Journal of Structural Geology 26 (2004) 519–535

JOURNAL OF
STRUCTURAL
GEOLOGY

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Crustal scale geometry of the Zagros fold–thrust belt, Iran

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Received 13 November 2002; received in revised form 30 June 2003; accepted 15 August 2003

Abstract

Balanced cross-sections across the Zagros fold–thrust belt in Iran are used to analyze the geometry of deformation within the sedimentary cover rocks, and to test the hypothesis of basement involved thrusting throughout the fold–thrust belt. Although the Zagros deformation front is a relatively rectilinear feature, the sinuous map-view morphology of the mountain front is a result of a 6 km structural step in the regional elevation of the Asmari Limestone that produces a pronounced step in topography termed the 'mountain front flexure'. Although the height of the mountain front flexure is sufficient to permit basement fault–bend folds at the front of the Lorestan and Fars regions, the taper of the orogen, low percentage of shortening, and consistent structural elevation from the mountain front flexure to the hinterland suggest that Lorestan and Fars segments of the fold and thrust belt are completely detached on lower Cambrian salt and that basement-involved thrusting occurs only in the hinterland of the orogen. Mass balance constraints necessitate that detachment folds throughout the fold–thrust belt are cored by faults that branch from the basal detachment. The steep dips of these faults and their depth within the lower Paleozoic sedimentary rocks can account for recorded earthquakes. This suggests that the ~11 ± 4-km-deep earthquakes throughout the fold–thrust belt may be nucleating within sedimentary rocks rather than in the basement as previously proposed. Total shortening in the Zagros fold–thrust belt is 70 ± 20 km, which corresponds to ~20% shortening of the Arabian block.

Keywords: Zagros; Fold–thrust belt; Salt tectonics; Basement deformation; Geometry

1. Introduction

The Zagros orogen is known for its spectacular fold trains, believed to be detached on lower Cambrian salt. Resistant limestone anticlines control the characteristic morphology of the region (Fig. 1). Widely distributed earthquakes that are similar in magnitude ($m_b \sim 5$–6), depth (11 ± 4), and geometry (40–50° NE-dipping nodal planes) (Jackson and Fitch, 1981; Ni and Barazangi, 1986) combined with preserved sedimentary cover rocks with thickness ranges of 6–15 km (Stocklin, 1968; Falcon, 1969; Colman-Sadd, 1978), have lead to a deformation model comprising distributed basement shortening in conjunction with, but decoupled from, folding of sedimentary cover rocks (Jackson, 1980; Jackson and Fitch, 1981; Ni and Barazangi, 1986; Berberian, 1995). Although crustal earthquakes in the Zagros fold–thrust belt may lie at the basement/cover interface where the stratigraphic sequence is undeformed, with gradual tectonic thickening of the deformed strata towards the hinterland, these earthquakes could potentially fall well above the basement cover interface within most of the orogen. Confirmation of the hypothesis of concurrent basement faulting and folding of sedimentary cover rocks requires knowledge of the depth to basement through the Zagros fold–thrust belt, the accurate location, in map view and depth, of $m_b > 5$ earthquakes, and the geometry of deformation within the Phanerozoic cover rocks. To evaluate the relationship between basement and cover deformation through the Zagros fold–thrust belt, this paper presents a series of cross-sections that extend across the Iranian–Arabian suture zone to the undeformed foreland of the Persian Gulf. The cross-sections illustrate the geometry and style of deformation of the Zagros fold–thrust belt, provide reasonable estimates for the amount of shortening of the Arabian block, and can be used to evaluate the necessity of basement shortening in the frontal portions of the fold–thrust belt.

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0191-8141/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsg.2003.08.009

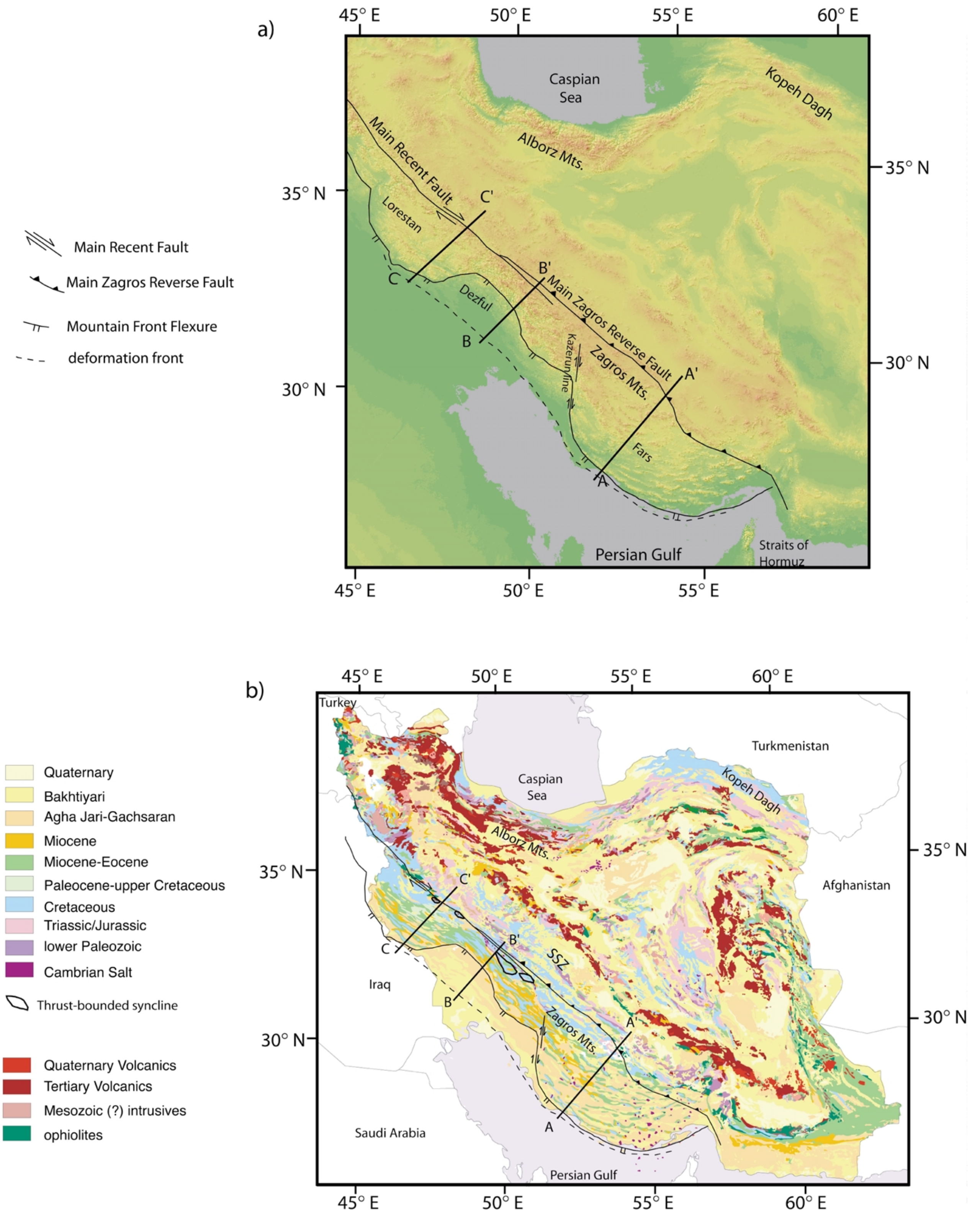

Fig. 1. (a) Topographic map of the Arabia /Eurasia collision zone in Iran. Reds indicate topography > 1.5 km. Lines A, B and C show location of cross-sections in Fig. 3. (b) Geologic map of Iran (Pollastro et al., 1997). SSZ represents the Sanandaj–Sirjan zone. Open ovals south of the Main Zagros Reverse fault represent thrust-bounded synclines (discussed in text).

