1-2015

The Effect of Basement Fault Reactivation on the Triassic—Recent Geology of Kurdistan, North Iraq

Caroline M. Burberry
University of Nebraska-Lincoln, cburberry2@unl.edu

Published in *Journal of Petroleum Geology* 38:1 (January 2015), pp 37-58.

Published online December 19, 2014.

The Effect of Basement Fault Reactivation on the Triassic—Recent Geology of Kurdistan, North Iraq

C. M. Burberry

Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln
214 Bessey Hall, Lincoln NE 68588-0340, USA; email cburberry2@unl.edu

Abstract

The Zagros orogenic belt is underlain by a complex faulted Precambrian basement. Major fault trends originating in this basement have been invoked to explain large-scale structural changes along the strike of the orogen, e.g. the development of the Kirkuk Embayment (Kurdistan, Iraq) and the Lurestan Salient (Iran). However, within the Kirkuk Embayment, these structural trends have not previously been considered as an interacting group of faults which are periodically reactivated. This contribution first presents a revised basement fault map for the Kirkuk Embayment, created from interpreted gravity data, existing fault maps and remote sensing lineament analyses. This map is then compared to surface structure maps, published facies maps and source rock maturity data using GIS techniques. The object is to define the relationship between the basement faults and surface structures, facies and source-rock maturity through time.

Surface anticline orientation and location, as well as a number of major facies changes within the cover sequence, and the maturity of Triassic source rocks, are constrained by the interaction of the Najd and Transverse fault trends. A third basement trend, the Nabitah trend, has a more subtle effect on Phanerozoic geology. The Kirkuk Embayment can be divided into a series of semi-independent basement blocks, defined by these basement fault trends. The interaction of these semi-independent blocks has created local but predictable differences in surface structures, sediment thickness and facies, and variations in the maturity of Triassic source units across the Kirkuk Embayment. An understanding of the location and behavior of basement faults within this hydrocarbon province is therefore a valuable predictive tool in exploration.

Key words: Zagros orogenic belt, Kurdistan, Iraq, Precambrian, basement faults, Kirkuk Embayment, Najd trend, Transverse trend.

Introduction

Many factors influence the present-day structural configuration of a geologic province, of which two are tectonic inheritance and facies variations (that is, mechanical variation) within the sediment pile. Within a given area, the resultant deformed geometry is therefore likely to be an expression of a combination of these two factors. These factors cannot be considered in isolation, however, as reactivation of inherited structures will influence the distribution of sedimentary facies and therefore mechanical variation within a region. The influence of reactivated inherited faults, with an emphasis on the effect on

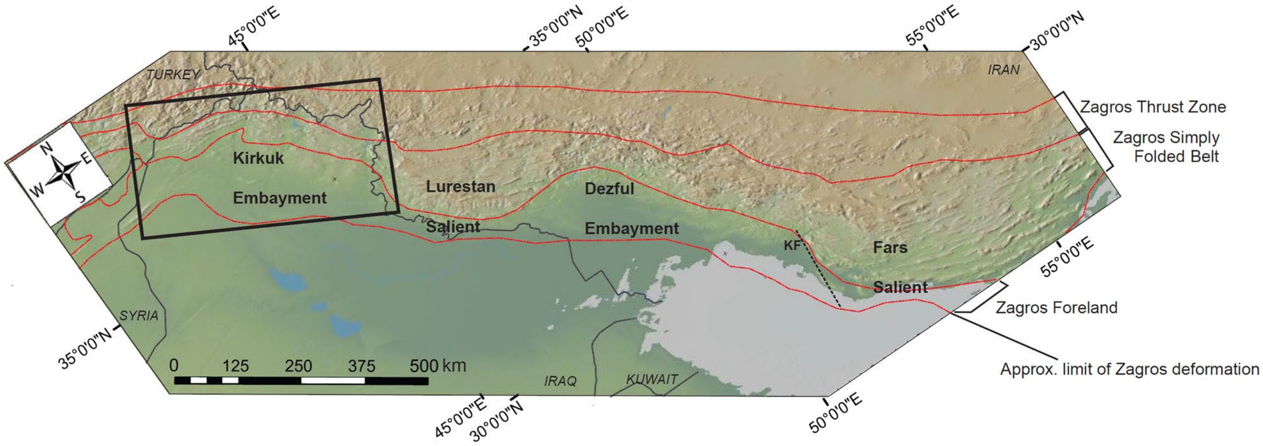

Figure 1. Regional map showing the location of the study area (box) with respect to political boundaries and the Zagros Belt as a whole. Key longitudinal divisions are marked (the Zagros Thrust Zone and the Simply Folded Belt) and the major salients and embayments are labelled. KF: Kazerun fault. The base image is a shaded relief DEM from GeomappApp.

subsequent structures, facies distributions and source rock maturity, will be investigated in this contribution, with particular focus on the northern part of the Zagros orogen in Iraq.

