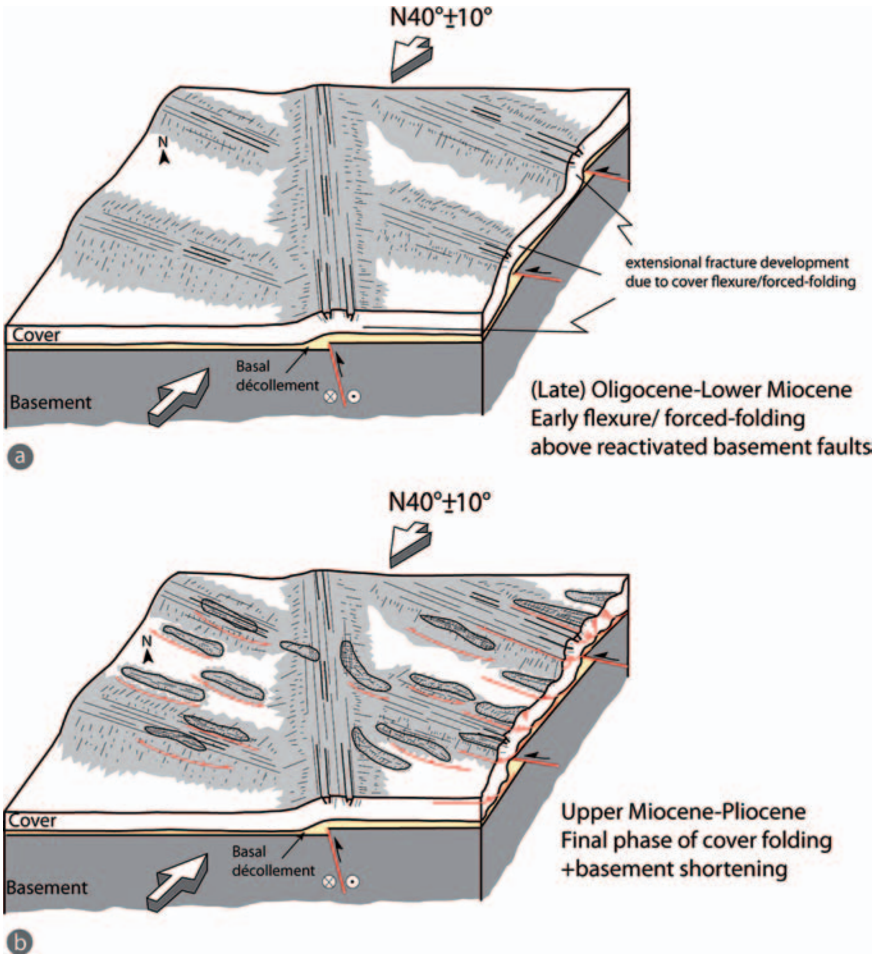

Fig. 14. Proposed model of early fracture development in the Central Zagros related to the reactivation of deep-seated main basement faults **a** followed by superimposition of Mio-Pliocene folds **b**

ed quite early and presumably synchronously with the reactivation of the NW-SE trending basement faults (Fig. 14). Edgell (1992) stated that the reactivation of N-S trending basement faults occurred since the latest Cretaceous. Our observations in the Asmari Formation suggest that this reactivation probably continued in the Lower Tertiary and that the N-S trending fractures are likely related to the reactivation of these transverse basement faults. This is in agreement with recently documented movements along the MFF and N-S trending faults during deposition of Gachsaran Fm (Abdollahiz et al., 2006).

However, as suggested by Fig. 4b, extensional fractures similar to those identified in the Central Zagros may develop whatever the type of vertical motion along basement faults, and it is generally difficult to distinguish between a normal and a reverse movement along basement faults if only extensional fractures are observed in the overlying cover. So one may question whether early extensional fractures were caused by flexure/forced-folding above either compressionally or extensionally reactivated basement faults (Fig. 4b). One should also consider the possibility that these extensional fractures developed in the cover in response to forebulge development and extensional stresses related to Arabian plate flexure.