2. Geologic background

The actively deforming Zagros fold–thrust belt is a result of the collision of Arabia with continental Eurasia (Fig. 1). The separation of Arabia from Africa and its subsequent collision with Eurasia was the last of a series of separation/collision events, all of which combined create the extensive Alpine–Himalayan orogenic system (Dewey et al., 1973; Sengor, 1984; Dercourt et al., 1986).

The Zagros fold–thrust belt is bounded on the northeast by both the Main Zagros Reverse fault and Main Recent fault. The Main Zagros Reverse fault is a proposed suture zone between the Arabian plate and Eurasia (Dewey et al., 1973; Sengor, 1984; Dercourt et al., 1986). The Main Recent fault, a young, active, right lateral fault, follows the trace of the Main Zagros Reverse fault from Turkey to approximately 32° S (Fig. 1). The Main Zagros Reverse fault is also the southern margin of the Sanandaj–Sirjan zone (Stocklin, 1968). The Sanandaj–Sirjan zone is a region of polyphase deformation, the latest reflecting the collision of Arabia and Eurasia and the subsequent southward propagation of the fold–thrust belt (Alavi, 1994). At the northeastern edge of the Sanandaj–Sirjan zone is the Urumieh Dokhtar arc (Fig 1). Interpreted to be an Andean type magmatic arc that has been active from the late Jurassic through present (Alavi, 1980; Berberian and King, 1981; Berberian et al., 1982), the Urumieh Dokhtar Arc represents the subduction of the Neotethys ocean as Africa moved northward with respect to Eurasia (Dewey et al., 1973; Alavi, 1980; Berberian and King, 1981; Sengor, 1984; Dercourt et al., 1986).

3. Cross-sections

3.1. Methods

Balanced cross-sections were constructed across the Lorestan and Fars salients and the Dezful Embayment from the undeformed foreland to the suture between the Arabian plate and Central Iran (Fig. 1). The cross-sections were balanced using the sinuous bed method (Dahlstrom, 1969). This method involves measuring the lengths of the top and bottom of each formation between faults and matching ramp and flat lengths on a restored section with those on the deformed section while maintaining bed thickness. Area balance was used to account for thickening and thinning of both the lower Cambrian Hormoz Salt in the Lorestan and Fars salients and the salt rich mid-Miocene Gachsaran Formation in the Dezful Embayment. The geometry of both the folds, and of the faults that are responsible for many of the folds within the fold–thrust belt was deduced from the geometry of dipping strata at the earth's surface. The parallel kink fold method (Suppe, 1983) was not applied because of the smooth, concentric nature of the folds through the Zagros.

The interpretations presented in the balanced cross-sections are based on 1:100,000 and 1:250,000 geologic maps from the National Iranian Oil Company and Iranian Geological Survey (O'B Perry et al., 1965a,b; O'B Perry and Setudehnia, 1966, 1967a,b; Setudehnia, 1967; Setudehnia and O'B Perry, 1967; Macleod, 1969, 1970; Sahabi and Macleod, 1969; Macleod and Fozoonmeyeh, 1971; Llewellyn, 1974; NIOC, 1979; GSI, 1991). Although the maps show detailed surface geology, important aspects of the Zagros orogen are not known, such as the dip of the basement surface and the stratigraphic level (base of Cambrian section or within the basement) of the master décollement. The following discussion describes and provides the rationale for the interpretations of the structures that are shown in the balanced cross-sections. The interpretations are based on map patterns, strike and dip data, changes in stratigraphic thicknesses across strike and select borehole data. The lack of published seismic data inhibits knowing completely the geometry of structures at depth, the depth to basement or how basement topography may change through the orogen. Even with these handicaps, knowing the undeformed thickness of strata (~12 km (Stocklin, 1968; Falcon, 1969; Colman-Sadd, 1978), and depth to basement (~11 km) determined from travel times for local earthquakes (Hatzfeld et al., 2003)) at the front of the Zagros fold thrust belt, provide a minimum depth to basement. In addition, using the constraints of equal line lengths, kinematic compatibility and detailed analysis of the geometry of rocks at the surface can provide insight into a wide variety of structures present at depth, including detachment folds, fault propagation folds, fault-bend folds, imbricate fans, and duplexes.

3.2. Stratigraphy

The sedimentary column of the Zagros fold–thrust belt comprises a ~12-km-thick section of lower Cambrian through Pliocene strata without significant angular unconformities (Stocklin, 1968; Falcon, 1969; Colman-Sadd, 1978). The oldest sedimentary unit believed to be involved in the fold–thrust belt is the late Proterozoic to early Cambrian Hormoz Salt (O'Brien, 1957; Falcon, 1969; Colman-Sadd, 1978; Kent, 1979) (Fig. 2). The Hormoz Salt is overlain by 6–10 km of platformal deposits that are predominantly sandstone, shale, and dolomite in the Cambrian through Triassic section and limestone (with subordinate shale and evaporite) in the Jurassic through Lower Miocene section (Stocklin, 1968; Colman-Sadd, 1978; Koop and Stonely, 1982). Strata thickness in the Jurassic through Pliocene section was obtained from map pattern and borehole data. Thickness variations within Paleozoic section were derived from exposures in the high Zagros, adjacent to the suture. The total thickness of Cambrian strata in the region of the Zagros is unknown; however, the Cambrian strata in the Zagros is most likely similar to the ~2-km-thick section in the Alborz Mountains

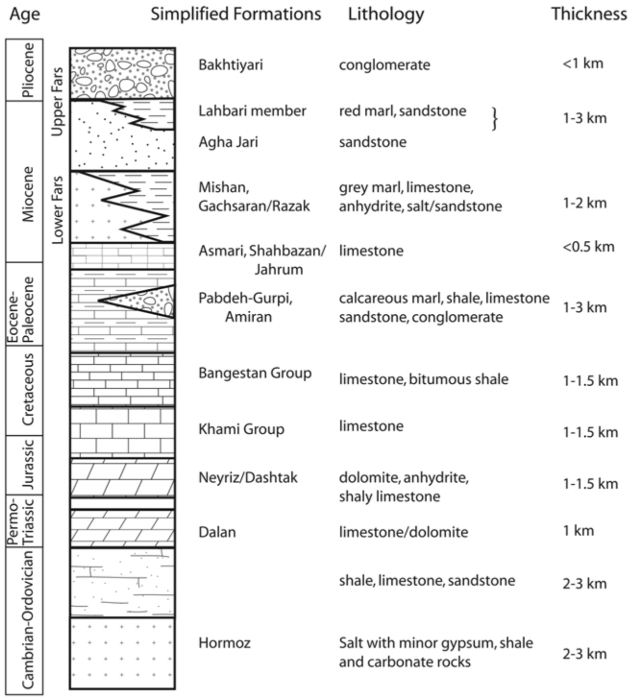

Fig. 2. Stratigraphic column through the Zagros fold–thrust belt. Data are from O'Brien (1957), Stocklin (1968), Falcon (1969), Colman-Sadd (1978) and Koop and Stonely (1982).

(Stocklin, 1968). Thickness changes of mapped strata depicted on National Iranian Oil Company and Iranian Geological Survey maps suggest an original sedimentary basin taper of ~0.5° (Fig 3).

The mid-Miocene and younger rocks in the section include gypsum, limestone, sandstone, shale and conglomerate. The thickness of these formations varies significantly through the fold–thrust belt, perhaps due to synorogenic deposition on, and erosion off of growing structures. Provenance data and interpretations of isopach-facies maps suggest that the Agha Jari and Bakhtiyari formations are synorogenic sedimentary rocks derived from a growing fold–thrust belt to the NE (Colman-Sadd, 1978; Koop and Stonely, 1982; Hessami et al., 2001).

