Quantifying vertical movements in fold and thrust belts: subsidence, uplift and erosion in Kurdistan, northern Iraq

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Abstract: Traditional structural analysis in fold and thrust belts has focused on quantifying horizontal movements. In this paper, the importance of quantifying vertical movements is illustrated using a case study from Kurdistan, northern Iraq. The subsidence history of this area can be determined by analysis of the stratigraphic record from deep exploration wells. A phase of thermal subsidence from Middle Permian to Late Cretaceous (tectonic subsidence 1.8–1.9 km) was followed by flexural subsidence in the Late Cretaceous and Cenozoic (tectonic subsidence >0.6 km) in response to the closure of the Neo-Tethys Ocean. The main phase of continental collision during the Neogene resulted in the development of the Zagros fold and thrust belt; the amount of uplift at individual anticlines can be estimated from their amplitude (up to 3 km), but regional cross-sections indicate that approximately 1 km of additional basement-involved uplift is present NE of the Mountain Front. The timing of basement-involved uplift is interpreted to be coeval with the deposition of a Pliocene–Quaternary growth sequence adjacent to the Mountain Front. The amount of erosion resulting from the uplift can be estimated from vitrinite reflectance and cross-sections; these estimates show a similar pattern, with maximum erosion in the mountains NE of the Mountain Front (>1.5 km) and lesser erosion in the adjacent foreland basin (generally <0.8 km). The results provide a quantitative understanding of subsidence, uplift and erosion, and have been used to define prospective and high-risk areas for petroleum exploration.

Structural studies in fold and thrust belts have traditionally focused on quantifying horizontal movements, beginning more than a century ago with the concept of line-length cross-section restoration (Busitosf 1916; analysis by Ramsay & Huber 1987). Since then, geological cross-sections have been widely used in fold and thrust belts to understand not only variations in longitudinal strain, but also palaeogeography, depth to detachment and plate reconstruction (Dahlstrom 1969; Hossack 1979; Munoz 1992). The corresponding vertical movements have received lesser attention but are arguably more important for petroleum geology. This is because of their impact on every element of the petroleum system, from source maturity and reservoir quality, to seal integrity and trap preservation. In this study established methods have been used in order to quantify subsidence, uplift and erosion in Kurdistan, northern Iraq. The techniques are analysis of well data (subsidence), changes in structural elevation (uplift) and vitrinite reflectance (erosion). Other methods are also available, but the advantage of these techniques is that they can be applied to surface and subsurface data which are readily available, even in areas of frontier exploration.

Background
Permian rifting along the northern margin of the Arabian Plate was followed by the opening of the Neo-Tethys Ocean starting in the late Early Permian (Stampfl & Borel 2002; Aqrawi et al. 2010). Thermal subsidence of the adjacent passive margin is indicated by the stratigraphic record in Kurdistan (this paper), but additional subsidence due to local rifting events is also known to have continued during the Mesozoic (Frizon de Lamotte et al. 2011). Sediment accumulation was dominated by carbonates and evaporites as the Arabian Plate moved into higher latitudes from the Permian to the Late Cretaceous (Sharland et al. 2001). The earliest evidence for the subsequent closure of the Neo-Tethys Ocean is provided by ophiolites that were obducted onto the Arabian Plate from Turkey to Oman during the late Campanian–early Maastrichtian, and the development of an incipient foreland basin (Aqrawi et al. 2010). Continued closure of the Neo-Tethys Ocean was accommodated by subduction towards the NE during the Paleogene (Frizon de Lamotte et al. 2011), followed by the main phase of continental collision and development of the Zagros Fold Belt.
during the Neogene (from c. 20 Ma). For at least the past 5 myr, north–south convergence between the Arabian Plate and Eurasia has been oblique to the NW–SE trend of the original passive margin; the strain associated with this convergence has been partitioned into a component of compression perpendicular to the inherited structures, and a component of dextral strike along the plate boundary (Blanc et al. 2003). Active compression continues today, as indicated by earthquakes (Dziewonski et al. 1981; Ekström et al. 2012), GPS measurements (see Le Pichon & Kreemer 2010 for a review) and unpublished borehole data (breakout and minimum stress measurements).

The Zagros Fold Belt has a long history of exploration, and is believed to contain almost half of the hydrocarbon reserves in global fold and thrust belts (Cooper 2007). The first well to be drilled in the Middle East was at Chia Surkh (SE Kurdistan) in 1902; this was followed by the discovery of the super-giant Kirkuk oilfield in 1927. Multiple oilfields were discovered in the fold belt and across Iraq in the following 50 years (Agrawi et al. 2010). Exploration in Kurdistan was suspended during the Iran–Iraq War (1980–88), the Gulf War (1990–91) and the Iraq Conflict (commencing in 2003), but re-started in 2004 with the re-entry of international oil companies. Since then, more than 10 new fields with more than 100 million barrels of recoverable oil each have been discovered; the most recent available production data for Kurdistan (Ministry of Natural Resources 2016) show an average production of more than 600 000 barrels of oil per day.

Structural domains in Kurdistan

Numerous legacy maps exist for the structural domains of Kurdistan (e.g. Jassim & Goff 2006; Agrawi et al. 2010). As part of this study these zones and their boundaries were refined using recent digital surface geological maps of the area (CGG NPA 2011; Geospatial Research 2016), combined with regional cross-sections which were used to integrate all of the available surface and subsurface data; one of these cross-sections is described in the section on ‘Uplift: regional cross-section’ later in this paper, where the timing of deformation in each domain is also addressed. The revised structural domains, their boundaries and the location of the cross-section are shown in Figure 1.

