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# Tectonic constraints for hydrocarbon targets in the Dezful Embayment, Zagros Fold and Thrust Belt, SW Iran

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ABSTRACT

Understanding of reservoir architecture is one of the most important steps in the petroleum exploration programs. New 2D/3D seismic data provided important insights into the tectonic evolution of the Dalpari prospect within the Dezful Embayment of the Zagros Fold and Thrust Belt, SW Iran. This hydrocarbon target has formed as a result of a transpressive dextral strike-slip fault activity mechanically interacting with reverse faults, out of the syncline thrusts and four orders of folds. In the northern part of the target, the existence of growth strata within the competent units of Gachsaran and Agha Jari Formations (i.e. Upper Miocene and Pliocene) helped to determine the time of the structural evolution of the hydrocarbon target. Finally, the existence of the incompetent strata (e.g. Gachsaran Formation and the Kalhur member of Asmari Formation) mechanically controlled the formation history of the Dalpari prospect. In a regional context, this architecture denotes local Zagros partitioning of the oblique convergence between the Afro-Arabian and Central-Iranian plates a problem that has been addressed by many other researchers in the past using.

## 1. Introduction

Understanding of the structural styles of petroleum reservoirs is important for their development and management. Today, the application of seismic data has an important role in the extraction and development for most of oil and gas reservoirs. The simplest types of structural traps of petroleum are domes or doubly plunging anticlines. These structures may be truncated by faults to form complex structural traps. The Dalpari prospect exemplifies such a complex structural oil trap. This prospect is located in the northern part of the Dezful Embayment within the Zagros Fold and Thrust Belt (ZFTB) (Figs. 1–3). The Dalpari prospect was discovered by the National Iranian Oil Company (NIOC) after the analysis of 2D seismic profiles shot in 1969. Initially, the Dalpari was considered to be a simple anticline but after two exploration wells, which found unpredicted stratigraphic successions, the obviously more complex structure had to be reevaluated. The structural style of oil fields in the Dezful Embayment, is complicated by shortening along the northern edge of the Afro-Arabian plate marked by the ZFTB (Abdollahie Fard et al., 2006; Movahed et al., 2014, Ghanadian et al., 2017a, 2017b). Therefore, NIOC decided to investigate the architecture of the Dalpari prospect in more detail using 3D seismic profiles. Despite several comprehensive studies (e.g. Bahroudi and Koyi, 2004; Abdollahie Fard et al., 2006; Allen and Talebian, 2011; Movahed et al., 2014; Barzgar et al., 2015) many questions about the structural styles in this region remain controversial. The main aim of this research is to constrain the reservoir-scale geology of the Dalpari prospect within the Dezful Embayment using 2D/3D seismic sections and well data. We also distinguish different styles of folding in this part of the ZFTB. We consider that understanding the detailed architecture of this target is a key to understand similar structures elsewhere in the ZFTB.

## 2. Geological and tectonic settings

The ZFTB results from the oblique collision between the Afro-Arabian and Central-Iranian plates during the subduction of the Neo-Tethys Ocean. (Talbot and Alavi, 1996; Stampfli and Borel, 2002; McClay et al., 2004; Authemayou et al., 2006; Alavi, 2007; Ali et al., 2014). This ocean formed as a consequence of the Permian-Early Triassic rifting (Stampfli and Borel, 2002). During Late Jurassic-Early Cretaceous, the Neo-Tethys Ocean began to subduct beneath the Central-Iranian plate

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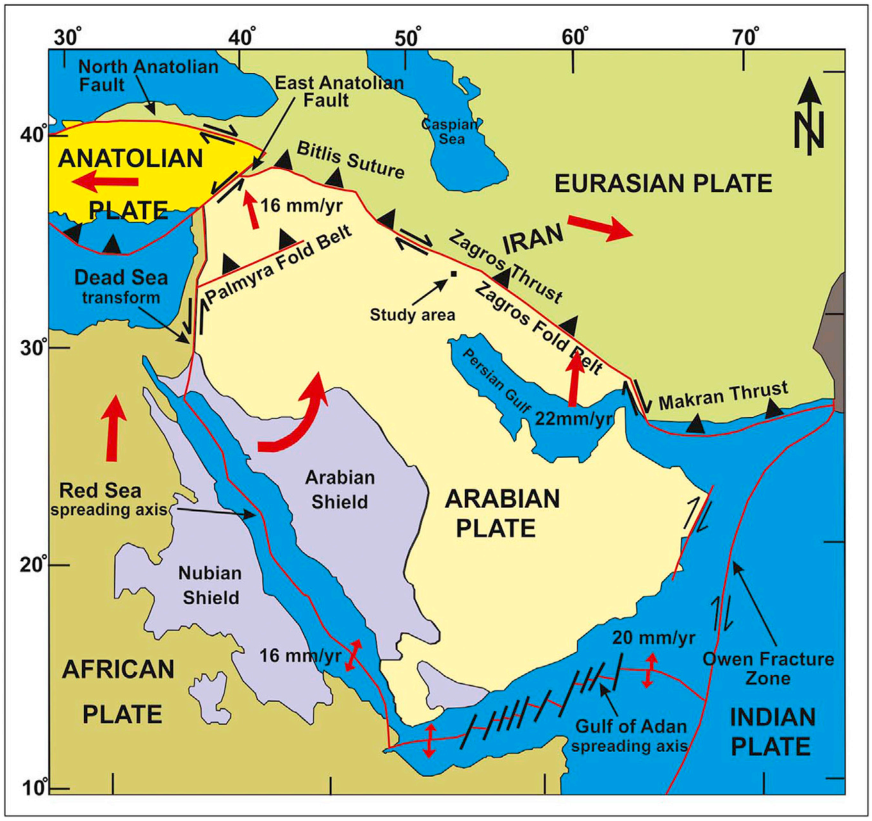


**Fig. 1.** Regional tectonic map of the ZFTB that resulted from the oblique convergence between the Afro-Arabian and Eurasian lithospheric plates showing plate boundaries, approximate plate convergence vectors, and principal geologic features (modified after Stern and Johnson, 2010). The fold belt trends parallel to the subduction zone and oblique to the nearly N–S tectonic shortening direction.