The possibility of creating extensional fractures in the cover (and also to extensionally reactivate NW-SE pre-existing basement faults) in response to plate flexure/forebulge development in the Central Zagros during Lower Miocene times has been investigated through a preliminary numerical modelling of bending stresses based of subsidence curves (Ahmadhadi, 2006). It is out of the scope of this paper to discuss this modeling in detail. First results suggest that bending stresses related to the Arabian plate flexure may have been high enough to cause development of early extensional fractures within the Asmari Fm., but that the area which underwent significant bending stresses appears smaller than the region where early extensional fractures were actually recognized in the field.

The earliest N040–050° regional joint set suggests that the Zagros basin was loaded by a N040–050° directed far-field compression during lower Miocene

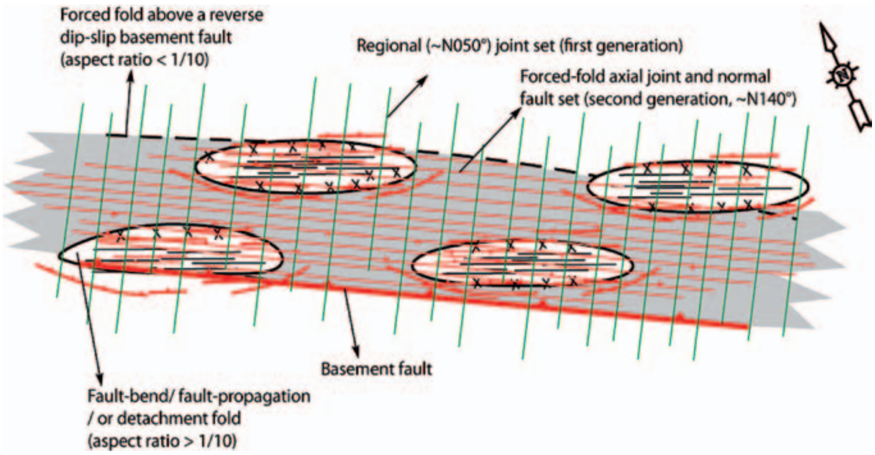

Fig. 15. Schematic model in map view of the superimposition of the Mio-Pliocene folds on an earlier large-scale forced-fold above a reactivated NW-SE-trending basement fault in the Central Zagros. This model makes it possible to explain the directional persistency of the fracture sets around the nose of an anticline and the presence of axis-parallel joint set in an adjacent syncline

times. So, as an alternate interpretation to plate flexure, we propose that the early extensional fractures developed locally above flexure/forced-folds related to the compressional reactivation of basement faults. In response to the N040–050° compression, and despite our limited knowledge on their geometry, the N140 and N-S-trending basement faults were likely reactivated with a component of vertical motion: a dip-slip component of reverse motion along N140° trending faults and an oblique-slip component of motion (reverse, right-lateral) along N-S-trending faults (Fig. 14).

Based on the previous discussion on the Asmari intra-basins, we propose that large-scale forced-folding above reactivated NW-SE trending basement faults may be a possible explanation for the development of NW-SE trending joints and normal faults during the first stage deformation in the Zagros. As explained before, paleogeography, facies variations and intra-basin development also support the onset of cover deformation in the form of large wavelength forced-folds before the whale-back anticlines developed during Mio-Pliocene shortening. One of the major differences in the geometry of early forced-folds and Mio-Pliocene buckle folds is their aspect ratio (half wavelength to axial length ratio) (Fig. 15). As the forcing members that generate the forced-folds generally result from long linear steps in the basement, the resulting folds frequently have a long aspect ratio and are, although not always, asymmetric (Sattarzadeh et al., 2000). The amount of aspect ratio in buckle folds has been proposed in the range of 1/5 to 1/10 (Sattarzadeh et al., 2000). So, we can expect to find evidence of early episodes of fracture development above basement faults around the terminations of some present folds in the Zagros and even in adjacent synclines despite the differential shortening of cover and basement (Figs. 14 and 15), in agreement with field observations.