Tectonic inheritance can be a major influence on the present-day expression of a deforming geologic province (Butler *et al.*, 1997). The concept of tectonic inheritance, that the pre-existing structures and zones of weakness in a system govern the development of subsequent structures, is frequently used to explain large-scale variations in the geometry of orogenic belts, or the locations of rift margins in supercontinent cycles (Thomas, 2004; Audet and Burgmann, 2011; Huerta and Harry, 2012). This idea has been convincingly applied to the geometry of the Appalachian Mountains to explain the development of the Pennsylvania and Tennessee Salients (Thomas, 1977, 2004; Bayona and Thomas, 2006). It has also been applied to the southern and central Sevier belt to explain the geometries of the Provo and Wyoming Salients (e.g. Paulsen and Marshak, 1998, 1999), and to the Alpine–Apennine portion of the Central Tethyan belt to explain the involvement of the basement in this region (Butler *et al.*, 2006). Such belts may be known as basin-controlled belts, in the terminology of Marshak (2004). The influence of the pre-existing structures can be displayed in a number of ways, including localization of subsequent structures above the pre-existing fault (e.g. Thomas, 2004), or complete or partial reactivation or inversion of the pre-existing structure (Butler *et al.*, 1997). A secondary effect of basement fault involvement or reactivation is the partitioning of strain onto several sets of structures within a single fold-thrust belt (McClay *et al.*, 2004).

Facies variations may occur as a result of changes in depositional environment including water depth (Handford and Loucks, 1993; Pomar, 2001) and sediment source (i.e. proportion of clastic input). Both of these factors can be influenced by the presence of reactivated faults. In addition, water depth and clastic input can be influenced by sea level changes, or by larger-scale plate flexure. In some areas, therefore, these complex effects are not easily separated. However, given that the tectonic history and the large-scale basement geometry of the study area in northern Iraq are well-constrained, as are the eustatic sea level variations for this region (Alsharhan, 2014), the facies variations due to tectonic inheritance should be readily identifiable.

Source rock maturity is a function of burial temperature (i.e. burial depth) and therefore of the thickness of the sediment pile above a potentially mature source rock interval (Tissot *et al.*,1987). Maturity is also a function of time, in that the temperature must equilibrate and the source unit remain within the oil window for a suitable length of time. Basement topography, affected by reactivation of existing faults and by larger-scale plate flexure, creates variable amounts of accommodation space across a broad region. If these variations in accommodation space are sufficiently large, and the basin is not significantly underfilled, facies, sediment thicknesses and thus source-unit burial depths may vary appreciably across a basin of the size of the Mesopotamian foreland basin. In addition, sediment accumulation rate must be sufficient for the source layer to reach maturity in a timely fashion.

The Zagros Orogen extends from the Makran Zone in the SE through southern and SW Iran and into northern Iraq. It can be divided into both longitudinal zones and a series of salients and embayments (Figure 1). The principal longitudinal zones are, from hinterland to foreland, the Thrust Zone (also known as the Imbricated Zone), the Simply Folded Belt (known in northern Iraq as the High Folded Zone), and the Foreland or Foothill Zone. The Simply Folded Belt and