The Main Boundary Thrust of previous authors can be defined along the SW margin of allochthonous units; this line is a major thrust and represents the suture zone along the margin of northern Arabia. This fault separates the Allochthonous Zone to the NE from the Imbricatied Zone to the SW, where the Arabian passive margin has been most intensely deformed. The Imbricated Zone is partly concealed beneath the overlying allochthonous units in much of Kurdistan, but in SE Turkey it is fully exposed.

To the SW of the Imbricated Zone lies the Uplifted Folded Zone (the High Folded Zone of previous authors), where Mesozoic stratigraphy is exposed in the cores of anticlines and Cenozoic stratigraphy is preserved only in the adjacent synclines. The SW boundary of this zone is the Mountain Front, which is expressed as a foreland-dipping monocline at surface for most of its length (and not a fault; see Vann et al. 1986). The Mountain Front is defined where Eocene limestone is exposed (top of the Pila Spi Formation); this line marks an important change in structural and topographic elevation. From regional cross-sections, the Mountain Front is interpreted to represent the surface expression of several major blind thrusts along its length in the subsurface.

The Mountain Front separates the Uplifted Folded Zone from the Foreland Folded Zone (the Low Folded Zone or Simple Folded Belt of previous authors) to the SW, where the lesser amount of uplift is demonstrated by surface exposure of almost exclusively Neogene stratigraphy that was deposited in a flexural foreland basin. The limit of compressional deformation in northern Iraq is defined by a line drawn along the SW margins of the Adaiyah, Makhul and Hamrin anticlines. This line separates the area of the foreland basin that has experienced significant compressional deformation, and where the crests of anticlines are exposed at the surface, from the relatively undeformed Mesopotamian foreland basin. There is an abrupt and corresponding change in seismic activity across this line that separates these two domains (e.g. Dziewonski et al. 1981; Ekström et al. 2012).

The key difference between the legacy and revised structural domains is recognition that the Tawke oilfield lies in the Foreland Folded Zone rather than the Uplifted Folded Zone (Fig. 1). The Tawke depocentre lies within a re-entrant in the Mountain Front which is interpreted to represent a major relay zone in the underlying blind thrust system.

Subsidence

1D subsidence analysis (‘backstripping’) is a standard technique for understanding basin history (Steckler & Watts 1978; Allen & Allen 2005). The stratigraphy and estimated palaeobathymetry from a well are converted to tectonic subsidence, also known as water-loaded subsidence. This has two advantages. First, the subsidence history of wells in the same area with different depositional environments and palaeobathymetric records can then be compared with these effects removed. Second, the
Fig. 1. Structural elements and domains in the study area of northern Iraq. The locations of the wells used for subsidence analysis, the line of cross-section used to estimate uplift, and the locations of well and outcrop data used to estimate erosion are indicated. Selected oilfields mentioned in the text are also shown together with unsuccessful exploration wells in the NE segment of the Uplifted Folded Zone. Abbreviations: EST, East Swara Tika oilfield; BS-1, Binari Serwan-1 exploration well; MBT, Main Boundary Thrust; LA, Lurestan Arc; ZA, GA, AA, MA and HA denote the Zap, Gara, Adaiyah, Makhul and Hamrin anticlines.
subsidence history can be compared to reference water-loaded subsidence models: for example, to determine the amount and timing of lithosphere stretching.

The Jabal Kand-1 exploration well in northern Iraq (Fig. 1) was drilled by the Iraqi National Oil Company in 1981–82 to a total depth of 5848 m. Non-commercial oil shows were encountered in the Triassic Kurra Chine and Geli Khana formations. The stratigraphic record for this well is available in the public domain (fig. 8 of Kent 2010); the ages of the lithostratigraphic units were taken from van Bellen et al. (1959) and Agrawi et al. (2010), calibrated to the timescale of Gradstein et al. (2012).

Jabal Kand-1 is ideal for subsidence analysis for four reasons. First, the well is exceptionally deep and provides a complete stratigraphic record from (a) Paleozoic pre-rift (Lower Carboniferous Harur Formation) to (b) Permian and Mesozoic post-rift and (c) younger foreland basin stratigraphy (Agrawi et al. 2010; Kent 2010) (Fig. 2); the absence of syn-rift stratigraphy is addressed in the discussion. Second, the well is located in a benign structural location; the well does not intersect any major faults and the angle of structural dip is low (fig. 19d of Kent 2010). Third, vitrinite reflectance data are available for this well (Jabbar 2010) and have been used to estimate almost 1300 m of erosion at the well location (the method for this is described in the section on ‘Erosion’ later in this paper). Fourth, the density log for this well covers the depth range 100–4730 m (+300 to −4330 m elevation relative to sea level). In order to represent correctly the mass of the lithosphere (McKenzie 1978) can be fitted to the tectonic subsidence points because the reference model provides a good fit to the tectonic subsidence points. Subsequent tectonic subsidence during flexural loading was 0.6 km at the well location; this value is expected to vary significantly across the region depending on the proximity to the zone of maximum flexural subsidence.

The tectonic subsidence at the well location has a negative-exponential profile from the Middle Permian to Late Cretaceous (Fig. 3). A reference model for post-rift thermal subsidence following stretching of the lithosphere (McKenzie 1978) can be fitted to the tectonic subsidence points during this period, assuming Airy (1855) isostasy and a standard lithosphere thickness of 125 km (Sclater & Christie 1980). A moderate lithosphere stretching factor (1.84) can be estimated in this way. The fit of the thermal subsidence model to the tectonic subsidence points provides confidence in the technique, the selected parameters and the estimated palaeobathymetry. For most of the subsidence history the basin was filled close to sea level; the maximum palaeobathymetry that was achieved at the well location was 40 m during deposition of prolific source rocks during the Middle and Late Jurassic (Sargelu and Naokelikan formations: Pitman et al. 2004; Agrawi & Badics 2015). This water depth is consistent with deposition of these formations in an intra-shelf basin, adjacent to a shallow-water carbonate platform (Najmah Formation: Agrawi et al. 2010).