(Alavi, 2007). The collision between the Afro-Arabian and Central-Iranian plates started in the Late Cretaceous and Neo-Tethys closed completely in Miocene times (Berberian and King, 1981; Alavi, 1994, 2007; Pireh et al., 2015). The ZFTB is characterized by a 7–14 km thick sedimentary cover ranging in age from latest Precambrian to Recent (James and Wynd, 1965; Berberian and King, 1981; Motiei, 1993), that was deposited along the north-northeastern edge of the Afro-Arabian plate. The Phanerozoic sedimentary cover (excluding the Hormuz salt) is thicker in the Dezful Embayment than adjacent regions (Sepehr and Cosgrove, 2004). During the Jurassic and Cretaceous, the sedimentary sequence was mainly marine carbonates that accumulated on a shallow continental shelf of a passive continental margin (Mehrabi et al., 2015). Following the continental convergence during Late Cretaceous to Recent, marine and continental deposits unconformably overlie the older Zagros sequence (Abdollahie Fard et al., 2006). Fig. 4 shows the lithostratigraphic units ranging from the Jurassic Surmeh Formation to the late Pliocene-Pleistocene Bakhtyari Formation exposed in the study area (James and Wynd, 1965; Carruba et al., 2006). Among these Formations, the Asmari Formation that consists of neritic limestones 350 m thick is the most prolific oil reservoir in Iran and is commonly regarded as a classic fractured carbonate reservoir (Stephenson et al., 2007; Soleimani and Zamani, 2015). The 1000–1550 m thick Gachsaran Formation contains evaporites (e.g. anhydrites, halite, marl, and limestone) and is for exploration purposes one of the most important Formations in the Zagros foreland basin. This is very mobile and caps the Asmari Formation (Soleimani and Bahadori, 2014; Soleimani and Zamani, 2015). Tectonically, the evaporitic units of this Formation also forms a detachment level above which the overlying Formations can decouple from deeper structures (Pirouz et al., 2011). The Agha Jari and Bakhtyari deposits actively influenced the mechanical balance and kinematic evolution of the folds developed in the Dezful Embayment. Both of these Formations contain growth strata. Major detachment horizons (in the Hormuz and Gachsaran Formations) were accompanied by local detachment levels (in the Dashtak, Gotnia, Gadvan, Kazhdumi and Gurpi Formations, Fig. 4) that rendered the foreland part of this fold-and-thrust belt even more complex (Bahroudi and Koyi, 2004).

The Dalpari prospect is located in the north of the Dezful Embayment within the ZFTB (Fig. 2). The Dezful Embayment is a region in which more than 4000 m of Neogene clastic sediments accumulated as a consequence of the oblique collision between the Afro-Arabian and Central-Iranian lithospheric plates. The northern, northeastern and eastern boundaries of this region are bounded by the Balarud, Mountain Front and Kazerun Fault Zones, respectively (Fig. 2).

## 3. Material and methods

This study is based on the NIOC geophysical data that includes seismic data, well data and satellite images. The high quality 3D seismic cube together with some 2D seismic sections were used to interpret the deformational style of the Dalpari prospect. The total area of the study region is about 120 $km^2$ (Fig. 2 and Fig. 5). Within the study area, the initial 2D seismic data acquisition began in 1969 and high resolution 3D seismic data acquisition by NIOC began in 2010. Four wells with an average depth of 3450 m have been drilled in the Dalpari prospect. The geological markers and electrical logs from these wells supported the seismic interpretation. At least six different horizons were picked and interpreted in each seismic section.