3.3. Structure

3.3.1. Detachment folds

The concentric folds of the Zagros have generally been interpreted as detachment folds above the lower Cambrian Hormoz Salt (e.g. Colman-Sadd, 1978; Alavi, 1980, 1994). The projection of concentric folds to depth eventually produces severe space incompatibilities requiring disharmonic folding of the weak/ductile layers above a basal detachment (Mitra, 1990). Due to the thickness (~6–10 km) of the competent stratigraphic section involved in folding within the Zagros, space problems in the core of all but the gentlest folds result in unequal line lengths from syncline to adjacent syncline. The cross-sections presented here resolve the space problem by inferring the presence of thrust faults in the competent rocks in the cores of the anticlines. Fault offsets are the greatest in the lower Paleozoic rocks and decrease up dip as more shortening is taken up by folding. For the large detachment folds within the Zagros (see Fig. 3 structures A1, 8, 9 and C1, 3) the amplitudes of the folds with respect to the minor offsets of the faults imply that most folding predated faulting (McNaught and Mitra, 1993; Wallace and Homza, 1997). Fault propagation through the fold from the detachment surface may produce the asymmetry of many of the anticlines.

3.3.2. Fault propagation folds

The short wavelength and small amplitude of many folds within the Zagros fold–thrust belt are unlikely to represent pure detachment folding from the base of the Hormoz Salt due to both the tightness of the folds (interlimb angle of 100–45°) and the competency of the Phanerozoic stratigraphy above the Hormoz Salt (Fig. 3; structures A3, 5 and C7, 9, 10). The depth to detachment for these folds varies from the base of the Cretaceous section to the base of the competent Paleozoic above the Hormoz Salt. These structures are best interpreted as fault propagation folds, where the propagating thrust fault loses slip up section and the resulting shortening is taken up by folding in front of the fault tip (Mitra, 1990; McNaught and Mitra, 1993).

3.3.3. Fault–bend folds

Many thrust belts are characterized by faults that display a ramp/flat geometry where the movement of thrust sheets over footwall ramps creates fault–bend folds and steps in the structural elevation of the fold–thrust belt (Suppe, 1983; Mitra, 1990). In map view, the fold–thrust belt within the Dezful Embayment shows four distinct steps in structural elevation. In the frontal portion of the fold–thrust belt, predominantly Pliocene rocks are deformed in gentle folds. To the northeast, the level of exposure is 3 km deeper in the disharmonically folded rocks of the mid-Miocene Gachsaran Formation (Fig. 3; B4, 5). At the mountain front flexure (Figs. 1 and 3; B8), the rocks involved in deformation at the surface are Cretaceous through Oligocene, another structural step of ~3 km. The most northerly structural step brings lower Paleozoic rocks to the surface in a series of imbricate thrust slices (Fig. 3; B12). Each of these changes in structural elevation is attributed to a footwall ramp that raises the rocks carried in the thrust sheet from a lower to a higher décollement. In the frontal portion of the fold–thrust belt the décollement is at the base of the Gachsaran Formation and small fault propagation folds from that décollement deform the Pliocene rocks exposed at the surface (B1, 2). To the northeast, the décollement is also at the base of the Jurassic section. Gentle folds in Mesozoic through early Tertiary rocks underlie the disharmonic folds in the Gachsaran Formation (B3–7). The outer arc of the lower folds is constrained by National Iranian Oil Company

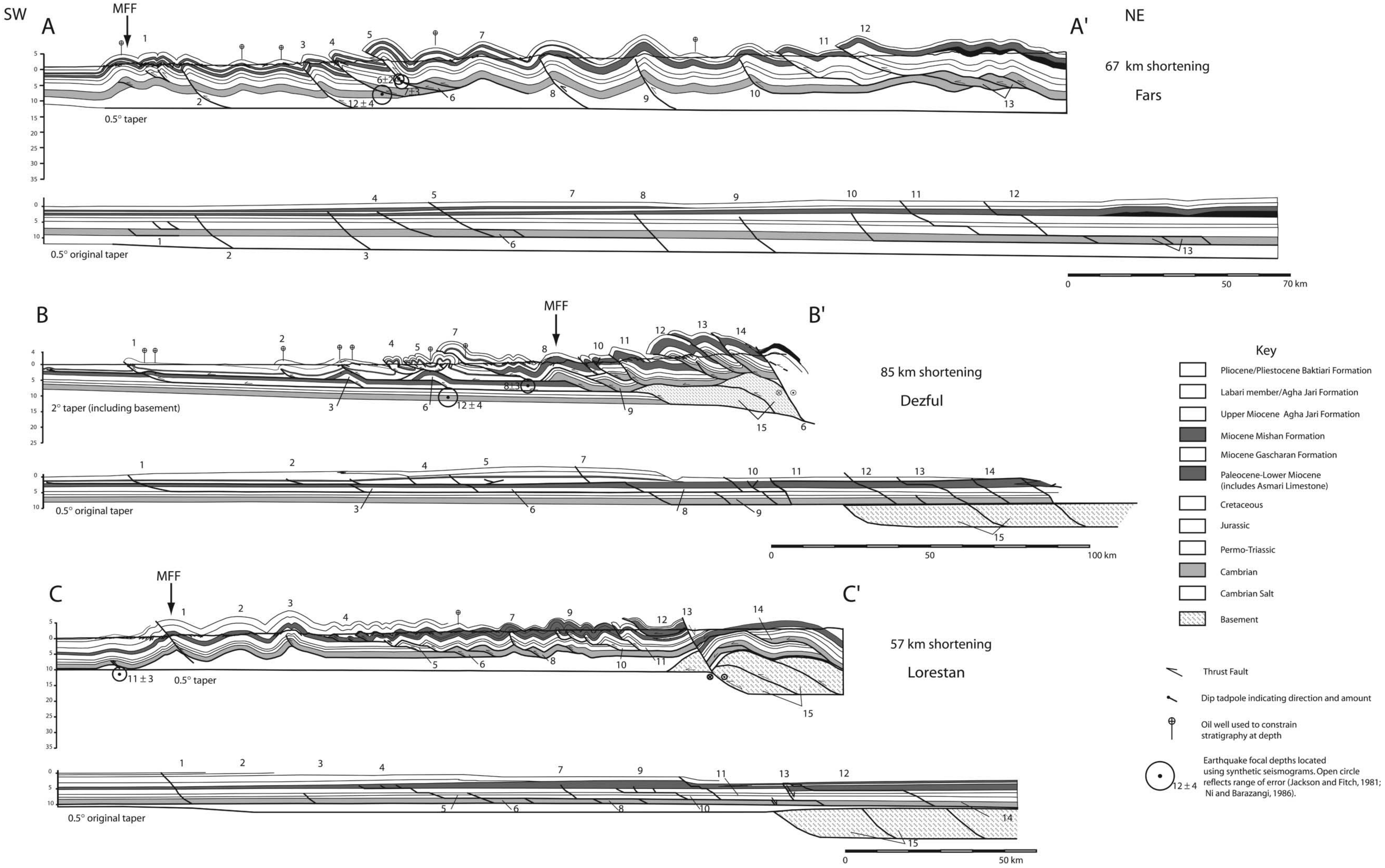

Fig. 3. Cross-sections through the Zagros fold–thrust belt. Numbers in cross-sections match numbers on restored sections and represent structures referred to in the text. See Fig. 1 for locations.

