Marine and Petroleum Geology 170 (2024) 107122

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Structural style & kinematic analysis of deformation in the northern Dezful Embayment, Zagros Fold-Thrust Belt, SW Iran

Masoud Joudaki [a], Ali Faghih [a,*], Soumyajit Mukherjee [b], Mohammad Seraj [c], Bahman Soleimany [d]

[a] Department of Earth Sciences, College of Science, Shiraz University, Shiraz, Iran
[b] Indian Institute of Technology Bombay, Mumbai, 400 076, India
[c] National Iranian South Oil Company (NISOC), Ahvaz, Iran
[d] National Iranian Oil Company, Exploration Directorate, Seoul Ave., Tehran, Iran

ARTICLE INFO

Keywords:
Structural style
Folding kinematic
Oilfields
Folding
Subsurface anticline
Northern Dezful Embayment
Zagros

ABSTRACT

A comprehensive understanding of structure and kinematic characteristics of fold and thrust belts provides significant information for hydrocarbon exploration and production. The kinematic evolution and structural style of three subsurface oilfields, Zeloi, Lali and Karun, in the northern part of the Dezful Embayment, a significant petroleum province of the Zagros Fold-Thrust Belt in SW Iran, were investigated using 2D seismic data. Interpretation of the 2D seismic profiles with up to 5 km depth consisting of upper Jurassic to Pleistocene sediments and the balanced cross-sections constructed revealed diverse geometries and kinematics along the oilfields. These results demonstrate that the structural style of the oilfields was controlled by the Gachsaran and Dashtak formations as upper and middle detachment levels, respectively. Tear faults affected the along-strike variations in structural style of the oilfields. Based on the analysis of growth strata, folding evolved as limbs rotated and hinges migrated, beginning in the mid-Miocene. During the later stages of deformation, the initial detachment folds transformed into fault-bend folds.

1. Introduction

In convergent regimes, relationship between faults and folding is one of the essential mechanisms that controls the structural style of the fold-thrust belt. Fault-related folds play an important role in developing hydrocarbon traps in fold-thrust belts (Mitra, 1990; Kent and Dasgupta, 2004; Kent, 2010; Brandes and Tanner, 2014; Ali et al., 2023).

The Zagros fold-thrust belt (ZFTB; Fig. 1a), one of the world's most oil-rich areas, formed due to the compression of Paleozoic-Mesozoic successions on the NE margin of the Arabian Plate, which in-turn resulted in deposition of thick foreland sequences during the Cenozoic. Foreland sequences (Berberian, 1995; Falcon, 1974; Sepehr and Cosgrove, 2004). The continental collision between the Afro-Arabian and Central Iranian lithospheric plates shortened crust significantly in the ZFTB and consequently folded and faulted the basement and overlying sedimentary cover (Berberian, 1995; Hessami et al., 2001a; Blanc et al., 2003; McQuarrie, 2004; Sepehr and Cosgrove, 2005; Alavi, 2007; Mouthereau et al., 2007b).

Recent studies have shown that the reactivation of basement faults (Hessami et al., 2001a; Bahroudi and Talbot, 2003; Sepehr and Cosgrove, 2005; Ahmadhadi et al., 2007; Mouthereau et al., 2007a, 2007b; Farzipour-Saein et al., 2009a; Nilfouroushan et al., 2013; Burberry, 2015) and the mechanical properties of sedimentary layers deposited in the ZFTB (Bahroudi and Koyi, 2003; Sherkati and Letouzey, 2004; Farzipour-Saein et al., 2009b) played a crucial role in shaping the geometry of the Zagros deformation front and its foreland basin.

Oblique-slip transverse faults in the ZFTB (Baker et al., 1993; Berberian, 1995; Hessami et al., 2001b; Bahroudi and Talbot, 2003; Sepehr and Cosgrove, 2005; Ahmadhadi et al., 2007; Farzipour-Saein et al., 2009a; Allen, 2010; Joudaki et al., 2016) have often been recognized as basement faults (Berberian, 1995; Hessami et al., 2001a; Bahroudi and Talbot, 2003). In many cases, these faults operated as tear faults and especially account for differences in the lateral geometric variation of the folds (Sherkati and Letouzey, 2004; Sepehr et al., 2006).

The configurations of the Neogene folding across the tear fault systems indicate that the fault systems are contemporaneous with or post-date folding (Sherkati et al., 2005; Sepehr et al., 2006; Ghanbarian and Derakhshani, 2022). Furthermore, the thicknesses and facies changes of

* Corresponding author.
E-mail address: afaghih@shirazu.ac.ir (A. Faghih).

https://doi.org/10.1016/j.marpetgeo.2024.107122
Received 8 June 2024; Received in revised form 30 August 2024; Accepted 17 September 2024
Available online 21 September 2024
0264-8172/

the overlying sedimentary cover are reflected in the present surface expression of most of these tear fault systems (Talbot and Alavi, 1996; Sherkati and Letouzey, 2004). On the other hand, mechanical stratigraphy is another important factor that controls structural styles in the ZFTB (Farzipour-Saein et al., 2009b). In particular, detachment levels have acted as controller of change in folding mechanism (Farzipour-Saein and Koyi, 2014a, 2016).

Fold and thrust belts usually do not have a substantial quantity of hydrocarbon. However, the converse is the case with the Zagros orogenic belt-it is one of the prolific petroliferous terrains with ~12% of

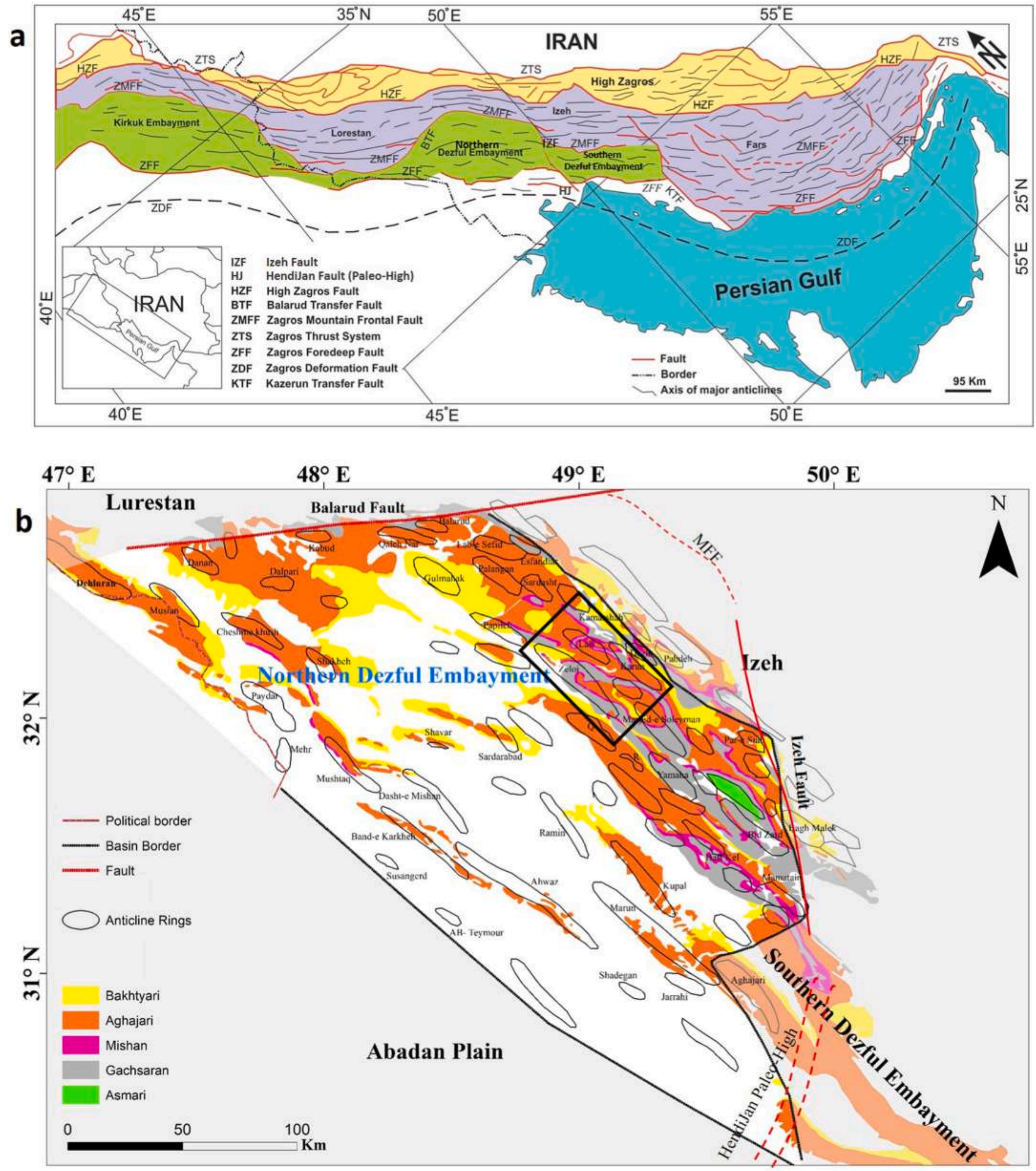

Fig. 1. (a) Structural map of the ZFTB and its subdivisions (Sherkati et al., 2005), (**B**) Geological map of the northern Dezful embayment (Modified after Abdollahie Fard et al., 2006). Black rectangle: study area.

the global hydrocarbon reserves (Razavi Pash et al., 2021; Alipour, 2024). The Dezful Embayment in the central Zagros is one of the structural subdivisions of the ZFTB (Fig. 1b). In this region subsurface anticlines trapped huge volumes of hydrocarbon and accommodated a major part of the oilfields of the ZFTB (Sherkati and Letouzey, 2004; Sarkarinejad et al., 2018). The structural complexity of folds can be observed both vertically and laterally in the Dezful Embayment (Razavi Pash et al., 2020, 2023). Thus, recognition of structural styles and folding mechanism are very important in hydrocarbon exploration and production from this region.

The Lali, Karun and Zeloi oilfields, are some of the very prolific oilfields in the northern Dezful Embayment (Fig. 1b), but our geo-scientific knowledge about them is limited. A number of researchers have published studies about these anticlines (**e.g.,** Asgari et al., 2019; Derikvand et al., 2019) but main aspects such as regional structural style and relationship of oil fields are still unknown.

In this study, we aim to document the folding mechanism, structural style and structural relationship between the Lali, Karun and Zeloi oil-fields in the northern Dezful Embayment based on the interpretation of 2D seismic data and construction of balanced and restored cross sections.

2. Geology

The sedimentary cover and associated basement in the ZFTB experienced 50–84 km of crustal shortening (McQuarrie, 2004, Vergés et al., 2011; Mouthereau et al., 2012; Saura et al., 2015) including faulting and folding caused by ongoing oblique convergence which started since the upper Cretaceous between the Afro-Arabian and Central Iranian lithospheric plates (Takin, 1972; Stöcklin, 1974; Berberian and King, 1981; Ghanbarian et al., 2021; Alipour, 2023). The ZFTB is located in the central part of the Alpine-Himalayan orogenic system and extends ~1800 km from SE Turkey to the straits of Hormuz, SW Iran (Berberian, 1995; Hessami et al., 2001a; McQuarrie, 2004; Sepehr and Cosgrove, 2005; Alavi, 2007; Sarkarinejad et al., 2008; Faghih and Nourbakhsh, 2015) (Fig. 1a).

From SW to NE the ZFTB is divided into three parallel structural zones including the foredeep, the Simply Folded Zone and the Imbricate Zone (Stocklin, 1968; Falcon, 1974; Berberian, 1995; Blanc et al., 2003; McQuarrie, 2004) (Fig. 1a).

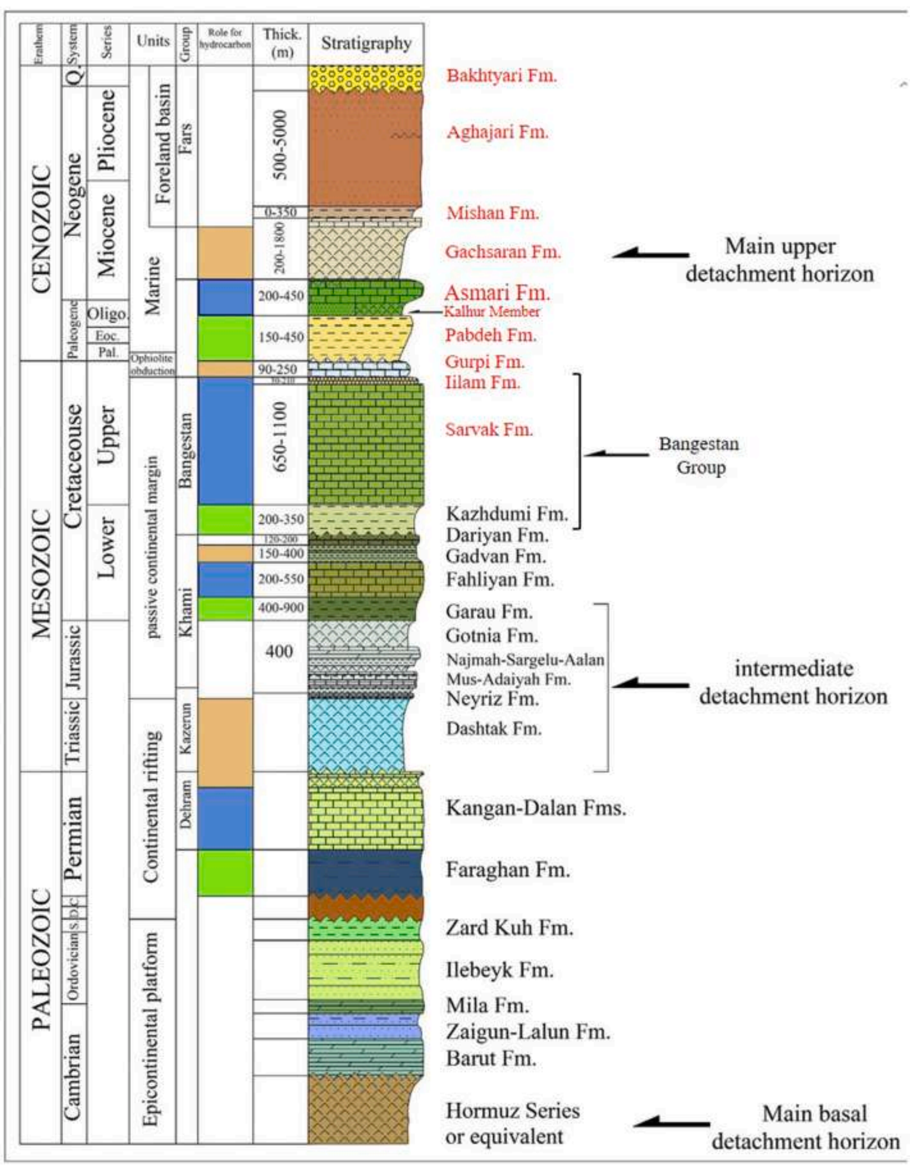

Fig. 2. Lithostratigraphic column of the Dezful Embayment showing competent and detachment units (Modified after Abdollahie Fard et al., 2006; Derikvand et al., 2019).

