Structural style of Taq Taq Anticline in the Zagros Fold-Thrust Belt in the Iraqi Kurdistan Region from the Integrated Surface and Subsurface Data

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Abstract
Taq Taq is a prolific oilfield in the Kurdistan Region of Iraq. It consists of a longitudinal double plunged anticline that is located within the Foothill Zone of the Zagros Fold-Thrust Belt. We studied the structural style of the Taq Taq Anticline from three balanced and retro-deformed structural cross-sections constrained by the integration of intensive surface geological observations, seismic sections and well data. The sections were constructed to understand the variation in the structural architecture of the anticline both along strike and up-section, and to describe the kinematic evolution and plausible fold model of the structure. The anticline exhibits symmetrical to slightly reverse asymmetry, and bounded by two main blind thrust faults (fore- and back-thrusts) that dip toward each other. The thrusts are interpreted to be detached along a deep-lying décollement in the KurraChine Formation (Upper Triassic) without involving basement fault. Thus, the structure can be considered as a faulted-detachment fold anticline with pop-up geometry. The average horizontal shortening value ranges between 5.6% and 8.1% with an average value of ca. 6.7%. Generally, the shortening values decrease gradually to the up section due to slight decrease in the fault offset value up-section. The increase in deformation intensity, asymmetry, shortening rate and geometry variation toward SE is mainly related to displacement variation on individual thrusts, fold wavelength and amplitude, or may be related to the effect of strike-slip fault. Therefore, the middle and NW parts of the structure can be considered as a better well location for the Taq Taq crestal reservoir.

Keywords: Balanced cross-section; Faulted detachment folds; Pop-up structure; Shortening; Structural style; Taq Taq anticline; Thin-skinned deformation

1. Introduction

Fold-thrust belts that existed throughout geological time are widely acknowledged as the most familiar mode that the crust accommodates shortening (Poblet and Lisle, 2011), and have a global distribution (Cooper, 2007). The structures within the fold-thrust belts are explained by several kinematic models of fault-related folding (Suppe, 1983; Suppe & Medwedeff. 1990; Poblet and McClay, 1996; Mitra, 2003; Brandes & Tanner, 2014). One of the models was proposed by McClay (2004), and it explains that the detachment folds change to a fault-propagation anticlines, and eventually to transported thrust-propagation anticline with increasing fault displacement during progressive evolution.

The Zagros Fold-Thrust Belt (ZFTB; including its foreland basin) is one of the richest provinces of oil and gas due to its favorable circumstances of hydrocarbon generation, migration and accumulation.
(Alavi, 2007). The current importance of petroleum provinces has increased interest in this area. Therefore, the northwestern segment of the belt in the Kurdistan Region-Iraq (KRI) become the focus of some latest investigations (e.g.: Bretis et al., 2011; Csontos et al., 2012; Reif et al., 2012; Awdal et al., 2016, Koshnaw et al., 2017; Le Garzic et al., 2019; Tozer et al., 2019, Yousif et al., ). In 1978, three wells (TT-01, TT-02, and TT-03) have been drilled by the Northern Oil Company, which led to the discovery of the Taq Taq oil field. Now, the Taq Taq is one of the prolific oilfields in the KRI (Garland et al., 2010; Al-Qayim and Othman, 2012; Al-Qayim and Rashid, 2012; Rashid et al., 2020; Baban and Ahmed, 2021).

In the belt as the ZFTB, it is critical to accurately depict the tectonic styles for seismic hazard mitigation and economic exploration; especially as the ZFTB is known for active seismicity abundant hydrocarbon reserves (Butler et. al., 2004; Lacombe and Bellahsen, 2016). Understanding the perspective geometry of the fold style and fault shape with depth is critical for economic exploration activities. Thus, balanced cross-sections are crucial for deciding on drilling locations and identifying structural traps (Mitra.,1990; Mitra,1992; Poblet & Lisle.,2011.). On the other hand, a set of valuable subsurface data (well and seismic data) is acquired through the exploration activity. When these data are integrated with the surface structural investigation, realistic constraints on the structural style and kinematic evolution can be made (Poblet & McClay,1996; Mitra.,2003 ; Shaw et al.,2005; Farzipour-Saein et al., 2009; Poblet & Lisle, 2011).

In this study, we aim to (i) disclose architecture of the fold and fault’s shape with depth to find out a reasonable fold model for the Taq Taq anticline, (ii) calculate the shortening amount by comparing the restored and balanced cross-sections, and (iii) understand the variation in the architecture of the fold and faults.