6 Implications for the Onset of Compressional Deformation and Stress Build-up in the Zagros Belt

6.1 Basement Fault Reactivation in the Foreland of the Zagros Orogen and Far-Field Arabia-Eurasia Orogenic Stresses

Our analysis of the early fracture pattern and basin architecture at the time of deposition of the Asmari limestones therefore supports the occurrence of early compressional reactivation of basement faults within the Zagros basin. Such intraplate compressional deformations basically require that the build-up of intraplate compressional stresses, which likely result from a (far-field) stress transmission from the plate boundary, leads to sufficient stress magnitudes to overcome the local strength of the crust and cause reactivation of pre-existing weaknesses. Frictional resistance is generally less than shear rupture strength under the same confining pressure (e.g., Etheridge, 1986), so the stress necessary to initiate sliding on favorably oriented pre-existing faults is less than that needed to initiate new faults in intact rocks. In addition, depending on the nature of fractured rocks, preexisting fractures may become overpressured during compression, thereby decreasing the effective normal stress holding the opposite walls of the faults together (Sibson, 1993). Preexisting N140° and N-S basement faults therefore acted as crustal weaknesses when the Arabian crust underwent later shortening.

Such an intraplate stress build-up requires an efficient transmission of orogenic stresses, which largely depends on the amount of coupling between the orogen and the foreland (Ziegler et al., 1998). Reactivation of the N140° and N-S striking pre-existing basement faults within the Arabian foreland indicates that the far-field stress transmission from the Arabia-Central Iran plate boundary, and therefore mechanical coupling between the Arabian and Eurasian plates were already efficient at that time. However, the transmission of stress through the pre-fractured Arabian crystalline basement was likely heterogeneous and complex, so the deformation front propagated in an irregular fashion through the basement and the cover. This is in agreement with the distinction made by Lacombe and Mouthereau (1999, 2002) between the front of the shallow thrust cover wedge, the reactivation front (the outermost inverted structure) and even the deformation front (the outermost microstructures related to orogenic stresses).

The timing of cover folding relative to basement shortening needs careful consideration since it reflects the sequence of deformation at the front of the orogen. It is of considerable importance when addressing the question of whether shortening in the basement occurred first and was transmitted to the cover, or the cover detached first because of low friction basal horizons, and deep-seated thrusting occurred second. The answer to this question is a key to understand how orogenic wedges reached a state of equilibrium. We provide herein evidence of an early involvement of the basement in shortening in Central Zagros through reactivation of inherited basement faults, before any significant involvement of the cover in the orogenic wedge. Folding/wedging of the cover occurred later, mainly during the Mio-Pliocene, together with a generalized involvement of the basement in collisional shortening.

6.2 Timing of Early Fractures and Reactivation of Basement Faults in the Central Zagros

Although the relative age of small-scale fractures can sometimes be established using for instance abutting relationships, their absolute age is generally more difficult to ascertain. Deformation in the Zagros belt including folding and fracturing is the consequence of the Arabia-Eurasia continental collision. The age for initiation of this collision has been estimated from ~64 Ma (Beberian and King, 1981), using the end of ophiolite obduction, to ~5 Ma (Philip et al., 1989), using the angular unconformity between Bakhtiary conglomerates and the underlying Agha-Jari Formation (Falcon, 1974). None of these approaches provides a date for the first time Arabian and Eurasian continental crusts came into contact in response to convergence (Allen et al., 2004). Deformation and syn-tectonic sedimentation took place on the northern side of the Arabian plate in the Early Miocene (~16–23 Ma) (Robertson, 2000; Sherkati et al., 2006), related to the overthrusting of allochthonous nappes originating on the Eurasian side of the Neo-Tethys (Allen et al., 2004). Other studies in the same region put the initial collision-related deformation in the Oligocene (Yilmaz, 1993), or even in the Middle Eocene (~ 40 Ma) (Hempton, 1987).