(NIOC) oil wells that penetrate the Asmari limestone (B3, 6) (O'Brien, 1957; O'B Perry and Setudehnia, 1966, 1967a,b; Macleod, 1969). Fault–bend folds in Jurassic through lower Miocene rocks match the shape of the folds and equal the amount of shortening from the higher level décollement (B3–7). The structural step that produces the mountain front flexure is interpreted to be a fault–bend fold that places Cambrian rocks over Miocene (B8). The structural elevation is maintained by the repetition of Cambrian through Tertiary rocks to the northeast. The final structural step that facilitates the exposure of Cambrian rock in the high Zagros (Fig. 3; B12–15) involves basement thrust sheets in the fold–thrust belt.

Fault–bend folds are also postulated within the Lorestan and Fars regions. In the Fars section of the fold–thrust belt, a fault–bend fold is needed to explain the structural elevation and to balance faulted stratigraphy at the surface with that in the subsurface (Fig. 3; A11). In the Lorestan section, larger wavelength folds behind a series of fault propagation folds can be explained as fault–bend folds that balance the shortening in the frontal fault propagation folds with thrust faulting in the lower stratigraphic units (Fig. 3; C9–11).

3.3.4. Klippen

Along the northern edge of the Zagros fold–thrust belt there are a series of synclines comprised of lower Paleozoic or Cretaceous and higher strata (Fig. 1). The synclines are completely surrounded by thrust faults, which place older rocks (from the core of the syncline) on younger. In the northeastern portion of the Lorestan section, Cretaceous rocks of Eurasian affinity occupy the core of a syncline and lie in thrust contact with Miocene and younger rocks (Figs. 1 and 3; C12). These relationships are explained by a larger thrust fault, carrying Eurasian Cretaceous rocks, that was emplaced over Miocene rocks and then folded over an underlying thrust duplex involving Cambrian and lower (basement?) rocks (Fig. 3; C15).

3.3.5. Imbricate fans

The series of thrust slices carrying Cambrian age rocks that occur in the hinterland portion of the Dezful cross-section are a classic example of an imbricate fan comprising listric thrusts that share a common décollement, and diverge upward. Displacement on lower and younger faults have rotated the higher and older thrusts into sequentially steeper dips (Fig. 3; B12–14). The structural elevation of this zone can be explained through the involvement of basement thrust sheets that raise the Cambrian and younger rocks above their regional elevation.

3.3.6. Duplexes

Although there are no duplexes exposed at the surface of the Zagros fold–thrust belt, the balanced cross-sections suggest that Cambrian rocks could be duplexed in the subsurface (Fig. 3; A6, 13 and C6, 8). The postulated duplexes balance the shortening of the Cambrian rocks with the shortening of the younger rocks that are exposed at the surface. The duplexes also account for the folding of higher-level décollement horizons as shown in the cross-sections. The involvement of basement rocks in the hinterland of the fold–thrust belt in the Dezful and Lorestan sections may also involve duplexing. These basement duplexes fill space between the master décollement and the rocks exposed at the surface without adding unaccounted for shortening. They also provide a mechanism for the folding of hinterland thrust sheets in the Lorestan area.

3.3.7. Late stage strike-slip and normal faulting

The suture zone between the Zagros fold–thrust belt and Eurasia is currently a right lateral fault zone with an unknown magnitude of displacement. Seismicity in the area of the Main Recent fault, north of the Dezful Embayment (Fig. 1), suggests that motion on the fault is right-lateral with a minor normal component (Jackson and McKenzie, 1984). Sharp topographic relief and young Quaternary basins on the northern side of the high Zagros along the trace of the Main Recent fault in the area between the Lorestan and Dezful sections also suggest a component of normal faulting in the motion of the Main Recent fault. The geometry of exposed rocks as recorded on geologic maps can be explained by an interpretation in which a thrust sheet carrying Cretaceous strata is emplaced over Miocene strata and then folded through the growth of a basement duplex. Normal faulting associated with the Main Recent fault may have utilized the pre-existing thrust ramp to lower the basement high (Fig. 3; C13).

3.4. Horizontal shortening across the belt

The amount of horizontal shortening across the Zagros fold–thrust belt is relatively small. In the Fars and Lorestan segments this results in 67 and 57 km of shortening, respectively. In the Dezful Embayment the fold–thrust belt has shortened 85 km. Higher amounts of shortening may be possible within the Sanandaj–Sirjan zone as suggested by Alavi (1994); however, the polyphase history of deformation within the area (Stocklin, 1968; Sengor, 1984; Alavi, 1994) complicates estimates of horizontal shortening.

4. Implications for large scale geometry of fold–thrust belt

4.1. Large-scale, morphological characteristics

The first-order morphological characteristic of the Zagros fold–thrust belt is the mountain front flexure (Fig. 1). This 6 km structural step raises Cretaceous age rocks to surface in the crests of anticlines, and is located at the frontal tip of the fold and thrust belt in the Fars and

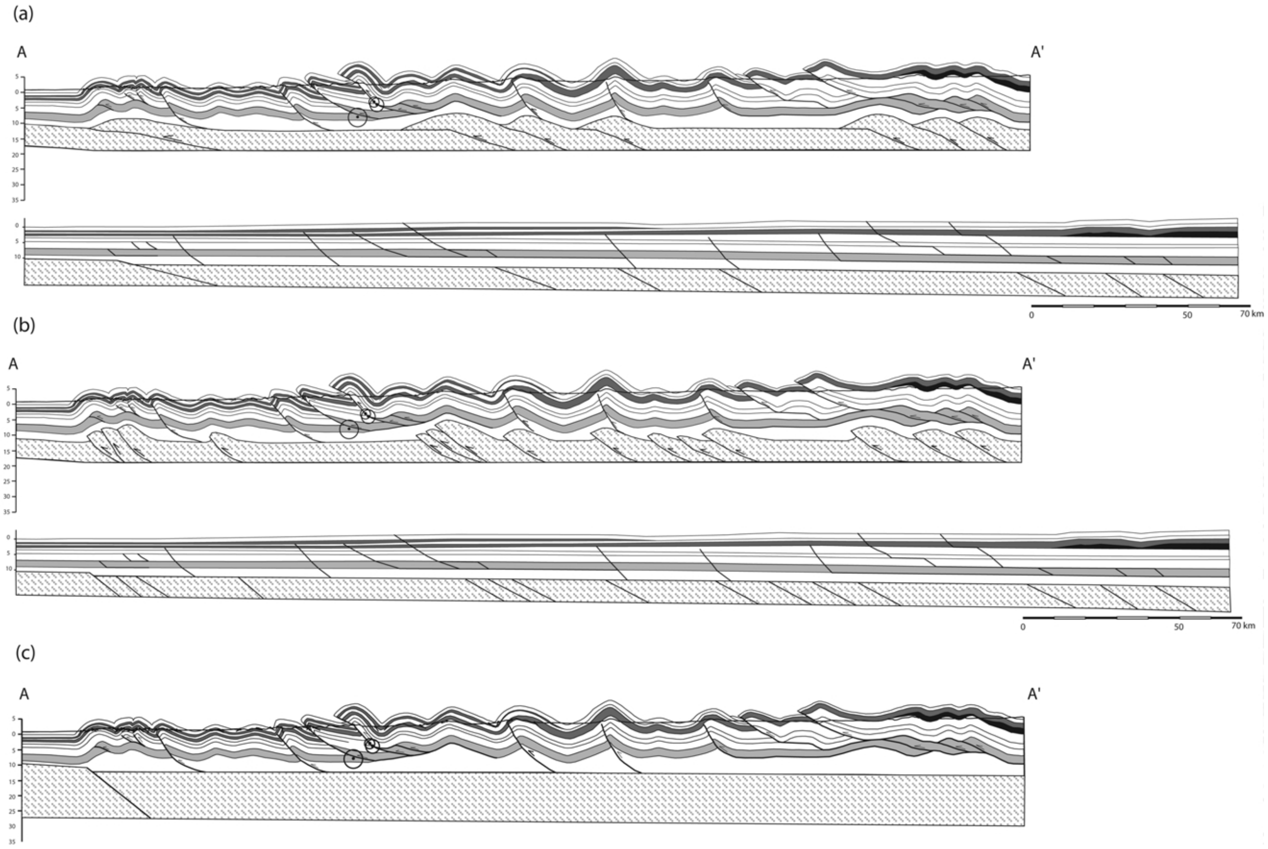

Fig. 4. Alternate balanced cross-section interpretations showing how basement-involved thrusting within the Zagros fold–thrust belt may account for high amplitude, broad anticlines, particularly the mountain front flexure. Cross-sections are through the Fars portion of the fold–thrust belt. (a) Thin-skinned basement thrust fault geometry, (b) thick-skinned basement thrust fault geometry, and (c) salt detachment geometry. Shading is the same as in Fig. 3, see Fig. 1 for location.