## 4. Results

### 4.1. Fault systems

#### 4.1.1. Strike-slip fault system

Based on the seismic sections in the northern parts of the Dezful

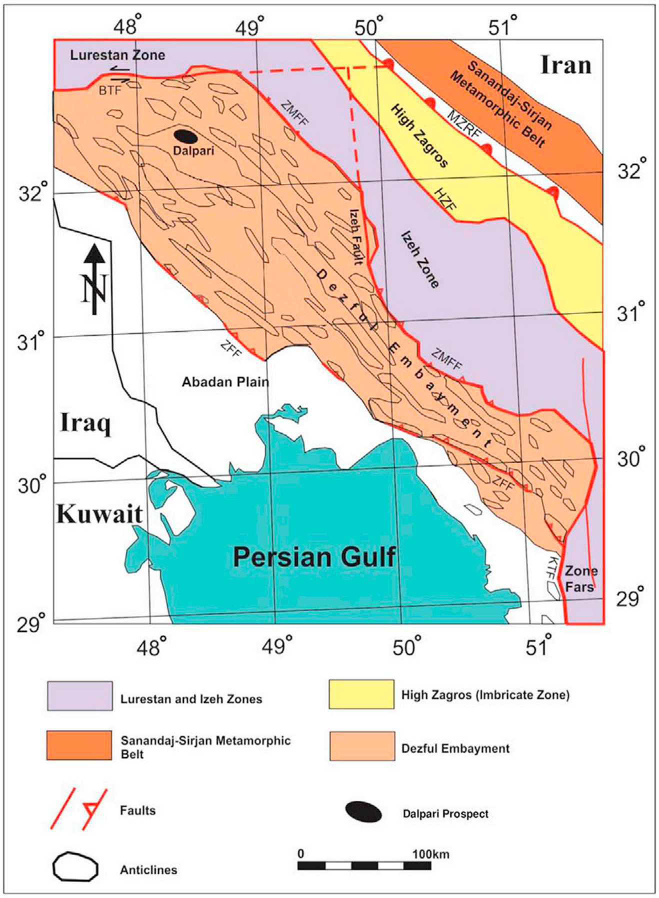


**Fig. 2.** Geological map of the western ZFTB (modified after Abdollahie Fard et al., 2006). The major anticlines are outlined. Major thrust faults subdivide the ZFTB into different sub-zones. The Dezful Embayment, with numerous oil fields, is bordered by the Balarud, Mountain Front and Kazerun Fault Zones, respectively.

Embayment and the regional geology, a compressional zone with a positive geomorphic relief in centre of the structure has been interpreted as an active transpressive fault system, that formed at a restraining bend along a strike-slip fault (Fig. 5). The NW-SE trend of the strike-slip fault parallels many other faults along the ZFTB. The strike-slip fault in the north is almost vertical but rotates to dip 45° to W in the southern part of the structure. Both, the dip and the dip directions of this fault differ in the northern and southern parts of the Dalpari prospect (Fig. 5). The reverse component of the fault is mechanically linked with folding of the Sarvak, Kalhur and Asmari Formations (Fig. 5). Dextral strike-slip displacement in the left stepping stepover formed a contractional bend. Here the Asmari Formation was pushed-up along oblique thrusts to form a positive flower structure (Fig. 5) within a transpressive strike-slip fault. Thus the structural relief in the restraining bend has uplifted its central part. This structure is clearly visible in the subsurface maps of the Asmari, Kalhur and Sarvak Formations (Fig. 5).

#### 4.1.2. *Reverse fault system*

In the northern part of the Dalpari prospect, two reverse faults root into the evaporitic units of the Gachsaran Formation (violet line, Fig. 5) and propagated up into the Agha Jari Formation (yellow line, Fig. 5). The near vertical dip of the strike-slip fault and its transpressive uplift component has lateral translated the lower members of the Gachsaran Formation. This lateral translation together with ductile thickening of salt and anhydrite bearing layers resulted in local gravitational collapse of the competent members of the Gachsaran, Bakhtiari and Agha Jari Formations. This gravitational collapse is delimited by steep dipping faults, which have, depending on their dip direction, either a normal or reverse component. In this configuration, the downward movement of footwall relative to hanging wall as a consequence of gravitational collapse of the Gachsaran Formation can be interpreted as reverse fault that didn't form due to compressional stress.

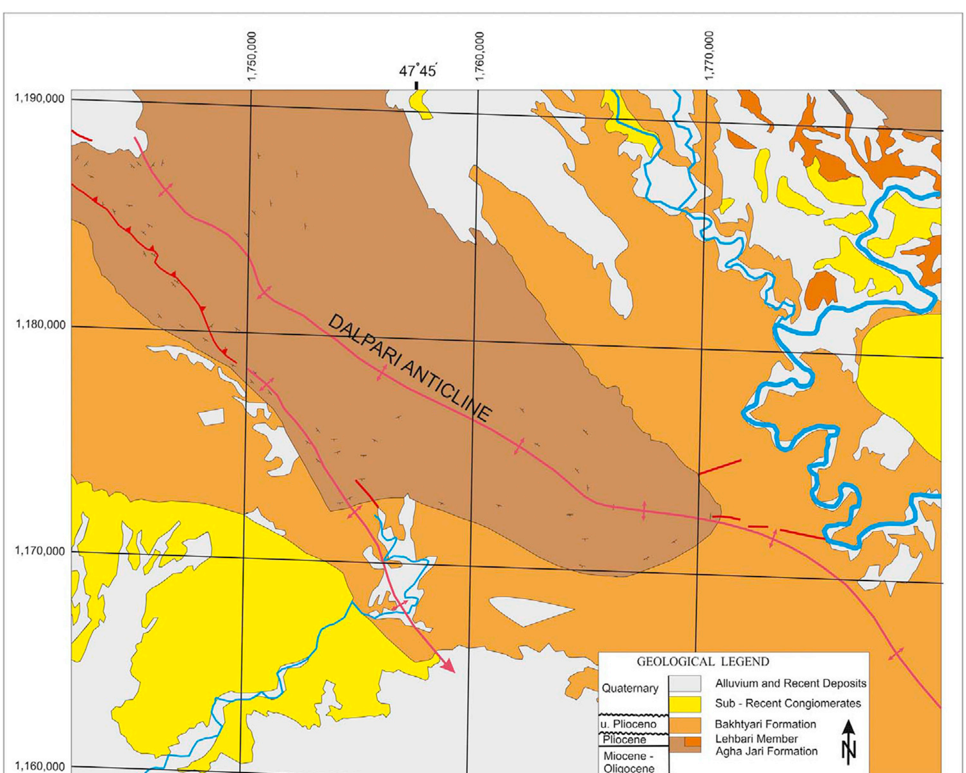


**Fig. 3.** Geological map of the Dalpari structure in the North of the Dezful Embayment (modified from 1:100,000 scale geological maps provided by the National Iranian Oil Company).

