A semi-balanced section in the northwestern Zagros region:
Constraining the structural architecture of the Mountain Front Flexure in the Kirkuk Embayment, Iraq

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ABSTRACT

The Mountain Front Flexure or Fault (MFF) of the Zagros Mountains separates the foreland or foothills area from the morphological apparent mountain belt. Across this feature the regional elevations of Mesozoic to Neogene stratigraphic horizons substantially rise towards the mountain belt. Thin-skinned and thick-skinned structural styles have been proposed for this rise in other parts of the Zagros region. In our study area, in the Kurdistan Region of Iraq (KRI), we integrated surface and subsurface data and constructed a (semi-) balanced cross-section across the MFF. The section features duplex structures in the deeper subsurface, related to a deeper Palaeozoic and a shallower Triassic decollement horizon. On a smaller scale, layer-parallel shortening and intense deformation is observed in the incompetent lithologies, leading to an incipient disharmonic folding. Restoration of the section reveals a distinct imbalance between shortening in the upper part of the stratigraphic section (approximately 4 km or 16% on top Jurassic level) to the lower part (approximately 20 km or 49% on top Permian level). The imbalance can only be equalised on a regional section if the shortening is transferred from the lower to the higher decollement levels, which is connected to folds and thrusts in the foothills area. Based on observations from the mechanical stratigraphy, geometric relationships in map and cross-section, as well as morphological considerations, we argue that the origin of the MFF in the area of the considered section is related to active roof duplexes rather than basement-involved thrusting.

INTRODUCTION

The Zagros Mountains in the Kurdistan Region of Iraq (KRI) experienced a recent increase in hydrocarbon exploration and geological studies activity (Mackertich and Samarrai, 2015). OMV Exploration and Production explored in this region during 2007–2014 in several blocks, operated and non-operated. In one of the blocks, Bina Bawi (Figure 1a), the structural architecture of the deeper subsurface was unknown.

The Bina Bawi Anticline is situated in the Bina Bawi exploration block and is the focus of our study (Figure 1a). It is located behind the sharp topographic boundary, which separates the southwestern lowlands and the abruptly rising mountains to the northeast (Figure 1a). This boundary is usually referred to as Mountain Front Flexure/Fault (MFF, cf. Ameen, 1991; Sepehr and Cosgrove, 2004; Csontos et al., 2012).

There had been some discussion regarding the involvement of basement in the Zagros fold-and-thrust system (e.g. Berberian, 1995; McQuarrie, 2004; Vergés et al., 2011). Berberian (1995) argues, based on seismological data, that blind master thrusts from the basement are responsible for the morpho-tectonic zones of the Zagros region. In contrast, McQuarrie (2004) points out that the observations of different structural elevations along the MFF can well be explained by a combination of thin-skinned tectonics in association with salt inflation. Relocated seismic hypocentres seem to support the predominantly thin-skinned explanation (McQuarrie, 2004). In contrast, for the Lorestan arc thick-skinned faulting underneath a thin-skinned system is proposed by Vergés et al. (2011), based on regional, crustal-scale balancing.
In the Bina Bawi area, which is located towards the hinterland of the MFF, the seismic imaging of the deeper subsurface is in general very poor because of near-surface karstified rocks, a rugged morphology and locally steeply dipping subsurface horizons. The seismic imaging and the extrapolation of the surface geology to depth insufficiently constrain the deep structure. For the sections crossing the Bina Bawi and Safeen anticlines (Figure 1a), several structural interpretations exist, all having their specific problems, as outlined in more detail in the local setting section.

Nevertheless, these sections all share a problem: they are missing a plausible interpretation of the structure at depth. The knowledge of the deeper structural architecture in this area is essential for the exploration of deeper targets and prospect generation. Therefore, the objective of our study
is to generate a consistent structural model of the MFF and Bina Bawi Anticline area. This model incorporates all available data (including field geology, mechanical stratigraphy, seismic interpretation and recent well results) and gives a reasonable explanation for the deeper part of the section that is plausible in a regional geodynamical to local geological context.

REGIONAL GEOLOGICAL SETTING

The Zagros Fold-and-Thrust Belt is located along the NE margin of the Arabian Plate extending over more than 1,800 km from northern Iraq to the Strait of Hormuz. It formed as the result of the oblique collision between the subducting NE Arabian margin and Eurasia (Homke et al., 2004; Awdal et al., 2013), displaying the continuous closure of the Neo-Tethys Ocean, that started in the Late Cretaceous and continues until the present-day (Dewey et al., 1973; Berberian, 1995; Talbot and Alavi, 1996; McQuarrie et al., 2003). Shortening between the Eurasian and Arabian plates with current horizontal velocities of 16–30 mm/year (Sella et al., 2002; McQuarrie et al., 2003), is partitioned in S-SW oriented folding and thrusting of the Tethys sediments and NW-SE to N-S trending dextral strike-slip faulting (e.g. Dewey et al., 1973; Talebian and Jackson, 2002; Blanc et al., 2003; McQuarrie, 2004). Sarkarinejad and Azizi (2008) calculated slip-partitioning and dextral transpression for the Iranian Zagros.