From 69 Ma, the subsidence profile at the well location deviates significantly from the reference model for thermal subsidence. This is interpreted to mark the onset of flexural subsidence, coeval with development of an incipient marine foredeep basin in the Late Cretaceous (Shiranish Formation). Maximum subsidence was achieved during the Pliocene; by this time sediment supply had caught up with accommodation and the foreland basin was filled by fluvial sediments (Bakhtiari Formation). However, subsequent uplift and erosion at the well location has almost entirely removed the youngest stratigraphy; the amount of erosion has been estimated using vitrinite reflectance (the method for this is described in the section on ‘Erosion’ later in this paper).

The vertical movements during each of these tectonic phases can be quantified from the subsidence analysis. Tectonic subsidence during thermal subsidence at the well location was 1.8 km; this can be determined with confidence because the reference model provides a good fit to the tectonic subsidence points. Subsequent tectonic subsidence during flexural loading was 0.6 km at the well location; this value is expected to vary significantly across the region depending on the proximity to the zone of maximum flexural subsidence.

The pattern of thermal subsidence followed by flexural subsidence can also be identified in a number of other deep exploration wells in northern Iraq; two of these are shown in Figure 4. Compared to Jabal Kand-1, the two additional wells are less ideal for analysis. The Middle Triassic and older stratigraphy (Geli Khana, Beduh Shale, Mirga Mir and Chia Zairi formations) is not penetrated in either well and is by necessity taken from Jabal Kand-1. In addition, vitrinite reflectance data are not available for Well-2, and therefore the amount of erosion has been estimated using data from an adjacent outcrop along strike. Well-3 is a composite well which combines Neogene and Oligocene stratigraphy from a well in the foreland with Eocene and older stratigraphy from an immediately adjacent well where uplift and erosion are greater (Fig. 2); this is consistent with the erosion estimates and density logs for both wells. Despite these limitations, the same pattern of thermal subsidence can be recognized at the locations of Well-2...
Fig. 2. Simplified chronostratigraphy for the study area. (a) Paleozoic stratigraphy of the Zap Anticline in SE Turkey from Janvier et al. (1984). (b) Stratigraphy of NW Kurdistan from Jabal Kand-1. (c) Mesozoic and Cenozoic stratigraphy of SE Kurdistan from Well-3. Formation ages are from van Bellen et al. (1959) and Aqrawi et al. (2010), calibrated to the timescale of Gradstein et al. (2012).
and Well-3 (tectonic subsidence 1.9 km at both wells). However, in SE Kurdistan, the tectonic subsidence during the flexural phase at Well-3, more than 1.2 km, is significantly greater than observed at the other two wells in NW Kurdistan.

Uplift: regional cross-section

A key geological observation in the Zagros Fold Belt is that there are significant changes in structural elevation, although major (>1 km displacement) emergent thrusts are not present SW of the Imbricated Zone. For example, the Mountain Front marks a major change in topographic and structural elevation, yet it is expressed at the surface as an un faulted foreland-dipping flexure. The end-member models that have been proposed to explain this apparent paradox are: (1) thin-skinned interpretations in which elevated structures are cored by imbricates above a planar basement surface (e.g. Hayward & Schelling 2014; Hinsch & Bretis 2015); and (2) thick-skinned interpretations in which deeper stratigraphy and/or the basement are also involved in the deformation (e.g. Blanc et al. 2003; Vergés et al. 2011). The fact that such contrasting models have been proposed for the fold belt gives an indication of the relatively limited availability of subsurface data in the area; for this reason it is more appropriate to describe the published cross-sections as ‘restorable’ because a truly ‘balanced’ cross-section through this area would have more limited room for alternative interpretation (Elliott 1983). In addition to the existing terminology, we propose the discrimination between ‘geometric restoration’ and ‘kinematic restoration’. In a geometric restoration the constituent structures can be fitted back together, whereas a kinematic restoration also provides an explanation for both the horizontal and vertical movements that occurred between the restored and deformed states.

The cross-section used in this study is shown in Figure 5. It was built to provide regional context for licence-scale activities to the north of the Mountain Front, but it can also be used to evaluate uplift and estimate erosion. The cross-section runs through northern Iraq (including the Kurdistan Region of Iraq) and SE Turkey, and has a total length of 240 km. The surface geology is constrained by