Lorestan regions. Northeastward of the initial structural step, the fold–thrust belt maintains a remarkably consistent structural elevation for 200–300 km in both the Lorestan and Fars regions. This same structural step is ~150 km inboard of the deformation front in the Dezful Embayment. However, in the Dezful region the structural elevation gradually increases from the foreland to the hinterland where deeper rocks are progressively exposed. First order problems that need to be addressed with any series of cross-sections across the Zagros are not only what structures are responsible for the mountain front flexure, but also how is this structural elevation maintained throughout the fold–thrust belt.

Two solutions that do not add unaccounted-for shortening to the fold–thrust belt and have the potential to maintain the structural elevation of the folds are: (1) basement faulting (either thin-skinned or thick-skinned) (Fig. 4a and b); or (2) excess thickening of the Hormoz Salt ‘trapped’ under the fold–thrust belt due to significant thinning of the salt layer under the Persian Gulf (Fig. 4c). The following sections evaluate the pros and cons of each option in explaining the large-scale geometry of the fold–thrust belt.

4.2. Possible basement geometry

Basement deformation within the Zagros fold–thrust belt has been proposed by numerous authors to account for widely distributed, teleseismically located, crustal earthquakes (Jackson, 1980; Jackson and Fitch, 1981; Jackson and McKenzie, 1984; Ni and Barazangi, 1986; Berberian, 1995). Basement deformation in fold–thrust belts typically falls into two categories: (1) thick-skinned structures with relatively steeply dipping faults (30–60°) that accommodate small (1–5 km) offsets; and (2) ‘thin-skinned’ basement thrust sheets that are transported 20 + km along regional décollements, the basal décollement typically being the brittle–ductile transition zone (Yonkee and Mitra, 1993). Due to the amplitude of the mountain front flexure, both forms of basement deformation are permissible through the Zagros and can explain some of the structural highs within the fold–thrust belt (Fig. 4), as well as account for mid-crustal earthquakes.

However, basement deformation within the Zagros has important implications for both the timing and style of deformation through the fold–thrust belt and the pre-collisional geometry of the Arabian Peninsula. The first

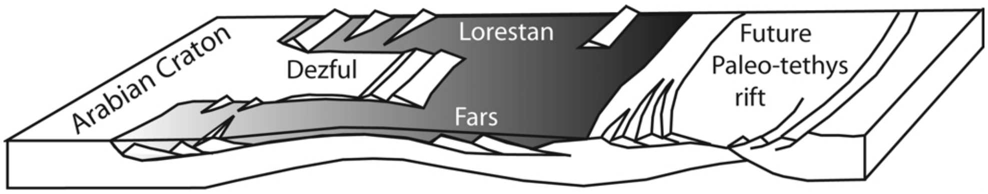

Fig. 5. Diagram showing possible basin geometry of a failed rift system in which the Hormoz Salt was deposited. Figure modified from Talbot and Alavi (1996).

implication is that shortening within the cover rocks is completely decoupled from shortening within the basement for both forms of basement deformation (Fig. 4). The necessity of decoupled deformation is illustrated by examining possible deformation histories of structures in the frontal-most portion of Fig. 4a as well as in the northeastern portion of Fig. 4b. Growth of the frontal monocline in Fig. 4a is due to a combination of cover rock deformation and uplift from an underlying basement fault–bend fold. Shortening accommodated by the basement thrust fault is much greater that the shortening within the cover rock immediately overlying it. Thus basement deformation in the front 40 km of the fold–thrust belt would need to be accommodated by cover deformation over 100–120 km. In the northeastern portion of Fig. 4b the reverse is true. Here sedimentary cover shortening exceeds the shortening of the underlying basement. This would suggest that the basement deformation and accompanying structural highs propagated southwestward faster that the overlying cover deformation to accommodate equal amounts of shortening.

The structural elevation profile of the Lorestan and Fars sections of the Zagros fold–thrust belt can be approximated by a step-function where ~6 km of structural elevation is gained rapidly in the at the mountain front flexure and then is maintained over the entire 300 + km length of the fold–thrust belt. Although basement deformation can account for some structural highs over this 300 km length, it cannot account for the entire area between the top of the undeformed basement and the base of the folded Paleozoic section (Fig. 4). With either form of basement deformation, a very mobile medium (Hormoz Salt) is required to maintain a constant structural high over the width of the fold–thrust belt by dampening out the amplitude of the basement folds (Fig. 4). Even though either form of decoupled basement cover deformation is plausible, geologic studies have shown that other broad, equal-amplitude fold trains occur over basement platforms with little to no topography (Laubscher, 1986) and that basement duplexing commonly imparts a structural topography (structural highs over basement highs) to the overlying detachment folds (Wallace and Hanks, 1990).

Requiring basement deformation to explain the location and amplitude of the mountain front flexure implies that the large-scale morphology of the fold–thrust belt is a function of pre-existing basement structures within the Arabian shield and not due to the presence (Lorestan and Fars salients) or absence (Dezful Embayment) of salt. These Arabian basement structures may be normal faults and associated transfer zones that pre-date the Paleozoic and younger platform sediments of the region, perhaps formed through an early, extensional Proto–Tethyan event proposed by Talbot and Alavi (1996). The geometry of the proposed rift would mimic the geometry of the present day fold–thrust belt. The mountain front flexure would be located at the southern edge of the extensional basin and the salients and reentrants of the mountain front flexure would be a direct result of the location of embayments and promontories within the original basin geometry (e.g. Thomas, 1977) (Fig. 5). Thus the broad arcs of the Zagros, commonly cited as classic examples of a fold–thrust belt with salt controlled morphology, would have more to do with the extensional basin geometry regardless of the actual distribution of salt within that basin.

4.3. Salt tectonics

Perhaps a simpler explanation for the large-scale geometry of the Zagros fold–thrust belt is a weak lower Cambrian salt décollement under the Lorestan and Fars segments of the fold–thrust belt and a lack of lower Cambrian salt within the Dezful Embayment.

3.3.8. Analogy to model results

Physical analog models of fold–thrust belts with weak décollements produce structures that mimic the structures in the Zagros in terms of the geometry of the folds and the overall morphology of the fold–thrust belt (Fig. 6). Physical analog models highlight the importance of salt thickness and distribution on both the geometry of the structures and the kinematics of the fold–thrust belt. Aspects of the Zagros that can be compared with physical analog models are asymmetry of structures, morphology of the fold–thrust belt, thickness of salt, frictional lateral boundary conditions, and kinematics of propagation.