The Taq Taq oil field is located to the south of Koya city, and about 50 km to the southeast of Erbil city. It is bounded by longitudes 44° 24′ 55″ and 44° 40′ 50″E and latitudes 35° 54′ 48″ and 36° 05′ 12″N, and covers 425 km2 within the Iraqi Kurdistan region (Fig. 1). The study area consists of a major anticlinal structure called the Taq-Taq anticline.
2. Geological Setting

2.1. Tectonic Setting

The Arabian Plate as a part of young and active Zagros orogeny that comprises the investigated structure has a complex tectonic history and comprises active and passive margins. As a part of the Alpine-Himalayan belt, the ZFTB represents the deformed NW margin of the Arabian plate that formed from its ongoing convergence with the Eurasian plate. The collisional belt of Zagros orogeny is extending about 2000km, onset from SE Turkey, passing throughout KRI and East of Iraq toward west of Iran, and in the SE of the belt ending at Hormuz Strait and Oman Mountains (Beydoun et al., 1992; Sharland et al., 2001; McQuarrie, 2004; Alavi, 2007; Kent, 2010; Homke et al., 2010; Koshnaw et al., 2017). Tectonic events such as subduction, obduction and collision in the NE margin of the plate affected the deformation style and stratigraphy of the investigated structure. Arabian Plate is bounded by a collisional belt to the north and northeast along Taurus/Zagros Mountain ranges, to the southeast by the Indian Ocean which has passive/rifted margins, to the southwest by Red Sea constructive margin and by a strike-slip margin to the west (Dead Sea Transform) (Berberian and King, 1981; Sharland et al., 2001).

The Phanerozoic sedimentary layers were subjected to folding, thrusting, and strike-slip faulting activities during contractional tectonic processes, over the Precambrian basement (Ameen, 1991; Numan, 1997; Sharland et al., 2001; Jassim and Goff, 2006). As a result of the folding and thrusting processes, the ZFTB experienced significant horizontal shortening. Jassim and Goff (2006) have divided the Zagros orogenic belt in KRI into five distinctive structural zones from hinterland toward foreland, which are named: Zagros Suture Zone (ZS), Imbricated Zone (IZ), Highly Folded Zone (HFZ), Foothill Zone (FHZ) and Mesopotamian Foreland Basin (Fig 1). The Highly Folded and Imbricate zones are characterized by mostly SW-verging fault-related anticlines, while the Foothill Zone characterized by major folds above blind thrusts (Awdal et al., 2013). Intensity of deformation and topographic relief decrease southwestward from the Main Zagros Thrust to foreland areas.

Tectonically Taq Taq anticline is located within the Foothill Zone/Low Folded Zone and northeastern part of Butmah-Chemchemal Subzone (Jassim and Goff, 2006). The anticlines in foothill zone are trending NW-SE in the southeast while in the northwest trending E-W. This Subzone has very obvious deep and long synclines with thick molasse sediment of Pliocene age (Jassim and Goff, 2006).

2.2. Mechanical Stratigraphy of the Study Region

The sedimentary cover over the Proterozoic crystalline basement of KRI is divided into several groups based on the mechanical stratigraphy (Kent, 2010.; Zebari and Burberry., 2015). The Phanerozoic succession in the Arabian plate is divided into 11 tectonostratigraphic megasequences (TMS) separated by main unconformities (Sharland et al., 2001). The sedimentary cover consists of interbedded incompetent, competent, and sub-competent strata depending on the mechanical stratigraphy point of view (Fig. 2). The variations in mechanical stratigraphy within the layers, both vertically and laterally, are important for general to overall architecture of fold-thrust belts and the formation of structures (O’Brien, 1957; Cotton and Koyi, 2000; Farzipour-Saein et al., 2009; Vergés et al., 2011; Cawood and Bond, 2018)

Thick Neogene and Quaternary syntectonic sedimentary successions which are corresponding to the Bakhtiarí and Fars formations exposed extensively through the FHZ. The ZFTB facies and Thickness variation and many regional and local unconformities were related to basement fault reactivation or foreland basin migration during L. Cretaceous – L. Miocene (Berberian and King, 1981; Hessami et al., 2001; Sherkati et al., 2006). The thickness of formations from Late Triassic to middle Miocene are
recorded from well no. TT-22 that provided by Ministry of Natural Resources (MNR) and TTTopco company. This well have penetrated deeper than 4.2 Km.

