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

Raana Razavi Pash[1], Mohammad Seraj[2], Soumajit Mukherjee*[3], Ahmad Radmehr[4]

[1]Fcaulty of Earth Sciences, Shiraz University, Shiraz, IRAN

[2]Structural geologist, National Iranian South Oil Company (NISOC), Ahwaz, IRAN

[3]Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai, 400 076, Maharashtra, INDIA

[4]Geophysicist, National Iranian South Oil Company (NISOC), Ahwaz, IRAN

*****Corresponding author: soumyajitm@gmail.com

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 (e.g., 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 2020). 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 (e.g., Sherkati and Letouzey 2004; Bordenave 2014). Ductile evaporitic Gachsaran Formation covers the fractured competent *As* Formation at shallow depths (e.g., McQuarrie 2004; Safari and Bagas 2020). The Qaleh Nar (*QN*), Lower Balarud (*LBR*), upper Balarud (UBR), Kabood and Lab-e Safid subsurface anticlines are the most important oil fields in the north of Dezful Embayment. These are located just south of the main Balarud fault zone (Fig. 1).

Previous studies in this area have shown that the Balarud fault has significantly affected these anticlines (Razavi Pash et al. 2020, 2021). 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. 2021b). Interpretation of subsurface data using seismic lines, well data and contour maps are the efficient ways to study blind anticlines (e.g., Sarkarinejad et al. 2017;

Razavi Pash et al. 2020, 2021b). Investigating the structural relation between subsurface anticlines and faults has assisted manifold in petroleum geoscience (Sarkarinejad et al. 2017; Razavi Pash et al. 2020; 2021b).

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 2015; Sarkarinejad et al. 2017; Razavi Pash et al. 2021a, 2021b). 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 (Figs. 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) (e.g., 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 et al. 2021).

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) (Fig. 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). Fig. 3 presents the stratigraphic succession of the northern Dezful Embayment. The sinistral Balarud shear zone separates Lurestan province from the North Dezful Embayment (e.g., Sherkati et al. 2006; Sarkarinejad et al. 2017; Razavi Pash et al. 2021a). 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. 2021a). Faults and folds at both sides of the Balarud fault have the en-echelon geometry (Sarkarinejad et al. 2017; Razavi Pash et al. 2020; 2021a). 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 et al. 2003; Sarkarinejad et al. 2017; Razavi Pash et al. 2020; 2021a).

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* and *UBR* and *LBR* subsurface anticlines

The *QN*, *UBR* and *LBR* anticlines define the main structures (Fig. 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*.

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* (Fig. 5). As in Fig. 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 (Fig. 5C), a back thrust cuts the anticline's back limb. The thrust fault (F1), at the SW of the *UBR* amticline is identified on the interpreted seismic profiles (Fig. 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 (Fig. 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) (Fig. 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.

Fig. 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.

4.1. 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 (Fig. 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 (Fig. 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 (Fig. 9). The Balarud fault, as an oblique-slip reverse fault has a strike-slip component (Razavi Pash et al. 2021a). 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 (Fig. 10). Additionally, the 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 (Fig. 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.

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) (Fig. 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 (Fig. 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 (Fig. 10).

Three transverse sections (AA', BB' and CC') and one structural longitudinal section (DD') (Figs.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 (Fig. 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 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. 2021b). 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%.

4.4.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 was prepared using Petrel software. Six sections were prepared from different parts of the anticlines as in Fig. 14A.

Section-1(Fig. 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 (Fig.14C) 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 (Fig.14D).

In section-4, (Fig. 14E), a transverse section in section-3 (Fig.14D), 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 (Figs. 14F, G).

Section-5 (Fig. 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 Fig. 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 fiel**ds atop ea**ch other, exploratory drilling targets should be decided carefully.

5. Conclusions

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.

Acknowledgements: We thank Prof. D. Chandrasekharam (Associate Editor) and two anonymous reviewers for providing insightful comments that improved the work.

References

Abdollahie fard ia, Sepehr M, Sherkati S (2011) Neogene salt in SW Iran and its interaction with Zagros folding. Geological Magazine 148(5-6): 854-867

Agard P, Omrani J, Jolivet L, Mouthereau F (2005) Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. International journal of earth sciences 94(3): 401-419

Allen M (2010) The nature of the Dezful Embayment and the Balarud Line in the Iranian Zagros. In EGU General Assembly Conference Abstracts (p. 10438)

Allen MB, Talebian M (2011) Structural variation along the Zagros and the nature of the Dezful Embayment. Geological Magazine 148(5-6): 911-924

Asl ME, Faghih A, Mukherjee S, Soleimany B (2019) Style and timing of salt movement in the Persian Gulf Basin, offshore Iran: Insights from halokinetic sequences adjacent to the Tonb-e-Bozorg salt diapir. Journal of Structural Geology 122: 116-132

Bahroudi A, Koyi H (2003) Effect of spatial distribution of Hormuz salt on deformation style in the Zagros fold and thrust belt: an analogue modelling approach. Journal of the Geological Society 160(5): 719-733

Berberian M, King G.C.P (1981) Towards a paleogeography and tectonic evolution of

Iran. Canadian journal of earth sciences 18(2): 210-265

Berberian M (1995) Master “blind” thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. Tectonophysics 241(3-4): 193-224

Bordenave M.L. Hegre J.A (2005) The influence of tectonics on the entrapment of oil in the Dezful Embayment, Zagros Fold belt, Iran. Journal of petroleum Geology 28(4): pp.339-368

Bordenave M.L (2014) Petroleum systems and distribution of the oil and gas fields in the Iranian part of the Tethyan region. In: Marlow L, Kendall CCG, Yose LA (Eds) Petroleum Systems of the Tethyan Region. AAPG Memoir 106. DOI: https://doi.org/10.1036/13431865M1063614

Cooper M (2007) Structural style and hydrocarbon prospectivity in fold and thrust belts: A global review. In: Ries AC, Butler RWH, Graham RH (Eds) Deformation of the Continental Crust: The Legacy of Mike Coward. Geological Society, London, Spec. Pub. 272: 447-472.

Emami H, Vergés J, Nalpas T, Gillespie P, Sharp i, Karpuz R, Blanc E.P, Goodarzi M.G.H (2010) Structure of the Mountain Front Flexure along the Anaran anticline in the Pusht-e Kuh Arc (NW Zagros, Iran): insights from sand box models. Geological Society, London, Special Publications 330(1): 155-178.

Hammerstein J.A, Dicuia R, Cottam M.A, Zamora G, Butler R.W.H (2020) Fold and thrust belts: structural style, evolution and exploration–an introduction. In: Hammerstein JA, R. Dicuia, Cottam MA, Zamora G, Butler RWH (Eds.) Fold and Thrust Belts: Structural Style, Evolution and Exploration, vol. 490, Geological Society, London, Special Publications 490: 1-8.

Hessami K (2002) Tectonic history and present-day deformation in the Zagros fold-thrust belt. Doctoral dissertation, Acta Universitatis Upsaliensis.

Homke S, Vergés J, Garcés M, Emami H, Karpuz R (2004) Magnetostratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Push-e Kush arc (Lurestan Province, Iran). Earth and Planetary Science Letters 225(3-4): 397-410

Mcquarrie N (2004) Crustal scale geometry of the Zagros fold–thrust belt, Iran. Journal of structural Geology 26(3): 519-535

Pirouz M, Simpson G, Bahroudi A, Azhdari A (2011) Neogene sediments and modern depositional environments of the Zagros foreland basin system. Geol. Mag 148 (5–6): 838–853

Razavi Pash R, Sarkarinejad K, Ghoochaninejad H.Z, Motamedi H, Yazdani M (2020) Accommodation of the different structural styles in the foreland fold-and-thrust belts: northern Dezful Embayment in the Zagros belt, Iran. International Journal of Earth Sciences 109(3) 109:959–970.

