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Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran

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Abstract

Structural style, and its relationship to sedimentary facies and the evolution of sedimentary depocenters since Late Cretaceous times have been studied, on the basis of one regional balanced transect and several updated isopach maps, in the Izeh zone and the Dezful Embayment, central Zagros. This study relies on fieldwork data, existing geological maps, seismic data and well information.

A new structural classification for part of the Zagros sedimentary cover is presented to highlight the different mechanical behavior of the formations in the stratigraphic column. It shows the existence of several local decollement levels activated during folding. These decollement levels separate lithotectonic units, which accommodate shortening in different ways. The Lower Paleozoic is the basal decollement level throughout the studied area. Triassic evaporites, Albian shales, Eocene marls and Miocene evaporites can act as intermediate decollement levels, and present variable facies in the Central Zagros. Lateral facies and thickness variations, the sedimentary overburden and the close relationship with inherited fault patterns influenced the wavelength, amplitude and style of folding in the study area. Furthermore, surface structures do not necessarily coincide with deeper objectives where these disharmonic levels are involved in folding.

The evolution of sedimentary depocenters from the Late Cretaceous (obduction episode) until early Miocene collision is described, based on updated isopach maps and tectonic subsidence curves. This analysis shows continuous compression and movements along N–S and NW–SE trending faults in the Zagros basement which predate the Neogene Zagros folding and influence sedimentation history. It also indicates a southwestward migration of the depocenters through time, in addition to the basement involvement below some folds during the Zagros orogeny.

Keywords: Zagros; Tectonic evolution; Iran; Structural section; Decollement; Fold style; Seismic; Isopach

1. Introduction

The Zagros mountain belt of Iran, a part of the Alpine–Himalayan system, extends from the NW Iranian border through to SW Iran, up to the Strait of Hormuz (Fig. 1). This orogenic belt is the result of the collision between the continental Arabian plate and the so-called Iranian block belonging to Eurasia (Berberian & King, 1981; Takin, 1972). These authors infer that the first compressive movements across the belt began during the Late Cretaceous due to the obduction of ophiolites on the northeastern margin of the Arabian continent. These movements accelerated and became more widespread following the continent–continent collision in Miocene times (Falcon, 1969; Stocklin, 1968). The convergence is still active at the present day, in a roughly N–S direction at a rate of approximately 25–30 mm yr^{-1} at the eastern edge of the Arabian plate (Sella, Dixon, & Mao, 2002). This direction is oblique to the NW–SE trend of the orogenic belt. Earthquake focal mechanisms and the GPS velocity field (Talebian & Jackson, 2002) suggest partitioning of this oblique shortening along the faults in the Zagros.

Several local and regional unconformities, in addition to thickness and facies variations have been related to continuous convergence and reactivation of deep seated faults in the Zagros basement between Late Cretaceous and Early Miocene times (Berberian & King, 1981; Koop & Stonly, 1982). Hesami, Koyi, Talbot, Tabasi, and Shabanian (2001) documented local post-Eocene unconformities

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and attributed them to the beginning of folding and uplift in the NE of the Zagros belt, which progressively propagated south-westwards through time.

Despite the interest in Zagros folds due to their major hydrocarbon reserves, and after extensive drilling by oil companies, geophysical and geological surveys, little has been published about the structural behavior of the sedimentary cover, the structural style and its relationship with sedimentary facies and evolution of the belt since the Late Cretaceous. O'Brien (1950) was the first to divide the stratigraphic column into five structural divisions. (1) Basement group (Precambrian), (2) Lower mobile group (Hormuz salt, decollement level), (3) Competent group (Cambrian to Lower Miocene), (4) Upper mobile group (Miocene salt, decollement level), and (5) Incompetent group (Lower Miocene to Plio-Pleistocene, mostly clastic sediments).

The oldest in situ rocks exposed in the Zagros range are Lower Cambrian sandstone and dolomite. These occur at the base of southwest directed thrust fault scarps which form the SW boundary of High Zagros. Late Protrozoic–Early Cambrian age has been assigned to evaporites and polygenetic assemblage of rocks which comprise the Hormuz group (Kent, 1986). These rocks are seen only in small, scattered, emergent salt plugs associated with thrust faults in the High Zagros and more abundantly in the Fars area. Some of these plugs contain an assemblage of intrusive rocks. Radiometric dating of these rocks show ages from Pre-Cambrian to Tertiary which correspond to different periods of magmatism (Motiei, 1995). Just one sample was dated as Pre-Cambrian by Player (1969), which provides the only indications of possible basement composition. Motiei (1995) suggests that the Zagros basement should be NE continuation of Arabian–Nubian shield, which exposed southwest of Arabian plate.

Large folds (with wavelength from 10 to 15 km) with relatively isopach simple structure which are rarely cut by thrust faulting are the main features of the Competent group (Colman-sadd, 1978). These structures are separated from the more rigid basement group and from the complexly folded and thrusted structures in the overlying incompetent group by the Lower and Upper mobile groups, respectively. Concentric geometry was considered for a long time to be the main structural style of folds in the Zagros fold belt (Colman-sadd, 1978). This interpretation implies thick accumulations of Hormuz salt in the cores of the anticlines.

This paper presents part of the results of a regional study of the Izeh zone and the Dezful Embayment, based on original fieldwork, seismic line interpretation, geological maps and well data. All data was provided by the National Iranian Oil Company (NIOC). We present a regional transect from the inner part of the Zagros fold belt to the Persian Gulf (Fig. 1a), in addition to several updated isopach maps. The aim of this paper is to illustrate the shape and style of folding and faulting, their relationship to decollement levels and sedimentary facies change. Furthermore, the evolution of deformation in the central part of the Zagros orogenic belt from Late Cretaceous until Early Miocene times was studied, to show the presence of movements which predate the Neogene Zagros folding and influenced sedimentary thickness and facies variation.

2. Geological framework and stratigraphy

The Zagros mountain belt is divided into several zones (Fig. 1a) that differ according to their structural style and sedimentary history (Berberian & King, 1981; Falcon, 1974; Motiee, 1994; Stocklin, 1968). The NW and SE boundaries of the studied area (the central Zagros) coincide with the Balarud and Kazerun faults, respectively. The central Zagros is subdivided from NE to SW into the part of High Zagros, Izeh zone and Dezful Embayment.

The Main Zagros reverse fault at the northeastern limit of the High Zagros is the suture between the colliding plates of central Iran and the Arabian passive continental margin (Berberian, 1995). Kazerun fault is located along a line marking the projected continuation of the Qatar peninsula

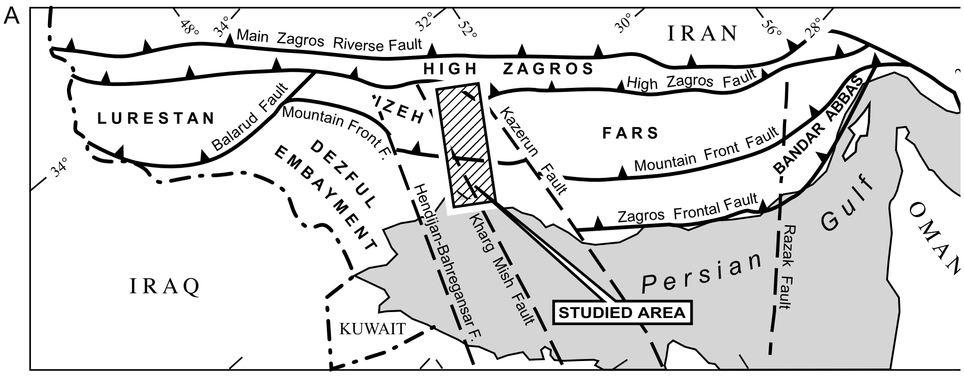


Fig. 1. Location map. (A) Main structural subdivisions of the Zagros fold and thrust belt. (B) Simplified geological map of the study area compiled from NIOC 1/250,000 geological maps (Evers, 1977; Fakhari & McQuillan, 1993) and location of structural transect. 1: Plio-Pleistocene, 2: Upper Miocene, 3: Middle Miocene, 4: Oligocene–Lower Miocene, 5: Eocene marls, 5a: Eocene flysch, 6: Cretaceous, 7: Jurassic, 8: Triassic, 9: Paleozoic, 10: Hormuz salt.

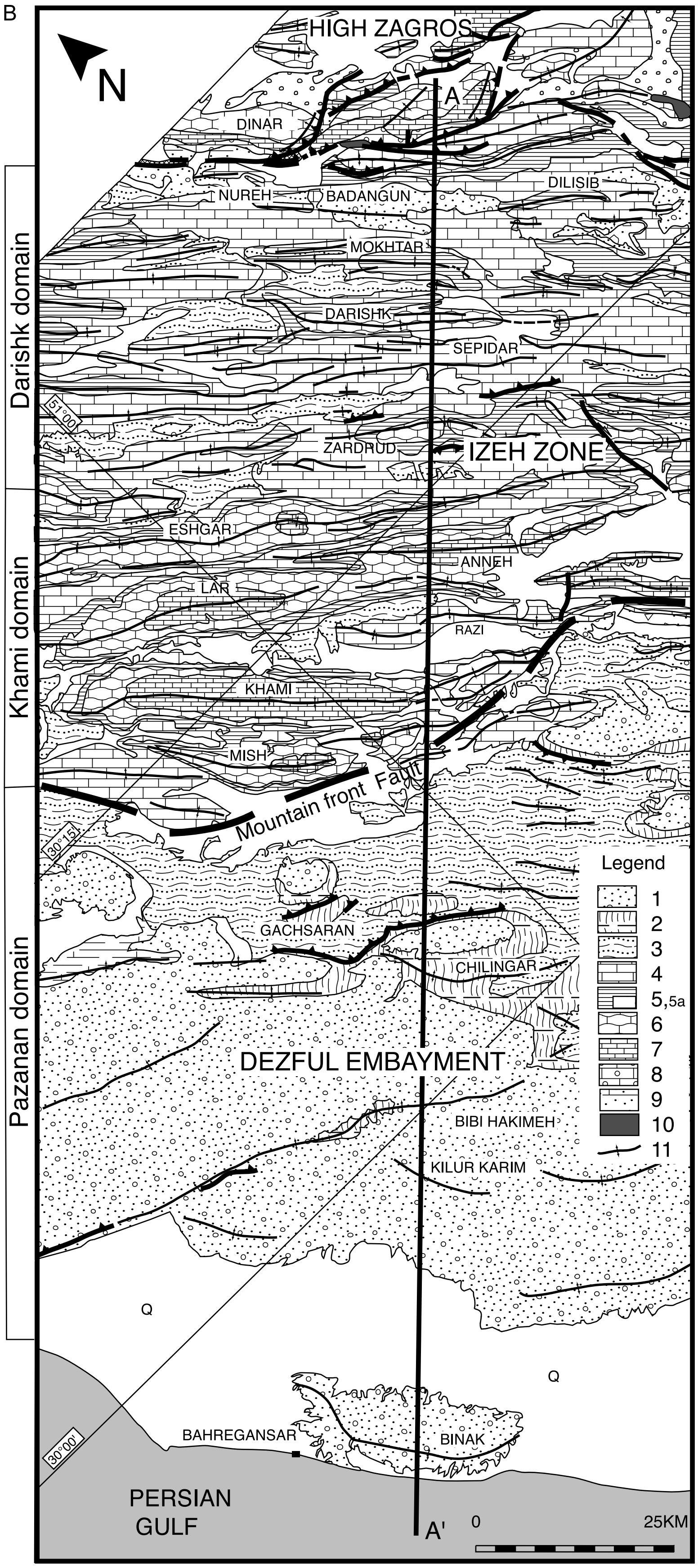


Fig. 1 (*continued*)

into Iran. It is a NS trending fault, which is seismicaly active and crosses the Zagros trend with bending, dragging and offset of the fold axes in a right lateral sense (Berberian, 1995). It is also visible on Aeromagnetic maps (Motiei, 1995, Talebian, personal communication). Balarud fault is a part of mountain front fault which is seismicaly active (Berberian, 1995).

The High Zagros to the southwest of the Main Zagros reverse fault is a narrow thrust belt up to 80 km wide, with NW–SE trend. It is bounded to SW by the High Zagros fault, which is currently seismically active along a few segments (Berberian, 1995). This narrow thrust belt has the highest topography (up to 4000 m) and the oldest exposures (the Lower Paleozoic outcrops in the core of some anticlines). The High Zagros is strongly faulted and upthrusted to the southwest along the different segments of the High Zagros fault. The Izeh zone lies across a sharp topographical break to the southwest of the High Zagros fault. This zone consists of a variety of structures of variable size and geometrical character. In the study area, the Izeh zone is subdivided into the Darishk and Khami domains on the basis of the age of outcrops and the folding style (Fig. 1b). Jurassic sediments are the oldest outcrops in this zone, and are exposed in the Khami domain. The Izeh zone is limited to the southwest by the Mountain front fault which is a segmented master blind thrust fault with striking structural, topographic, geomorphic and seismotectonic characteristics (Berberian, 1995). In the southwest of the Mountain front fault, the Dezful Embayment corresponds to a low lying alluvial plain passing into dissected foothills generally less than 1000 m high and entirely covered by Tertiary sediments (Fig. 1b). It shows a sharp topographic difference with the Izeh zone across the Mountain front fault. The difference in elevation of the same formations, from the crest of Khami anticline north of Mountain front fault, to the bottom of the adjacent syncline south of the fault, only 6 km away, is over 5000 m.

