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Along-strike variation of structural style: Mansourabad Anticline in the Dezful Embayment, SW Iran

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ABSTRACT

Understanding the governing factors that influence structural style and fault-related folding mechanisms is crucial in the Dezful Embayment, an area of ~ 60,000 km^2 which accounts for most of oil production from Iran. Such studies enable the subsurface kinematic modeling of structures and structural geological analysis of hydrocarbon traps. In this study, variations in geometry and folding mechanism along the strike of the Mansourabad anticline are studied through field data, 2D and 3D seismic lines interpretation and well data. The displacement-distance profile of the forelimb thrust fault indicates that the anticline is a fault propagation fold in its central and NW parts. In the SE part of the anticline, there is a north-verging detachment fold, which is opposite to the southward vergence at the NW part. Due to structural variations, the amount of slip along the NW-SE trending Behbahan Fault varies. This variation in structural style results from changes in slip along the Behbahan Fault's forelimb. This blind thrust, which trends NW-SE, extends along the entire length of the Mansourabad anticline. The variable thickness of the syn-folding sediments controlled the structural style of the anticline, which interacted with the migration of the Gachsaran Formation and the deformation of the competent rocks.

1. Introduction

Geometric and kinematic models of thrust-related folding are useful for interpreting structural style and subsurface interpretation of the fold and thrust belts (e.g., Jia et al., 2006). The exercise is vital for the exploration and production of hydrocarbons, which are commonly trapped in structural culminations formed by the hangingwalls of the fault-related folds. Variation in the amount of fault displacement in the fault-related folds increases the complexity of the structural deformation. As a result, the structural style of anticlines changes both vertically and horizontally (Sarkarinejad et al., 2018). In such terrains, detailed structural analyses would be critical for oil and gas field exploration and development.

The Zagros Fold and Thrust Belt (ZFTB) is one of the most petroliferous regions among collisional orogens, accounting for 12% of global oil reserves (Bordenave and Burwood, 1990). According to another estimate, this collisional mountain belt contains 9% of the world's oil and 15% of the world's gas reservoirs (e.g., Bordenave and Hegre, 2005). Significant fault-related folds host the main hydrocarbon oilfields in the Dezful Embayment as one of the structural regions of the ZFTB (e.g., Allen, 2010; Najafi et al., 2014). The Oligo-Miocene Asmari Formation, which is the most productive fractured reservoir for several giant oil fields in the Dezful Embayment (Iran), plays a crucial role in controlling oil production (e.g., McQuillan, 1985; Afroogh et al., 2023). Collisional fold and thrust belts have usually been considered less suitable for hydrocarbon exploration (reviewed in Hammerstein et al., 2020). Notwithstanding, this has not been the case with the Zagros orogenic belt.

The NW-SE trend of the ZFTB resulted from the Permian-Early Triassic opening and the Late Cretaceous to Miocene closure of the neo-Tethys Ocean between the Central Iran and the Arabian plate. This closure significantly influenced the generation, migration and

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entrapment of hydrocarbons in the ZFTB which is particularly important in the Dezful Embayment with ~ 45 major oil fields of the ZFTB (Bordenave, 2014; Esrafili-;Dizaji and Rahimpour-Bonab, 2019; Alipour, 2024). Folding in the ZFTB and the Dezful Embayment (Table 1) resulted in the main structural traps. Therefore structural style and kinematic evolution of folds and faults are important aspects in the exploration and development of the oil and gas fields.

The folding and faulting style in the ZFTB is controlled by multiple incompetent detachment levels in the sedimentary sequence (Table 2). Nevertheless, there has been limited emphasis on the quantitative interplay among variations in shortening along-strike, fault displacement, growth strata, and changes in structural style.

In this study, we investigate the Mansourabad anticline, which is a complex structure situated in the Dezful Embayment. Our aim is to determine the factors that control the structural variation along the fold strike in an area of ~ 20*6 km^2. To achieve this goal, we use a combination of field data, 2D and 3D seismic data (of relatively appropriate quality for the top of the Pabdeh Formation, PF), and well data (drilled to the Asmari Formation, AF).

The goals of this article are to *(i)* characterize structural style based on fold-fault interaction; *(ii)* quantify slip in the deep-rooted fault and its effects on structural variation; and *(iii)* comprehend the role of mechanical stratigraphy and syn-deformation deposits in folding style. The aims of this research are crucial for advancing structural geology and its applications in resource issue. By characterizing structural styles based on fold-fault interactions, we improve our ability to predict subsurface geometries, which is essential for accurate structural modeling and hydrocarbon exploration. Quantifying slip in deep-rooted faults allows for precise assessment of fault-related deformation, providing insights that are crucial for field development and the safe placement of drilling infrastructure. Additionally, understanding the influence of mechanical stratigraphy and syn-deformation deposits on folding styles enhances our ability to model and handle reservoirs by affecting the distribution and flow of hydrocarbons. These insights advances our scientific understanding of geologic processes and facilitate efficient exploration and development of natural resources.

2. Geology

The Mansourabad anticline is located at the northeastern boundary of the Dezful Embayment, in front of the Mountain Front Fault (MFF). The MFF is one of the major structures of the Zagros folded belt, which is made up of a topographic step that separates the belt from its foreland basin (Fig. 1). The Mansourabad anticline has a length of approximately 5.8 km along the strike and 21 km across the strike.

The NW-SE trending of the ZFTB was formed as part of the Alpine-Himalayan orogenic system during the Late Cretaceous by the opening and subsequent closing of the Neo-Tethys between the central Iranian and Arabian plates (e.g., Berberian and King, 1981; Frizon de Lamotte et al., 2011). Convergence started with the subduction of the Neo-Tethys Ocean beneath the Iranian plate since the Middle-Late Cretaceous. This was followed by the emplacement of ophiolites and the first deformation in the Imbricate Belt (High Zagros, e.g., Agard et al., 2005; Carruba et al., 2006). Oligocene oceanic closure and continental collision continued until recent times (Homke et al., 2004; Emami, 2008; Fakhari et al., 2008; Khadivi et al., 2010). Based on along-strike variations of structural styles, the position of the deformation front and stratigraphy of the ZFTB is subdivided into several zones.

The main Oligocene to recent foredeep basins of the Zagros orogen, the Dezful as well as the Kirkuk Embayment, resulted from uplift of the hinterland units to the NE of theMFF and accommodated a thick pile of post-collisional deposit (Berberian, 1981; Fard et al., 2006; Sherkati et al., 2006; Van Buchem et al., 2006). The Dezful Embayment boundary coincides with the Kazerun Fault Zone (KZF), Zagros Frontal Fault (ZFF), Mountain Front Fault (MFF), and Balarud Fault Zone (BFZ) (Fig. 1), which generated/ reactivated as continents collided (Alavi, 1994; Berberian, 1995; Fard et al., 2006; Sepehr and Cosgrove, 2007; Allen and Talebian, 2011; Alipour, 2023). The bending of the NE-SW trend of the Zagros folds to N-S direction and facies variation of the sedimentary pile characterize the activation/reactivation of the N-S trending Kazerun Fault Zone and the paleohighs such as Hendijan, Kharg, and Azadegan (Koop and Stoneley, 1982; Sepehr and Cosgrove 2004). The anticlines in the Dezful Embayment display 4–8 km wavelength and 5:1–10:1 aspect ratio (axial length divided by half the wavelength). These are usually parallel and open folds (interlimb angle 60–120°) and are characterized by sub-rounded hinges.

Table 1
A list of some previously published papers on folding styles in the ZFTB.

Authors	Studied terrain	Folding mechanism
Sattarzadeh et al. (1999)	Zagros deformation belt	Pure buckle folds, pure forced folds and folds intermediate between the two
Blanc et al. (2003)	Zagros Simple Folded Zone	Thick-skinned and thin-skinned deformation
McQuarrie (2004)	Zagros fold thrust belt	Many of the folds are cored by faults in the lower Paleozoic strata.
Molinaro et al. (2005)	Bandar Abbas syntaxis	Basement fault controlling on folding in western side which is absent in the eastern side
Sherkati and Letouzey (2004)	Central Zagros (Izeh zone and Dezful Embayment)	Transition from detachment folding to progressive fault propagation (faulted detachment folds)
Vergés et al. (2011)	NW Zagros belt	Thick-skinned and thin-skinned deformation
Razavi Pash et al. (2021)	Northern Dezful Embayment	Inverted pre-existing blind basement faults have an important role in the deformation style of the overlying sedimentary cover.
Razavi Pash et al. (2020)	Northern Dezful Embayment	Tear faults accommodated different structural styles of anticlines in the Zagros

Table 2
Review of decollement levels involved in structural style in the ZFTB.