Physical and theoretical models of thrust belt development above ductile detachments demonstrate that generally the developing structures should have no preferred vergence (Davis and Engelder, 1985; Cotton and Koyi, 2000). However, Costa and Vendeville (2002) showed that folds are asymmetric towards the foreland if the model had a deformable backstop, a salt pinch out in the foreland and a sufficiently thick décollement layer (Costa and Vendeville,

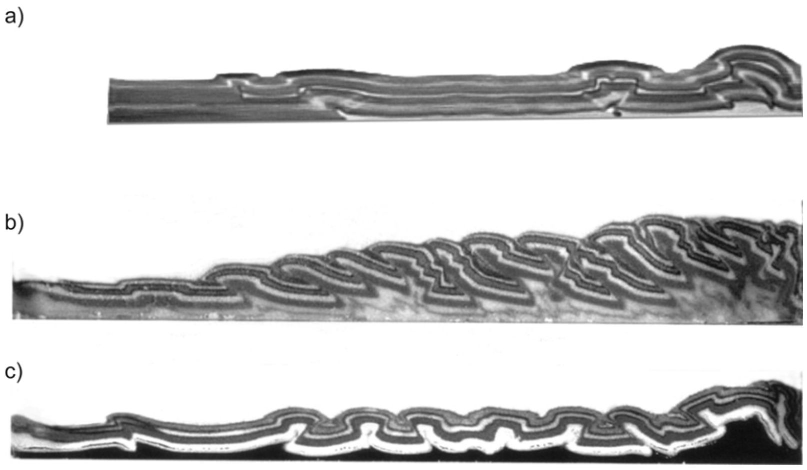

Fig. 6. Physical analog models showing: (a) the importance of a salt pinch-out in the deformation history of salt-detachment fold–thrust belts (fig. 3 from Letouzey et al. (1995). AAPG © (1995), reprinted by permission of the AAPG whose permission is required for further use). (b) Physical analog model of a fold–thrust belt with a frictional décollement. Deformation was accommodated by slip along forethrusts that propagated leftward (fig. 1 from Costa and Vendeville, 2002). Compare with cross-section through Dezful Embayment (Fig. 3b). (c) Physical analog model of fold–thrust belt detached on a ductile décollement; folds did not have a preferred sense of vergence and grew coevally (fig. 1 from Costa and Vendeville, 2002). Compare with cross-sections through the Lorestan and Fars salients (Fig. 3a and c).

2002). A key aspect of their model was lubricated lateral boundaries to reduce the influence of friction. In this scenario the structures did not sequentially propagate forwards but jumped to the frontal salt pinch-out and then internally shortened (through out-of-sequence thrusting) with no further propagation. Models that incorporate edge effects to model the lateral terminations of salt basins (Cotton and Koyi, 2000) show a sequentially forward breaking propagation of structures over a weak décollement. These structures, however, show no preference in vergence. Cotton and Koyi (2000) also modeled the contrasting morphology of a weak décollement fold–thrust belt adjacent to one that develops over a much stronger substrate (Fig. 7). The deformation front above a weak décollement propagates farther and faster than the adjacent deformation above a detachment with high friction. The boundary between the two zones becomes a zone of transpression analogous to the Kazerun line in Iran that separates the Fars salient from the Dezful Embayment (Cotton and Koyi, 2000) (Fig. 1).

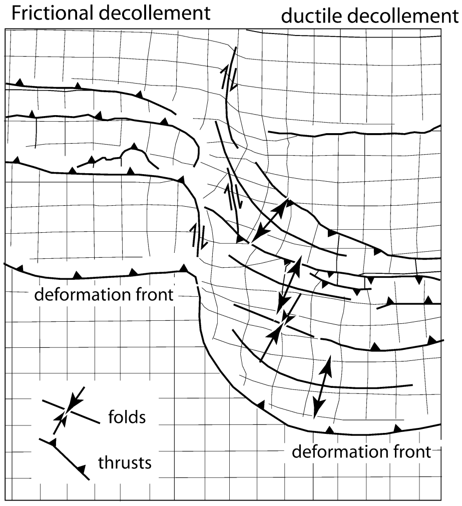

Fig. 7. Line drawing of physical analog model showing pronounced deflection in the deformation front at the ductile décollement/frictional décollement boundary. Modified from Cotton and Koyi (2000). Compare geometry with Kazerun line in Fig. 1.

The Zagros fold–thrust belt is a southwest verging, asymmetric orogen. Comparing the asymmetry in the Zagros with asymmetric physical analog models by Costa and Vendeville (2002) supports the large thickness of salt shown in the cross-sections (2–3 km) and suggests that the Sanandaj–Sirjan zone (SSZ on Fig. 1) may be viewed as a deformable backstop to the fold–thrust belt. The lack of salt through the Dezful Embayment and the lateral boundary of salt at the Oman line (eastern edge of Persian Gulf) may have acted as frictional lateral boundaries (Cotton and Koyi, 2000) to allow for the sequential propagation of the fold–thrust belt as suggested by foreland basin studies (Koop and Stonely, 1982; Beydoun et al., 1992; Hessami et al., 2001). The large amplitude and wavelength frontal anticlines of the Fars and Lorestan salients have the appearance of structures that formed early over a salt pinch-out (Cotton and Koyi, 2000; Costa and Vendeville, 2002). This boundary cannot represent the extreme southwestern extent of the Hormoz Salt because numerous salt plugs breach the surface or produce domal mounds south of the Persian Gulf. However, the frontal edge of the fold belt could represent a sharp transition in salt thickness.

4.3.1. Salt pinch-out

Comparisons of the Zagros cross-sections with both physical analog models and classic examples (the Jura Mountains and the Perdido fold–thrust belt) of salt controlled fold–thrust belts argue for the importance of a

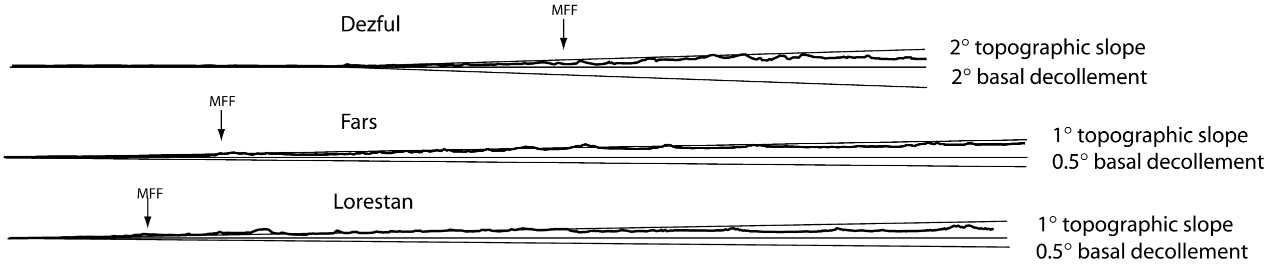

Fig. 8. Diagram depicting taper variations within the Zagros fold–thrust belt. The basal décollement angle of the Dezful section takes into account the basement ramp in the hinterland. MFF corresponds to the location of the mountain front flexure on each profile.

salt pinch-out or a dramatic thinning of the salt layer at the southern limit of the Fars and Lorestan segments (Letouzey et al., 1995; Trudgill et al., 1999; Cotton and Koyi, 2000; Costa and Vendeville, 2002). Previous estimates of salt thickness within the Zagros indicated the salt could be 1–1.5 km thick (Kent, 1970). However, the amount of salt needed to fill the space between the minimum depth to basement (assuming a décollement dip of 0.5°) and the base of the competent Paleozoic section (Fig. 3, cross-sections), restores to an original salt thickness of 3–4 km (Fig. 3, restored sections). It also allows for a substantial decrease in salt thickness (from 3–4 km to perhaps as little as 1–0.5 km) at the front of the fold–thrust belt, which can account for both the southern termination of the fold–thrust belt at the mountain front flexure and the presence of salt diapirs under the Persian Gulf. The southern edge of the thick Hormoz Salt basin could be controlled by pre-existing normal faults as depicted in Fig. 5. Basement structure and associated variations in stratigraphic thickness of weak rocks have been recognized as important controls on the localization and growth of frontal anticlines in fold–thrust belts (Trudgill et al., 1999; Thomas, 2001).