In addition to orogen-parallel zonation, based on structural features, the Simply Folded Zone can also be divided (along strike from east to west) into the Fars, Izeh, Dezful Embayment, Lurestan and Kirkuk Embayment (Sherkati and Letouzey, 2004) (Fig. 1a).

The Kirkuk and Dezful Embayments were the main foredeep basins of the Zagros orogen that accommodated a thick pile of the post-collision deposits (Berberian and King, 1981; Abdollahie Fard et al., 2006). The foredeep depression began after deposition of the lower part of the Asmari Formation (Sherkati et al., 2006; Van Buchem et al., 2010) and migrated southwest towards the Persian Gulf (Abdollahie Fard et al., 2006)

The Dezful Embayment is one of the most productive petroleum provinces worldwide, which is bound by the Zagros Foredeep Fault (ZFF) to the southwest, the Mountain Front Fault (MFF) to the northeast and the Izeh- Hendijan Fault (IZHF) zone to the southeast, the Balarud Fault Zone (BFZ) to the west, and the Kazerun Fault Zone (KFZ) to the east (Berberian, 1995; Sepehr and Cosgrove, 2005; Abdollahie Fard et al., 2006; Allen and Talebian, 2011) (Fig. 1).

The Dezful Embayment displays sharp differences in geological and morphological properties compared to the adjacent zones. In the Lurestan, Izeh and Fars zones, the exposed units in the core of the anticlines are carbonates of the Khami Group (Lower Cretaceous), Bangestan Group (Upper Cretaceous) and Asmari Formation (Oligo-Miocene) that form rough topography in these zones. In contrast, the Fars Group (Middle Miocene-Quaternary) crops out in the Dezful Embayment with gentle topography (Fig. 2). This distinct difference is caused by the activity of the main faults, which mark the boundaries of the Embayment (Sherkati and Letouzey, 2004; Vatandoust et al., 2020b; Shamszadeh et al., 2022a,b). The Dezful Embayment is divided into two subdivisions including northern and southern parts. Due to basement steps and deep stead faults, these parts are characterized by distinct tectono-sedimentary histories (Fig. 1).

3. Mechanical stratigraphy

Based on mechanical properties, the stratigraphic columns in the different parts of the ZFTB display noticeable variations (Sherkati and Letouzey, 2004; Sepehr et al., 2006; Ezati-Asl et al., 2019; Faghih et al., 2019; Sarkarinejad and Goftari, 2019).

The 10–14 km thick sedimentary cover of the ZFTB contains carbonates, evaporites, marls, shales and sandstones (James and Wynd, 1965; Colman-Sadd, 1978; Alavi, 2007) (Fig. 2). These sediments were deposited in various tectono-sedimentary environments during the Late Proterozoic to Cenozoic time (Alavi, 2004). From a mechanical stratigraphic point of view, the sedimentary succession of the ZFTB is divided into four groups. Evaporites of the Hormuz Series (Late Proterozoic-Early Cambrian) are covered by epicontinental sediments (including sandstones and shales with interbedded evaporites and carbonates) of Cambrian-Early Permian age (Alavi, 1994, 2004) (Fig. 2). The sedimentary successions associated with continental rifting of the initial Neo-Tethys Ocean during Permian-Triassic time is composed of siliciclastic rocks and carbonates, which unconformably overlie the older units (Alipour et al., 2021). Throughout the lower Jurassic-upper Turonian, stable passive margin conditions were marked by both shallow and deep-water carbonates and also some evaporites and siliciclastic sediments. After that, the Neo-Tethys Ocean started closing in the Late Cretaceous and therefore, the Zagros basin entered the compressional regime. During the Late Turonian to the Recent, marine and continental sedimentary rocks were deposited along the active margin of the Arabian plate (Stöcklin, 1974; Berberian and King, 1981; Koop et al., 1982; Alavi, 1994, 2004, 2007) (Fig. 2).

Accordingly, the stratigraphic column of the Dezful Embayment (Fig. 2) contains a series of competent and incompetent rock units. The competent units are divided into two groups as the lower competent units (Bangestan Group and Asmari Formation) and the upper competent units (Aghajari and Bakhtiari formations) (Fig. 2). The competent units are detached by the incompetent units including the Kazhdumi and Pabdeh-Gurpi shales as intermediate detachments, and the Gachsaran evaporites, as the main upper detachment (Sherkati and Letouzey, 2004; Derikvand et al., 2018).

The Hormuz Series or their equivalents (Eo-Cambrian-Cambrian evaporites or shales) on the crystalline basement formed the basal detachment horizon in the folding phase of the Dezful Embayment and the Paleozoic rocks are a competent unit in the different parts of the ZFTB (Sherkati et al., 2006; Farzipour-Saein et al., 2009b). The Dashtak Formation (Triassic evaporites) is considered as an intermediate detachment horizon in most parts of the ZFTB (Najafi et al., 2014). Towards the northeast of the Zagros belt, these evaporites were replaced by competent units of the Khaneh Kat carbonates (Szabo and Kheradpir, 1978; Alipour et al., 2021).

The activity of the Izeh and Kazerun faults during the Jurassic-Cretaceous is reflected by changes in the thickness and facies from evaporites and shales (e.g., from Adaiyeh up to the Garau formations) to carbonates (e.g., the Surmeh Formation and the Khami Group) in the Lurestan and Dezful Embayment. During the folding process, the Khami and Bangestan group carbonates and Asmari Formation, as main reservoirs of the study area, acted as a thick competent units (Abdollahie Fard et al., 2006; Sherkati et al., 2006; Hosseinpour et al., 2023).

The Late Cretaceous-Eocene Pabdeh-Gurpi formations are a potential to act as a detachment horizon. These formations in the northern part of the Izeh zone (Sepehr et al., 2006), the southwestern part of the Lurestan zone (Farzipour-Saein et al., 2009b; Farzipour-Saein and Koyi, 2016), and the southeastern parts of the Dezful Embayment (Carruba et al., 2006) formed a strong detachment horizon. Evaporites of the Kalhur Member (i.e., at the base of the Asmari Formation) can act as a subordinate and minor detachment horizon in some part of the ZFTB (Vergés et al., 2011; Mehdipour et al., 2024).

In the Dezful Embayment, the most important detachment horizon is the Gachsaran Formation (Sepehr et al., 2006; Sherkati et al., 2006). The Gachsaran Formation contains seven members. Members 2–5 mainly include salt and marl, and form a strong detachment horizon. High mobility of the evaporitic Members 2–5 developed disharmonic folding from surface to depth so that these units decoupled small emergent folds from large subsurface folds. In contrast, Members 1, 6 and 7 are competent units, which harmonically deformed together with older and younger units, (Motiei, 1994; Sherkati et al., 2006).

The Gachsaran Formation in the Dezful Embayment separate the smaller folds on the surface from the larger buried anticlines which are in most cases producing oilfields (Abdollahie Fard et al., 2006; Sherkati et al., 2006). These subsurface anticlines in the northern Dezful Embayment formed between two décollement horizons including upper décollement (Gachsaran Formation) and intermediate décollement horizons (especially Garau and Dashtak formations) (Ghanadian et al., 2017a, b, c; Sarkarinejad and Zafarmand, 2017). The presence of growth strata in the Gachsaran Formation indicates folding in the northern Dezful Embayment started in the Middle Miocene time (Sherkati et al., 2006).

The growth strata (Aghajari and Bakhtyari formation) affected the mechanical evolution of the folds in the Dezful Embayment. These formations accumulated in this basin as syn-tectonic deposits and were produced by uplift and then erosion of the hinterland during the Zagros orogeny (Abdollahie Fard et al., 2006; Sarkarinejad et al., 2018; Vatandoust et al., 2020b)

The position of such intermediate incompetent layers is an important factor controlling both structural style and fold wavelength (Farzipour-Saein and Koyi, 2014b, 2016). The competent strata are influenced by a series of anticlines and synclines associated with thrusts and reverse faults with NW-SE strikes within the Dezful Embayment

(Allen et al., 2011; Allen and Talebian, 2011).

4. Data and method

To study the lateral variations of the structural style in the northern Dezful Embayment, geological maps, seismic profiles and well data were used to interpret the structures at depth and construct balanced cross sections (Fig. 3). All data was provided by National Iranian South Oil Company (NISOC).

Several scientific software packages such as Petrel (v. 2016.3) and 2D Move (v. 2018.1) were used to analyze the subsurface data. Petrel software allows us to model structural elements such as faults and horizons to construct 3D structural models. Cross-section balancing was performed using the 2D Move software. The kink method applied for preparation of cross sections because the dip of layers in folds changes at small distances. In other words, the fold exhibits a series of kinks rather than smooth curvature.

Software used in this study aided the followings: (1) data uploading and creating a database, (2) data verification, (3) data processing, (4) interpretation of seismic data based on VSP and well data, (5), constructing 3D structural model, (6) check for data accuracy and QC, (7) constructing balanced cross sections by 3D Move software and (8) final QC and export the results.

5. Results

5.1. Data interpretation

In this study several subsurface data such as 2D seismic profiles, well data and underground contour maps (UGC maps) (Fig. 3) were used to better understand of subsurface structural style of the Zeloi, Lali and Karun oilfields (Fig. 4). Seismic profiles including 21 inline (perpendicular to axial plane) and 11 xline (parallel to axial plane) were interpreted in Petrel using well and check shot data (Figs. 5–9). We have adequate data and check shots from 19 wells in the Zeloi oilfield, 36 wells in the Lali oilfield and 7 wells in the Karun oilfield (Fig. 3). For better visualization, the geometric shapes of the subsurface anticlines were constructed, using 3D structural modeling in Petrel. The horizons identified and interpreted in the seismic sections across the studied oilfields range from the top of the Khami Group to Recent sediments.

We interpreted several seismic data by Petrel software and some of most important of them are presented in this study (Figs. 5–9). Figs. 5–9 display several parts of the subsurface anticlines (e.g. the NW plunge of the Zeloi anticline in Fig. 5, the SE part of the Zeloi anticline in Fig. 6, the NW plunge of the Lali anticline in Fig. 7, the middle part of the Lali anticline in Fig. 8 and the Karun anticline in Fig. 10).

These seismic profiles were interpreted very exactly and targeted reflectors were checked by wells data and check shut data (VSP data). Wells data allowed us to identify all stratigraphic surfaces from recent sediments to top of the Khami Group. The most complex unit in data

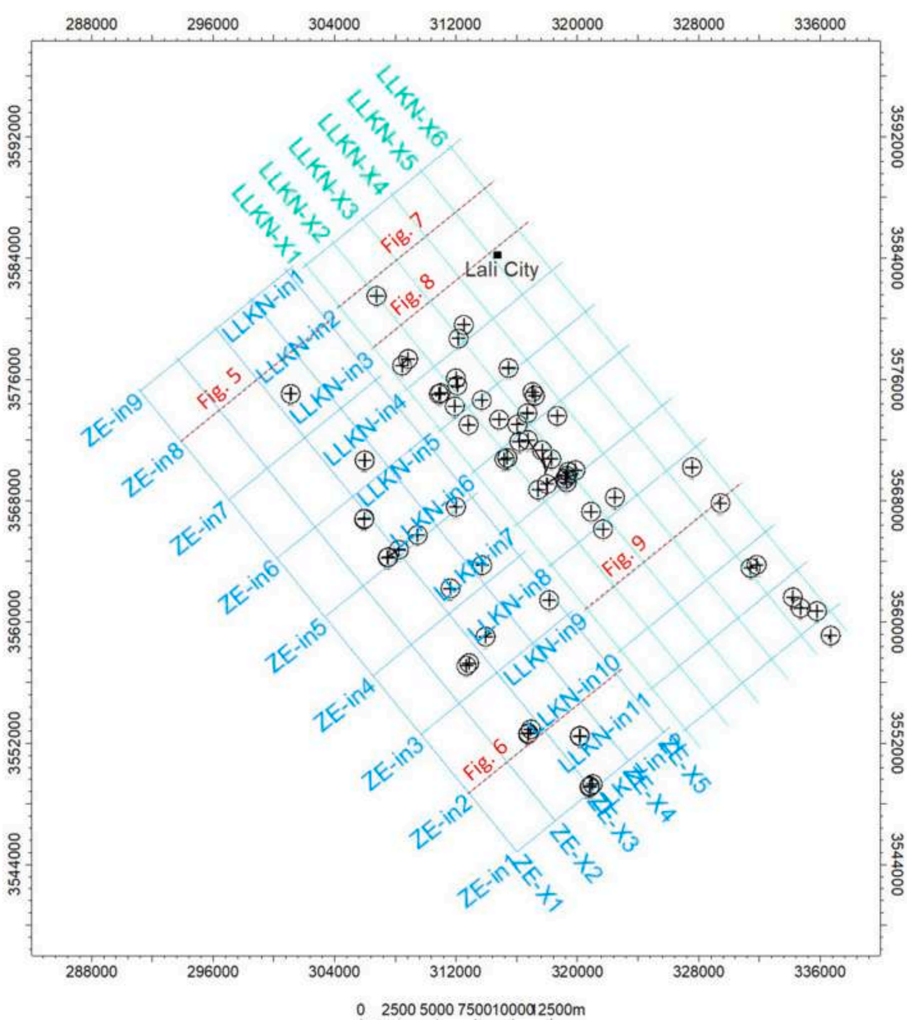

Fig. 3. Map showing the location and distribution of the seismic and well data used in this study.