The Kurra Chine Formation (Late Triassic) (only the upper 80m penetrated by Well no. TT-22) composed of 850–1137 m of alternating limestone beds with intercalation of thick bed of dolomite and papery shales (Fig. 2). There are also thick evaporite intervals within the formation in the subsurface sections (Aqrawi et al., 2010). The incompetent layers act as a detachment bed beneath the Taq Taq anticline and some other structures in the region.

Fig.2. The Stratigraphic column in the investigated region, clarifying the formation names, age, lithology, competency and thickness depending on the well & field information.

The oldest exposed rocks of the Injana Formation in the study area is distinguished by the first presence of sandstone and consists of repetitive interbedded sandstone strata separated by erodible mudstones (Fig. 3 a,b). The boundary of this Formation with its underlying Fatha (Lower Fars) Formation and overlying Mukdadiya (Lower Bakhtiyari) Formation are gradational (Jassim and Goff., 2006, Fig. 2). Pirouz et.al. (2011) indicated that the Injana Formation comprised synorogenic sediments which were formed during collision by erosion of the uplifted Zagros Mountain belt. The Mukdadiya Formation is composed of 830-1050m thick of mostly mudstone and intercalated sandstones. Poorly cemented, gray in color, coarse-very coarse grained sandstones are arranged into beds 3–7m thick with
intercalated pebbles (Fig. 3c). The Bai-Hassan Formation (Pliocene-Pleistocene) represent the youngest synorogenic sediment in the Zagros foreland basin. It is primarily composed of 5–10m thick conglomerate beds with intercalated gravel, sandstone lenses and claystone intervals (Fig. 3d). It displays deposits of alluvial fan that originating from High Folded Zone and Zagros suture zone (Jassim and Goff., 2006).

**Fig. 3.** Field photographs show, a. the Injana formation shows thick beds of sandstone interbedded by mudstones in the southwestern limb. b. thick sandstone beds of Injana formation. c. the sandy gravel of Mukdadiya formation. d. Thick conglomerate beds intercalated with sandstone, gravel, and mudstone of the Bai-Hassan formation at the SW limb of Taqaltu Syncline

3. Methodology

3.1. Field Investigations

In the Taq Taq anticline, 129 field stations were used to collect comprehensive field measurements and observations of well-exposed surface geological features. The field investigations were carried out along the best representative section paths across the fold. The investigations have begun to collect detailed structural data (bedding plane attitude), stratigraphic thicknesses and sedimentological information. Fieldwork was carried out by following three traverses across the fold hinge line. Field measurements were plotted on a detailed topographic map at a scale of 1:20,000 which was used as a base map and constructing geological map. Each station was chosen based on the availability of well-exposed bedding planes, dip panel variation across different structural positions (i.e., backlimb, forelimb, hinge zone) and formation boundaries.

3.2. Subsurface Data

Three interpreted seismic reflection lines, two depth maps and a master log of well no. TT-22 provided by the Ministry of Natural Resources, KRI and TTopco company. The seismic and well data reached the Triassic rocks at depth 4.2km.
3.3. Cross-section Construction and Restoration

Three structural cross-sections were constructed and restored to their pre-deformed states using line-length restoration methods. These traverses (A-A’, B-B’, C-C’; Fig. 4) cross the anticline in its northwestern, central, and southeastern segments.

To construct balanced cross-sections, surface field measurements were integrated with seismic and well data (Figs. 4,5,6). The two-dimensional geometric model have been established by projecting surface geologic data to subsurface through their related stratigraphic layers. The projections were constrained by well data and seismic sections. The geological cross-sections were manually constructed, applying kink methods (Woodward et. al., 1989; Mitra, 1992; Groshong, 2006). Because most deformed rocks comprise competent layers which maintain its orthogonal thicknesses and have parallel style that are deformed mainly through flexural-slip mechanisms. The constructed sections were manually restored to their un-deformed state by removing the entire cumulative effects of folding and faulting processes. During balancing processes, at the axial surfaces of the adjacent synclines two vertical pin lines were positioned, supposing that have no interlayer slip (Woodward et. al.,1989; Mitra & Namson,1989; Mitra,1992). Then, the bed length balancing began at the forward pin-lines backward to the hinterland pin-lines. The sections later digitized and illustrated using Canvas software 14, moreover, to conduct analysis of fold elements which have strongly related to geometry of fold, hundreds of bedding plane measurements were analyzed and projected by utilizing Schmidt (equal area) net.

