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STRUCTURES OF THE ZAGROS FOLD-THRUST BELT IN IRAN

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ABSTRACT. The Zagros fold-thrust belt in Iran forms the external part of the Zagros active orogenic wedge. It includes a sequence of heterogeneous latest Neoproterozoic–Phanerozoic sedimentary cover strata, ~7 to 12 km thick and composed of alternating incompetent and competent layers, overlying Precambrian crystalline basement with a complex pre-Zagros structural fabric. Balancing structures of the cover statigraphic units in the Zagros fold-thrust belt requires in-sequence and out-of-sequence involvement of the Precambrian basement in the deformation. Six detailed balanced and retrodeformable cross-sections, which are constructed based on geological and geophysical data across various sectors of the belt, show fault-bend and fault-propagation folds interpreted to have formed by slip on their subjacent thrusts. Out-of-sequence, basement-rooted thrusts, as the interpretations in the constructed cross-sections suggest, have breached the cover/basement interface and, using incompetent cover strata for propagation, cut across the cover structures and have created associated new folds superimposed upon the pre-existing structures. This style of deformation, which has resulted in structural complexity of the belt, characterizes a ~200 to 300 km-wide zone of distributed, partly synchronous, deformation with along-strike and across-strike variations. It also implies that the Zagros fold-thrust belt, as the external part of the orogenic wedge, is still in its subcritical condition with internal deformation to achieve a critical taper. In creating structural complexity, in addition to out-of-sequence thrusting, mechanically weak layers (evaporites and mudstones) of the cover strata have played a significant role by providing several detachment horizons. Shortening estimates across the belt are variable; based on the constructed cross-sections and their restorations, minimum shortening estimates range from 16 percent to 30 percent in different sectors of the belt.

INTRODUCTION

More than 65 percent (~107.5 billion cubic meters) of the remaining proven oil reserves (~159.6 billion cubic meters) and nearly 34 percent (~49.5 trillion cubic meters) of the total gas reserves (~146.4 trillion cubic meters) of the world have accumulated in numerous giant and supergiant hydrocarbon fields of the Middle East [http://energy.cr.usgs.gov]. The distribution of these fields is shown in figure 1. The fields are predominantly located either in the Zagros fold-thrust belt or just in front (southwest) of it. Clearly, the accumulation of hydrocarbons in the Middle East has been intricately related to the stratigraphic and structural evolution of the Zagros fold-thrust belt.

Within the complex tectonic framework of the Middle East, the Zagros fold-thrust belt (ZFTB) is the deformed state of the Zagros sedimentary basin, a basin that extended over the northeastern (present coordinates) Afro-Arabian continental margin and was affected by Early Cretaceous to present Zagros orogeny. The ZFTB, as the external part of the Zagros orogen (Alavi, 1980, 1991, 1994), extends southeast for nearly 2000 km from southeastern Turkey through northern Syria and northeastern Iraq to western and southern Iran (fig. 1). It has been a subject for numerous geological and geophysical investigations since the earliest days of petroleum discovery in the region almost a century ago.

The stratigraphy and sedimentological characteristics of prominent lithostratigraphic units of the ZFTB are now fairly well established (Alavi, 2004). Also, the tectonic setting of the belt, as an integral part of the Zagros orogen, has been reasonably understood (Alavi, 1994). Understanding various petroleum systems of the belt for exploration purposes, however, requires paleogeographic reconstructions of

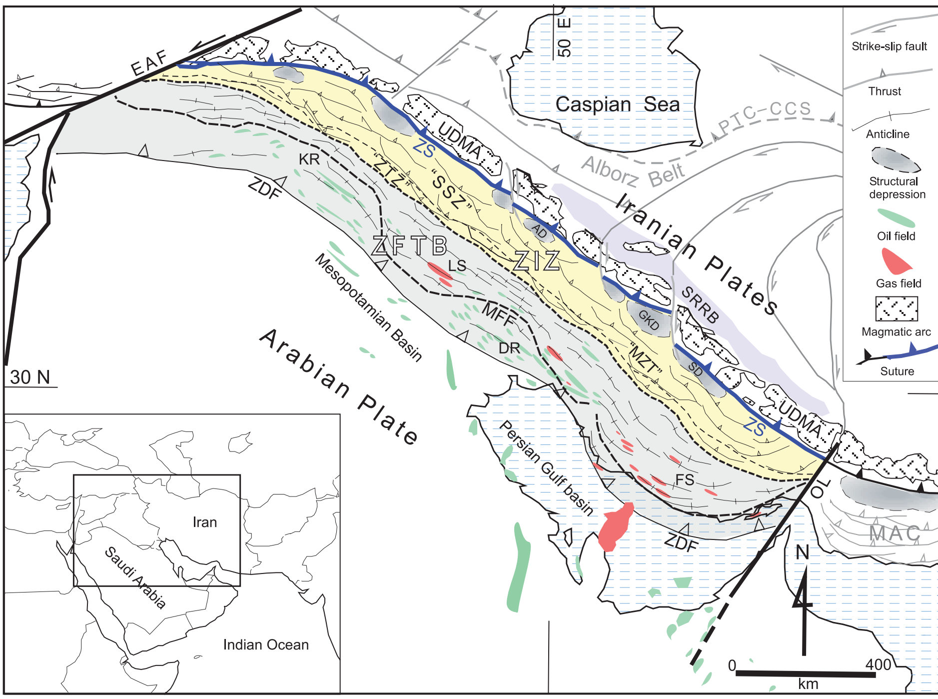

Fig. 1. Subdivisions of the Zagros orogenic belt. Abbreviations: AD– Arak depression; DR– Dezful recess; EAF– East Anatolian Fault; FS– Fars salient; GKD– Gav Khooni depression; KR– Karkuk recess; LS– Lorestan salient; MAC– Makran accretionary complex; MFF– "Mountain front flexure"; "MZT"– "Main Zagros Thrust"; OL– Oman Line; PTC-CCS– Paleo-Tethyan continent-continent collisional suture; SD– Sirjan depression; SRRB– Saveh-Rafsanjan retroforeland basin; "SSZ"– Sanandaj-Sirjan zone; "ZTZ"– Zagros thrust zone; UDMA– Urumieh–Dokhtar magmatic assemblage; ZDF– Zagros deformational front; ZFTB– Zagros fold-thrust belt; ZIZ– Zagros imbricate zone; ZS– Zagros suture. Hydrocarbon fields of the region, oil in green and gas in red, are shown.

various lithostratigraphic units and their regional and local lithofacies variations. These reconstructions must be based on geometrical and kinematic analyses of the structures of the belt. Previous presentations of facies variations of the ZFTB, such as those of Murris (1980) and Koop and Stoneley (1982), which are extensively reiterated in numerous later publications including recent ones (for example, Sharland and others, 2001; Bahroudi and Koyi, 2004; Sepehr and Cosgrove, 2004), are not based on palinspastic restorations and, consequently, have very limited value in petroleum systems analyses. Therefore, the first step towards palinspastic restoration of the Zagros sedimentary basin is to establish the structural deformation of the belt.

In the last three decades, several fold-thrust belts of the world have undergone extensive investigations, from which a general understanding of their prominent structural characteristics and involved deformational processes (from geometrical, kinematic, and mechanical viewpoints) have emerged. The critical wedge theory provides a conceptual framework for analysis of the state of stress, the kinematics of material transport, and the geometrical aspects of the structures formed in the fold-thrust belts (Chapple, 1978; Stockmal, 1983; Davis and others, 1983; Dahlen and others, 1984; Platt, 1986; Dahlen, 1984, 1990). This theory considers the fold-thrust belts as orogenic wedges (or prisms), and emphasizes the importance of frictional resistance at the base of the wedges (Davis and others, 1983; Davis and Engelder, 1985), the influence of the basement morphology on final architecture of the wedges

(Boyer, 1995; Mitra, 1997), the contribution of syntectonic sedimentation and erosion rates on the wedge mechanics (Beaumont and others, 1992; Storti and McClay, 1995; Willett, 1999), and the effects of mechanical stratigraphy within the wedges (Woodward and Rutherford, 1989; Dixon and Liu, 1992; Erikson,1996; Fermor, 1999; Turrini and others, 2001; Teixel and Koyi, 2003; Ravaglia and others, 2004).

In this paper, utilizing modern concepts of geometrical, kinematic, and mechanical aspects of deformation of the fold-thrust belts, I address structural deformation of the ZFTB and, by presenting a series of retrodeformable cross-sections and their pre-Zagros orogeny restorations, provide a basis for future palinspastic reconstruction of the Zagros sedimentary basin.

ZAGROS OROGEN

The Zagros orogen as a part of the Alpine-Himalaya mountain chain is a well-defined active doubly-vergent and asymmetric orogenic belt (Alavi, 1994). The northwestern boundary of the orogen is chosen to be the East Anatolian strike-slip fault (EAF in fig. 1) in southeastern Turkey. This fault separates the Zagros from the Eastern Taurides of Turkey, and offsets the two orogens left-laterally for ~300 km. The southeastern boundary of the Zagros orogen is the Oman Line (Falcon, 1969). This is distinguished by intense seismic activity (Kadinsky-Cade and Barazangi, 1982), pronounced negative gravity anomalies (Snyder and Barazangi, 1986; Bushara, 1995), sharp facies variations in the Phanerozoic stratigraphic units (Falcon, 1974), a change in structural style of deformatiom (Molinaro and others, 2004), and a change from continental crust under the Zagros belt to oceanic crust under the Makran accretionary prism to the southeast (Farhoudi and Karig, 1977; White and Ross, 1979; Byrne and others, 1992; Kopp and others, 2000). This boundary, similar to a number of other NE–SW trending major faults in the Afro-Arabian plate (for example, the Dibba and Masirah faults; see below) is here considered to be a remnant transform fault related to the initial opening of the Neo-Tethyan ocean.

Subdivisions

The Zagros orogen consists of three distinctive parallel tectonic zones (figs. 1 and 2). To the northeast, the *Uremiah–Dokhtar magmatic assemblage* (UDMA) is a relatively narrow (50–80 km), linear belt of intrusive and extrusive rocks (Schroeder, 1944; Stocklin, 1968a, 1974; Falcon, 1974; Alavi, 1980, 1994; Berberian and others, 1982), thrust on their northeastern side onto the associated retroarc/retroforeland deposits, and transected by a number of right-lateral strike-slip faults (fig. 1). The assemblage includes a thick (~ 4 km) pile of calc-alkaline (ensialic in the southeast and ensimatic in the northwest) and highly potassic alkaline (locally shoshonitic) andesites, dacites, andesibasalts, trachyandesites, and rhyolites intruded by diorites and various granitoids that are associated with extensive pyroclastic layers (mostly bedded tuffs and agglomerates), siliciclastic strata, and ignimbrites. The oldest rocks in the UDMA (the Shir Kuh granitoid complex) are of Early Cretaceous age (Nabavi, 1972; Hajmolla-Ali, 1993; Hajmolla-Ali and others, 2000). Lower and Upper Cretaceous interlayered lava flows and pyroclastic strata are reported from the central and northwestern parts of the assemblage (Bolourchi, 1979; Alavi-Naini and Hajian, 1982). The youngest rocks in the assemblage include Recent lava flows and pyroclastic layers. Regional geological considerations suggest that maximum intensity of magmatism may have occurred during Eocene times.

The UDMA is interpreted to be a subduction-related magmatic arc formed by the northeastward movement of the Neo-Tethyan oceanic plate beneath the Iranian plates (Takin, 1972; Dewey and others, 1973; Haynes and McQuillan, 1974; Falcon, 1974; Pamic and others, 1979; Alavi, 1980, 1994; Berberian and others, 1982).

