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Structural relationship between subsurface oil fields in the North Dezful Embayment: Qaleh Nar, Lower and Upper Balarud Anticlines (Central Zagros, Iran)

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ABSTRACT

How subsurface anticlines (oil fields) link structurally with faults is of great relevance in the exploration and development of oil fields. In this context, we investigate the geometric relation between lower Balarud (LBR), upper Balarud (UBR) and Qaleh Nar (QN) subsurface anticlines that are the main oil fields in the Northern Dezful Embayment, central Zagros. The Asmari (As) and the Bangestan (Bng) reservoirs are studied geophysically using seismic profiles, well data and underground contour maps (UGC). Interpretation of 3500 m deep seismic profiles indicates the geometry of the studied subsurface anticlines differs vertically and horizontally to a significant proportion. The interpreted structures much resemble As and Bng horizons in each anticline. The UBR got overturned on the LBR due to thrusting possibly in the Late Miocene. The LBR, like a rabbit-ear structure, is situated at the northern edge of the QN. The lower and upper Chenareh and LBR and UBR resemble structurally and are separated mutually by a steep (strike-slip) fault. The fault separates the LBR and UBR from the QN. Interaction of different factors change in overburden pressure, rate of deformation and uplift in the different parts of the subsurface anticlines moved and accumulated Gachsaran Formation towards both limbs of the anticlines.

1. Introduction

The Zagros fold-and-thrust belt is one of the prolific petroliferous regions (Cooper, 2007) with ~ 12% of the global oil reserves (Bordenave and Burwood, 1990). Fold and thrust belts have otherwise been questioned to be the suitability for hydrocarbon exploration (review in Hammerstein et al., 2020). Notwithstanding, such a question never arose for the Zagros orogenic belt (Asl et al., 2019). Previous studies in the Zagros belt (especially in the North of Dezful Embayment) reveal that the oil reservoirs are located at several Formations and depths (Safari and Bagas 2021). Major hydrocarbon reserves in the Zagros belt are hosted by anticlines in the Late Cretaceous rocks within the Bangestan (*Bng*) Group and the Oligo-Miocene Asmari (*As*) Formation (Sherkati and Letouzey, 2004; Bordenave, 2014). Ductile evaporitic Gachsaran Formation covers the fractured competent *As* Formation at shallow depths (McQuarrie, 2004; Safari and Bagas, 2021). The Qaleh Nar (*QN*), Lower Balarud (*LBR*), upper Balarud (*UBR*), Kabood and Lab-e Safid subsurface anticlines

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are the most important oil fields in the north of Dezful Embayment. These are located just south of the main Balarud fault zone (Figure 1).

Previous studies in this area have shown that the Balarud fault has significantly affected these anticlines (Razavi Pash et al., 2020; 2021*a*). The subsurface anticlines define most of the hydrocarbon traps in this region (Allen, 2010; Sarkarinejad et al., 2017; Razavi Pash et al., 2020; Razavi Pash et al., 2021*b*). Interpretation of subsurface data using seismic lines, well data and contour maps are the efficient ways to study blind anticlines (Sarkarinejad et al., 2017; Razavi Pash et al., 2020, 2021*b*). Investigating the structural relation between subsurface anticlines and faults has assisted manifold in petroleum geoscience (Sarkarinejad et al., 2017; Razavi Pash et al., 2020; 2021*b*).

Previous studies conducted in the studied area have investigated the effect of the Balarud fault and the detachment horizons on the geometry of the anticlines (e.g. Hajialibeigi et al., 2015; Sarkarinejad et al., 2017; Razavi Pash et al., 2021*a*, 2021*b*).

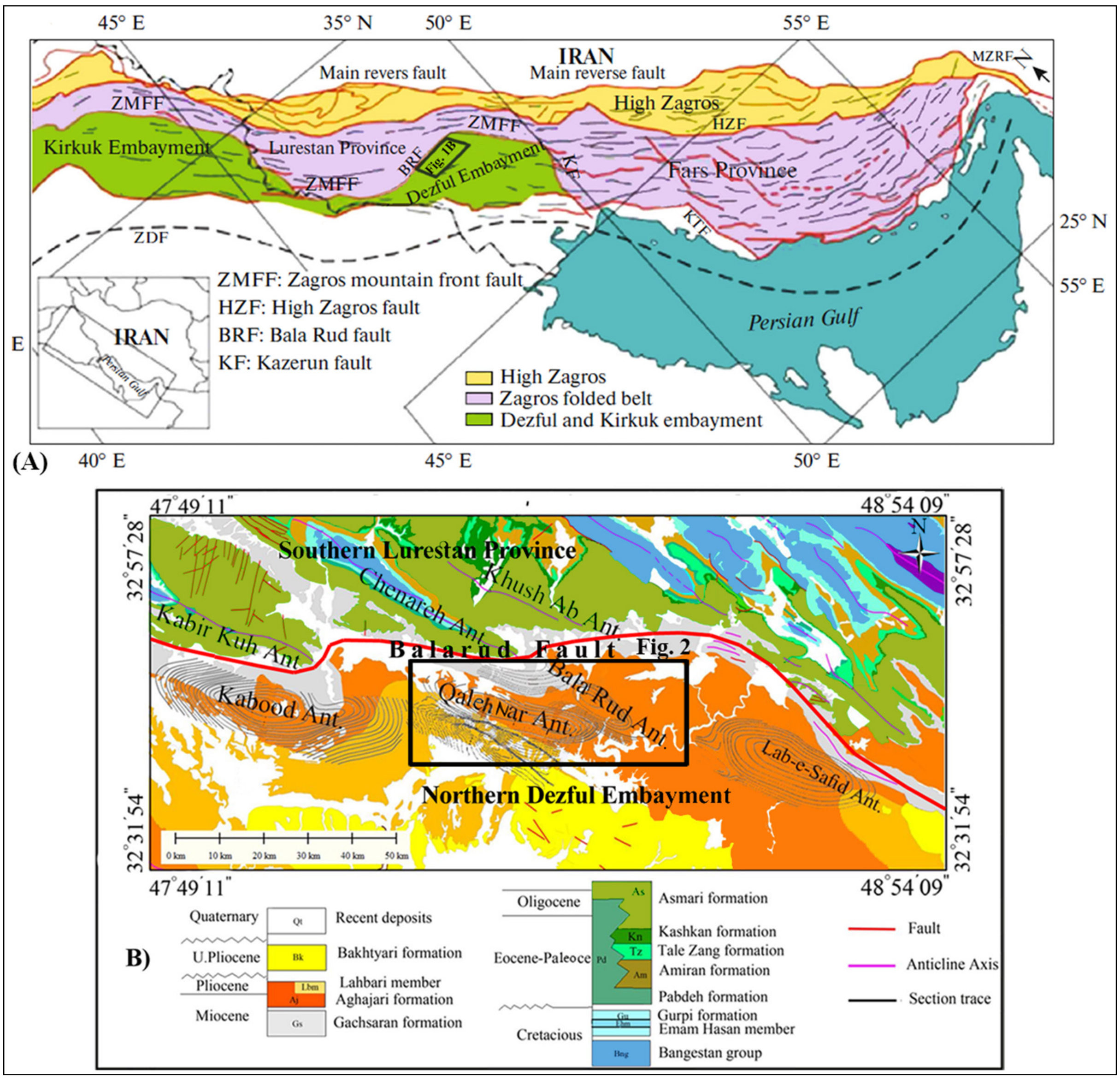

Figure 1- a) Location of the studied anticlines in the central Zagros b) simplified geologic map of the study area and location of the subsurface anticlines with respect to the Balarud fault (Razavi Pash et al. 2021 *a*). Rectangle: location of the studied anticlines. Contours show the underground map of the *As* Formation for anticlines.

However, the structural relationship between these subsurface anticlines has not been investigated. In this research, high-quality seismic profiles [produced by the National Iranian South Oil Company (NISOC)] have been interpreted and the structural relationship between the structures has been investigated. We investigated the geometric relation of the *LBR*, *UBR* and *QN* subsurface anticlines in the footwall of the Balarud fault (Figure 1 and 2). These structures are the major oil fields in the Northern Dezful Embayment. We interpret seismic images, well data and underground contour maps (UGC).

It is worth mentioning that the interpretation of the *LBR* anticline (as an oil field in the region located in the repeated layers below the *UBR* anticline) and its structural relationship with the *UBR* and *QN* have been investigated for the first time in this research.