4. Results: Structural Analyses

To provide a comprehensive structural picture of the Taq Taq anticline, this part is divided into three sections:

4.1. Map View Description of the Taq Taq Anticline

A comprehensive geological map has constructed for Taq Taq anticline with adjoining syncline (Fig. 4). The anticline is obviously visible on the surface, where sandstones beds of Injana Formation (L. Miocene) crops out arising ridges in an elliptical shape with ca. 14km long and 7km wide with maximum crest line elevation ca. 640 m. The overall geometry of an elliptical shape can be noticed from satellite images. the synclines form low terrains and covered by recent deposits. The structure is considered to be the last well-expressed structure in the Foothill Zone towards the foreland, it is bounded from the North by Bina Bawi anticline, the Taqaltu Syncline at the NE separates the Taq Taq anticline from the Haibat Sultan ridge which is part of the Khalakan anticline (Fig. 4). At the SW a wide syncline (Erbil Syncline) separates Taq Taq anticline from Kirkuk structure. Generally, the Taq Taq anticline hinge line trending 324°-144°, parallel to the main NW-SE trending axis of the Zagros fold belt. The anticline’s double-plunging nature in map view is well expressed. This anticline toward NW is plunged near the Goptappa, while it plunges southeasterly near Talaban village (Fig. 4).

The exposed deformed formations range from the Late- Miocene (Injana Formation) to Pliocene-Pleistocene (Bai-Hassan Formation) with recent deposits (Fig.4). The fold’s hinge area is gradually terminated toward northwest and southeast. The exposed rock units across the backlimb dip toward NE. The dip amount of the backlimb starts from ca. 6°NE around the hinge region and increases to ca. 25-28°NE near the inflection line. On the other hand, the forelimb deformed rocks are dipping southwestward, and dip angle progressively rises from ca. 3°SW in the hinge area to ca. 25°SW near the inflection line. Except, there is rapid increase to 41-51°SW within Injana Formation around traverses A-A’ and B-B’, but this abrupt increase is not observed in cross-section C-C’.

The blind thrusts of TT1 and TT2 broke through the backlimb and forelimb respectively (Figs. 4,5). The length of the TT1 and TT2 are 10.2 and 14.3 km on the contour depth map of the top of Qamchuqa
formation. While the TT1 has shorter length at the contour depth map of the top of Shiranish, because TT1 is not reached the Shiranish formation near the northwestern plunge (Fig. 5a).

Fig. 4: Detailed geological map of the Taq Taq structure and nearby area constructed from field data.

Fig. 5 Interpreted depth contour map of top of (a): Shiranish formation, (b): Qamchuqa Formation which show the blind reverse faults. This structural map is based on 2D seismic interpretations (After TTOPCO 2006.).
4.2. Description of the Taq Taq Anticline from Different Cross-sectional View

To investigate the fold and fault system, detachment depth and shortening of Taq Taq Anticline, three balanced and retro-deformable structural cross-sections parallel to SW tectonic transport direction were constructed from the topographic surface to the detachment in the Kurra Chine Formation (Upper Triassic). These sections display that the fold architecture varies both laterally and vertically. The length of the sections vary between 15.045 km and 16.42 km.

The anticline is slightly asymmetric, the hinge area is rounded to sub-rounded, and its limbs are curved relatively. The fold amplitude and the aspect ratio in section A-A’ were measured at the top of Fatha Formation are ca. 722m and 0.1, respectively (Fig. 6a). While, it increases from the section B-B’ to c. 924m and 0.121, respectively. While, in section C-C’ at the top of the same formation level also increased and reached to c. 1250 m and 0.144, respectively. The measured half wavelength at the top of Fatha formation from the sections A-A’, B-B’ and C-C’ are 7.37km, 7.639km and 8.677km, respectively (Fig. 7). This indicates there are a gradual increase in fold amplitude, fold aspect ratio and half-wavelength from section A-A’ to C-C’. The balanced and interpreted seismic sections show that the anticline is bounded to the NE by a blind back-thrust (TT1) and by a main blind fore-thrust (TT2) to the SW. The thrusts are interpreted to be detached along a deep-lying décollement in Kurra Chine Formation (Upper Triassic) (Fig. 7a,b,c). The Fore-thrust (TT2) broke the SW limb and traced from the 5-6 km deep core of the anticline upwards to the M.–L. Eocene (Pila Spi Formation), where it appears to tip out, the TT2 has a listric geometry down-section. On the other hand, a back thrust (TT1) has cut the NE limb and affected Shiranish Formation and older units but not affected younger layers in the section A-A’ (Fig. 7). This indicates a fault tip in the weak marls at the top of Shiranish Formation. In contrast, in the section A-A’, the TT1 only affecting the top of Qamchuqa Formation but not affected the Shiranish Formation. The geometry of the cross-sections of Taq Taq anticline that the back thrust broke up from the related fore-thrust and resulted in the growth of pop-up structures.