Folding in the Zagros involves practically continuous series from Cambrian to Recent in age (Fig. 2). The thickness and facies of the Paleozoic are not well controlled

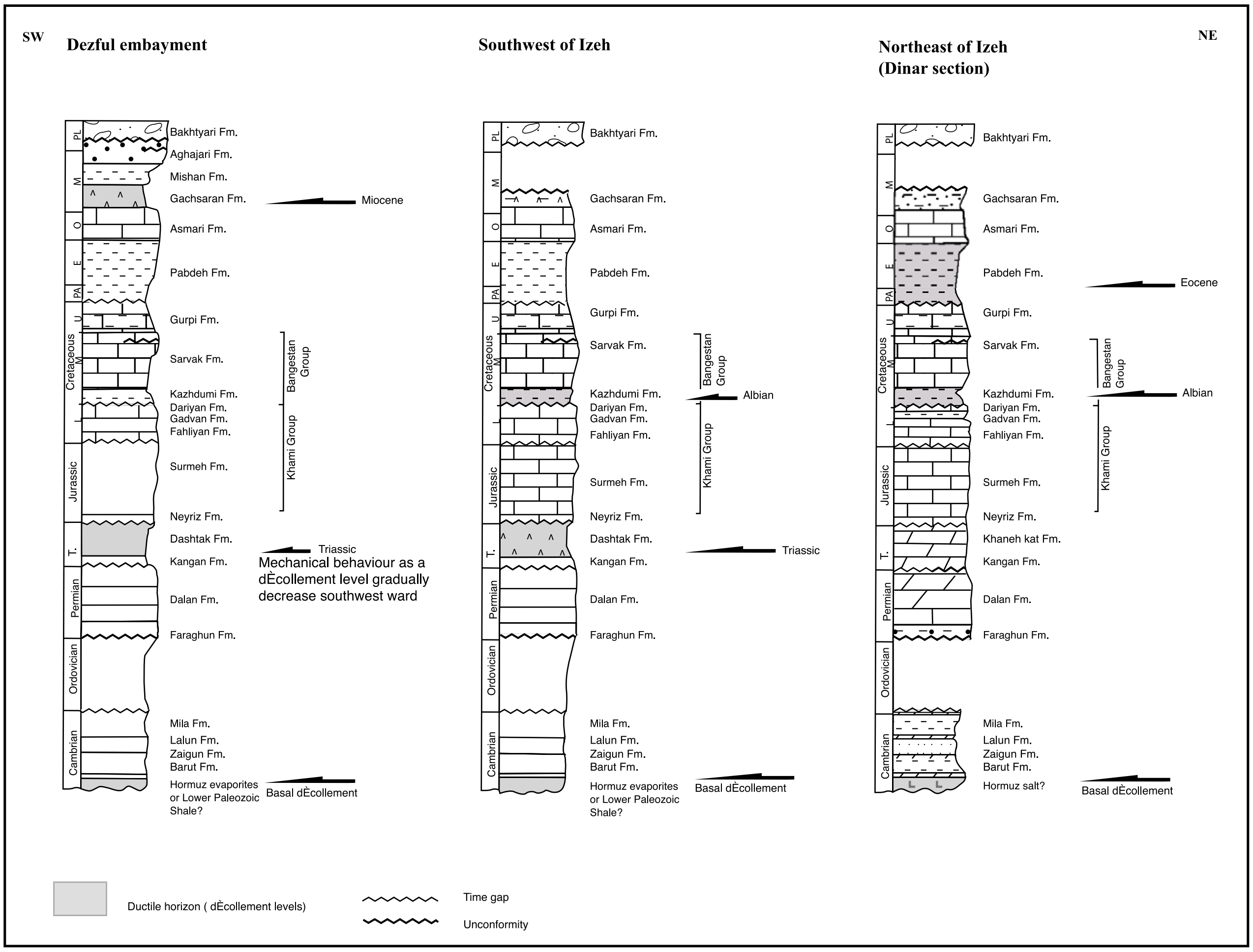


Fig. 2. Stratigraphy and main decollement levels along the transect in the Izeh zone and the Dezful Embayment, from the Dinar thrust to the Binak anticline are based on the Dinar surface section (Cretaceous to Lower Paleozoic) and the Mokhtar well in northeast of the Izeh zone (Eocene to Middle Cretaceous), the Khami surface section and Kuh-e-Bangestan well in the southwest of the Izeh zone (Oligocene to Triassic) and numerous wells in the Dezful Embayment (Pleistocene to Lower Cretaceous). Deeper parts of the section derived from regional interpretation. Vertical axis is in time.

in the SW of the Izeh zone and Dezful Embayment due to the lack of outcrops and deep well data. In this study, Paleozoic thickness and facies are inferred from the minimum visible thickness on seismic lines and the extrapolation of few outcrops in Zagros fold belt.

Fig. 2 presents new structural subdivisions of the stratigraphic column, which consists of several competent structural units that are separated by incompetent levels resulting in a disharmonic fold style in the study area. This disharmony is the expression of the different mechanical behavior of the units, which seems to be more complex than what was described by O'Brien (1950). From the NE to the SW of study area, our classification is based on data such as the Dinar surface section (Lower Paleozoic to Upper Cretaceous), the Mokhtar well (Middle Cretaceous to Eocene), the Khami surface section (Jurassic to Oligo-Miocene) and the Nemours well data (Lower Cretaceous–Pleistocene) in addition to regional seismic interpretation and field mapping. The main basal decollement horizon is located in Lower Paleozoic Hormuz salt or Cambrian Shale beds, over the entire study area. The Hormuz evaporitic series is known from outcrops along the southern border of the High Zagros thrust (Edgel, 1996; Letouzey & Sherkati, 2003), Fars region and also from seismic data in the Persian Gulf. Instead, there is no outcrop or seismic halokinesis evidence for Hormuz salt in Izeh zone and Dezful Embayment.

Due to lateral variations in their sedimentary facies, the overlying incompetent horizons are not of regional extent, and occur in varying positions along the structural cross-section. In the northeast of study area, Albian Kazhdumi shale, rich in organic matter, is one of major decollement levels. Based on regional isopach maps, its thickness should be less than 350 m but in the Mokhtar well it is over 1100 m thick (see later). The Kazhdumi shale facies gradually change to carbonate facies southwestwards in the vicinity of the Mish anticline (Fig. 1b) where it no longer behaves as a decollement level. Eocene Pabddeh marls are the second major intermediate decollement level southwest of the Dinar segment of the High Zagros fault. They consist of over 1000 m of marine shale, thinning rapidly south-westward to less than 200 m in the Khami anticline (Fig. 1b).

Due to the facies change of Triassic sediments from the Dashtak evaporites in the southwest to the Khanehkat dolomite in northeast, this unit does not act as décollement level throughout the studied area. This facies change from evaporites to carbonates along the Neotethys margin is shown by paleogeographic maps (Szabo & Kheradpir, 1978). Triassic carbonates (Khanehkat Fm.) outcropping in the Dinar anticline (High Zagros) and Mongasht anticline (Izeh zone) change to Triassic evaporites (Dashtak Fm.) to the southwest of Izeh zone (Szabo & Kheradpir, 1978), where it is suggested that they behave as an intermediate décollement level. Dashtak evaporite was drilled into two wells in Izeh zone (Kuh-e-Bangestan and Gurpi anticlines). Dip meter data from these two wells show disharmonic features in Triassic level. The size of the structures in southern part of the Izeh zone and the Dezful in addition to the seismic data prove continuous folding down to the Paleozoic. The Triassic Dashtak evaporites lose their mechanical behavior as a disharmony level south of Dezful Embayment, in the Persian Gulf, although their sedimentary facies remains constant (Fig. 1b).

In the Dezful Embayment, the Miocene Gachsaran Fm. is the main intermediate incompetent horizon. Its thickness changes very rapidly from several hundred to 2000 m. This thickness variation is related to faulting, folding and diaprism after deposition and also syntectonic sedimentation during the folding. It consists of salt at the base, which is overlaid by anhydrite, marls and thin-bedded carbonates. Our observations show differences in size, structural configuration and tectonic complexity of the structures across the study area which are interpreted as being related to sedimentary facies variations.

3. Cross-section

In order to study the lateral variations of structural geometry in the southeast of the Izeh zone and the Dezful Embayment, surface observations, well and seismic data were used to construct a balanced cross-section from the inner part of the belt to the Persian Gulf (Fig. 3). Surface data such as structural style, sedimentary facies and dips were obtained from field reconnaissance. We also used the 1/100 000 NIOC geological maps (Evers, 1977; Fakhari & McQuillan, 1993; McQuillan, 1974a,b; McQuillan, Roohi, & Evers, 1978; Setudehnia & Perry 1966a,b,c). Furthermore, unpublished well data and seismic profiles were also used to interpret the structures at depth. Seismic quality was frequently poor in the North Dezful and Izeh zone. Therefore, a composite transect which contains several dog-legs was drawn in order to take into account the best subsurface data while remaining roughly perpendicular to structural trends.

The depth of the basal decollement level in the Izeh zone and the Dezful Embayment is not clearly imaged by the seismic. On the basis of the parallel folded seismic horizons down to the Paleozoic level, the basal decollement should be still deeper, the basal decollement was considered to be at a minimum of 9000–10,000 m below sea level in the southeast of Dezful Embayment (Letouzey et al., 2002). It has been suggested, based on topographic observations, that the Precambrian basement of the Zagros is involved in deformation. Furthermore, information on recent seismicity shows that seismic thrusting and strike slip faulting is taking place at a maximum ~8 to12 km depth below the basal decollement (Berberian, 1995). Below this depth in lower continental crust, active deformation is accommodated by aseismic plastic flow. Based on the folding style and the salt plug intrusions, decoupling of basement from cover occurs by the Late Proterozoic–Early Cambrian Hormuz salt in the Fars area (Fig. 1a; ColmanSadd, 1978). However, there is no evidence of the presence of the Hormuz salt level in the Izeh zone and the Dezful Embayment. Salt intrusions are known along the footwall of the Dinar thrust in the northern part of the studied section (Fig. 3). South of the section in the Persian Gulf area, circular to elongated structures, like as Kharg anticline, are thought to be draped over deep pillows of Hormuz salt. Thickness variations along the Binak anticline in northern coast of Persian Gulf since Cenomanian times may be related to salt movements. Anyhow in the case of the absence of Hormuz salt, Cambrian shale horizons could be good candidate for basal decollement level in the Izeh zone and the Dezful Embayment. Such a decollement is visible in the core of deeply eroded anticline north of the Lurdegan City.

Excellent outcrops of rocks younger than Early Cambrian along the Dinar Thrust (Fig. 1b) provide good thickness constraints for section construction in the Izeh zone. Towards the SW, however, due to the absence of deep outcrops and well data, there is no direct information about the thickness of formations older than the Triassic. The minimum thickness for Paleozoic strata in the SW of the transect was estimated based on seismic horizon correlation with the Fars area, and the depth to the basal decollement is based mainly on a comparison with the magnetic basement map (Morris in Motiei, 1995).

Comparing the depth of Mesozoic and Paleozoic seismic horizons in the different synclines allows us to demonstrate stepwise uplift of these formations from southwest to northeast (Letouzey et al., 2002). Furthermore, thrust faulting affecting the basement is suggested by present-day seismicity (Berberian, 1995; Jackson, 1980). These steps are therefore interpreted as basement uplift breaching the basal decollement level, and correspond to the High Zagros fault, the Mountain front fault and the frontal fault along the section (Fig. 3).