2. Geology

The Zagros Fold-and-Thrust Belt (ZFTB) is a portion of the Alpine-Himalayan belt located in the SW Iran. The Zagros belt is a product of first the opening of the Neo-Tethyan ocean at the Late Permian–Early Triassic (Stocklin, 1968) and subsequently closing at Tertiary time (Late Miocene) (Berberian and King, 1981; Sherkati et al., 2006). Iran converged with the Arabian plate in the Late Cretaceous (Agard et al., 2005). In the Late Miocene, the main folding took place in the Zagros (Homke et al., 2004; Emami et al., 2010; Razavi Pash et al., 2021*b*).

The Dezful embayment (central Zagros) is bound in the northeast by Mountain Front Fault (MFF), in the north by Balarud Fault, in the east to southeast by Kazerun and Izeh transverse faults, and in the southwest by the Zagros fore-deep (Frontal) Fault (ZFF) (Berberian, 1995; Hessami, 2002; Safari et al., 2009) (Figure 1a). Most of Iran's oil fields are situated in this embayment.

The Dezful Embayment is the main foreland basin since the Late Cretaceous (Sepehr et al., 2006). The interaction between the basement faults, folding and faulting of overlying rock units during and after deposition of Oligocene-Miocene carbonate beds (*As*) evolved the Dezful Embayment (Allen and Talebian, 2011). The folded *As* Formation is situated below the Gachsaran evaporate Formation in the Dezful Embayment. This has provided suitable conditions for creating the oil fields (Sepehr et al., 2006; Sherkati et al., 2006; Abdollahie Fard et al., 2011). The Aghajari and Bakhtyari Formation above the Gachsaran Formation deposites syn-tectonically due to the uplift and erosion of the hinterland part of the Zagros belt (Sherkati et al., 2006; Pirouz et al., 2011). Figure 3

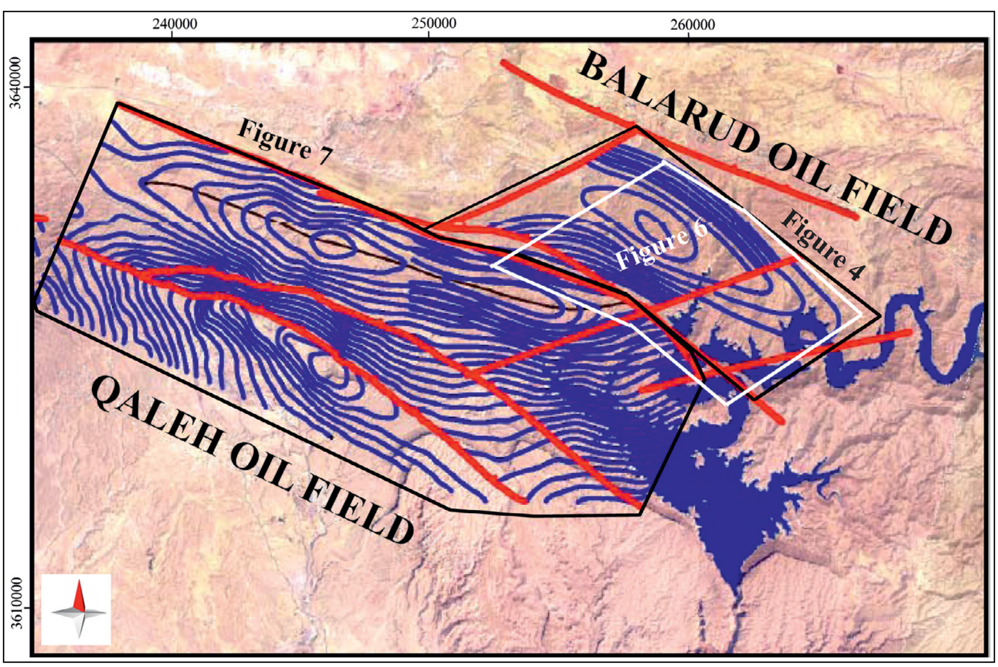

Figure 2- UGC map of the studied anticlines on the satellite image. The location of this Figure is shown in Figure 1b.

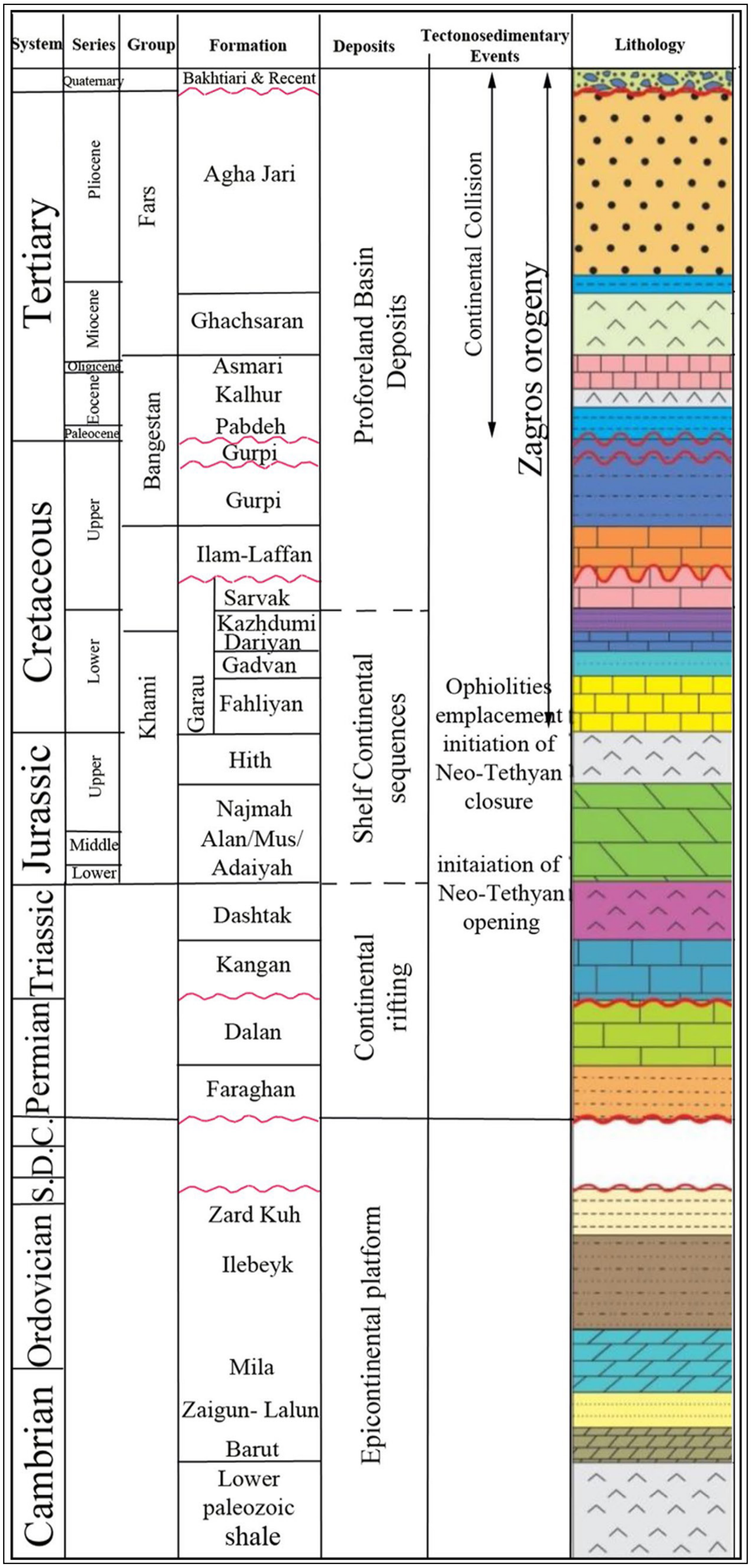

Figure 3- Stratigraphic column of the northern Dezful Embayment based on surface and well data (Abdollahie Fard et al., 2011).

presents the stratigraphic succession of the northern Dezful Embayment. The sinistral Balarud shear zone separates Lurestan province from the North Dezful Embayment (Sherkati et al., 2006; Sarkarinejad et al., 2017; Razavi Pash et al., 2021*a*). Deformation in the north Dezful Embayment has happened mainly by the Balarud left-lateral shear zone (Razavi Pash et al. 2020; Razavi Pash et al., 2021*a*). Faults and folds at both sides of the Balarud fault have the en-echelon geometry (Sarkarinejad et al., 2017; Razavi Pash et al., 2020; 2021*a*). Curved anticlines axes (e.g., NW-trending Kabir Kuh and Chenareh anticlines) in the southern part of Lurestan province can be deciphered at the surface (Bahroudi and Koyi, 2003; Sarkarinejad et al., 2017; Razavi Pash et al., 2020; 2021*a*).