![Fig. 3. Subsidence analysis for the Jabal Kand-1 well. The total subsidence (yellow points) and palaeobathymetry (blue points) have been converted to tectonic (‘water-loaded’) subsidence (red points) using compaction parameters determined for each interval. Starting at 272 Ma, the tectonic subsidence for the well has a negative exponential profile. A reference model for post-rift thermal subsidence following lithosphere stretching (McKenzie 1978) can be fitted to the tectonic subsidence profile from this time; the best-fit stretching factor is 1.84. From 69 Ma, the subsidence profile at the well location deviates from the reference model for thermal subsidence; this is interpreted to mark the onset of flexural subsidence. Subsequent uplift and erosion at the well location has almost entirely removed the youngest stratigraphy; the amount of erosion has been estimated using vitrinite reflectance. The vertical movements are: tectonic subsidence during thermal subsidence 1790 m; tectonic subsidence during flexural loading 620 m.](image-url)
Subsidence analyses for two additional wells. The vertical movements at Well-2 in NW Kurdistan are: thermal subsidence 1920 m; flexural subsidence 540 m. The vertical movements at Well-3 in SE Kurdistan are: thermal subsidence 1940 m; flexural subsidence 1220 m. The analysis indicates that lithosphere stretching was quite similar at both locations (1.90 and 1.92, respectively). The onset of flexural subsidence is interpreted to have occurred slightly earlier in SE Kurdistan (72 Ma) compared to NW Kurdistan (69 Ma).
Fig. 5. Present-day regional cross-section through Northern Iraq and SE Turkey (top), and restorations at approximately 4 Ma (centre) and 69 Ma (bottom). The compressional structures form a kinematically closed system with displacement along the northern and southern crustal ramps transferred into the sedimentary cover. Only limited displacement is evident along exposed thrusts. Anticlines mentioned in the text are named according to their well penetrations. Additional anticlines are: BA, Baeshiqa Anticline; SA, Simrit Anticline; MA, Mateen Anticlines; KA, Karsani Anticline; ZA, Zap Anticline. Other abbreviations: EST, East Swara Tika; FZ, Foreland Zone.
digital compilations of field and satellite geological mapping by CGG NPA (2011) and Geospatial Research (2016). Below this, the stratigraphy is calibrated by four exploration wells (Table 1), including proprietary stratigraphic and dip data for the East Swara Tika-1 and Gara-1 wells in the Uplifted Folded Zone. The position of an additional four wells is also shown for illustration (no data were available for these wells).

Within Kurdistan, four 2D seismic reflection profiles were used to complete the cross-section at depth. To the south of the Mountain Front, a single 2D seismic profile in time is available across the Maqlub Anticline (12 km: Afren 2011); this line was tied to outcrop data and was depth stretched to match adjacent well data. To the north of this, two good-quality 2D seismic profiles are available in depth covering the Shaiakan Anticline (10 km: Gulf Keystone 2013) and the Atrush Anticline (9 km: Shamaran 2010); the geometry of these structures is well resolved down to the top of the Triassic. Further north, one proprietary 2D seismic profile is available across the East Swara Tika and Gara anticlines (18 km; pre-stack depth-migrated data). This line provides a good image of the limb and syncline on the north side of Atrush, and the synclines between East Swara Tika and the Gara anticline. However, the image of the Gara Anticline is poor, and the geometry of this structure is instead constrained by outcrop data and the Gara-1 well (formation tops and dipmeter data) 7.2 km to the west. The topographic profile is interpolated from NASA (2000), and the cross-section has been completed at depth using a global grid of Moho depth (Laske et al. 2014) which is derived from gravity modelling.

The anticlines within the Uplifted Folded Zone and the Foreland Folded Zone are interpreted to be detached along the Lower Triassic Beduh Shale Formation. This interpretation is based on: (1) dipmeter data from the Gara-1 well where the underlying Lower Triassic (Mirga Mir Formation) and Paleozoic stratigraphy dip uniformly at 20° towards the SW; and (2) core dip data from the Atshan-1 well showing that the Mirga Mir and Chia Zairi formations are subhorizontal, whereas the overlying formations are inclined (by up to 11° in the Butmeh Formation). Based on experience from the East Swara Tika-1Z and Tika-1Y wells, distributed strain within the anticline cores above the Beduh detachment is interpreted to be accommodated within interbedded dolomite and anhydrite of the Upper Triassic Kurra Chine Formation and the Middle Triassic Geli Khana Formation. Along the southern edge of the Foreland Folded Zone, the anticlines penetrated by Adaiyah-1 and Atshan-1 are interpreted as detachment folds. However, the deep structure of these folds is unknown to the authors because no seismic profiles were available in this area; an alternative interpretation is that they are inversion structures (the hypothesis of Kent 2010).

The structure within the Imbricated Zone is constrained only by outcrop data; Mesozoic and Paleozoic stratigraphy are exposed in the Karsani and Zap anticlines (Figs 2 & 5) down to the Lower Cambrian (Sadran Quartzites) in the core of the Zap Anticline (Janvier et al. 1984). These structures are interpreted to be detached within the Precambrian basement (Zap Anticline) or along the base of the Cambrian (Karsani Anticline) based on the units that are exposed in the cores of these anticlines. No information was available regarding the geometry of structures in the Allochthonous Zone.

Beneath the limit of control from seismic profiles and well data, the structural interpretation is strongly model driven. In our interpretation the deformation and uplift of the sedimentary cover was driven by displacement along high-angle crustal-scale ramps detached along the Moho. This choice of detachment depth is consistent with deep seismic reflection profiles from other orogens (e.g. Duff 1993, p. 769; Steer et al. 1998) and studies of earthquake data showing that the full thickness of the crust can be seismogenic (Jackson et al. 2008), but the involvement of the upper mantle in deformation (e.g. Butler et al. 2004) is not ruled out. The deep and shallow structures form a kinematically closed system in which displacement is transferred from the crustal ramps into the sedimentary cover. This interpretation provides an explanation for the major changes in structural elevation without the requirement for major emergent thrusts (which, as discussed, are not observed at the surface). In NW Kurdistan, the Foreland Folded Zone plunges westwards beneath the Foreland Zone (Fig. 1). If the anticlines were duplex-cored (high-displacement, thin-skinned model: e.g. Hinsch & Bretis 2015) and not basement-cored (low-displacement, thick-skinned model: this study) then all of the additional displacement would have to die out along strike. This argument is well rehearsed (e.g. Coward 1996, p. 72). Hinsch & Bretis (2015) correctly noted the possibility that ‘the interpretation of duplexes in the core of the anticlines as an explanation for the structural uplift… is wrong. In that case… basement-involved structures [are inferred]’.