Author	Studied terrain	Decollement levels
Sherkati and Letouzey (2004)	Central Zagros (Izeh zone and Dezful Embayment)	Gachsaran, Dashtak, Hormuz, KazhdumiandPabdeh
Casciello et al. (2009)	Lurestan Province	Alan, GotniaandGarau formations
Vergés et al. (2011)	Pusht-e Kuh Arc	Dashtak, Kazhdumi/Garau, Amiran/Gurpi, Kalhur, and Gachsaran level
Farzipour-Saein et al. (2009)	Lurestan and Izeh zones	Gurpi, Garau, Gotnia, Sargelu, Alan, Dashtak, Kazhdumi and Hormuz
Ghanadian et al. (2017)	Dezful Embayment	Gachsaran, Kalhur member, Pabdeh, Kazhdumi, Gotnia, Dashtak, Hormuz
Derikvand et al. (2018)	Dezful Embayment	Dashtak, Garau, Gurpi, Pabdeh formations and Kalhur Member
Najafi et al. (2014)	North Dezful Embayment	Gachsaran
Alipoor et al. (2019)	Dezful Embayment	Gachsaran, Garau
Lashgari and Derikvand (2020)	NE Dezful Embayment	Gachsaran
Vatandoust et al. (2020)	Southern Dezful Embayment	Gachsaran, Kazhdumi, Pabdeh-Gurpi and Dashtak
Heydarzadeh et al. (2020)	Dehdasht Basin	Gachsaran, Dashtak, Garau and Hormuz
Najafi and Lajmorak (2020)	South Dezful embayment	Gachsaran
Sarkarinejad et al. (2018)	Northern Dezful Embayment	Gachsaran and Dashtak

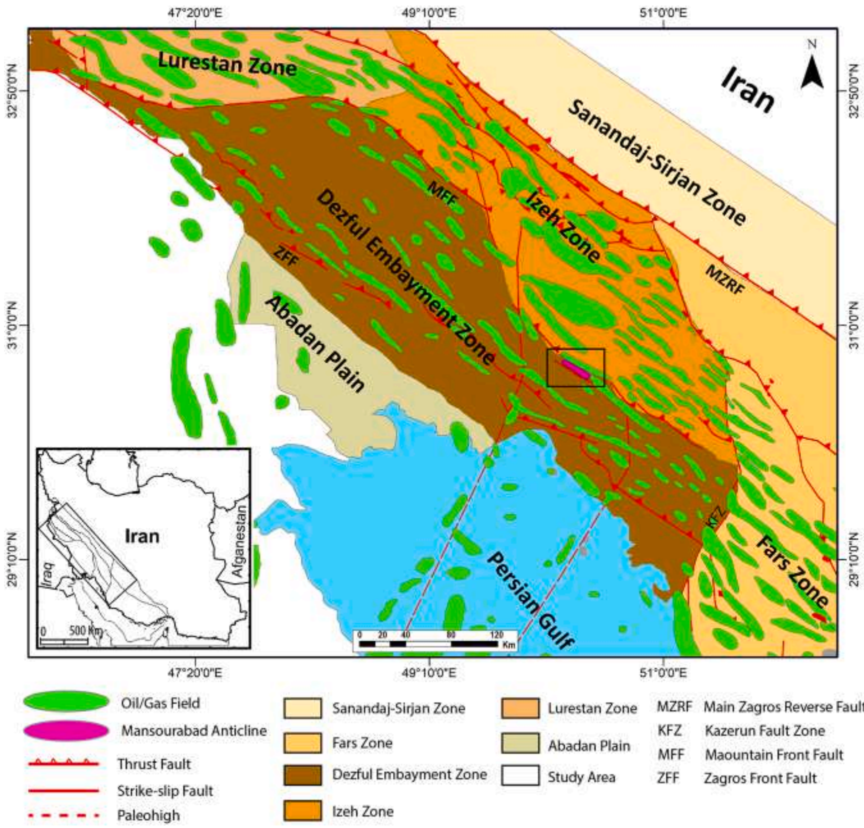

Fig. 1. The structural map of the ZFTB shows tectono-stratigraphic subdivisions (modified after Fard et al., 2006). The Mansourabad anticline is marked in pink at the northern boundary of the Dezful Embayment.

3. Stratigraphy

The Dezful Embayment displays different characteristics compared to the adjacent region, Izeh and Lorestan zones (e.g., Alipour, 2023). The anticlinal cores of the Dezful Embayment are formed by the Fars Group of Miocene-Pliocene rocks (Gachsaran, Mishan, Aghajari, and Bakhtyari formations). In contrast, the Asmari Formation and the Bangestan Group (Late Cretaceous Ilam-Sarvak Formation) and older rocks in some cases crop out as anticlinal cores in the Izeh and Lorestan zones (Motiei, 1993).

In the Dezful Embayment, the stratigraphy exhibits variations in both thickness of units and their facies spatially and temporally. On the other hand, the relationship between mechanical stratigraphy and folding and thrusting has a crucial effect on variations in structural style. The stratigraphy column of the Dezful Embayment consists of 10–12 km Phanerozoic sedimentary sequence. It includes several competent and incompetent rock units (Fig. 2).

The stratigraphy column of the ZFTB can be divided into five groups: 1) Basement (Precambrian) 2) lower mobile group (Precambrian-Cambrian Hormuz salt), 3) competent group (Cambrian to Early Miocene strata), 4) upper mobile group (Miocene Gachsaran Formation) and 5) passive group (Mishan, Aghajari and Bakhtyari Formation). However, recent research has shown that the competent group is detached at multiple detachment levels (Table 2). The crystalline basement group only crops out where the salt diapirs have brought it to the surface. Around 1–1.5 km thick Hormuz salt (e.g., Kent, 1979) belonging to the lower mobile group is the main basal detachment in different parts of the ZFTB. This blind detachment decoupled the Precambrian basement from the Phanerozoic sedimentary units, and was not penetrated by drilling in the Dezful Embayment (e.g., Farzipour-Saein et al., 2009). However, some researchers (e.g., Vergés et al., 2011) regarded Eo-Cambrian evaporites or Cambrian shales as the Dezful Embayment's equivalent of the Hormuz salt (Fig. 2).

In the competent group, the Middle Triassic evaporates (the Dashtak Formation), which acts as an intermediate detachment level, loses plasticity at the Persian Gulf and also at the northeast of the ZFTB (Szabo and Kheradpir, 1978; Setudehnia, 1978). Furthermore, the Paleocene-Eocene Pabdeh and Gurpi Formations, Kalhur Member of the Asmari Formation, and also the Gachsaran Formation (main upper detachment level) acted as sub-ordinate detachment levels in various parts of the ZFTB (Fig. 2; e.g., Fard et al., 2006; Vergés et al., 2011). Therefore, the Asmari Formation and Bangestan and Khami Groups, as main reservoirs and mechanically competent units, are located between the two incompetent units.

In the study area, the upper mobile Gachsaran Formation, consisting of salt, anhydrite, marl, and limestone, is divided into seven members. These units were deposited over the Asmari Formation. Of these, the Members 2–5 (salt and marl) acted as incompetent units and the Members 6–7 are competent units (e.g., Abdollahie Fard et al., 2011). This group varies in thickness from the southwest to the northeast of the Dezful Embayment. It reaches up to ~ 4000 m due to faulting, folding and flow (Abdollahie Fard et al., 2011). The passive Group (Lower Miocene to Plio-Pleistocene) is the upper part of the stratigraphic column formed by the growth of the ZFTB. In this group, the Aghajari and Bakhtyari formations show syn-folding geometries within growth strata and they affected the structural style of the study area (Fig. 2) (e.g., Abdollahie Fard et al., 2011).

4. Data & methods

To analyze the structural style and along-strike variations of the geometric and folding mechanisms of the Mansourabad anticline, we used several data sets, including 2D and 3D seismic and well data, provided by the National Iranian South Oil Company (NISOC). In

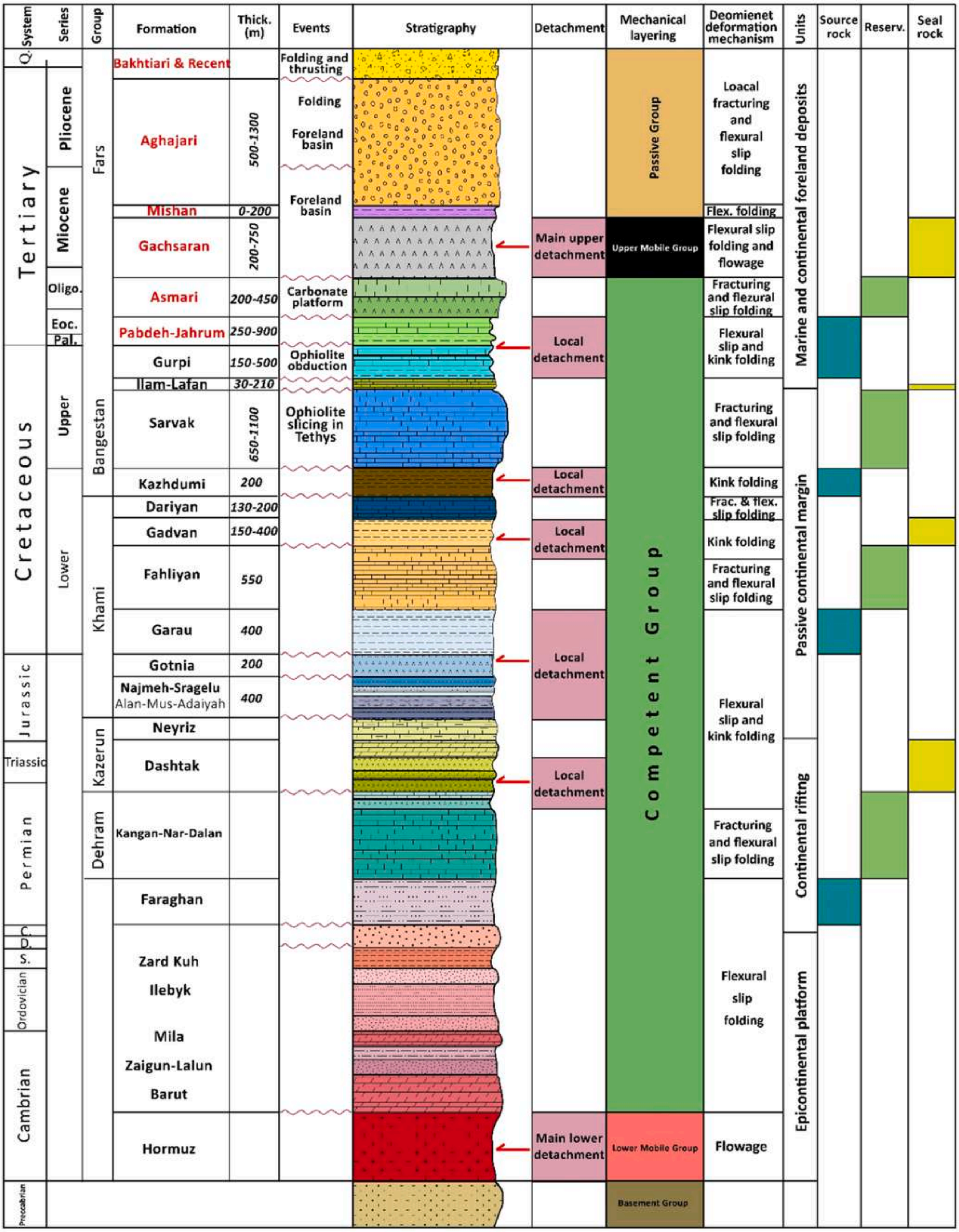

Fig. 2. Lithostratigraphic column of the study area, also shows mechanical zones, detachment units and tectonic events (Modified after Fard et al. 2006; Bordenave and Heger, 2010). Units in the study area (as seen in the black rectangle in Fig. 3) are stated in red.

addition, surface data were collected during field observation, remote sensing mapping using Google Earth, a geological map with a 1:100,000 scale, and surrounding cross sections (Fig. 3).