North-south Arabia-Eurasia convergence across the northwest Zagros is achieved through a combination (partitioning) of NE-SW shortening and right-lateral strike-slip faulting on the Main Recent Fault (MRF) in the NW Zagros (Fig. 1b) (Talebian and Jackson, 2004). Talebian and Jackson (2002) reported an offset of about 50–70 km along the right-lateral strike-slip MRF based on a restoration of the drainage patterns and geological markers. Then they proposed an age of about 3–5 Myr for the initiation of the MRF. This represents an average velocity of about 15 mm/yr along this fault. There are at the present day no other major, northwest-southeast-trending seismically active right-lateral strike-slip faults within this part of the Zagros belt that could help partition the overall convergence in this way (Allen et al., 2004). Furthermore, based on recent GPS measurements of convergence between the Central Iranian block and the Arabian plate (Vernant et al., 2004), the Central Zagros accommodates about 4–7 ± 2mm/yr of north-south shortening. The maximum slip rate along the MRF would be of 4 ± 2.5 mm/yr if the fault achieves complete partitioning of this shortening. This is not in agreement with a Pliocene (3–5 Ma) initiation of the MRF (Talebian and Jackson, 2002) and with a cumulative lateral slip of 50–70 km along that fault, which leads to a long-term slip rate of 10–17 mm/yr (Talebian and Jackson, 2002). If the cumulative right-lateral offset on the MRF is correct, and if the age of the Bakhtiari Formation, which is essential from establishing the age of the MRF, is not underestimated, it is possible that horizontal slip may have occurred along precursor faults to the MRF or in the vicinity of the future MRF between the Late Cretaceous (using the age of the Ophiolite body as an offset marker (Talebian and Jackson, 2002) and the Pliocene, during dominantly transpressive deformation in the High Zagros. Agard et al. (2005) already suggested occurrence of belt-parallel strike-slip movement within the Crushed zone much before the Plio-Quaternary right-lateral movement along the MRF reported by Talebian and Jackson (2002).

Based on the evidence of facies changes, forced folding above basement faults in the Central Zagros strongly affected the Asmari basin during Aquitanian times (Lower Miocene) and possibly continued up to the final stage of deformation in the Upper Miocene – Pliocene times. Fig. 16 shows a tentative scenario of the geodynamic evolution of the Central Zagros basin. The geodynamic evolution of the basin during the lower Tertiary, at least in the Central Zagros, is not clear. Most parts of the Paleocene sediments, based on pale-