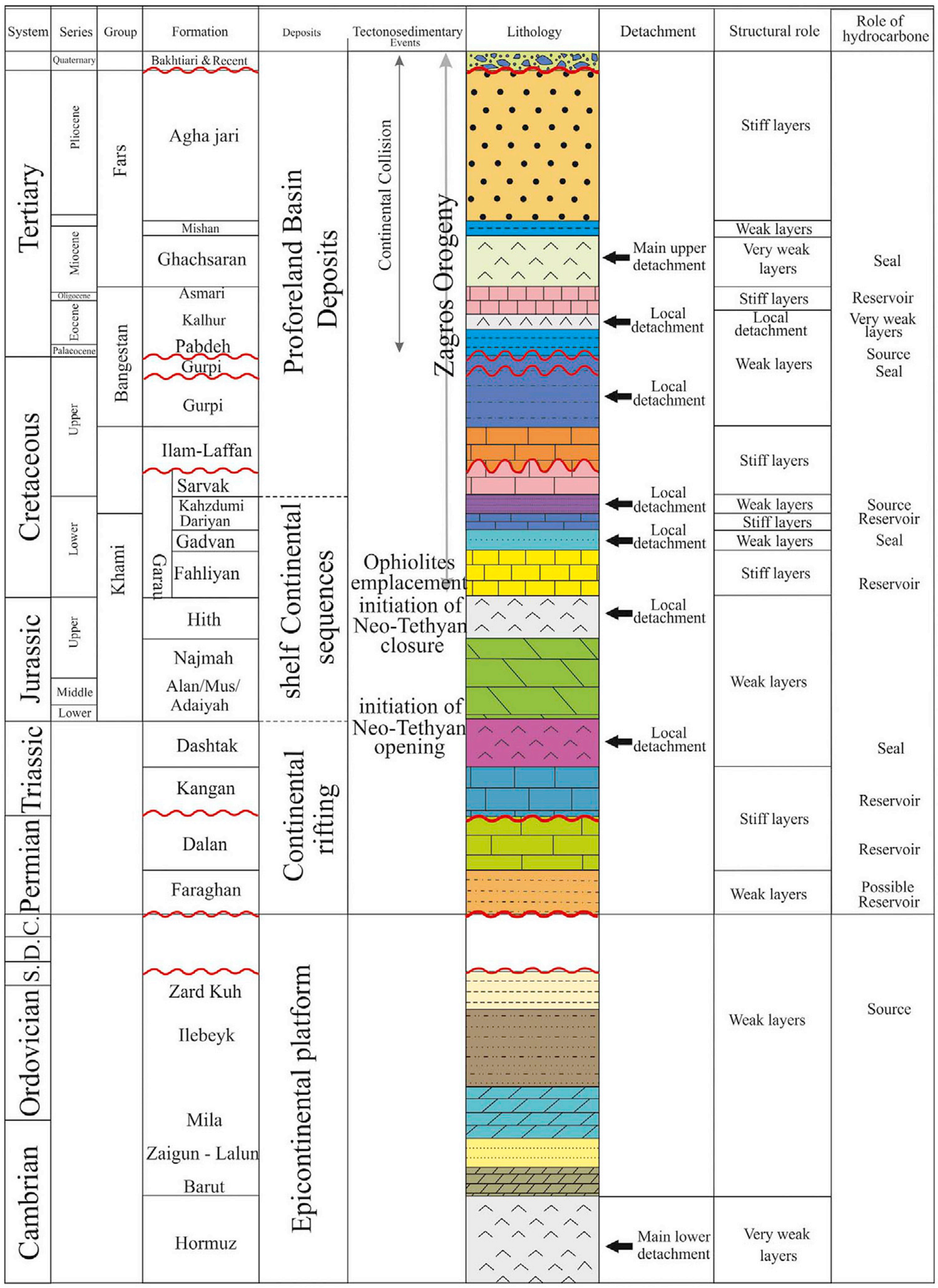


**Fig. 4.** Simplified stratigraphy of the area depicting the major lithological successions and main tectonic events in the Dezful Embayment. The stratigraphic column is modified after Abdollahie Fard et al. (2006) and Alavi (2007).