The Precambrian, that has experienced various phases of metamorphism, is covered by more than 10 km of sedimentary rocks in front of the MFF that have been deposited since the Early Palaeozoic (Jassim and Goff, 2006). During pre-Cretaceous time, the deposition was mainly controlled by continental rifting along NW-striking normal faults and the opening of the Neo-Tethys Ocean (Alavi, 2004). During the Early Cretaceous the NE-directed subduction of the Neo-Tethys crust commenced and caused the SW-directed obduction of ophiolites in Campanian–early Maastrichtian times (Jassim and Goff, 2006; Agrawi et al., 2010). In parallel, the inner Zagros Orogen was uplifted (Hooper et al., 1995) and subsequently, as a result of ongoing subduction, the Neo-Tethys Ocean closed in the Miocene. The continent-continent collision of the Arabian and Eurasian plates in Pliocene to Pleistocene times represents the main phase of the Zagros orogenic compression and led to the development of the fold-and-thrust belt that can be observed today (Homke et al., 2004).

The current configuration of the Zagros region can be divided into five distinct structural zones, all trending NW–SE, parallel with the fold-and-thrust belt. These zones are, from the NE hinterland to the SW foreland: (1) Zagros Suture, (2) Imbricated Zone, (3) High Folded Zone (equivalent to the Simply Folded Belt in the Iranian part of the Zagros as defined by Berberian, 1995), (4) Foothill Zone, and (5) Mesopotamian Foreland Basin (Sepehr and Cosgrove, 2004; Jassim and Goff, 2006). Of these provinces, the major surface-reaching, SW-verging thrusts are found in the Imbricate and High Folded zones, whereas major folds above blind thrusts characterise the Foothill Zone (Awdal et al., 2013).

The boundary along the Suture Zone is usually referred to as the Main Zagros Fault (MZF). The boundary between the Imbricated Zone and the High Folded Zone is the High Zagros Fault (HZF). The transition between the High Folded Zone and the Foothill Zone is marked by a regional morpho-tectonic feature, the Mountain Front Fault or Flexure (MFF, Figure 1), which causes a marked step in topography and level of exposed sedimentary layers. This morpho-tectonic step can be observed all along the Zagros from the NW to the SE. It is still a matter of debate as to whether this step is purely associated with thin-skinned tectonics (e.g. McQuarrie, 2004) or also includes faulting/thrusting on basement faults (e.g. Berberian, 1995; Vergés et al., 2011).

In addition to the zonation, the Zagros region has some distinct along-strike segments (e.g. Sepehr and Cosgrove, 2004). These segments are mainly salients and re-entrants of the morphological mountain front, mainly corresponding to the MFF. Starting in the north, the first Zagros segment is the EW-trending Taurus part of northern KRI and southern Turkey (Csontos et al., 2012). South of the bend zone is the Kirkuk Embayment, followed by the Iranian segments of the Lorestan Arc (or Pusht-e Kuh Arc), the Dezful Embayment and the large Fars Arc (Figure 1b). Some of these segments are connected to the presence and non-presence of the Hormus Salt (Bahroudi and Koyi, 2003).
STRUCTURAL AND STRATIGRAPHIC SETTING OF THE STUDY AREA

Structural Uncertainties in the Study Area

A compilation of different cross-sections through the MFF at Bina Bawi Anticline and adjacent areas is shown in Figure 2. These cross-sections document the problem of the unknown or uncertain deeper structural architecture.

Figure 2a shows a simplified interpretation sourced by surface structural dips only and their extrapolation, leaving the unconstrained areas blank (Bretis et al., 2011). Figure 2b shows a conceptual section through the area with thin-skinned thrusting (Awdal et al., 2013). This section also lacks a deeper structural interpretation, because the accommodation of the surface fold at depth is not taken-up by the thrust fault but is hiding in (ductile?) deformed Jurassic and Triassic strata. The section also does not show any plausible reason for the structural step of the MFF, apart from some elevated

Figure 2: Published regional cross-sections across the Bina Bawi/Permam anticlines (a) after Bretis et al. (2011); (b) after Awdal et al. (2013); (c) after de Vera et al. (2009); and (d) after Frehner et al. (2012). Question marks denote areas which lack plausible explanation. The colour code in the figures follows a standard stratigraphic scheme and is also explained in Figure 3. Note different scale of the sections.
basement rocks underneath Bina Bawi Anticline. Additionally, the fault tip in the southern limb of Bina Bawi Anticline is problematic. The section shows a clear offset of mid-Cretaceous rocks but none for the top Cretaceous. Instead there is a significant thickness change for Upper Cretaceous rocks, without any obvious deformation. Either the thrusting is pre-Late Cretaceous or the illustrated structure is implausible.

A third section (Figure 2c) shows an interpretation that combines thin-skinned thrusting at the base of the Palaeozoic sediments with thick-skinned, high-angle reverse faulting of the basement to explain the observed structure and structural steps (de Vera et al., 2009). This model assumes a basal detachment in unspecified Ordovician and Silurian shales. The kinematics of the individual folds is not clear on this section. Apparently Permam Anticline is sketched as a flexure/forced fold and Safeen Anticline as a fault-propagation fold. In addition, there are other less clear fault-fold relationships with and without thrust tip (Hareer Anticline and anticlines NE of it). The section does not show any deformation SW of the MFF, which contradicts the existing structures in the foreland.