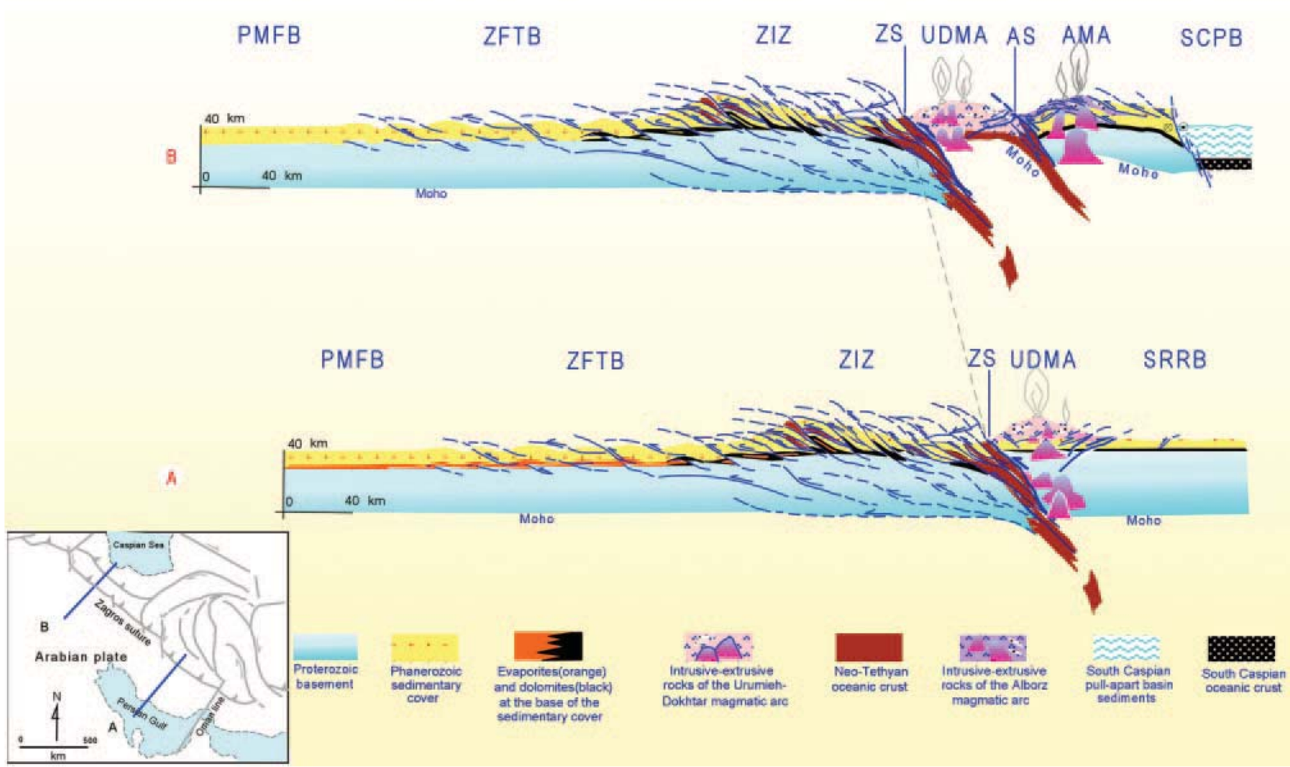

Fig. 2. Two schematic cross sections across the Zagros orogen, showing interrelationships of the major tectonic zones. For description of the tectonic zones, see the text. AMA– Alborz magmatic assemblage; AS– Alborz suture; PMFB– Persian Gulf–Mesopotamian foreland basin; SCPB– South Caspian pull-apart basin; other abbreviations as in figure 1.

Southwest of the UDMA, the *Zagros imbricate zone* (ZIZ) includes both the "Sanandaj–Sirjan zone" and the "Zagros thrust zone" of Stocklin (1968a, 1974) (figs. 1 and 2). The ZIZ forms the core of the orogen and consists of thrust systems ranging in age from Late Cretaceous to Recent (Alavi, 1994). The thrusts have transported various interleaved metamorphosed and non-metamorphosed Paleozoic, Mesozoic, and Cenozoic strata (including continental shelf, slope, and rise facies) and magmatic units, as well as ophiolite complexes, as either single thrust sheets or composite duplex structures from the northeast, where the intensity of deformation has reached its maximum, to the southwest, where rock successions within each thrust sheet have remained less-strained and largely intact. Locally, among the transported rocks, there are thrust slivers which consist of Cretaceous–Tertiary pyroclastic and volcaniclastic strata, interpreted to be remnants of the Uremiah–Dokhtar forearc basin deposits destroyed during the collisional events. Geological mapping of the ZIZ reveals that in general the ages of stratigraphic units carried by the thrust sheets become younger from NE to SW; that is, the Paleozoic rocks are predominantly exposed in the northeast, whereas the Mesozoic rocks occupy the central parts, and Cenozoic successions are in the southwest (for example, Alavi, 1996a). Large exhumation ($>$6 km) has removed the younger stratigraphic units of the belt in the central and northeastern parts so that preserved Cenozoic successions are rare. Because of structural complexity, the amount of horizontal shortening is uncertain, but is roughly estimated to be $>$ 50 percent.

Following Stocklin (1968a), several workers have considered Stocklin's "Sanandaj–Sirjan zone" as an integral part of the "central Iranian block". The boundary between this zone and his "Zagros thrust zone" (referred to as the "Main Zagros Thrust") (fig. 1) has been regarded as the suture between the Afro-Arabian continent and the Iranian plates (for example, Takin, 1972; Dewey and others, 1973; Haynes and McQuillan, 1974; Ricou, 1976; Berberian and King, 1981; Kadinski-Cade and Barazangi, 1982; Dercourt and others, 1986; Şengor, 1990; Hessami and others, 2001; Talebian and Jackson, 2004). However, the results of more than two decades of extensive geological investigations in various parts of the ZIZ (for a review see Alavi, 1994), followed by more recent mapping and structural analyses along the so-called "Main Zagros Thrust" (Molinaro and others, 2004, 2005), and the fact that "Main Zagros Thrust" does not show seismic and/or geodetic activity (Tatar and others, 2002), argue against these assignments. Instead, this zone should be considered as the northeastern passive continental margin of the Afro-Arabian continent. Here, following this latter interpretation, the northeastern boundary of the ZIZ, where the magmatic assemblage is juxtaposed against the ZIZ, is considered to be the suture zone between the Afro-Arabian and Iranian plates (ZS in figs. 1 and 2). This suture zone is characterized by structural depressions (for example, the Sirjan, Gav Khooni, and Arak depressions), ophiolitic mélange complexes, gold-bearing greenschists, and intense structural deformation (Alavi, 1994).

The *Zagros fold-thrust belt* (ZFTB) (the Zagros "simple folded zone" of Falcon, 1974), with an average width of ~300 km, extends parallel and to the southwest of the ZIZ (fig. 3). It constitutes the external, hence less-strained, part of the orogen. In contrast with the ZIZ, in which exposed structures are predominantly thrust faults, the ZFTB is distinguished by its long (up to ~150–200 km), en echelon, "whale-back" anticlines, which are spectacularly displayed on satellite images. The boundary between the two zones (chosen arbitrarily, as shown in figs. 1 and 3) is gradational. The imbricate overlapping thrust sheets of the southwestern ZIZ gradually disappear beneath the large-scale folds of the ZFTB.

In the ZFTB, a cover sequence composed of ~7 to 12 km of uppermost Neoproterozoic and Phanerozoic strata, intruded by nearly 120 salt diapirs in the southeast (fig. 3), rests on a Precambrian basement. The cover successions with their underlying basement rocks are progressively deformed from northeast to southwest. Sedimentary characteristics of the growth strata and embedded progressive unconformities in the orogen-derived siliciclastic stratigraphic units indicate late Cretaceous and Cenozoic development of the structures (Alavi, 2004). Tilted unconsolidated recent sediments on the limbs of the growing folds (for example, Lee and Falcon, 1952; Oberlander, 1965; Vita Finzi, 2001), active salt diapiric extrusions induced by fault movements (for example, Harrison, 1930; Stocklin, 1968b; Kent, 1979; Talbot and Alavi, 1996; Talbot and others, 2000), and seismic activity along the belt (for example, Maggi and others, 2000; Tatar and others, 2004) indicate that structural deformation continues. Seismicity maps of the region shows that the distribution of earthquake epicenters define a zone of about 200 km width, whose southwestern boundary coincides with the Zagros deformational front (ZDF) (for example, Ni and Barazangi, 1986). Focal depths of the earthquakes are reported to be largely from 10 to 20 km (Niazi and others, 1978; Maggi and others, 2000; Tatar and others, 2004).

A topographic feature in the ZFTB is the traditionally-known "mountain front flexure" (MFF), along which elevation increases sharply (fig. 3). This line separates the elevated mountainous inner highlands, exposing the deeper parts of the anticlines, from the outer lowlands, in which most structures are either hidden under Quaternary molasse or expose only the youngest Neogene strata. Along the strike of the belt, the width of the outer lowlands varies from ~50 to 70 km in Lorestan and Fars provinces to >150 km in Khuzestan and Karkuk (Iraq) regions (figs. 1 and 3). Northeast of the MFF, the inner highlands of the ZFTB, like many other fold-thrust belts of the world [for example, the Appalachian of eastern North America (Rankin, 1976; Thomas, 1977; Marshak and others, 1992), the Cordilleran of western U.S. (Mitra, 1997; Paulsen and Marshak, 1999), and the Western Himalaya in Pakistan (Lillie and others, 1987; Jadoon and others, 1992)], are segmented by pre-Zagros reactivated basement-rooted faults, which strike at high angles to the main Zagros trend (NW–SE), and constitute two lobate salients alternating with two recesses (figs. 1 and 3). In this paper, the salients and recesses of the ZFTB from southeast to northwest are referred to as: Fars salient (FS), Dezful recess (DR) (formerly "Dezful embayment"), Lorestan salient (LS), and Karkuk recess (KR). This paper focuses on the first three segments in the Iranian ZFTB; the fourth segment, the Karkuk recess (KR) of Iraq, will not be discussed here owing to lack of sufficient data.

Evolution

The Zagros orogen is a product of closure of the Neo-Tethys. It is superimposed upon the continental shelf/slope and platform on the wide northeastern margin of the Afro-Arabian continent. The Zagros orogeny involved three major sequential geotectonic events (Alavi, 1994). These events, shown in a series of schematic time-slice paleogeographic maps (fig. 4) are, from oldest to youngest: 1) Subduction of the Neo-Tethyan oceanic crust beneath the Iranian plates, 2) emplacement of slivers of oceanic crust over the Afro-Arabian continental margin, and 3) collision of the Afro-Arabian continental margin with the Iranian plates.

First, the closing stage of the Neo-Tethys began during the latest Jurassic–Early Cretaceous. Northeastward subduction of oceanic crust and its underlying upper mantle under the Iranian plates was accompanied by intense magmatism, forming the UDMA. The Iranian plates were partly continental (to the SE) and partly oceanic (to the NW). Consequently, subduction of oceanic crust beneath them created a mainly ensialic continental-margin type magmatic arc in the southeast and an ensimatic island arc to the northwest (fig. 4A). The arc assemblage (UDMA) was linear and narrow along the strike of the orogen, indicating that the Wadati–Benioff zone of the subduction system may have been steep or subvertical.

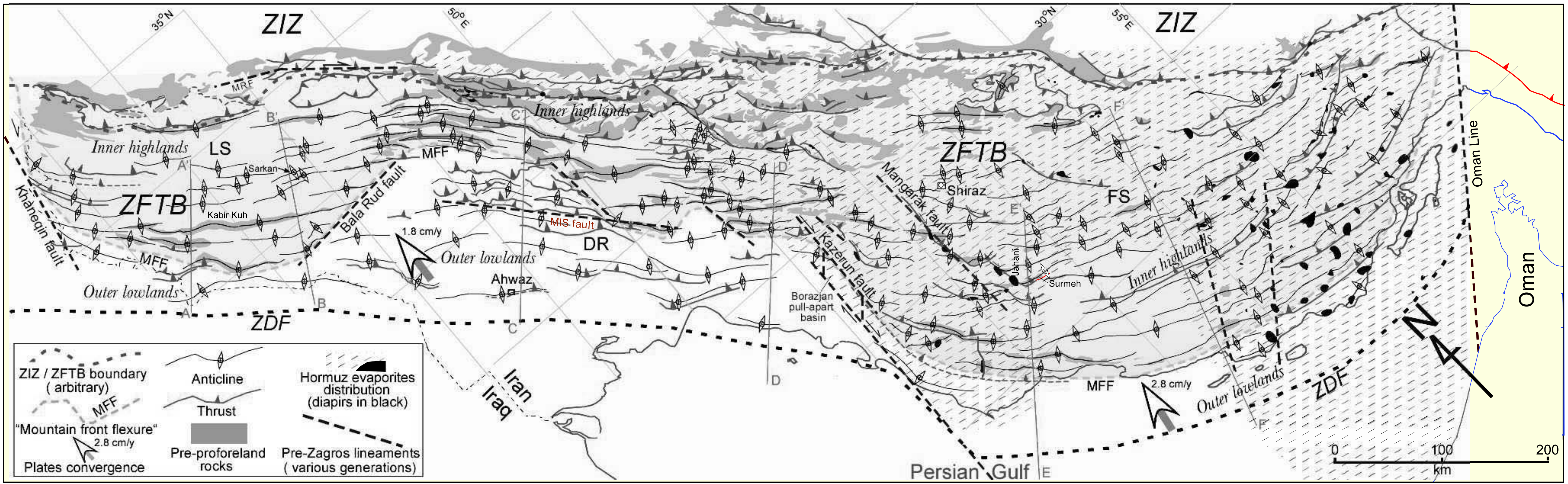

Fig 3. Structural map of the ZFTB in Iran. Abbreviations as in figure 1. Locations of the six cross sections in figures 13–18 are indicated.

Second, during the latest Turonian (~90 Ma) stacked thrust sheets, composed of oceanic crust and upper mantle rocks (ophiolites), were emplaced ("obducted") onto the northeastern Afro-Arabian passive continental margin (the future ZIZ and ZFTB) (fig. 4B). The latest Turonian regional unconformity, which marks a drastic change from a continental shelf tectonosedimentary setting to a relatively narrow and elongated proforeland basin, records the initiation of this "obduction" event (Alavi, 2004). The emplacement of many slices of ophiolites, which may have continued until late Campanian (~75 Ma), loaded the continental margin and resulted in flexural bending of the lithosphere. This formed the Zagros proforeland basin (ZFB in fig. 4B), whose siliciclastic sediments (Amiran Formation) were largely derived from the ophiolites.