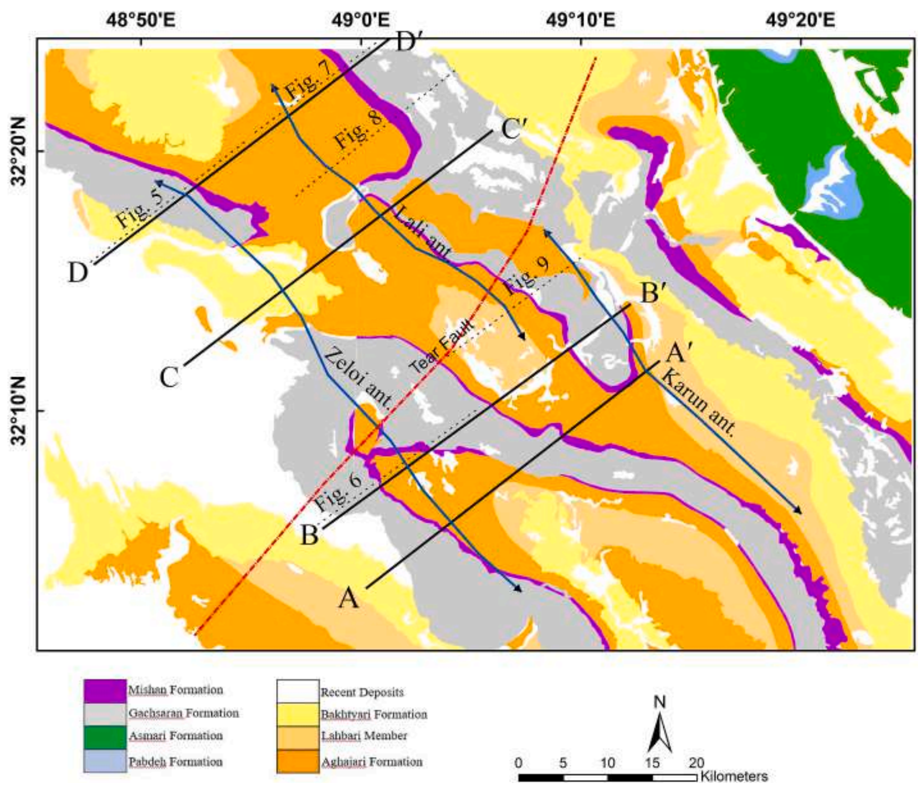

Fig. 4. Geologic map of the study area, solid and dashed black lines show the locations of the balanced cross sections and presented seismic profiles, respectively. Blue lines: location of the anticline axis at the Asmari level.

interpretation is Gachsaran Formation because of flowing and mobility of this formation, but fortunately, all members of this formation have been identified in well profiles carefully and we interpreted this formation with very high precision.

5.2. Balanced cross-sections

For investigation of the variations of structural style of deformation along the study area, five balanced and restored cross sections were constructed. Locations of these cross sections are shown in Fig. 4. The NW-SE trending Zeloi anticline is a regional fold that extends thorough the study area and the Karun and Lali anticlines are parallel to the Zeloi anticline. This is evident on Fig. 4 and appears in the following.

5.2.1. Cross sections across the Zeloi and Karun anticlines

Two cross sections across the Zeloi and Karun anticlines (Fig. 10a and b) were selected to investigate the structures and geometry of the Karun anticline and southeastern part of the Zeloi anticline. The cross section A–A′ (trending NE-SW) constitutes southeastern plunge of the Zeloi anticline (Fig. 10a). Length of this section is ~27 km. Shortening percentage in this section is calculated ~25 %, which equals ~9.15 km.

The cross section B–B′ is across the southeastern part of the Zeloi anticline (Fig. 10b). Length of this section is 26.8 km. The section also constitutes the northwestern part of the Karun anticline. Shortening percentage in this section is calculated to be ~19 %, which equals ~6.2 km.

The study of seismic lines (Fig. 9) and cross sections A–A′ and B–B′ (Fig. 10a and b), reveals another anticline between the Zeloi and Karun anticlines. This structure has hitherto been unknown and can be a potential prospect for hydrocarbon exploration.

5.2.2. Cross sections across the Zeloi and Lali anticlines

For better understanding of structures and geometry of the Karun and Zeloi anticlines we constructed two cross sections across the Zeloi and Lali anticlines (Fig. 10c and d). These sections contain the Lali and northwestern part of the Zeloi anticlines and demonstrate the relationship of the oil fields and their structural style.

The 22.5 km long cross section C–C′ is across approximately the middle part of the Zeloi anticline (Fig. 10c). The Lali anticline is located in east of the Zeloi anticline and this section is across both of them. Shortening percentage along this section is calculated to be ~13 %, which equals ~3.4 km.

The 23 km long cross section D–D′ is across northwestern part of the Zeloi anticline (Fig. 10d). The section is also across of northwestern part of the Lali anticline. Shortening percentage in this section is calculated ~20 %, which equals ~6 km.

5.3. Geometry of the oilfields

In the following section, the structures that appear in the interpreted 2D seismic profiles and the constructed balanced cross sections are described (Figs. 5–10). The Zeloi, Lali and Karun anticlines (Fig. 4) are the important oil fields of the ZFTB in north of Dezful Embayment (Fig. 1b) that are separated by a number of main thrusts.

The Zeloi anticline trends NW-SE and verges towards SW. According to the cross sections (Fig. 10), this anticline has interlimb angles of $\alpha = 160^\circ$ (A–A′ section), 146° (B–B′ section), 164° (C–C′ section) and 166° (D–D′ section), and is classified as a gentle anticline (Fleuty, 1964). As per Ramsay's (1967) scheme, it is a class 1B fold. The Zeloi anticline has different kink-shaped folds. In northwest, the fold is asymmetric and toward southeast its geometry changes to symmetric. The fold originated by detachment folding mechanism.

The Karun anticline trends NW-SE and verges SW. According to the cross sections, this anticline has interlimb angles of $\alpha = 164^\circ$ (A–A′ section), 160° (B–B′ section), and is classified as a gentle anticline (Fleuty, 1964) and as per Ramsay's (1967) scheme it is also a class 1B fold. Seismic data quality towards the east of the fold is not good but it seems that fold shape of the Karun changes between asymmetric and

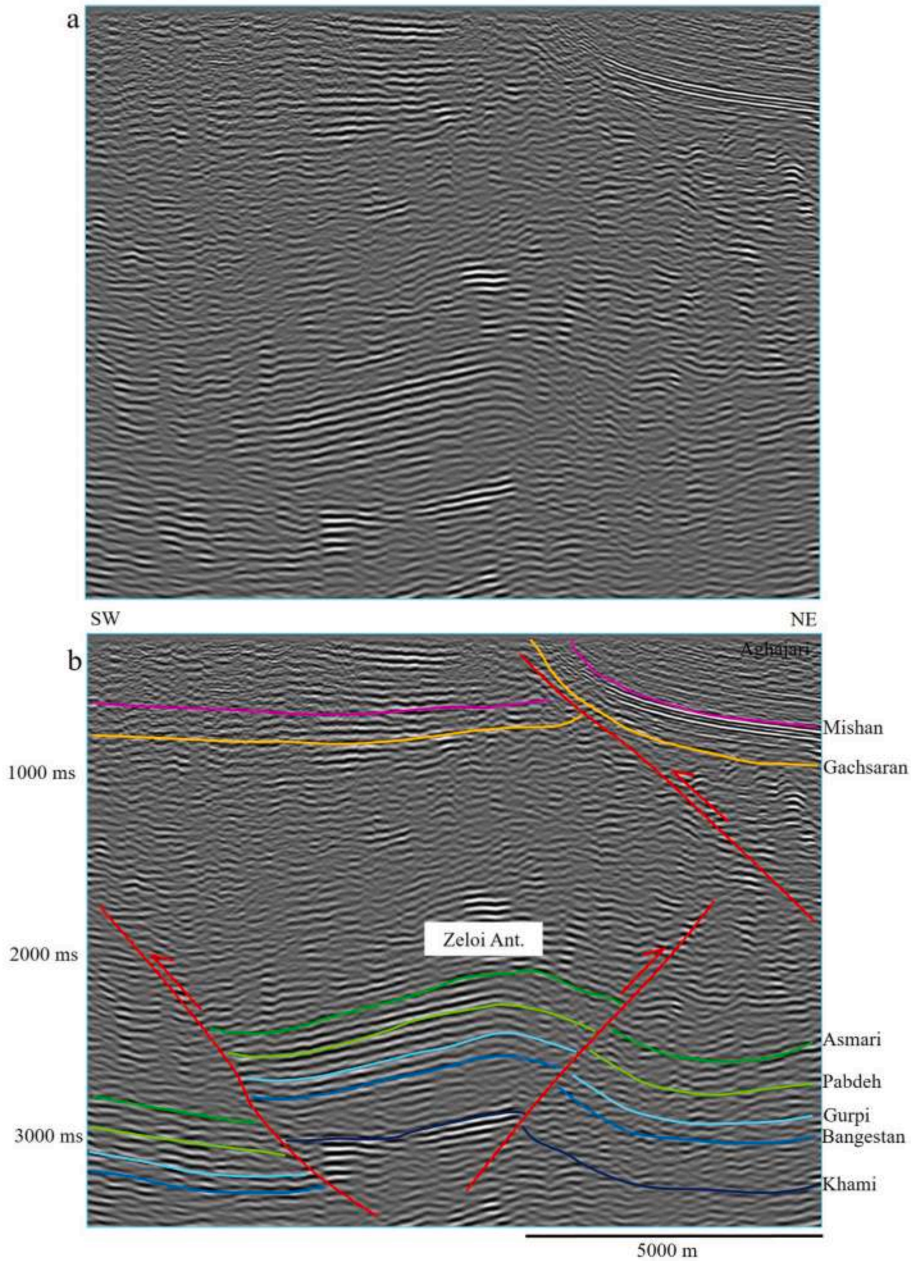

Fig. 5. (a) Uninterpreted and **(b)** interpreted of the 2D seismic profile across NW plunge of the Zeloi anticline with three times magnification in vertical scale. Top of each formation is labeled by colored continuous lines (see Fig. 3 for location).

symmetric and the fold has a detachment folding mechanism.

The Lali anticline trends NW-SE and verges SW. As per the cross sections, this anticline has interlimb angles of $\alpha = 156^{\circ}$ (C–C′ section) and 162° (D–D′ section), and is classified as a gentle anticline (Fleuty, 1964). As per Ramsay (1967) scheme, it is a class 1B fold. The Lali anticline has an asymmetric shape with detachment folding mechanism.

The hitherto unknown anticline between the Zeloi and the Karun anticlines formed like a pop-up structure being governed by a forethrust and a backthrust. The fold is a disharmonic detachment fold with double hinges that can be subject of a new study (Fig. 10a and b).

5.4. Syn-tectonic sediments

The surface synclines accommodated syn-tectonic deposits (growth strata) in the Dezful Embayment (Fig. 1b). In the study area the synclines on both sides of the anticlines are filled by the Bakhtyari, Aghajari and Mishan formations (Fig. 4). The thickness of these units is up to 4 km in the study area. The growth strata include a series of sediments from the Bakhtyari Formation to the top of competent members of the Gachsaran Formation. The Gachsaran Formation plays an important role in geometry and style of its upper and bottom unites. Actually, variation of vertical structural style in the basin occurs by the mobility of this formation. The Gachsaran Formation has flowed during progressive deformation in structures. Flow and accumulation of the Gachsaran Formation during the structural evolution of the area has caused the formation of thrust faults. The structural style of the strata beneath the Gachsaran Formation has played a key role in the behavior of the Gachsaran incompetent units. It should be noted that during progressive deformation and evolution of the sedimentary basin and structures, a collection of factors played role simultaneous. Meanwhile, the mobility of the Gachsaran Formation has more fundamental role in the current feature of this formation (Abdollahie Fard et al., 2011; Ghanadian et al.,

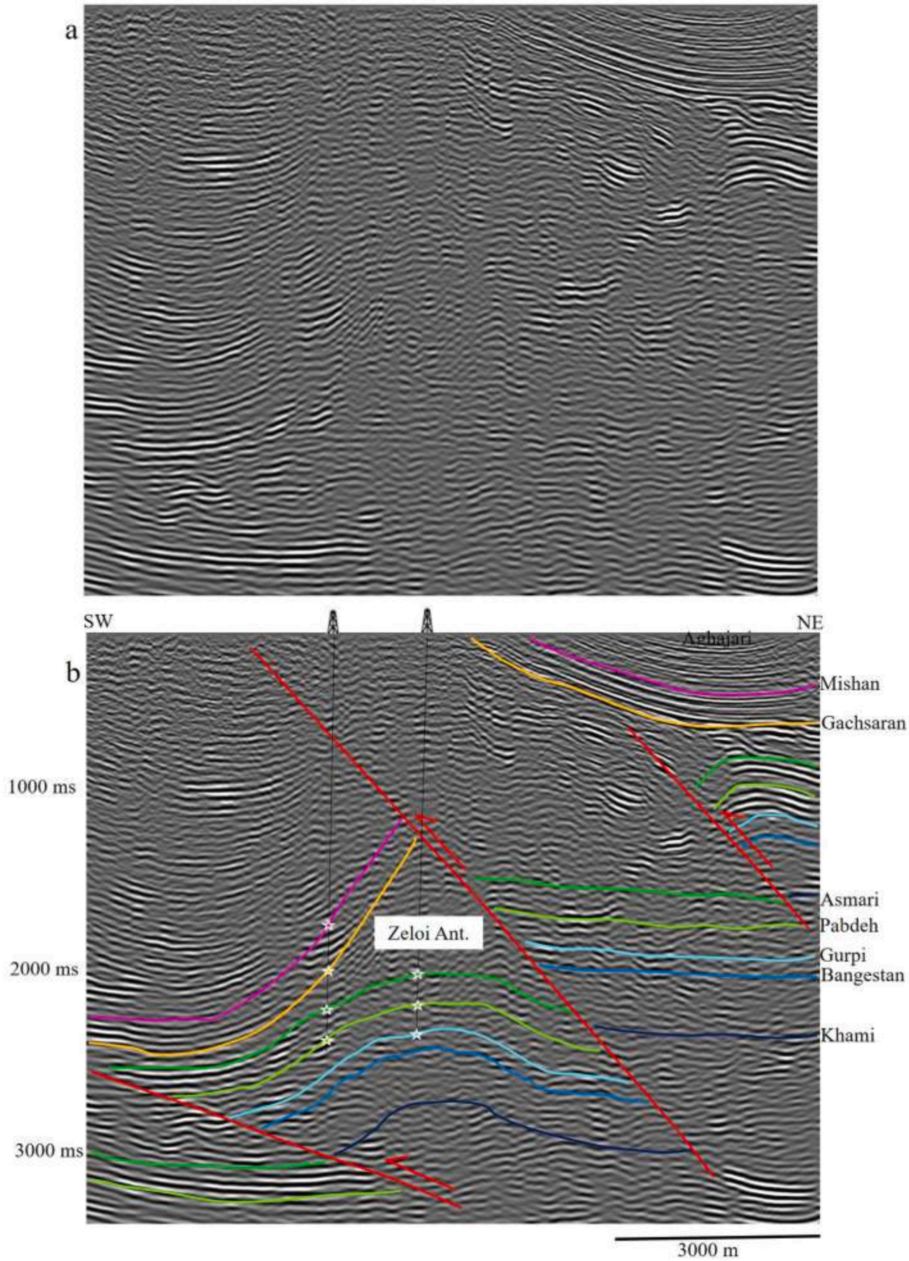

Fig. 6. (a) Uninterpreted and **(b)** interpreted of the 2D seismic profile across SE part of the Zeloi anticline with three times magnification in vertical scale. Top of each formation is labeled by colored continuous lines **(locations in Fig. 3).**

2017b).