The fourth section (Figure 2d; Reif et al., 2012; Frehner et al., 2012) was constructed by integrating geological maps, digital elevation models and bedding strike-dip data from the field (Bretis et al., 2011; Reif et al., 2011). The section is balanced (Frehner et al., 2012), but does not consider any pre-Jurassic strata, propagating all geometric and kinematic problems into the space underneath the shown section.

Despite the uncertainties of the sections, we can use the regional elevation of the pre-tectonic strata SW of the MFF and compare it to the elevation in the syncline NE of Bina Bawi. This gain in regional elevation is in the order of at least 2,500 m for Palaeocene to Jurassic levels and needs to be explained by a plausible cross-section.

**STRATIGRAPHY AND MECHANICAL STRATIGRAPHY**

The stratigraphy of the Cenozoic and Mesozoic is quite well known from regional outcrops and wells. The deepest well in our study area reached the Lower Triassic Beduh Shale Formation. In the study area in the KRI Palaeozoic strata has not been reached by wells to date and is known primarily from distant outcrops, mostly situated close to the Turkish border in the EW-trending Taurus Mountains (Al-Hadidy, 2007; Aqrawi et al., 2010). The stratigraphy used in this study was mainly adapted from OMV well reports, studies and as documented in Aqrawi et al., 2010 and references herein. Figure 3 shows an overview of the stratigraphy, known and expected, for KRI. The total thickness of the undeformed stratigraphic succession in the study area is in the order of 12 km. In addition, local to regional thickness variations of the adopted stratigraphy might have an influence on our results.

The stratigraphic column is characterised by several competent layers (mainly carbonates), interbedded with mechanically weak lithologies like shales and evaporitic deposits (mainly anhydrite). The weak layers can act as local or regional decollement horizons. Our assumed basal detachment is in the weakest formation overlying the basement. This might be Ordovician-aged shales (as tentatively indicated in Figure 3) or any other mechanically weak layer in the Lower Palaeozoic section. Apart from the Lower Fars detachment, it is unclear which of the horizons act as the main regional detachments (cf. Figure 3). This is especially true for the older part of the stratigraphic section.

The Lower Triassic to Palaeozoic rocks in our study area might be different to what is known from the distal outcrops in the northwestern Zagros. The mechanical stratigraphy of the study area plays a major role for the interpretation and cross-section construction as it has been shown by several authors that the different lithologies influence the style of folding (Sepehr et al., 2006; Vergés et al., 2011; Frehner et al., 2012). The competent layers also dominate the erosional pattern and thus the morphological expression of the folds at surface (Figure 4). The competent banks of Palaeogene Pila Spi and Khurmala formations build morphological ridges in the forelimb and at the lateral plunges of Bina Bawi Anticline. The cores of Bina Bawi and Safeen anticlines often follow the bedding of the Cretaceous carbonates (Figure 4).
### FIELD WORK

In order to assess the detailed structural architecture field work was carried out by OMV (unpublished OMV report: Structural Fieldwork Bina Bawi Anticline 2012). In their field trip, surface geological data and observations were collected and interpreted. Photographs taken in the field highlight the competent and less competent formations, and thus give indications about the mechanical stratigraphy (Figure 4b). Detailed outcrop investigations documented intraformational deformation.

In Figure 5a the Cretaceous Shiranish Formation shows buckling above an internal detachment fault. At a large scale, this behaviour would be recognised as layer-parallel shortening of the formation, as illustrated in the inset. Figure 5b shows an example of much stronger internal deformation in the Palaeocene Kolosh Formation. At the very least a lower and a roof detachment are required to explain the observed fold. On a larger scale, the fold would represent a thickening of the weak formation squeezed between competent carbonate beams, which build the large map-scale structure. Thus, the internal deformation and resulting thickness changes of the incompetent formations partly resolve the space problems of the large-scale structure.

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**Figure 3: Stratigraphic scheme for the study area compiled after Aqrawi et al. (2010), van Bellen et al. (2005-1959), Cohen et al. (2013), Zebari (2013) as well as OMV unpublished drilling reports.**

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- Sandstone / Conglomerate
- Shale
- Siltstone
- Limestone / Dolomite
- Evaporites
- Volcanics
- Major Detachment (Used)
- Minor Detachment (Used)
- Possible Detachment (Not Used)
Figure 4: Competent limestone formations dominate the large-scale morphological expression of the folded stratigraphy. (a) Oblique view of the Bina Bawi and Safeen anticline area in Google Earth with 2 times vertical exaggeration. Numbers indicate photograph positions or are discussed in the text.

(b) Field photograph showing details of large-scale fold expression marked for Eocene Khurmala Formation and Upper Cretaceous limestones in orange and green respectively. Photo taken from point 1 in (a).
Figure 5: (a) Uppermost Cretaceous Shiranish Formation showing flexural slip deformation with layer-parallel shortening, as illustrated in inset. Persons for scale. Location point 2 in Figure 4a.