The sequence of deformation can be estimated from the stratigraphic relationships along the cross-section. In southern Turkey, the structures in the Imbricated Zone may have developed at some time in the Paleogene based on an unconformity between Eocene (Hoya Formation) and Cretaceous (or older) stratigraphy (CGG NPA 2011). Along strike to the SE in Kurdistan, a younger overstep relationship can be observed in the Imbricated Zone between Miocene (Suwais Formation) and Cretaceous stratigraphy (CGG NPA 2011). Subsequent displacement along the northern crustal ramp resulted in the
Table 1. Wells shown along the regional cross-section (Fig. 5)

| Well                          | Adaiyah-1/Mityaha-1/Khleisia-1 | Atshan-1 | Maqlub-1 | Shaikan-6 | Atrush-3 | East Swara Tika-1Z, 1Y | Gara-1 and Gara-1Z | Cepkenli-1A (SE Turkey) |
|-------------------------------|--------------------------------|----------|----------|-----------|----------|----------------------|-------------------|------------------------|
| Start of drilling operations | 1936/1978/1958                 | 1954     | 2013     | 2011      | 2013     | 2013 and 2015         | 2012              | 1982                   |
| Structural domain             | Foreland Folded Zone           | Foreland Folded Zone | Foreland Folded Zone | Uplifted Folded Zone | Uplifted Folded Zone | Uplifted Folded Zone | Uplifted Folded Zone | Allochthonous Zone     |
| Datum elevation (m above sea level) | 380                           | 457      | 460      | 525       | 990      | 1323                 | 1250              | 2650                   |
| Total depth (m below datum)   | 5232                           | 3448     | 4540     | 3545      | 1806     | 4035                 | 3847              | 4021                   |
| Formation (age) at total depth| Khabour (Ordovician)           | Chai Zairi (Permian) | n/a      | n/a       | n/a      | Geli Khana (Triassic) | Khabour (Ordovician) | n/a                    |
| Data                          | Formation tops                 | Formation tops | None (location only) | None (location only) | None (location only) | Formation tops and dipmeter data | Formation tops and dipmeter data | None (location only) |
| Source(s)                     | van Bellen et al. (1959); Al-Sheikhly (1980); Jassim & Goff (2006); Aqrawi et al. (2010) | Jassim & Goff (2006); Aqrawi et al. (2010) | n/a      | n/a       | n/a      | Proprietary           | Proprietary         | n/a                    |
| Comments                      | Pre-Jurassic stratigraphy from Mityaha-1 and Khleisia-1 | Deviated well | Deviated well |           |           |                      |                   |                        |

The wells are listed from south (left) to north (right). At the Adaiyah-1 well location, the thickness of Triassic and older stratigraphy is taken from the Mityaha-1 and Khleisia-1 wells in the Foreland Zone, which are 70 and 140 km further SW, respectively.
development of the anticlines in the Uplifted Folded Zone; these structures are interpreted to have developed in post-Miocene time based on the observation that the Miocene stratigraphy (Fars Formation) is the youngest isopachous unit in this area where it is preserved in synclines. Following this, displacement along the southern crustal ramp resulted in uplift of these anticlines and the development of the Shaikan Antcline and structures of the Foreland Folded Zone to the south. The timing of this event can be dated with greater confidence based on the presence of a Pliocene–Quaternary growth sequence that is present on the south side of the Shaikan Antcline (seismic profile of Gulf Keystone 2013 tied to surface geological mapping by CGG NPA 2011). Below this growth sequence the underlying Lower Pliocene stratigraphy (Bakhtiari Formation) is isopachous and predates development of the Shaikan Antcline; the same isopachous unit is observed in central Kurdistan across the Taq Taq Antcline (Garland et al. 2010). Therefore, the timing of movement along the southern crustal ramp is interpreted to have occurred during the Late Pliocene and Quaternary: that is, in approximately the last 3.6 Ma.

Horizontal movements have been quantified by restoration of the cross-section (Fig. 5). The line of section has been constructed to follow the best available data, and therefore the assumption of plane strain (Dahlstrom 1969; Hossack 1979) is only approximately true. The shortening can be divided into the ‘internal’ structures to the northern end of the cross-section (Mateen Anticlines and Imbricated Zone) and the structures that developed in response to movement on each crustal ramp to the south of this. The division in this way shows a progressive decrease in longitudinal strain, \( e \), from 0.30 (23.4 km) in the north to 0.11 (3.6 km) and finally 0.06 (7.0 km) in the south. The total shortening estimated from restoration of the cross-section is 34.0 km (\( e = 0.14 \)) from the southern edge of the Foreland Folded Zone to the northern edge of the Imbricated Zone.

**Uplift: quantification**

The amount of uplift at the crest of individual anticlines can be quantified by constructing a structural datum connecting the same horizon in the adjacent synclines. The elevation of the same horizon at the crest of the anticline measured from this datum provides an estimate of the apparent uplift. However, this method can only be used in the Foreland Folded Zone due to the additional basement-involved uplift to the north of the Mountain Front. Within the Uplifted Folded Zone to the north of this line it is therefore necessary to use a structural datum at the depth of maximum burial; along the regional cross-section it is estimated that this datum is represented by an approximately horizontal line constructed from the depth of the horizon of interest at the base of the syncline to the south of the Mountain Front (on the south side of the Shaikan Antcline). The two structural datums are illustrated in Figure 6.