Third, in the middle Maastrichtian (~68 Ma), after emplacement of the ophiolites, the Afro-Arabian continent collided with the UDMA (fig. 4C). In the overriding Iranian plates, the collision increased differential rotation of the Iranian minicontinents ("blocks") (for example, Soffel and Forster, 1980, 1984; Wensink, 1983; Schmidt and Soffel, 1984; Alavi and others, 1997). Collision also shortened the magmatic arc (UDMA) and its associated Saveh–Rafsanjan retroforeland basin (SRRB) by thrust faulting. It also started the destruction of the forearc. Within the arc proper, volcanic and plutonic activity rejuvenated or intensified. With strong involvement of the continental crust, magmatism became more alkaline and shoshonitic. In the northwest, the effect of collision was shortening across a remnant part of the Neo-Tethys, which had been left as a marginal basin behind the UDMA (fig. 4C). Contraction of this marginal basin as part of one of the overriding Iranian plates, namely the Alborz plate, resulted in development of a new subduction system. Oceanic crust and underlying mantle began to underthrust beneath the continental part of the Alborz plate. This new subduction system (fig. 4D) created its own ensialic magmatic arc, the Alborz magmatic assemblage (AMA) (Alavi, 1996b). Subduction of the Neo-Tethyan marginal sea beneath the Alborz continental margin lasted from latest Cretaceous to Early Eocene, when, after consumption of oceanic crust, the UDMA started to collide with the AMA. At this time, a new collisional orogen, an epioceanic-arc–epicontinental-arc type, began to develop. This process, which initiated in the Eocene and has continued until present time, has acted as a determinant factor in the structural evolution of the central and western Alborz.

To the southwest of the UDMA, in the Zagros imbricate zone (ZIZ), as a result of the collision, processes such as metamorphism, S-type granitoid plutonism (Valizadeh and Cantagrel, 1975), intense structural deformation, and accumulation of coarse to fine siliciclastic sediments affected the entire region. Several generations of thrusts breached the pre-existing ophiolite masses, and carried many structural sheets. These sheets were composed of Phanerozoic stratigraphic units and presumably their underlying basement rocks. Thrust sheets were carried from the suture zone towards the southwest, and stacked to build a mountain range (Alavi, 1994; Alavi and Mahdavi, 1994). This mountain range further loaded the underlying Afro-Arabian plate and became a major source of polymict siliciclastic deposits in the proforeland basin to the southwest (Alavi, 2004).

The collisional mountain-building that began in the middle Maastrichtian (~68 Ma) has continued with variable intensity until present. Episodic contractional movements in a transpressional regime have dominated. Shortening of continental crust mainly by thrust faulting and folding, accompanied by subordinate strike-slip displacements, first affecting the upper crustal levels and then propagating through time to lower levels, has been the dominant style of deformation. Intense crustal shortening has caused southwestward migration of the mountain range as a gigantic orogenic wedge. Thrust faults in the interior parts of the orogen, where seismic activity is

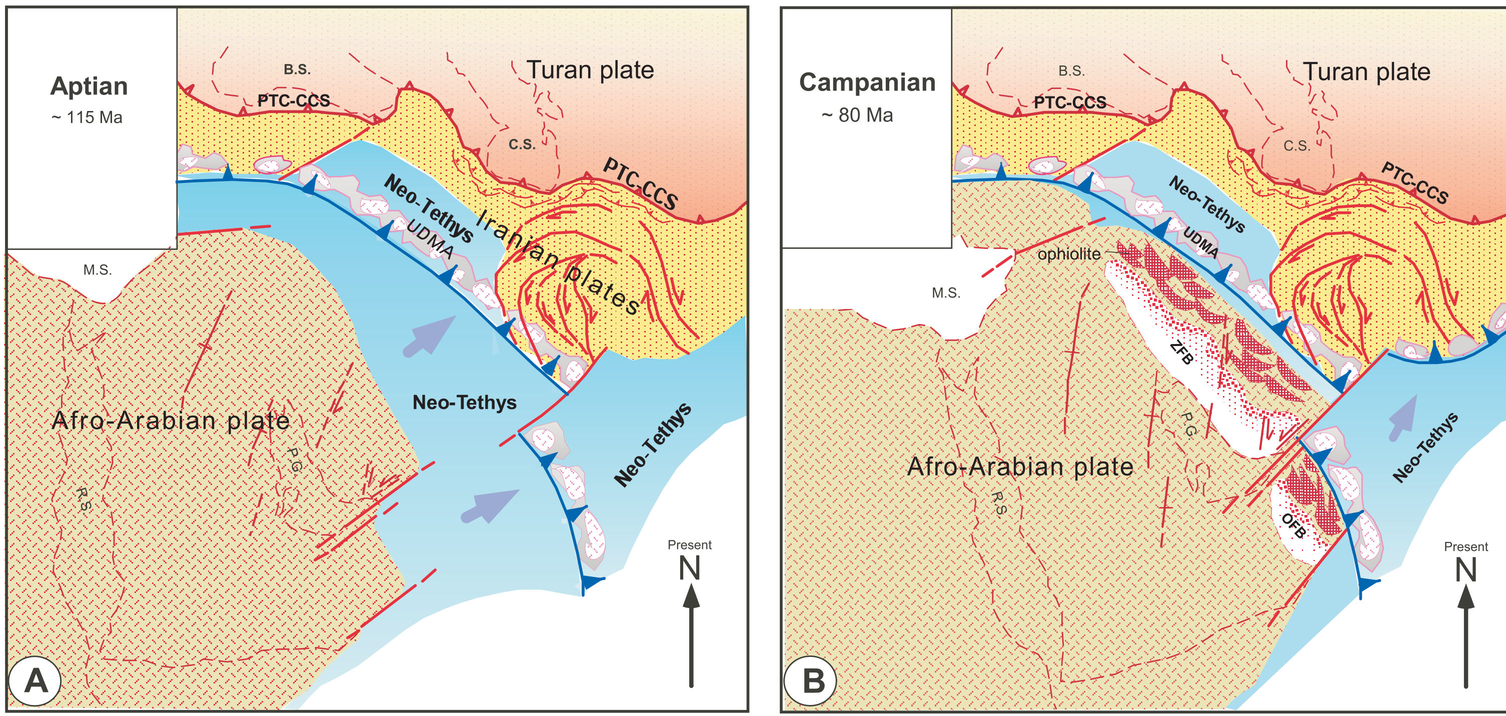

Fig. 4. Schematic paleogeographic maps showing closure of the Neo-Tethys and evolution of the Zagros orogen. For explanation see the text. AMA– Alborz magmatic assemblage; B.S.– Black Sea; C.S.– Caspian Sea; M.S.– Mediterranean Sea; OFB– Oman foreland basin; P.G.– Persian Gulf; PTC-CCS– Paleo-Tethyan continent–continent collisional suture; R.S.– Red Sea; UDMA– Urumieh–Dokhtar magmatic assemblage; ZFB– Zagros foreland basin.

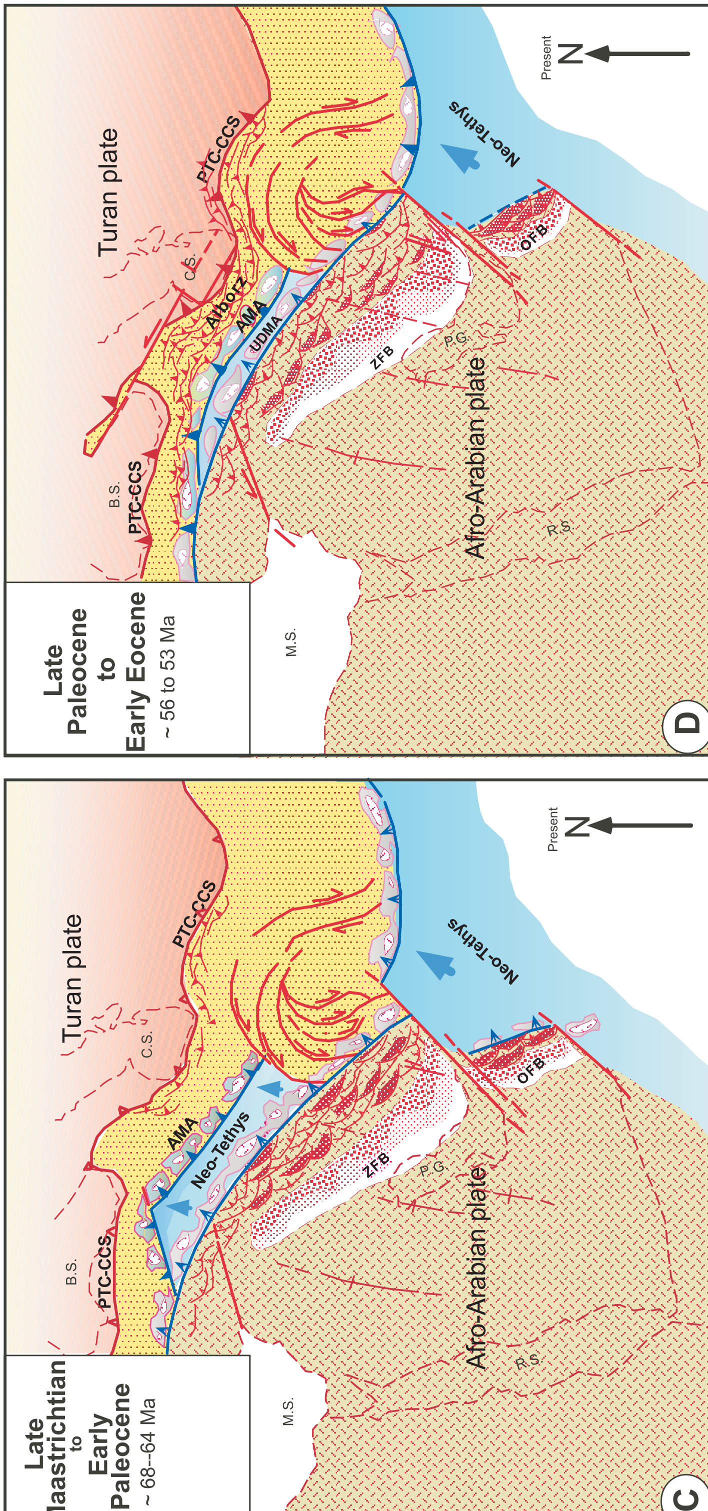

Fig. 4 (continued)

negligible, presumably became locked so that recent deformation has been concentrated in the outermost part of the orogen.

GEOLOGICAL OBSERVATIONS

Any regional cross-section across the ZFTB must account for the following observations.

Plate Setting

The ZFTB forms the upper part of the northeastern present-day Arabian continental margin. The Arabian continental crust has a thickness ranging from ~36 km near the Red Sea (Rodgers and others, 1999) to ~55 km in central parts of the ZFTB (Al-Amri, 1999; Hatzfeld and others, 2003). In the southwestern part of the ZIZ, the crustal thickness is estimated to be ~60 km (Dehghani and Makris, 1983; Snyder and Barazangi, 1986). The average thickness of the Arabian crust may be considered as ~40 km (Mooney, 1985; Badri, 1991; Alavi, 1994); the thickness of the Arabian plate is suggested to be ~120 km (Reches and Schubert, 1987).

The Arabian and Eurasian (including Turan and Iranian) plates are converging in a NNE–SSW direction (DeMets and others, 1990, 1994; McCluskey, 2000; Sella and others, 2002). The convergence rate varies along the strike of the Zagros orogen. It ranges from ~1.5 to ~1.8 cm/yr (McCluskey, 2000) in the northwest (closer to the Euler pole near the Libyan coast in the northern part of the African plate) to ~2.8 cm/yr (Sella and others, 2002) near the Oman Line to the southeast. Recent GPS-geodesic data suggest a convergence rate of ~1 cm/yr for the northwestern part of the Fars salient (Tatar and others, 2002; Vernant and others, 2004).

The Arabian and Iranian plates converge at an angle of ~60° to the collisional plate boundary. So, convergence resolves into two components: one is parallel to the NW–SE Zagros trend at ~0.3 cm/yr (Vernant and others, 2004), driving slip on right-lateral strike-slip faults such as the Main Recent Fault (Tchalenco and Braud, 1974) and the Kazerun and Mangarak fault systems (Baker and others, 1993; Talbot and Alavi, 1996) (fig. 3). The other component is at right angles to the Zagros trend at ~0.65 cm/yr (Vernant and others, 2004), producing the dominant Zagros contractional folds and thrusts.