Figure 5: (b) Complex deformation in incompetent shales of Palaeocene Kolosh Formation. Formation internal thrusting is accommodated by ductile deformation of the shales. A prominent fault-propagation fold is overlain by relatively flat strata, indicating the presence of a roof thrust. OMV geologist A. Rath for scale. Location point 3 in Figure 4a.
The geological attitude data, besides being used for constructing the cross-section (see below), can also be analysed to define the fold axis. It can be plotted on a tangent diagram to separate cylindrical from conical folds, and to characterise different types of plunging conical folds (Groshong, 2006). The analysis of the geological attitude data shows that the crest of the Bina Bawi Anticline plunges into different directions along strike indicating several segments (Figure 6). Individual segments show cylindrical to slightly conical fold shapes. Only very few slickenside data was collected. This data is from small-scale structures as documented in Figure 4, or from bedding planes of the larger-scale structure. The latter ones showing bedding-parallel slip is consistent with the observed folding. The amount of data did not permit a statistical analysis.

Figure 6: Fold axis plunge analysis on tangent diagrams for sectors A–F of the Bina Bawi Anticline, modified after unpublished OMV report: Structural Fieldwork Bina Bawi Anticline (2012). Results of field work plotted on a geological map of the study area, redrafted based mainly on GEOSURV (1997) with added bedding strike and dip from several field campaigns. Note: Analysis in Figure 6 A–F was done on uncorrected field measurements; after correction for the declination in KRI of about 5°, the best section orientation in the northern sector is SW-NE 47°. Bina Bawi fold plane orientation of Segment 1 is vertical, while in Segment 2 the surface dips ca. 70° towards SE.
CONSTRUCTION OF A PLAUSIBLE (SEMI-) BALANCED SECTION

The main objective in this study is to generate a cross-section for exploration purposes that is sufficiently accurate on a local scale (Bina Bawi Anticline), and that is consistent and plausible on a regional scale. We decided to construct the section in the NW-part of Bina Bawi Anticline because of the apparently greater structural complexity in this area compared to the central part of the anticline. In this part the Bina Bawi Anticline has an apparent hinterland vergency (i.e. the axial plane dips to the foreland) as seen in Figure 2d.

The well logs from the borehole, which is positioned on the section, indicate a twice-repeated section in the upper and in lower parts of the Kurra Chine Formation (Figure 7a). The amount of duplicated section is of the order of 100–150 m measured depth. The Kurra Chine Formation is generally considered as an incompetent stratigraphic layer and the repetitions reflect the presence of small-scale, sub-seismic duplexing/layer-parallel shortening caused by heterogeneous layering.

An apparent NE-dipping fault is imaged on seismic in the forelimb of our section (Figure 7b, point 4). It clearly offsets the top Jurassic reflector, but does not affect the top Eocene (Pila Spi Formation). There is a notable apparent thickness increase of Cretaceous–Palaeocene strata on the SW of the fault (Figure 7b, above upper arrow of point 4), similar to what is shown in the forelimb of Bina Bawi Anticline in Figure 2b. Because the thickness change occurs across the NE-dipping fault there are two possible explanations for this observation: the thickness increases due to: (1) growth strata in the footwall of a reverse fault (which seems implausible in Cretaceous–Palaeocene times); or (2) a structural thickening (consistent with our field observations for the mechanical behaviour of Shiranish to Kolosh formations).

Integration of Data and Section Location in the NW of Bina Bawi Anticline

The first important step for the construction of the section was the integration of all available measured data. For this purpose, we used the software MOVE (Midland Valley, 2013). In addition to the abundant field measurements of strike and dip of bedding planes, we integrated the geological map with a digital elevation model (SRTM data, Jarvis et al., 2008), well data (i.e. formation tops and dip-meter measurements), as well as depth-migrated 2-D seismic data (Figure 7b). For confidentiality reasons, it is not possible to show more details of well and seismic data than in Figure 7. Nevertheless, the Figure gives an impression of the quality of the data.

The seismic shown is a common reflection surface (CRS), depth-migrated 2-D seismic line. A relatively good seismic image is present in the foreland/foothills area and the southern limb of Bina Bawi Anticline, approximately down to Upper Triassic reflectors (ca. 5,500 m below surface). Below the Upper Triassic, the frequency and signal-to-noise ratio decreases and the image is rather poor. Due to near-surface karstification and rugged morphology in the area of the crest of the Bina Bawi Anticline the seismic signal is strongly attenuated and dispersed resulting in a very poor image over the anticlinal core.

The well displayed in Figure 7 has its total depth in the Triassic Kurra Chine Formation. Our working section is oriented SW-NE 47°, perpendicular to the fold axes (Figure 6, sector B) and crossing the well location. The seismic has been projected onto that plane (angle difference is 15°).

Solutions for some Detailed Problems in Section Construction

MOVE software helps to construct parallel folds with kink-bend geometries by displaying angle bisectors and parallel beds for a chosen template bed (Figure 7c). To use this method the thickness of the individual formations must be given. Of course, it is likely that minor variations of thicknesses exist. Therefore thicknesses were manually adapted where necessary, especially in the SW of the Bina Bawi Anticline, where a relatively good seismic image allows stratigraphic interpretation. However, the range of local thickness variations does not influence the large-scale structural interpretation of our section.
Figure 7: (a) Gamma-ray (GR) log from well highlighting two repeated sections in the Kurra Chine Formation (depth and API scale not shown for confidentiality reasons). (b) 3-D oblique view of data integration in MOVE software. Coloured arrows indicate approximate stratigraphic age of seismic reflectors: Neogene (yellow), Palaeogene (orange), Cretaceous (green), Jurassic (blue), Triassic (purple), undifferentiated Palaeozoic (brown). Numbers in the inset also refer to Figure 7c. (c) Construction of section for the NW section crossing the used Bina Bawi Well in MOVE section view.