The Taq Taq anticline in section A-A’ has symmetrical to slightly reverse asymmetry with a steeper back-limb. In contrast, the sections B-B’ and C-C’ exhibit slightly reverse asymmetry with a steeper NE limb (Hinterland verging). The increase in asymmetry toward SE is related to the intensity of fault slip at these sections. The TT2 accommodates a slightly larger displacement relative to the TT1. Displacement along these blind thrusts generally increases down-section. There is a progressively upsection decrease in fault displacement from c. 150 to 30m along TT2 as calculated from seismic section. The decrease in thrust displacement upsection (i.e. decreases in shortening due to faulting) is balanced by increment in fold-related shortening (Mitra, 1986.; Pennock et. al., 1989).
4.3. Geometrical Analysis of Taq Taq Anticline along Different Cross-sections

This research involved 232 field measurements dispersed along three traverses perpendicular to the fold axis used to describe the fold style of the Taq Taq anticline. At each station a number of bedding surfaces (including true dip direction and amount) were recorded then their average was used to construct the sections (Fig. 4). Poles to planes and calculated average attitude of each limb were plotted on the equal area (Schmidt) net using stereonet program, the axial surface and fold axes orientation was determined by Pi diagrams.

The stereographical representation of the 72 bedding plane measurements through section A-A shows that the mean attitude is 045°/13° for NE limb, and 230°/11° for the SW limb of the Taq Taq anticline. This reveals symmetrical to slightly reverse asymmetrical style. The hinge line trend is 317° and plunges at 1°, while the axial surface is dipping 89° toward 227°. The interlimb and folding angles are 156° and 24° respectively. Subsequently, the structure belongs to the gentle and upright folds depending on Fleuty Classification (1964, 1987).

While, the synoptical stereographic projection of strata (80 measurements) through section B-B shows that the average attitude of the NE and SW limbs are 054°/21° and 227°/15°, respectively, which imply reverse asymmetric anticline with lesser dip angle at the forelimb. The orientation of hinge line and axial surface are 141°/1° and 231°/87°, respectively. Consequently, the Taq Taq structure has hinterlandward vergency and classified as upright fold. The SW flank of the anticline through sections A-A and B-B reveal two separated pole clusters (Fig. 4, 8, 9), but section C-C shows only a pole cluster.

Fig. 7 The Balanced cross-sections and retro-deformed complement of the Taq Taq anticline through section lines (a): A-A, (b): B-B, and (c):C-C.
Fig. 8. The field photo show different dip domain at the Fatha Formation at the SW-limb of the anticline.

The lower hemisphere stereogram of the exposed beds (80 measurements) via section C-C' in the Taq Taq structure shows that the average attitude of the back and forelimbs are 058°/19° and 210°/10°, respectively, which imply reverse asymmetry. The dip of hinge surface is 85° toward 228°. thus, the anticline’s vergency is toward hinterland (Fig. 9).

Fig. 9. Synoptic stereographic projection of Taq Taq anticline along sections (A-A', B-B' and C-C')

5. Discussion

5.1. Time-Space Shortening in Taq Taq Anticline

The overall horizontal shortening (fold-related shortening and thrust-related shortening) of the Taq Taq anticline have been calculated in different times (stratigraphic level) by comparing the three constructed restored and balanced sections. The estimated shortening in Table 1 shows vertical and along strike variation at different geologic times. The upper boundary of Gercus Formation has minimum shortening amount (5m) due to thrusting, contrary, the maximum shortening amount (56m) at top of Kurra Chine formation was calculated in section A-A'. The average shortening estimation of cross-section A-A' is 562 m (4.85%). Generally, the structure exhibits a slight increment in thrust-related shortening down-section A-A'. The main cause of this rise is the slightly increase in the fault offset value down-section. The thrust fault loses its slip up-section, and the ensuing shortening is accommodated by folding in front of the fault tip (Mitra, 1990; McNaught & Mitra, 1993; McQuarrie, 2004). The estimated shortening due to folding of the same section shows a little non-uniform variation and slightly increment in their shortening downsection (Fig. 9, Table 1). This is mostly due to uneven variation of wavelength-amplitude ratio upsections in various stratigraphic levels.