Basement

Basement involvement.—Deformation of the ZFTB is classically considered to be thin-skinned, with the cover detached from the underlying basement along a "thick" layer of Hormuz evaporites and affected by mainly buckle folds and thrust faults (Stocklin, 1968a; Falcon, 1974; Evers and others, 1977; Huber, 1977; Mapstone, 1977, 1978; Verrall, 1978; Verrall and Christophy, 1978). Seismicity, however, indicates that the basement is involved in the deformation (for example, Nowroozi, 1972; Bird, ms, 1976; Jackson and others, 1981; Ni and Barazangi, 1986; Maggi and others, 2000; Tatar and others, 2004). Existence of basement rocks as exotic blocks (granitoids, basalts, metasediments, and ultramafic rocks) embedded in the Hormuz evaporites (Kent, 1979; Gansser, 1992; Alavi, 2004), which have surfaced by diapirism, also suggests faulting and involvement of the basement (Alavi, 1994). McQuillan (1991), Talbot and Alavi (1996), Hessami and others (2001), and Bahroudi and Talbot (2003) noted the deflection of the Zagros structures along pronounced pre-Zagros lineaments trending at high angles to the Zagros NW–SE strike, and suggested they are basement faults reactivated during Zagros deformation. Moreover, the total magnetic intensity map of the region (fig. 5) displays distinctive NW–SE trending anomalies parallel to the Zagros structural grain. Because of the absence of Phanerozoic magmatic activity and any stratigraphic unit significantly rich in magnetic minerals in the ZFTB, these anomalies are attributed to the basement (Morris, 1977; Orbell, 1977). All these data and

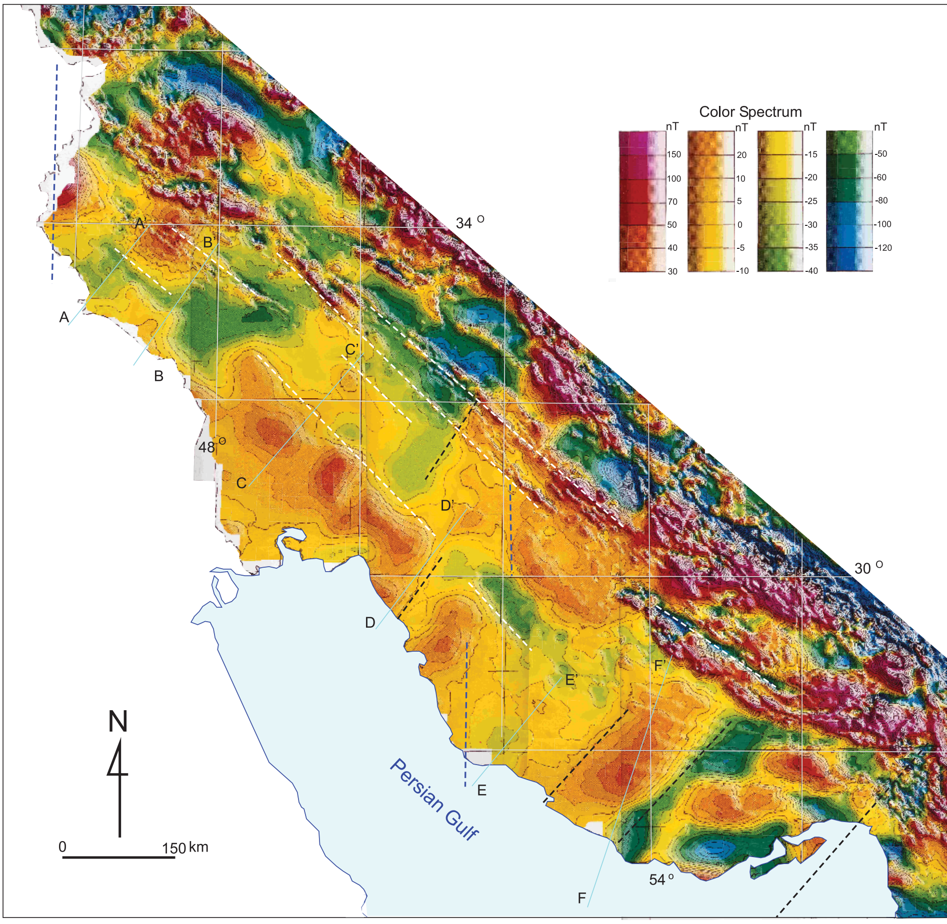

Fig. 5. Total magnetic intensity map of the ZFTB (courtesy of the Geological Survey of Iran). Major lineaments represent basement-rooted pre-Zagros structures. Locations of the cross-sections shown in figures 13–18 are also indicated.

observations indicate that the basement in the ZFTB is part of the active orogenic wedge.

Type and morphology.—No Precambrian basement is exposed in the ZFTB, but exotic blocks of latest Neoproterozoic age (mentioned above) embedded in the Hormuz evaporites are attributed to the basement (Kent, 1958; Gansser, 1992; Alavi, 2004). The nearest exposures of Precambrian basement are mapped in central Iran (Saghand area) (Ramezani, 1997; Ramezani and Tucker, 2003). The basement of the ZFTB is most probably the northeastward extension of the eastern minicontinent within the Precambrian continental mosaic (for example, Stoesser and Camp, 1985; Johnson, 1996; Genna and others, 2002) of the Arabian plate. This eastern minicontinent is distinguished by its low- to moderate-intensity, broad wavelength magnetic anomalies (Johnson and Stewart, 1995).

The basement/cover interface morphology in the ZFTB is critical to understand its structural development. The depth-to-magnetic basement map by Kugler (1973) and Morris (1977) for the Iranian ZFTB shows several magnetic-basement "highs" and

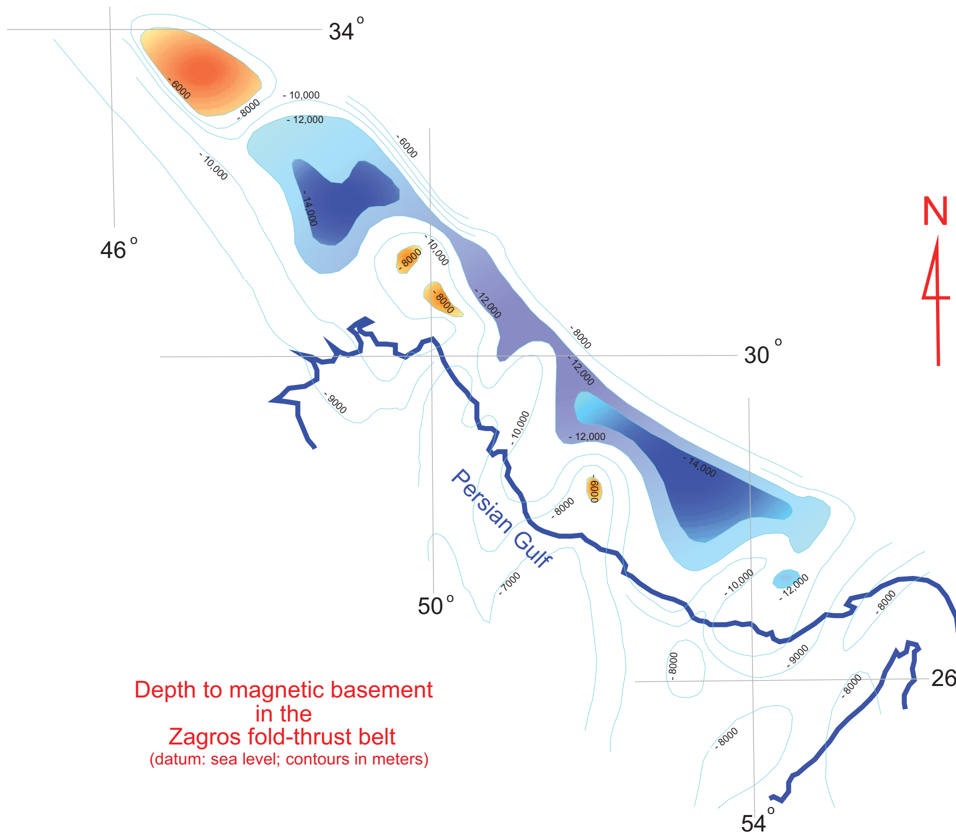

Fig. 6. Top-magnetic basement map of the ZFTB (after Morris, 1977). Blue and orange shades indicate basement "lows" and "highs", respectively.

"lows" (fig. 6). The map suggests that in the north and northwestern parts of the Dezful recess and northeastern parts of the Fars salient, the top of basement is low, and that the cover is up to ~15 km thick. Stratigraphic data indicate that the total thickness of the cover (sum of the thicknesses of stratigraphic units measured at their type sections) is ~9 km in the Dezful recess and ~7 km in the Fars salient (Alavi, 2004). On this basis, the cover in the northeastern Fars salient and north and northwestern Dezful recess may have been thickened by thrust faulting.

Structures.—The aforementioned reactivated pre-Zagros structures in the basement of the ZFTB (fig. 2) are addressed by several workers (Falcon, 1974; Iranpanah, 1989; McQuillan, 1991; Barzegar, 1994; Talbot and Alavi, 1996; Bahroudi and Talbot, 2003). These structures constitute a part of the complex structural fabric that is recognized in the continental basement of the Arabian plate (fig. 7) (for example, Johnson and Stewart, 1995; Husseini, 2000; Genna and others, 2002). They are identified by their seismic activity, magnetic imprints, gravity anomalies, and reactivation of younger exposed structures. Here, they are assigned to three groups, attributed to three major geotectonic events, which have affected the Afro-Arabian plate.

The first group includes the generally N–S trending lineaments which are thought to originate from the Pan-African orogeny (~670–570 Ma). Examples of these structures in the ZFTB are the Khaneqin, Kazerun, and Mangarak fault systems (figs. 3

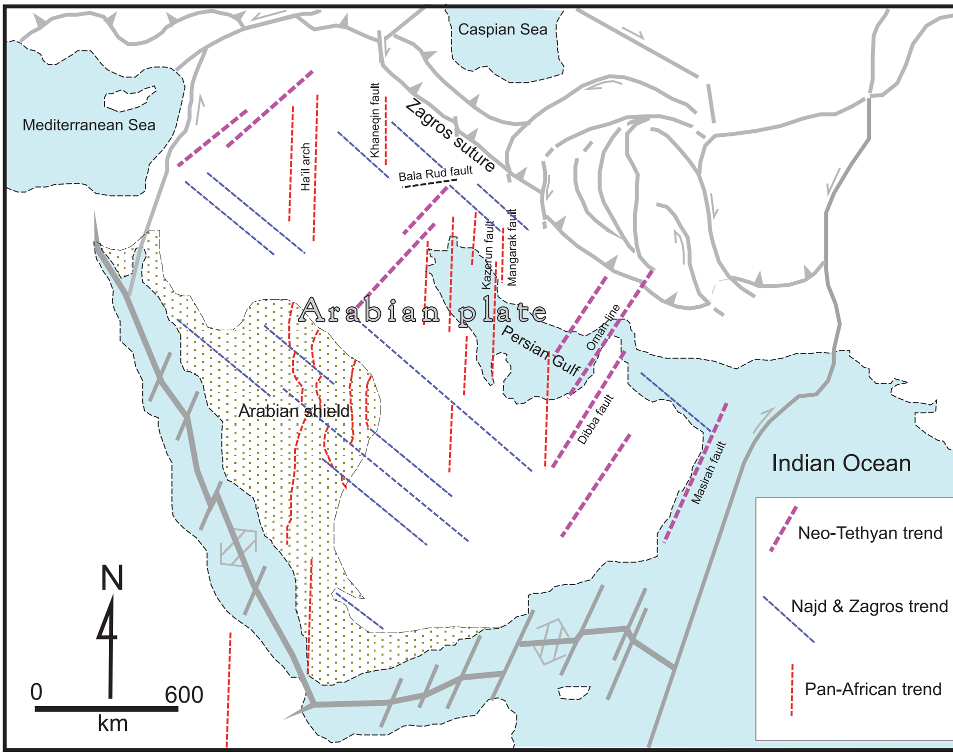

Fig. 7. Prominent basement-rooted lineaments in the Arabian continental crust.

and 7). In addition, several N–S trending gentle folds (or broad "arches") are attributed to the Pan-African structural grain superimposed by the Zagros folds near the Zagros deformational front to produce local broad domes by structural interference.

The second group comprises NW–SE trending lineaments attributed to the latest Neoproterozoic–earliest Cambrian Najd strike-slip tectonism (~550–540 Ma). Within the Arabian shield, these faults transect and displace the Pan-African structures. To the northeast, in the Zagros orogen, the Main Recent Fault (MRF) and other NW–SE trending blind faults delineated by magnetic anomalies [for example, the Masjed-i-Solayman (MIS) basement fault in fig. 3] may be reactivated faults of this category (figs. 3 and 7).

The third group consists of structures developed during the opening of the Neo-Tethys ocean in Permian and Triassic times. These structures form major NE–SW trending transfer/transform faults, such as the Oman Line, Dibba, and Masirah fault systems (fig. 7). The seismically active Bala Rud thrust (figs. 3 and 7) trends ~30 to 35° to the general trend of other structures in this group. This thrust may be either a member of this group that rotated during later (younger) deformation, or an exceptional basement structure reactivated by the Zagros orogeny.

Among the basement structures, the Khaneqin and Bala Rud fault systems, which bound the Lorestan salient to the northwest and southeast, and the Kazerun-Mangarak and the Oman Line fault systems, which form the northwestern and southeastern boundaries of the Fars salient, may be considered as transverse zones (in the sense of Thomas, 1990), forming relatively narrow bands rather than discrete lines. In these transverse zones, Zagros structures are either terminated or deflected. Thus, during the Zagros orogeny, the reactivated basement-rooted pre-Zagros fault systems bounding the salients acted as lateral ramps for the Zagros folds and their associated subjacent thrusts (Talbot and Alavi, 1996; Sepehr and Cosgrove, 2005). More recent kinematic analysis of fault slip data supports this interpretation (Authemayou and others, 2006).