Spatial integration of data (3-D oblique view)

1. Geological map and DEM
2. Dip and strike from outcrops
3. Dip and strike from well log measurements
4. Apparent fault on seismic depth section
5. Flat reflectors in Triassic to Palaeozoic
6. Interpreted continuous horizon used as template bed
7. Bisectors (red) used to guide horizon construction
8. Zone of intraformational thrusting
Figure 7c shows an intermediate construction step of the section. By using a template bed (top Jurassic) it is possible to obtain a parallel-fold geometry for the Miocene to Jurassic beds that fits the surface geology, the well data, and most of the seismic. The surface data constrain the hinterland vergent fold. However, the parallel-fold geometry observed in the upper part of the section cannot be applied to the Triassic section below. Dip data from the well indicate horizontal to partly slightly SW-dipping strata (Figure 7c). In contrast, the dip panels constructed from the surface and Jurassic down into the section would imply NE-dipping strata in the Triassic at the well location (Figure 7c). This mismatch can be solved by considering the observed repeat sections (Figure 7a).

By inserting two internal duplexes into the Kurra Chine Formation (Figure 7c, annotated with point 7) the thickening results in the required shift of the dip panel. As a result, a relatively horizontal dip domain evolved in the centre of the fold at base Kurra Chine/top Geli Khana (Figure 7c, lowermost, magenta horizon with stippled angle bisectors); dip domains in and underlying Kurra Chine Formation now fit to FMI-derived (Formation Micro-image) dip-data.

The next major question is how to continue the section into the lowermost Triassic and Palaeozoic succession, which is unknown/undrilled in the study area and is affected by a very poor seismic image. However, the deeper reflectors remain rather flat-lying instead of following the dip of the Mesozoic reflectors (Figure 7b, point 5 versus point 4). To approach this from a geometrical point of view, it seems reasonable to simplify the multiple dip domains constructed from surface outcrop measurements (i.e. all panels between the red bisectors in Figure 7c). Dip domains can reflect the amount of ramp sections in the subsurface (Figure 8c; Suppe, 1983).

Two reasonable assumptions are taken at this point:

1. The broad-scale structure is indeed related to ramp sections in the subsurface.
2. The multiple small dip domains as seen in Figure 7c are a result of small-scale deformation, camouflaging the first-order structure with less general dip domains.

Figure 8a shows the generalised first-order structure down to the base of the Middle Triassic (Geli Khana Formation), which one can construct as a simplified version. The gaps underneath the folds need to be filled, as marked by question marks. Assuming a relatively horizontal to slightly NE-dipping continuation of the regional elevation, we could project top basement and the speculative undeformed strata of Lower Triassic to Lower Palaeozoic underneath the folds. The total thickness of the assumed strata is in the order of 12 km, consistent with the literature considerations. Here, it is assumed, that the Cambrian–Ordovician coarse clastics have a high-friction contact to the basement and thus, that the first significant shale layer in the stratigraphic sequence will act as a main decollement (Figure 3). Two forward modelled duplex “horses” of Lower Triassic to Ordovician rocks, deformed in a forward-breaking sequence, fill the gaps underneath Bina Bawi and Safeen anticlines comfortably, with only minor misfits (Figure 8b).

Interestingly, the forelimb dip of the Bina Bawi Anticline of approximately 28° (Figure 8b, points 1) fits very well with the chosen ramp angle of 23° (Figure 8b, point 2; see Suppe, 1983, for angle relations from ramps and fold limbs). The back limb of the Safeen Anticline, showing ca. 33° dip in the simplified kink model (Figure 8b, point 3), shows some mismatch with the back limb of the second duplex. Indeed, in the duplex we are observing two dip domains, one with approximately 23° (Figure 8b, point 4) and a second one with approximately 45° (Figure 8b, point 5). Thus, our simplified model of Safeen Anticline is oversimplified because we roughly averaged the two dip domains \([23° + 45°)/2 = 34°\), which is close to the 33° initially constructed. Bedding dip data at the surface would actually allow the presence of two dip domains in the back limb of the Safeen Anticline as well. Thus, geometrically the solution with two in-sequence duplexes underneath Bina Bawi and Safeen anticlines is kinematically very reasonable for the folding of these anticlines. An additional duplex horse might fill the remaining gap at (Figure 8b, point 6).
Figure 8: Assessing the deeper structure of the Bina Bawi and Safeen anticline area. (a) Simplified structure in Neogene to Lower Triassic strata and hypothetical undeformed Lower Triassic to Basement. Red lines are angle bisectors. (b) Same as (a) but with two duplex horses in the Lower Triassic to Ordovician section. Numbers are discussed in the text. (c) Sketch of dip domains over ramps in the subsurface. Modified from Shaw et al. (2005).
If we add some additional observed and suspected deformation we converge on the (partly complex) structural architecture that we observe today (Figure 9a). This additional deformation is as follows.