The structural geometry of the transect in the northern part of the Izeh zone has been well constrained in shallower levels by excellent outcrops and a single well (Mokhtar#1 down to Lower Cretaceous). However, the part of the transect below 2000 m has been constructed using fragmentary seismic reflectors, geometric and thickness constraints, regional and local décollement levels, structural interpretation and cross-section balancing techniques (Dahlstrom, 1969; Harrison, 1991; Harrison & Bally, 1988; Woodward, Boyer, & John Suppe, 1985). In contrast, in the Dezful Embayment the constraint from surface geology is poor, and the section was constructed with the help of the best seismic lines and well data down to the Lower Cretaceous. There is a marked contrast along the section (Fig. 3) between the widely spaced asymmetric folds which have open interlimb angles in the Dezful embayment and the smaller and closer-spaced folds in the Izeh zone. Synclines are essentially the mirror image of anticlines in the Izeh zone. In this zone, the wavelength to amplitude ratio of the anticlines is different in northern and southern areas. The ratio for northern half is less than 5 meanwhile for southern half is more than 5. On the other hand, northern folds are tight folds with short wavelength compare to the folds in southern part.

The transect was divided into three different structural domains on the basis of these contrasting structural styles, namely the Darishk, Khami and Pazanan domains from NE to SW (Fig. 3). The Pazanan domain in this study corresponds to southern Dezful Embayment.

Darishk domain (Fig. 3). This part which is limited to the north by the Dinar segment of the High Zagros fault is dominated by anticlines which are cored by Cretaceous or younger sediments. Along the section, the Yasuj, Mokhtar, Darishk, Sepidar, and Zardrud anticlines, and southeastern prolongation of the Eshgar anticline, are characterized by tight and chevron folds within Cretaceous levels. These folds are asymmetric, verging southwest with a typical wavelength of about 5 km (Zardrud anticline is a exception probably due to the inefficiency of Albian shale as a intermediate decollement level). Oligocene–Lower Miocene Asmari carbonates in this domain are shortened by folds with wavelengths of 1–2 km on the flank of the main structures, which are locally breached by thrust faults. Our structural interpretation for the deeper horizons is based on information provided by the Mokhtar well and on fragmentary seismic reflectors, which indicate larger structures at depth. The Albian Kazhdumi and Eocene Pabdeh formations are intermediate decollement horizons that separate three distinct sets of structures in the area: tight folds with short wavelength in Oligocene Carbonates that tend to out in Eocene marls, folds at Cretaceous level, which do not coincide with folds in deeper horizons, and finally folds in Early Cretaceous and older rocks, such as the structure which is penetrated by the Mokhtar well (Fig. 4).

'Rabbit ear' structures in Oligocene and Cretaceous carbonates on the flanks of main structures (Fig. 4), provide evidence of the effect of the Albian and Eocene intermediate disharmonic levels on fold geometry. This fold style is similar to the physical (analogue) model which was presented by Letouzey et al. (1995) to illustrate fold style in the Atlas mountains of Algeria and to the geometrical 'limb wedges' thrust model of Mitra (2002a).

These less competent levels effectively control fault ramp-and-flat patterns, and transfer the deformation from one anticline forward to the next one. The northwestern plunge of the Anneh anticline is seen as an impressive example of this phenomenon (Fig. 5). Shortening above the roof thrust is usually accommodated by forward displacement. Therefore, it is not possible to use hinge of synclines as pin line for restoration.

South of the Darishk domain, the thickness of the Albian and Eocene shales decreases and they no longer act as efficient intermediate decollement levels.

Khami domain (Fig. 3). Jurassic rocks are the oldest exposures in the cores of anticlines in this domain. The Anneh, Razi, Khami and Mish anticlines have a more open interlimb angle and are less asymmetric. Anticline

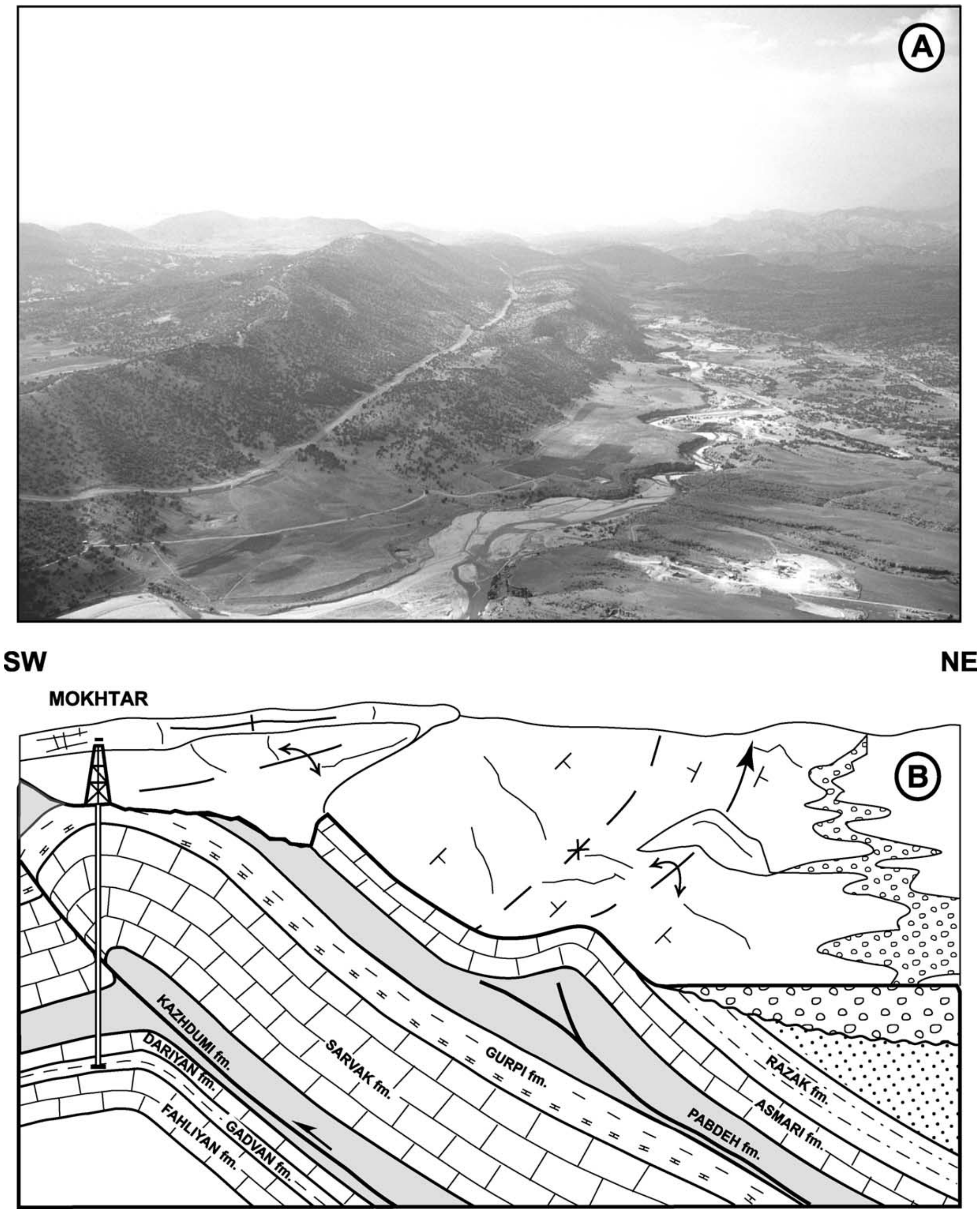


Fig. 4. (A) Photograph of Mokhtar anticline, (B) Line drawing and section of the Mokhtar anticline. The Mokhtar well proved thickening and thrusting of the Albian shales (Kazhdumi fm.) in the core of the structure. 'Rabbit ear' structures on the flank of the main fold show the influence of intermediate décollement level (Eocene Pabdeh Fm.) on fold style.

wavelength is clearly larger compared to the Darishk domain. Jurassic to Lower Miocene sediments are most probably folded together. We attribute this feature to decreasing thickness of Albian shales and Eocene marls and their consequently lesser effect as disharmonic levels in this domain.

The role of Triassic evaporites as a decollement level has been proved in parts of the Fars area, east of the Izeh zone, by seismic and well data (Fig. 6a; Comby, Lambert, & Coajon, 1977; Letouzey et al., 2002). We suggest that Triassic evaporites are also an intermediate decollement level in the Khami domain, based on the occurrence of

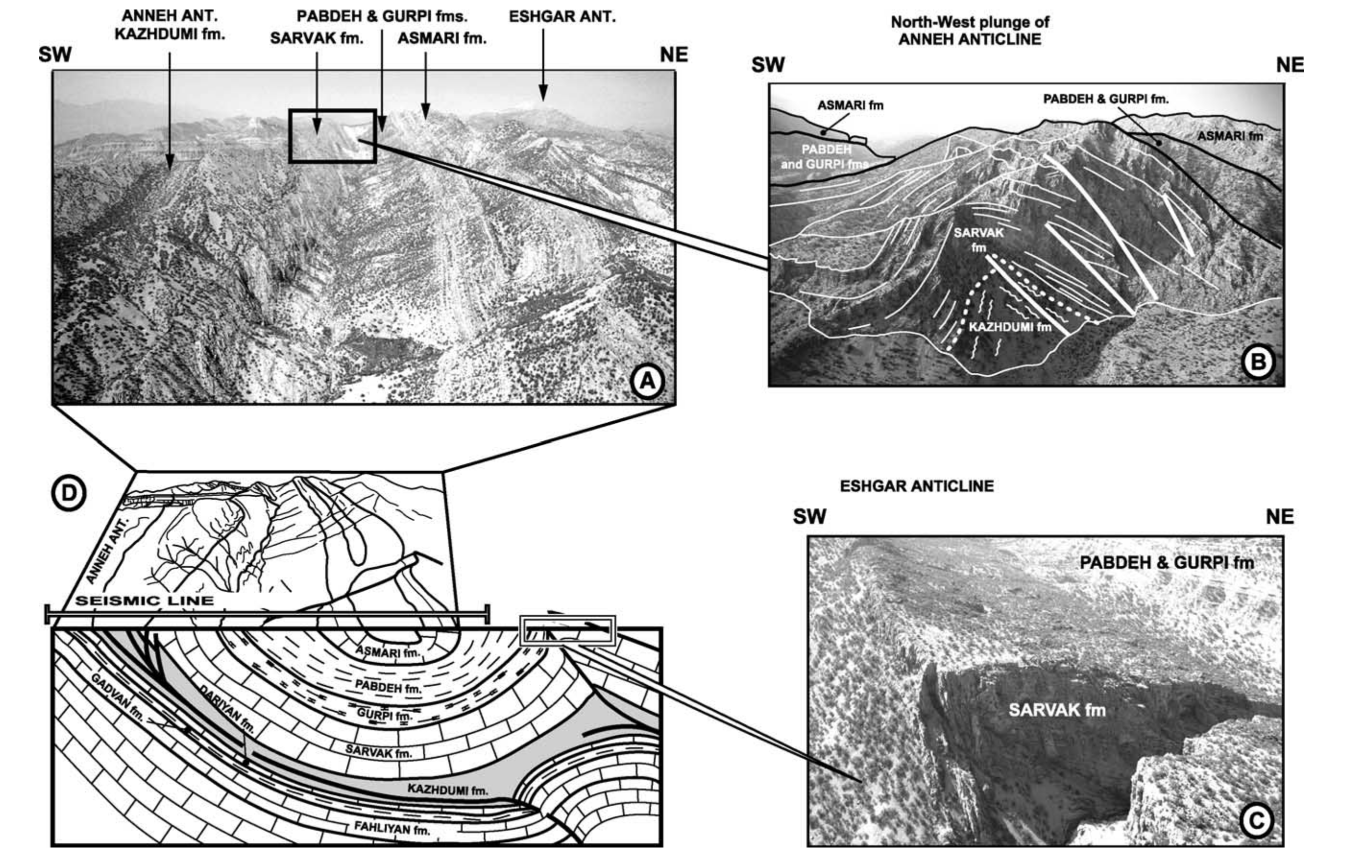


Fig. 5. (A) Photograph of a syncline between the Anneh and Eshgar anticlines involving the Oligo-Miocene Asmari Fm., note the overturned northern limb. (B) Photograph of Middle Cretaceous limestone imbrication (Sarvak fm.) on the northern flank of the Anneh anticline. (C) Photograph of the southeasterly plunge of the Eshgar anticline, which is a very tight and asymmetric structure at Cenomanian carbonate level (Sarvak fm.). (D) Block diagram, based on seismic data and surface geological mapping, shows disharmony within the Albian Shale (Kazhdumi Fm.) which could control fault geometry and transfer deformation.

'Rabbit ear' structures at Jurassic and Lower Cretaceous levels in the Eshgar and Anneh anticlines, respectively. We also observed some hinterland ward displacement along the Anneh anticline.

Pazanan domain (Fig. 3). The Pazanan domain is located south of the Mountain front fault, and a significant topographic step marks the boundary with the Khami domain. With the exception of a few outcrops of Oligo-Miocene Asmari carbonates in this domain, the Neogene Fars group is well exposed over practically the entire area. The Miocene Gachsaran formation generally covers the anticlines and is composed of marls, anhydrite, thin limestone and locally large quantities of salt. Disharmonic features in this level are well imaged by seismic data (Fig. 6b). This formation has been identified as a level of decollement and disharmony by previous workers (ColmanSadd, 1978; O'Brien, 1950). In the southern area, the quality of seismic data is poor when the Gachsaran evaporites are just below the surface.