The following methodologies were adopted- *(i)* collection and review of 3D cubes and 2D seismic data, which were supported by other data such as formation tops, checkshots, vertical seismic profiles (VSP) and petrophysical logs from 14 wells), *(ii)* time-depth conversion of the geologic interpretation of few seismic profiles, *(iii)* interpretation of selected seismic profiles including NE-SW transverse seismic profiles (perpendicular to the Mansourabad anticline's strike) and NW-SE longitudinal seismic profiles along-strike of the anticline, *(iv)* construction of four structural cross-sections based on the seismic and field data, *(v)* sequential restoration of geological cross sections obtained from depth-converted seismic lines to calculate shortening, and *(vi)* analysis of the structure and the tectonostratigraphic relationships, and investigation of the structural style variations in the different segments of the anticline. For this purpose, we quantitatively analyzed the along-strike shortening, forelimb separation, thickness of the syn-folding strata, and interlimb angle to investigate the variation of the structural style of the Mansourabad anticline.

5. Results

5.1. General structural features

The overall axial trend of the Mansourabad anticline is ~ NW-SE and its geometry is affected by thrusts at N and S limbs. Field observations and a geologic map (Fig. 3), as well as seismic data (Figs. 4, 6–8) show that the Khaviz anticline adjacent to the Mansourabad anticline to the northeast developed in the hangingwall of the Mountain Front Fault (MFF) and thrust over the Mansourabad anticline. In the forelimb, a part of the Gachsaran Formation thrust over the younger units (Fig. 3). The MFF created strong variations in topography and structural step in the study area (e.g., Sherkati el al., 2006). In the study area, the MFF divides the Khaviz anticline in the Izeh zone from the Mansourabad anticline in the south Dezful Embayment (Fig. 3).

Miocene to Pliocene siliciclastic (from the Mishan to Bakhtyari Formation) and evaporitic (Gachsaran Formation) syn-folding sediments represent the exposed portion of the multilayer sediment cover in the study area. These covers include the Oligo-Miocene Asmari Formation and the Upper Cretaceous-Eocene Pabdeh and Gurpi Formation. Such formations overlie the Late Cretaceous Ilam and Sarvak Formation, which in turn cover the older formations to the north in the Khaviz anticline (Fig. 3). The Mansourabad anticline is surrounded by a large syncline in the southwest. This syncline accommodates syn-tectonic depositional features with varying thicknesses along the anticline such that the Gachsaran Formation displays different thicknesses along the strike reaching ~ 4 km locally. It is noteworthy that this thickness was not original, but was caused by its mobile behavior, the forelimb-fault activity, and presumably sliding over the Asmari Formation at a nascent stage of folding (Najafi and Lajmork, 2020). The mechanical properties of the Gachsaran evaporites created primary salt welds between the top of the Asmari Formation and the Members 6 and 7 (herein named as U. Gachsaran Mb) of the Gachsaran Formation (Figs. 4–8).

5.2. Structural cross-sections

Generally, in all seismic cross-sections for the Mansourabad anticline its northeastern part has a poor resolution (e.g., Fig. 4). This is because of the steep southern flank of the Khaviz anticline, which thrusts over

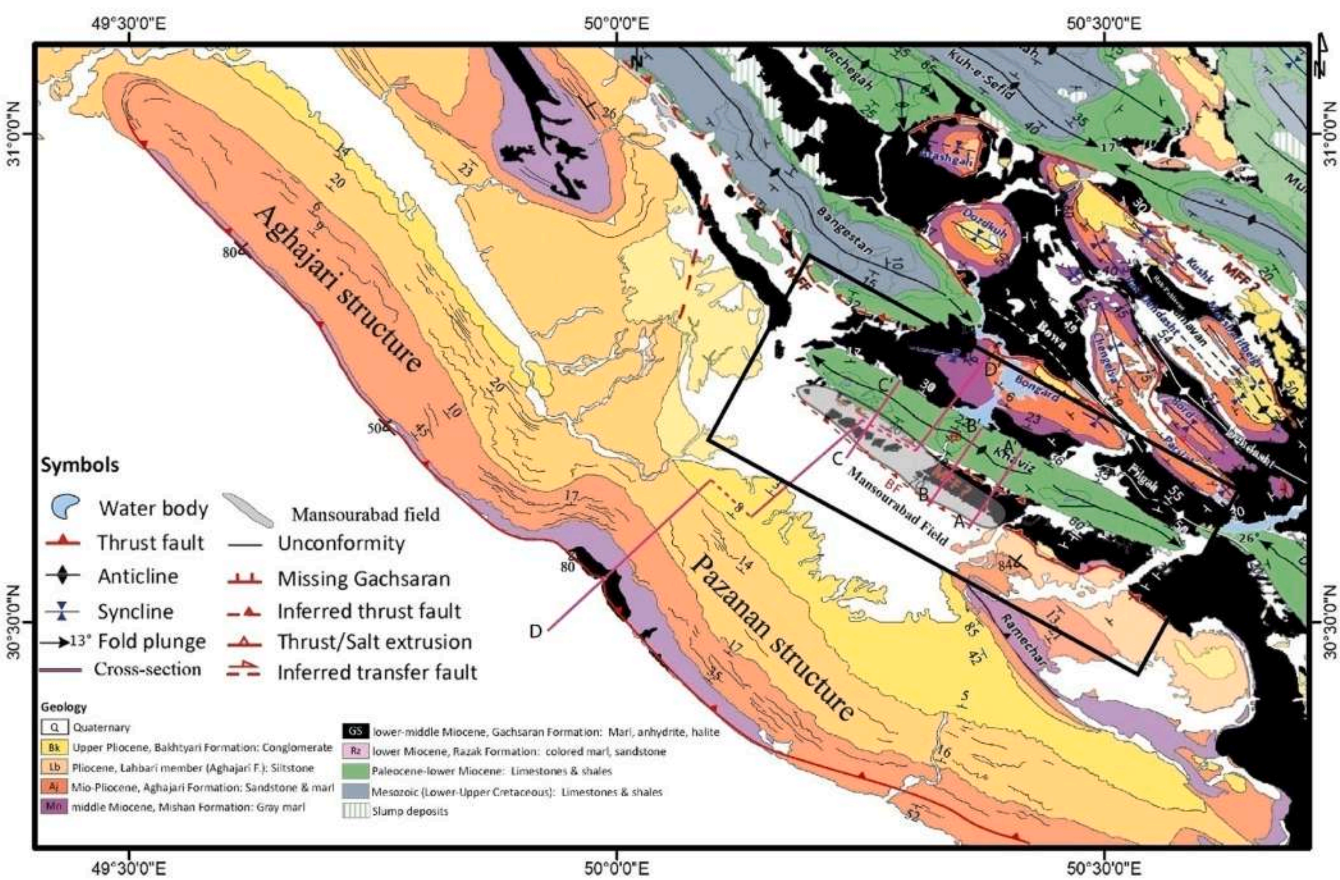

Fig. 3. Geologic map of the study area. Locations of the studied anticline (Mansourabad and Khaviz anticlines) are shown by the gray polygon. (modified after Najafi and Lajmorak, 2020; Heydarzadeh et al. 2021). The MFF and BF refer to the Mountain Front Fault and Behbahan Fault, respectively.