- Intra-formational layer-parallel shortening for the weak horizons, as discussed above (Figure 9a, points 1).

- Post-folding shortening, manifested by structurally thickened Cretaceous and Lower Palaeogene in the forelimb of Bina Bawi Anticline (Figure 9a, point 2). For the apparent fault in the seismic several interpretations had been tested with forward modelling. The version shown in Figure 9a, linking a lowermost Palaeocene/uppermost Cretaceous (Kolosh/Tanjero) and a Palaeozoic detachment with limited amount of shortening, seems most plausible.

- Post-folding tightening of the Safeen Anticline is observed in the field by radial faults in outcrops of Cretaceous carbonates (Figure 4, at location point 4).

- Minor wrenching; some strike-slip deformation can be expected from the regional setting that would impose strain partitioning (Figure 1b). There are indications for some steep faults bordering or cross-cutting the Safeen Anticline, slightly offsetting the axial trend (Figure 4, location point 5). Dextral strike-slip faulting here seems likely, but the reference areas have not been visited in the field campaign to confirm this. For the final cross-section a slight movement with inclined shear was applied to the Safeen Anticline between two anticipated post-folding faults (stippled lines in Figure 9a, points 3). Due to the cross-cutting relationships these faults are considered to represent post-folding wrench faults, probably connecting to the deeper detachment system in order to accommodate a small part of the regional strain partitioning. The exact shape and position of these faults remain speculative based on the data present.

### Section Restoration and Balancing

Section restoration was done using the line length/template bed method (Woodward et al., 1987). This approach has been chosen because it is the easiest and quickest. The gross structure was constructed by the parallel-fold method and the major faults have been tested kinematically by forward modelling upfront. Nevertheless, that approach could hide or accumulate errors. This effect is considered of less importance here, as some degrees of freedom are still present and caused by unknown amounts of formation internal deformation (i.e. layer parallel shortening and ductile behaviour in the more incompetent beds), which can be best assessed by areal balancing.

The restored section (Figure 9b) shows a major discrepancy between shortening values in the upper sedimentary cover (Neogene to Lower Triassic) and the lower sedimentary succession (Lower Triassic and Palaeozoic). The upper succession is shortened approximately 4 km (approximately 16%, assessed on top Jurassic level between blue pins, Figure 9a, b). In contrast the lower sedimentary succession shows approximately 20 km of shortening (approximately 49%, assessed on Top Permian level between red pins, Figure 9a, b). The apparent mismatch between upper and lower succession requires a plausible explanation if the section is to be considered to be “balanced”.

There are several possibilities to explain the mismatch:

- the interpretation of duplexes in the core of the anticlines as an explanation for the structural uplift at the MFF is wrong. In that case we likely need to infer basement-involved structures.

- the “missing” shortening of the upper section is accommodated outside the studied cross-section area. In this case, the excess shortening of the lower section is transferred to the Lower Triassic detachment and about 16 km of shortening of the Neogene and Mesozoic section should be observable SW of Bina Bawi Anticline. The sketch in Figure 9c illustrates this concept and Figure 10a shows the presence of such anticipated folds in the foothills sector.
The second option, favouring duplex structures underneath the MFF and Bina Bawi rather than basement involvement, is regarded as our preferred, most plausible explanation for the section shown. The reasons are discussed in the next section.

DISCUSSION

With the detailed construction of the section through the northern Bina Bawi Anticline, we were able to integrate all observations, regional and local, into a consistent framework.
The upper stratigraphic section has been shortened by approximately 16%, which is of the same order as the result from Frehner et al. (2012), who calculated a mean value of 11% shortening on a nearby section. The small difference can likely be attributed to the position of the section and pins, details considered and drafting errors. The amount of shortening in the lower part of the section (49%) is a common value for strongly shortened areas of fold-and-thrust belts, and is thus assumed to be a realistic estimate.

Our framework assumes duplex structures of mainly Palaeozoic age in the core of the anticlines NE of the Mountain Front Flexure (MFF). Duplex structures can explain the rise in regional elevation across the MFF by thin-skinned structural thickening. Having only one detachment (e.g. at the base of the Triassic or Palaeozoic), the strata would return to regional elevation in the synclines between the anticlines.

Elsewhere, the gain of regional structural elevation across the MFF feature has been explained by basement involvement (Emami et al., 2010; Vergés et al., 2011), or by thin-skinned deformation including salt inflation (McQuarrie, 2004). The reference sections, however, are located further SE in the Lorestan Arc segment of the Zagros region (Figure 1b). This arc is a salient of the Zagros region where the MFF is situated close to the deformation front. The area behind the MFF is structurally uplifted to a more-or-less constant regional elevation. Basement involvement there might be a plausible explanation, as otherwise implausible amounts of salt might be required to explain the uplift. The area of our study is situated in the Kirkuk Embayment, where the thick Hormuz Salt is considered to be absent (Bahroudi and Koyi, 2003; Aqrawi et al., 2010).