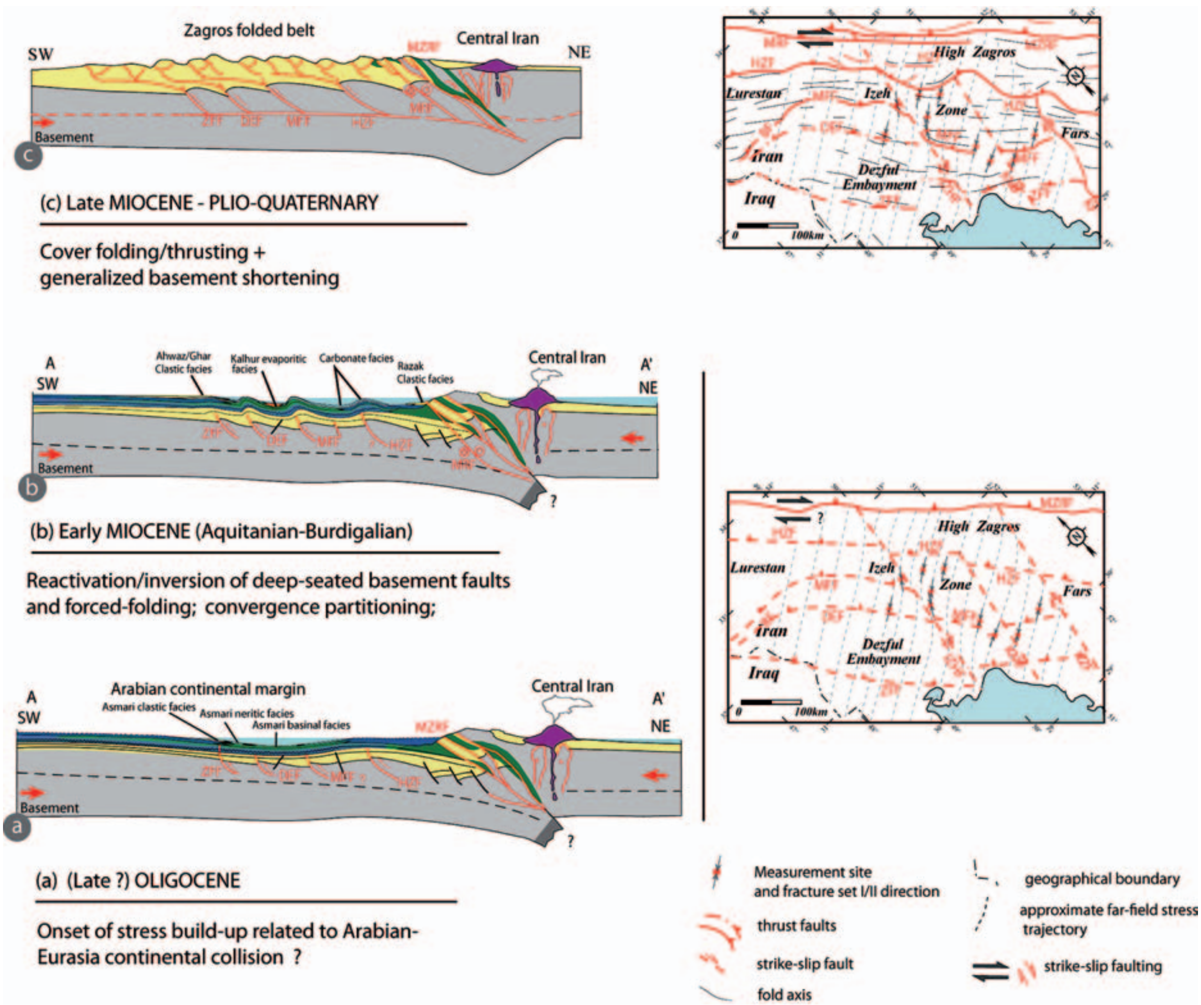

Fig. 16 Proposed lower Tertiary geodynamic evolution of the Central Zagros basin, on lithospheric cross-sections (left) and in map view (right) during **a** (late?) Oligocene; **b** Early Miocene (Aquitanian-Burdigalian); **c** Upper Miocene-Plio-Quaternary. This model suggests early involvement of the basement in shortening before any significant involvement of the cover in the orogenic wedge. The main episode of cover deformation and the generalized involvement of the basement in collisional shortening occurred later, during the Upper Miocene-Pliocene times

olog data in the Dezful Embayment, have been eroded and this unconformity sometimes reaches Maastrichtian formations in this region. Documented emergent zones near N-S basement fault (e.g., IZHF) during the latest Cretaceous and even Paleocene times suggest that these N-S-trending basement fault may have been reactivated. Progressive basin restriction and sedimentary flux progradation toward the depocenter of the previous Pabdeh basin, and the emergence of the Eocene carbonate platform (Jahrum/Shahbazan carbonates) in the southern part of the basin (Fig. 12b) during Eocene-Oligocene times, suggests that the NW-SE-trending basement faults were presumably reactivated by a far-field stress resulting from Arabia-Eurasia continental collision. During Early Miocene (Aquitanian) times, significant changes in the basin architecture and facies distribution occurred. At this time, early reactivation of basement faults (e.g., MFF, DEF) led to forced-folding (Fig. 16) which at least partly controlled the formation of the Kalhur evaporitic intra-basin which is located between the Mountain Front Fault (MFF) and the Dezful Embayment Fault (DEF).