In the northeast of the Pazanan domain, the Gachsaran, Garangan, Pazanan and Bibihakimeh anticlines form widely spaced folds with open interlimb angles. They are separated by wide synformal areas, often with subhorizontal planar troughs.

Seismic lines have allowed good control of the northeast flank (gently dipping limb), whereas the southwest flank is very steep and poorly imaged. Below the Miocene decollement level (Gachsaran evaporite), there is usually an abrupt change in the depth of the Oligo-Miocene Asmari carbonates from the top of the structure to the adjacent, southerly syncline, of over 1000 m (Fig. 6b). Furthermore, production tests show varying water pressure and salinity in the Asmari aquifer in the Dezful Embayment, which was suggested as providing evidence of faulted anticlines by Motiei (1995). However, direct evidence to show whether or not the steep limb is faulted is lacking for some of the structures. But we suggest that it is most likely that large thrust faults climb from the basal décollement in the Lower Paleozoic up to the Triassic evaporites, the Miocene Gachsaran Formation. Fig. 6b and c shows some seismic evidence supporting this interpretation. Along the Mountain front fault, NW of Dezful Embayment, Upper Jurassic Goutnia formation and Lower Cretaceous Garu formation become two other efficient decollement levels.

Southwest of the Pazanan domain, continuous seismic horizons are visible in synclines and anticlines without any disharmony at the Triassic level. This shows that Triassic sediments lose their role as an intermediate décollement level southwestward. South of the section, in the Pars anticline, Persian Gulf, Triassic facies are still evaporitic but show no evidence of disharmonic features.

In the southwest of the Pazanan domain, anticlines are less affected by faults and show symmetrical open shapes. The wavelength of the Kilurkarim and the Binak anticlines is clearly different from the other structures of the transect, and the pre-Hormuz (basement?) levels are most probably involved in deformation. Furthermore, in the Binak anticline (Fig. 7), rapid thickness variation since Cenomanian times, must be related to vertical movements in this area (Section 5).

4. Basin evolution

To follow the structural evolution of the Zagros basin from the Mid-Cretaceous to the Neogene folding event (Zagros orogeny), several isopach maps and cross-sections were prepared (Figs. 8–10a–c). These maps and sections represent a compilation of surface and subsurface data made

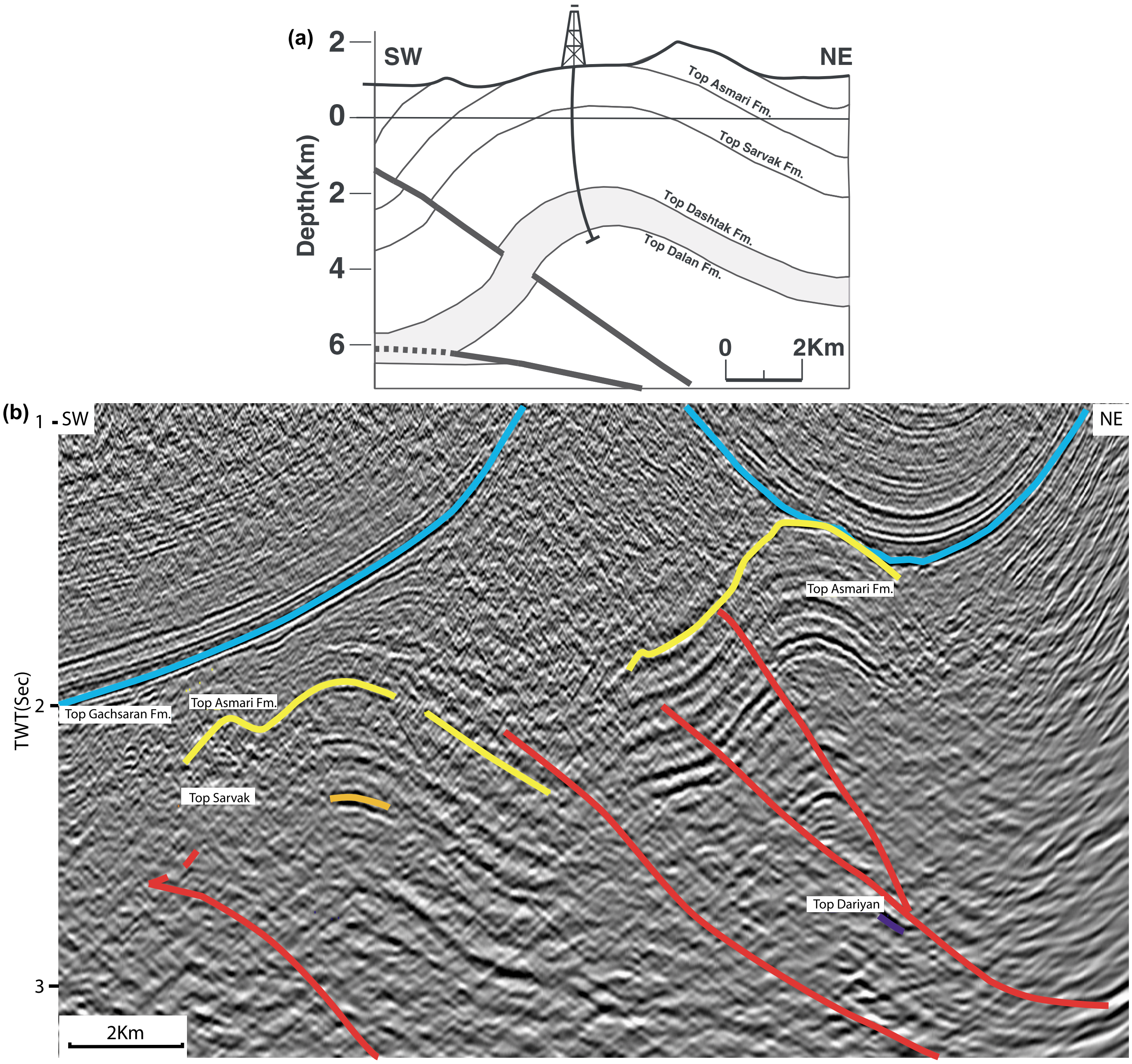


Fig. 6. Examples of decollement levels. (a) Decollement at Triassic level (Dashtak evaporites) in Fars area, based on deep meter logging. (b) Disharmonic nature of Gachsaran Miocene evaporite and abrupt change in the depth of Oligo-Miocene carbonate from the crest to the adjacent southerly syncline in the Dezful Embeyment, south of the Mountain front fault (north-west of our study area). syn-sedimentary folding is deduced from Sedimentary pinch out of the upper Gachsaran horizons (Early middle Miocene). Furthermore, Upper jurassic Gotnia formation, Lower Cretaceous Garau formation and Albian Kazhdumi shales are the other different decollement levels. (c) Interpreted seismic reflection profiles (No. I) through the Gachsaran anticline showing the upper decollement within Gachsaran formation and a possible decollement level within Triassic evaporites.

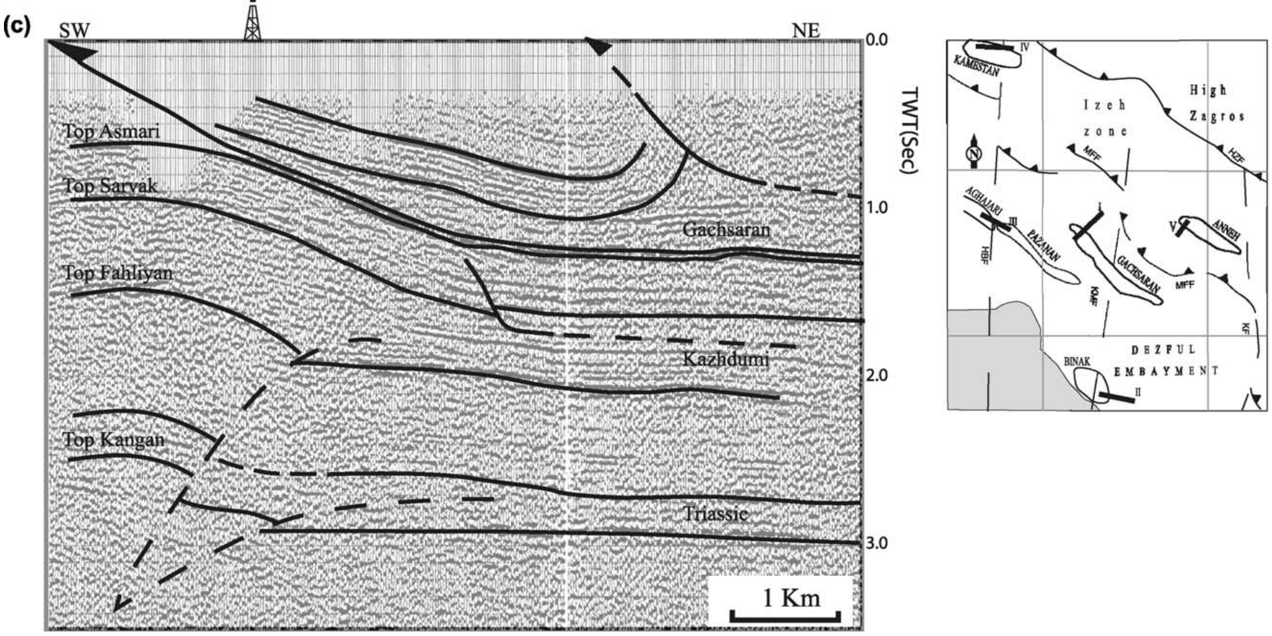


Fig. 6 (*continued*)

in the studied area up to 2001 by a number of different geological teams and by operating oil companies. All thicknesses shown on the maps are preserved thicknesses (no attempt was made to measure eroded thickness). The stratigraphic transect (Fig. 8) is drawn sub-parallel to the structural cross-section, using surface sections and well data.

The Kazerun fault (KF), the Kharg–Mish Fault (KMF) and the Hendijan–Bahregansar fault (HBF) correspond to a series of roughly N–S striking linear uplifts along pre-existing basement trends (Motiei, 1995) (Fig. 1a and 9). Koop and Stoneley (1982) show that these trends were strongly reactivated in response to the ophiolite obduction at late Cretaceous. The Hendijan–Bahregansar and Kazerun faults are seismically active at the present day, with right lateral movement in the Precambrian basement (Berberian, 1995). Comparing the depth of Mesozoic seismic reflectors in different synclines in the Dezful show stepwise uplift from northwest to southeast along these faults. Motiei (1994) shows that the activity of the Kharg–Mish fault (Fig. 8), based on thickness and facies variations seen in wells, started after Lower Aptian times, during the deposition of the Khalij member limestone. During the Albian, the activity of this fault increased remarkably and caused a clear thickness variation (Fig. 8a and b).

We also found some indications on seismic lines and outcrops, concerning the thickness and facies variations in the Albian–Cenomanian strata along the Hendijan–Bahregansar fault. Two examples are presented in Figs. 11 and 12. These similar patterns could be seen in a narrow zone just above the Hendijan–Bahregansar fault from the Persian Gulf up to the Izeh zone. They show that the relatively higher area affected sedimentation at least after Albian. Most probably they are evidences for continuation of the NS Arabian trends in the basement of Iranian Zagros reactivated during the time at least after Albian. They probably correspond to linear paleo-highs, which influenced sedimentation by creating a flexure in the sedimentary basin. A thickness and facies pattern paralleling the Zagros NW–SE trend was gradually superimposed on the N–S trending subsidence after Late Cretaceous (Figs. 8 and 10).

Fig. 8a and b shows a substantial change in the basin architecture with considerable subsidence at a crustal scale on the north-eastern margin of the Arabian plate, between Turonian and Maastrishtian times. This period is marked by the obduction of ophiolites onto the continental crust. This event has been dated as Early Coniacian–Late Santonian (Berberian, 1995; Berberian & King, 1981; Falcon, 1974; Ricou, 1971). This age corresponds approximately to the period of ophiolite obduction in Oman (Coleman, 1981).

The isopach map of Campanian–Maastrishtian time (Fig. 10a) reveals a thick accumulation of sediments in the present-day High Zagros area. The thickness of the Campanian–Maastrishtian interval decreases rapidly south-westward in the Dezful Embayment (Fig. 8b). Turbidite, deep water marls, shales and marly limestones were deposited in the High Zagros at this time. Clastic intervals within the Maastrishtian sediments increase toward the Main Zagros reverse fault. They consist mostly radiolarite components which suggest erosion of the radiolarian and ophiolitic nappes. Comparison with Oman geology suggests that the Radiolarian are relic from the Zagros Mesozoic margin south of the Neo-tethys.