Razavi Pash R, Sarkarinejad K, Zarehparvar Ghoochaninejad H, Motamedi H (2021) Application of 3D Structural Modeling to Analyze the Structural Geometry and Kinematic Evolution: A Case Study from Lab-e-Safid and Qale Nar QN Subsurface Anticlines in the Northern Dezful Embayment, Iran. Geotectonics 55(2): 261-272.

Razavi Pash R.R, Sarkarinejad K, Sherkati S, Motamedi H (2021) Analogue model of the Bala Rud Fault, Zagros: an oblique basement ramp in a fold-and-thrust belt. International Journal of Earth Sciences 110(2): 741-755.

Safari H.O, Bagas L (2021) A transpressional model for deformation patterns in northern part of Dezful Embayment's oil fields in Zagros (Iran), using geo-information technologies. Marine and Petroleum Geology 123: 104736.

Safari H.O, Pirasteh S, Pradhan B (2009) Uplifting estimation in Zagros Transverse faults Iran: An application of Geoinformation Technology. Remote Sensing 1: 1240–1256.

Sarkarinejad K, Razavi Pash R, Motamedi H, Yazdani M (2017) Deformation and kinematic evolution of the subsurface structures: Zagros foreland fold-and-thrust belt, northern Dezful Embayment, Iran. International Journal of Earth Sciences 107(4): 1287-1304.

Sepher M, Cosgrove J, Moieni M (2006) The impact of cover rock rheology on the style of folding in the Zagros fold-thrust belt. Tectonophysics 427(1-4): 265-281.

Seraj M (2021) Structural relationship study of Balarud and Qaleh Nar oi fields. National Iranian South Oil Company. Report, p. 70.

Sherkati S, Letouzey J (2004) Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. Marine and Petroleum Geology 21(5): 535-554.

SherkatiS, Letouzey J, Frizon de lamotte D (2006) Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modeling. Tectonics 25(4), TC4007.

Sherkati S, Molinaro m, DE Lamotte DF, Letouzey J (2005) Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control. Journal of Structural Geology 27(9): 1680-1696.

Stöcklin, J (1968) Salt deposits of the Middle East. Geological Society of America, Special Issue 88: 157-181.

Figs and Captions

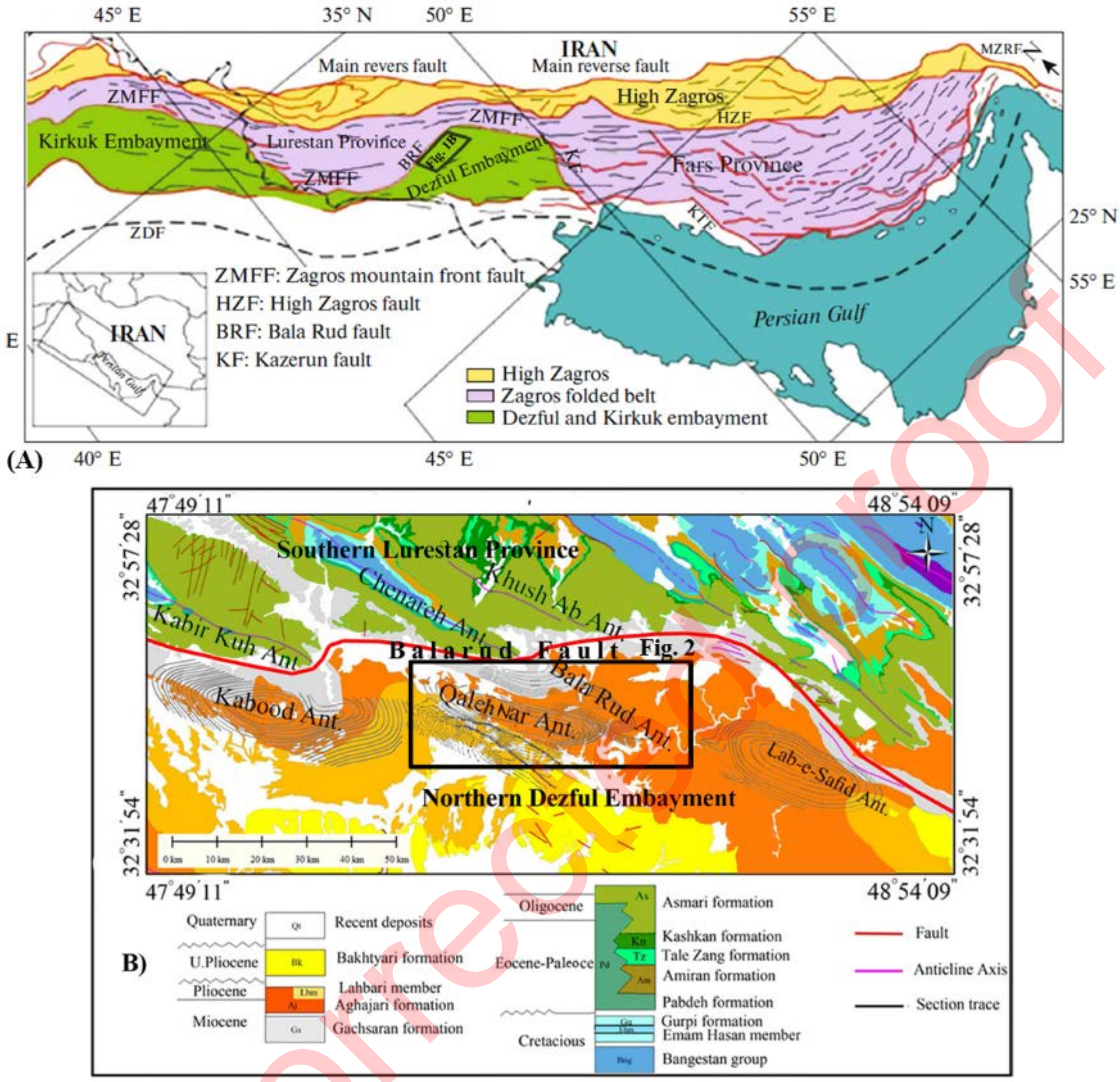

Fig. 1. (A) Location of the studied anticlines in the central Zagros, and **(B)** simplified geolog**ic** map of the study area and location of the subsurface anticlines with respect to the Balarud fault (Razavi Pash et al. 2021a). Rectangle: location of the studied anticlines. Contours show the underground map of the *As* Formation for anticlines.