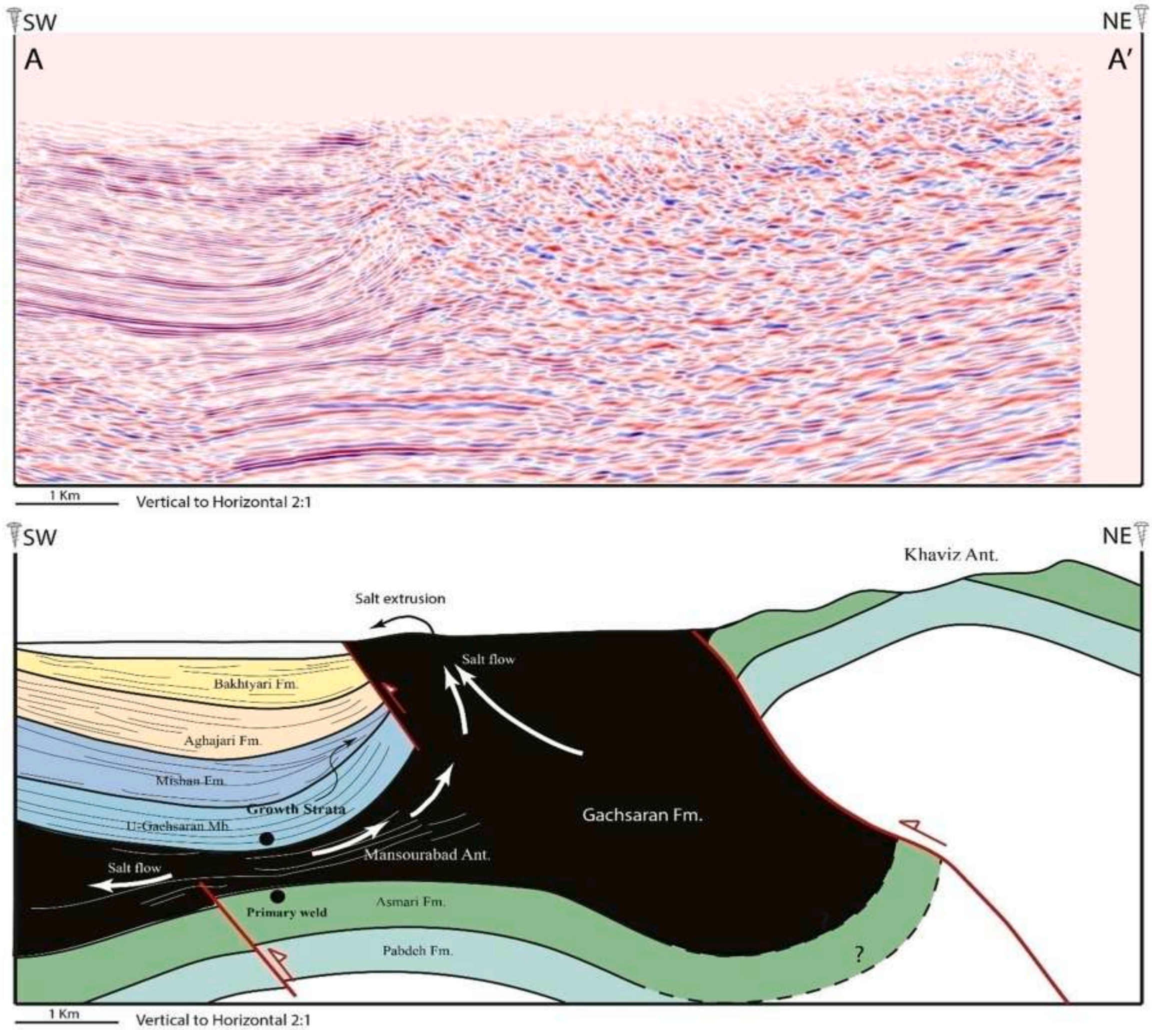

Fig. 4. Uninterpreted (upper) and interpreted (lower) seismic profile through the SE plunge of the Mansourabad anticline. Fig. 3 presents the location of the profile. In this profile, the Mansourabad anticline is a gentle detachment fold with NE-verging. The right side of the image is extrapolated from surface data e.g., Heydarzadeh et al. (2021).

the Mansourabad anticline.

Therefore, the dip of the horizons as well as the geometry of the MFF with the Khaviz anticline on its hangingwall, should be modeled. However, for this part of the cross- section as well as for the long cross-section, we used surrounding cross-sections from previous studies (Najafi and Lajmorak, 2020; Heydarzadeh et al., 2021) to improve our interpretations. Furthermore, as per the cross-sections (Figs. 4, 6, 7), the Gachsaran Formation acted as a decollement layer and shows the material migration (decreasing thickness) from the crest of the Mansourabad anticline towards the adjacent syncline.

In the A-A´ section (Fig. 4) located on the SE termination of the structure, the Mansourabad anticline displays a ~ 134° interlimb angle and can be named a gentle anticline. The northeastern reverse fault (MFF) places the Oligo-Miocene Asmari on top of the Miocene Gachsaran Formation. This slip caused a sharp topographic difference and presently shows ~ 2000 m elevation in the Asmari Formation from the crest of the Khaviz anticline (hangingwall of the MFF) to the lowermost portion of the adjacent syncline (south of the fault and northeastern syncline of the Mansourabad anticline). The anticline in this section is near-symmetric, with a steeper backlimb opposite the folding vergence in the central and northwesterly terminations of the anticline (Fig. 4).

Field data (Fig. 5) and seismic profiles (Figs. 4, 6 and 7) show that the Gachsaran Formation crops out along with a thrust fault originating from this Formation and passes through the top of the Mansourabad anticline. In the field, the effect of this fault can be seen in the steep to overturned geometry of the Gachsaran layers (Fig. 5). The southwestern flank of the Mansourabad anticline is cut by the Behbahan thrust fault, which passes through the competent Asmari Formation and terminated at the Upper Mobile Group (i.e. Gachsaran Formation). This fault dies out in the Lower-Middle Members of the Gachsaran Formation (Figs. 2 and 4). This occurs because of the mechanical properties (salt and anhydrite) of those stratigraphic units (members of 1–5), which accommodates strain plausibly at the fault tip. This fault shows low displacement in the Asmari Formation in this part of the anticline (Fig. 4).

Further, as per the geometry of the onlaps, in this cross-section (Fig. 6) the oldest growth units are related to the Mishan Formation. The B-B´ section, the Mansourabad anticline shows a weakly symmetric gentle fold geometry with a low-offset thrust fault cutting the forelimb. However, the forelimb thrust fault shows higher displacement than in the A-A′ section and has created a drag in the Lower-Middle Members of the Gachsaran Formation. On the other hand, because of their higher mobility, the Gachsaran evaporates (lower-middle Members) migrated by folding and show unequal thickness. The Gachsaran Formation is ~ 3000 m thick when measured in a well located in the central part-northeastern flank. This observation follows previous studies that suggested that the maximum thickness of the Gachsaran Formation is located to the south of the MFF (e.g., Abdollahie Fard et al., 2011; Najafi

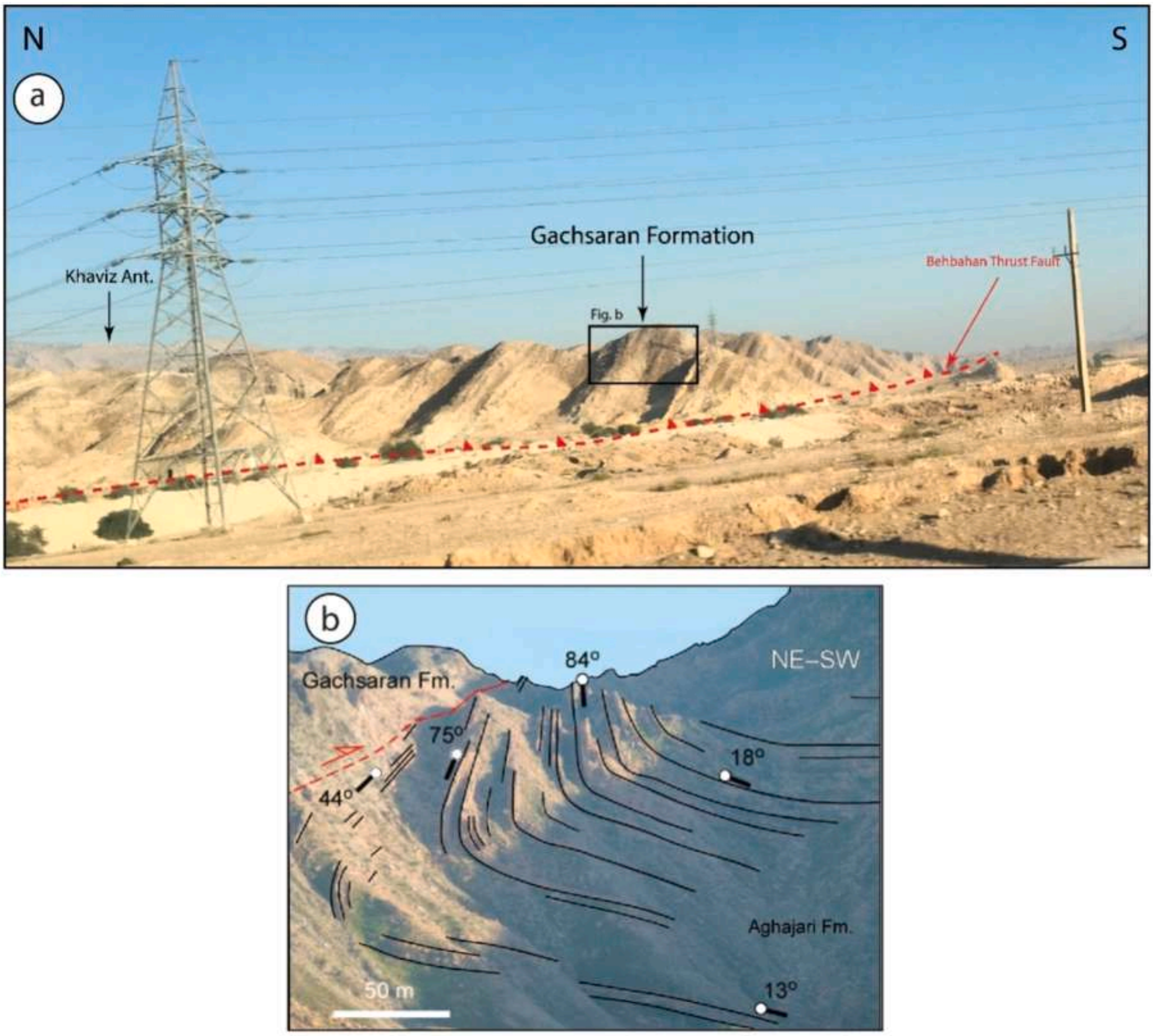

Fig. 5. a,b. Effect of Behbahan thrust fault in the Gachsaran Formation, which thrust over the Aghajari Formation at the southern flank of the subsurface Mansourabad anticline, (the inset b is from Najafi and Lajmorak, 2020).

and Lajmorak, 2020). This thickness anomaly in the Gachsaran Formation is related to the flow of the Lower-Middle units from the crest of the subsurface anticline.

On the B-B´ section (Fig. 6), the vergence of the anticline changes to the southwest, which is opposite to that on the A-A´ section (Figs. 4 and 6). The forelimb of the anticline in this section is affected by two thrusts with same dip direction but different dip angles and slips, which terminated within the ductile Lower-Middle units of the Gachsaran Formation. This triangular geometry of the deformation zone possibly represents a trishear zone related to the Mansourabad anticline.

In the C-C´ section (Fig. 7), the increase in slip on the forelimb thrust fault led to steep to overturned forelimb of the anticline. Furthermore, the thickness of the passive group (Mishan, Aghajari, and Bakhtyari Formation) in the southwestern syncline increases up to 3300 m due to the steeper forelimb as well as migration of the lower-middle units of the Gachsaran Formation. (Figs. 2, 7 and 8). An increase in sedimentary thickness of the southwestern syncline can also be seen in the sections located in the northwestern portion of the anticline. The Mansourabad anticline in this section (Fig. 7) is geometrically similar to a fault propagation fold, resembling an asymmetric faulted detachment fold. (Mitra, 2002).