Cover

Mechanical stratigraphy.—The latest Neoproterozoic–Phanerozoic cover strata of the ZFTB constitute a well-bedded, heterogeneous, strongly anisotropic succession displaying considerable lateral facies and thickness variations (Alavi, 2004). Weak incompetent layers can form detachments, whereas strong competent units deform largely in a brittle manner. This anisotropy has resulted in disharmonic deformation at several levels (O'Brien, 1950; Falcon, 1969). These authors, and many subsequent ones, have focused on only two evaporitic units, namely the Lower Miocene Gachsaran Formation and the latest Neoproterozoic–Lower Cambrian Hormuz "series" (O'Brien, 1950; Stocklin, 1968a; Falcon, 1969, 1974; Huber, 1977; Mapstone, 1977, 1978; Verrall, 1978; Verrall and Christophy, 1978; Bahroudi and Koyi, 2003). However, several other incompetent layers can provide ductile or frictional detachments. Figure 8 shows main lithostratigraphic units of the ZFTB, and summarizes their response to deformation based on the author's field observations. In addition to the Gachsaran and Hormuz units, other stratigraphic units contain evaporites: the Permian Dalan Formation, the Triassic Dashtak Formation, and the Jurassic Alan, Adaiyah, Gotnia, and Hith formations. Several other units with shale or thinly-bedded argrillaceous lime mudstones (marls) may well constitute major frictional or ductile decollements: the Silurian and Ordovician strata, the Triassic Aghar Formation, the Lower Jurassic Neyriz Formation, the Lower Cretacous Gadvan, Garau, and Kazhdumi formations, and the Surgah, Gurpi, and Pabdeh proforeland deposits (fig. 8).

Cover structures.—The ZFTB is distinguished from the Zagros imbricate zone (ZIZ) by its numerous generally NW–SE trending, doubly plunging folds. The anticlines are typically asymmetric, overturned, SW-verging, parallel style (with constant bed thicknesses), formed mostly by flexural slip mechanisms (Evers and others, 1977; Coleman-Sadd, 1978; Alavi, 1994) (figs. 3 and 9). The folds are predominantly fault-propagation folds (Suppe, 1985; Suppe and Medwedeff, 1990; Mitra, 1990) or fault-bend folds (Suppe, 1983). Their short wavelengths and small amplitudes suggest shallow subjacent thrusts. In the northeastern parts of the belt, folds are older and closed or tight (locally isoclinal) with interlimb angles ranging from 0° to nearly 70°. Southwestward, anticlines become younger and more open (interlimb angles: ~110°–140°), and finally very gentle (interlimb angles: ~170°) and of late Pliocene to Recent age near the Zagros deformational front. Their aspect ratios (axial length to half wavelength ratios) are typically >10, which can be used to characterize them as "forced folds" (folds formed by the shape of a forcing member below) (Cosgrove and Ameen, 2000; Sattarzadeh and others, 2000). In aerial photographs and satellite images, the Zagros anticlines appear as "whale-back"-style, concentric folds. Field examination, however, reveals that folds are predominantly angular in the core and only nearly-rounded (composed of a number of straight segments) in the outer arc (fig. 9). In many places, folds have overridden adjacent structures by thrust faulting (Beydoun and others, 1992) to cover the intervening synclines partly or completely.

Variations from open, upright geometry to tight, and then to overturned forms along trend of the folds are common (fig. 10). The Sarkan anticline in Lorestan salient (figs. 3 and 10) is an upright open anticline in the southeast, changing to a tight overturned fold in the middle part, and to an open structure near the northwestern end.

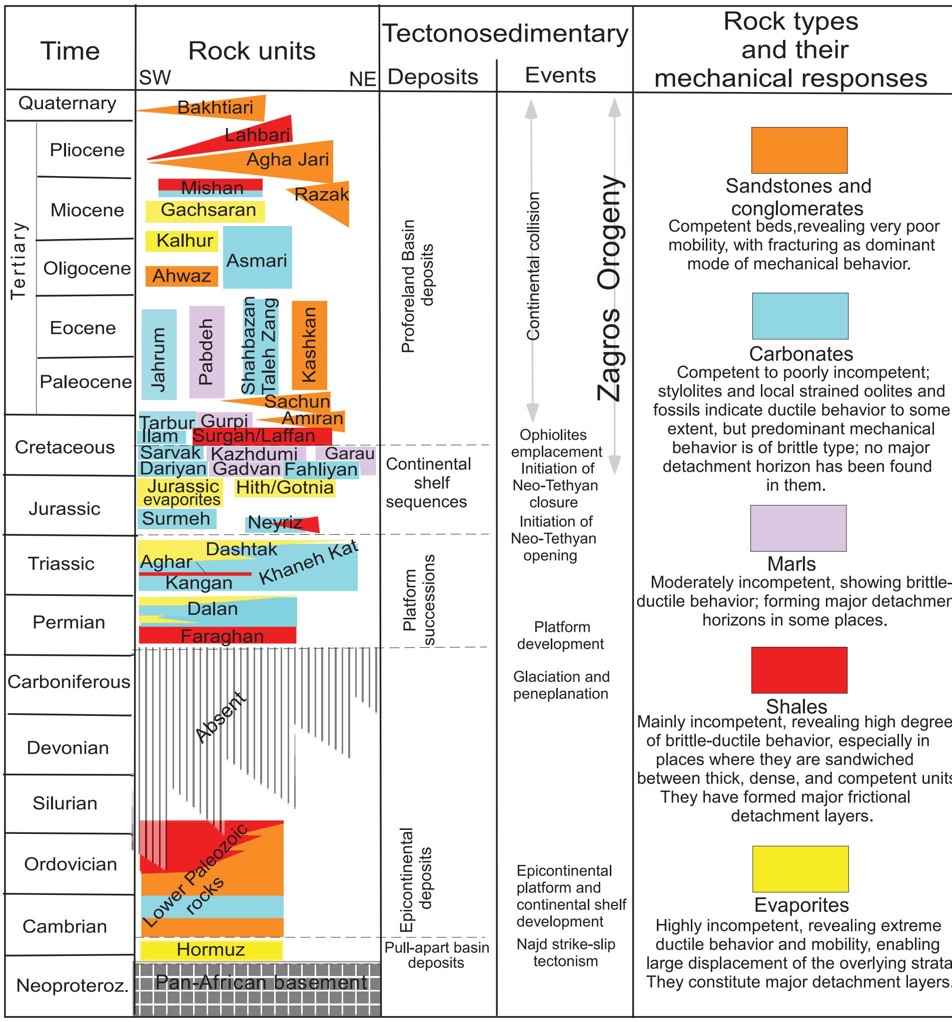

Fig. 8. Generalized mechanical characteristics of the lithostratigraphic units in the ZFTB.

Faults in the ZFTB are largely NE-dipping, SW-verging thrusts. They are mostly young and low-angle in the outer lowlands near the Zagros deformational front, but older and high-angle (most probably due to back-rotation resulting from displacement of rocks on the lower thrusts) in the inner highlands. Near the northeastern boundary of the belt, where elevation is generally ~2 to 3 km, large overlapping thrust nappes, composed of various cover strata and also ophiolite slivers, have been mapped (Gray, 1950; Braud, 1971; Hajmolla-Ali, 1989; Alavi and Mahdavi, 1994). Secondary fold-accommodation faults (in the sense of Mitra, 2002), as out-of-syncline thrusts or limb-wedge thrusts, mostly with only a few meters displacement, form common minor structures. Extensional normal faults with relatively minor displacements are mapped locally in anticlinal crests either parallel or at high angles to hinge surface traces. Major thrusts generally developed progressively in-sequence from northeast to southwest, as growth strata and progressive unconformities indicate. However, out-of-sequence thrusts formed also either as splays from the in-sequence thrusts or as new faults

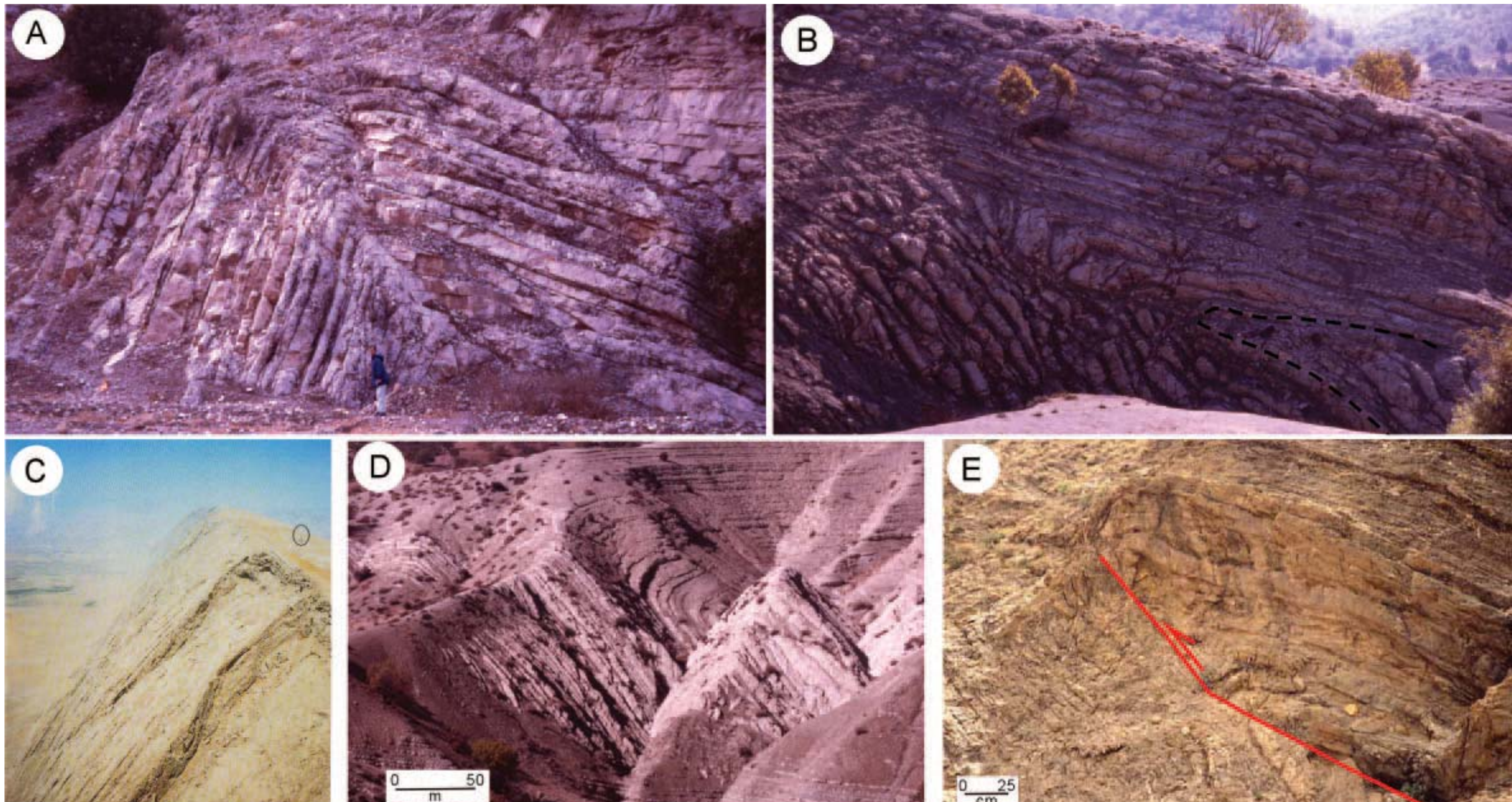

Fig. 9. Examples of the Zagros angular and rounded folds (all photographs are taken looking NW). (A) A fold with angular core and rounded outer arc in the Sarvak Formation. (B) An overturned, tight, angular fold in the Cretaceous limestones (the trees on the top of the outcrop are ~4 m tall). (C) An angular upright fold in the Asmari limestones (the drilling rig on the top of the structure is encircled for scale). (D) An overturned fold in the thin-bedded Cretaceous marly limestones. (E) An angular fault-propagation fold in the Cretaceous argillaceous carbonates.