3. Methods

To study the lateral variations of the structural style of folding in this area, geologic maps scale 1:100,000 scale, underground contour maps (UGC), seismic profiles and well data were interpreted for the sub-surface fold geometry and to construct the cross-sections using the Petrel software (version 2014). Since the two most important reservoirs are *Bng* and *As* Formation (As) (Sherkati and Letouzey, 2004; Sherkati et al., 2005; Bordenave and Hegre, 2005; Bordenave, 2014), we interpret them for structures. UGC maps were prepared based on interpreted seismic lines and well data.

4. 2D Structural Analyses of the *QN*, *UBR* and *LBR* Subsurface Anticlines

The *QN*, *UBR* and *LBR* anticlines define the main structures (Figure 4). The *LBR*, like a rabbit ear structure, is located at the northern edge of the *QN*. The *UBR* with a thrust fault is completely driven on the *LBR*.

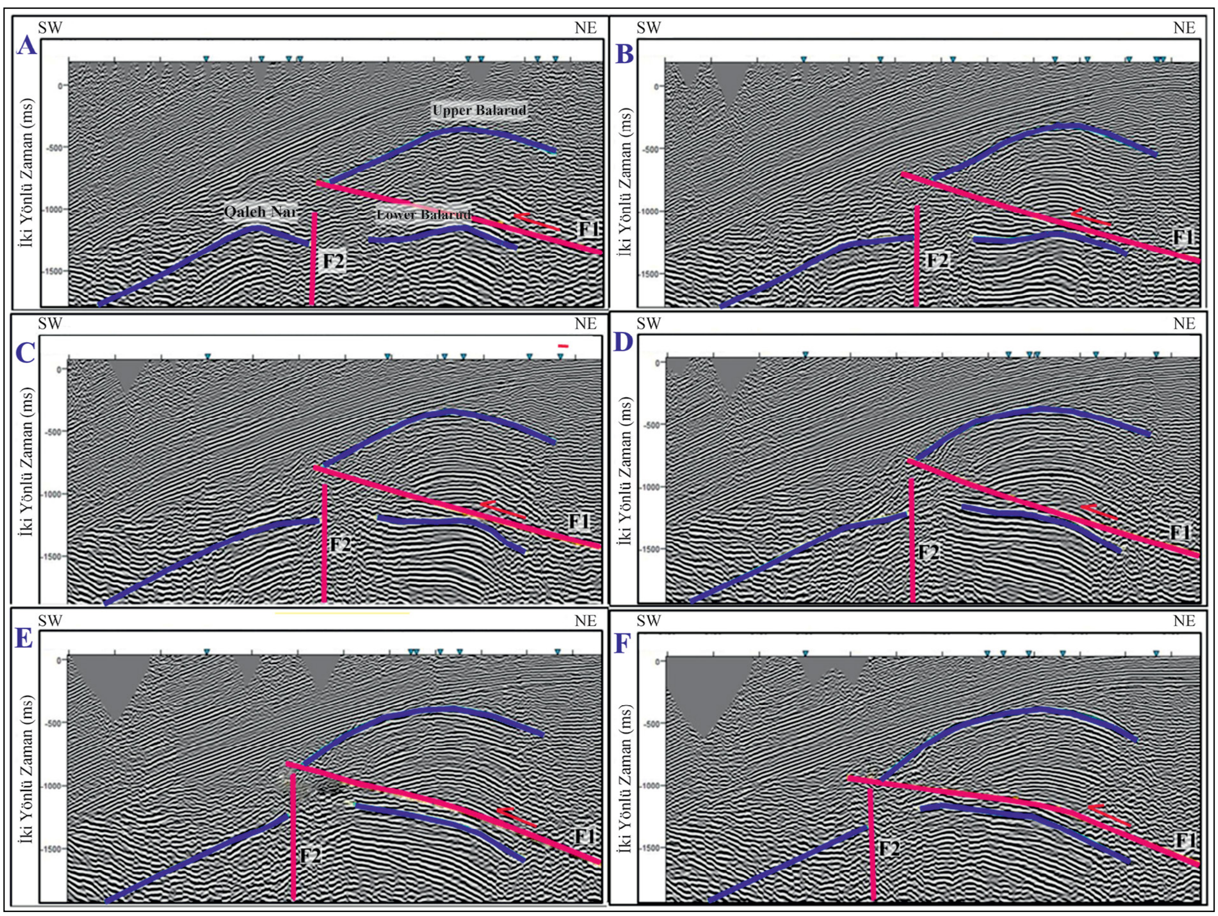

Figure 4- Structural relationship between the *UBR*, *LBR* and *QN* anticlines [based on interpreted seismic lines of the *As* horizon (blue lines)] from the west (A) to east (F). Red lines show the faults (F1 and F2). Uninterpreted images in Repository Figure 2.

The *QN* is an asymmetric anticline with WNW-ESE trending hinge line with double culminations. Its southern forelimb dips steeper than the northern limb. The geometric pattern varies along this anticline. On the east and central sides, is a rounded fold and on the west side, gradually becomes a box fold with average aspect ratio 0.1. It is classified as wide fold. The average interlimb angle in the central part of this anticline is 145°, thus it is a gentle anticline. Forelimb of the *QN* got faulted. The south limb is cut by two faults. Faults are restricted to the middle décollement downward and the Gachsaran Formation as an upper décollement horizon. A footwall syncline developed.

The *UBR* is an asymmetric anticline with NNW-SSE trending fold axis and it is formed in the hanging wall of thrust. The dip of its southern limb or forelimb is more than the northern limb. Since it has an aspect ratio 0.11, it is classified as wide anticline. The interlimb angle is 155°, thus, it is a gentle anticline.

Drilled wells in the crest of the *UBR* indicate repetition of the Gachsaran and *As* Formations downward, after passing through the Sarvak Formation that confirms the presence of the thrust fault on the seismic profile. Based on the seismic profile interpretation, in the footwall of this fault has been developed another anticline in the repeated horizons, called the *LBR*. This anticline is also asymmetric and with respect to the *QN* has lower elevation.

4.1. Structural analysis of the LBR, UBR and QN anticlines on the Bng horizon

The *Bng* UGC map (2100 to 4200 m depth range) and seismic profiles are interpreted to analyze the geometry of the *UBR* (Figure 5). As in Figure 4, in the *Bng* horizon, the forelimb of the *UBR* is cut by a thrust. The dip of this fault in the Gachsaran evaporate Formation is very gentle. The geometry of this anticline is a gentle fold in all sections. In the western part (Figure 5c), a back thrust cuts the anticline's back limb. The thrust fault (F1), at the SW of the *UBR* anticline is identified on the interpreted seismic profiles (Figure 5). It can be a reactivated basement fault (Seraj, 2021).

In the UGC map of the *Bng* horizon, a fault (F2), sinistral strike-slip fault, defines the boundary between the *LBR* and the *QN* anticlines (Figure 6). This fault is a reactivated basement fault (Seraj, 2021). The boundary between the *UBR* and *LBR* at the base of the Bng is a thrust (F1) (Figure 7). The *Bng* horizon in the *LBR* structure has two culminations defining an *en-echelon* structure. This structure to the northwest is also traceable through the Chenareh anticline. Figure 8 presents a UGC map of the *Bng* horizon of the *QN*. Two thrusts cut the southern limb of the *QN*. Also, a large syncline has developed in the southern portion of this anticline.

4.2. Structural analysis of the LBR, UBR and QN anticlines on the As horizon

The *LBR* is adjacent to the *QN* anticline (in the north of *QN* and in the footwall of the *UBR* anticline). A steep fault (F2), sinistral strike-slip fault, between them (Figure 4) is plausibly a reactivated basement fault (Seraj 2021). Like Bng, the boundary of the *LBR* and *UBR* anticlines is a thrust (F1) on the *As* horizon. The horizon in the *LBR* anticline has three en-echelon culminations and shows the effect of the deep-seated fault between the *UBR*, *LBR* and *QN* anticlines (Figure 4). The *en-echelon* structure towards the northwest part also occurs in the Chenareh anticline. The Chenareh anticline is located in the southern Lurestan province and at the hangingwall of the main Balarud fault (Figure 9). The Balarud fault, as an oblique-slip reverse fault has a strike-slip component (Razavi Pash et al., 2021*a*). This fault skirts the Chenareh anticline and the *UBR* anticline.