5.3. Along-strike variations in the fold shortening

To analyze the kinematic evaluation of the anticlines, several balanced cross-sections perpendicular to the Mansourabad and Khaviz anticlines were constructed after the interpretation of the seismic profiles. Shortening of the anticlines were calculated for the Asmari Formation from NE-SW trending cross-sections that were 12 km long (Fig. 9). In the structural analysis involving the determination of shortening amount for the Asmari Formation, fault parallel flow and flexural-slip folding mechanism algorithm were applied in constructed cross-sections using unfolding modules of the Move 2D (2018.1) software. Structural cross-sections have been restored to an undeformed state by removing the effects of the faulting and folding. The choice of the flexural-slip folding mechanism is based on the previous works in the study area (e.g., Carruba et al., 2006, Vatandoust et al., 2020).

The shortening percentage for the Asmari Formation is calculated by dividing the final length minus the initial length by the initial length of the Asmari Formation. As in Fig. 9, the total shortening amount from the SE to the NW part of the Mansourabad anticline changes from 10% up to 15% in sections of A-A´ and L-L´, respectively. These different shortenings were accommodated by thrusting. In other words, changes in shortening percentage may be due to variations in slip amount along the fault. However, the shortening amounts in the Khaviz anticline decrease towards the NW in contrast to the Mansourabad anticline (Fig. 9). The

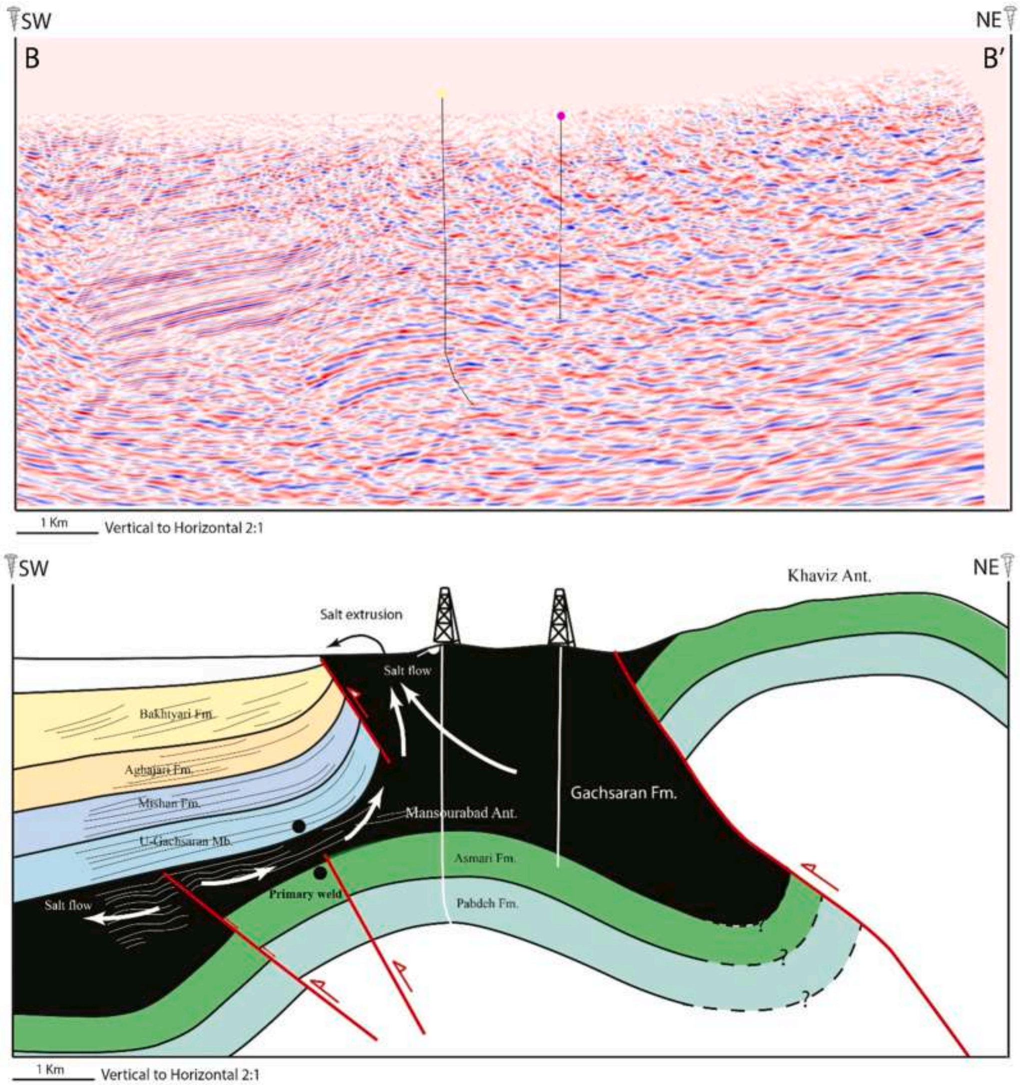

Fig. 6. Uninterpreted (upper) and interpreted (lower) seismic profile through the near the central part of the Mansourabad anticline. Fig. 3 for location. Mansourabad anticline appears slightly symmetric. The right side of the image is extrapolated not from the seismic image but from some surface data (e.g., Heydarzadeh et al. 2021).

shortening amounts in the Khaviz anticline are 21.9% in the A-A´ and 8% in the L-L´ section. According to the difference in shortening amounts in the Mansourabad and Khaviz anticlines, it can be concluded that the southeastern part of the Mansourabad anticline started growing earlier than the central and northwestern parts.

5.4. *Along-strike variation of fault's vertical separation*

Fault separation on the forelimb thrust is calculated for the Asmari Formation using seismic profiles of the Mansourabad anticline. An analysis of the along-strike structural variability is implemented in fault separation and then ascertained its relation to changes in structural style (Fig. 10). The fault separation-distance profile shows that, in the SE - part of the Mansourabad anticline, the fault created minimum separation (295 m). This is consistent with the presence of the detachment fold style in this part. In the central part (section F-F´) the fault separation reaches a maximum of 1063 m, which is consistent with the Fault Propagation Fold (FPF) style. The fault separations in the K-K and L-L sections are 1022–993 m to the NW of the anticline. This constant value of fault separation towards the NW part of the anticline (Fig. 10) is likely due to the lack of seismic coverage in the NW-plunge of the anticline which is expected to show the minimum separation values again.

5.5. *Growth strata patterns in syn-folding deposits*

Based on fold geometry and the growth strata patterns on the forelimb of the Mansourabad anticline, this fold indicates limb rotation. The dips of the growth strata layer remain constant for different formations when the hinge migration mechanism works (e.g., Rafini and Mercier, 2002). In the case of the limb rotation mechanism, dips vary (Fig. 11). Plots of growth strata horizons versus dips related to each cross-section indicate the difference in the growth strata horizons from SE to the NW of the anticline. The variation in dips of the layers with a fanning pattern indicates that the starting time of the folding varies along the Mansourabad anticline and grows with the limb rotation mechanism (Fig. 11).

Furthermore, *(i)* along-strike variations in the pinch-out positions as well as *(ii)* changes in syn-folding sedimentation with growth strata patterns indicate along-strike variations in sedimentation to uplift ratio (Fig. 12). In the southeastern part of the Mansourabad anticline, the oldest growth horizon with a fanning pattern that shows thickening in the forelimb, is the Middle Miocene Upper Gachsaran Formation (Members 5–7). In this part, the pinch-out is located above the axial surface of the Mansourabad anticline, which indicates a higher sedimentation rate than the shortening rate. Toward the central and