The geometry of syn-tectonic sediments is affected by fault-related folding. During folding by kink-band migration, material moves across the axial surfaces and therefore the width of the limbs increases, but the dip is maintained constant (Suppe et al., 1992). Migration of material through the axial surfaces progressively extends the rock volume.

5.5. Depth of detachment

Several methods have been presented to estimate the depth of basal detachment in constricted cross sections based on seismic data or in regions where detachment surface are not outcropped (Groshong Jr, 1994, Groshong Jr, 2015; Bulnes and Poblet, 1999). We followed Chamberlin's (1910) and Bulnes and Poblet's (1999) method to estimate the detachment depth beneath the studied anticlines. Chamberlin's (1910) method, based on the area-conservation principle, predicts that the detachment depth equals the excess area beneath a particular horizon uplifted above the regional, divided by the shortening undergone by this horizon. This method is based on plotting the depth levels and thickness of stratigraphic surfaces on a diagram. In such a way that thickness of each formation and cumulative thickness of all stratigraphic units are plotted on a diagram. Then depths of surfaces are calculated and by drawing a best-fit graph, depth of basal detachment will be estimated. Thus, the detachment depths (excess area divided by shortening) and cumulative stratigraphic thicknesses were calculated for different horizons and then the results were plotted (Fig. 11). Finally, by the best-fit detachment depth graph technique, the intersection between the best-fit line through the plotted points and the y-axis shows the position of the detachment surface within the stratigraphic section. Based on these methods, the depth of the detachment level for the anticlines was estimated (Fig. 11).

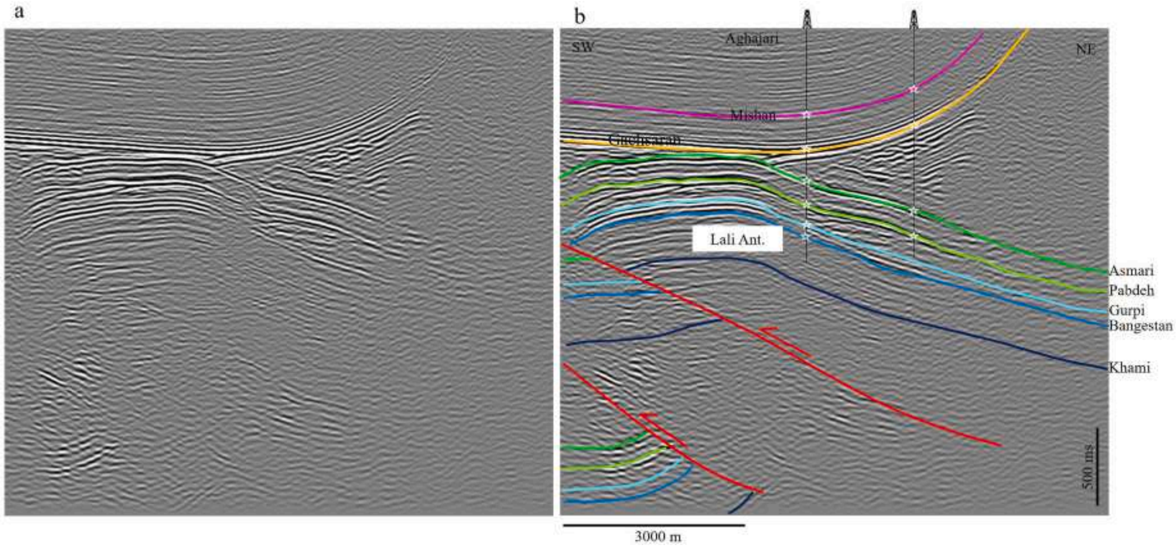

Fig. 7. (a) Uninterpreted and **(b)** interpreted of the 2D seismic profile across NW plunge of the Lali anticline with three times magnification in vertical scale. Top of each formation is labeled by colored continuous lines **(locations in Fig. 3).**

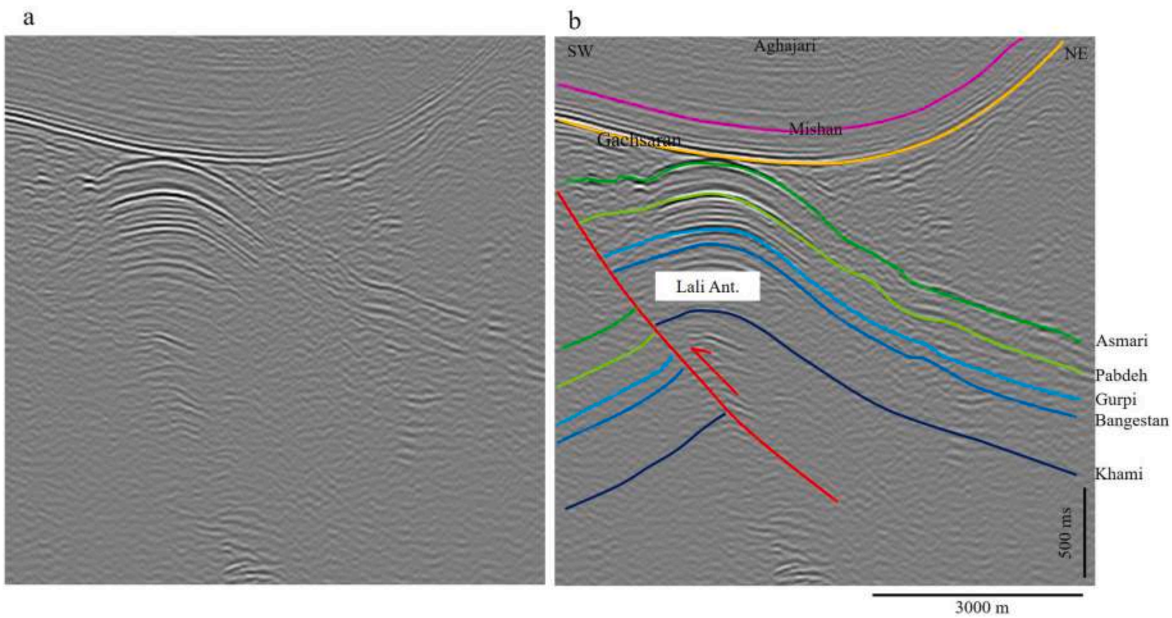

Fig. 8. (a) Uninterpreted and **(b)** interpreted of the 2D seismic profile across middle part of the Lali anticline with three times magnification in vertical scale. Top of each formation is labeled by colored continuous lines **(locations in Fig. 3).**

5.6. Along-strike structural variation in the oilfields

Along-strike or arc-parallel structural variation of orogens have been studied for pure and applied aspects of research (Dutta et al., 2019; Biswas et al., 2022). To better understand the structural style and geometry of the studied anticlines, a constructed 3D structural model, interpreted 2D seismic sections and balanced cross sections were provided for the Zeloi, Lali and Karun oilfields (Figs. 5–10). According to these results, the geometry of the anticlines varies from NW to SE in the study area, that is, along the trend of the anticlines and the attitude of the axial plane varies also from place to place. From NW to SE, the Zeloi anticline appears as a pop-up structure in the NW to the central part of the study area (Fig. 5). In the SE part, the Zeloi anticline does not display the same backthrust and the pop-up geometry (Fig. 6).

Both of the Karun and Lali anticlines become tighter from the SE to the NW, but, the Zeloi anticline has the same interlimb angle in most parts along the NW-SE trend. It shows a tighter interlimb angle in the B–B′ cross section (Fig. 10).

The axis of the anticlines has a curved shape in particular along the Zeloi anticline, and the greatest amount of deformation has occurred in the SE part of the study area. This may be due to the different amount of slip along faults.

6. Discussions

6.1. Structural styles and folding mechanism

Determination of fold geometry is very important in hydrocarbon exploration. Folding of more competent layers above a weak detachment or decollement occurs at various scales in the uppermost crust (Motamedi et al., 2012; Vatandoust et al., 2020a). The detachment is typically overpressured shale or salt, overlain by more competent layers

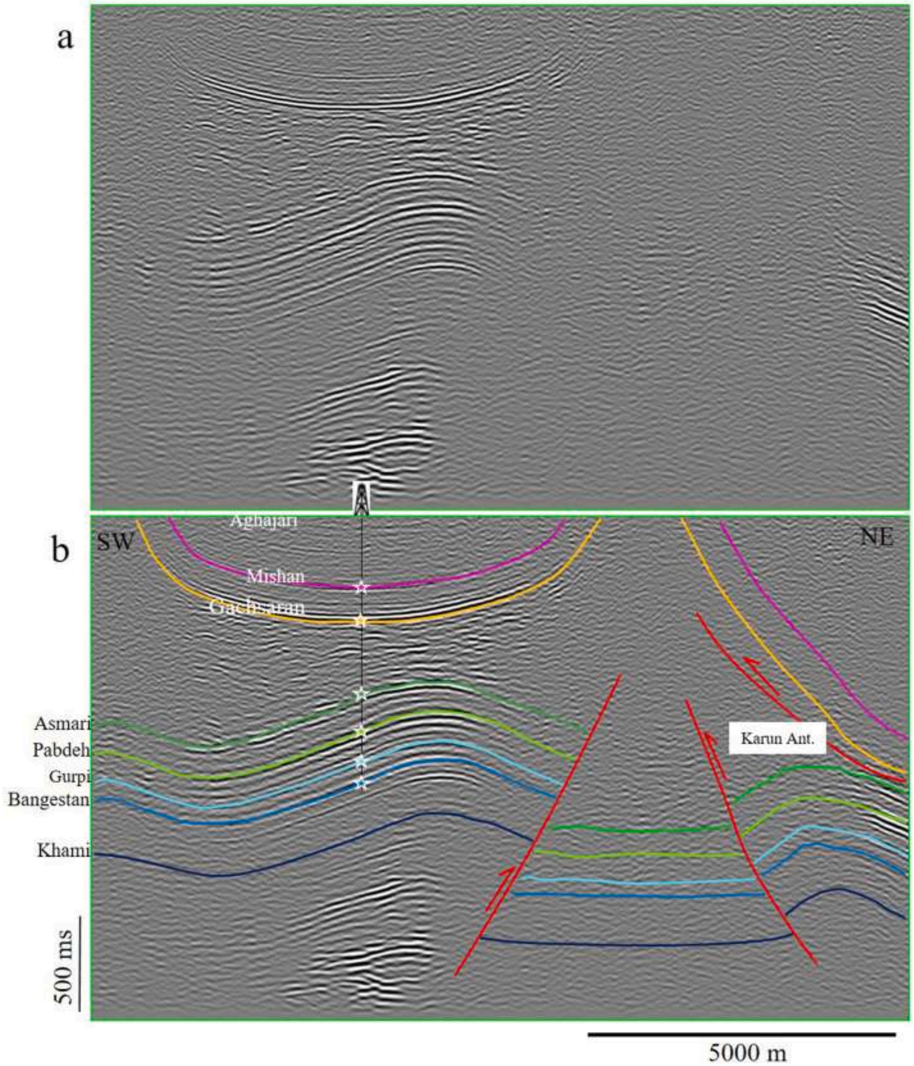

Fig. 9. (a) Uninterpreted and **(b)** interpreted of the 2D seismic profile across the Karun anticline and new introduced anticline with three times magnification in vertical scale. Top of each formation is labeled by colored continuous lines **(locations in Fig. 3).**

of sandstone or limestone. The folds may be concentric, chevron or box shaped, showing symmetric, asymmetric, disharmonic, lift-off and multi-detachment styles (Nabavi and Fossen, 2021). However, the folds vanish abruptly towards the underlying detachment. These folds are commonly found in the fold-thrust belts, such as the ZFTB and have played a dominant role in the kinematics of thin-skinned tectonics (Dahlstrom, 1969; Jamison, 1987; Poblet and McClay, 1996; Mitra, 2003; Brandes and Tanner, 2014).