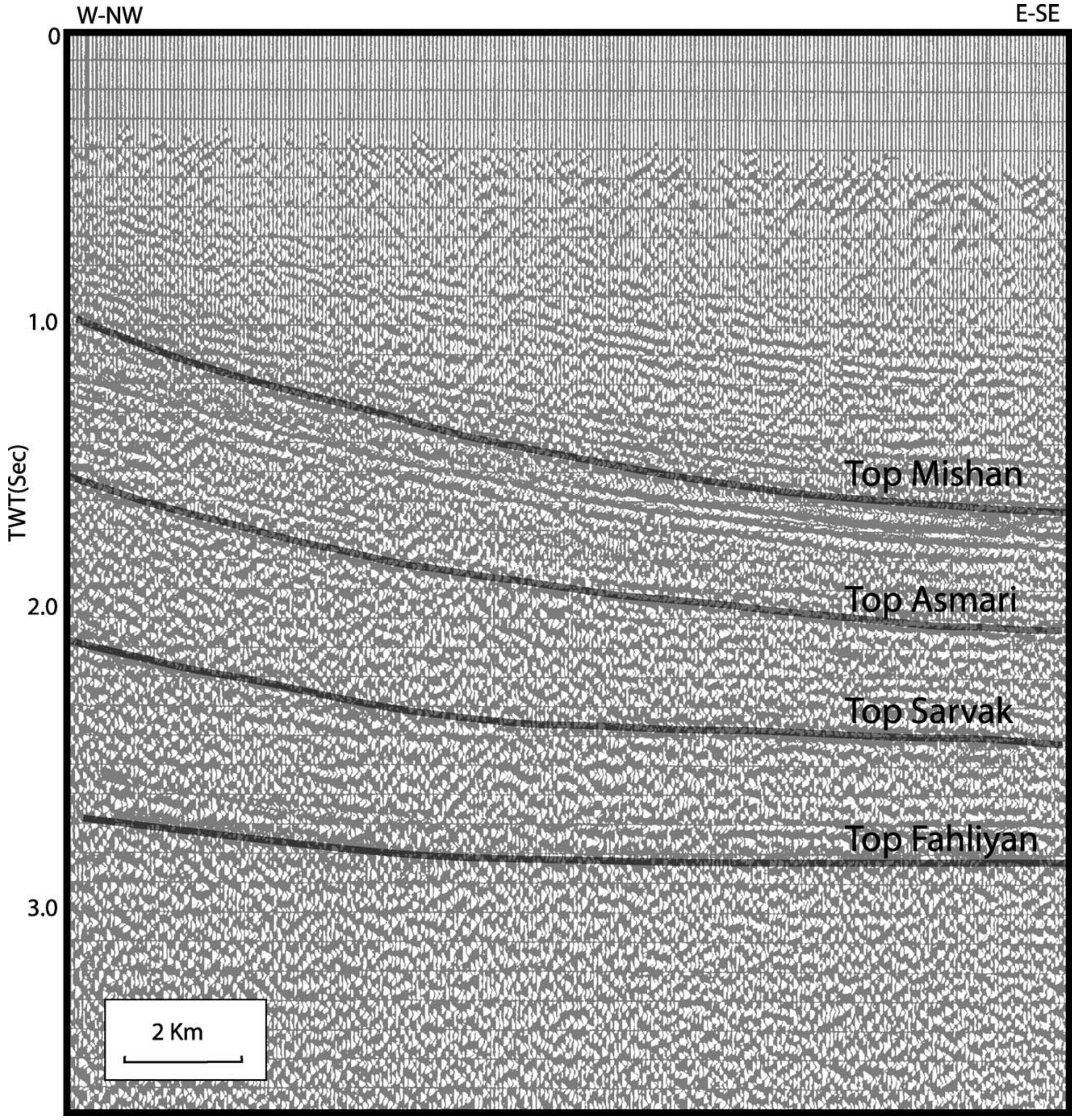


Fig. 7. Interpreted seismic reflection profile through the northern flank of Binak anticline, showing thickness variations at the crest of the anticline in the Neocomian–Lower Miocene time interval. For location, see Fig. 6, II. It might be related to the influence of deep seated NS fault (Kharg–Mish) on sedimentation by causing flexure in sedimentary basin.

Progressive deformation following the obduction of oceanic crust caused the depocenter to migrate southwestward. The thickest accumulation of Eocene sediments occurs south of the High Zagros fault (Dinar Thrust; Fig. 10b). First compressive movements along High Zagros fault in this area uplifted the High Zagros relative to the Izeh zone. The Eocene 'piggyback' Flysch basin was formed in the High Zagros whereas thick Eocene marine marls were deposited in the Izeh zone (Figs. 1 and 8c).

The Isopach map of the Oligocene–Lower Miocene time interval (Fig. 10c) shows two separated depocenters in Northeast of the Izeh zone and Dezful Embayment (Fig. 8d). Thinning of the sediments between these two depocenters is trending parallel to the suture zone (Fig. 10c). We suggest that it could be representative of a bulge effect due to the continental collision between Central Iran and Arabian plate.

Subsidence curves in the study area confirm the age of the Zagros orogeny and also reactivation of deep seated

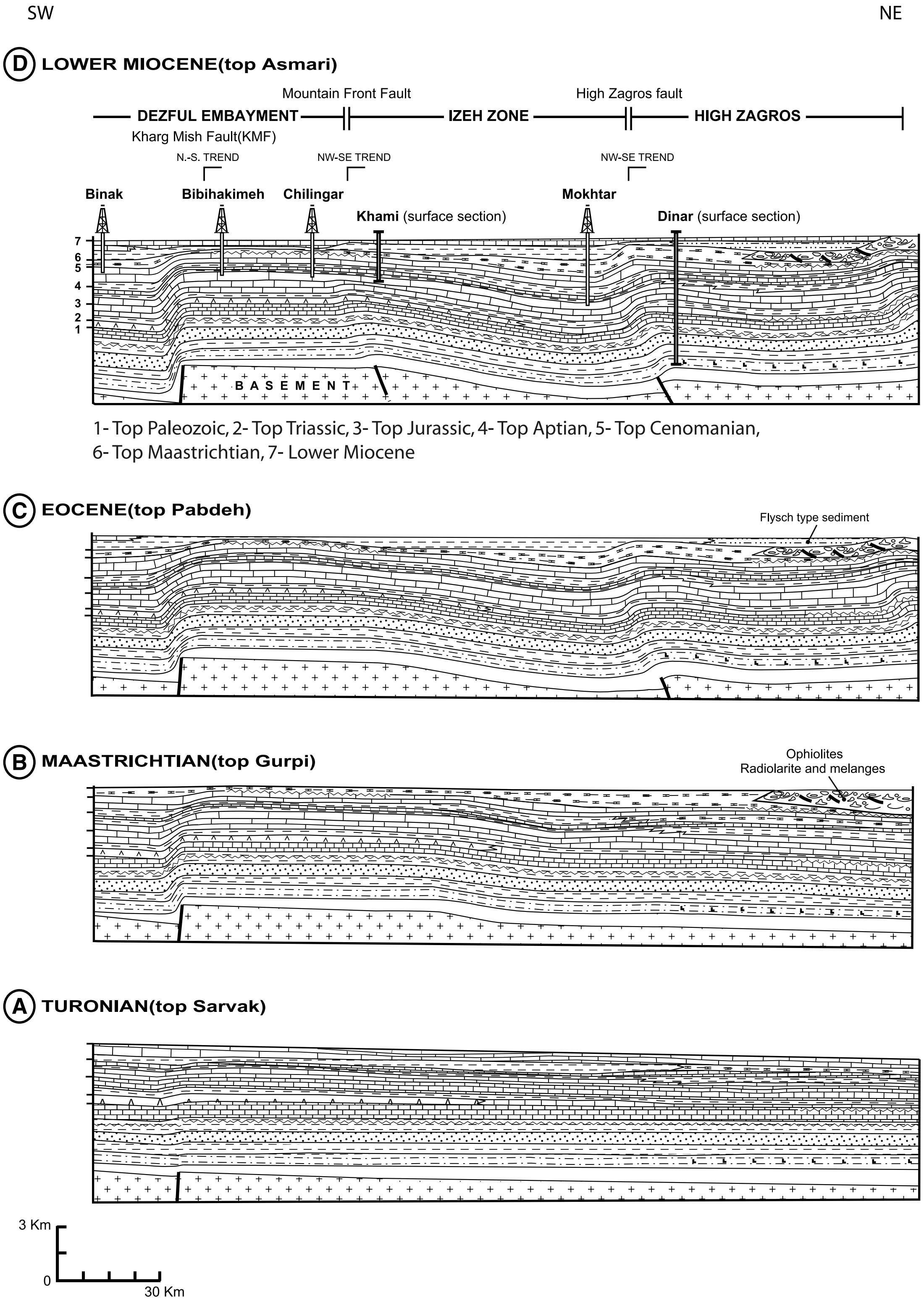


Fig. 8. Schematic stratigraphical transect from the Turonian time to the Lower Miocene time showing basin evolution, based on wells and surface sections (see Figs. 9 and 10 for location map). (A) *Top Turonian (Sarvak fm.)*: during Cenomanian times, the Zagros basin was the passive margin of the Arabian plate. Thickness variations along N–S faults such as Kharg–Mish fault (KMF) since Albian times show that basement faults were still active. Reactivation of deep-seated N–S faults and the appearance of intrashelf basins in Turonian times are possibly related to the obduction of ophiolites at the Turonian–Coniacian boundary, along the NE margin of the Arabian plate. (B) *Top Maastrichtian (Gurpi Fm.)*: a thick sequence of marine sediments accumulated in front of the ophiolites and radiolarian nappes. (C) *Top Eocene (Pabdeh Fm.)*: progressive deformation caused southward migration of the depocenter. The first movements along HZF are identified on the basis of sedimentary thickness and facies changes. (D) *Oligo-Miocene*: Thinning of sediments southwest of Izeh zone could be related to the bulge effect which uplifted the area during the Zagros orogeny.