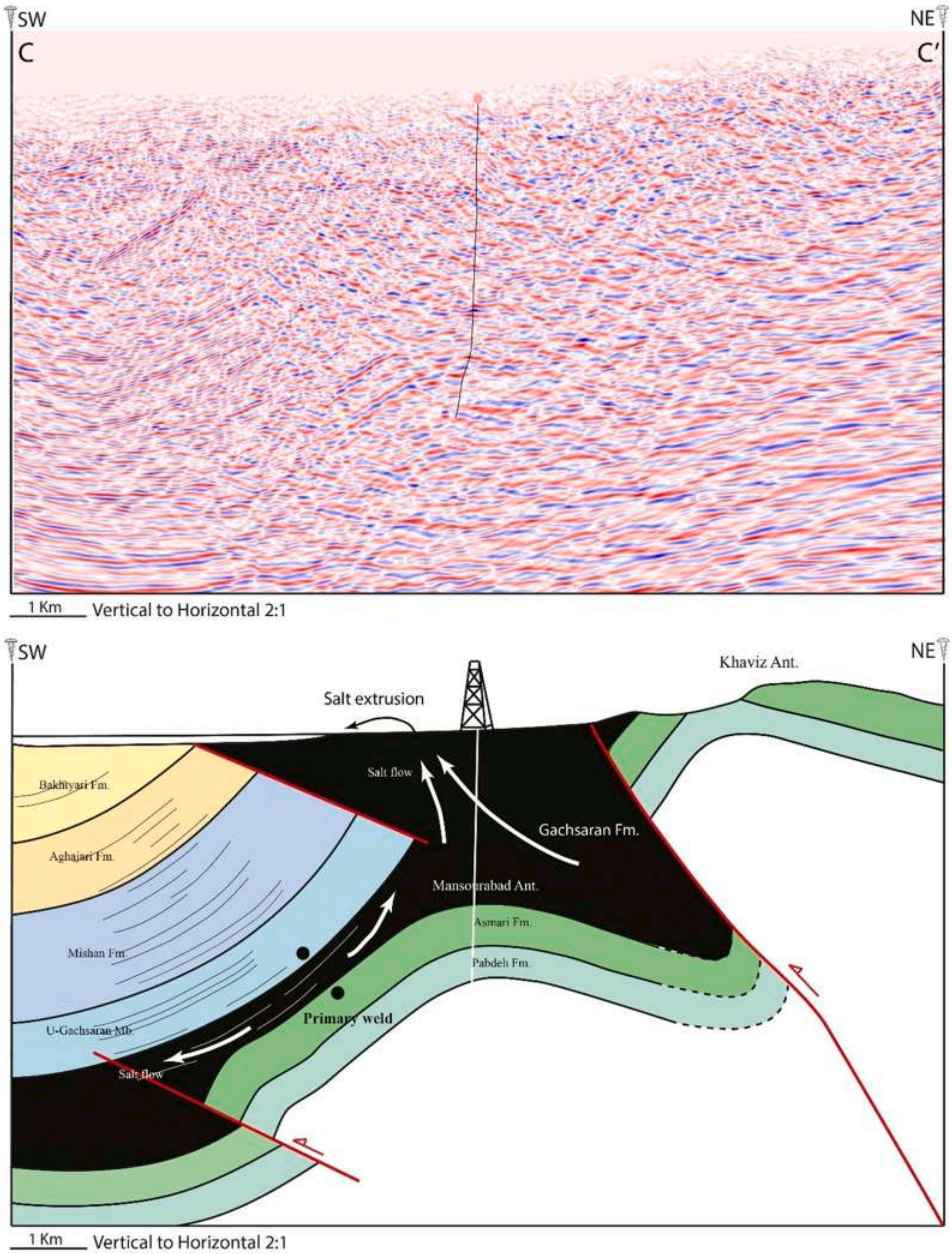

Fig. 7. Uninterpreted (upper) and interpreted (lower) seismic profile through the NW part of the Mansourabad anticline. Fig. 3 for location. The right side of the image is extrapolated from surface data e.g., Heydarzadeh et al. (2021).

northwestern parts of the anticline, the pinch-outs migrate toward the syncline axis. The Mio-Pliocene Aghajari Formation replaces the oldest growth horizon in these areas.

6. Discussions

Folding style in the Dezful Embayment is the result of interaction between several parameters such as mobility of salt (Hormuz and Gachsaran Formation), activity of multiple detachment levels, reactivation of basement faults, and geometry of syntectonic deposition (e.g., Derikvand et al., 2018). The structural style of the Mansourabad anticline resulted from *(i)* geometry of syntectonic deposition, and *(ii)* along-strike variations of fault displacement. Despite the importance of growth strata in estimating fold deformation timing and kinematics, there have been few detailed studies on their patterns in the Dezful Embayment (Table 3). Variations in the structure of the Mansourabad anticline along the NW-SE trend are linked to differences in forelimb-fault displacement.

Further geophysical studies are required to comment on *(i)* the present-day distribution of hydrocarbon deposits in the study area (especially in the Khaviz and Mansourabad anticlines), *(ii)* timing of hydrocarbon generation from prospective source rocks.

6.1. Relationship between growth strata and structural deformation

The growth strata patterns generally record the timing and kinematic

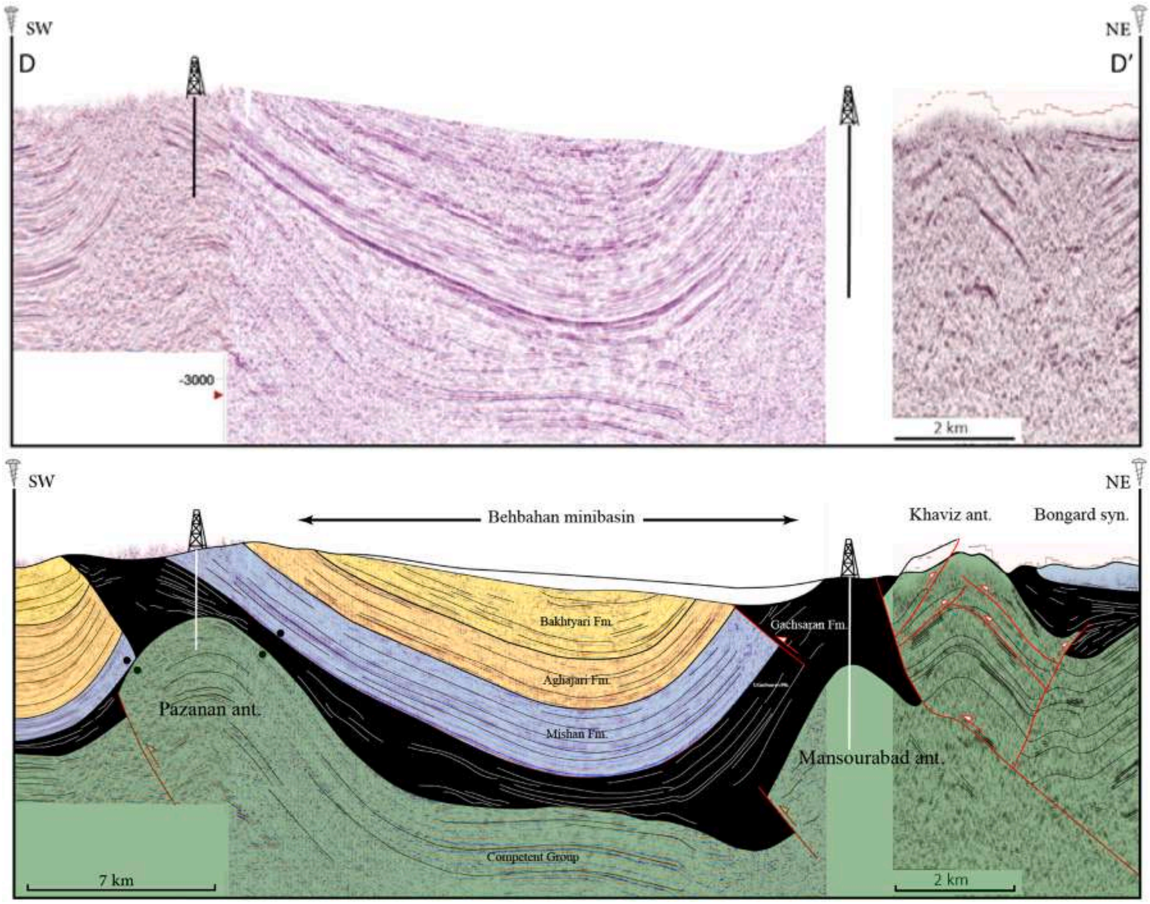

Fig. 8. Uninterpreted and interpreted NE-SW-oriented time-migrated seismic line across the Khaviz, Mansourabad and Pazanan structures. Fig. 3 for location. See also Heydarzadeh et al. (2021).

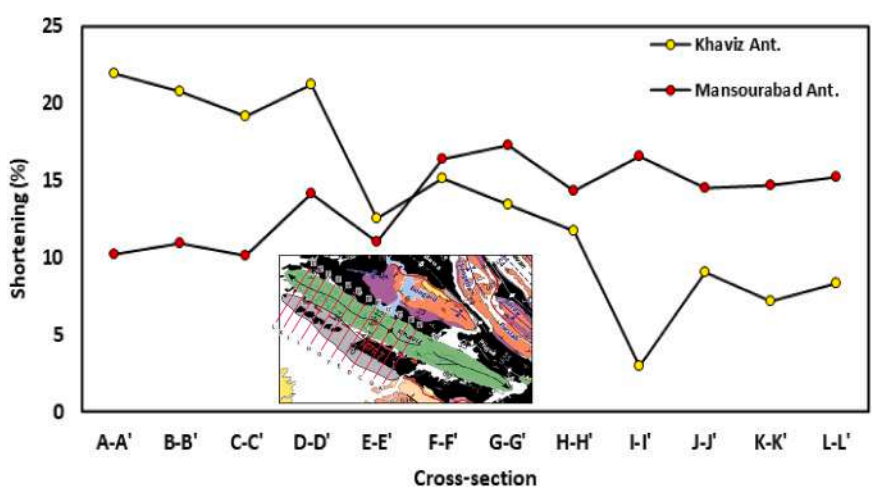

Fig. 9. Along-strike shortening percentage of the Mansourabad and Khaviz anticlines. The inset illustrates location of the cross-sections (also see Fig. 3 for more details).

evolution of the folding and provide useful insight into the folding mechanism in fault-related folds. Different folding mechanisms produce diverse patterns of growth strata in terms of onlaps, pinch-outs, and the direction of the onlaps migration. Kink-band migration widens limbs yet maintains temporal dips, and each increment of folding produces fold scarps. In this folding mechanism, onlaps and corresponding stratigraphic pinch-outs develop above the fold limb. In cases with an active axial surface, the growth strata do not display deformation and the pinch-outs migrate to the anticline axis. However, in the active syncline axial surface, the growth strata and the pinch-outs deform and displace laterally (Shaw et al., 2004). In the limb rotation folding mechanism developing with fixed hinges, the pinch-out locations along the fold are controlled by the sedimentation to the uplift ratio (Hardy et al., 1996; Poblet et.al., 1997). As per Hardy and Poblet (1994), when the sedimentation to uplift ratio is less than unity, onlaps migrate toward the syncline axis. Migration happens upward toward the anticline axis when

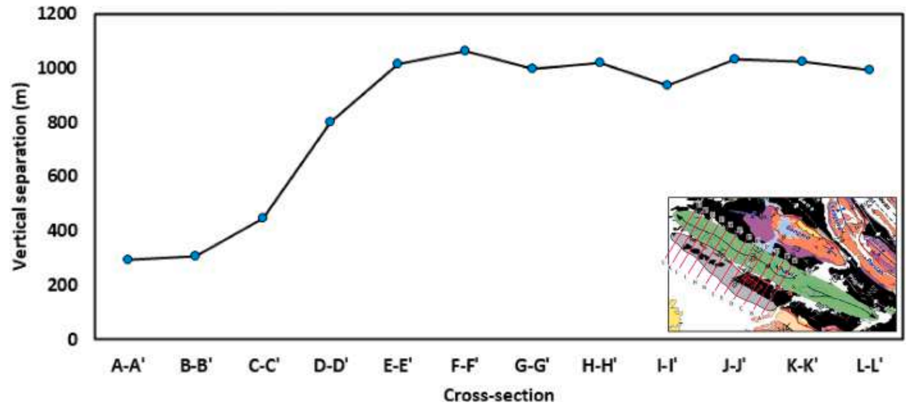

Fig. 10. Vertical separation profile of forelimb Behbahan thrust fault along the Mansourabad anticline for the Asmari Formation. The inset illustrates location of the cross-sections (also see Fig. 3 for more details).