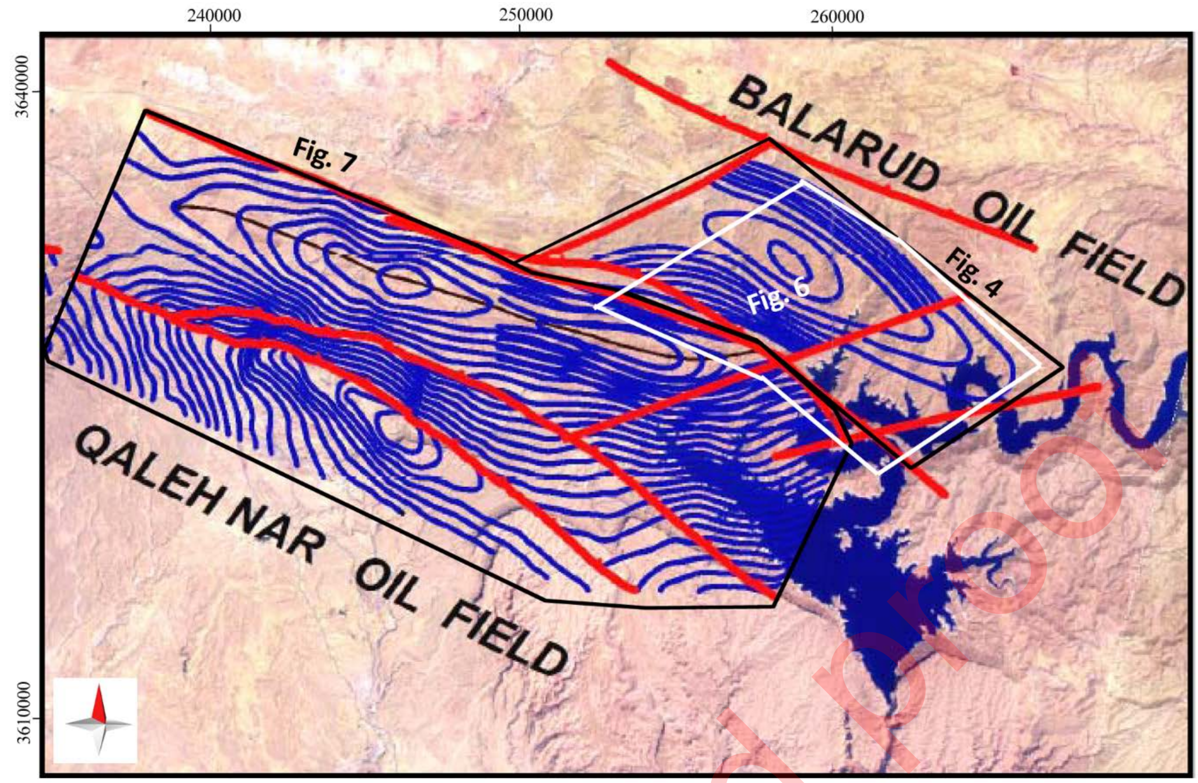

Fig. 2. UGC map of the studied anticlines on the satellite image. The location of this Figure is shown in Fig. 1B.

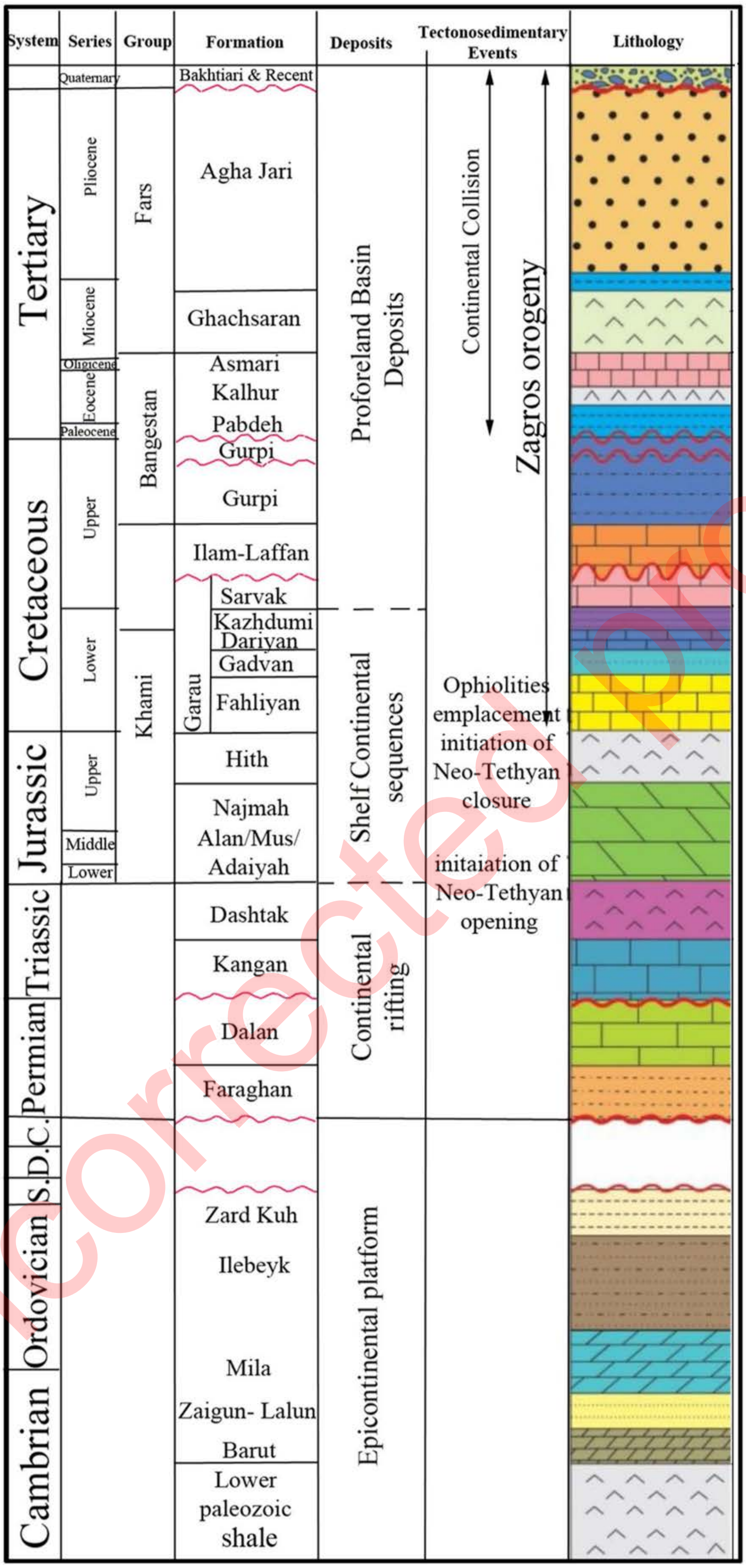

Fig. 3. Stratigraphic column of the northern Dezful Embayment based on surface and well data (Abdollahie Fard et al. 2006).