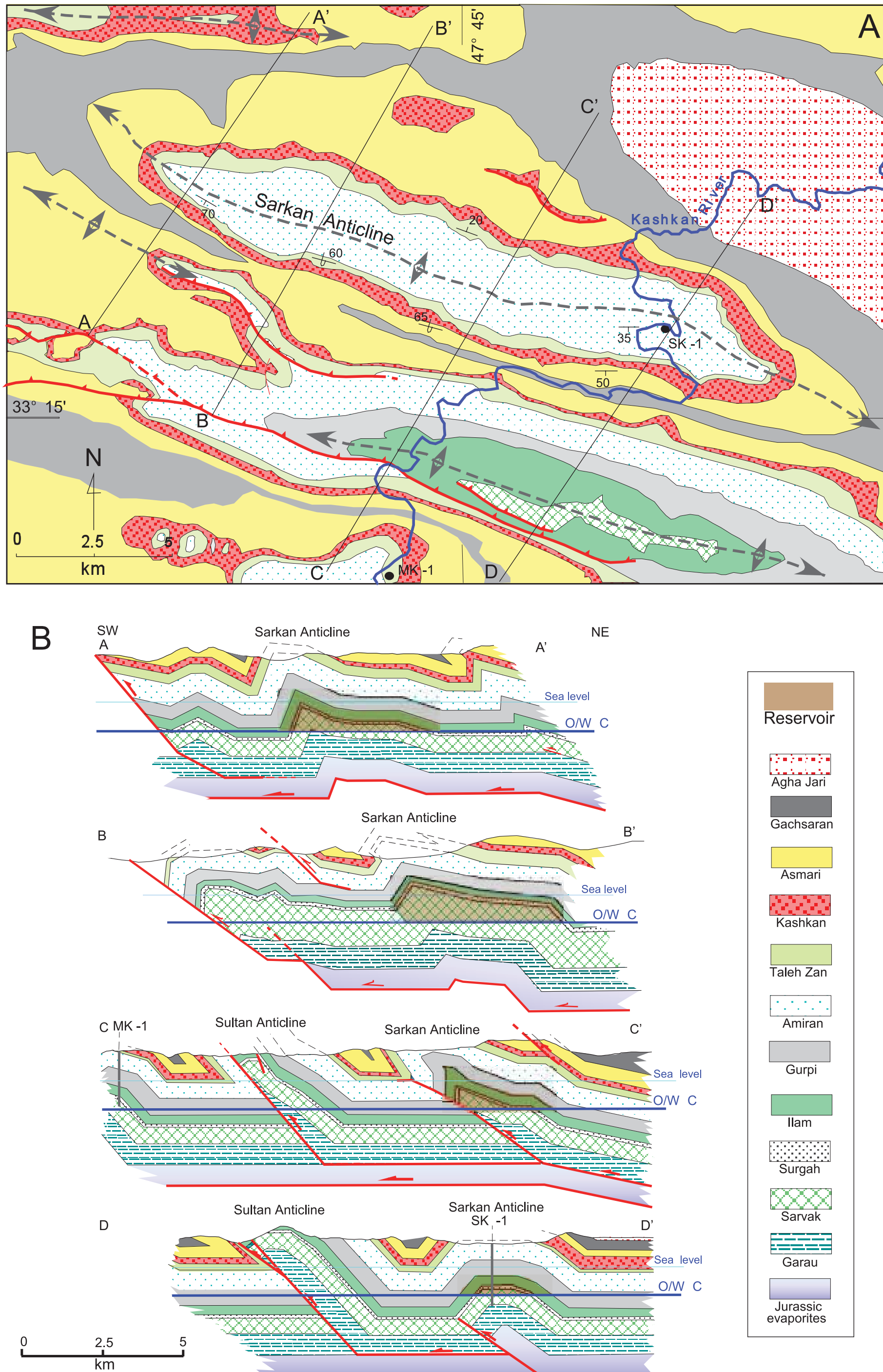

Fig. 10. (A) Generalized geologic map of the Sarkan anticline in the Lorestan salient (modified after Takin and Macleod, 1970) (fig. 2). (B) Serial cross sections across the Sarkan fold. The Sarkan oil-producing reservoir is distinguished (O/W C – oil/water interface in the reservoir).

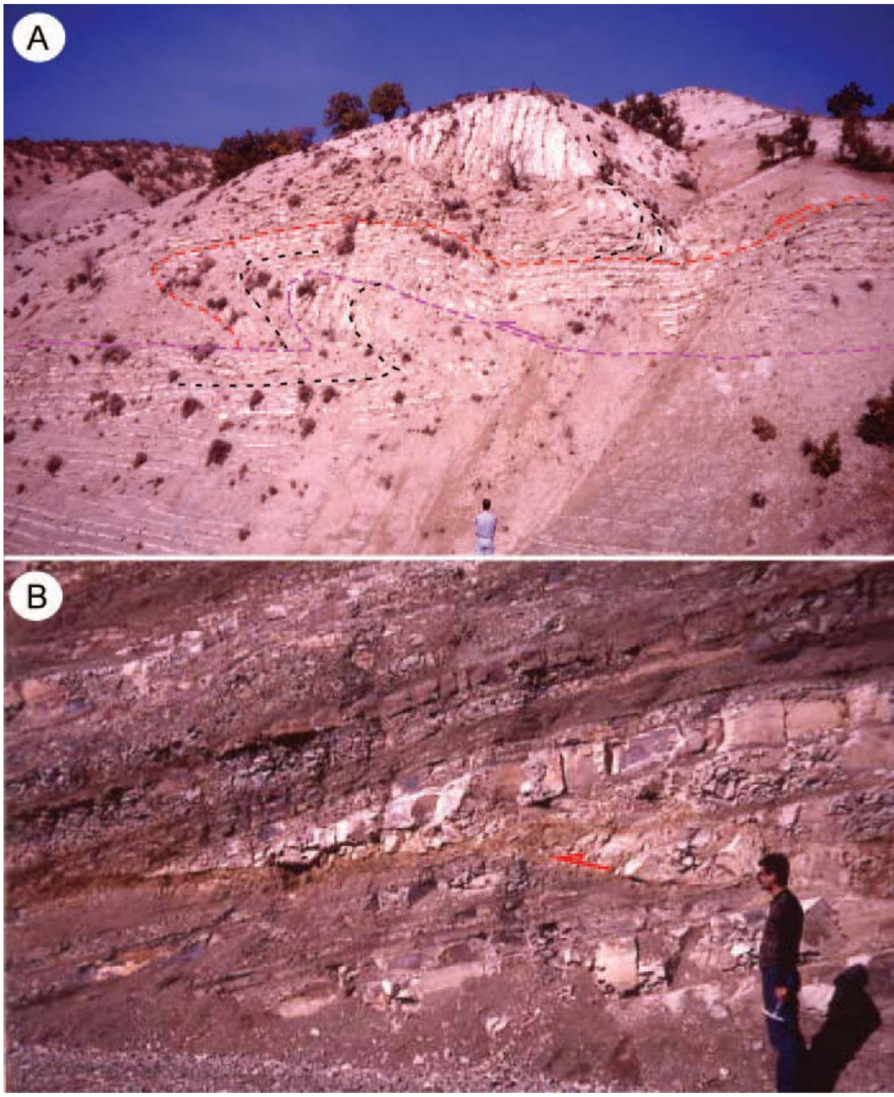

Fig. 11. (A) Folded thrusts (red and purple lines) in the Gurpi Formation (bedding traces in black). (B) A sharp thrust with a thin layer of cataclastic fault-rock.

breaching the older ones. The youngest stratigraphic units affected by the thrusts can be used to constrain the latest thrusts slips. Back-thrusts are rare, shallow, and typically have displacements less than a few hundred meters. Distinct lithofacies differences of time-equivalent stratigraphic units exposed across the thrusts in some places indicate displacements of several kilometers. Both field observations and borehole data indicate that some thrusts are affected by later folding (fig. 11A). Locally, small-scale ($\sim$10 m in length) thrust systems form hinterland-dipping duplex structures. Also, interacting blind thrusts have locally produced associated fold interference patterns (as discussed by Savage and Cooke, 2004), which are conspicuous on the geological maps.

Thrusts are commonly of brittle or brittle-ductile types. Those associated with evaporites, however, have behaved ductilely. Brittle thrust planes are either straight and sharp (fig. 11B), having very thin (~10–20 cm) cataclasites (mostly gouges) as fault-rocks, which reveal anastomosing shear planes, or diffuse with a rather thick (~10–30 m) zone of coarse, poorly consolidated fault breccia, which locally display slickensides and slickenlines.

Hormuz effects.—Hormuz evaporites facies are not ubiquitous in the ZFTB (for example, Harrison, 1930; O'Brien, 1957; Kent, 1979; Edgell, 1991; Talbot and Alavi, 1996) (fig. 3). These evaporites are known only in some parts of the Fars salient and in the highlands northeast of the Dezful recess. In the rest of the ZFTB, Hormuz is presumably replaced by mudrocks of either time-equivalent Jubaylah Group known in Saudi Arabia (Steinke and others, 1958; Hussaini, 1989) or younger lower Paleozoic Khabour Formation of Iraq (Alsharhan and Nairn, 1997). It is remarkable, however, that the Zagros structures, either where the Hormuz exists or where it is thin or absent, persistently display the same geometry. Indeed, many folds and thrust faults cross the Hormuz presumed facies boundary (fig. 3) without any change in their trend and style.

Experimental analogue modeling suggests that deformation of a brittle cover succession shortened on a thick viscous substrate forms doubly-verging thrusts and their associated basically symmetrical, box-type, pop-up folds (for example, Mulugeta, 1988; Liu and others, 1992; Cotton and Koyi, 2000; Smit and others, 2003). In the ZFTB, thrusts detaching on the Hormuz are distinctively asymmetrical and SW-vergent. Recent physical modeling by Costa and Venderville (2002) suggests that asymmetrical folds verging towards the foreland may develop if the backstop is deformable. These experiments also show that deformation migrates both forward and backward. Considering the Zagros imbricate zone as a deformable backstop for the ZFTB wedge, the experiments carried out by Costa and Vendeville (2002) may explain the asymmetry of the Zagros folds, but they do not explain why deformation in the ZFTB has propagated from northeast to southwest, nor do they explain why folds above where 'thick' Hormuz evaporites exist are similar to those formed elsewhere.

The thickness of the Hormuz interval is uncertain. Different authors have estimated thicknesses ranging from ~500 m to >2000 m. These estimations, however, are highly speculative. Even detailed geologic mapping of Hormuz diapirs in the Fars salient (for example, the Jahani salt plug about 110 km south of Shiraz; fig. 3) (Talbot and others, 2000), has not constrained the Hormuz thickness. Ductility of the evaporites has radically changed original thicknesses. Experimental modeling of fold-thrust belts shows that the thickness of the viscous substrate greatly affects how overlying structures form (for example, Davis and Engelder, 1985; Mulugata, 1988; Cobbold and others, 1989; Liu and others, 1992; Stewart, 1999; Cotton and Koyi, 2000). Thus, concepts derived from physical modeling should be applied only with caution to the ZFTB, because the original thickness of the Hormuz evaporites is so poorly constrained.

CROSS SECTIONS

With the above observations as a basis for structural interpretations, six retrodeformable cross sections at a scale of 1: 100,000 are constructed across different sectors (Lorestan, Khuzestan, and Fars) of the ZFTB of Iran (figs. 1 and 3). Each cross section extends from the essentially flat-lying undeformed strata to the southwest of the Zagros deformational front (ZDF) towards the northeast as far as data have permitted. The cross sections are restored to their pre-Zagros-deformation states. Because of high degree of variability in the stratigraphic thicknesses for each unit, a range of thicknesses is adopted (fig. 12). Construction of the cross sections and their restoration followed standard techniques (Dahlstrom, 1969; Suppe, 1983, 1985; Marshak and Woodward, 1988; Woodward and others, 1989; Mount and others, 1990; Epard and Groshong, 1993). Data used include the results of field work and laboratory structural analyses by the author as well as the following sources:

Rock units	Approximate thickness							Remarks
	Type section	Adopted for cross sections						
		A–A'	B–B'	C–C'	D–D'	E–E'	F–F'	
Bakhtiari	544	0–400	300	0–800	0–600	0–800	0–400	
Lahbari	1560	900	1000–1700	0–800	0–500	0–800	Absent	
Agha Jari	2938	0–900		400–2000	700–2300	0–850	400–1000	
Mishan*	703	Absent	0–150	150–300	0–500	0–600	100–650	*Including the Guri limestones.
Gachsaran*	455	150–500	200–900	300–1300	0–900	0–650	0–300	*Including the Champeh limestones.
Razak	767	Absent	Absent	Absent	Absent	Absent	0–250	
Kalhur	128							
Asmari	311	100–400*	200–300*	350–600*	100–500	0–450*	0–300*	*Collectively shown as the Asmari unit.
Ahwaz	21							
Jahrum	463	Absent	Absent	0–200	0–700	0–300	0–650	
Pabdeh	791	200–500	200–600	0–700	0–1000	*	0–450	*Included in the underlying Gurpi unit.
Kashkan	340	0–400	0–300	0–350	Absent	Absent	Absent	
Shahbazan/ Taleh Zang	509*	0–400	0–400	0–500	Absent	Absent	0–600	*Sum of thicknesses of the two units.
Sachun	1415	Absent	Absent	Absent	Absent	Absent	0–600	
Tarbur	522	Absent	Absent	Absent	0–600	Absent	0–500	
Amiran	893	0–500	0–950	Absent	Absent	Absent	Absent	
Gurpi	317	300–650	100–700	100–550	100–400	0–500		
Ilam	189	150–200	100–200	150–250	0–200	*	0–250	*Just a few meters, included in the Sarvak unit.
Surgah/Laffan	174	100–200	100	0–150	300–500	0–200*		*Only in the southwesternmost side of the ZFTB.
Sarvak	814	0–1000	600–1200	700–1000		150–400		
Kazhdumi	208	Absent	Absent	150–200*	150–300	75–150		
Garau	695	650*		600	Absent	Absent	500–600	*Including Lower Cretaceous siliciclastics and carbonates of Iraq that extend into Iran.
Dariyan	284	Absent	500–1400	0–450				
Gadvan	106	Absent		50–200	900–1050*	200–550		*Including the Fahliyan, Gadvan, Dariyan, and Zubair units.
Fahliyan	362	Absent		0–450				
Hith/Gotnia	136	650	650–1000	0–200	150–200*	0–100	50–150	*Only Hith exists.
Jurassic evaporites*	468			0–100	Absent	Absent	Absent	*Including the Najmeh, Sargelu, Alan, Mus, and Adaiyah units.
Surmeh	666	500	500	200–650	450–500	250–700	600–800	
Neyriz	286		100		200	100–250	100–150	
Dashtak (Triassic rocks*)	814							
Khaneh Kat (Triassic rocks*)	360	200–1000	200–1100	500–1000	700–1100	600–1000	500–700	*Thickness of each unit varies.
Aghar (Triassic rocks*)	16							
Kangan (Triassic rocks*)	178							
Dalan	748	600	600–700	650–800	700	900	600	
Faraghan	112		100		100	100–150	100–150	
Lower Paleozoic rocks*	?	1000	1400	1300–1400	1200	900	700	*Middle Cambrian to Lower Permian rocks.
Hormuz	?	300*		0–100		1000	1000	*Hormuz time-equivalent shales.