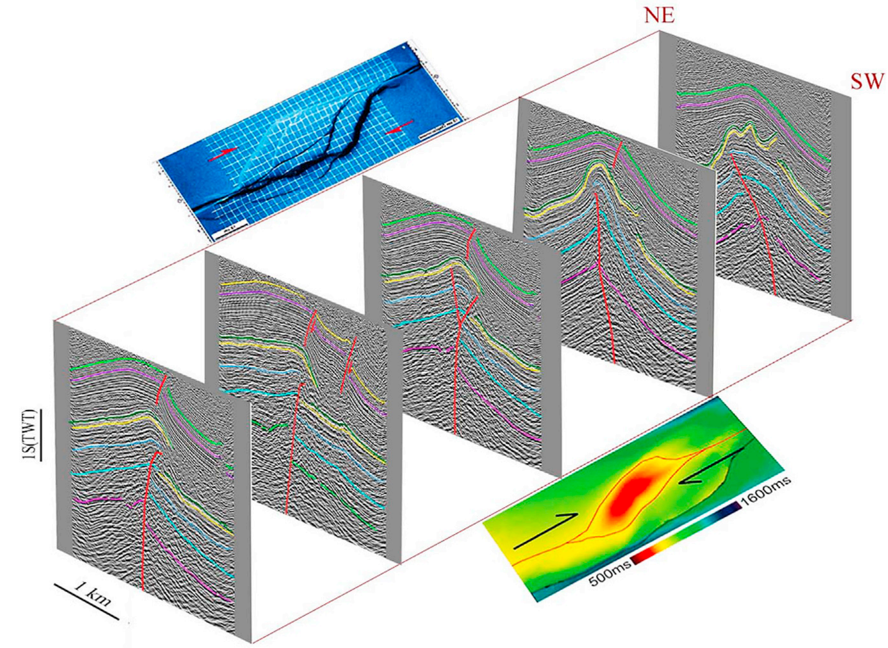


**Fig. 5.** Depth map of the top of the Asmari Formation. The Dalpari prospect includes a transpression zone along in its centre and strike-slip faults. The dip directions of the faults change along the prospect. Two strike-slip faults with right-lateral kinematics are linked by transpressional stepovers and associated uplift zones to the central part of the Dalpari structure. For comparison, an analog model of a restraining stepover is shown (McClay and Bonora, 2001).

#### 4.1.3. *Out of the syncline thrust faults*

In the Agha Jari Formation, some out of syncline thrust faults dip SW in the central part of the Dalpari prospect. These thrusts translated the Asmari, Kalhur and Sarvak Formations into the evaporitic Gachsaran Formation which accommodated space problems by ductile flow and collapse of the overlying Formations delimited by out of syncline thrust faults. Because of the competence contrast of the upper members of the more competent Gachsaran and less competent Agha Jari formations, the out of syncline thrusts dip more steeply in the upper members of the Gachsaran Formation than in the Agha Jari Formation.

### 4.2. *Folding*

We will distinguish the folds in Fig. 6 into three different orders based on their scale. The first (largest) order fold is about 2 km across and has amplitude of 0.8 km. It is an asymmetric fold formed as a result of the strike-slip fault movement with a thrust component offsetting the Daryian, Sarvak and Asmari Formations and Kalhur member (Fig. 6a). This asymmetric fold has an axial plane approximately parallel to fault plane. Based on the inter-limb angle (of about 70°) the structure can be classified between a close to open fold. The second order folds with their 200 m wavelength have amplitudes of about 50 m. These fold the Asmari Formation between the Kalhur member and the Gachsaran Formation in the southern parts limb of the first order anticline (Fig. 6b).

Third order folds are less than 100 m across with amplitude of several tens of meters and form asymmetric folds in the competent units of the Gachsaran Formation in the south of the pop-up structure (Fig. 6c).

### 4.3. *Growth strata*

Growth or syntectonic strata are stratigraphic intervals that were deposited as structures like folds and/or faults grow (Suppe et al., 1992; Soleimany and Sàbat, 2010). The upper members of Gachsaran and Agha Jari Formations are thicker in the footwall of the reverse fault (SW limb) (Fig. 6d). In other words, the Gachsaran and Agha Jari Formations in SW limb of the Dalpari anticline record growth thickening, which is not observed in the NE limb of the structure.

## 5. Discussion

As a result of our investigations of the seismic sections we conclude that Dalpari prospect represents a right-lateral strike-slip zone that popped up from a restraining bend along a regional strike-slip fault trending NW-SE. This interpretation is based on the depth map (Fig. 5) which shows a restraining bend in the centre of structure associated with a structural relief. We attribute to a right-lateral strike-slip fault. The hanging- and footwalls dip to the NW and SE respectively. The target has the typical geometry of a pop-up due to transpressional uplifts due to restraining bends or stepovers developing in strike-slip fault zone systems (Sylvester, 1988; Zolnai, 1991). The right-lateral strike-slip displacement in the central part of the structure resulted in a transpression zone forming the Dalpari prospect (Fig. 5). Anticlinal uplifts (pop-ups or transpressional uplifts) with doubly plunging axes are common in regional transpression fault systems. Anticlinal uplifts are often lozenge or rhomboidal-shaped structures in map view (McClay and Bonora, 2001). They are limited to convex-upward fault-planes in cross section and often lead to the formation of the positive flower or palm tree structures (Sylvester, 1988). The depth maps of the Asmari, Sarvak and Darian Formations and Kalhur member define a clear doubly plunging fold with a rhomboidal map form in the transpression zone in at a restraining bend near the centre of the strike-slip fault (Fig. 5). Both the dextral strike slip fault and also the transpression zone in the Dalpari prospect highlight the significance of a dextral shear component in the ZFTB. This is in agreement with McClay et al. (2004) and Sarkarinejad et al., (2013, 2015) who suggested that such shears are due to the oblique convergence between the Afro-Arabian and Central-Iranian plates.