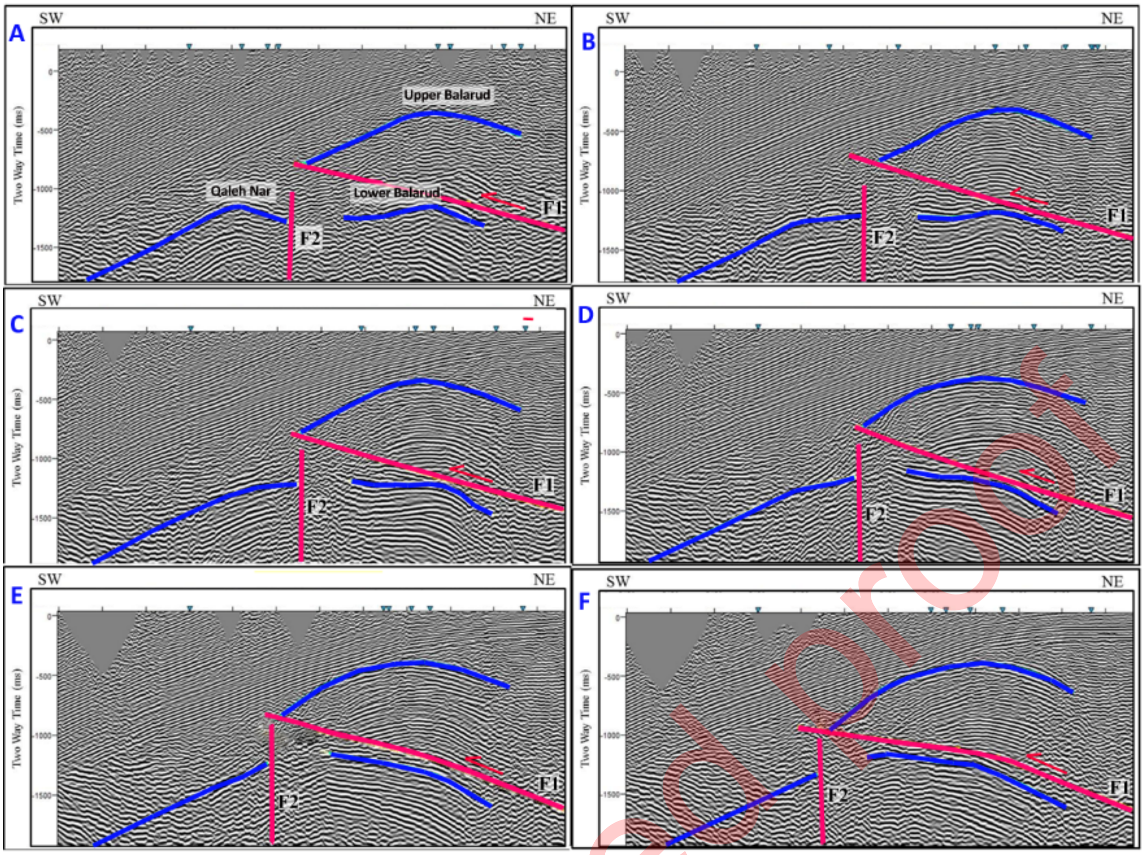

Fig. 4. Structural relationship between the *UBR*, *LBR* and *QN* anticlines (based on interpreted seismic lines of the *As* horizon (blue lines)) from the west (A) to east (F). Red lines show the faults (F1 and F2). Uninterpreted images in Repository Fig. 2.

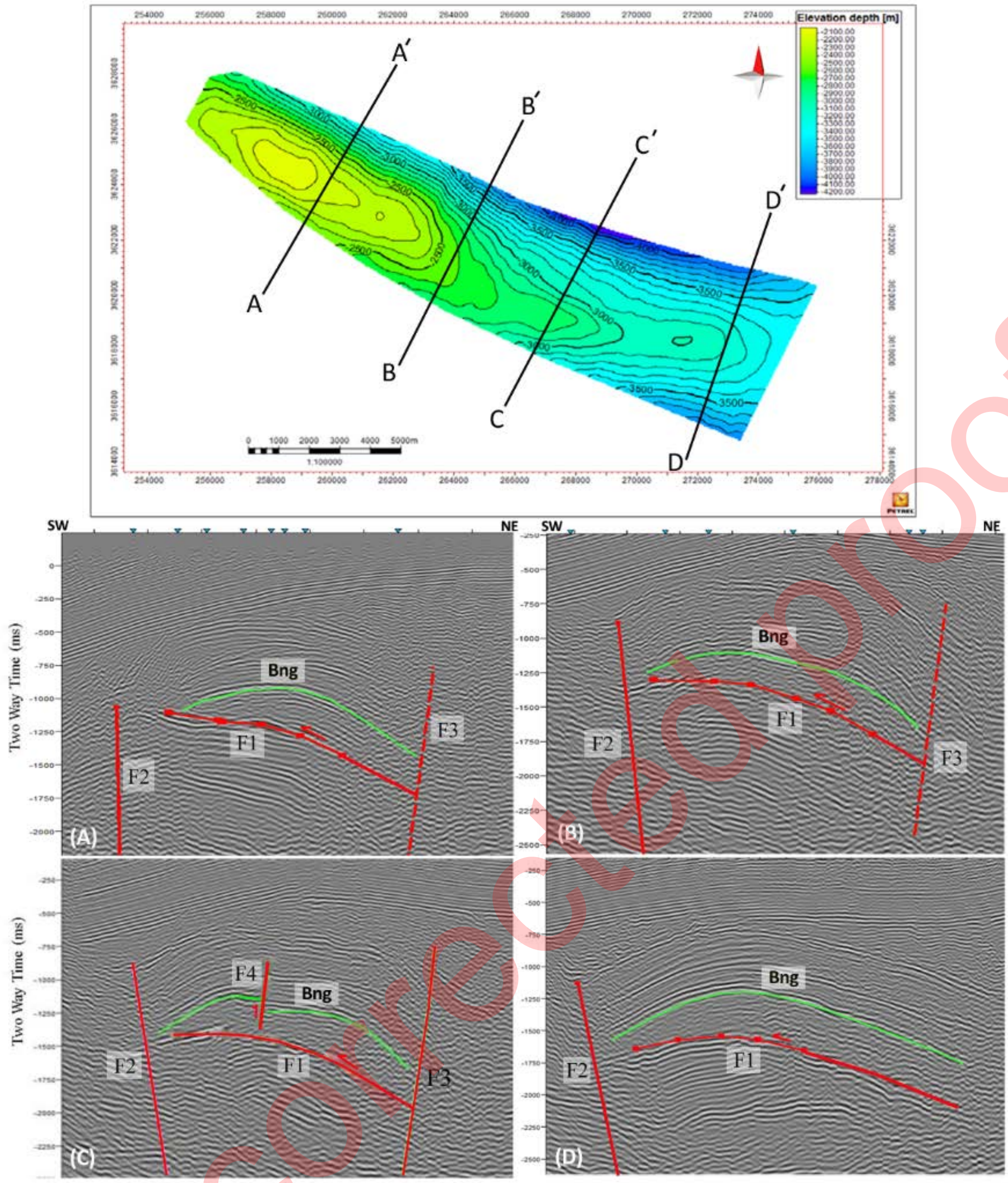

Fig. 5. UGC map and interpreted seismic profiles indicating structural geometry of *Bng* horizon throughout the *UBR* anticline. The location of this Figure is shown in Fig. 2. Lines AA'- DD' on the UGC map indicate the location of the interpreted seismic profiles. Uninterpreted images in Repository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

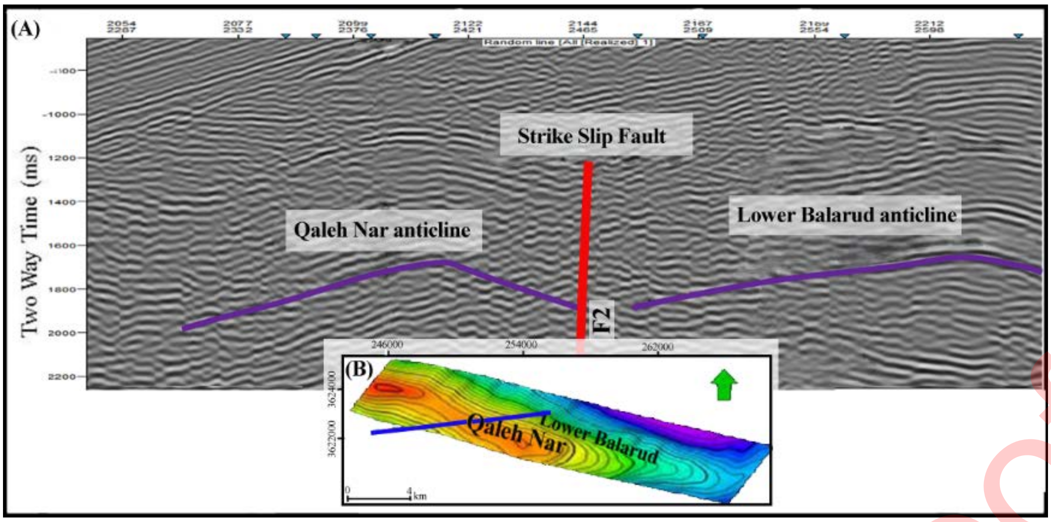

Fig. 6. Bangestan horizon (purple lines) in the *LBR* and *QN* anticlines on the (A) seismic profile and (B) UGC map. The red line indicates F2. The blue line shows the location of the seismic profile on the UGC map.