In the study area, folded competent units located between two main detachment surfaces, Gachsaran and Dashtak formations (Fig. 2), developed concentric detachment folding as per Dahlstrom (1969) and Sherkati et al. (2005). Few researchers (Bordenave and Hegre, 2005; Sherkati et al., 2005; Abdollahie Fard et al., 2006; Derikvand et al., 2018, 2019; Razavi Pash et al., 2020, 2023; Vatandoust et al., 2020b) have also reported a detachment folding mechanism in the northern Dezful Embayment (see Tables 1 and 2 for more information).

As occurred in the right limb of the Lali anticline, existence of a minor detachment level (originated from the Pabdeh-Gurpi formations) caused rabbit ear structures (Le Garzic et al., 2019) (Figs. 7 and 8).

The Zeloi anticline is a pop-up structure related to two thrust faults in the NW part of the fold (Figs. 5 and 10c, d). Because of the existence of the intermediate detachment horizons, the kinematic evolution of this symmetric pop-up structure can be explained by the model of symmetric faulted detachment folds (Mitra, 2002) (Fig. 12). The geometry of the Lali and Karun anticlines and also the geometry of SE part of the Zeloi anticline display a similar geometry of fault-propagation folds. Although, fault-propagation folding mechanism is dominant, because of the complexity of the region, it seems fault-bend folding also can be considered or, at least there is a combination of both fault-propagation and fault-bend folding mechanisms (Suppe et al., 2004). Also the new discovered unnamed fold in this study is deciphered to be a detachment fold. However, these anticlines show mutually different evolutionary steps associated with different shortening percentage. Detachment folding is the main folding style at least for the initial stages of deformation. This was followed by fault-bend folding in most parts of the study area (Fig. 12).

In the study area, there are evaporite units as detachment horizons, which separate the competent units (Fig. 2). The thickness ratio of competent units to the incompetent ones controlled the geometry of the fold. The relation between the activity of the incompetent layers and the structural style in the foreland fold-and-thrust belt has been studied (Sherkati et al., 2005; Abdollahie Fard et al., 2011; Farzipour-Saein and Koyi, 2016).

Intensity of deformation and geometry of folds in the underlying competent units influenced deformation of the Gachsaran Formation (Bahroudi and Koyi, 2004; Mashal et al., 2014). The Gachsaran

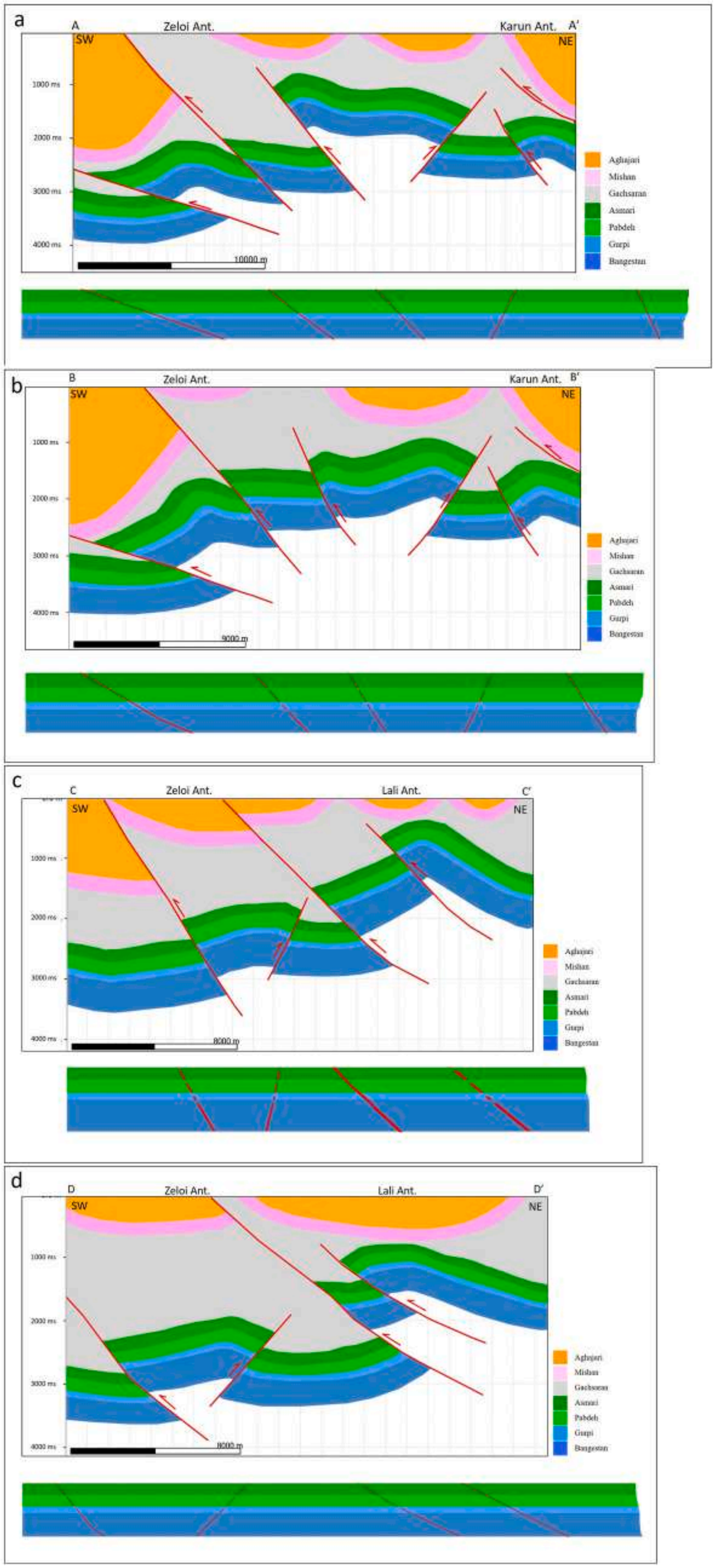

Fig. 10. (a) A-A' balanced and restored cross section across the Zeloi and Karun anticlines and the deciphered anticline between them. (b) B-B' balanced and restored cross section across the Zeloi and Karun anticlines and the deciphered anticline between them. (c) C-C' balanced and restored cross section across the Zeloi and Lali anticlines. (d) D-D' balanced and restored cross section across the Zeloi and Lali anticlines (locations in Fig. 4).

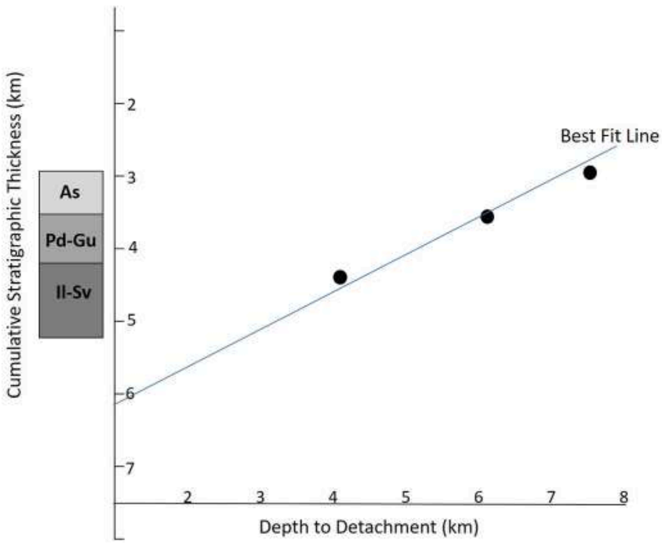

Fig. 11. The graph of the best-fit detachment depth for the study area (methods of Chamberlin, 1910; Bulnes and Poblet, 1999).

Formation has moved from anticlinal areas into synclinal areas during folding of the underlying competent layers (Fig. 10). This incompetent layer flowed from anticlinal to synclinal parts and accumulated in syncline in limbs of anticlines (O`Brien, 1957; Abdollahie Fard et al., 2011). Then, thickness of the Gachsaran Formation in crest of the anticline is less than in both limbs of the fold due to salt ductile flow, as observed in the study area (Figs. 5–10). Hence, thickness of Gachsaran Formation in the crest of subsurface anticline is less at the limbs particularly in the footwall syncline in the forelimb. This observed phenomenon in the study area is presented throughout the Dezful Embayment (Abdollahie Fard et al., 2011). Due to migration of the Gachsaran Formation disharmonic folding is developed across the uppermost parts of the fold profiles (Sepehr et al., 2006; Abdollahie Fard et al., 2011; Mashal et al., 2014). On the top of the Gachsaran Formation, the Aghajari Formation collapsed due to salt's ductile flow. Normal faulting in Aghajari Formation i.e., extensional tectonics within the compressional orogen is possibly a result of gravitational collapse.

Vertical variation in style and geometry of the folds can be followed by the synclines in uppermost of the sedimentary succession of the area. As mentioned before, because of flowing the Gachsaran Formation during the progressive deformation, geometry of folds has been changed in vertical scale where synclines developed atop the anticlines.

Folding in the growth strata are found in the 2D seismic profile of the studied anticlines. It seems that the folding started in the Middle Miocene (coeval to the upper Gachsaran's deposition) in the study area. The pattern of the reflectors of growth strata in the upper Gachsaran Formation at the forelimb of the anticlines indicates combined hinge migration and limb rotation during the fold growth (Figs. 5–9).

In addition to the Gachsaran Formation as the upper décollement horizon at the north Dezful Embayment, there is another main décollement known as the middle décollement horizon. Component layers folded between the upper and the middle décollement horizons form subsurface anticlines in north of the Dezful Embayment and act as the main oil reservoirs in this region. The Garau to Dashtak formations (Fig. 2) act as intermediate décollement levels that controlled the geometry of competent layers in the study area (Sherkati et al., 2006). Folding style of the studied anticlines beneath the Gachsaran Formation was controlled by thickness variation of the intermediate detachment horizon (Garau to Dashtak formations) along strike of these anticlines.

In the foreland ZFTB, structural style varies due to the presence of thrusts, tear faults and intermediate and upper décollement horizons. The Miocene compressional tectonic regime was associated with the

Table 1
Summary of work, approaches and terrain of several references about the tectonics of the Dezful Embayment.

Authors	Summary of work	Approaches	Terrains
Sherkati and Letouzey (2004)	This study suggests ongoing movement along faults in the Zagros basement before the Neogene Zagros folding. It also indicates a southwestward migration of depocenters over time and basement involvement below some folds during the Zagros orogeny.	Surface and subsurface data analysis	Dezful Embayment, Zagros
Sherkati et al. (2005)	In the Zagros region, detachment folds formed during a thin-skinned phase of deformation, followed by the current thick-skinned stage. This can be observed clearly in the Eastern Zagros, where basement faults cut across early detachment folds obliquely.	Surface and subsurface data analysis	Dezful Embayment, Zagros
Bordenave and Hegre (2010)	The study suggests that Zagros folding started around 10 million years ago and continued through the Late Miocene and Pliocene. It also indicates that oil expulsion from the Kazhdumi and Pabdeh source rocks began between 8 and 3 million years ago during the Aghajari Formation deposition, depending on the location.	Laboratory analysis of samples and subsurface data	Dezful Embayment, Zagros
Abdollahie Fard et al. (2006)	This study reveals a variety of fold styles in the Dezful Embayment. Toward the foreland, the folds are gentle and upright, showing initial detachment folding. Toward the hinterland, fault-propagation folding, fault-bend folding, and duplexes are found in stiff limestone.	subsurface data analysis	Dezful Embayment, Zagros
Carruba et al. (2006)	In this study, a restored cross-section shows an 11.5% shortening in the region and discusses the involvement of the crystalline basement in thrusting, the deep structural style, and their implications for earthquake mechanisms and structural analysis.	Surface and subsurface data analysis	Dezful Embayment, Zagros
Bordenave and Hegre (2010)	This study demonstrates that the Zagros folding started in the northeast part of the Dezful Embayment after the Mishan Formation deposition ended 12.5 Ma ago.	Laboratory analysis of samples and subsurface data	Dezful Embayment, Zagros
Derikvand et al. (2018)	The arrangement of structures in the study area is influenced by the	Surface and subsurface data analysis	Dezful Embayment, Zagros

(continued on next page)

Table 1 (*continued*)

Authors	Summary of work	Approaches	Terrains
	interaction of competent and incompetent units, as well as the growth-strata of the Miocene-Pliocene deposits in later stages of deformation.		
Sarkarinejad et al. (2018)	In the northern Dezful Embayment, anticlines are observed to form through the evolution of the anticline on the middle décollement horizons. They initially manifest as detachment folds, transition into fault-propagation folds, and eventually develop into fault-bend folds in the later stage of deformation.	subsurface data analysis	Dezful Embayment, Zagros
Razavi Pash et al. (2020)	In the central part of the Zagros foreland fold-and-thrust belt, there are tear fault systems caused by the differential lateral propagation of folds. These tear faults accommodate different structural styles during compressional tectonics in the Zagros belt.	subsurface data analysis	Dezful Embayment, Zagros
Vatandoust et al. (2020b)	In the Middle Miocene, detachment folding with limb rotation started and continued with the migration of the basal detachment horizon into the core of the anticlines. The development of a disharmonic folding style was controlled by the upper detachment surface through migration and by the reactivation of the basement faults. The total shortening amounts changed between 21% and 12% from the northwest to the southeast part of the area.	subsurface data analysis	Dezful Embayment, Zagros
Shamszadeh et al., 2022a, b	The study suggests that the basic structure of the sedimentary basin, influenced by basement structures and salt layers, plays a vital role in the formation and evolution of geological structures and their timing.	Analogous modeling and subsurface data analysis	Dezful Embayment, Zagros
Razavi Pash et al. (2023)	This study demonstrates how various factors like overburden pressure, deformation rate, and uplift interacted to move and accumulate the Gachsaran Formation towards both limbs of the anticlines.	subsurface data analysis	Dezful Embayment, Zagros

activity of the pre-existing inverted basement fault. These reactivated pre-existing basement tear faults caused a change in location of the anticlines relative to each other. In the foreland fold-and-thrust belts, tear faults run across the strike of the belt to accommodate differential displacement or various structural styles between two segments of the ZFTB.

Table 2
Summary of work, approaches and terrain of several references about the studied oil fields and the North Dezful Embayment.