Evaporites in the Gachsaran Formation acted as a main upper detachment surface in the Dezful Embayment (Sherkati et al., 2005, 2006; Abdollahie Fard et al., 2006, 2011; Mouthereau et al., 2012). Several in-sequence and out-of-sequence thrusts and back-thrusts root down into the Gachsaran Formation in the ZFTB (e.g., Abdollahie Fard et al., 2006). In the Dalpari prospect, ductile deformation of the evaporites in the Gachsaran Formation prevented the propagation of strike-slip faulting in the upward into Agha Jari Formation. The fault displacement is partitioned into ductile deformation in the Gachsaran Formation so

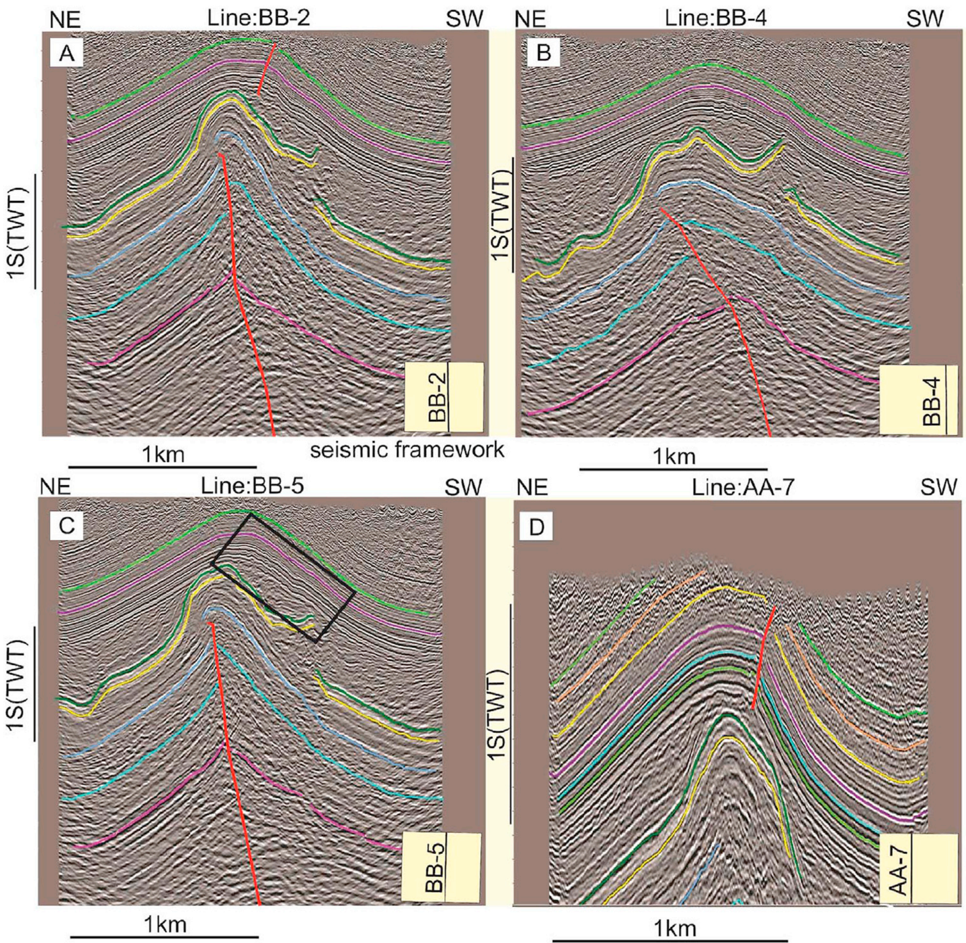


**Fig. 6.** Seismic profiles of the prospect, light green line shows the top of the Agha Jari Formation, violet line shows the top of the Gachsaran Formation, dark green shows the top of the Asmari Formation, yellow line shows the top of the Kalhure member, dark blue line shows the top of the Sarvak Formation and light blue line shows the top of the Darian Formation. (A) First order folding (the largest scale) formed as a result of slip along a strike-slip faults with a thrust component in the Daryian, Sarvak and Asmari Formations and Kalhur member (B) The second order folding affects the Asmari Formation (C) The third order folding (black box) formed as the result of the thrust component of the strike-slip fault in the upper members of the Gachsaran Formation. The fourth order folds (smallest scale) developed only in the Agha Jari and Gachsaran Formations. (D) Growth strata in the Aghajri and Gachsaran Formations formed because of the uplift associated with the reverse component of strike-slip fault associated uplift. The top members of the Gachsaran and Aghajri Formations were deposited as growth strata during the folding. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that only the overlying upper strata folded (Figs. 5 and 6).

Vergés et al. (2011) attributed the occurrence of normal faults and graben in the Agha Jari Formation in ZFTB due to ductile flow of the Gachsaran Formation in the north part of the Dezful Embayment. Legrand (2009) also attributed the gravity-collapse structures in the Dezful Embayment to ductile flow in the Gachsaran Formation. Abdollahie Fard et al. (2006) suggested three mechanisms that could change the thickness of Gachsaran Formation:1) thrust-propagation in the Gachsaran Formation 2) flow from fold crest to limbs (Fig. 7) and 3) local thrust stacking. Transpressive strike-slip fault activity in the Dalpari prospect, vertically translated the Sarvak and Asmari formation. This process caused the anhydrite, salt and shales of the Gachsaran Formation to flow laterally towards the northeast of the structure (Fig. 7).