Vergés et al. (2011) suggested that the position of structures in the competent groups control the variation in the wavelength and amplitude. The mechanical stratigraphy of the current area have some
similarity with Pusht-e-Kuh arc by Vergés et al. (2011), their conclusions may be analogous to the observed in the Taq Taq anticlinal structure. These findings are in consistent with previous related structural research, including as, Balaki and Omar (2019) described the Bradasot anticline (65 km close to the study area) and show the same variation in increasing fold-related shortening down-section. The changes in fold wavelength and amplitude in the Rocky Mountains are related to competent stratigraphical levels (McMichan, 2012).

The cross-section B-B’ exhibit an average horizontal shortening of 890 m (7.21%), Late Miocene (top of Injana Fn.) have the minimum amount of shortening of 743m (6.10%), while Top of Kurra chine (LateTriassic) formation have the maximum amount of shortening which is around 950m (8.61%) (table 1). Similar to cross-section A-A’, the structure revealed gradual decrease in thrust-related shortening up section B-B’. Fold-related shortening exhibit non-uniform and slightly increase down-section which is results from changes in the fold amplitude and wavelength (Fig.10). Generally, the total horizontal shortening amount in section B-B’ is greater than the value in the section A-A’, because section B-B’ runs at the center of the anticline which characterized by increment in intensity of folding and faulting processes.

The Taq Taq anticline In section C-C exhibit maximum total shortening value of 1.049 km (7.961%) relative to other sections. The maximum and minimum amount of shortening of Top of Kurra chine Formation and top of Injana Formation are 9.99% and 6.38% respectively (table 1). The value of thrust-related shortening also revealed increment in shortening value down-section similar to other sections, due to increase in fault displacement down-section which reached to ca. 250m. because this section passes close to middle part of the fold, and the fault displacement increased toward SE part of the structure as measured from seismic lines. Similarly, the fold-related shortening show slightly gradual increasing in shortening value down-section (Fig. 10, Table 1).

The along strike variation in geometry and shortening rate may be reflect fold wavelength, amplitude and displacement variation on individual thrusts or related to the effect of strike slip fault which corresponds to subsurface lineaments. It is anticipated that when the displacement of fault increases, the fault’s lateral length will increase at greater rates than the displacement rate (Jackson et. al., 1996; Keller et al., 1999; Ramsey et al., 2008).

The average vertical shortening value range between 5.64% and 8.07%, while the maximum and minimum shortening value are 9.99% and 4.459% with average value ca. 6.67%. The results of this study are well-matched with the shortening amounts from former sections at NW Zagros. Koyi and Mansurbeg (2021) calculated ca. 7.9% of shortening at Taq Taq anticline depending on the seismic section. Frenner et al. (2012) calculated the mean shortening values at the nearby Bina Bawi anticline (in High folded Zone) as 11%. Doski and McClay (2022) measured amount of 7.13 % of total shortening in Duhok area along a cross-section that passes through high and Foothill zone. Balaki and Omar (2018) measured the average shortening of Barda Rash anticline in LFZ at 9.67%. The Pirmam Dagh anticline (HFZ) located 40 km NW of the study area is shortened by 9.398% (Al-Azzawi et al., 2014). Falcon (1969) estimated shortening by 6.5%-21.5% during his research on folded zone of Iraq. These shortening amounts in Iraq are less than in the Iranian Zagros (Blanc et.al., 2003; McQuarrie. 2004; Alavi,. 2007; Zebari et.al., 2020). This variance can be suggested by anticlockwise rotation of the Arabian Plate to the west (Reilinger et.al., 2006; ArRajehi et.al., 2010, Zebari et al., 2020).
Fig. 10: Relation between fault and fold -related shortening (in km) with different geologic time in the Taq Taq anticline at sections A-A', B-B', and C-C'.