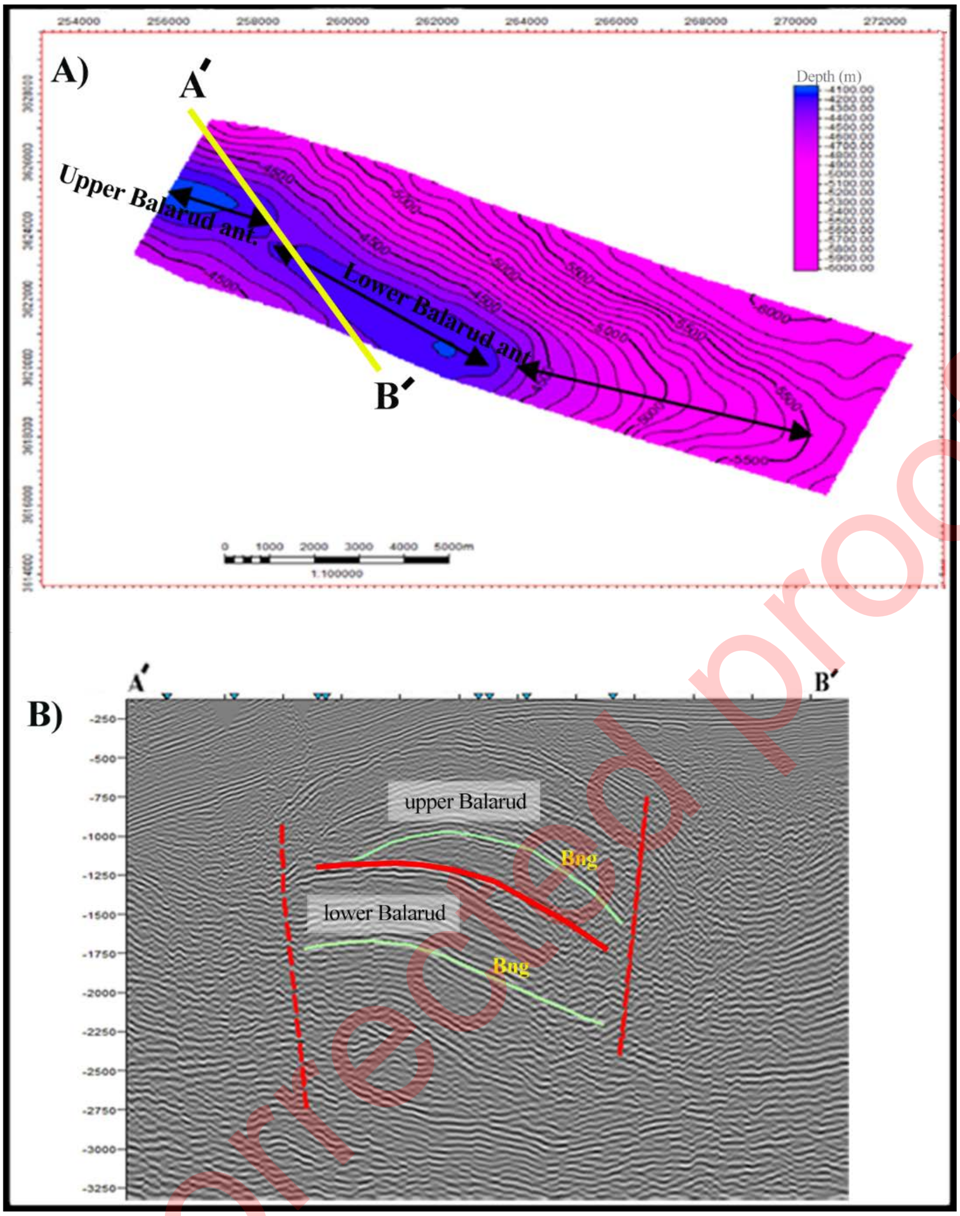

Fig. 7. En-echelon structure on the *Bng* horizon between *UBR* and *LBR* anticlines based on UGC map (A) and seismic lines (B). yellow line in Fig. 7A shows the location of the seismic profile on the UGC map.

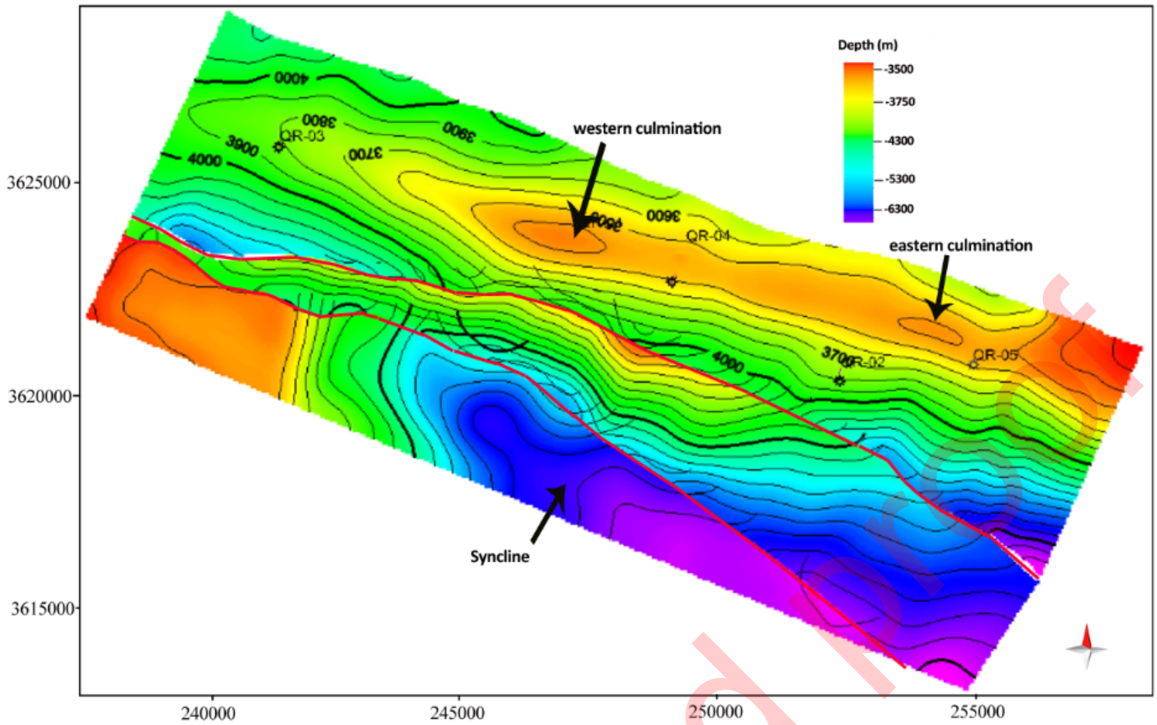

Fig. 8. UGC map of *Bng* horizon of the *QN* anticline.