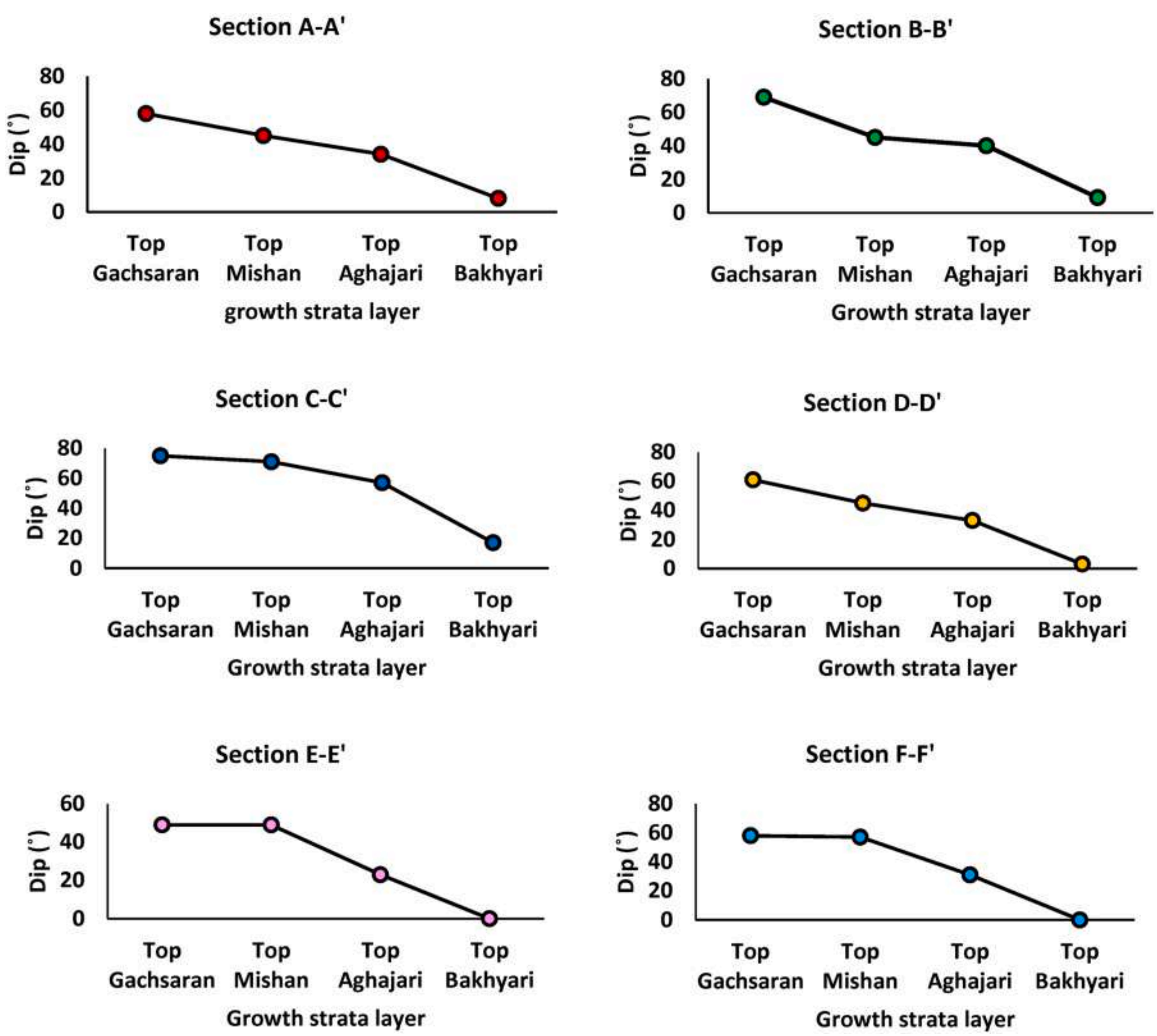

Fig. 11. Variations of the dip of growth strata layers in different selected seismic profiles at the junction with the Behbahan Fault (Figs. 4–8).

the sedimentation rate exceeds the shortening rate. The latter is similar to the onlaps pattern in the kink-band migration folding with an active axial surface. However, the growth strata in the kink-band migration mechanism do not develop a fanning pattern when limbs rotate.

Along the strike of the Mansourabad anticline, the growth strata patterns can be seen in various units, which are related to different geologic times (Figs. 4–7 and 12). In the SE part of the Mansourabad anticline, the growth strata pattern is related to the Middle Miocene-Upper Gachsaran Formation. However, this pattern is related to the younger Mio-Pliocene Aghajari Formation in the NW part of the anticline. Therefore, it can be inferred that the start of folding in the SE part of the anticline has been synchronous with the deposition of the Upper Gachsaran Formation (i.e., Middle Miocene) and that folding began in the Mio-Pliocene in the NW, concurrent with the deposition of the

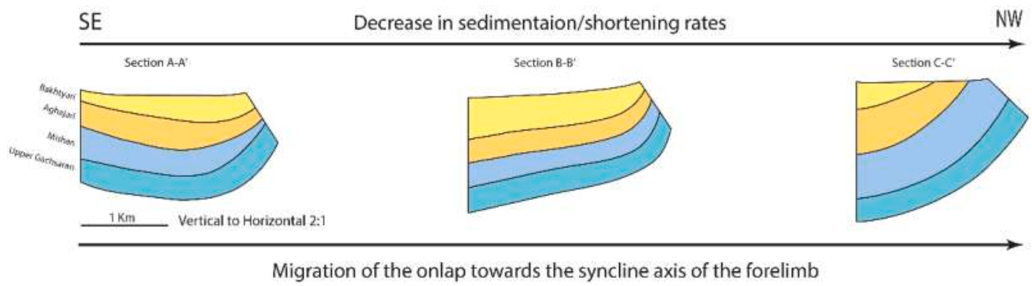

Fig. 12. Migration of pinch-out in the growth strata layers along the Mansourabad anticline related to the southwestern syncline. Locations are shown in Figs. 4, 6 and 7.

Table 3
Review on the role of growth strata in the folding mechanism.

Authors	Terrains	Results
Ahmadi et al. (2013)	Southern Tunisia	Progressive fan unconformities are possible only if hinges are fixed during anticline deformation by flank rotation.
Vergés et al. (2002)	Ebro Basin to the south of the Pyrenees	The rates of vertical motion on specific tectonic structures were similar to the rates of growth strata accumulation specifically during the Ebro Basin's intermontane evolution.
Derikvand et al. (2018)	Dezful Embayment	The growth-strata of the Miocene-Pliocene deposits have had a major role on the geometry of the structures.
Lashgari and Derikvand (2020)	Dezful Embayment	Thickness changes in the Passive Group affected by folding style
Vatandoust et al. (2020)	Dezful Embayment	The growth strata pattern revealed limb rotation as main folding mechanism.

Aghajari Formation. These timings match with magnetostratigraphic information in the NW of the study area, which shows 14.5 Ma and 12.8 Ma for the ages of the growth strata of the upper Gachsaran and Lower Aghajari Formations, respectively (Lashgari et al., 2020). On the other hand, a comparison of shortening along the strike of the Khaviz and Mansourabad anticlines shows an opposite mode of variation. Consequently, the folding of the Mansourabad anticline initiated in its SE segment prior to the NW segment. These relative timing differences in deformation are in contrast with the situation of the Khaviz anticline where deformation commenced in the NW segment. Furthermore, after the onset of folding, due to differences in fault displacement along the Mansourabad anticline, more shortening can be seen in the NW part of the anticline- from 10% in SE up to 15% in the NW. On the other hand, along-strike variation of the thickness of the syn-folding deposits (Fig. 13) acted as an obstacle to progressive deformation, which probably controlled the structural style.

6.2. *Kinematic evolution of the Mansourabad anticline*

Interpretation of the seismic profiles indicates that the Mansourabad anticline varies structurally along-strike from detachment folds to fault propagation fold (Fig. 14). In the southeastern plunge (Fig. 4), the Mansourabad anticline appears as an open, gentle fold with a rounded hinge zone. Also, it shows slightly asymmetric geometry with a northward vergence. This fold geometry resembles the asymmetric detachment folds of Mitra (2003). In the innermost part of the southeastern plunge (Fig. 6), this rounded anticline was affected by a low-displacement fault with NE dip direction in the forelimb. The rounded detachment fold in the southeastern part changes to an asymmetric faulted detachment fold (or fault propagation fold) in the central and northwestern parts of the anticline (Figs. 6, 7). Furthermore, the anticline's northward vergence in the SE plunge changes to southward vergence in the central and northwestern parts. These changes are related to the along-strike variation of the fault displacement, which increases towards NW of the anticline (Fig. 10). This tightened the anticline with a much steeper forelimb than the back limb (Fig. 14). The interlimb angles of the anticline in the different cross-sections indicate a decrease in the interlimb angle toward NW (Fig. 15).

In all the seismic profiles, the southern limb of the Mansourabad anticline is bounded by a steep-dipping limb of the syncline, which indicates the growth strata. The thickness of the accommodated sediments as well as the dimensions of the adjacent southern syncline (i.e., the accommodation space) varies from the SE to the NW of the anticline.