The present study clearly emphasizes the overall importance of basement tectonics in the early structural evolution of the foreland of the Zagros collisional orogen. We propose a sequence of deformation in which the basement is involved early in the shortening, i.e., through Oligocene-Lower Miocene localized inversion of pre-existing basement faults in response to early intraplate stress build-up. During this time the cover was loaded by a N040°–050° compression, but did not suffer any important deformation, except forced-folds or large-scale flexures above reactivated basement faults which induced local extensional states of stress. During the Mio-Pliocene paroxysm of deformation, the cover was involved in the orogenic wedge, while generalized involvement of the basement in shortening gave birth to the main morphotectonical regions in the Zagros fold belt (Figs. 16 and 1b).

6.3 Geodynamic Implications

The group of NW-SE-trending fractures are thought to have formed during the early stage of forced-folding above the main Zagros basement faults, and within the Asmari Formation during its deposition. Taking into account the earliest N050° regional joint set (Ahmadhadi et al., submitted) and also the second group which formed above forced folds, it is suggested that collisional stress build-up could have started, at least, as early as the Aquitanian (~23 Ma) and maybe earlier (Oligocene).

The first stage of basement fault reactivation may have started as early as the Oligocene, during the deposition of the Asmari Formation. This early basement fault reactivation may, together with the regional early N050° joint set, mark the onset of compressional stress build-up related to the Arabia-Central Iran continental collision (Fig. 16a). Then, amplification of basement fault movements during the Upper Oligocene to Lower Miocene (Chattian- Early Aquitanian, ~ 27–23 Ma) led to different isolated intra-basins in the studied area and initiated a series of fractures, parallel to general trends of these intra-basins and basement faults (Fig. 16b). In agreement with Allen et al. (2004) and Agard et al. (2005), we propose that 22–30 Ma (Chattian-Aquitanian) is a likely minimum age for initial plate collision, and that partitioning of the N-S Arabia-Eurasia convergence into belt-perpendicular shortening and belt-parallel strike-slip faulting in the NW Zagros happened long before what has been estimated for the initiation of the MRF.

Conclusions

The majority of fracture sets observed in the Asmari Fm in the Central Zagros are not compatible with conventional fold/fracture models. We proposed herein that they have been initiated before the main Mio-Pliocene shortening episode. Intra-basin architecture and facies changes during Lower Tertiary times suggest that large-scale forced-folds or flexures above compressionally reactivated basement faults controlled the Asmari sub-basins. The timing of reactivation of the main basement faults was estimated early Aquitanian in age, possibly before (late Oligocene). The non-compatibility between fracture populations in the Central Zagros folds and classical fold-related fracture models arises from the differences between the geometry and orientation of early large-scale and likely gentle forced-folds above reactivated basement faults and the superimposed Mio-Pliocene smaller-scale folds. This study emphasizes that early basement block movements may have an impact on fracture development in the cover rocks. However, the transmission of orogenic stress through the fractured crystalline basement of the Zagros was probably heterogeneous and complex, so the deformation front likely propagated in an irregular fashion through the basement and the cover leading to a complex chronology of fracture development in the cover. Such a complexity should be taken into account in further studies of folded and fractured reservoirs.

Finally, from a geodynamic point of view, it comes from our study that partitioning of the Arabia-Eurasia N-S-trending convergence and initiation of belt-parallel strike-slip movements (as currently along the Main Recent Fault) probably occurred as early as 22–30 Ma (Chattian-Aquitanian), which is likely to be the minimum age for the onset of Arabia-Eurasia plate collision in the Central Zagros.

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