Fig. 12. Chart showing stratigraphic units and their thicknesses (in meters) adopted for the construction of cross sections shown in figures 13 to 18.

1. Geological maps of the Consortium Agreement Area, scale 1: 100,000 [65 sheets prepared and published by the Oil Service Company of Iran (OSCO)];
2. Geological maps of the ZFTB of Iran, scale 1: 250,000 [publications of the National Iranian Oil Company (NIOC)];
3. Geological map and cross sections of the Surmeh area, scale 1: 50,000 (Evers and others, 1977);
4. Geological Compilation Map of Southeast Fars, scale 1: 250,000 (Perry and others, 1965);
5. Borehole data and seismic reflection profiles (courtesy of NIOC);
6. Aeromagnetic maps of southwestern Iran, scale 1: 250,000 [courtesy of the Geological Survey of Iran (GSI)];
7. Total Magnetic Intensity Map of Iran (courtesy of GSI);
8. Top-magnetic Basement Map of the ZFTB (Morris, 1977).

Additionally, a detailed stratigraphic synthesis of the ZFTB (Alavi, 2004), several structure contour maps of the top of various stratigraphic units (for example, Asmari and Fahliyan formations) based on seismic surveys (Sbresini and Haydon, 1978), and a number of structural interpretations of the seismic profiles (Pattinson and Takin, 1971; Mapstone, 1977, 1978; Verrall, 1978; Verrall and Christophy, 1978) were consulted.

The cross sections display prominent facies and thickness variations of the stratigraphic units, geometry and interrelationship of the cover structures, morphological features of the cover/basement interface, and structural relations at various detachment horizons in the cover. They also provide shortening estimates across the ZFTB (table 1). These estimates are minimal because internal strains are not included in the restorations. Because of the uncertainty of the basement structural fabric, the

Table 1

Shortening estimates for the Lorestan, Khuzestan, and Fars sectors of the Zagros fold-thrust belt

Sector	Cross Section	Final Length (km)	Original Length (km)	Shortening (km)	Shortening (%)
Lorestan	A – A′	149	211	62	29.3
	B – B′	176	219	43	19.6
Khuzestan	C – C′	229	273	44	16.1
	D – D′	167.5	240	72.5	30.2
Fars	E – E′	184	228	44	19.2
	F – F′	348	442	94	27.0

cross sections are not extended to the fundamental regional detachment at the base of the wedge, which must be in the upper basement. The sections are not claimed to be verified unique solutions. Instead, they are more detailed, alternative interpretations to numerous previously-published cross sections which were constructed within various, justifiable or unjustifiable, conceptual Zagros geotectonic frameworks, and based on variable amounts of data, across either a part or the whole width of the ZFTB at different scales (see, for example, Mapstone, 1977, 1978; Verrall, 1978; Verrall and Christophy, 1978; Blanc and others, 2003; McQuarrie, 2004; Sherkati and Letouzey, 2004; Molinaro and others, 2005; Bosold and others, 2005; to mention a few). Comparisons between the cross sections presented here and the previously published ones, which require lengthy discussions, are beyond the scope of this paper. In the following subsections, only the most prominent structural features and interpretations displayed in the cross sections A – A′ through F – F′ are discussed.

Lorestan Structures

Cross sections A – A′ and B – B′ (figs. 13 and 14), with lengths of 149 km and 176 km respectively, display structures of the Lorestan salient and the outer lowlands to the southwest of it. In the lowlands, stratigraphic units in the Iraqi and Iranian boreholes are approximately 10.3 km thick. Towards the northeast, in the Lorestan salient, many units change facies or thicknesses; some pinch out. In the same direction, proforeland strata appear in the stratigraphic column. Except for the lowermost Paleozoic shales, including the Hormuz-equivalent [Hormuz(?) in cross section A – A′, fig. 13] strata, the rest of the Phanerozoic stratigraphy (including Ordovician shales) is partly exposed and partly penetrated by wells [for example, Kabir Kuh 1 drilled in the crestal zone of the Kabir Kuh anticline; for details see Alavi (2004)]. Here, exhumation reaches ~5.5 km.

A distinctive package of Jurassic strata, penetrated by several boreholes, forms a major decollement in the Lorestan salient. This package is composed of evaporites and shales interlayered with subordinate argillaceous limestones, ranging in thickness from ~1000 m in the southwest to ~650 m in the northeast (fig. 12). Balancing cross section B – B′ suggests that the lowermost Paleozoic Hormuz(?) shales also provide a major detachment horizon at the base of the cover. Other possible detachments include the Triassic evaporites at the top of the Dashtak Formation and the basal marls of the Upper Cretaceous Gurpi Formation (cross sections A – A′, fig. 13).

The structures in cross sections A – A′ and B – B′ are interpreted as a series of fault-bend and fault-propagation folds developed in response to slip on the subjacent

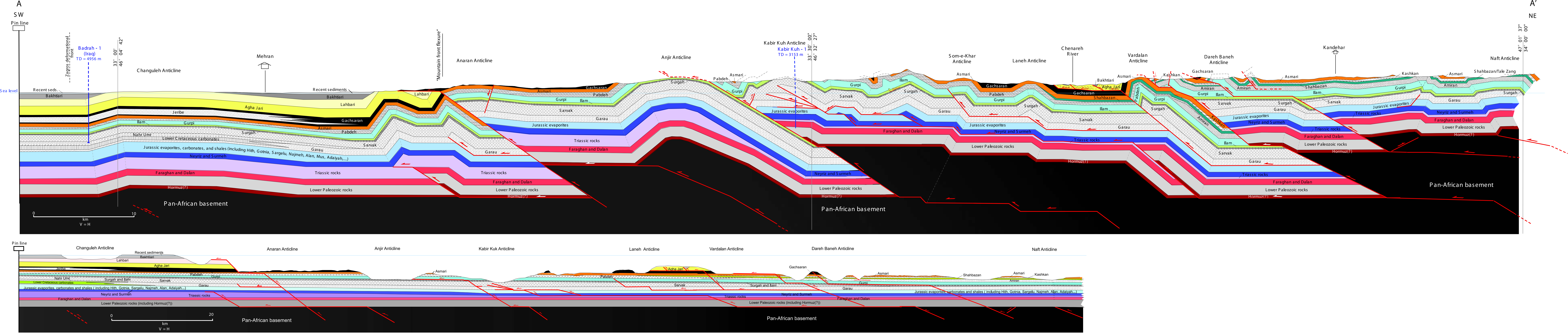

Fig. 13. Cross section A–A´ showing structures in the northwestern part of the Lorestan sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

Fig. 14. Cross section B–B´ showing structures in the southeastern part of the Lorestan sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

thrusts. Displacement on the thrusts is much higher in the NE, and decreases considerably to the SW. A prominent structure is the Kabir Kuh anticline, more than 200 km long. The total magnetic intensity map of the ZFTB (fig. 5) suggests that along this structure the basement is deeper than to the northeast and southwest. Borehole data in the northwest of the Lorestan salient (fig. 13), however, indicate that the lower Paleozoic strata are only ~4 to 5 km deep. Thus, the Kabir Kuh anticline is interpreted as a fault-propagation fold that has overridden the lower part of the cover by a thrust, which uplifted not only the cover but also a ~5 km thick slice of basement (fig. 13). Similar thrusts farther northeast and southwest of the Kabir Kuh anticline have created basement highs, manifested by high magnetic anomalies (fig. 5).

Towards the southeast, along the strike of the Kabir Kuh anticline, the basement-rooted thrust, which is considered to be responsible for the development of the anticline, presumably dies out. Here, balancing cross-section B –B′ (fig. 14) does not require any basement involvement, and therefore another interpretation, different from the one presented for the northwestern part of the anticline, is presented. In this southeastern part of the Kabir Kuh anticline, the fold is considered to be a result of slip on an out-of-sequence, out-of-ramp splay which originated on a thrust that developed along the basement/cover interface. Along-strike structural variations of the type suggested for the Kabir Kuh anticline are common in the ZFTB.

The sequence of development of some folds, as interpreted in the cross-section B – B′, implies that deformation has migrated forward by in-sequence faulting and backward by out-of-sequence faulting. During an earlier stage of progressive deformation, the basal cover thrust created the Kuh Siah and Kabir Kuh anticlines. Then, two basement-rooted thrusts, after breaching the basal cover thrust, used basal Jurassic evaporite detachments for propagation, and formed the Halush and Maleh Kuh anticlines to the northeast and on the backside of the previously developed structures. In a later stage of deformation, an out-of-sequence, basement-rooted thrust, breached the two pre-existing thrusts, then cut up stratigraphic section and, by using the top-Gachsaran detachment, produced the Sultan anticline on the northeastern limb (on the back) of the Maleh Kuh anticline. This type of forward and backward migration of deformation, which is a result of out-of-sequence thrusting, is inferred in other sectors of the ZFTB as well (see below), and is thought to be a common characteristic of Zagros structural evolution.

It is also notable that along the Kabir Kuh structure, the thickness of the Triassic carbonates decreases from almost 1000 m in the southwest to 200 m in the northeast. This reduction in thickness is attributed to the late Triassic extensional (normal) faulting and erosion associated with the opening stage of the Neo-Tethys. On this basis, one may hypothesize the possibility that the two high-angle reverse faults uplifting the basement beneath southeastern part of the Kabir Kuh and Halush anticlines (fig. 14) are reactivated Triassic normal faults.

In the northeastern part of cross section B – B′ (fig. 14), the Zangul structural sheet (nappe) overlies the lower Cretaceous Sarvak Formation. The Sarvak and Surgah formations do not exist here, and the Ilam and Gurpi formations show a drastic change in thickness across the basal thrust of the sheet. Therefore, stratigraphic units of the sheet cannot be tied to the underlying units. This indicates that the Zangul sheet was transported a great distance, so cannot be restored to its original pre-Zagros position.

Bulk shortening estimates vary along the strike of the Lorestan sector (table 1). Cross section A – A′ suggests a shortening of 29.3 percent or 62 km. Towards the southeast, based on cross section B – B′, shortening is estimated as 19.6 percent or 43 km.

Khuzestan Structures

The Khuzestan sector of the ZFTB includes the Dezful recess (DR) and the intensely folded highlands to the NE (fig. 2). Cross section C – C′ with a length of 229 km (fig. 15) and cross section D – D′ with a length of 167.5 km (fig. 16) show the structures. Here, the facies and thicknesses of the pre-proforeland stratigraphic units persist laterally, except for the Hormuz, which is exposed as a ~100 m thick unit in the highlands but gradually pinches out towards the SW. However, the syntectonic proforeland strata show drastic changes in their facies and thicknesses as might be expected. The total thickness of the sedimentary cover near the Zagros deformational front is estimated to be ~8.8 km, based on subsurface data. In contrast with the Lorestan sector, the Jurassic evaporites here are <200 m thick, and restricted to the uppermost Jurassic Hith (or Gotnia) Formation, which forms a detachment layer only locally in the southeastern part of the sector (fig. 16). In northwestern Khuzestan, Jurassic strata in wells do not show any thickening caused by evaporite mobility. Here, the Hith Formation is not considered to be a significant detachment horizon (fig. 15). Instead, the upper Triassic evaporites of the Dashtak Formation are interpreted to be a major detachment (fig. 15). Another evaporite succession forming a major regional detachment is the famous Lower Miocene Gachsaran Formation (for example, Falcon, 1969). In addition, local detachments are provided by thin Hormuz evaporites or basal shales of the lower Paleozoic strata, the Ordovician Zard Kuh shales (unconformably overlain by the Permian Faraghan and Dalan formations), and the Albian Kazhdumi shales and thin-bedded argillaceous lime mudstones (figs. 15 and 16).