Authors	Summary of work	Approaches	Terrains
Derikvand et al. (2018)	This study show that the Zeloi Anticline is symmetric and asymmetric faulted detachment fold in the central part and SE plunge, respectively. But the reduction of the thickness of the Garau to Dashtak formations to the NW plunge led to the formation of shear fault-bend fold.	subsurface data analysis	North Dezful Embayment, Zagros
Talebi et al. (2018)	This study show that in situ stress magnitudes in the Lali oil wells are consistent with a strike-slip regime, while in the Zeloi oilfield, normal faulting regime is estimated.	subsurface data analysis	North Dezful Embayment, Zagros
Asgari et al., 2019	In this study, the role of incompetent strata and fault geometry on the folding mechanism of the Karun oil field are investigated. The results of these investigations showed that the structure style of the Karun anticline was controlled by the interaction of stratigraphy units and faults and folding mechanism of the Karun anticline is the faulted-detachment fold and changing in the thickness of the Dashtak Formation changed the geometry of the Karun anticline.	subsurface data analysis	North Dezful Embayment, Zagros

Several tear fault systems exist in the central part of the ZFTB (Fig. 1), which have been attributed to inherited basement-level faults (Falcon, 1969; Berberian, 1995; Talbot and Alavi, 1996; Hessami et al., 2001a; Bahroudi and Talbot, 2003; Authemayou et al., 2006; Mouthereau et al., 2006, 2007b; Allen, 2010; Farzipour-Saein et al., 2013; Joudaki et al., 2016). The High Zagros Fault (HZF), the Mountain Front Fault (MFF) and the Zagros Foredeep Fault (ZFF) are the important basement faults. The N–S trending basement faults and the Izeh-Hendijan Fault (IZHF), the Kharg-Mish Fault (KMF) and the Kazerun Fault (KZF) formed in the latest Proterozoic and the Early Cambrian in the Arabian basement and the Triassic and Late Cretaceous, respectively (Beydoun, 1991) (Fig. 1).

The existence and orientation of the IZHF has been investigated in the neighboring anticlines of the study area (Falcon, 1974; Sherkati and Letouzey, 2004; Ahmadhadi et al., 2008). It seems that the Karun and Lali anticlines were influenced by Izeh fault system and its associated tear faults also played a role in deformation in the study area.

Deformation transition is accommodated by tear faults (Razavi Pash et al., 2020; Seraj et al., 2020). Major boundary of this variation is a NE-SW lineament located between the Karun and Lali anticlines and in the middle part of the Zeloi anticline. Interpretation of 2D seismic profiles reveals an important tear fault located between the Karun and Lali oilfields. Location of these anticlines on both sides of the tear faults suggests a left-lateral strike-slip. Syn-tectonic sediments have covered the effect of these tear faults at surface and there is no field evidence of these faults at the surface.

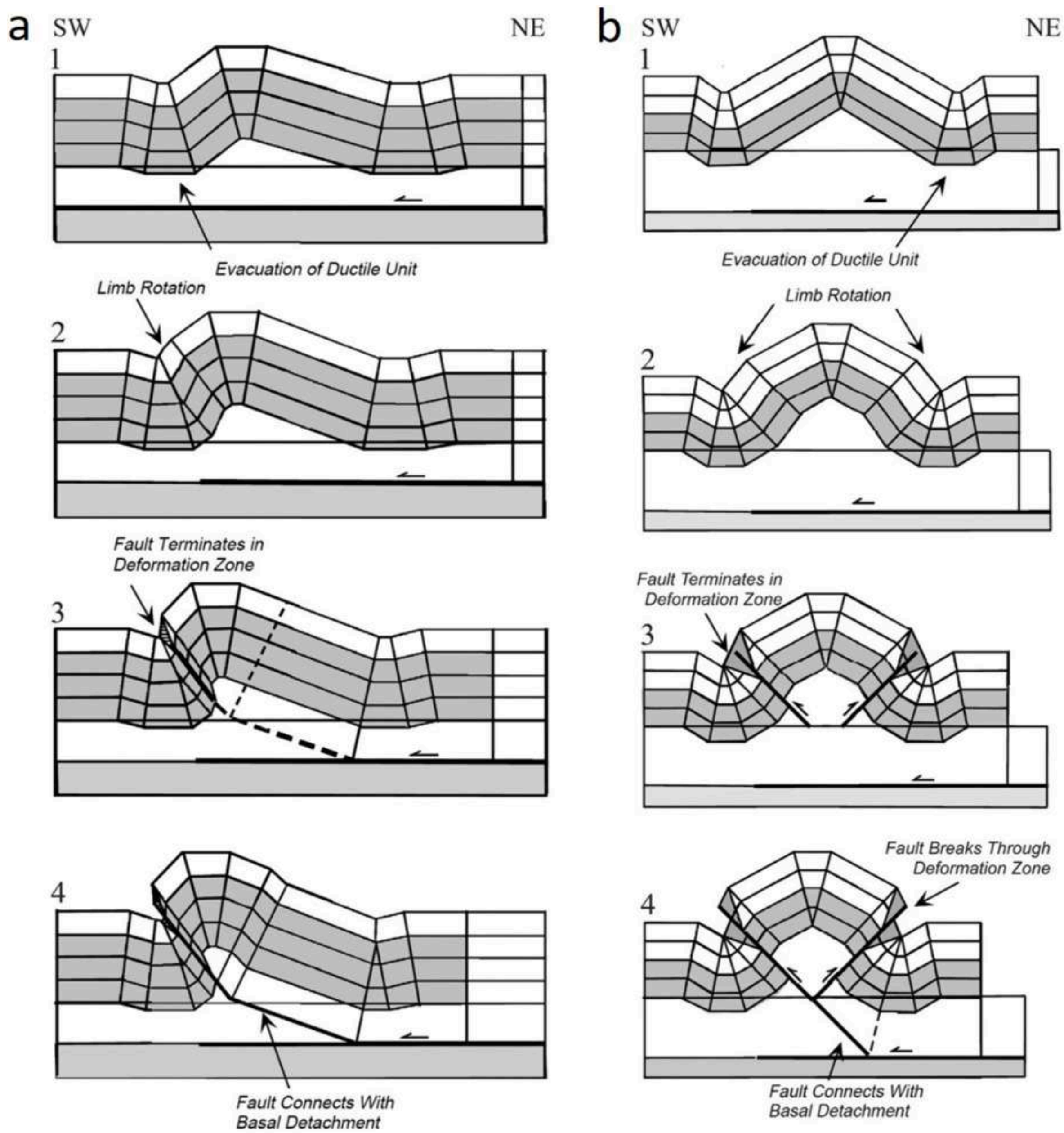

Fig. 12. (a) Kinematic evolution model for asymmetric faulted detachment fold and (b) symmetric faulted detachment fold (Mitra, 2002).

6.2. Kinematic evolution

Following Poblet and McClay (1996), four different geometric and kinematic models may be considered for the kinematics of individual folds with a detachment mechanism in which a homogeneous competent unit detached over a ductile unit (Fig. 13).

In Model 1 (Mitchell and Woodward, 1988) the dip of the fold limb is maintained constant and limb lengthening results in fold amplification. In Model 2 (Sitter, 1964) the limb rotates maintaining its same length and leads to deformation. The basis of Model 3 (Dahlstrom, 1990) is the law of conservation of area for both the competent and the ductile unit, and both mechanisms of limb rotation and lengthening are responsible for the crustal shortening. Model 4 (Blay et al., 1977) indicates that both limb rotation and limb lengthening accommodate fold amplification, but the point of intersection of the axial surface is fixed such that it occurs on the detachment surface (Fig. 13).

Both of forelimb lengths and dips of the studied anticlines vary spatially. Comparing the shape of the best-fit functions with these models (Poblet and McClay, 1996) demonstrate that the kinematic evolution of the Zeloi, Lali and Karun anticlines are in accordance with Model 3 of Poblet and McClay (1996). Subsurface anticlines such as Zeloi, Lali and Karun anticlines formed on a thick middle décollement horizon (Sherkati et al., 2005).

The presence of growth strata in the upper parts of the Gachsaran Formation can be observed that indicates the start of folding simultaneously with the deposition of the Gachsaran Formation in Middle Miocene (Sherkati and Letouzey, 2004). This time has already proven using magnetostratigraphic, sedimentology and low-temperature thermochronometry of Miocene detrial sediments ~19.7–14.8 Ma (Khadivi et al., 2010).

In the earlier stages of the folding process, migration of incompetent formations towards the core of anticlines produced detachment folds. The folding was followed by a change in structural style due to progressive deformation and increasing shortening (Fig. 14). Limb rotation and/or hinge migration took place during folding (Poblet and McClay, 1996).

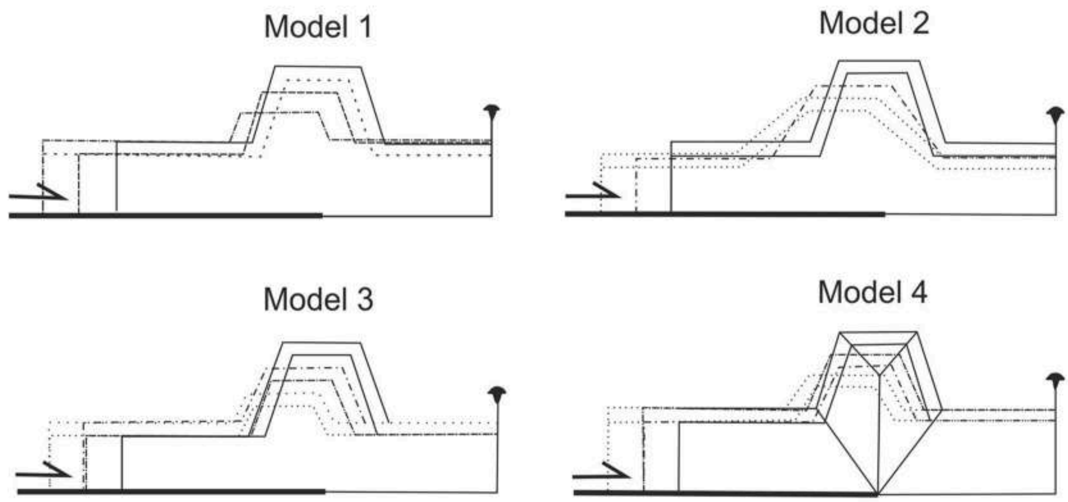

Fig. 13. Kinematic evolution of the detachment folds based on limb dip and limb length (Poblet and McClay, 1996). Models 1 and 2 evolves with the limb migration (changeble limb lenght and constant limb dip) and limb rotation (constant limb length and changeble limb dip) respectively, while, the model 3 and 4 evolves both limb migration and limb rotation (variable limb rotation and variable limb dip) (Poblet and Mcclay, 1996).

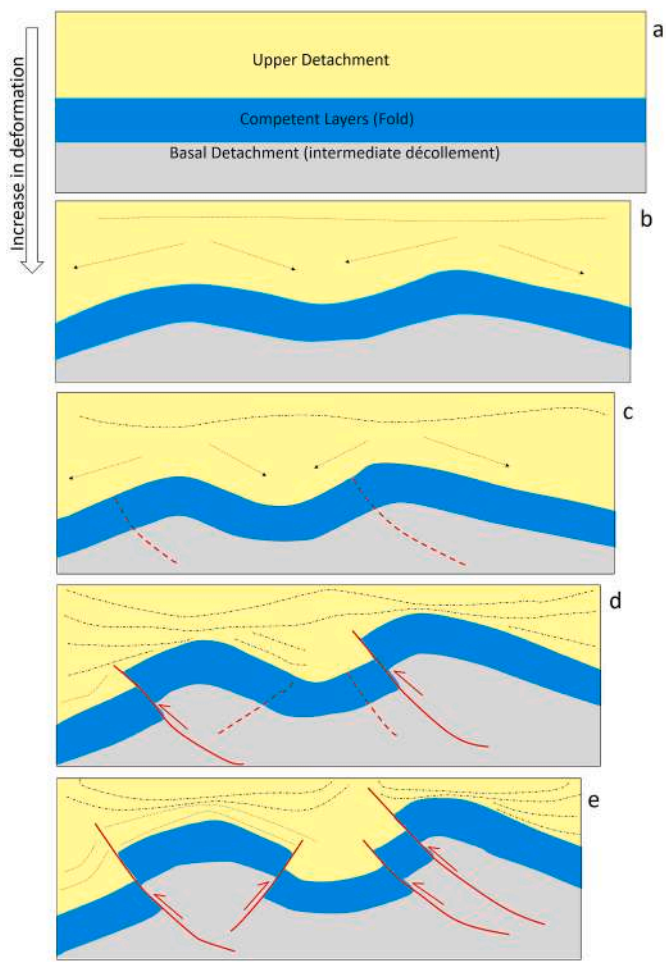

Fig. 14. Kinematic evolution model of the subsurface anticlines in the study area. (a) undeformed layers, (b) first step of deformation and formation of detachment fold, (c) increase of forelimb dip and generation of faults, (d) propagation of thrusts upward and corporation of them in deformation and generation of second thrust and back-thrust and (e) propagation of second thrust and back-thrust upward and formation of imbricate structure.

In all cases, the underlying detachment horizons flow into the core of fold until no more material is available (Sherkati and Letouzey, 2004; Sherkati et al., 2005) whereupon the shortening is accommodated by faulting (Fig. 14). The upper detachment gradually thickens above the shortened competent layers and flows into the synclines (Fig. 14). As shortening is then accommodated by faulting, and the synclines are overridden by the faulted anticline limbs, the overlying detachment horizon thickens and the layers above, the Mishan and the Aghajari formations, are in turn folded as the Zagros orogeny progressed. Then, the Gachsaran Formation underwent upward ductile flow due to ongoing shortening. These processes led to the propagation of a thrust fault in the upper competent strata. This finally led the Gachsaran Formation to crop out (Fig. 14).

Faulting of fold limbs and development of faulted detachment folds usually occurs due to high strains on fold limbs during limb rotation (Mitra, 2002). In the context of the Zeloi anticline, if the two limbs are symmetric and faults propagate through steep limb segments simultaneously on both sides of the anticline, this phenomenon occurs. This results in a symmetric pop-up structure bound by two faults (Fig. 14e). According to the model of detachment folding presented by Mitra (2002), finally, one of these two faults connects with basal detachment and controls future asymmetric growth of the structure, whereas the other fault terminates against the main fault. This stage can be observed on the cross-sections C-C′ and D-D'. Pop-up structure in the Zeloi anticline continues from NW to the central part of the anticline and mechanism of folding spatially changes to a fault propagation geometry (Fig. 10c and d).