The *UBR* symmetric anticline trends NW-SE. The *LBR* anticline is located at more depth and is along the *QN* anticline. The *UBR* anticline in the *As* horizon, on the UGC map, is 8.5 km long and 5.5 km wide on average, while the *LBR* anticline in the interpreted *As* horizon is 4.5 km long. The southern limb of the *UBR* has a dip of 20-37°and is steeper than the northern limb (a dip of 12-27°). The *LBR* limb has a dip of 5-30°.

The *As* horizon of *QN* is interpreted from 3D seismic data. A sinistral strike-slip fault (F2) defines the boundary between the *LBR* and *QN* anticlines, which might be a reactivated fault (Seraj, 2021). Interpreted seismic profiles of *QN* indicate fold varies spatially in terms of geometry. Different parts of the *QN* anticline show various geometry (Figure 10). Additionally, the

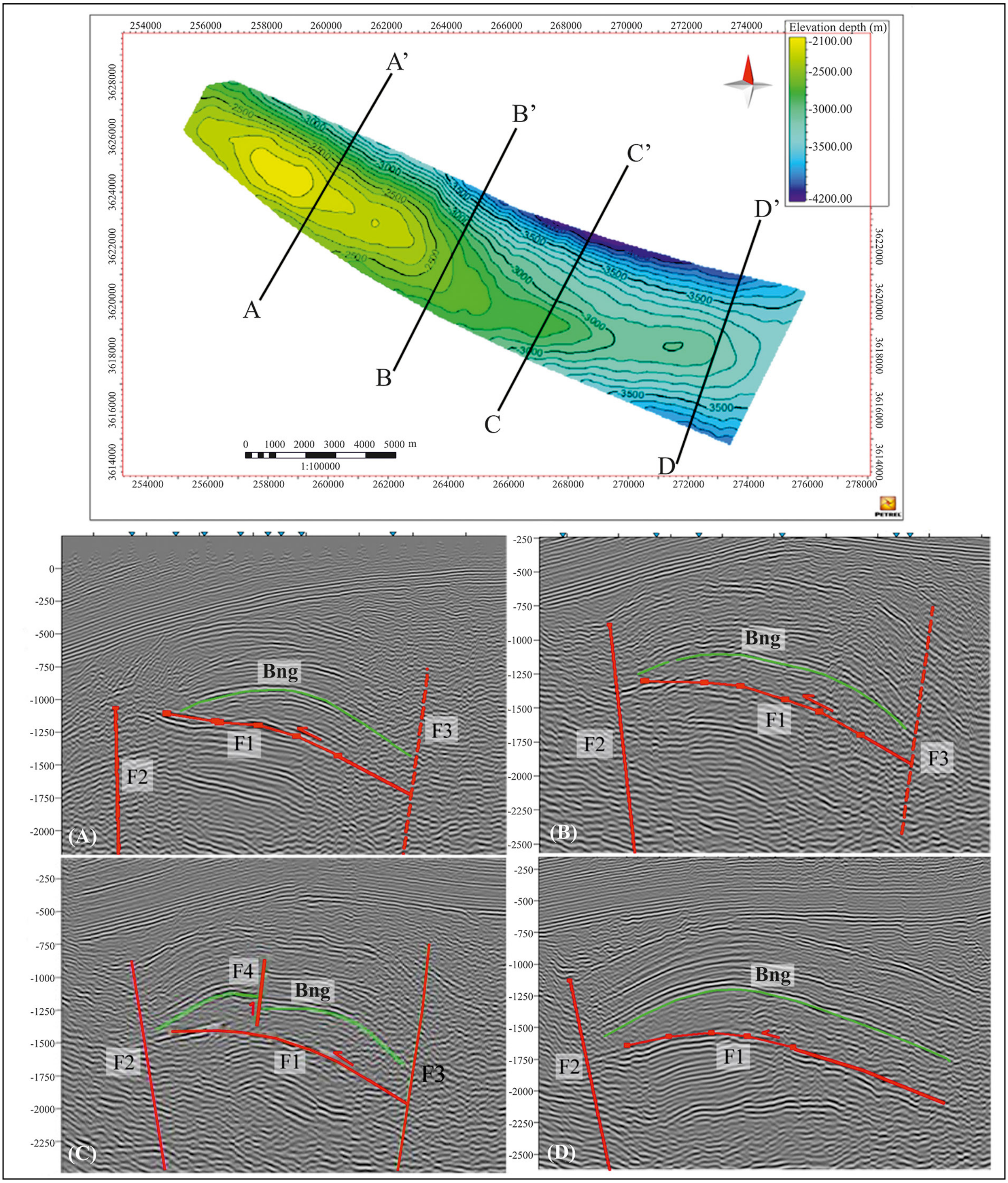

Figure 5- UGC map and interpreted seismic profiles indicating structural geometry of *Bng* horizon throughout the *UBR* anticline. The location of this Figure is shown in Figure 2. Lines AA'- DD' on the UGC map indicate the location of the interpreted seismic profiles. Uninterpreted images in Repository Figure 1. Green lines are the top of the Bangestan group (*Bng*) horizon and the red lines are faults.

southern forelimb is longer and steeper than the back limb. Based on the transverse seismic profiles of the *QN* anticline, there are two thrusts (T1 and T2) in the southwest limb of the *QN* anticline (Figure 10). The highest slip is the result of maximum deformation in the culmination of the anticline. This is true, especially in the western culmination (Sarkarinejad et al., 2017). However, the slip at the noses of this anticline is less.

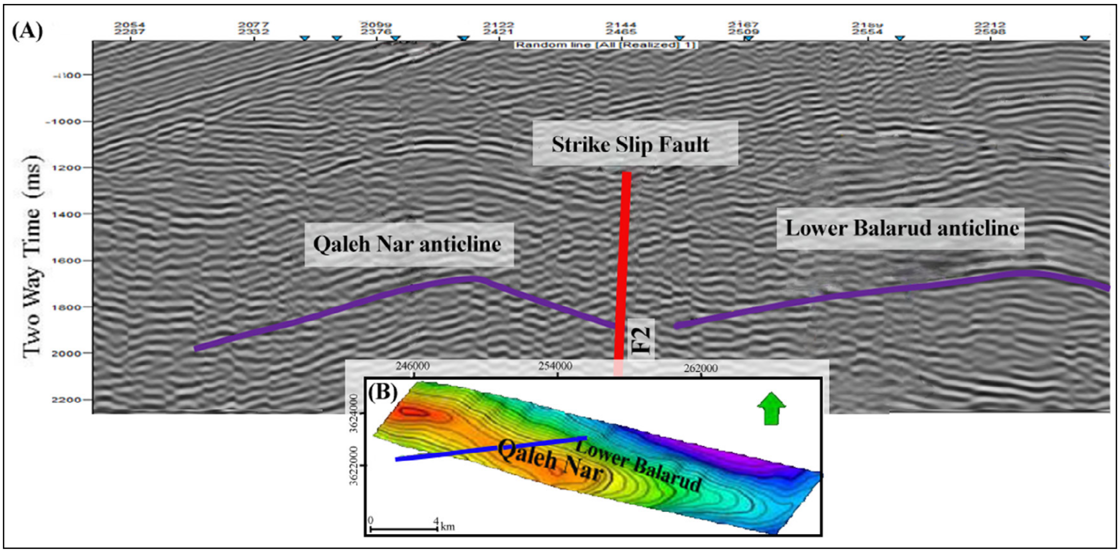

Figure 6- Bangestan horizon (purple lines) in the *LBR* and *QN* anticlines on the (A) seismic profile and (B) UGC map. The red line indicates F2. The blue line shows the location of the seismic profile on the UGC map.