Using the Gara Antcline as an example, the apparent uplift of the top Jurassic horizon is 3.0 km measured from the local datum (−1.0 km elevation) to the crest of the reconstructed anticline (+2.0 km elevation), whereas the gross uplift measured from the structural datum at the base of the syncline to the south of the Mountain Front (−3.1 km elevation) is 5.1 km. However, in order to calculate the net uplift due to basement involvement, an allowance must be made for the thickness of Neogene stratigraphy that was never deposited over the Gara Antcline. The Miocene stratigraphy (Fars Formation) is the youngest isopachous unit that is preserved in the synclines either side of the Gara Antcline, and we can be confident that the Pliocene–Quaternary growth sequence (maximum thickness 760 m) was only deposited to the south of the Mountain Front (Fig. 6). The original presence or absence of the intervening Pliocene stratigraphy (Bakhtiari Formation) across the Gara Antcline is uncertain; Figure 5 (centre) shows one possible interpretation in which the Pliocene stratigraphy partially covered this area. Therefore, the thickness of this unit where it is preserved on the south side of the Shaikan Antcline (850 m) is used to provide an estimate of the error associated with quantification of the net uplift. The calculation is as follows:

\[
\text{Gross uplift measured from structural datum} - \text{thickness of growth stratigraphy} = \text{Net uplift} \\
5.1 - 0.76 - (0.85/2) = 3.90 \pm 0.4 \text{ km.}
\]

The additional uplift due to basement involvement has resulted in the failure of seals within the Triassic Kurra Chine Formation; the intervening reservoir units in this formation were charged in the past but contained only residual tar staining in the Gara-1 exploration well. In contrast, oil discoveries have been made at the Atrush and East Swara Tika anticlines to the south of Gara (Figs 5 & 6). Using the same method, the net uplift determined from the elevation of the top Jurassic horizon at these structures is 2.2 and 2.0 km (±0.4).

The zone of severe uplift identified at the Gara Antcline can be extrapolated along strike using a line connecting the SW margins of anticlines in which Jurassic or older stratigraphy is exposed (Fig. 1). This line separates oil and gas discoveries to the SW from six unsuccessful exploration wells to the NE (Mateen-1, Gara-1, Shireen-1, Khalakan-1, Binari Serwan-1 and Zewe-1), and provides a pragmatic subdivision of the Uplifted Folded
Zone into prospective and high-risk areas for petroleum exploration.

Erosion

The amount of erosion during and after uplift in northern Iraq can be estimated using measurements of vitrinite reflectance (reflectance in oil or %Ro). This is an optical maturity parameter that shows an exponential and irreversible increase with depth (Bostick 1971; Teichmüller 1979; Taylor et al. 1998; Allen & Allen 2005). A number of different relationships of vitrinite reflectance v. depth are recognized (fig. 9.31 of Allen & Allen 2005); in the simplest of these, the vitrinite reflectance values form a straight line on a graph of log vitrinite reflectance v. linear depth. The line should intercept the surface between 0.1 and 0.25% Ro, which is the range of vitrinite reflectance values yielded by peaty organic matter (Dow 1977; Cohen et al. 1987). In this situation, vertical deviations from the expected log-normal trend can be used to estimate the amount of erosion; a linear and regionally uniform geothermal gradient is assumed.

Two of the assumptions deserve additional consideration. First, irregular vitrinite reflectance trends have been described in other basins (e.g. Law et al. 1989; Mello & Karner 1996; McTavish 1998; Suggate 1998; Carr 2000; Petersen et al. 2012); these are commonly attributed to significant variations in sediment thermal conductivity and/or overpressure-induced retardation of maturation. However, wells in the study area with sufficient vitrinite reflectance data appear to form a log-normal vitrinite reflectance trend without significant irregularities.
Second, variations in the present-day geothermal gradient and heat flow have been described in the study area (e.g. Abdula 2016; Hakimi et al. 2017), but the approach described is an acceptable simplification in view of the multiple sources of data and variations in data quality.

Vitrinite reflectance data for northern Iraq have been compiled for 11 outcrops and 15 wells from multiple sources (Ranyayi 2009; Abdula 2010; Aqrawi et al. 2010; Jabbar 2010; Al Ahmed 2013; Mohialdeen et al. 2013; Baban & Ahmed 2014; proprietary data). The samples are almost exclusively from the crest of major anticlines and therefore represent the maximum amount of erosion; the adjacent synclines are less deeply eroded and remain closer to maximum burial. A significant amount of time was spent on quality control of the data due to measurement uncertainty and variations in data quality. Due to the sparse distribution of data in NW Kurdistan, the vitrinite reflectance equivalent ($R_{eqv}$) has been calculated from measurements of bitumen reflectance (formula of Jacob 1989) for the Swara Tika-2 (1.11% $R_{eqv}$ at 3547 m) and East Swara Tika-1Z (0.78% $R_{eqv}$ at 1730 m) wells, and vitrinite reflectance values derived from $T_{max}$ values have been used at two wells and one outcrop (Tawke-15 well and Gara outcrop from Abdula 2010; Ajeel-8 well from Al-Ameri et al. 2014).

The compilation of vitrinite reflectance data are shown in Figure 7. The trend of vitrinite reflectance with depth below surface is defined by seven vitrinite reflectance values from a reference well with good data spanning a vertical distance of 1700 m. However, at least 400 m of erosion can be estimated at this well and therefore a vertical shift of 400 m has been applied to this trend to define an empirical zero-erosion baseline with a surface intercept at 0.17% $R_o$. The vertical displacement of each point from this vitrinite reflectance–depth line has then been used to estimate the amount of erosion at that location. Key datapoints are labelled: GA, Gara Anticline; EST-1Z, East Swara Tika-1Z; ST-2, Swara Tika-2; JK-1, Jabal Kand-1. The vitrinite reflectance data were compiled from Ranyayi (2009), Abdula (2010), Aqrawi et al. (2010), Jabbar (2010), Al Ahmed (2013), Mohialdeen et al. (2013), Baban & Ahmed (2014) and proprietary data.