4.3.2. Taper

The taper of each segment of the fold–thrust belt was determined from the forelandward dipping slope of the modern day topographic surface, combined with the hinterland dipping slope of the basal décollement of the fold–thrust belt as deduced from the restored sections. For the Lorestan and Fars segments the angle of the basal décollement corresponds to the postulated 0.5° taper of the restored sedimentary basin (Fig. 3). For the taper of the Dezful Embayment, the basal décollement reflects the original basin taper and a series of ramps as the décollement climbed from the basement to the Gachsaran décollement horizon giving a basal décollement dip of 2° (Fig. 8). The topographic slope is 1° for the Lorestan and Fars cross-sections and 2° in the Dezful Embayment. Theoretical and geophysical studies indicate the importance of taper (the angle between the topographic slope and the basal décollement) in the evolution of fold–thrust belts (Davis et al., 1983; Dahlen et al., 1984; Mitra, 1997). The taper angle is directly related to the strength of the décollement such that a fold–thrust belt with a very weak décollement has a very low (1–2°) taper angle (Davis et al., 1983; Dahlen et al., 1984; Mitra, 1997). The change in taper from 4° in the Dezful Embayment segment of the fold–thrust belt to 1.5° for the Lorestan and Fars segments (Fig. 8) strongly suggests that the Hormoz Salt is the basal décollement in the frontal portions of the fold–thrust belt in the Lorestan and Fars region and that the Hormoz Salt is not present within the Dezful Embayment.

4.3.3. Salt escape and current rate of deformation

The ability of salt to produce the mountain front flexure depends strongly on the nature of the salt pinch-out in the foreland limit of the deformation (Letouzey et al., 1995; Cotton and Koyi, 2000; Costa and Vendeville, 2002). As stated previously, the geographic distribution of salt extends well south of the fold–thrust belt into the foreland of the Persian Gulf and Arabia; however, the original thickness of salt may thin dramatically at the modern day deformation front. The difference between the inferred 6–8 km of salt under the mountain front anticline (Fig. 3; structures A1 and C1) and the ~1 km of salt underneath the Persian Gulf involves a topographic head that will cause the salt to flow southwestward at a rate that depends on the viscosity of salt and the rate of shortening in the fold–thrust belt. The effectiveness of a pronounced decrease in the thickness of the salt to inhibit the southwestward escape of salt was tested to see whether the viscosity of salt is sufficient to maintain the mountain front flexure over time scales that match the current rate of deformation in the Zagros. By assuming that the salt will behave as a Newtonian fluid as it travels through a channel equivalent in height to the thickness of the salt under the Persian Gulf, it is possible to use the average viscosity of salt to determine the rate of salt 'escape', because viscosity calculations are dependent on the height of the assumed channel and the distance of flow. The following equations are based on the analytical approach presented by Kruse et al. (1991) for channel flow in continental crust. Two-dimensional linear viscous flow through a channel is described by the equation:

$$q = \frac{D^3}{12\mu}\frac{\mathrm{d}p}{\mathrm{d}x} \qquad (1)$$

where q = flow rate, μ = viscosity, D = channel thickness, and $\mathrm{d}p/\mathrm{d}x =$ lateral pressure gradient. The initial pressure gradient can be approximated by the difference in pressure due to marked variations of salt thickness and can be expressed as:

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\rho_s g \Delta h}{L/2} \tag{2}$$

where $\rho_s =$ the density of the salt, $g =$ gravity, $\Delta h =$ elevation of salt above its regional elevation in the frontal monocline, and $L =$ length scale of transport. The flow stops when lateral pressure variations are removed and half of the mobile material has moved half of the distance from the thick to the thin region. Thus Eq. (1) can also be written:

$$q = \frac{\Delta h L}{4\Delta t} \tag{3}$$

By combining Eqs. (1)–(3) and assuming that pressure gradients over time, Δt, may be represented by an average pressure equal to half the original pressure, we can solve for the viscosity required for 'complete' flow:

$$\mu = \frac{D^3 \rho_{\mathrm{mc}} g \Delta t}{3L^2} \tag{4}$$

By assuming a reasonable viscosity range (10^{17}–10^{18} Pa s) and density $\rho_s = 2200\ \mathrm{kg/m^3}$ for salt and allowing the channel height (D) to vary from 0.5 to 2 km, Eq. (4) can be solved for the length of the channel (L) to determine the horizontal rate of salt escape over 1 m.y. On the basis of these values and equations, the rate of salt escape is 5–140 mm/yr. The lower end of these estimates ~10–20 mm/yr., is roughly the rate of shortening within the frontal folds (Lees and Falcon, 1954; Vita-Finzi, 1979). The rate of salt escape is compatible with the hypothesis that a narrowing of the salt 'channel' may act as a sufficient impediment to salt flow over the time scale that the fold–thrust belt has been developing. Thus a salt 'pinch-out' may be an effective mechanism for the development of the mountain front flexure in the Lorestan and Fars portions of the Zagros fold–thrust belt.

4.4. Relation to regional seismicity

If the large-scale geometry of the Zagros fold–thrust belt is primarily a function of lateral ramps controlled by the presence or absence of salt along the strike of the orogen, and basement deformation is not required by the geometry of the deformed sedimentary strata, it is important to test whether the earthquake record of the Zagros requires basement deformation as suggested previously by various authors (Jackson, 1980; Jackson and Fitch, 1981; Ni and Barazangi, 1986; Berberian, 1995).

Seismicity in the Zagros is spread over the frontal 200 km of the fold–thrust belt and correlates well with topographic elevations >1.5 km (Jackson and McKenzie, 1984; Ni and Barazangi, 1986; Berberian, 1995). Fault-plane solutions for several of these earthquakes consistently show high-angle (40–50°) reverse faulting, have estimated depths that range from 8 to 13 ± 4 km with no tendency to deepen towards the main Zagros thrust, and have magnitudes that range from 4 to 6 (Jackson and Fitch, 1981; Ni and Barazangi, 1986). The thickness of the Cambrian through Pliocene stratigraphic section is ~12 km (Stocklin, 1968; Falcon, 1969). Thus most of the earthquakes in this region fall close to the interface between the basement and cover of an undeformed section. Erosive removal of 4 km of Tertiary rocks within much of the fold–thrust belt and the presence of ~2 km of Hormoz Salt at the base of the section has lead several authors to propose that the earthquakes are nucleating in the uppermost basement (Jackson and McKenzie, 1984; Ni and Barazangi, 1986; Berberian, 1995).

Integral to testing the hypothesis of concurrent basement faulting and surface folding is information on the depth to basement within the Zagros fold–thrust belt, the accurate location, in map view and depth, of $m_b > 5$ earthquakes, and the geometry of deformation within the Phanerozoic strata. The alternate hypothesis that earthquakes nucleate in the sedimentary cover instead of the basement is tested by comparing the depth locations of relocated earthquakes with the projected depth of the basement within the fold–thrust belt and by comparing the location of earthquakes with structures within the fold–thrust belt.