Table 1. Shortening values calculation of Taq Taq anticline in different sections A-A', B-B' & C-C'

<table>
<thead>
<tr>
<th>Formation/ Age</th>
<th>Cross-section</th>
<th>Original length (km)</th>
<th>Deformed length (km)</th>
<th>Total shortening Δl (km)</th>
<th>Fault-related shortening (km)</th>
<th>Fold-related shortening, (Km)</th>
<th>Shortening %</th>
<th>Average %</th>
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<tbody>
<tr>
<td>Top Injana(U.Fars)/Late Miocene</td>
<td>A-A-</td>
<td>11.534</td>
<td>11.020</td>
<td>0.514</td>
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<td>0.514</td>
<td>4.453</td>
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<td></td>
<td>B-B-</td>
<td>12.193</td>
<td>11.450</td>
<td>0.743</td>
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<td>6.094</td>
<td>6.375</td>
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<td></td>
<td>C-C-</td>
<td>12.928</td>
<td>12.104</td>
<td>0.824</td>
<td>-</td>
<td>0.824</td>
<td>6.750</td>
<td></td>
</tr>
<tr>
<td>Top Fatha (L.Fars) Fm./Middle Miocene</td>
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<td>11.545</td>
<td>11.020</td>
<td>0.525</td>
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<td>0.525</td>
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<td></td>
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<td>B-B-</td>
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5.2. Fault-Related Fold Mode and Kinematic of Taq Taq Anticline

A plausible model for structures can be determined using the geometry of the constructed balanced sections. Detachment folds, fault propagation folds (fault-tip folds) and fault-bend folds, are the three basic systems of fault-related folds used to define the structural characteristics of fold-thrust belts (Jamison, 1987; Mitra, 2003). Fold geometry analysis and kinematics evolution of the Taq Taq anticline are discussed and compared with these main models of fault-related folds. An understanding the geometry, kinematic evolution and controlling parameters of the structures is critical in interpreting the architecture of the structure and tectonic evolution of fold and thrust belts (Mitra, 2002).

Fault-bend folds are shaped when the beds move through bended faults (Suppe, 1983). Due to the geometry of the structure not reveal shape of bended fault and the nonappearance of the upper flat, therefore this model of the structure is ruled out. Furthermore, at footwall of the major thrust instead of horizontal strata there are folded beds which indicates that the wrapped layers have folded before being broken by fore-thrust. The detachment fold model for Taq Taq anticline also excluded due to the following reasons. First, both models of detachment fold (disharmonic and lift-off) are symmetrical (Mitra and Namson, 1989; Mitra, 2003). Second, the flat-topped detachment-fold characterized by broad hinge area and steeper orientation than at rims (Mitra &Namson, 1989). Taq Taq anticline is asymmetrical and has broad hinge area beside a steeper and shorter backlimb. Detachment folds are distinguished by the termination of a parallel fold inside a ductile unit at a basal detachment (Dahlstrom, 1969; Jamison,1987; Mitra & Namson, 1989; Mitra,1992; Poblet et al., 1997). Then thrust ramp propagates through both limbs of the structure with progressive folding and tightening (Mitra, 2002).

Mitra (1990) suggested that Fault-propagation folding is formed when thrust-fault loses slip and ends up-sections by transferring shortening to a fold emerging at its tip. The transition from detachment-fold to progressive fault-propagation produce faulted detachment folds, consequently, it superficially resembles fault-propagation folds (Mitra, 2002). Thus, the geometrical modifications of faulted detachment fold to complex anticlinal geometry may be misinterpreted as fault-propagation folds (Mitra & Namson, 1989; Mitra,2002). Therefore, several characters were considered to determine whether the fold model of the structure was a fault propagation fold or a faulted detachment fold. (1) Mitra (2002) determined that the majority of faulted detachment folds begin as low amplitude and large wavelength folds, while in trishear or self-similar fault-propagation fold the wavelength is directly correlatable to the shortening (Mitra, 2002). The Taq Taq anticline has large wavelength and low amplitude. (2) Usually, faulted detachment fold has rounded shape and more open than fault propagation fold (Mitra, 2002), this description is also coincident with the current structure. (3) Faults propagate across preceding folds in faulted detachment folds, allowing behind footwall syncline (Mitra, 2002). The existence of thicker beds of Mukdadiya and Bai Hasan and folded beds instead of horizontal strata at the footwall of Taq Taq forethrust, indicates that the folding of the wrapped beds is preceded broken of the layers by the fore-thrust ramp. (4) The slip of fault may be constant for a portion of the stratigraphic level or may decrease or increase up section in faulted detachment folds (Mitra, 2002). In present structure the fault slip commonly decreases up-section, in section A-A the displacement shows some non-uniform variation and complexity. (5) In faulted detachment fold model the backlimb may dipping in an angle steeper than the fault (Mitra, 2002, Fig.7). The dip of the backlimb of Taq Taq faulted detachment fold
is greater than the dip amount of the fault ramp. This model also reveals a well-developed syncline behind and in front of the fold and lesser displacement on the fault, especially at deeper levels. Fold-accommodation thrust can be considered as the developed thrust fault that formed as a result of migration and squeezing of material in the crestal region (Balaki, 2018). Both limbs of the structure almost have the same length and dip during this development. Consequently, both thrust-ramp TT1 & TT2 of steep rim domains grew simultaneously on both flanks (Mitra, 2002). Afterward, the back-thrust TT1 terminated against major forethrust (TT2), whereas, the major forethrust (TT2) coupled to the subsurface detachment and affected the consequent asymmetric propagation of the Taq Taq anticline (Mitra, 2002).