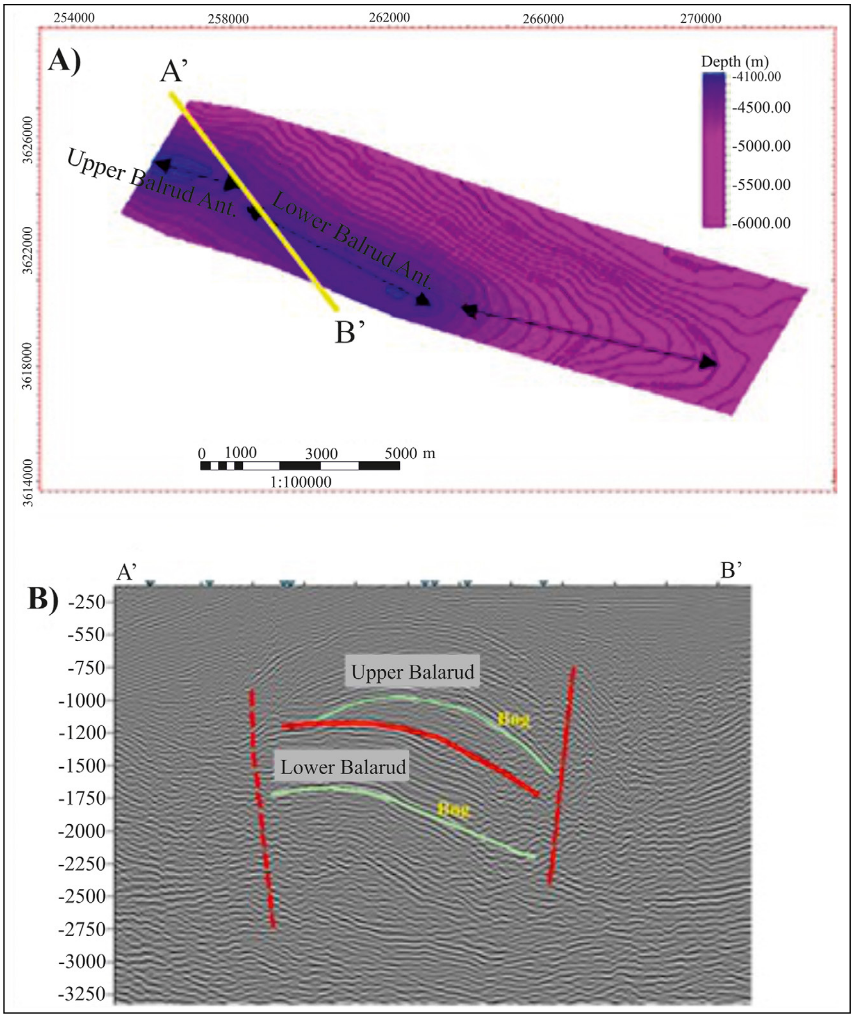

Figure 7- En-echelon structure on the Bng horizon between UBR and LBR anticlines based on a) UGC map and b) seismic lines. Yellow line in Figure 7A shows the location of the seismic profile on the UGC map.

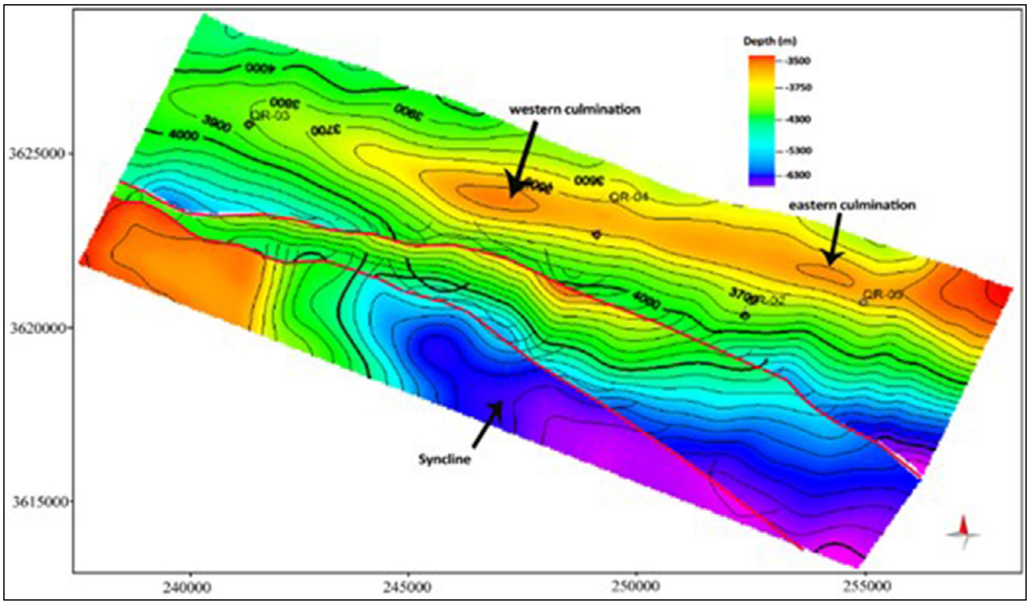

Figure 8- UGC map of *Bng* horizon of the *QN* anticline.

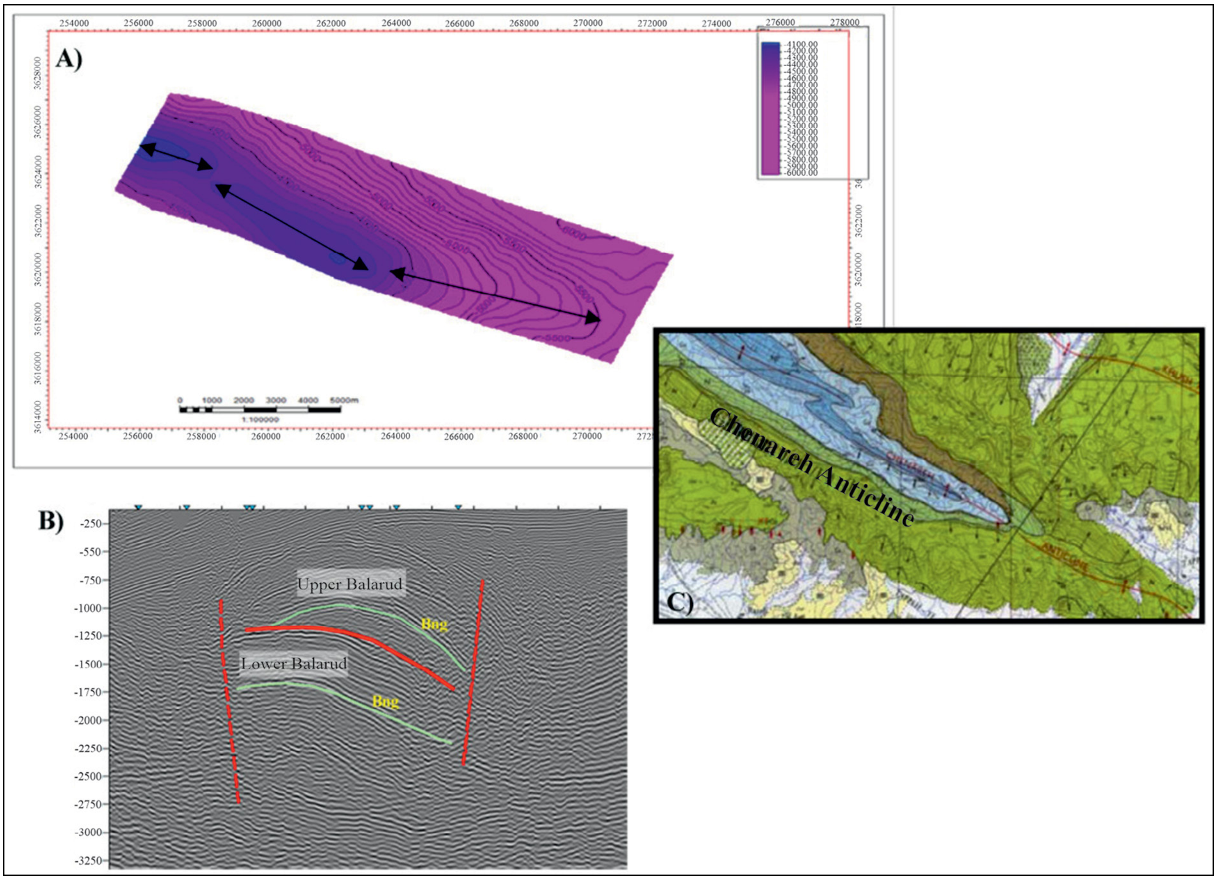

Figure 9- a) En-echelon structure in the As horizon of the LBR on the UGC map, b) the Chenareh anticline at the surface on the geology map (legend in Figure 1b) and c) structural geological map of the study area. Location shown in Figure 2.