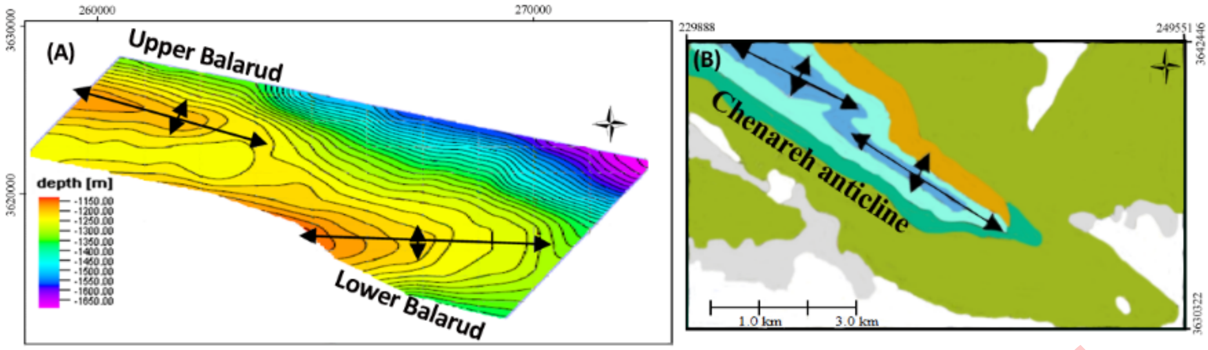

Fig. 9. (A) en-echelon structure in the *As* horizon of the *LBR* on the UGC map and (B) the Chenareh anticline at the surface on the geology map (legend in Fig. 1B). Location shown in Fig. 2.

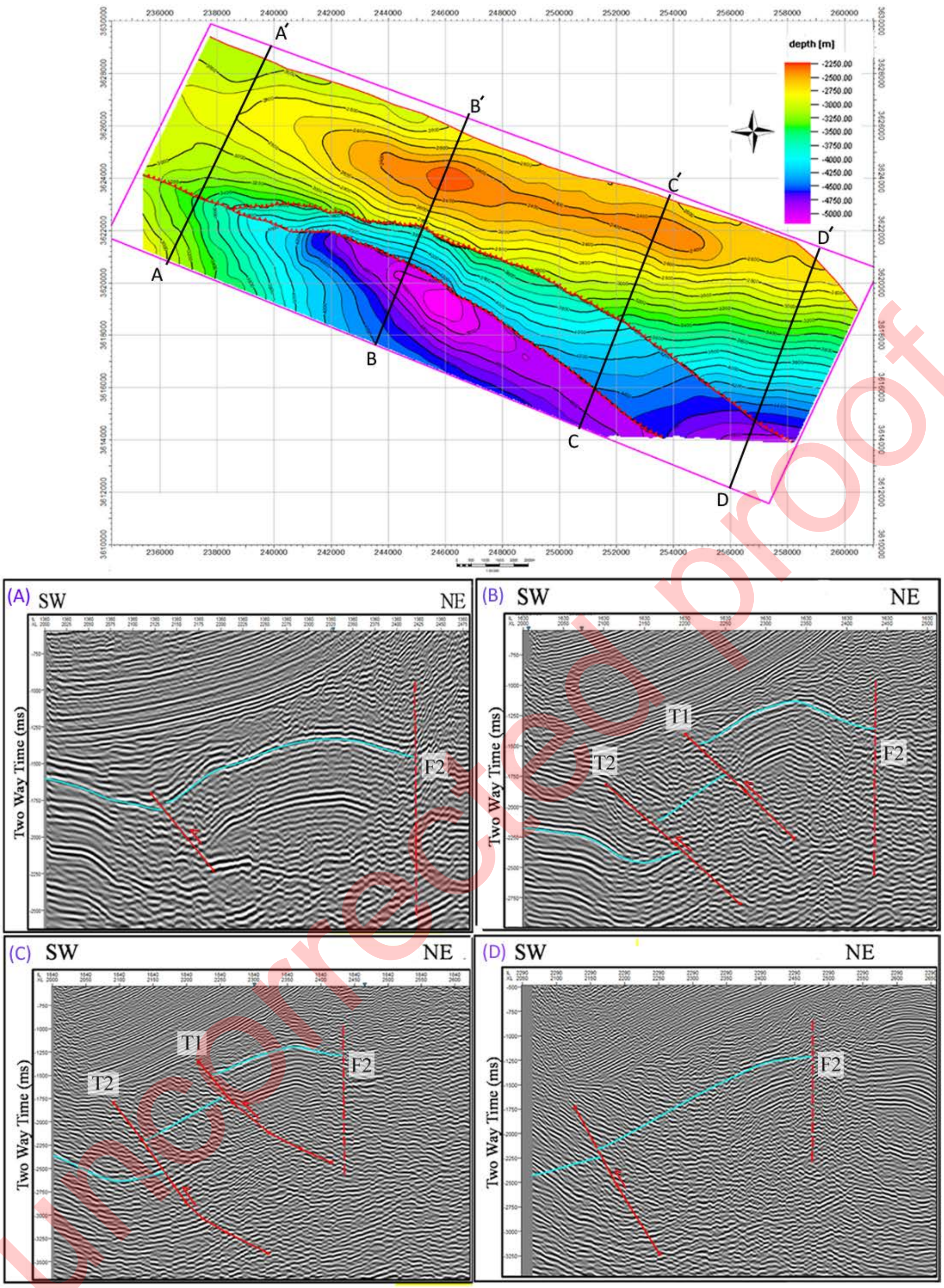

Fig. 10. Structural changes of *As* horizon (blue line) along *QN* anticline based on the interpreted seismic sections. Lines AA'-DD' show the location of the interpreted seismic sections (up to 3500 m depth). Red lines indicate the faults. Location in Fig. 2. Uninterpreted seismic profiles in Repository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