Instead of having the weak decollement horizon at the base of the stratigraphic column (i.e. the Hormuz Salt) our study area is characterised by a mechanical layering of the stratigraphy comprising several detachment horizons with evaporites and shales (Figure 3). This presence of multiple stacked decollement horizons would favour duplex generation (Couzens-Schultz et al., 2003). Deformation would start on the weakest decollement that is linked to the already accreted wedge and subsequently step onto the other zones of weakness as shortening continues and the taper of the orogen builds up. Geometrically, the duplexes constructed underneath Bina Bawi and Safeen anticlines are linked to deformation structures in the foothills, thus representing an active-roof duplex following the definition in Couzens-Schultz et al. (2003).

Thus, the amount of shortening in the duplex structures should be balanced by the amount of convergent structures SW of the MFF. Without having the appropriate subsurface data of all structures in the foothills we can only estimate and discuss if a regional balance can reasonably be assumed.

A digital elevation model and geological maps prove the existence of several NW-trending folds towards the SW of the MFF (Figure 10a).

At least 4 to 5 apparent folds are in the line of section, additional folds might be buried. Depending on decollement levels, stratigraphic thicknesses and ramp angles, every fold in the foreland might accommodate shortening in the order of 3,000–5,000 m (roughly estimated from forward modelling).

Additionally, shortening can partly be accommodated by layer-parallel shortening and layer-parallel compaction. Layer-parallel compaction is generally low above ductile/weak decollements, but can still reach several percent in analogue models (Koyi et al., 2003). The distance from the MFF at Bina Bawi Anticline to the southwesternmost fold in the foothills is around 150 km. Assuming 2–5% layer parallel compaction this would correspond to 3,000–7,500 m of additional shortening taken-up along the section.

Shortening of these folds is likely to be linked to movements on Triassic and Palaeocene to Miocene detachments (for geometrical reasons likely Geli Khana, Kolosh and Lower Fars formations) as anticipated in the sketch in Figure 9c. Detailed structural examinations of these structures would be necessary (level of detachment and associated shortening values) to better constrain the regional
balance. At least for the Kirkuk-Hamrin subzone the long elongated fold-structures (Figure 10) are indeed described as thin-skinned structures (Aqrawi et al., 2010 and references herein). The anticlines in this area partly host large oilfields (e.g. Kirkuk Field). In contrast, the structural framework in the region north of the Hadar-Bekhme lineament, showing short en-echelon folds might likely be related to elements of thick-skinned inversion tectonics and/or strike-slip (Aqrawi et al., 2010). Thus, the
active roof duplex system underneath Bina Bawi Anticline is likely to be limited to the zone south of the Hadar-Bekhme lineament and thus might not play a major role in the EW-trending Taurus part of the Zagros.

Our interpretation of the active roof duplex with at least two active detachment horizons can be supported also by morphological indications.

For our study area the topographic slope from the mountains into the foreland displays a continuous wedge with two surface slope domains (Figure 10b). The wedge shape is dependent on the internal strength of the wedge and the strength of the decollement. Thus, we cannot unequivocally determine the strength of the detachment from the shape of the taper alone. However, if we consider that the material properties in the wedge do not change significantly, such changes of topographic slope can be interpreted as the result of different frictional properties of the basal detachment (Suppe, 2007). In this case the very "gentle" surface slope (α = ca. 0.3–0.4°, Figure 10b, orange slope) corresponds to a very low friction decollement (i.e. evaporites), while the "steeper" surface slope (α = ca. 2°, Figure 10b, green slope) corresponds to a decollement with some higher friction, in this case likely shale.

Assuming a basal detachment angle (β) of 1°–2° (from seismic) the wedge shape of the rear part of the wedge displays a shallow taper of α + β < 4°. Other subaerial fold-and-thrust belts with shale detachments show similar taper geometries. Taiwan (α + β = ca. 4.7°, Suppe, 2007), the Central Subandean Fold-Thrust belt (α + β = 2.5–3.5°, Oncken et al., 2012) and parts of the Alpine-Molasse detachment (various angles, generally increasing towards the hinterland, von Hagke et al., 2014) have very weak shale detachments that either can be explained by increasing pore pressure or by processes of strain weakening.

The interpretation of duplexes in the study area also aligns very well with the observed segmentation of the Bina Bawi Anticline fold crest (Figure 6), and the implied growth history of the fold (Bretis et al., 2011). Following their analysis, this segmentation is interpreted as a remnant structure from the process of fold linkage of former embryonic folds. The Bina Bawi-Permam and Safeen anticlines consist of 3 and 4 segments, respectively, with a length between 5 to 25 km. These segments linked up over time in a linear and en-echelon manner (Bretis et al., 2011). We speculate that the original perturbations that caused the embryonic folds to develop are linked to individual duplex horses evolving in the deeper subsurface, rather than to basement thrust units, which would likely cause larger primary fold segments. Whether linear or en-echelon fold linkage geometry is evolving is related to the position of the initial perturbations (Grasemann and Schmalholz, 2012), hence the size and position of the initially growing duplexes.