More deformation can be observed in the Lali anticline. A significant element at this stage is generation and development of a double thrust in the forelimb of the Lali anticline. During progressive folding, thrusts developed in the steeper forelimb. These thrusts accommodate strain variations during folding. Thrusts formed in middle décollement with upward growth during progressive folding from faulted décollement fold (Mitra, 2002, 2003). These thrusts are restricted to the upper décollement above and the middle décollement at the base (Fig. 14).

Distribution of deformation of the Karun anticline differs from the other two anticlines. Due to thrusting on both sides of the fold as well as more overburden thickness, the Karun anticline has subsided and lies deeper than the Lali anticline.

Kinematic evolution of subsurface anticlines in the northern Dezful Embayment involved several steps: buckling of undeformed layers and migration of middle décollement horizons (Garau and Dashtak formations) towards the anticline's core and formation of décollement folds.

Also, progressive deformation is associated with migration and flow of the Gachsaran Formation towards the footwall syncline (Fig. 14). This happened by limb rotation and hinge migration. In this stage, thrusting started to accommodate shortening in underlying units and a footwall syncline formed in the forelimb. Through time, second stage of thrusting formed as an out-of-sequence fault and grew upward with increasing shortening (Fig. 14). These thrusts that formed between different anticlines are in-sequence faults. Thrusting in forelimb happens as an out-of-sequence event. Geometry of thrusts in the forelimb plays particular role in final shape of the anticlines. As a consequence, the final geometry of the anticline in kinematic evolution, from décollement fold to fault-bend fold, depends on the geometry of formed thrusts during progressive shortening of the anticline's forelimb.

7. Conclusions

We examined the kinematic evolution and structural style of three oilfields (Zeloi, Lali and Karun) in the northern Dezful Embayment of SW Iran using 2D seismic data. Through interpretation of the 2D seismic profiles and balanced cross-sections, we discovered a wide range of geometries and kinematics among the oilfields. Oilfields' structural style was influenced by the Gachsaran and Dashtak formations, acting as upper and middle detachment levels, respectively. Additionally, the presence of tear faults played a role in the along-strike variations in the oilfields' structures. Analysis of the growth strata indicated that limb rotation and hinge migration were involved in the evolution of the folds that initiated in the Middle Miocene. Initial detachment folds transformed into fault-bend folds during the later deformation. Results from this study provide new insights about styles of deformation and geometric configurations of hydrocarbon target levels (i.e., the Asmari reservoir and Bangestan Group reservoirs) in the study area. These findings can be very useful in future exploration/production and field development activities in the NW part of the prolific Dezful Embayment.

CRediT authorship contribution statement

Masoud Joudaki: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Ali Faghih:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Soumyajit Mukherjee:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation. **Mohammad Seraj:** Writing – original draft, Methodology, Investigation, Conceptualization. **Bahman Soleimany:** Writing – original draft, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The research is supported by the Shiraz University Research Council (SURC) grant, which is gratefully acknowledged. The authors thank the National Iranian Oil Company (NIOC) and National Iranian South Oil Company (NISOC) for providing the data. The authors are very grateful to anonymous reviewers and the Associate Editor Dario Civile for providing helpful comments.

References

Abdollahie Fard, I., Braathen, A., Mokhtari, M., Alavi, S.A., 2006. Interaction of the Zagros Fold–thrust belt and the arabian-type, deep-seated folds in the abadan plain and the Dezful embayment, SW Iran. Petrol. Geosci. 12, 347–362.

Abdollahie Fard, I., Sepehr, M., Sherkati, S., 2011. Neogene salt in SW Iran and its interaction with Zagros folding. Geol. Mag. 148, 854–867.

Ahmadhadi, F., Daniel, J.M., Azzizadeh, M., Lacombe, O., 2008. Evidence for pre-folding vein development in the Oligo-Miocene Asmari Formation in the central Zagros Fold belt, Iran. Tectonics 27.

Ahmadhadi, F., Lacombe, O., Daniel, J.-M., 2007. Early reactivation of basement faults in Central Zagros (SW Iran): evidence from pre-folding fracture populations in Asmari Formation and lower Tertiary paleogeography. Thrust Belts and Foreland Basins. Springer, pp. 205–228.

Alavi, M., 1994. Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. Tectonophysics 229, 211–238.

Alavi, M., 2004. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. Am. J. Sci. 304, 1–20.

Alavi, M., 2007. Structures of the Zagros fold-thrust belt in Iran. Am. J. Sci. 307, 1064–1095.

Ali, M., Koyi, H., Bosworth, W., Ligi, M., Ball, P.J., Decarlis, A., 2023. Geometry and kinematics of the middle to late Miocene salt tectonics, central Egyptian red sea margin. J. Struct. Geol. 176, 104955.

Alipour, M., 2023. Collision along irregular plate margin controlled the tectono-stratigraphic evolution of the Iranian Zagros fold and thrust belt. Mar. Petrol. Geol. 154, 106311.

Alipour, M., 2024. Petroleum systems of the Iranian Zagros Fold and thrust belt. Results in Earth Sciences 2, 100027.

Alipour, M., Alizadeh, B., Mirzaie, S., 2021. Tectono-stratigraphic evolution of the Permo-Triassic succession in the fars platform of Iran: implications for future exploration of the Paleozoic petroleum system. J. Asian Earth Sci. 221, 104945.

Allen, M.B., 2010. Roles of Strike-Slip Faults during Continental Deformation: Examples from the Active Arabia–Eurasia Collision, vol. 338. Geological Society, London, Special Publications, pp. 329–344.

Allen, M.B., Kheirkhah, M., Emami, M.H., Jones, S.J., 2011. Right-lateral shear across Iran and kinematic change in the Arabia–Eurasia collision zone. Geophys. J. Int. 184, 555–574.

Allen, M.B., Talebian, M., 2011. Structural variation along the Zagros and the nature of the dezful embayment. Geol. Mag. 148, 911–924.

Asgari, G.R., Ghaemi, F., Soleimany, B., Rahimi, B., Shekarian, Y., 2019. Role of incompetent strata and geometry of faults on the folding mechanism, a case study: the Karun oil field in the Dezful Embayment, Iran. Modeling Earth Systems and Environment 5, 1781–1800.

Authemayou, C., Chardon, D., Bellier, O., Malekzadeh, Z., Shabanian, E., Abbassi, M.R., 2006. Late Cenozoic partitioning of oblique plate convergence in the Zagros fold-and-thrust belt (Iran). Tectonics 25 (TC3002), 21.

Bahroudi, A., Koyi, H., 2003. Effect of spatial distribution of Hormuz salt on deformation style in the Zagros fold and thrust belt: an analogue modelling approach. J. Geol. Soc. 160, 719–733.

Bahroudi, A., Koyi, H.A., 2004. Tectono-sedimentary framework of the Gachsaran Formation in the Zagros foreland basin. Mar. Petrol. Geol. 21, 1295–1310.

Bahroudi, A., Talbot, C., 2003. The configuration of the basement beneath the Zagros basin. J. Petrol. Geol. 26, 257–282.

Baker, C., Jackson, J., Priestley, K., 1993. Earthquakes on the Kazerun line in the Zagros mountains of Iran: strike-slip faulting within a fold-and-thrust belt. Geophys. J. Int. 115, 41–61.

Berberian, M., 1995. Master "blind" thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. Tectonophysics 241, 193–224.

Berberian, M., King, G., 1981. Towards a paleogeography and tectonic evolution of Iran. Can. J. Earth Sci. 18, 210–265.

Beydoun, Z.R., 1991. Arabian Plate Hydrocarbon Geology and Potential—A Plate Tectonic Approach. American Association of Petroleum Geologists.

Biswas, T., Bose, N., Dutta, D., Mukherjee, S., 2022. Arc-parallel shears in collisional orogens: global review and paleostress analyses from the NW Lesser Himalayan Sequence (Garhwal region, Uttarakhand, India). Mar. Petrol. Geol. 138, 105530.

Blanc, E.-P., Allen, M.B., Inger, S., Hassani, H., 2003. Structural styles in the Zagros simple folded zone, Iran. J. Geol. Soc. 160, 401–412.

Blay, P., Cosgrove, J., Summers, J., 1977. An experimental investigation of the development of structures in multilayers under the influence of gravity. J. Geol. Soc. 133, 329–342.

Bordenave, M.L., Hegre, J.A., 2005. The influence of tectonics on the entrapment of oil in the dezful embayment, zagros FOLDBELT, Iran. J. Petrol. Geol. 28, 339–368.

Bordenave, M., Hegre, J., 2010. Current distribution of oil and gas fields in the Zagros Fold Belt of Iran and contiguous offshore as the result of the petroleum systems. Geol. Soc. Lond. Spec. Publ. 330, 291–353.

Brandes, C., Tanner, D.C., 2014. Fault-related folding: a review of kinematic models and their application. Earth Sci. Rev. 138, 352–370.

Bulnes, M., Poblet, J., 1999. Estimating the detachment depth in cross sections involving detachment folds. Geol. Mag. 136, 395–412.

Burberry, C.M., 2015. The effect of basement fault reactivation on the Triassic-Recent geology of Kurdistan, north Iraq. J. Petrol. Geol. 38, 37–58.

Carruba, S., Perotti, C.R., Buonaguro, R., Calabrò, R., Carpi, R., Naini, M., 2006. Structural Pattern of the Zagros Fold-And-Thrust Belt in the Dezful Embayment (SW Iran), vol. 414. SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA, p. 11.