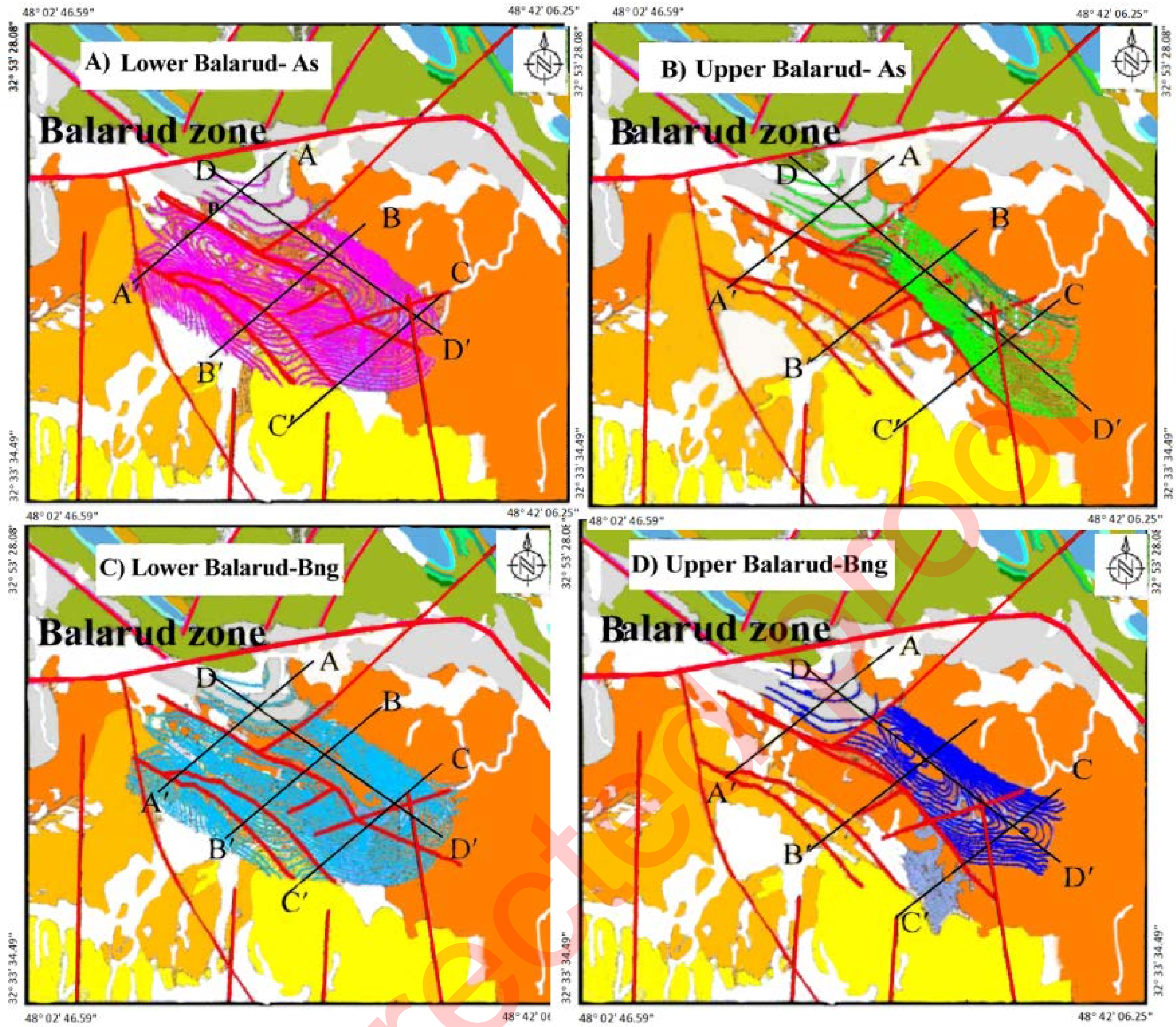

Fig. 11. Geological map (with a scale of 1:100000) of the study area (Legend in Fig. 1B) and location of the structural sections (AA'-DD'). Contours are the UGC map (*As* and *Bng*) for *UBR*, *LBR* and *QN* anticlines and indicate the location of these anticlines. Red lines show faults.

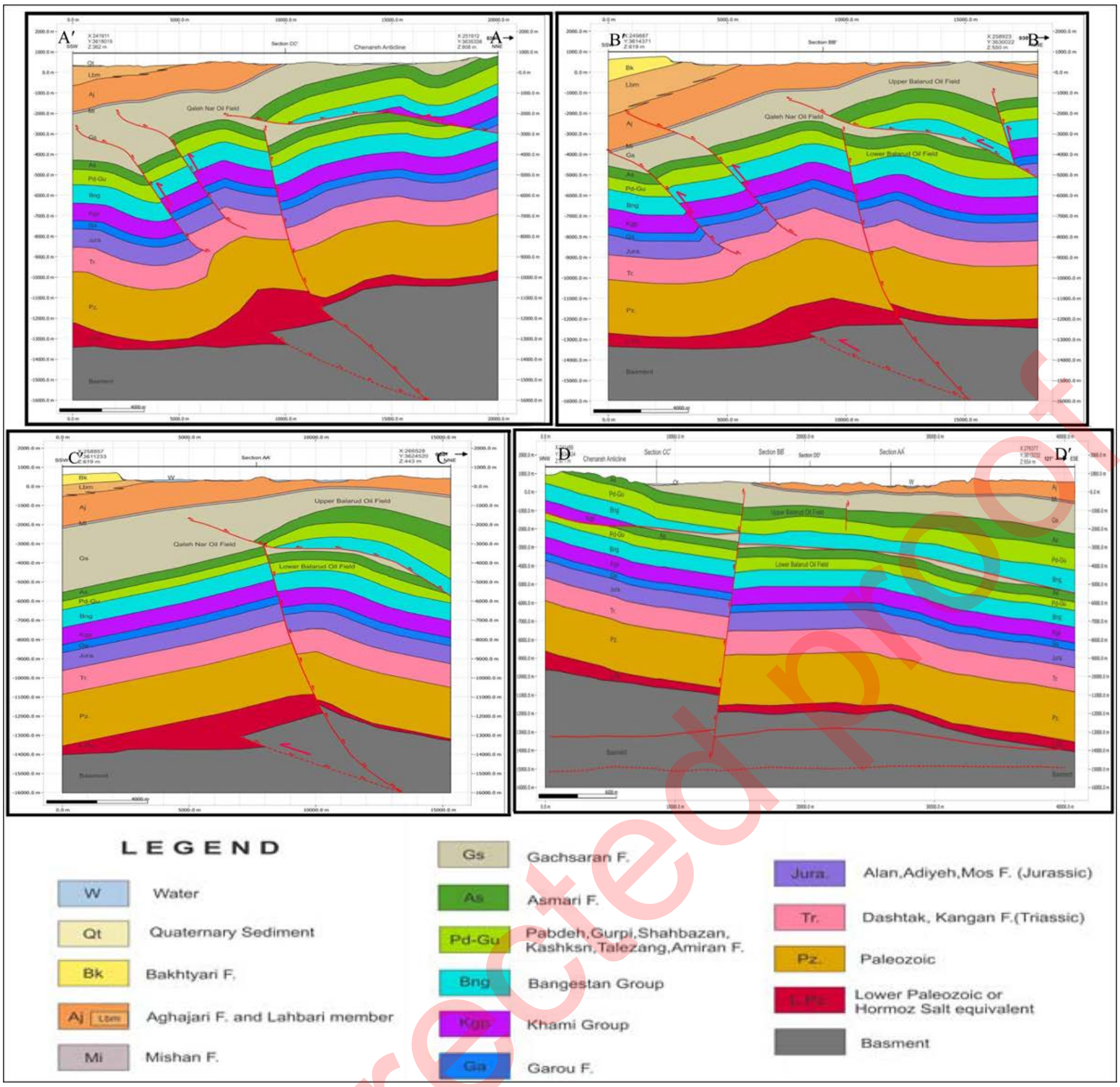

Fig. 12. (A) Cross-section AA', **(B)** Cross-section BB', **(C)** Cross-section CC'; and **(D)** Cross-section DD'.