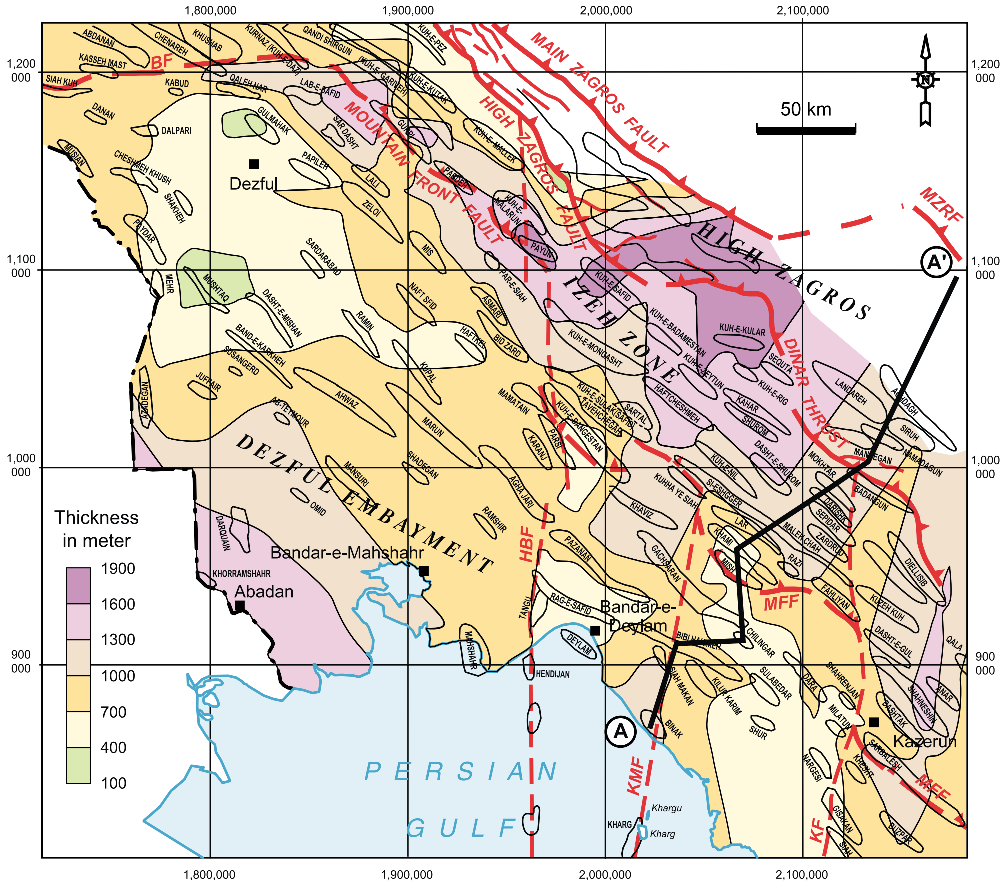


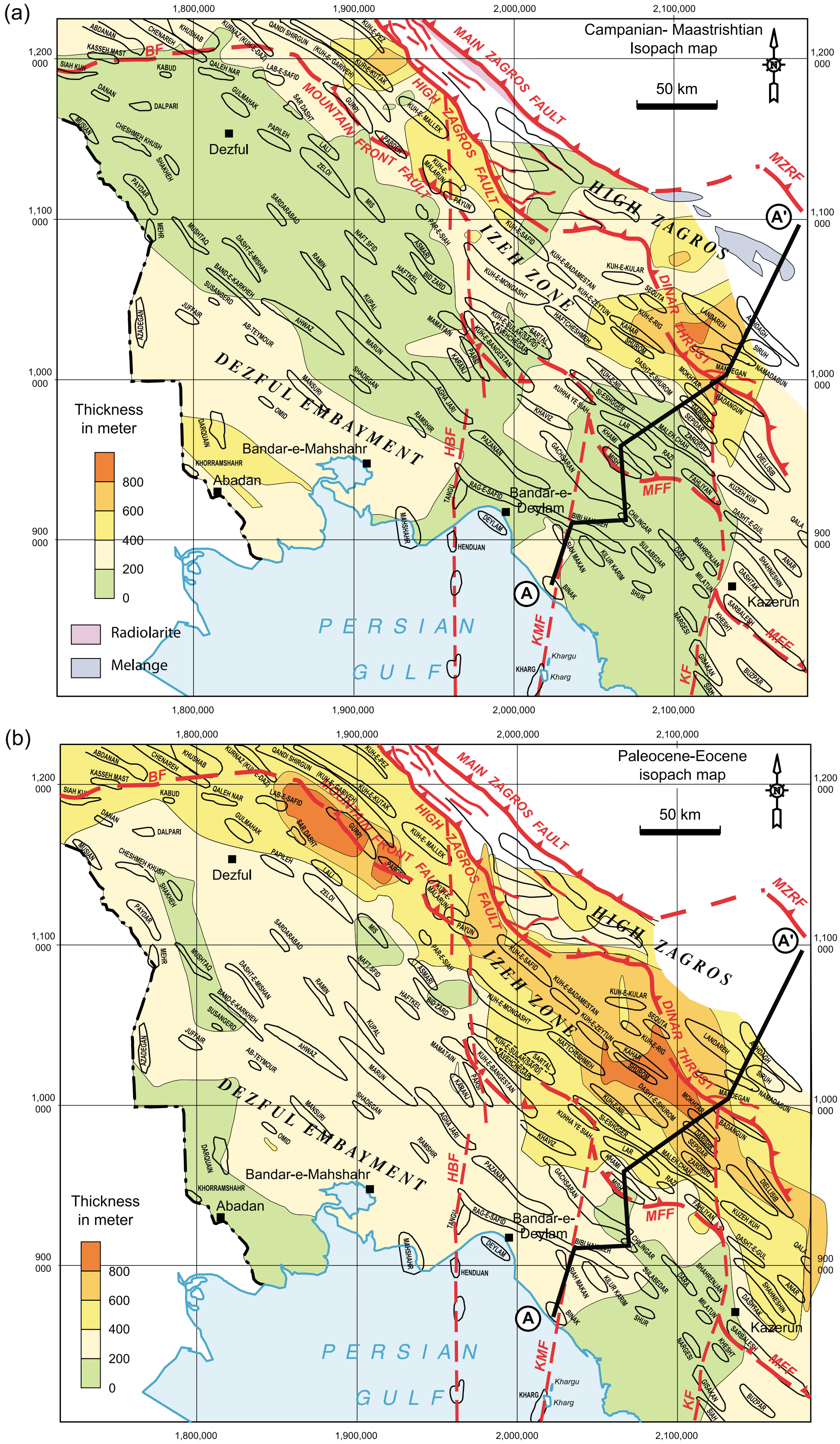
Fig. 9. Top Cenomanian- Lower Miocene isopach map. Sedimentary thickness variations show N–S trends which can be interpreted as being related to reactivation of inherited structures in the basement. Kz: Kazerun fault, BF: Balarud fault, KMF: Karg–Mish fault, HBF: Hendijan–Bahregansar fault.

faults (Fig. 13). Vertical movements related to the Neogene Zagros orogeny started in the Late Oligocene in the Pazanan, Gachsaran and Mokhtar anticlines (Fig. 13), whereas subsidence curves in the Fahliyan anticline close to the Mountain front fault show pre-Oligocene uplift in the southeastern part of Izeh zone. Preorogeny vertical movements along present day Mountain front fault area might be the reason of sedimentary thinning in Oligocene–Lower Miocene time interval (Fig. 10c). Fig. 10c shows also thinning toward the Northeast of High Zagros which is the basinal facies time equivalent of Asmari formation. Some earlier uplifts in Gachsaran anticline area might be related to the reactivation of the Kharg–Mish deep seated NS fault (Fig. 13).

The Zagros orogeny, after deposition of the Asmari carbonate Formation coincided with thin-skinned folding and faulting over the Lower Paleozoic basal décollement level. Whereas NW–SE trending basement faults continued to control uplift the inner part of the belt, The Middle to post-Miocene depocenter was shifted southwestwards to the Dezful Embayment. Rapid subsidence allowed a thick accumulation of Middle Miocene Gachsaran evaporites, Upper Miocene Mishan marls, Pliocene Aghajari sandstone and molasse deposits. Facies and thickness change of Gachsaran evaporites along the Mountain front fault show its activity during the sedimentation. The Pleistocene Bakhtiary conglomerate lies above an unconformity surface sealing the underlying folded and eroded structures. Tilted Bakhtiary conglomerate show that the folding is still active in Zagros.

5. Discussion

A north-eastward increase in the intensity of deformation is displayed by the intensity of shortening and folding along the transect. The most external anticlines in the study area are probably the less deformed structures, and therefore they can show the initial stages of fold development. The more internal structures in the northeast of the transect are more complex, and illustrate the intermediate and advanced stages of folding. Foot wall synclines, steep thrust faults and fold tightening by limb rotation and hinge migration are characteristic of the transition in deformation behavior from detachment folding to progressive fault propagation folding with increasing shortening. This fold style could be similar with what was named ‘faulted detachment folding’ by Mitra (2002b). Large competency contrasts within the sedimentary pile result in a more complex geometry in the Central Zagros folds. Intermediate decollement levels separate


(a)
Campanian- Maastrishtian
Isopach map
50 km
MAIN ZAGROS FAULT
HIGH ZAGROS FAULT
MOUNTAIN FRONT FAULT
HIGH ZAGROS
IZEH ZONE
DINAR THRUST
DEZFUL EMBAYMENT
MZRF
BF
HBF
KMF
MFF
KF
Dezful
Bandar-e-Mahshahr
Abadan
Bandar-e-Deylam
Kazerun
PERSIAN GULF
Kharg
Khargu
A
A'
Thickness in meter
800
600
400
200
0
Radiolarite
Melange
1,800,000
1,900,000
2,000,000
2,100,000
1,200 000
1,100 000
1,000 000
900 000
(b)
Paleocene-Eocene
isopach map
50 km
MAIN ZAGROS FAULT
HIGH ZAGROS FAULT
MOUNTAIN FRONT FAULT
HIGH ZAGROS
IZEH ZONE
DINAR THRUST
DEZFUL EMBAYMENT
MZRF
BF
HBF
KMF
MFF
KF
Dezful
Bandar-e-Mahshahr
Abadan
Bandar-e-Deylam
Kazerun
PERSIAN GULF
Kharg
Khargu
A
A'
Thickness in meter
800
600
400
200
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1,800,000
1,900,000
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1,100 000
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900 000

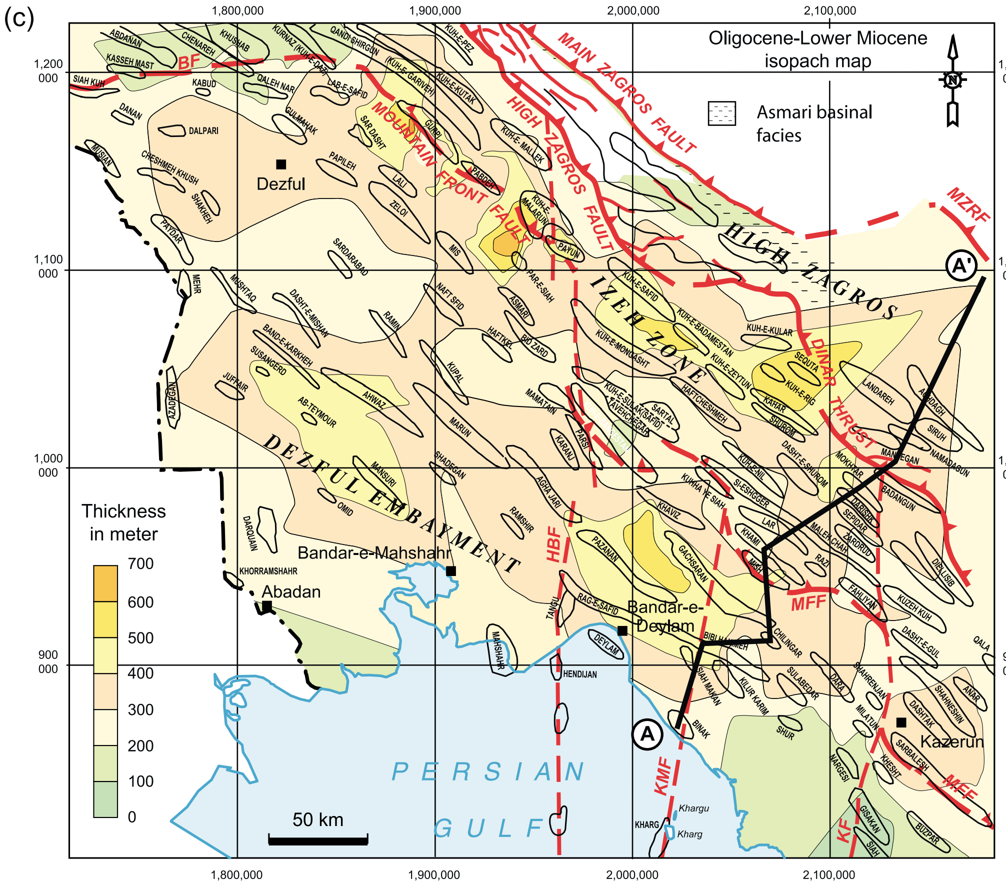

Fig. 10 (*continued*)

distinct lithotectonic units with different structural geometry and kinematics. They present different modes of accommodation of the same shortening and can control ramp-and-flat geometry of fault patterns and backthrust propagation. They favor the development of the classic 'triangle zone' as described by Harrison and Bally (1988) in Melville island and 'fish-tail' structures (Fig. 14; Letouzey et al., 1995), as well as 'fold accommodation faults' (Mitra, 2002a).

Sedimentary loading is the other factor which has influenced the geometry of folds and faults (Hafner, 1951). The relationship between tectonic style and sedimentary overburden is particularly clear in the Khami domain. The relatively small overburden in this domain may have facilitated the vertical growth of symmetrical folds, whereas the greater overburden in the other domains may instead have favored the formation of more asymmetric folds. Similarly, the reduced overburden in the Khami domain may have resulted in backthrust displacement, whereas forward displacement is observed to the southwest. The frictional coefficient of the basal decollement level is the other parameter which can control thrust vergence. Low basal friction could also explain the free development of forethrusts and backthrusts without any preferred vergence (Letouzey et al., 1995).

A balanced and restored cross-section (Fig. 3) across this part of the range indicates around 25 km of shortening. This corresponds to an average of around 13% shortening of the sedimentary cover in the Izeh zone and the Dezful Embayment. Shortening in the Darishk, Khami and Pazanan domains is around 18, 14 and 6%, respectively, as shortening decreases from the inner part of the fold belt towards the foreland, with an abrupt drop

Fig. 10. Central Zagros Isopach maps. (a) *Campanian–Mastrichtian*: in the High Zagros province, a thick accumulation of marine sediments was deposited in front of the ophiolitic nappes. Sedimentary thickness decrease rapidly southwestward and clearly was influenced by Kazerun and Balarud faults. (b) *Paleocene–Eocene*: southwestward migration of depocenters and uplift in the High Zagros is observed during this time interval. Compressive movements along the Dinar segment of the High Zagros fault during the Early Tertiary are supposed by thickness and facies variations across the structure. (c) *Oligocene–Lower Miocene*: despite of the transgression leading to the deposition of Oligo-Miocene carbonates (Asmari Fm.) throughout the Zagros platform, isopach map of this time interval show thinning in SW of Izeh zone. These could be related to the bulge effect which caused vertical movements and separated two dipocenters in NE Izeh and Dezful Embayment from each other. Small area north of the High Zagros fault, which shows sedimentary thinning, is the basinal facies of Carbonate platform in SW. Kz: Kazerun fault, BF: Balarud fault, KMF: Karg–Mish fault, HBF: Hendijan–Bahregansar fault.