In the Dezful recess, the syntectonic Gachsaran Formation, with its distinctive basal evaporite layer (~30 m thick), deserves attention. In addition to the fact discussed by previous workers (for example, O'Brien, 1950; Falcon, 1969) that the base of the formation forms a major decollement, it shows conspicuous thickness variations and repetition by faulting. Slip on basal Gachsaran evaporites has caused development of several thrusts, which displace the Gachsaran and its overlying units from northeast to southwest. A complex structure along the cross-section C – C′, composed of Gachsaran and overlying formations, highly disturbed by several thrusts, sits on the Masjid-i-Soleyman (MIS) anticline (fig. 15). The structure is interpreted as a hinterland dipping duplex, comprising several horses. It must be rather young, because the frontal horses have overridden the Pliocene strata of the Lahbari Formation. Also, overlying this duplex, there is a specific structural sheet (~400 m-thick) of Gachsaran strata on the northern side of the Masjid-i-Soleyman (MIS) anticline (cross section C – C′, fig. 15), which is unconformably overlain by the Lower to Middle Miocene Mishan Formation and in fault contact with the underlying Gachsaran siliciclastic and evaporitic strata and carbonates of the Asmari Formation. The sheet is rather thin and mechanically incapable of transmitting compressive stresses along its length. This weakness and reconnaissance field work suggest that the sheet perhaps emplaced by gravity. Gravitational sliding of thin structural sheets ("collapse structures") is locally recognized in the ZFTB (Harrison and Falcon, 1934, 1936; Falcon, 1974). If this interpretation turns out to be realistic, then gravitational emplacement of the Gachsaran sheet must be a late Early Miocene (~17 Ma) event.

Thrust faults with staircase geometry and displacements of several kilometers characterize the Khuzestan sector of the ZFTB (cross sections C – C′ and D – D′, figs. 15 and 16). Again, similar to the Lorestan sector, balancing the structures along the cross-sections C– C′ and D – D′ requires both in-sequence and out-of-sequence involvement of the basement in the deformation. Two basement-rooted thrusts have structurally uplifted the basement by ~5 km in the highlands northeast of the Dezful recess. A comparison between the cross sections constructed across the Khuzestan and

Fig. 15. Cross section C–C′ showing structures in the northwestern part of the Khuzestan sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

Fig. 16. Cross section D–D′ showing structures in the southeastern part of Khuzestan sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

Lorestan sectors of the ZFTB suggests that the degree of basement involvement in the Lorestan sector is much higher than that in the Khuzestan sector.

Towards the northeast, near the end of the cross-section C – C′, the Zard Kuh thrust has juxtaposed lowermost Paleozoic rock units (including the Hormuz evaporites) with the Pleistocene Bakhtiari conglomerates (fig. 15). The thrust is considered to be an out-of-ramp splay of the Mafarun thrust, which is exposed on the northeastern limb of the Kuh-e-Malek anticline to the southwest. In this interpretation, the amount of displacement of, for example, lower Paleozoic unit (~15 km) is the sum of the slips on the Mafarun (<6 km) and Zard Kuh thrusts.

The juxtaposition of the Paleozoic rocks with the syntectonic Bakhtiari Formation by the Zard Kuh thrust implies that the thrust has been active during the Pleistocene. To the southwest, other thrusts along the same cross-section (C – C′, fig. 15), such as those responsible for the development of the Kamarun and Naft Safid anticlines, are also interpreted as coeval active structures, because they have caused tilting of the Pleistocene Bakhtiari growth strata. Similar deformational synchroneity (in the sense of Boyer, 1992) is also inferred in cross-section D – D′ (fig. 16). Along this cross-section, growth of the anticlines such as Murd, Mish, Khami, and Razi is interpreted to be a result of the movements on an underlying thrust, which has been active during deposition of the Bakhtiari Formation. Also, further southwest along the same cross-section, slip on the thrust that is responsible for the growth of the Chilingar anticline, has synchronously tilted Bakhtiari syntectonic conglomerates. This general synchroneity in deformation across the Kuzestan sector is also inferred in other sectors of the belt (see below). It, indeed, constitutes one of the characteristics of structural evolution of the ZFTB.

In cross-section D – D′, to the north of the Chilingar anticline (fig. 16), a thick package of Gachsaran siliciclastic and evaporite layers is penetrated by several boreholes (Gachsaran oil field). Subsurface data indicate repetition of the stratigraphic units and intense structural disturbance. The complex structure is interpreted to be a hinterland-dipping duplex, whose horses are composed of the Asmari and Gachsaran Formations. The structure is considered to be a result of slip on a long top-Pabdeh flat, which constitutes an upper flat of an in-sequence basement-rooted thrust.

Further to the northeast, along the cross-section D – D′, behind the "mountain front flexure", fault-bend and fault-propagation folds characterize the structural style of the belt. Examples are the Siuk anticline that is thought to be a fault-propagation fold formed by the slip on a bottom-Hith detachment, and the Darishk overturned anticline that is considered to have formed by the movements on a top-Hith detachment, which itself is folded (Mokhtar upright anticline) by a bend in the underlying thrust.

The Anneh anticline, with its overturned southwest limb, is interpreted to have formed on an out-of-sequence splay of a basement-rooted thrust (with an essentially staircase geometry) which has transported the Phanerozoic successions and by uplifting them and forming anticlines such as Murd, Mish, Khami, and Razi, is responsible for the development of the "mountain front flexure". In this interpretation, the significant role that mechanical stratigraphy has played by providing incompetent layers potentially capable of becoming detachment horizons, and the change in deformation from being progressively forward-migrating to shifting backward and creating new structures in the backside of the previously formed folds, are critical issues in understanding structural evolution of the ZFTB.

Cross sections C – C′ and D – D′ suggest 16.1 percent (44 km) and 30.2 percent (72.5 km) bulk shortening, respectively, for the Khuzestan sector of the ZFTB (table 1). The substantial difference in the amount of shortening is a result of the fact that in the southeastern DR, where it is narrow (~105 km width) in comparison to the much wider northwestern DR (~156 km width), more intense deformation has affected the rocks (compare cross sections C – C′ and D – D′).

Fars Structures

Cross sections E – E′ and F – F′ (figs. 17 and 18) represent structures of the Fars sector of the ZFTB. Cross section E – E′ is 184 km long and extends from the Zagros deformational front to the Siakh anticline in the central part of the belt. Cross section F – F′ is longer (348 km), and crosses almost the entire belt, from nearly undeformed strata beneath the Persian Gulf to ophiolites near the northeastern boundary. The total thickness of the cover successions, including the ~1000 m-thick basal Hormuz unit, is ~7 km here. The pre-proforeland Cretaceous units are much thinner than the same units in Khuzestan sector (fig. 12). But the proforeland strata again show drastic lateral thickness and facies variations expected of syntectonic deposits.

The interpretations presented in cross sections E – E′ and F – F′ emphasize that in addition to the basal Hormuz, which forms a widespread (although not entirely continuous) detachment, several other incompetent units have formed significant detachment levels. The upper Triassic evaporites accommodated large displacement and development of short-wavelength and small-amplitude, near-surface folds such as the Beyram, Pishvar and Qareh Bulagh anticlines (fig. 18). Low-angle thrusts with tens of kilometers displacement repeated part of the cover stratigraphy in the northeastern parts of the Fars salient.

Similar to the Lorestan and Khuzestan sectors of the belt, structures in the Fars salient are considered as fault-bend and fault-propagation folds formed by slip on both in-sequence and out-of-sequence thrusts. Here, again, cross-sections E – E′ and F – F′ (figs. 17 and 18) suggest synchronous development of some structures. For example, syntectonic siliciclastic strata of the Agha Jari and Bakhtiari formations accumulated during the growth of the Darz, Shir Khan, Alhar, and Kahneh anticlines, are tilted and truncated by the underlying thrusts, whose movements created the anticlines. This indicates that the thrusts, similar to those previously discussed from the Khuzestan sector (see above), must have been coevally active during the Pliocene–Pleistocene times.

Out-of sequence, basement-involved thrusting in the Fars salient, as in the other sectors discussed above (Lorestan and Khuzestan), is required in order to balance the structures along cross-sections E – E′ and F – F′. Examples are the thrusts that are responsible for the development of the Shahini anticline in cross-section E – E′ (fig. 17), and the Darz anticline in cross-section F – F′ (fig. 18). These thrusts, which are initiated in the basement and have breached the pre-existing thrusts at the bases of the Hormuz and the Neyriz stratigraphic units, have developed anticlines that are younger than the structures to their southwest. Again, they suggest that Zagros deformation has propagated southwestward not along a single frontal line, but rather in a zone as wide as the ZFTB.

Out-of-sequence thrusts variably transport and uplift basement rocks and cover structures (cross sections E – E′ and F – F′). These thrusts become more common to the northeast. Their effects in uplifting the basement is much less (<2 km) than that of similar thrusts elsewhere in the belt (Lorestan and Khuzestan).

The Surmeh anticline in cross section E – E′ (fig. 17), in which the Triassic Dashtak Formation is thinner than the time-equivalent rocks in the underlying structural sheet as a result of the late Triassic erosion, exposes Ordovician shales and siltstones in its core (Evers and others, 1977). The anticline has overridden the adjacent Kalagh complex structure to its southwest by a steep out-of-sequence splay of an underlying thrust with a long hanging-wall flat at the base of the Hormuz unit. In this interpretation, the Surmeh anticline is considered as a fault-propagation fold, which has raised the Hormuz evaporites to <3 km depth. Northwest along the trend of

Fig. 17. Cross section E–E′ showing structures in the northwestern part of the Fars sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

Fig 18. Cross section F–F′ showing structures in the central part of the Fars sector. For location see figure 3. Restored state of the cross section is shown below. Note the difference in scale.

the anticline is the Jahani diapir of Hormuz salt (fig. 2). Its extrusion is attributed to reactivation of the basement-involved Mangarak strike-slip fault, which cuts across the northwestern end of the anticline (Talbot and Alavi, 1996; Talbot and others, 2000). The Surmeh structure exemplifies a two stage evolution in which thrust faults transported Hormuz salt to shallow depths, and then strike slip provided access for salt to reach the surface. This evolution may indeed be the dominant mechanism for diapirism in the southeastern ZFTB.

The thrust responsible for development of the Zireh anticline in cross-section E – E′ (fig. 17) deserve special attention. Balancing this structure with the other structures along the cross-section requires an initial pre-existing normal-fault displacement of the stratigraphic units (with throw of about 1.0 km) prior to thrust faulting. In the interpretation presented here, the thrust has used normal fault surface to transport the overlying strata upward. No stratigraphic evidence is found for the inferred normal faulting in the Phanerozoic units of the Zireh and Kahneh anticlines or in its vicinity. Therefore, the normal fault is tentatively considered as a structure formed and reactivated by the Zagros deformation.

Small, locally developed, normal faults with negligible displacements are inferred in some parts of the basement, where small steps (without any strata disruption) in the basement/cover interface have been observed (see, for example, the Surmeh anticline in cross section E – E′, and the Pishvar, Kahneh, and Alhar anticlines in cross-section F – F′; figs. 17 and 18). Slip on these within-basement normal faults, echoed in the overlying rocks and producing small steps (or bends), have affected the cover successions as young as Neogene. Therefore, their activity is regarded as a component of the Zagros deformation.

Near the northeastern end of cross-section F – F′ (fig. 18), field data indicate that a dismembered Neo-Tethyan ophiolite sheet is thrust onto the Lower Cretaceous Sarvak carbonates. The Upper Cretaceous (lower Maastrichtian) Tarbur carbonates unconformably overlie the ophiolite sheet, indicating that the ophiolite must have been transported by its underlying thrust in Late Cretaceous time. The thrust, however, towards the southwest, cuts across stratigraphic units as young as Eocene (Shahbazan or "Jahrum" Formation). On this basis, the thrust is considered to be a structure formed in the Late Cretaceous and reactivated during the Tertiary.

Minimum shortening estimates, based on cross sections E – E′ and F – F′, across the Fars sector are 19.2 percent (44 km) and 27.0 percent (94 km) respectively (table 1).

CONCLUSIONS

1. The ZFTB is the external part of an active orogenic wedge (the Zagros). Complex shortening in the wedge began in the Late Cretaceous, and has migrated southwestward into the northeastern Afro-Arabian continental margin, continuing today. The wedge includes both cover strata and basement rocks, which are displaced along weak horizons at various levels and transported southwestward by numerous in-sequence and out-of-sequence thrusts. Out-of-sequence, basement-involved thrust faulting with associated younger folds, which are superimposed upon the previously developed structures by in-sequence thrusting, implies two important aspects of the Zagros deformation: 1) progressive deformation has migrated from northeast to southwest, not along the frontal line, but as a zone as wide as the ZFTB itself; and 2) the orogenic wedge, whose external part is defined by the ZFTB, is still in its subcritical condition with internal deformation to attain a critical state. The regional basal detachment for the outermost part of the wedge (ZFTB) is probably developing in the upper basement at a depth of ~10 to 20 km, as indicated by most of the earthquake foci.

2. Mechanical stratigraphy of the heterogeneous cover of the wedge in the ZFTB has played a significant role in development of the structures by allowing formation of several evaporitic and mudstone detachment horizons. Because of non-uniform distribution of the lithostratigraphic units potentially capable of forming detachment levels, distinctive structural variations occur along the strike of the belt.

3. In addition to the mechanical stratigraphy, the variable degree of basement involvement in different sectors of the belt, which increases from southeast to northwest, has significantly affected along-strike structural variations.

4. Six regional balanced cross sections across the ZFTB show that exposed small-amplitude and short-wavelength fault-bend and fault-propagation folds are related to variable displacement on the subjacent thrusts with basically staircase geometry.

5. Restoration of the cross sections to their pre-Zagros states provides minimum shortening estimates, which range from ~16 percent to ~30 percent in different parts of the ZFTB. The shortening estimates and the restored cross sections may be used to prepare palinspastic maps of facies and thickness variations for petroleum exploration purposes.

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