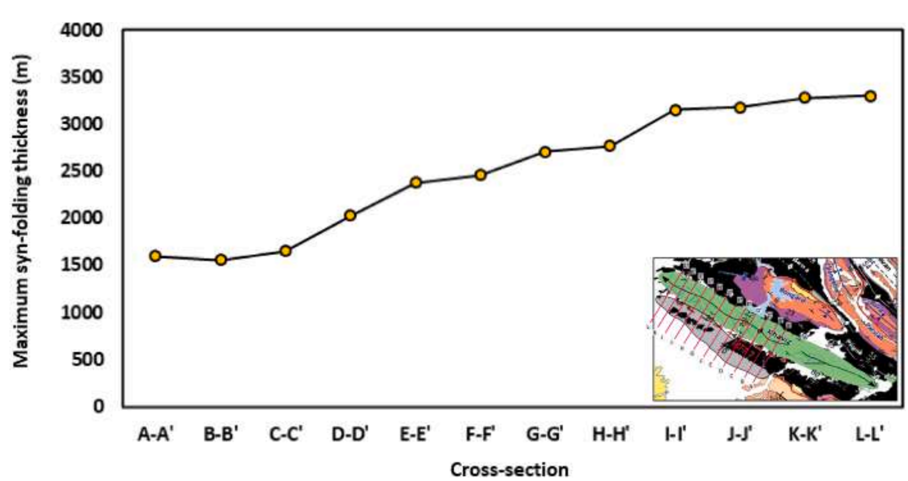

Fig. 13. Maximum thickness of syn-folding strata (Mishan, Aghajari, and Bakhtyari Formations) along the Mansourabad anticline. The inset illustrates location of the cross-sections (also see Fig. 3 for more details).

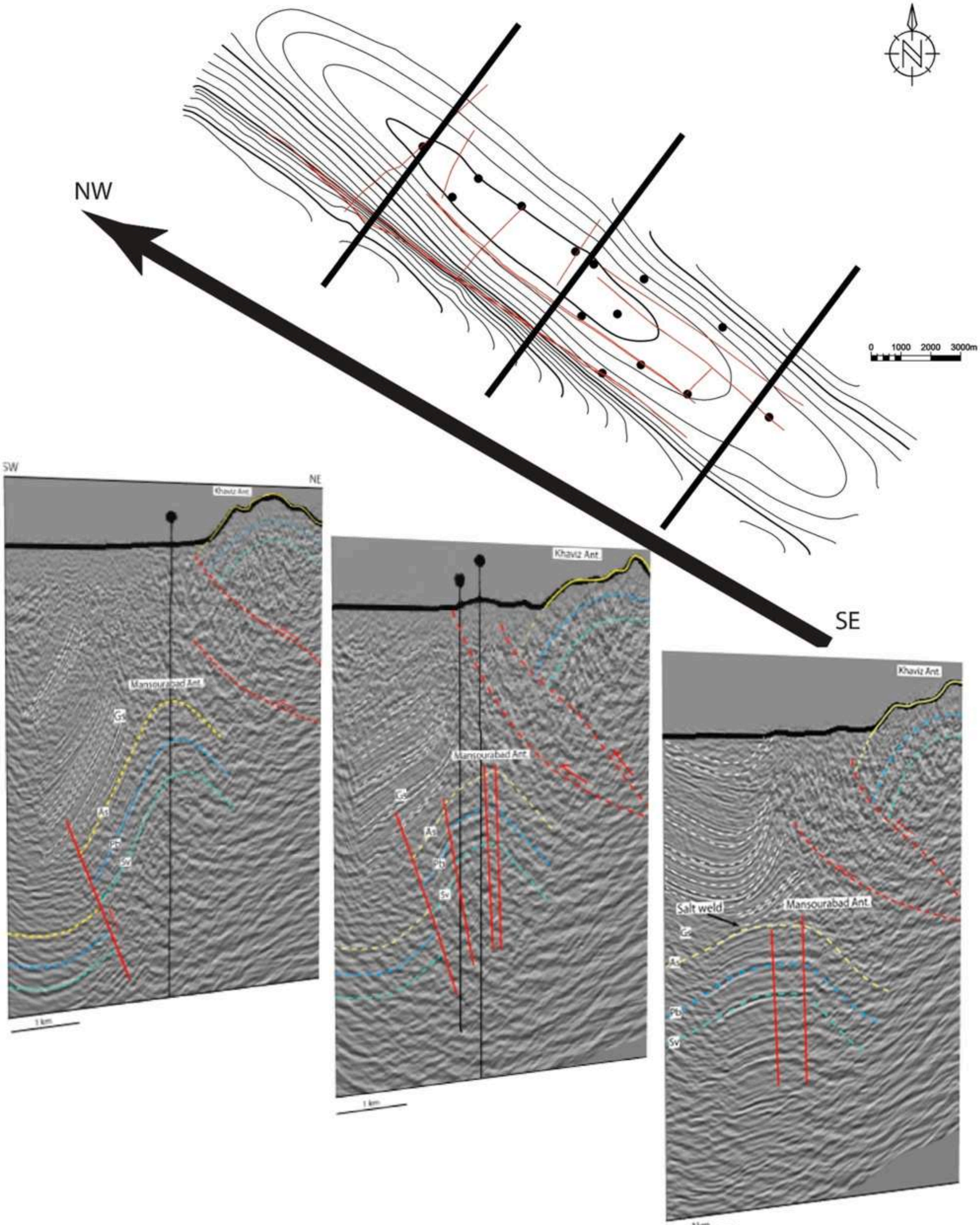

Fig. 14. Variations of structural style along the Mansourabad anticline from detachment fold in the southeastern part to fault propagation fold in the northwestern part. Black dots- wells; red lines- faults.

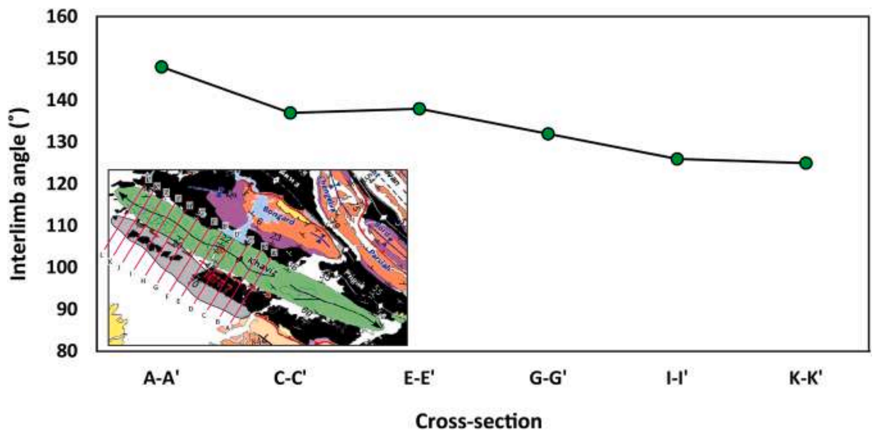

Fig. 15. Interlimb angle of the Mansourabad anticline in different selected seismic profiles.

Also, the Gachsaran evaporites, which migrated during anticline deformation from its hinge zone of high pressure to the adjacent syncline of low pressure, in some seismic profiles indicate primary welded salt between the Asmari and Upper Gachsaran Formations (Fig. 14). Therefore, the gravity-driven Gachsaran salt migration towards the synclines is produced either by anticlinal growth or syn-folding deposition in the synclines.

Progressive subsidence of the synclines (especially the southern syncline) due to the load of the accumulated syn-folding depositions may accelerate the Gachsaran salt migration. Furthermore, Sherkati et al. (2004) suggested an early folding during or just after the deposition of the Gachsaran Formation that migrated salt toward the synclines. In the seismic profiles of the Mansourabad anticline, the southern syncline shows various geometries. This could be a result of differential subsidence or loading on the thrust faults. Therefore, one of the factors that controlled Mansourabad anticline geometry was that of the adjacent syncline. The large volume of the syn-folding depositions in the southern syncline obstructed the southward propagation of deformation, which was accommodated by the Mansourabad anticline.

After comparing seismic profiles and the growth strata layers' dip, it is apparent that the Mansourabad anticline experiences limb rotation and is tighter in the northwestern cross-sections. It is possible to conclude that the displacement of the south thrust (i.e., the Behbahan thrust) is greater in the northwest of the field than in the southeast. Furthermore, this thrust, which can be seen on the surface as steep to overturned beds in the Gachsaran Formation, moved the Gachsaran evaporites, and thrust the latter on the younger units. The Gachsaran Formation in response to the forelimb fault, displays smaller-scale folding documented both in the surface and sub-surface (Fig. 5). These folds are the results of the flow of incompetent units in the Gachsaran Formation, and the flow direction can be deciphered from the fold vergence.

The anticline becomes tighter, with a 120–127° interlimb angle from the SE to the NW, respectively. Deformation intensified in the northwestern part of the structure, leading to structural culmination (Fig. 15). This is due to the disparity in slip along the fault surface (Fig. 10).

7. Conclusions

The present-day geometry of the Mansourabad anticline as a fault-related fold is the result of interactions between displacement on the forethrust and syntectonic deposition The slip-distance profile of the forethrust indicates a correlation between fault slip distributions and fold geometry, which is the main factor controlling the overall fold geometry. The difference in syncline dimensions, which accommodated syn-folding deposits and fault displacement distributions, resulted in the along-strike variations of the folding mechanism in the competent group. The Mansourabad anticline is a slightly asymmetric detachment fold with a gentle northward vergence in the SE part of the anticline. The anticline changes to a faulted detachment fold and fault propagation fold with southward vergence in the central and NW parts, respectively. Shortening changes from 10.9% in the SE part to 16.6% at the NW of the anticline. Growth strata indicate that the folding initiated in the Middle Miocene. In the study area, limb rotation acted as the main mechanism in the formation of the present geometry of the Mansourabad anticline.

CRediT authorship contribution statement

Javid Hassanzadeh Azar: Investigation, Formal analysis. **Soumyajit Mukherjee:** Writing – review & editing, Supervision, Project administration. **Mohammad Seraj:** Investigation, Formal analysis. **Jaber Shoghi:** Methodology, Investigation. **Abdolvahab Afroogh:** Writing – original draft, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

No conflict of interest with anyone regarding this research work.

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Data availability

Data will be made available on request.

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