Taq Taq symmetric geometry changed to slightley reverse asymmetrical fold, because deformation comparatively concentrated on the backlimb during further propagation of the structure (Mitra, 2002). The thickness of Mukdadiya Formation at the SW flank of the Taq Taq varies and have greater thickness than the NE flank which indicate that the structure was active throughout deposition processes. This outcome is consistent with previous studies (Koshnaw et al., 2017 and Balaki and Omar, 2018). Koshnaw et al. (2017) deemed the Mukdadiya Formation’s syn-tectonic growth strata to be indicative of syn-kinematic deposition along the Kirkuk frontal fault structure. Therefore, The Mukdadiya Formation was thought to have been deposited while the Kirkuk frontal thrust was active (Koshnaw et al., 2017).

5.3. Is Taq Taq Anticline a Pop-up Structure?

Globally, in fold-thrust belts the Pop-up structures may form and comprise of an uplifted block restricted by a hinterland-verging backthrust and a foreland-verging thrust ramp (Butler, 1982). Identifying pop-up structure is essential for regional scale valuation of fold-thrust belt styles (Maystrenko et al., 2003), and occurrence of hydrocarbone traps (Ferguson and McClay, 1997; Morley et al., 2011). Numerous parameters are controlling growth of pop up structures such as, deformation mechanisms, stratigraphy, décollement type, rates of thrust/fold propagation and rheological contrasts (e.g., Daves et al., 1983; Massoli et al., 2006, Fabbi and Smeraglia (2019).

This type of structure generally arise in fold-thrust belts that characterized by multilayered sedimentary succession (alternation of competent and incompetent rocks), weak décollement, and by thin-skinned tectonics, (Philippe et al., 1996; Watkins et al., 2017; Fabbi and Smeraglia, 2019). These conditions are available in the study area. The pop-up structures observed in many fold-thrust belts worldwide (eg. Northern Apennines, Coward et al., 1999; Jura Mountains; Watkins et al., 2017, BardaRash Anticline (Zagros), Balaki and Omar, 2018; Bekhair anticline (Zagros), Doski and McClay, 2022, Central Apennines, Fabbi and Smeraglia, 2019).

6. Conclusions

The Balanced and interpreted seismic sections show that the Taq Taq anticline is faulted detachment fold that bounded by a main blind fore-thrust to the SW and to the NE by a blind back-thrust. The thrusts are interpreted to be floored and detached along a deep-lying décollement in Kurra-Chine Formation (Upper Triassic) that not involved basement fault. Thus, the deformation style of Taq Taq anticline is interpreted as a thin-skinned, Th Fore-thrust has a listric geometry down-section that broke the SW limb and traced from the 5-6 km deep core of the anticline upwards to the Pila Spi (Middle–Late Eocene) Formation, where it appears to tip out. The geometry of the cross-sections suggests that the back thrust broke up at the related fore-thrust and resulting in growth of pop-up structures. The Taq Taq symmetric geometry changed to a slightly revers asymmetrical anticline, because deformation comparatively concentrated on the backlimb during further propagation of the structure. the hinterland vergent fault changed the vergence of the fold from NE to SW.
The average horizontal shortening value in the studied transects ranges between 5.6% and 8.1. The average shortening value decreased gradually up-section due slightly decrease in the fault offset value up-section. The estimated shortening due to folding shows a little non-uniform variation and slightly increment in their shortening down-section. This is mostly due to the uneven variation of the wavelength-amplitude ratios up-sections in various stratigraphical levels.

The along strike variation in geometry and shortening rate may reflects displacement variation on individual blind thrusts and fold wavelength and amplitude, or related to the effect of NE-SW strike slip fault which corresponding to subsurface lineaments. The structure is classified as upright sub-horizontal and gentle fold. The middle and northwestern part of the structure can be considered as a better well location of the Taq Taq crestal reservoir due to its relatively low intensnisy of deformation.

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References