**Fig. 7.** Log-normal plot of vitrinite reflectance ($R_o$) against depth below surface. The trend of vitrinite reflectance with depth is defined by seven vitrinite reflectance measurements from a reference well with good data spanning a vertical distance of 1700 m. At least 400 m of erosion can be estimated at this well and therefore a vertical shift of 400 m has been applied to this trend to define an empirical zero-erosion baseline with a surface intercept at 0.17% $R_o$. The vertical displacement of each point from this vitrinite reflectance–depth line has then been used to estimate the amount of erosion at that location. Key datapoints are labelled: GA, Gara Anticline; EST-1Z, East Swara Tika-1Z; ST-2, Swara Tika-2; JK-1, Jabal Kand-1. The vitrinite reflectance data were compiled from Ranyayi (2009), Abdula (2010), Aqrawi et al. (2010), Jabbar (2010), Al Ahmed (2013), Mohialdeen et al. (2013), Baban & Ahmed (2014) and proprietary data.
the reference well from the thickness of isopachous stratigraphy that is present in the synclines on either side of the well location. Therefore a vertical shift of 400 m has been applied to this trend to define an empirical zero-erosion baseline with a surface intercept at 0.17% $R_o$. The vertical displacement of each point from this baseline vitrinite reflectance–depth trend has been used to estimate the amount of erosion at that location. The erosion estimates range from 300 m to more than 5 km. Confidence in the technique can be improved by comparison with erosion estimates from the regional cross-section. At the Gara Anticline there is good agreement between the erosion estimated by projecting the thickness of isopachous stratigraphy above the well location (3760 m) and the erosion estimated from vitrinite reflectance (3750 m). Although the corresponding pair of erosion estimates at East Swara Tika (2050 m from cross-section and 2450 m from vitrinite reflectance) are in less-good agreement, they are of the same order of magnitude and provide an indication of the error bar (±400 m) associated with the erosion estimates.

The erosion estimates from vitrinite reflectance ($n = 25$ + reference well) have been supplemented by six erosion estimates from cross-sections to provide a more uniform dataset across Kurdistan. Despite the assumptions described, there is a clear regional trend of increasing erosion towards the Mountain Front and within the Uplifted Folded Zone to more than 3 km of erosion in the northern part of the Uplifted Folded Zone to the NE of this line (Fig. 8). Five domains have been defined from the compilation of erosion estimates, ranging from less than 750 m of erosion in the Foreland Folded Zone to more than 3 km of erosion in the northern part of the Uplifted Folded Zone. Individual structures are not resolved by the sparse compilation of points, with the exception of Sangaw Mountain in SE Kurdistan where erosion estimates have been made for both wells drilled on this structure.

Discussion

The subsidence analyses provide some insight into the main tectonic events affecting the area. The onset of this thermal subsidence is interpreted to be coeval in the three wells analysed, commencing in the Middle Permian (c. 272 Ma; Figs 3 & 4). The stratigraphic record for the three wells can be explained by thermal subsidence alone from the Middle Permian until the Late Cretaceous (Campanian–Maastrichtian); no additional rifting events are necessary during this time to explain the stratigraphic record.

Prior to thermal subsidence, a puzzling aspect of the stratigraphic record at the Jabal Kand-1 well location is that no obvious synrift sequence appears to be present. A significant hiatus separates Lower Carboniferous (Harur Formation) and Mid–Upper Permian (Chia Zairi Formation) stratigraphy. This is fully consistent with outcrop relationships at the Zap Anticline in SE Turkey where the same hiatus separates Lower Carboniferous (Koprulu Formation) from Upper Permian (Harzo Formation) stratigraphy (Janvier et al. 1984) (Fig. 2). The absence of Lower Permian synrift stratigraphy across the Arabian Plate has previously been noted (Aqrawi et al. 2010). One possible explanation is that the distribution of strain in the lithosphere was non-uniform during stretching (e.g. Crosby et al. 2011), with crustal thinning confined to a relatively narrow zone of high strain and stretching of the mantle lithosphere distributed over a more extensive area of lower strain. An alternative model is that the rift basin remained elevated during lithosphere stretching due to the presence of melt trapped in the asthenosphere (Quirk & Rüpke 2018). Melt-related buoyancy offers an explanation for how the upper surface of the plate might have remained above sea level during lithosphere stretching and, consequently, why no synrift stratigraphy was preserved. This would have been followed by rapid subsidence and sediment accumulation after continental break-up when any melt would have been incorporated into oceanic crust.

The primary value of quantifying the subsidence record in any basin is that the corresponding heat flux can be estimated from this (Allen & Allen 2005). In northern Iraq, the most important source rocks were deposited in the Middle and Upper Jurassic (Sargelu and Naokalekan formations: Pitman et al. 2004; Aqrawi & Badics 2015). By this time the basin was at least 100 myr into thermal subsidence, and the heat flow would have reduced almost to the background level following the period of highest heat flow at the end of lithosphere stretching (fig. 3 of McKenzie 1978). For simplicity, it is therefore acceptable to model the maturity of these source rocks using steady-state heat-flow assumptions. However, for exploration targets where Triassic or older source rocks are required, it would be advisable to include the full thermal history, including the transient heat flow.

Thermal subsidence was followed by flexural subsidence during closure of the Neo-Tethys Ocean and subsequent continental collision. Flexural subsidence is interpreted to have commenced slightly earlier in SE Kurdistan (72 Ma: Well-3, see Fig. 4) compared to NW Kurdistan (69 Ma: Jabal Kand-1 and Well-2, see Figs 3 & 4), based on the observation that marly limestone of the Maastrichtian Shiranish Formation rests directly on limestone of the Turonian–Santonian Kometan Formation in Well-3. The same stratigraphic arrangement is observed in other wells in the immediately surrounding area, whereas the Shiranish Formation overlies limestone of the
Campanian–Maastrichtian Aqra and Bekhme formations in Jabal Kand-1 and Well-2, respectively. Additional dating of the Shiranish Formation would be required in order to validate this interpretation.