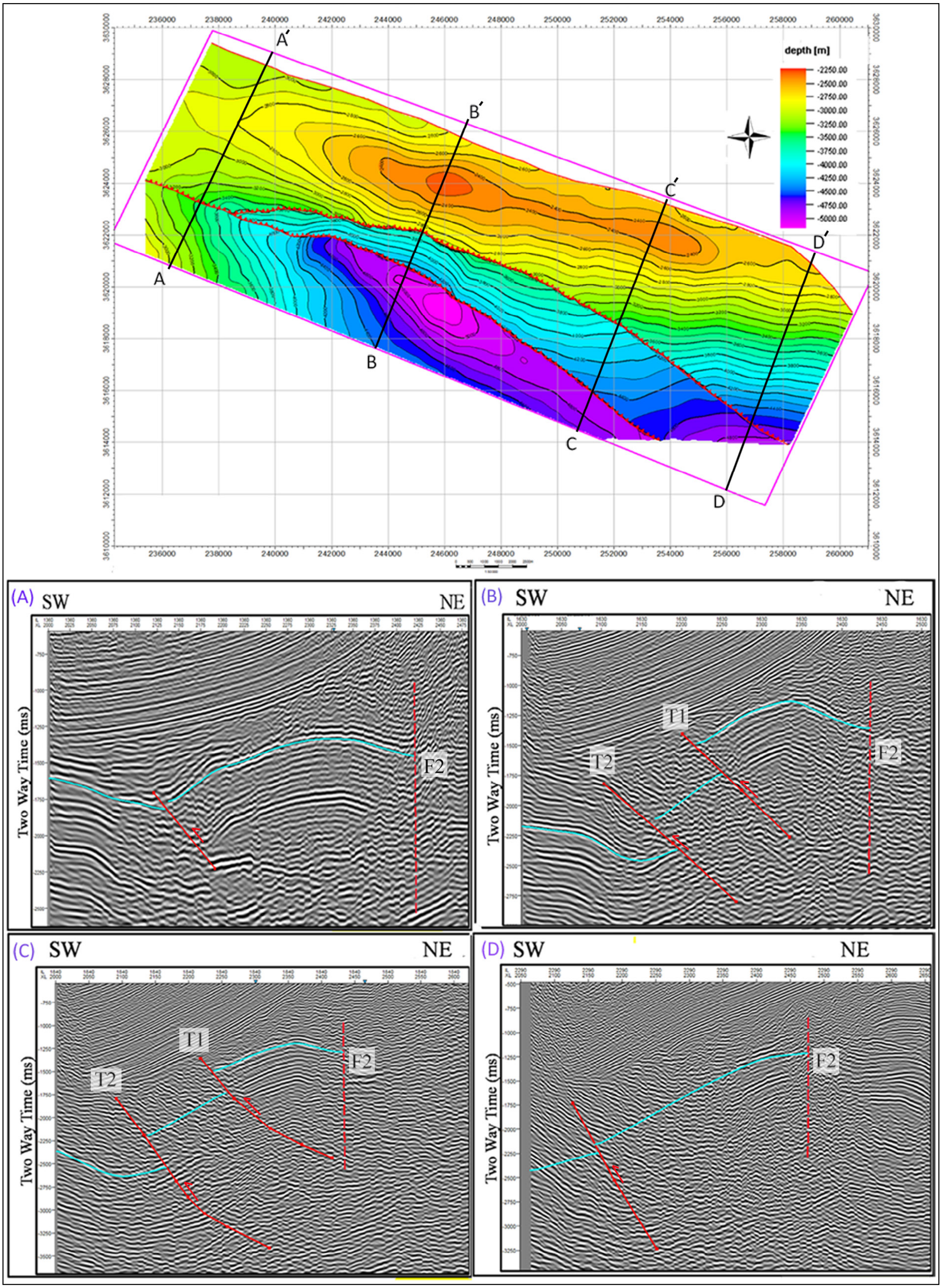

Figure 10- Structural changes of *As* horizon (blue line) along *QN* anticline based on the interpreted seismic sections. Lines AA'-DD' show the location of the interpreted seismic sections (up to 3500 m depth). Red lines indicate the faults. Location in Figure 2. Uninterpreted seismic profiles in Repository Figure 3.

The main structure of *QN* is formed between two faults (T1 and F2). One is a thrust (T1), and the other is a basement reactivated fault (F2) (Figure 10) (Seraj, 2021). The thrust trends NW-SE and the basement fault is steep /sub-vertical) (Seraj, 2021). The basement fault is between the *QN* and *LBR* anticlines (Figure 4). It is one of the main branches out of the Balarud fault zone (Seraj, 2021).

The limbs of the *QN* anticline have a dip of ~ 5°, and a maximum of 25°. The southern limb of the *QN* anticline has a dip of 15-25° and it is 5-10° for the northern limb. The *QN* anticline has two culminations. A very gentle syncline separates the two culminations. NW-SE trending *QN* field on the *As* horizon is 25 km long with ~ 5 km width on average. The *QN* anticline on the *As* horizon is an asymmetric doubly plunging fold. Two thrust faults (T1 and T2) cut in the southern limb of this anticline (Figure 10).

Three transverse sections (AA', BB' and CC') and one structural longitudinal section (DD') (Figure 11, 12) from the surface to the basement are prepared. Based on transverse and longitudinal structural sections and after comparing the 3D views of the *UBR*, *LBR* and *QN* anticlines, deformation intensity along the *UBR* anticline is found to decrease toward the east (Figure 13). As the displacement of the Chenareh and the *UBR* anticlines increase towards the northwest, so is the generally increasing trend of uplift of the *UBR* towards the east. This explains why the flow of the Gachsaran Formation (to the southwest) in

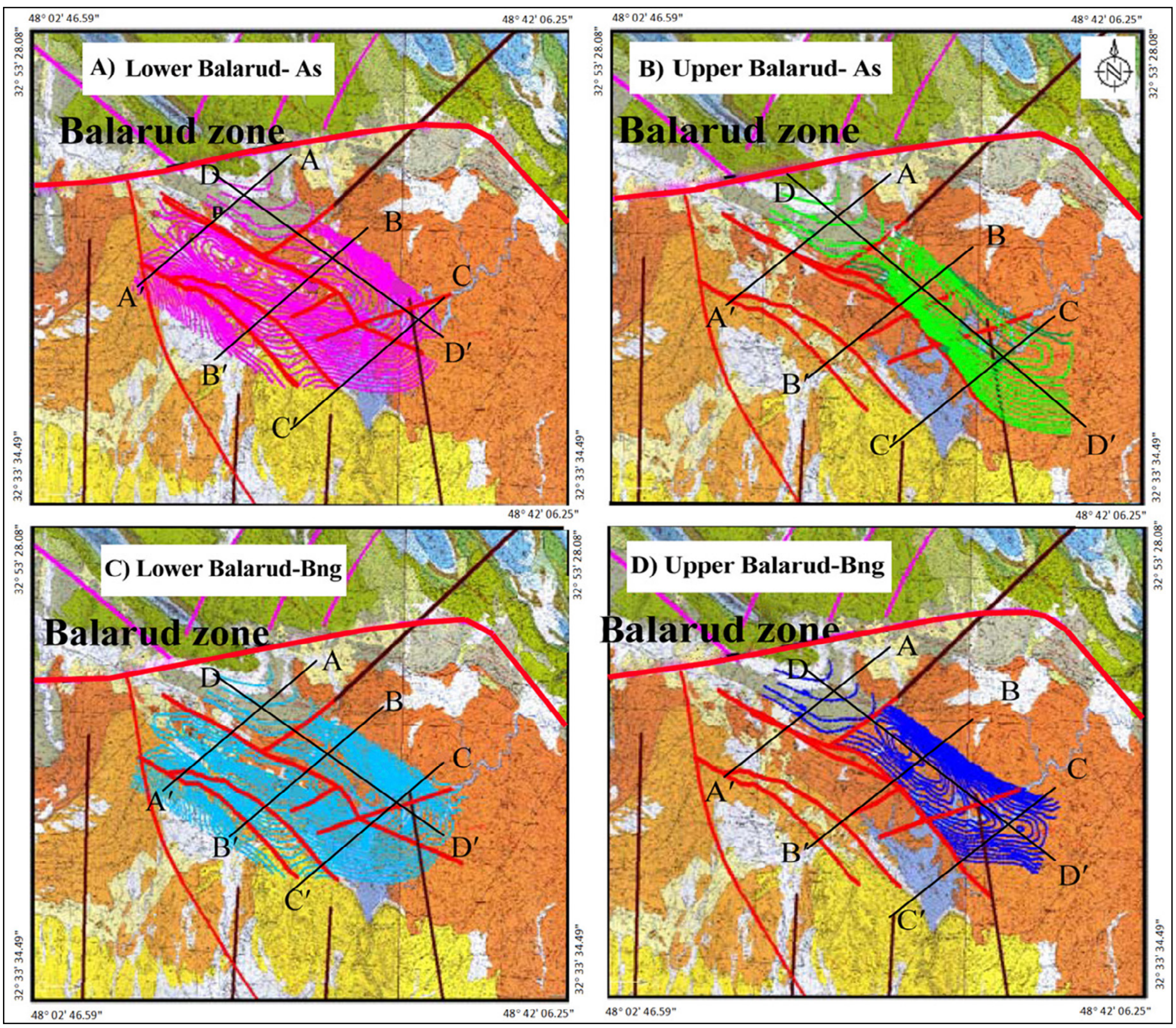

Figure 11- Geological map (with a scale of 1:100000) of the study area (Legend in Figure 1B) and location of the structural sections (AA'-DD'). Contours are the UGC map (*As* and *Bng*) for *UBR*, *LBR* and *QN* anticlines and indicate the location of these anticlines. Red lines show faults.