Carruba, S., Perotti, C.R., Buonaguro, R., Calabrò, R., Carpi, R., Naini, M., 2006. Structural pattern of the Zagros fold-and-thrust belt in the Dezful Embayment (SW Iran). Spec. Pap.-Geol. Soc. Am. 414, 11.
Chamberlin, R.T., 1910. The Appalachian folds of central Pennsylvania. J. Geol. 18, 228–251.
Colman-Sadd, S., 1978. Fold development in Zagros simply folded belt, southwest Iran. AAPG (Am. Assoc. Pet. Geol.) Bull. 62, 984–1003.
Dahlstrom, C., 1969. The upper detachment in concentric folding. Bull. Can. Petrol. Geol. 17, 326–346.
Dahlstrom, C.D., 1990. Geometric constraints derived from the law of conservation of volume and applied to evolutionary models for detachment folding: geologic notes. AAPG (Am. Assoc. Pet. Geol.) Bull. 74, 336–344.
Derikvand, B., Alavi, S.A., Fard, I.A., Hajialibeigi, H., 2018. Folding style of the Dezful Embayment of Zagros Belt: signatures of detachment horizons, deep-rooted faulting and syn-deformation deposition. Mar. Petrol. Geol. 91, 501–518.
Derikvand, B., Alavi, S.A., Fard, I.A., Jalali, L., 2019. Changing in fold geometry from faulted detachment fold to fault-bend fold, a case study: the Zeloi Anticline in the Dezful Embayment, southwest of Iran. J. Petrol. Sci. Eng. 173, 381–401.
Dutta, D., Biswas, T., Mukherjee, S., 2019. Arc-parallel compression in the NW Himalaya: evidence from structural and palaeostress studies of brittle deformation from the clasts of the Upper Siwalik, Uttarakhand, India. J. Earth Syst. Sci. 128, 1–20.
Ezati-Asl, M., Faghih, A., Mukherjee, S., Soleimany, B., 2019. Style and timing of salt movement in the Persian Gulf basin, offshore Iran: Insights from halokinetic sequences adjacent to the Tonb-e-Bozorg salt diapir. J. Struct. Geol. 122, 116–132.
Faghih, A., Ezati-Asl, M., Mukherjee, S., Soleimany, B., 2019. Characterizing halokinesis and timing of salt movement in the Abu Musa salt diapir, Persian Gulf, offshore Iran. Mar. Petrol. Geol. 105, 338–352.
Faghih, A., Nourbakhsh, A., 2015. Appraisal of relative tectonic activity along the Kazerun Fault Zone, Zagros Mountains, Iran: insight from spatial analysis of geomorphic indices. Geol. J. 50, 783–798.
Falcon, N.L., 1969. Problems of the Relationship between Surface Structure and Deep Displacements Illustrated by the Zagros Range, vol. 3. Geological Society, London, Special Publications, pp. 9–21.
Falcon, N.L., 1974. Southern Iran: Zagros Mountains, vol. 4. Geological Society, London, Special Publications, pp. 199–211.
Farzipour-Saein, A., Koyi, H., 2014a. Effect of lateral thickness variation of an intermediate decollement on the propagation of deformation front in the Lurestan and Izeh zones of the Zagros fold-thrust belt, insights from analogue modeling. J. Struct. Geol. 65, 17–32.
Farzipour-Saein, A., Koyi, H., 2014b. Effect of lateral thickness variation of an intermediate decollement on the propagation of deformation front in the Lurestan and Izeh zones of the Zagros fold-thrust belt, insights from analogue modeling. J. Struct. Geol. 65, 17–32.
Farzipour-Saein, A., Koyi, H., 2016. Intermediate decollement activation in response to the basal friction variation and its effect on folding style in the Zagros fold-thrust belt, an analogue modeling approach. Tectonophysics 687, 56–65.
Farzipour-Saein, A., Nilfouroushan, F., Koyi, H., 2013. The effect of basement step/ topography on the geometry of the Zagros fold and thrust belt (SW Iran): an analog modeling approach. Int. J. Earth Sci. 102, 2117–2135.
Farzipour-Saein, A., Yassaghi, A., Sherkati, S., Koyi, H., 2009b. Mechanical stratigraphy and folding style of the lurestan region in the Zagros Fold–thrust belt, Iran. J. Geol. Soc. 166, 1101–1115.
Farzipour-Saein, A., Yassaghi, A., Sherkati, S., Koyi, H., 2009a. Basin evolution of the lurestan region in the ZAGROS FOLD-AND-THRUST belt, Iran. J. Petrol. Geol. 32, 5–19.
Fleuty, M., 1964. The description of folds. Proc. Geologists' Assoc. 75, 461–492.
Ghanadian, M., Faghih, A., Abdolahie Fard, I., Grasemann, B., Soleimany, B., Maleki, M., 2017a. Tectonic constraints for hydrocarbon targets in the Dezful embayment, Zagros fold and thrust belt, SW Iran. Journal of Petroleum Science and Engineering 157, 1220–1228.
Ghanadian, M., Faghih, A., Fard, I.A., Kusky, T., Maleki, M., 2017b. On the role of incompetent strata in the structural evolution of the Zagros Fold-Thrust Belt, Dezful Embayment, Iran. Mar. Petrol. Geol. 81, 320–333.
Ghanadian, M., Faghih, A., Grasemann, B., Abdolahie Fard, I., Maleki, M., 2017c. Analogue modeling of the role of multi-level decollement layers on the geometry of orogenic wedge: an application to the Zagros Fold–Thrust Belt, SW Iran. International Journal of Earth Sciences 106, 2837–2853.
Ghanbarian, M.A., Derakhshani, R., 2022. The folds and faults kinematic association in Zagros. Sci. Rep. 12, 8350.
Ghanbarian, M.A., Yassaghi, A., Derakhshani, R., 2021. Detecting a sinistral transpressional deformation belt in the Zagros. Geosciences 11, 226.
Groshong Jr, R.H., 1994. Area balance, depth to detachment, and strain in extension. Tectonics 13, 1488–1497.
Groshong Jr, R.H., 2015. Quality control and risk assessment of seismic profiles using area-depth-strain analysis. Interpretation 3, SAA1–SAA15.
Hessami, K., Koyi, H., Talbot, C., 2001a. The significance of strike-slip faulting in the basement of the Zagros fold and thrust belt. J. Petrol. Geol. 24, 5–28.
Hessami, K., Koyi, H.A., Talbot, C.J., Tabasi, H., Shabanian, E., 2001b. Progressive unconformities within an evolving foreland fold–thrust belt, Zagros Mountains. J. Geol. Soc. 158, 969–981.
Hosseinpour, M., Arian, M., Maleki, Z., Qorashi, M., 2023. Investigating for Hydrocarbon Potential in the Sarvak and Ilam Formations Using Fuzzy Logic in the Fars Region, vol. 46. International Union of Geological Sciences, Iran, pp. 361–374.
James, G., Wynd, J., 1965. Stratigraphic nomenclature of Iranian oil consortium agreement area. AAPG (Am. Assoc. Pet. Geol.) Bull. 49, 2182–2245.
Jamison, W.R., 1987. Geometric analysis of fold development in overthrust terranes. J. Struct. Geol. 9, 207–219.
Joudaki, M., Farzipour-Saein, A., Nilfouroushan, F., 2016. Kinematics and surface fracture pattern of the Anaran basement fault zone in NW of the Zagros fold–thrust belt. Int. J. Earth Sci. 105, 869–883.
Kent, W.N., 2010. Structures of the Kirkuk embayment, northern Iraq: foreland structures or Zagros Fold belt structures. GeoArabia 15, 147–188.
Kent, W.N., Dasgupta, U., 2004. Structural evolution in response to fold and thrust belt tectonics in northern Assam. A key to hydrocarbon exploration in the Jaipur anticline area. Mar. Petrol. Geol. 21, 785–803.
Khadivi, S., Mouthereau, F., Larrasoaña, J.C., Vergés, J., Lacombe, O., Khademi, E., Beamud, E., Melinte-Dobrinescu, M., Suc, J.P., 2010. Magnetochronology of synorogenic Miocene foreland sediments in the fars arc of the Zagros folded belt (SW Iran). Basin Res. 22, 918–932.
Koop, W., Stoneley, R., Ridd, M., Murphy, R., Osmaston, M., Kholief, M., 1982. Subsidence history of the Middle East Zagros basin, permian to recent [and discussion]. Phil. Trans. Roy. Soc. Lond. Math. Phys. Sci. 305, 149–168.
Le Garzic, E., Vergés, J., Sapin, F., Saura, E., Meresse, F., Ringenbach, J., 2019. Evolution of the NW Zagros Fold-and-Thrust Belt in Kurdistan Region of Iraq from balanced and restored crustal-scale sections and forward modeling. J. Struct. Geol. 124, 51–69.
Mashal, M., Kermani, M.P., Charchi, A., 2014. Role Gachsaran Formation in geological structures in dezful embayment. J. Curr. Res. Sci. 2, 22.
McQuarrie, N., 2004. Crustal scale geometry of the Zagros fold–thrust belt, Iran. J. Struct. Geol. 26, 519–535.
Mehdipour, Z., Shad Manaman, N., Kadkhodaie, A., Ashtari, A., 2024. Rock characterization of rupelian-chatian Asmari carbonate formation using the simultaneous pre-stack inversion technique and lame parameters in the Kopal oilfield, Dezful embayment, Zagros basin. Carbonates Evaporites 39, 53.
Mitchell, M.M., Woodward, N.B., 1988. Kink detachment fold in the southwest Montana fold and thrust belt. Geology 16, 162–165.
Mitra, S., 1990. Fault-propagation folds: geometry, kinematic evolution, and hydrocarbon traps. AAPG (Am. Assoc. Pet. Geol.) Bull. 74, 921–945.
Mitra, S., 2002. Structural models of faulted detachment folds. AAPG (Am. Assoc. Pet. Geol.) Bull. 86, 1673–1694.
Mitra, S., 2003. A unified kinematic model for the evolution of detachment folds. J. Struct. Geol. 25, 1659–1673.
Motamedi, H., Sherkati, S., Sepehr, M., 2012. Structural style variation and its impact on hydrocarbon traps in central Fars, southern Zagros folded belt, Iran. J. Struct. Geol. 37, 124–133.
Motiei, H., 1994. Stratigraphy of Zagros. Geological Survey of Iran Publications, p. 583 (in Persian), Tehran.
Mouthereau, F., Lacombe, O., Meyer, B., 2006. The Zagros folded belt (Fars, Iran): constraints from topography and critical wedge modelling. Geophys. J. Int. 165, 336–356.
Mouthereau, F., Lacombe, O., Tensi, J., Bellahsen, N., Kargar, S., Amrouch, K., 2007a. Mechanical Constraints on the Development of the Zagros Folded Belt (Fars), Thrust Belts and Foreland Basins. Springer, pp. 247–266.
Mouthereau, F., Tensi, J., Bellahsen, N., Lacombe, O., De Boisgrollier, T., Kargar, S., 2007b. Tertiary sequence of deformation in a thin-skinned/thick-skinned collision belt: the Zagros Folded Belt (Fars, Iran). Tectonics 26, TC5006, 28.
Nabavi, S.T., Fossen, H., 2021. Fold geometry and folding–a review. Earth Sci. Rev. 222, 103812.
Najafi, M., Yassaghi, A., Bahroudi, A., Vergés, J., Sherkati, S., 2014. Impact of the late triassic Dashtak intermediate detachment horizon on anticline geometry in the central frontal fars, SE Zagros fold belt, Iran. Mar. Petrol. Geol. 54, 23–36.
Nilfouroushan, F., Pysklywec, R., Cruden, A., Koyi, H., 2013. Thermal-mechanical modeling of salt-based mountain belts with pre-existing basement faults: application to the Zagros fold and thrust belt, southwest Iran. Tectonics 32, 1212–1226.
O'Brien, C., 1957. Salt diapirism in south Persia. Geologie en Mijnbouw, ns 19.
Poblet, J., McClay, K., 1996. Geometry and kinematics of single-layer detachment folds. AAPG (Am. Assoc. Pet. Geol.) Bull. 80, 1085–1109.
Razavi Pash, R., Davoodi, Z., Mukherjee, S., Dehsarvi, L.H., Ghasemi-Rozveh, T., 2021. Interpretation of aeromagnetic data to detect the deep-seated basement faults in fold thrust belts: NW part of the petroliferous Fars province, Zagros belt, Iran. Mar. Petrol. Geol. 133, 105292.
Razavi Pash, R., Sarkarinejad, K., Ghoochaninejad, H.Z., Motamedi, H., Yazdani, M., 2020. Accommodation of the different structural styles in the foreland fold-and-thrust belts: northern Dezful Embayment in the Zagros belt, Iran. Int. J. Earth Sci. 109, 959–970.
Razavi Pash, R., Seraj, M., Mukherjee, S., Radmehr, A., 2023. Structural relationship between subsurface oil fields in the North Dezful embayment: Qaleh nar, lower and upper Balarud anticlines (central Zagros, Iran). Bulletin of the Mineral Research and Exploration 1, 1-1.
Sarkarinejad, K., Faghih, A., Grasemann, B., 2008. Transpressional deformations within the Sanandaj–Sirjan metamorphic belt (Zagros mountains, Iran). J. Struct. Geol. 30 (7), 818–826.
Sarkarinejad, K., Goftari, F., 2019. Thick-skinned and thin-skinned tectonics of the Zagros orogen, Iran: constraints from structural, microstructural and kinematics analyses. J. Asian Earth Sci. 170, 249–273.
Sarkarinejad, K., Pash, R.R., Motamedi, H., Yazdani, M., 2018. Deformation and kinematic evolution of the subsurface structures: Zagros foreland fold-and-thrust belt, northern Dezful Embayment, Iran. Int. J. Earth Sci. 107, 1287–1304.
Sarkarinejad, K., Zafarmand, B., 2017. Stress state and movement potential of the Kar-e-Bas fault zone, Fars, Iran. J. Geophys. Eng. 14, 998–1009.

Sepehr, M., Cosgrove, J., 2004. Structural framework of the Zagros fold–thrust belt, Iran. Mar. Petrol. Geol. 21, 829–843.
Sepehr, M., Cosgrove, J., 2005. Role of the Kazerun Fault Zone in the formation and deformation of the Zagros Fold-thrust belt, Iran. Tectonics 24, TC5005, 13.
Sepehr, M., Cosgrove, J., Moieni, M., 2006. The impact of cover rock rheology on the style of folding in the Zagros fold-thrust belt. Tectonophysics 427, 265–281.
Seraj, M., Faghih, A., Motamedi, H., Soleimany, B., 2020. Major tectonic lineaments influencing the oilfields of the Zagros fold-thrust belt, SW Iran: insights from integration of surface and Subsurface Data. J. Earth Sci. 31, 596–610.
Shamszadeh, A., Sarkarinejad, K., Ferrer, O., Mukherjee, S., Seraj, M., 2022a. Effect of inherited structural highs on the structure and kinematics of the South Dezful Embayment, SW Iran. Geol. Mag. 159, 1744–1766.
Shamszadeh, A., Sarkarinejad, K., Ferrer, O., Mukherjee, S., Seraj, M., 2022b. Interaction of inherited structures and contractional deformation in the south Dezful embayment: insights from the Gachsaran oilfield, SW Iran. Mar. Petrol. Geol. 145, 105871.
Sherkati, S., Letouzey, J., 2004. Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. Mar. Petrol. Geol. 21, 535–554.
Sherkati, S., Letouzey, J., Frizon de Lamotte, D., 2006. Central Zagros fold-thrust belt (Iran): new insights from seismic data, field observation, and sandbox modeling. Tectonics 25.
Sherkati, S., Molinaro, M., Frizon de Lamotte, D., Letouzey, J., 2005. Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control. J. Struct. Geol. 27, 1680–1696.
Sitter, L.U., 1964. Structural Geology. McGraw-Hill.
Stocklin, J., 1968. Structural history and tectonics of Iran: a review. AAPG (Am. Assoc. Pet. Geol.) Bull. 52, 1229–1258.
Stöcklin, J., 1974. Possible ancient continental margins in Iran. The Geology of Continental Margins. Springer, pp. 873–887.
Suppe, J., Chou, G.T., Hook, S.C., 1992. Rates of folding and faulting determined from growth strata. Thrust Tectonics. Springer, pp. 105–121.
Suppe, J., Connors, C.D., Zhang, Y., 2004. Shear Fault-Bend Folding.
Szabo, F., Kheradpir, A., 1978. Permian and Triassic stratigraphy, Zagros basin, south-west Iran. J. Petrol. Geol. 1, 57–82.
Takin, M., 1972. Iranian geology and continental drift in the Middle East. Nature 235, 147–150.
Talbot, C., Alavi, M., 1996. The Past of a Future Syntaxis across the Zagros, vol. 100. Geological Society, London, Special Publications, pp. 89–109.
Talebi, H., Alavi, S.A., Sherkati, S., Ghassemi, M.R., Golalzadeh, A., 2018. In-situ stress regime in the Asmari reservoir of the Zeloi and Lali oil fields, northwest of the Dezful embayment in Zagros fold-thrust belt, Iran. EarthSciences 27, 53–68.
Van Buchem, F., Allan, T., Laursen, G., Lotfpour, M., Moallemi, A., Monibi, S., Motiei, H., Pickard, N., Tahmasbi, A., Vedrenne, V., 2010. Regional Stratigraphic Architecture and Reservoir Types of the Oligo-Miocene Deposits in the Dezful Embayment (Asmari and Pabdeh Formations) SW Iran, vol. 329. Geological Society, London, Special Publications, pp. 219–263.
Vatandoust, M., Faghih, A., Asadi, S., Azimzadeh, A.M., Heidarifard, M.H., 2020a. Study of hydrocarbon generation and 1D-2D modeling of hydrocarbon migration at the Karanj and Parsi oilfields, Southern Dezful Embayment, SW Iran. Mar. Petrol. Geol. 113, 104095.
Vatandoust, M., Faghih, A., Burberry, C.M., Shafiei, G., 2020b. Structural style and kinematic analysis of folding in the southern Dezful Embayment oilfields, SW Iran. J. Struct. Geol. 134, 103989.
Vergés, J., Goodarzi, M., Emami, H., Karpuz, R., Efstathiou, J., Gillespie, P., 2011. Multiple detachment folding in Pusht-e Kuh arc, Zagros: role of mechanical stratigraphy. AAPG Memoir 94, 69–94.