Abdollahie Fard et al. (2006) reported out of the syncline thrust faults in the Dezful Embayment and Abadan Plain in the southwest of the ZFTB. Translation and rotation of the sediments in the foot walls of reverse faults, resulted in an asymmetrical syncline. In addition, the lack of adequate space for the displaced sediments in the core of the syncline led to the formation of out of syncline thrust faults in the footwall of the thrust faults (Fig. 5). The existence of several out of syncline thrusts in each syncline represents reflects the space problem accommodated by the evaporative Gachsarn Formation in the hanging wall of the reverse faults. It is noticeable that the dips of the out of the syncline thrusts changes because the faults are refracted across stratigraphic layers with different competence (e.g. Gachsaran and Agha Jari Formations).

The first order fold is a tight asymmetric fold of the Sarvak and Asmari Formations and Kalhur member in the northern part of the Dalpari prospect with almost 2 km across and 0.8 km amplitude (Fig. 6a). The axial plane of this fold is approximately parallel to the transpressive strike-slip fault plane. In the south of the Dalpari prospect, the competent Asmari Formation has been folded between the incompetent layers of the Gachsaran Formation and Kalhur member. As a result of this deformation, the second order of folds with almost 200 m wavelength and about 50 m amplitudes formed in the Asmari Formation (Fig. 6b), facilitating ductile flow of the Kalhur evaporites from the limbs to the fold hinges. Flow of incompetent strata from limbs to hinges during the folding is also observed in the Sarvak Formation in the northern Dezful Embayment (Fig. 8). The third order folds are the small asymmetric folds in upper unites of the Gachsaran Formation with less than 100 m across and several tens of meters amplitude. The axial planes of these folds are parallel to the main fault plane (Fig. 6c).

In the past three decades, numerous studies have been carried out on the growth of thrusts and normal faults (Davison, 1987; Suppe et al., 1992; Ford et al., 1997; Nigro and Renda, 2004; Kazem Shiroodi et al., 2015). Faults and folds growing coeval with sediment deposition are known as growth strata (Gawthorpe and Leeder, 2000; Vergés et al., 2002; Pochat, 2004; Pochat, 2009; Clement, 2010; Ahmadi, 2013). The concept of growth strata helps to improve our understanding of coupling

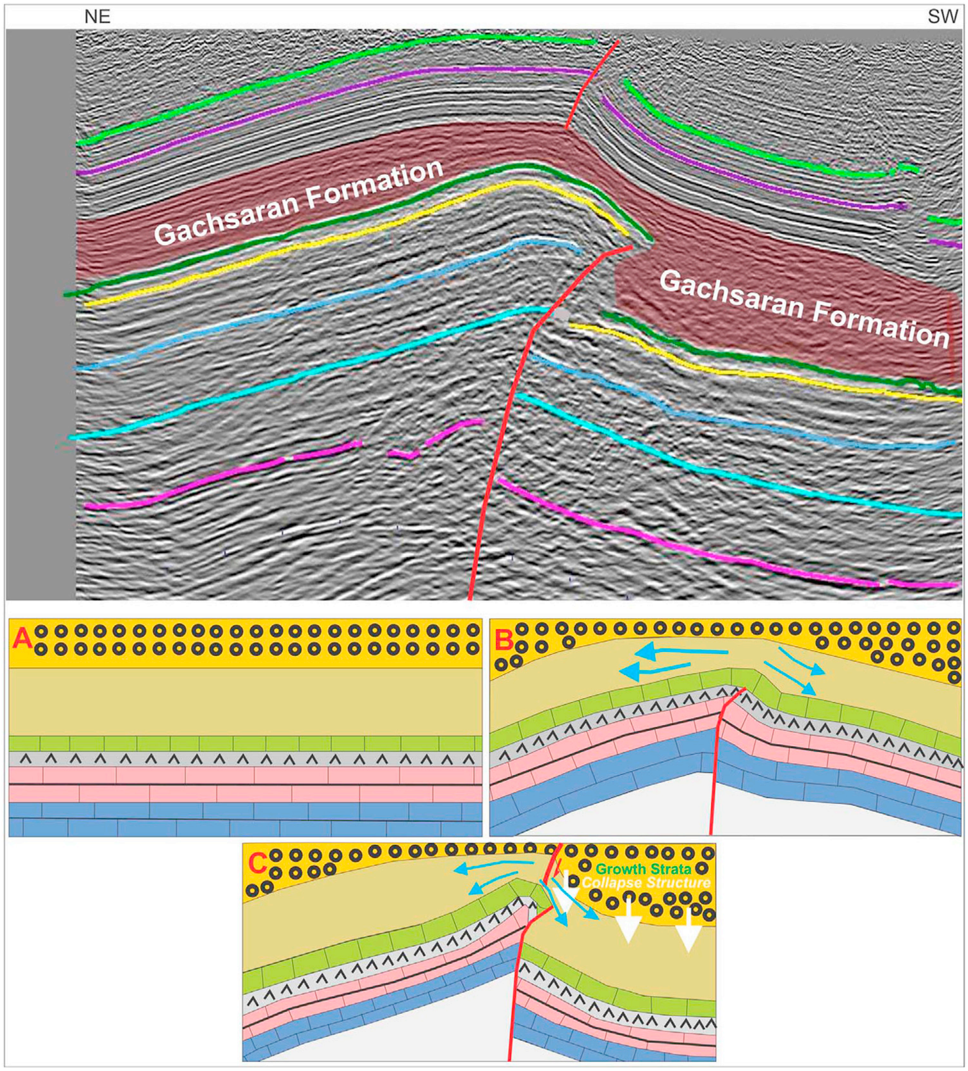


**Fig. 7.** The thickness of the evaporates in the Gachsaran Formation were significantly modified by movement along the strike-slip fault with its reverse component. These induced local gravitational collapse and the deposition of growth strata in Agha Jari Formation.

mechanisms between syntectonic sedimentation and related folding and faulting. The same concept also improves the accuracy of the structural models developed during hydrocarbon exploration, especially in regions where growth geometries can be highly complex (Vergés et al., 2002).