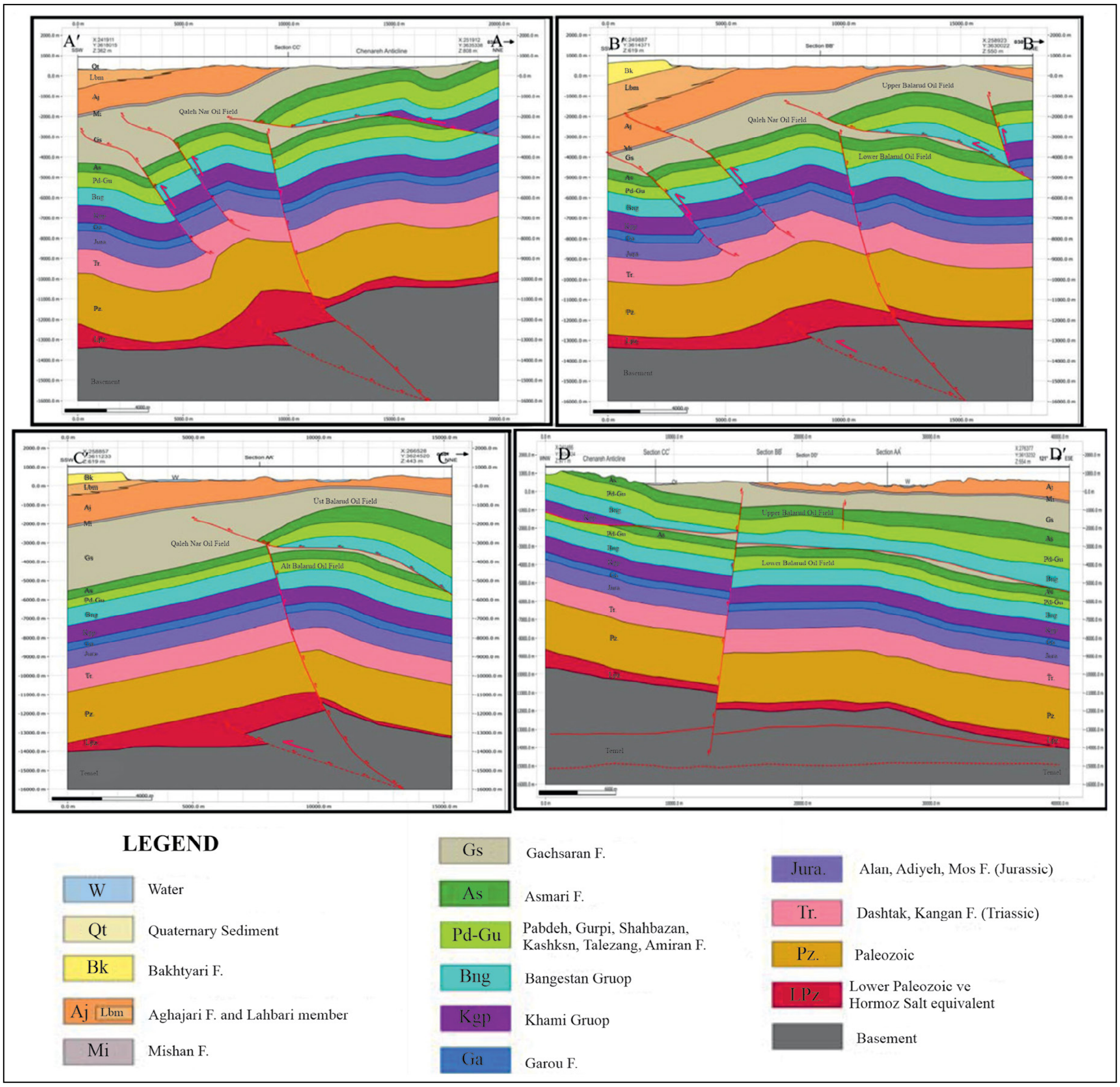

Figure 12- a) Cross-section AA', b) Cross-section BB', c) Cross-section CC'; and d) Cross-section DD'. Locations of the cross-sections are seen at Figure 11.

the west and northwest exceed than that at the center and at the east in this area. Furthermore, the increase of sedimentary overburden (Aghajari Formation to the present-day deposits) and the rate of deformation (and uplift) in the *UBR* moved and accumulated Gachsaran Formation. In other words, higher overburden pressure and greater rate of deformation and uplift are associated with the flow of the Gachsaran Formation towards both NE and SW limbs of anticlines. Therefore, the interaction of the three factors (increase and decrease the rate of overburden pressure, rate of deformation and uplift) in different parts has caused the movement and accumulation of the Gachsaran Formation. More shortening rate indicates more structural relief in the studied anticlines (Sarkarinejad et al., 2017; Razavi Pash et al., 2021*b*). Based on Sarkarinejad et al. (2017), the minimum shortening in the eastern and western parts of the *QN* is ~3% and the maximum amount in the western culmination is ~22%.

4.3. Structural Modelling

After interpreting subsurface information from various sources (surface maps, subsurface and longitudinal-transverse and regional structural sections), digital information on the structures of these horizons were prepared using Petrel software. Six sections were prepared from different parts of the anticlines as in Figure 14a.