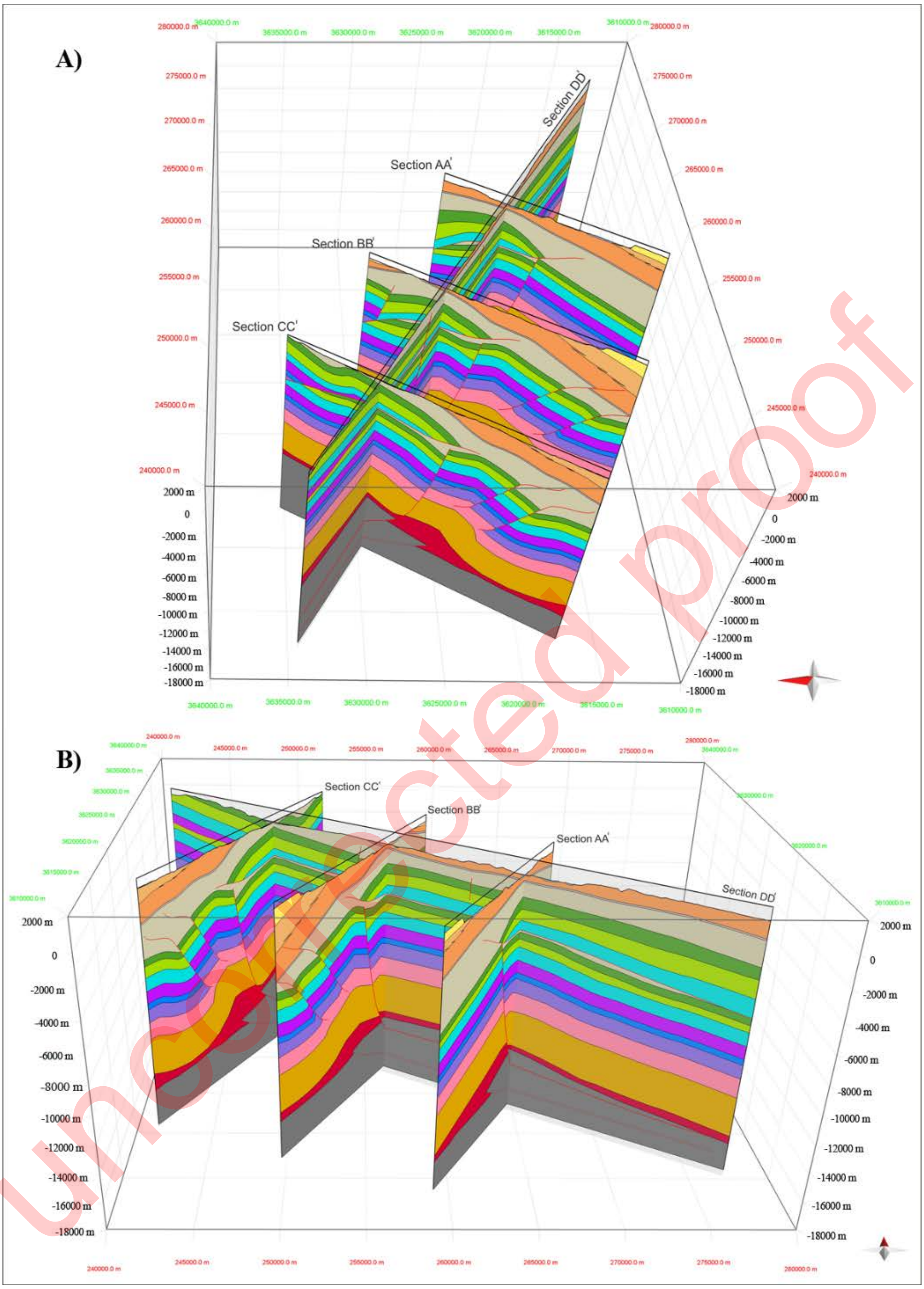

Fig. 13. 3D view of transverse and longitudinal structural sections. **(A)** View from northwest to southeast, and **(B)** view from southwest to northeast.

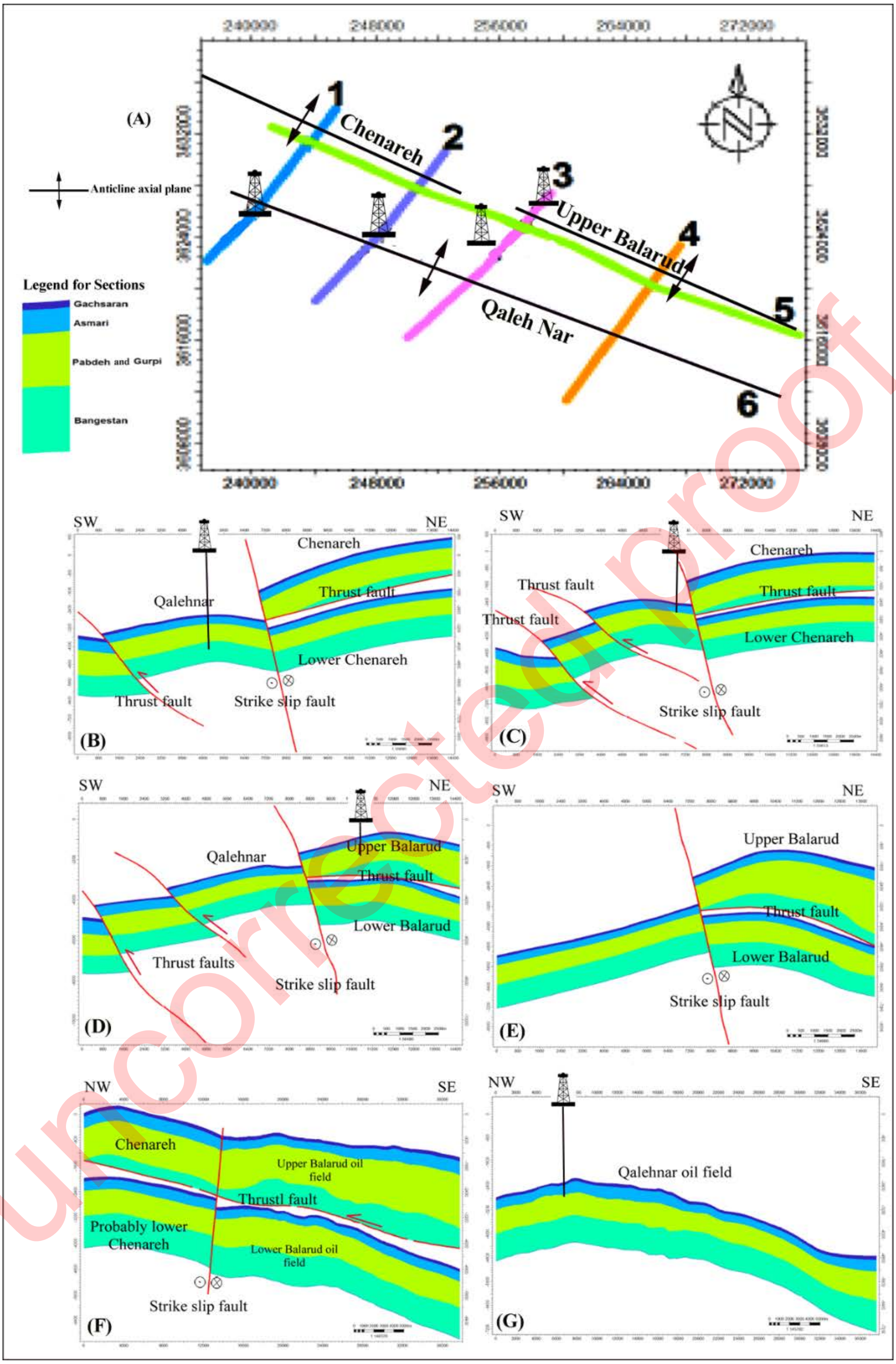

Fig. 14. Position of the sections relative to the axis of the folds **(A)**, and schematic view of sections 1-6 **(B-G)**.