Compared to NW Kurdistan, significantly more flexural subsidence is observed in SE Kurdistan (Well-3) where the Cenozoic stratigraphy reaches its maximum thickness (e.g. fig. 8.1 of Aqrawi et al. 2010).

Campanian–Maastrichtian Aqra and Bekhme formations in Jabal Kand-1 and Well-2, respectively. Additional dating of the Shiranish Formation would be required in order to validate this interpretation.

Compared to NW Kurdistan, significantly more flexural subsidence is observed in SE Kurdistan (Well-3) where the Cenozoic stratigraphy reaches its maximum thickness (e.g. fig. 8.1 of Aqrawi et al. 2010).

Fig. 8. Estimated erosion values in metres and corresponding erosion domains in northern Iraq. There is a regional trend of increasing erosion towards the Mountain Front and within the Uplifted Folded Zone to the NE of this line. This has been used to define the five erosion domains that are illustrated. Individual structures are not resolved, with the exception of Sangaw Mountain (SM) in SE Kurdistan where erosion estimates have been made for both wells drilled on this structure.
This is attributed to additional loading of the plate in SE Kurdistan by both the Zagros fold and thrust belt in Kurdistan and the Lurestan Arc in Iran.

The technique of evaluating uplift using a datum constructed at the depth of maximum burial gives a higher estimate than the uplift estimated from the local structural datum: 3.9 v. 3.0 km in the Gara Anticline example. The additional uplift is due to basement-involved deformation to the north of the Mountain Front, and provides an explanation for why hydrocarbon exploration in the northern part of the Uplifted Folded Zone during 2011–15 was unsuccessful. During this period, six exploration wells (from NW to SE: Mateen-1, Gara-1, Shireen-1, Khalakan-1, Binari Serwan-1 and Zewe-1) were drilled on clearly defined anticlines in this area, but none of these wells was successful. The true uplift of these anticlines cannot be assessed at the scale of existing 2D and 3D seismic reflection surveys in the area, and must instead be determined by construction and evaluation of regional cross-sections. A pragmatic subdivision of the Uplifted Folded Zone into prospective and high-risk areas for petroleum exploration can be made using a line connecting the SW margins of anticlines in which Jurassic or older stratigraphy is exposed (Fig. 1).

The erosion estimated from the compilation of vitrinite reflectance data shows a clear trend of increasing erosion towards the Mountain Front and within the Uplifted Folded Zone to the NE (Fig. 8). In the far north of Iraq, the anomalously low erosion in the Tawke Trough (<1 km) is notable. This area is located within a major re-entrant of the Mountain Front (Fig. 1); consequently, the amount of uplift and resulting erosion are significantly less than the adjacent anticlines at Mateen (to the NE) and Gara (to the east). These factors are at least partly responsible for the preservation of the Tawke oilfield. To date, no discoveries have been made in Kurdistan where the amount of erosion is estimated to exceed 3 km. With respect to the erosion domains, the commercial discovery furthest NE at the time of writing is the East Swara Tika oilfield (estimated erosion >2 km).

Conclusions

Understanding the vertical movements in fold and thrust belts is important due to their impact on every element of the petroleum system. A case study from Kurdistan, northern Iraq, shows how existing techniques can be applied in order to quantify these movements:

- **Subsidence**: 1D analysis of well data indicates that Middle Permian–Late Cretaceous thermal subsidence of 1.8–1.9 km (tectonic subsidence) followed moderate lithosphere extension (stretching factor of 1.84–1.92; Figs 3 & 4). The absence of synrift stratigraphy in well or outcrop data is attributed to non-uniform stretching of the lithosphere or melt-related buoyancy. The onset of flexural subsidence in the Late Cretaceous can be recognized from the deviation of subsidence profiles from a reference thermal subsidence model. Flexural subsidence continued in the Cenozoic and, in the wells analysed, reached 0.6 km in NW Kurdistan and 1.2 km in SE Kurdistan (tectonic subsidence).
- **Uplift**: the amount of uplift corresponding to the amplitude of folding has been enhanced by additional basement-involved uplift to the north of the Mountain Front (Fig. 6). At the Gara Anticline, the apparent uplift is 3.0 km; however, an additional 0.9 km (net) of basement-involved uplift can be determined using the correct structural datum determined from a regional cross-section (Fig. 6). The domain of severe uplift can be extrapolated along strike using a line connecting the SW margins of anticlines in which Jurassic or older stratigraphy is exposed.
- **Erosion**: this has been estimated using vitrinite reflectance data with additional erosion estimates from cross-sections where these data are sparse (Fig. 7). There is a regional trend of increasing erosion towards the Mountain Front and within the Uplifted Folded Zone (Fig. 8). Five domains have been defined from these estimates, ranging from less than 0.8 km of erosion in the Foreland Folded Zone to more than 3.0 km of erosion in the northern part of the Uplifted Folded Zone.

In Kurdistan, it is the uplift that is the most important of these vertical movements for petroleum exploration. The domain of severe uplift can be defined using a line drawn along the SW limit of Jurassic exposure. To the NE of this line, the uplift is estimated to be greater than 3.0 km; six unsuccessful hydrocarbon exploration wells have been drilled in this area. To the SW of this line, seal integrity has been maintained; at the time of writing, the commercial discovery closest to this line is the East Swara Tika oilfield. In Kurdistan, the SW limit of Jurassic exposure provides a pragmatic subdivision of the Uplifted Folded Zone into prospective and high-risk areas for petroleum exploration.

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