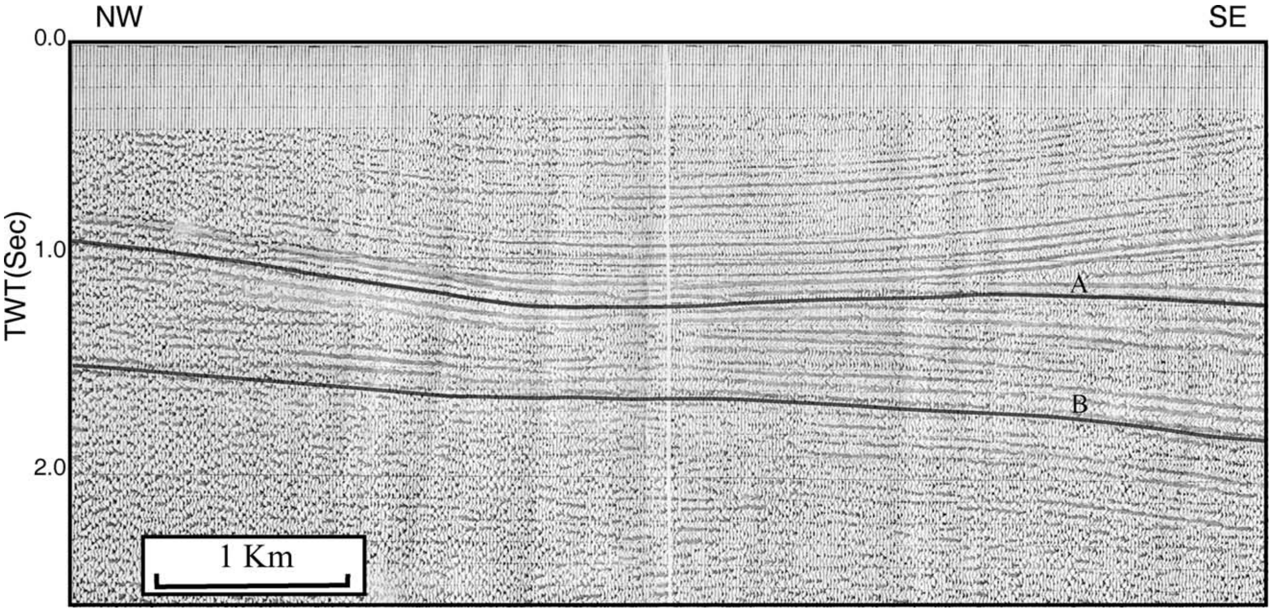

Fig. 11. Interpreted seismic profile through the Hendijan–Bahregansar fault between the Aghajari and Pazanan anticlines. It shows clear thickness changes during the Middle Cretaceous–Lower Miocene time interval. For location, see Fig. 6, III. Both of anticlines were drilled down to the Lower Cretaceous, and no fault or disharmonic features were reported. (A) Top Asmati Fm., (B) Top Fahliyan Fm.

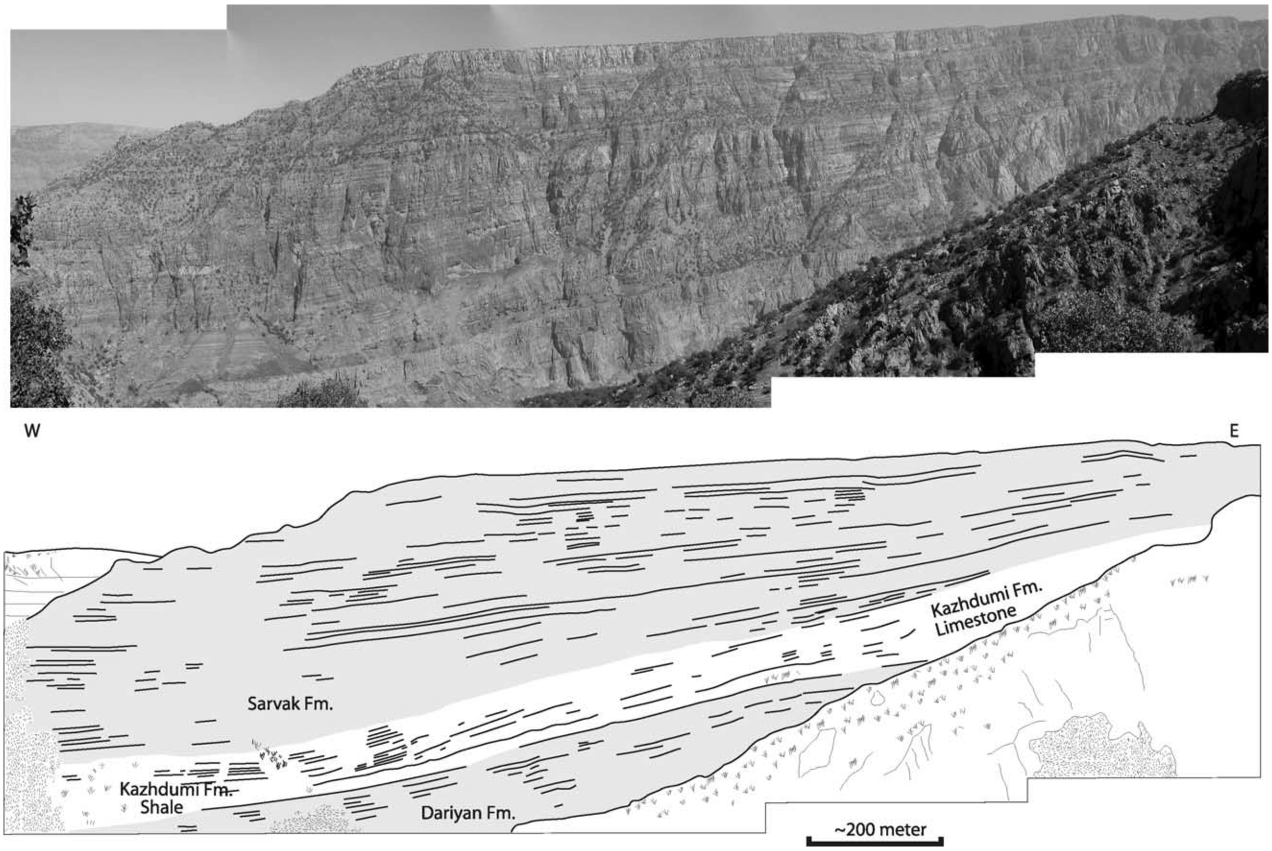

Fig. 12. Thickness and facies variations in Albian and Cenomanian sediments north of Izeh city. The area to the east should be relatively higher during the sedimentation. This outcrop in addition to the other similar evidences (like as Fig. 11) could be interpreted as continuation of NS Arabic trends in the basement of Iranian Zagros and its influence on sedimentation. For location, see Fig. 6, IV.

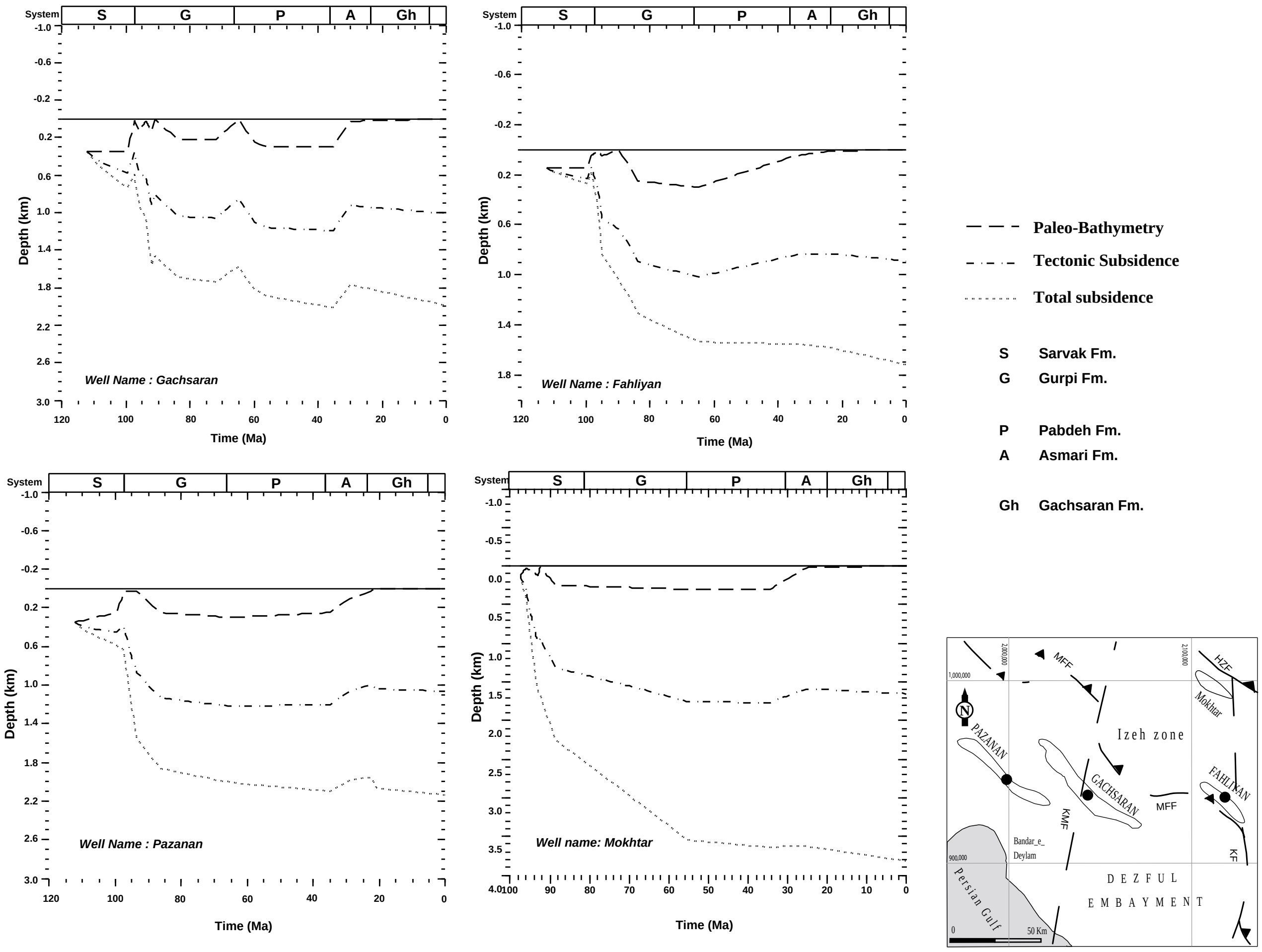

Fig. 13. Subsidence curves, show substantial uplift around the Gachsaran anticline compared with the Pazanan anticline. This is possibly related to reactivation phases of the Kharg–Mish fault after ophiolite obduction in the Late Cretaceous. Vertical movements around the Fahliyan anticline before the Neogene Zagros orogeny coincide with sedimentary thinning in Oligo-Miocene time interval (Fig. 10c). It can be attributed to the bulge effect, which uplifted this area compare to the inner part (Mokhtar anticline).

between the Izeh zone and the Dezful Embayment. We suggest that the thick overburden in the Dezful Embayment constituted a resistant mass which forced the SW moving thrusts and folds in the Izeh zone and the high Zagros to pile up behind it into tightly folded or thrusted and highly shortened structures.

Thickness and facies variations of sediments enormously increased from Late Cretaceous times onward. In the literature, these features are related to two different origins. Koop and Stoneley (1982) have related it to the reactivation of N–S deep-seated faults after the Late Cretaceous ophiolite obduction and to the Zagros thrust belt formation which started in the Early Miocene. Later, Hessami et al. (2001) proposed that the thrust belt formation starts during Late Eocene. Our study, based on fieldwork, updated isopach maps, subsidence curves and a balanced cross-section, supports these two origins. The variations in sedimentary thickness and facies are an expression of regional uplift controlled by N–S trending inherited faults (Arabic trends), as well as NW–SE faults (Zagros trends) within the basement. Furthermore, field and seismic data suggest that the N–S Arabic trends in the study area affected the sedimentary basin as early as Middle Cretaceous.