Such lateral linking of duplexes is strongly supported by observations from the surface geological map. At the location point 1 in Figure 10a the fold axis of Bina Bawi-Permam and Safeen anticlines plunge underneath the Neogene and Quaternary sediments. This observation can best be explained by lateral ramps/lateral terminations of duplexes in the subsurface. It is remarkable that at location point 2 the regional elevation of the Mesozoic returns to the level of the foothills. This can be best be explained by a long flat section in a duplex horse in the subsurface (i.e. a thin-skinned explanation). If a large basement-involved thrust was the cause of the MFF in the study area (thick-skinned explanation), it would have uplifted also the area underneath point 2.

For all the reasons discussed, it seems most plausible that duplex structures are present underneath Bina Bawi and Safeen anticlines. However, as in most thrust belts, towards the hinterland there will be a transition to basement-involved thrusting at a certain point. The repeated rise of the regional elevation of the Mesozoic strata towards the Main Zagros Fault (MZF) creates a continuously larger cross-sectional area that needs to be filled. This could be achieved by more or thicker duplexes, or by a thicker duplex that contains basement rocks. A basement-involved duplex horse has been drafted in the rear part of the regional sketch section of Figure 9c. The frontal tip of this basement slice approximately corresponds to the northward projection of the High Zagros Fault (HZF; cf. Sepehr and Cosgrove, 2004), which is not a distinct fault in this part of the Zagros anymore.
Jurassic rocks crop out at elevations higher than at the Bina Bawi and Safeen anticlines, marking another rise in structural elevation. Nevertheless, it remains quite speculative if this transition to basement involvement is located at this position, or possibly further east underneath the Main Zagros Fault (MZF).

Besides a likely transition to basement-involved thrusting, we expect right-lateral wrenching towards the hinterland as a result of strain partitioning caused by oblique convergence in this part of the Zagros region. Some amount of wrenching has already been added to Safeen Anticline (Figure 9a) in line with the observed step of the fold hinge as indicated in Figure 4a (point 5).

However, this step could also be caused by en-echelon linkage of early folds as proposed by Bretis et al. (2011) and discussed above for the along-strike segmentation of Bina Bawi anticline. Nevertheless, right-lateral, strike-slip faults have been proposed for the area towards the hinterland of Safeen Anticline by Csontos et al. (2012). Regional strain partitioning is also evident by right-lateral deformation along the Main Recent Fault (Talebian and Jackson, 2002), which is interpreted as a sub-vertical splay of the Main Zagros Fault (Vergés et al., 2011).

Csontos et al. (2012) discussed several alternative structural models for the Taurus trend and the bend towards the Zagros trend (Figure 1b; for details of the different models see discussion in Csontos et al., 2012). In one of their models they suggest left-lateral, strike-slip faulting in the foothills north of our study zone. We consider that these faults might be restricted to the Mosul-Buthma subzone. In that region the strong morpho-tectonic appearance of the Hadar-Bekhme Lineament clearly separates different structural styles in the foothills area, as evident from morphology and geological map (Figure 10a).

On a local scale we generated a model, that is consistent and plausible and that can be tested by wells and then possibly verified or modified. Potential trapping geometries can be assumed in Lower Triassic and Palaeozoic rocks. Due to the incipient disharmonic folding, fold (and thus trap) apexes might not necessarily be stacked underneath the axial plane of the outcrops. Any wells targeting for deeper traps would need to take this into account.

CONCLUSIONS

Until now, the deeper (Lower Triassic to Palaeozoic) structural architecture in the Bina Bawi region was unknown, mainly because of poor seismic imaging. With an integrated approach, combining field work, the analysis of geological maps, regional literature study and analysis of subsurface data (seismic and wells) covering the Neogene to Triassic section, it is possible to constrain a balanced cross-section that includes the Palaeozoic section.

For the Bina Bawi Anticline this study predicts duplexes comprising Triassic and Palaeozoic rocks in the deeper subsurface. Slight disharmonic folding was observed. Due to decollement on evaporitic layers and thickening of incompetent strata (layer parallel shortening) the duplex crest might be slightly offset compared to the Mesozoic anticlinal crest (incipient disharmonic folding), an observation that has to be taken into account if exploring for deeper targets. The deformation with duplexes causes an imbalance of shortening in a section on a local scale. In fact, regionally the related shortening is horizontally partitioned. While most of the shortening in the lower stratigraphic section is accommodated in the duplexes underneath the morphological Zagros Mountains of KRI, shortening of the Mesozoic to Neogene section is transferred into the Foothills Zone on Triassic evaporitic and possibly younger detachments.

Elsewhere (i.e. Lorestan Arc) it has been shown that the MFF is likely to be related to basement involvement (e.g. Vergés et al., 2011). For the part of the Kirkuk Embayment studied here, it can be concluded that active roof duplexes related to a step-up from a deeper Palaeozoic decollement horizon to a higher Mesozoic decollement are the cause of structural uplift at the MFF. Thus, the structural uplift along the MFF in the different segments along-strike the Zagros trend (Figure 1b), is very likely caused by varying structural architectures.
Regional differences in the mechanical stratigraphy and structural inheritance are the most likely causes for the different structural configurations in these segments. Palaeogeographic and palaeogeological parameters thus are the most important controls on the thrust-belt architecture.

The integration of regional observations and realistic assumptions (like mechanical stratigraphy) in the construction of a local cross-section helps to increase our understanding of how structures most likely have formed; a knowledge that might be vital for exploration success on deeper targets.

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