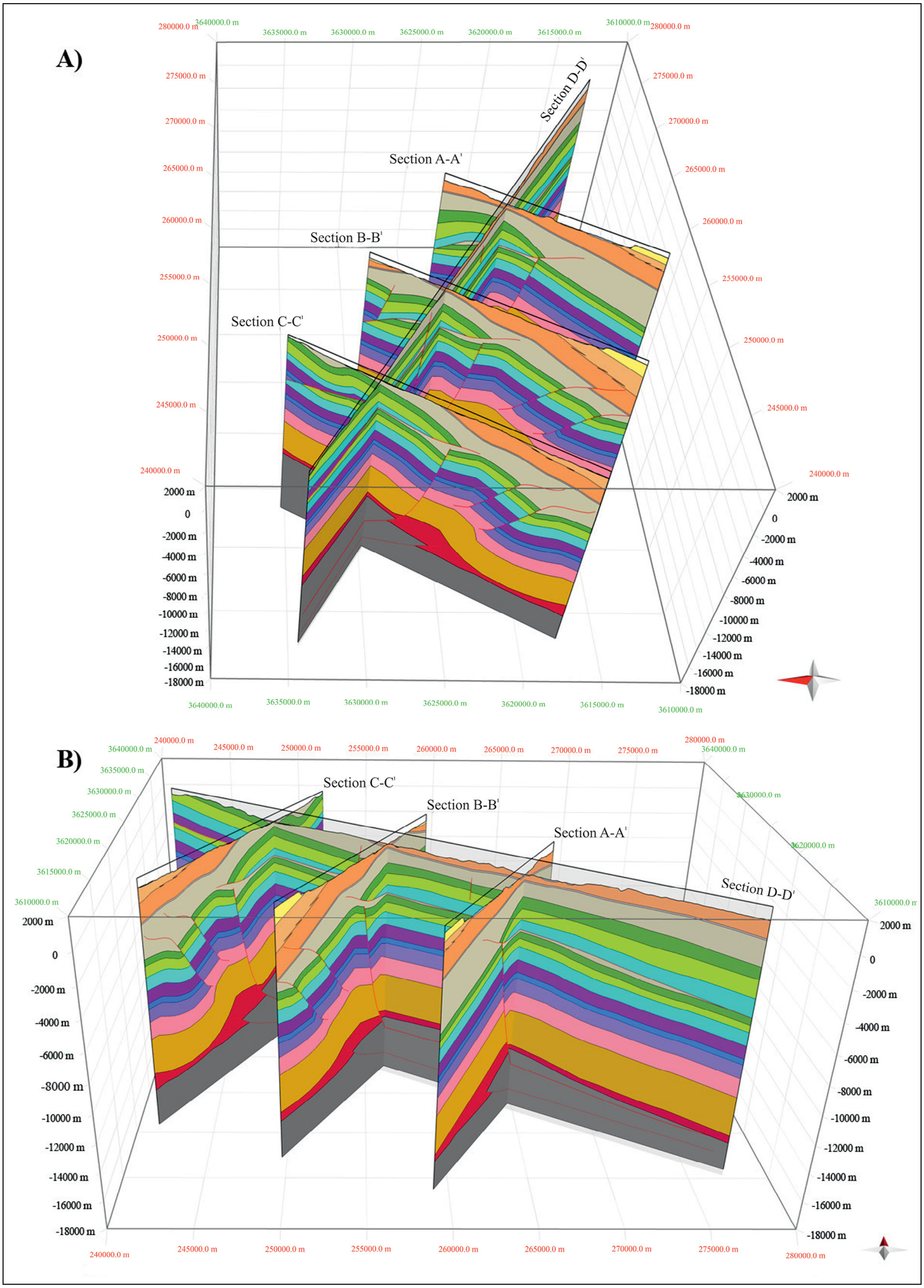

Figure 13- 3D view of transverse and longitudinal structural sections. a) View from northwest to southeast and b) view from southwest to northeast.

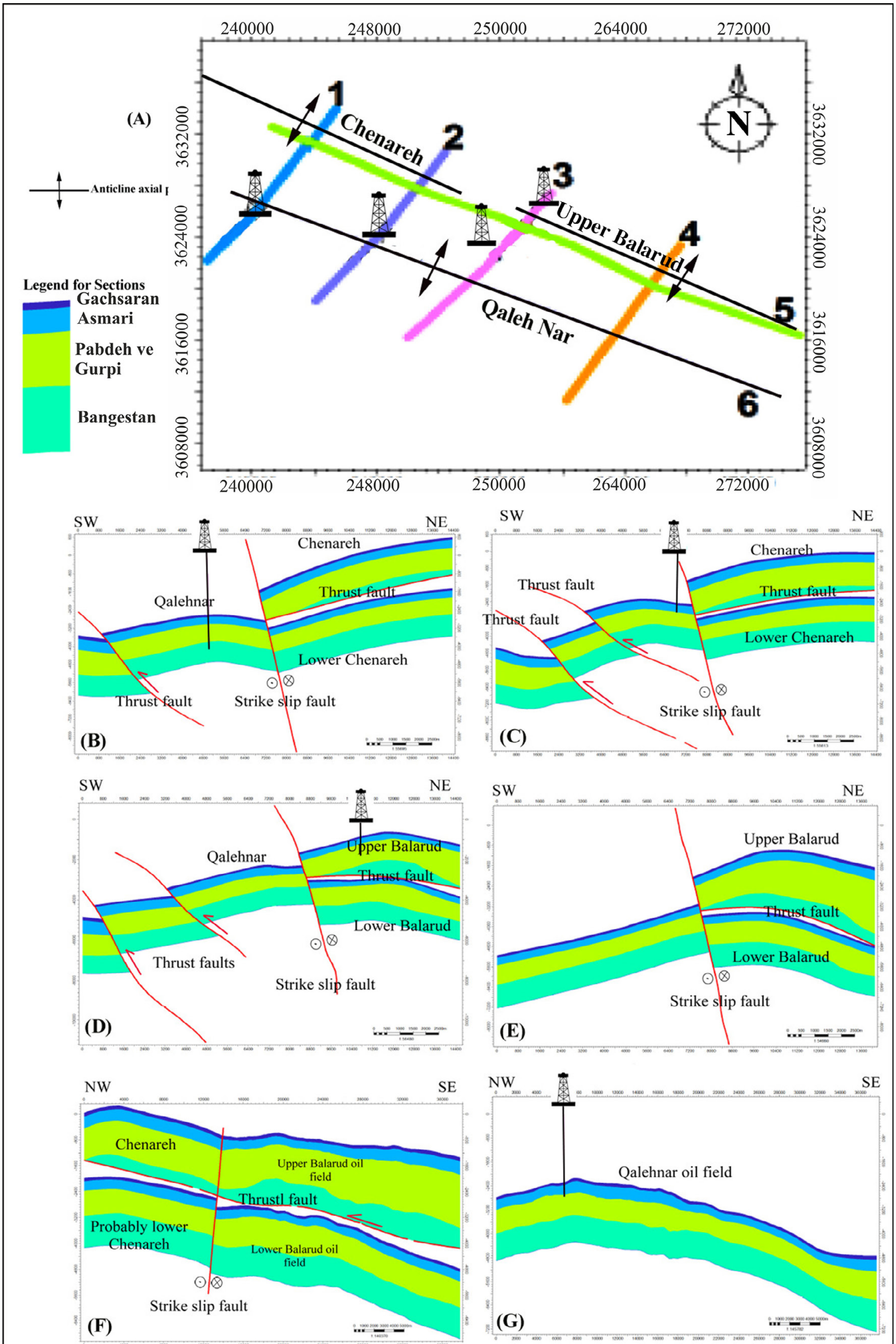

Figure 14- Position of the sections relative to the axis of the folds a, and schematic view of sections 1-6 (b-g).

Section-1 (Figure 14b) passes through the northwestern end of the study area, southeast of the Chenareh anticline and northwest of *QN*. The structural pattern of the section shows that the Chenareh anticline is probably overturned similar to the *LBR* (known as the Lower Chenareh). This structural feature is separated from the *QN* towards the southwest by a steep fault [sinistral strike-slip fault (F2)]. Structural section- 2 (Figure14c) parallels section-1. Structures resemble these sections. The only difference is that in the southern limb of *QN*, two thrust faults are parallel and dip towards the northeast.

Structural section-3, parallel to sections 1 and 2, from northeast to southwest, shows the thrusting of the *UBR* on the *LBR* by a low-dipping thrust. As in sections 1 and 2 and after this structural section, a steep fault (sinistral strike-slip fault (F2) separates the *UBR* and *LBR* folds from the *QN* anticline. The *QN* is characterized by two parallel reverse faults at its southwest limb (Figure14d).

In section-4, (Figure 14e), a transverse section in section-3 (Figure14d), the *UBR* fold is thrust over the *LBR*, and a basement fault separates these anticlines from the *QN*. Sections 5 and 6 are longitudinal with NW-SE trends (Figure 14f, g).

Section-5 (Figure 14f) is along the axial plane of the Chenareh anticline in the southern Lurestan province and the *UBR* anticline in northern Dezful Embayment. As in Figure 14f, a thrust separates the *UBR* and the *LBR* anticlines as well as the upper and lower Chenareh anticlines. In other words, the *UBR* and the upper Chenareh anticlines have been overturned by this thrust fault over the *LBR* and lower Chenareh anticlines, respectively. Due to the complicated structure created and the repetition of layers with the formation of oil fields atop each other, exploratory drilling targets should be decided carefully.

5. Results

Investigating the structural relation between subsurface anticlines/oil fields and the faults that affected them will be a great help in developing oil fields. The main structures in the study area are the *QN*, *UBR* and *LBR* anticlines in the northern Dezful Embayment. These anticlines are the subsurface oil fields. The *Bng* and *As* horizons are the main reservoirs. This study investigated the geometric relationship between the mentioned anticlines based on Bng and As horizons. Interpretation of the seismic profiles indicates the geometry of the studied subsurface anticlines differs vertically and horizontally. The interpreted structures much resemble in As and Bng horizons. The *UBR* anticline overturned on the *LBR* anticline by a thrust. The *LBR* anticline, resembling a rabbit ear structure, is situated at the northern edge of the *QN*. The upper and the lower Chenareh anticlines in the southern Lurestan province and *UBR* and *LBR* anticlines in the northern Dezful Embayment are much similar. The main Balarud fault (a basement fault) separates the mentioned anticlines. Also, the *LBR* anticline is separated from the *QN* by a sinistral strike-slip fault (F2). Interaction of three factors, change in overburden pressure, the rate of deformation and uplift in different parts of the subsurface anticlines moved and accumulated Gachsaran Formation. More overburden pressure and more intense deformation and uplift are associated with flow of the Gachsaran Formation towards both limbs of the anticlines towards the NE and SW.

The structural relation of adjacent anticlines/oil fields can be complex. The existence of thrust faults caused the repetition of reservoirs (As and Bng), as in the *UBR* and *LBR* anticlines. Drilling locations and depths must be determined by considering the sub-surface structures.

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