Fig. 10a and b shows rapid thickening of Companian–Maasrtishtian sediments in High Zagros area. It could be interpreted as a flexure in northeastern margin of the Arabian plate. Early Coniacian–Late Santonian ophiolite–radiolarite obduction and erosion provided the detritus material of the clastic beds within the Gurpi formation and its time equivalents in the High Zagros and northwest of the Izeh zone. After this incident and before the Early Miocene closure of Neotethys and Zagros orogeny, progressive deformation regional in scale affected the northeast margin of the Zagros basin and caused southwestward migration of sedimentary depocenter (Figs. 8c and 10b).

Oligo-Miocene isopach map and the subsidence curves in the Central Zagros (Figs. 10c and 13) show thinning of sedimentary deposits southwest of the Izeh zone. It might be related to the bulge effect, which affected the NE margin of Arabian plate during the closure of Neotethys.

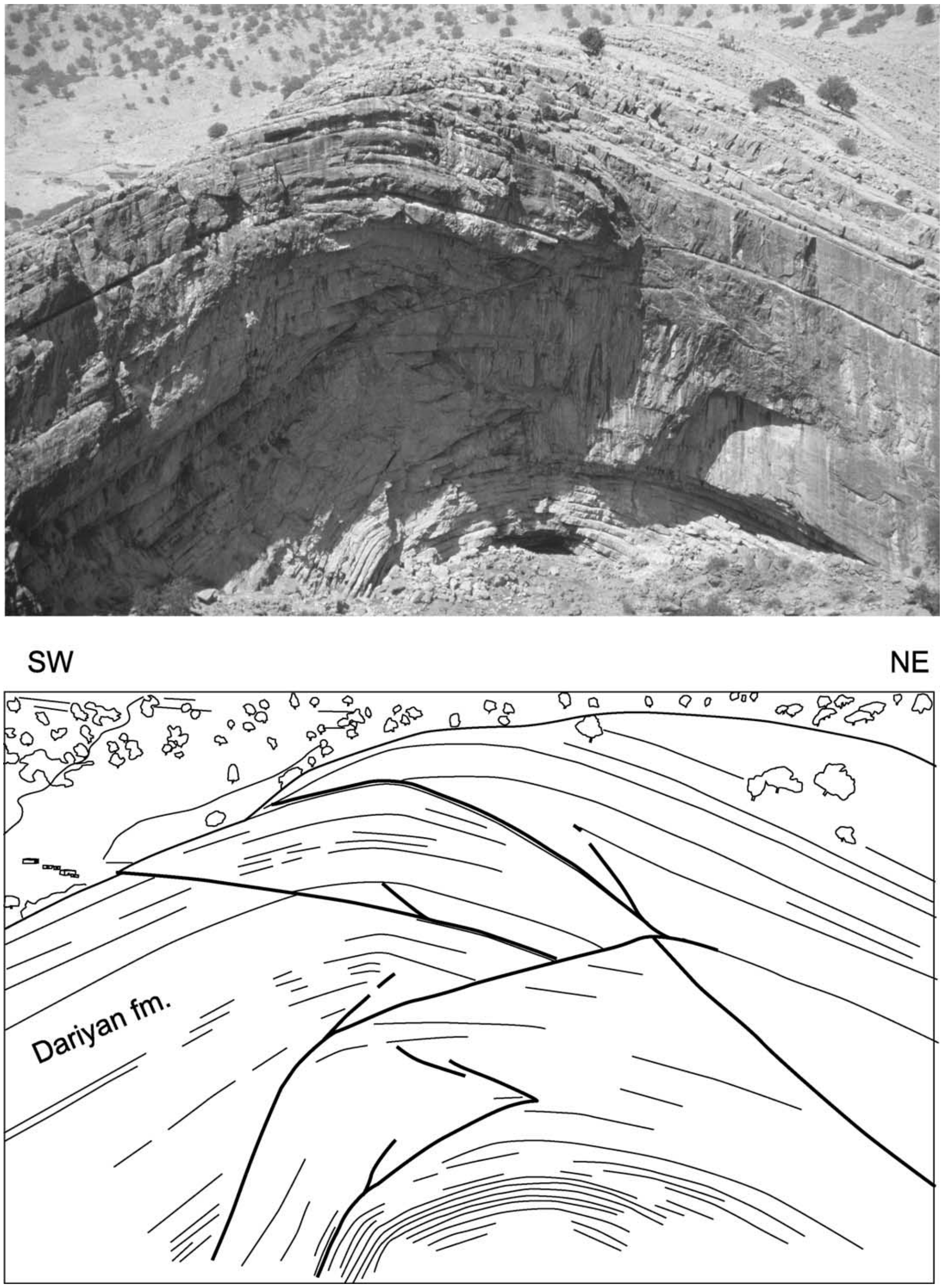

Fig. 14. Triangle shear geometry in Dariyan Fm. For location map, see Fig. 6, V.

Based on seismicity and topographical evidence in addition to compared depth of Palaeozoic and Mesozoic seismic reflectors in different synclines, our favorite interpretation, as was shown in the balanced regional cross-section, is stepwise uplift from SW to NE and basement involvement in the main structures (Fig. 3). Marked topographic steps along the section correspond to the High Zagros fault and the Mountain front fault which separate the High Zagros from the Izeh zone and the Izeh zone from the Dezful Embayment, respectively. Although we do not have direct evidence of basement involvement, present-day seismicity (Berberian, 1995; Jackson, 1980) as well as a basement gravimetry map (Morris in Motiei, 1995) support the idea of basement involvement and a breached Lower Palaeozoic decollement level.

6. Conclusion

This study of the southeastern part of the Dezful and Izeh zones in the Zagros mountain range clearly demonstrates the relationship between structural geometry and the lithological composition of the formations involved in the folding. The Palaeozoic to mid-Tertiary strata cannot be regrouped as a single tectonic 'unit' everywhere in the Zagros as has been suggested by previous workers (ColmanSadd, 1978; O'Brien, 1950). In addition to the basal decollement level located within Lower Palaeozoic and present throughout the study area, Triassic evaporites, Albian shales and Eocene marls acted as local intermediate decollement levels. They divide the sedimentary series into separate structural-stratigraphic units that have accommodated shortening differently. As a consequence, the surface configuration of some folds does not always reflect subsurface structural conditions, and so modern seismic acquisition and processing are necessary to image deep structures and reduce the uncertainties regarding the various assumptions.

Footwall synclines, high angle thrust faults, limb rotation and reduction in anticlinal wavelength during fold evolution are the specific characters of folds in the central Zagros. They can be interpreted as a transition in deformation behavior from detachment folding to progressive fault propagation, as it has been proposed for 'faulted detachment folds' by Mitra (2002b). Intermediate decollement levels with high competency contrasts with the surrounding series influenced fold and fault geometry by favoring triangle shear zones and Fish tail structures (Harrison & Bally, 1988; Letouzey et al., 1995) or fold accommodation faults (Mitra, 2002a).

The architecture of the sedimentary basins in the study area was clearly influenced by deep-seated pre-existing north–south Arabian trends. These faults were reactivated most strongly after the Late Cretaceous episode of ophiolite obduction (Koop & Stoneley, 1982). However, some rapid thickness variations and facies changes of Albian and Cenomanian sediments are documented by seismic lines and outcrops along the Kharg–Mish and Hendijan–Bahregansar N–S faults, which provides evidence of their activity and influence on sedimentary basin development before ophiolite obduction. Structural transect shows an abrupt drop in amount of shortening from approximately 16% in the Izeh zone to 6% in the Dezful Embayment. We suggest that a Middle to Post Miocene shift of sedimentary depocenter to the southwest allowed rapid subsidence and thick accumulation of the Fars group in the Dezful Embayment. Meanwhile, the inner part of the belt was subjected to folding, uplift and erosion. This mechanism constituted a resistant mass in the Dezful Embayment in front of the SW moving thrust and folds, in the Izeh zone and High Zagros, to form tightly folded or thrusted and highly shortened structures.

Thick accumulation of the Companian–Maastrishtian Gurpi formation in the High Zagros area, could be related to crustal subsidence and flexure in the northeastern margin of Arabian plate due to the ophiolite obduction. Progressive deformation following the obduction of oceanic crust caused the depocenter to migrate southwestward at the Eocene time. Later in Oligo-Miocene during closure of Neotethys and Zagros orogeny, vertical movements, which is interpreted as a bulge effect, affected the sedimentary basin southwest of Izeh zone.

Basement involvement parallel to the Zagros trend is deduced not only from the present-day seismicity of the area (Berberian, 1995) and present-day topography, but also from the difference in the elevation of Palaeozoic and Mesozoic formations between the main structural provinces: the Dezful embayment, the Izeh zone and high Zagros.

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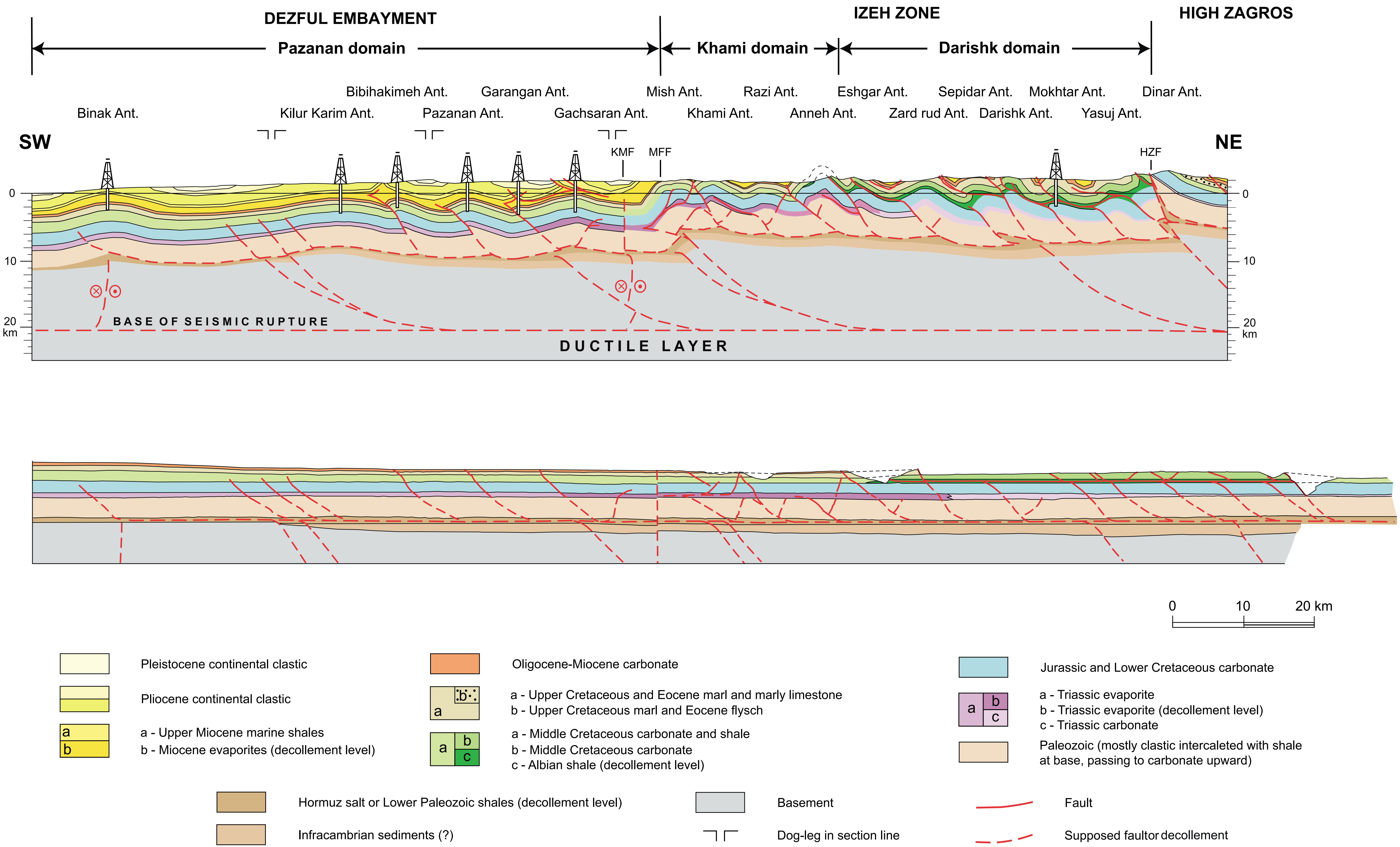

Fig. 3. Structural transect and balanced restoration of the central Zagros folded-and-thrust belt in the area east of the Izeh zone and the Dezful Embayment, (location of the section is shown in Fig. 1). HZF, MFF and KMF are abbreviations of High Zagros fault, Mountain front fault and Kharg–Mish fault, respectively. Formation boundaries were drawn in black solid line, when they are based on one of different sources of data (surface geology, seismic and well data), to separate from interpreted colorless boundaries.