To determine the timing of deformation of folds and thrusts, it is necessary detail exact relationship between sedimentation and tectonics. One of the best ways to accomplish this goal is to study the geometries of growth sediment (Muthereau et al., 2012). Growth strata in the upper Miocene to Pliocene Agha Jari Formation reveal the time of folding in the Dezful Eembayment (Homke et al., 2004; Sherkati et al., 2005; Lacombe et al., 2006; Abdollahie Fard et al., 2006, 2011; Leturmy et al., 2010; Emami et al., 2010). Syntectonic sediments and growth structures have been reported from different stratigraphic levels all over the ZFTB (Hessami et al., 2001; Sherkati et al., 2005; Mouthereau et al., 2007). The Gachsaran Formation is considered to record pre-growth strata (Homke et al., 2004; Emami et al., 2010; Mouthereau et al., 2012) while pre-growth and growth units are observed in the Agha Jari and Bakhtiari Formations from Middle Miocene to Pliocene (McQuarrie, 2004; Mouthereau et al., 2007, 2012; Khadivi et al., 2010; Agard et al., 2011; Homke et al., 2004; Emami et al., 2010). The growth strata in the competent members of Gachsaran Formation were formed during the transpressive strike-slip faulting (Fig. 6d and Fig. 9). However, in the Dalpari prospect the growth strata occur only in upper the members of Gachsaran and Agha Jari Formations (Lower Miocene) in the northern part (Fig. 6d and Fig. 10) No growth strata have been observed in the southern part of the Dalpari structure. We attribute this lack to the southern part of the strike-slip fault having been inactive during the Lower Miocene. Alternatively, the dip and therefore the associated structural uplift of the southern part of the fault is less than that of the northern part (Fig. 10).

## 6. Conclusions

We interpreted our seismic profiles as implying that the reverse component of the strike-slip faulting caused the formation of important petroleum traps in the northern part of the Dezful Embayment within the ZFTB. The restraining bend in the centre of the right-lateral strike-slip fault led to the formation of a transpressional pop-up in the Dalpari prospect. The right-lateral transpressional zone in the Dalpari prospect was due to the oblique convergence between Afro-Arabian and Central-Iranian plates. The activity of this fault, plus the thick evaporites in Gachsaran Formation acting as a detachment level, mechanically influenced the structural style of the petroleum trap in the Dalpari prospect. The strike-slip faults and the evaporites in the Gachsaran Formation and Kalhur member of the Asmari Formation played important roles in the formation of the folds. The growth strata in the upper members of

**Fig. 8.** Ductile deformation during the folding of the Sarvak Formation in the northern Dezful Embayment caused flow of incompetent material from the limbs to the hinge area. View towards SW. (location: UTM, Zone: 38 S, X: 677513 Y: 3761760, picture curtesy of Iraj Abdollahie Fard).


**Fig. 9.** Growth strata geometry in the Agha Jari Formation in the northwest part of the Dalpari structure, northern Dezful Embayment (location: UTM, Zone: 39 R, X: 409623 Y: 3425126, picture curtesy of Iraj Abdollahie Fard).

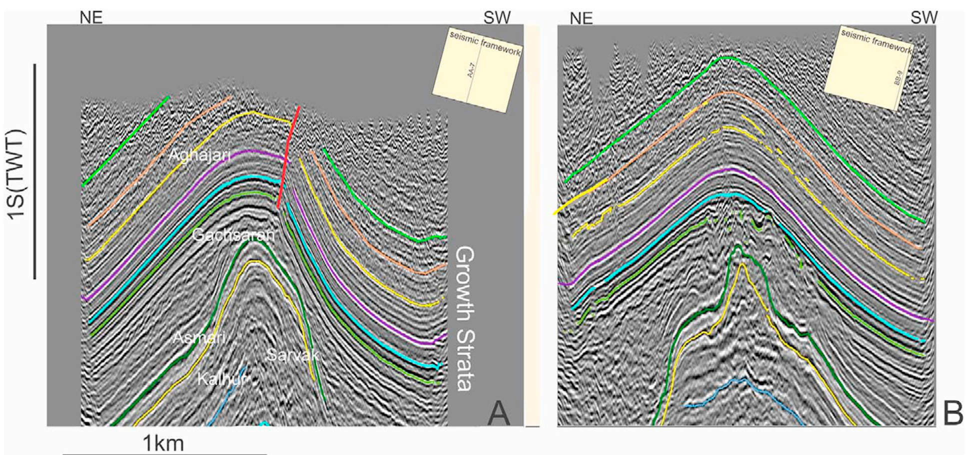


**Fig. 10.** (A) Growth strata accumulated in the upper members of Gachsaran and Agha Jari Formations as a result of reverse fault activity close to the collapse structures of the northern part of Dalpari structure. (B) There are no growth strata in the Gachsaran and Agha Jari Formations suggesting that the folding formed after Miocene.

Gachsaran and Agha Jari Formations date the activity of the northern part of the strike-slip fault to Miocene times. The absence of growth strata in the southern part of the Dalpari prospect may indicate Miocene inactivity; alternatively it could indicate that the fault had a gentle dip there.

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