Fig. 9 shows the relationship between the focal depths of relocated earthquakes (Jackson and Fitch, 1981; Ni and Barazangi, 1986) and the depth of the underlying basement. Seventeen earthquakes in the Zagros fold–thrust belt have been relocated using synthetic seismograms (Jackson and Fitch, 1981; Ni and Barazangi, 1986). The uncertainties in depth locations are approximately ±4 km because of uncertainties in the crustal velocity structure of the Zagros and errors involved in exactly matching the observed and calculated waveform (Jackson and Fitch, 1981; Ni and Barazangi, 1986). The depth to basement has been estimated by taking the elevation of the basement at the deformation front and projecting it to the northeast at décollement dips of 0, 0.5, 2 and 5°. The depth to the basement at the front of the fold–thrust belt is 10, 8 and 12.5 km in the Lorestan salient, Dezful Embayment and Fars salient, respectively. The graph documents that all of the earthquakes, within their error bars, may be in the overriding sediments, even with an unlikely 0° dip of the Hormoz Salt décollement.

The second way to test whether the earthquakes could be located within the sedimentary section is to consider the relationship of the earthquakes to the structures depicted on the cross-sections (Fig. 3). The steep dips of the faults that core many of the folds in the cross-sections and the depth of the faults within the lower Paleozoic sedimentary rocks suggest that many of the recorded earthquakes in the Zagros are nucleating within the sedimentary section. Relocated focal depths for seven earthquakes with magnitudes ranging from 5.4 to 6.0 (Jackson and Fitch, 1981; Ni and Barazangi, 1986), within 25 km distance from each cross-section, were projected onto the lines of section. The depth of each

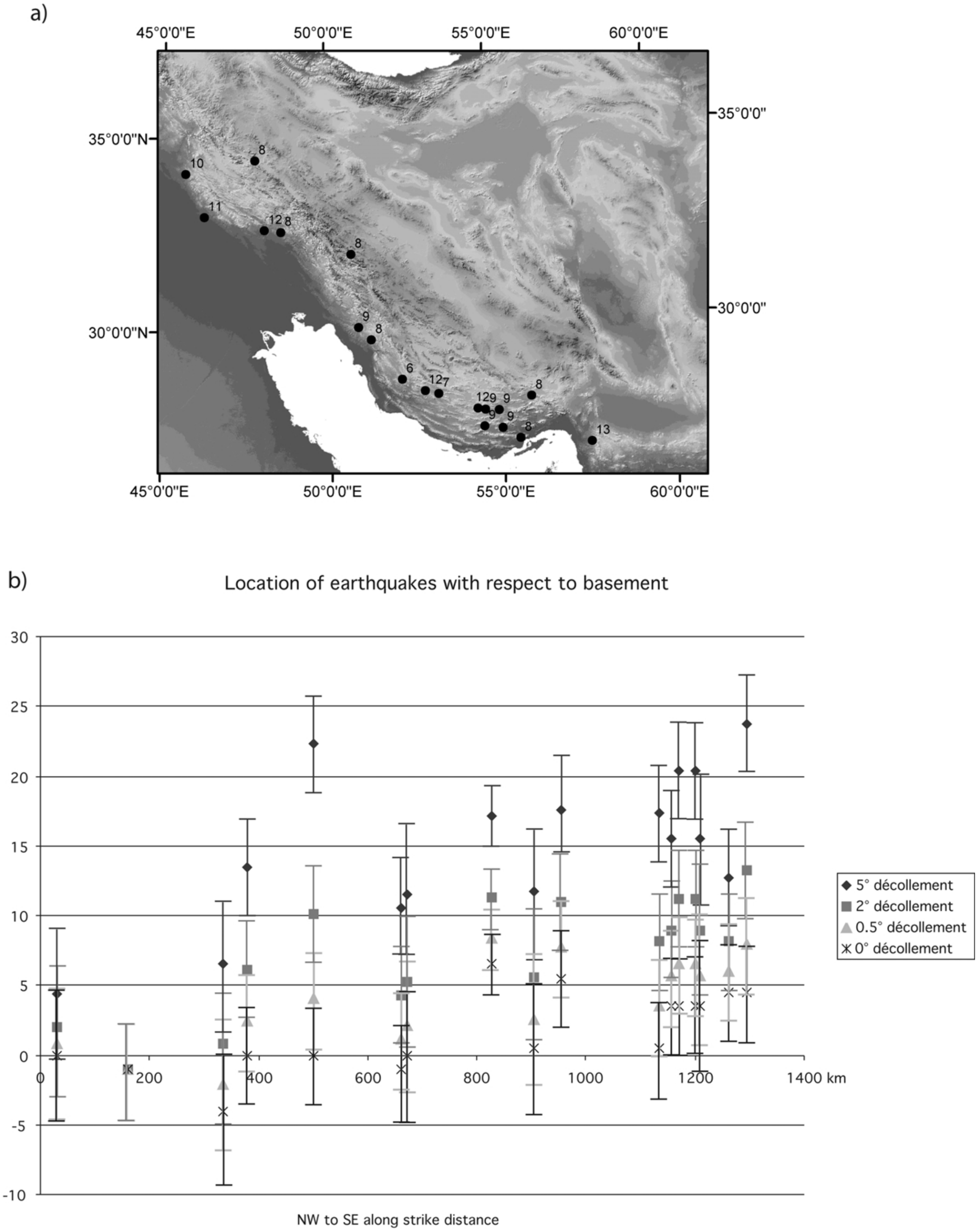

Fig. 9. (a) Relocated earthquakes from Jackson and Fitch (1981) and Ni and Barazangi (1986). Numbers reflect focal depths, errors range from ± 2 to ± 4 km. (b) Graph showing location of relocated earthquakes with respect to the projected basement cover interface.

earthquake with an associated circle showing the uncertainty in focal depth location is plotted on the cross-sections (Fig. 3). All but two of the earthquakes fall well within the sedimentary sequence and only one earthquake is located within the basement. The earthquakes are all associated with ramps within the sedimentary sequence within the range of uncertainty associated with their locations. Scaled analog models of fold–thrust belts above weak décollements show that active faulting occurs on several faults simultaneously, because the basal décollement is active over a wide area at a given time (Koyi et al., 2000). Comparing the seismogenic rupture surface and average fault displacement of the model with natural examples, Koyi et al. (2000) argue that an active thrust above a weak décollement could produce

$m_b \sim 5$ earthquakes over the zone of deformation. The magnitude of the earthquakes predicted by the model along with the broad zone of distribution is analogous to the pattern of earthquakes through the Zagros suggesting much of the seismicity in the Zagros fold–thrust belt could be concentrated above the basement–cover interface.

5. Conclusions

Although the amplitude and wavelength of the folds within the Zagros, especially the frontal folds that produce the MFF, permit basement shortening, basement deformation is not required by the geometry of the structures or by earthquake focal mechanisms. The geometry of deformation within the Zagros fold thrust belt suggests that many of the folds are cored by faults in the lower Paleozoic strata. The inferred dips and locations of these fault surfaces are compatible with the magnitude, depth, and nodal plane orientation of earthquakes throughout the fold–thrust belt. Future studies that can provide accurate depth to basement within the Zagros fold–thrust belt, and precise locations, in map view and depth, of $m_b > 5$ earthquakes, are necessary to distinguish between Cambrian salt or the brittle/ductile transition zone as the master décollement of the Zagros fold–thrust belt. Until these data become available, the large-scale geometry of the Zagros orogen may best be explained as a weak salt décollement within the Lorestan and Fars region that is not present within the Dezful Embayment.

Acknowledgements

This research was supported by the Caltech Tectonics Observatory. I have benefited greatly from discussions of Iranian Geology with Gary Axen, Mohammad Fakhari, Jamshid Hassan Zadeh, Brian Horton, Rowena Lohman, Daniel Stockli, Brian Wernicke and careful reviews from William Thomas, Ray Price and an anonymous reviewer.

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