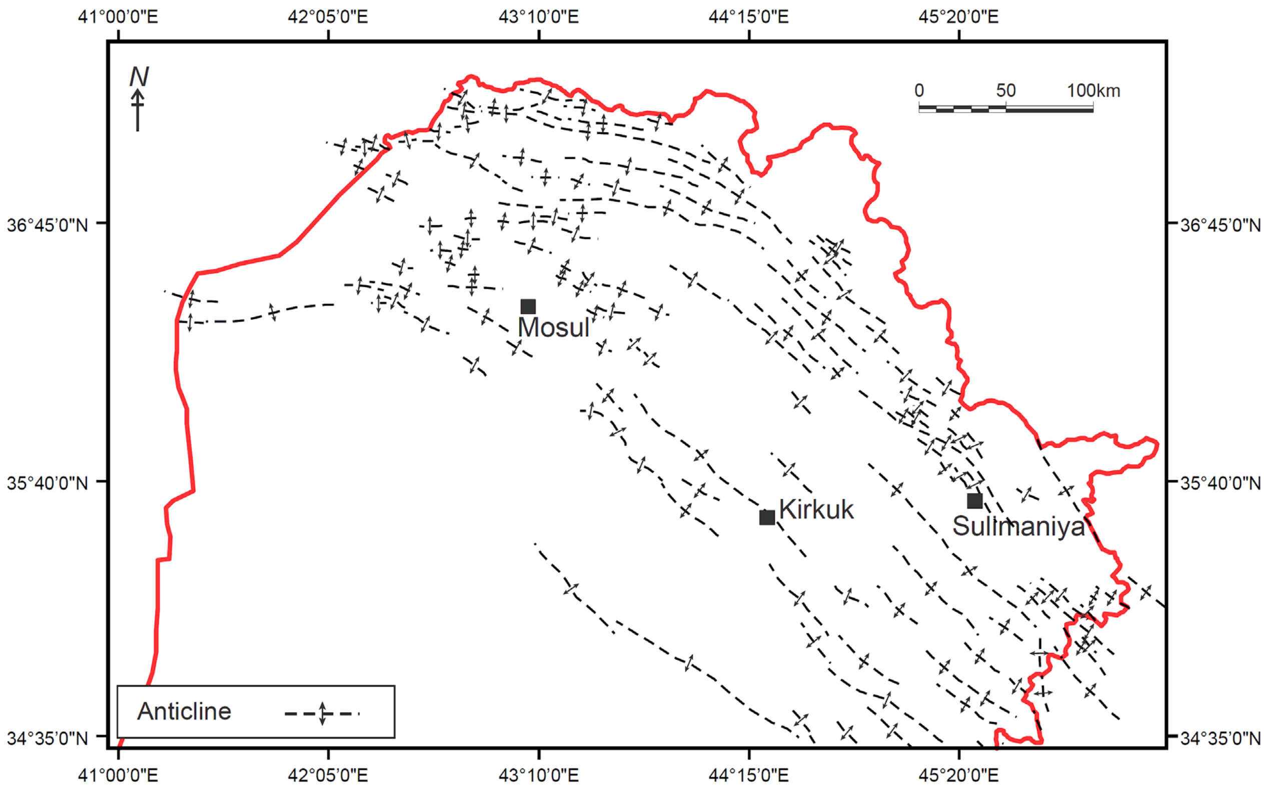

Figure 2. Surface anticline location and orientations within the Kirkuk Embayment of the Zagros fold-and-thrust belt, digitized from satellite images and DEMs. The dominant anticline orientation is NW-SE, becoming closer to east-west in the Mosul area. Main cities Mosul, Kirkuk and Sulimaniya are marked for reference.

Foothill Zone can be divided into a series of salients and recesses: from SE to NW, the Fars Salient, the Dezful Embayment, the Lurestan Salient and the Kirkuk Embayment, bounded in some cases by major strike-slip faults. Strain is considered to be partitioned along the major strike-slip faults and the major thrust faults, since the shortening direction is oblique to both sets of structures (Berberian, 1995; Hessami *et al.*, 2001a; Sella *et al.*, 2002). Earthquakes in northern Iraq have focal mechanisms showing both thrust and strike-slip movement, as listed in the online USGS database. This paper focuses on features within the Kirkuk Embayment, defined as the study area on Figure 1, but also refers to other parts of the orogen.

The concept that the geometry of a previously rifted margin may govern the location of salients and embayments has been used to explain the large-scale geometry of the entire length of the Zagros orogen (e.g. Navabpour *et al.*, 2014). However, most previous structural studies of this orogen (e.g. Blanc *et al.*, 2003; Alavi, 2004; Sepehr and Cosgrove, 2004; McQuarrie, 2004; Sepehr *et al.*, 2006; Alavi, 2007) have focused on the hydrocarbon-rich Fars and Lurestan Salients or the Dezful Embayment regions of Iran, with emphasis on the relationship of mechanical stratigraphy to deformation style (e.g. Casciello *et al.*, 2009; Farzipour-Saein *et al.*, 2009a). In addition, some authors have investigated the effects of specific basement structures (e.g. Sepehr and Cosgrove, 2004, 2005; Sherkati *et al.*, 2005; Farzipour-Saein *et al.*, 2009b). Much of what is known about the Kirkuk Embayment is derived from remote sensing studies, coupled with studies from Iran, since access to this region has been restricted for many years. However the Kirkuk Embayment has recently become a focus of interest for the hydrocarbon industry and the structure of this region have therefore been investigated (de Vera *et al.*, 2009; Bretis *et al.*, 2011; Reif *et al.*, 2012; Csontos *et al.*, 2012; Frehner *et al.*, 2012).

This contribution aims to test the hypothesis that present-day variations in the surface structure, as well as facies changes and variations in source rock maturity within the Kirkuk Embayment, can be attributed in part to reactivation of basement faults. If this is the case, it can be expected that surface structures, facies changes and the maturity of source rocks of different ages, when overlain on maps of basement faults, will show an organization related to basement fault distribution. Although some previous studies have discussed the influence of basement trends on the surface structure and cover thicknesses (e.g. Berberian, 1981; Ameen, 1992; Jassim and Buday, 2006a; Csontos *et al.*, 2012), there is limited agreement about the exact locations and orientations of the basement faults.

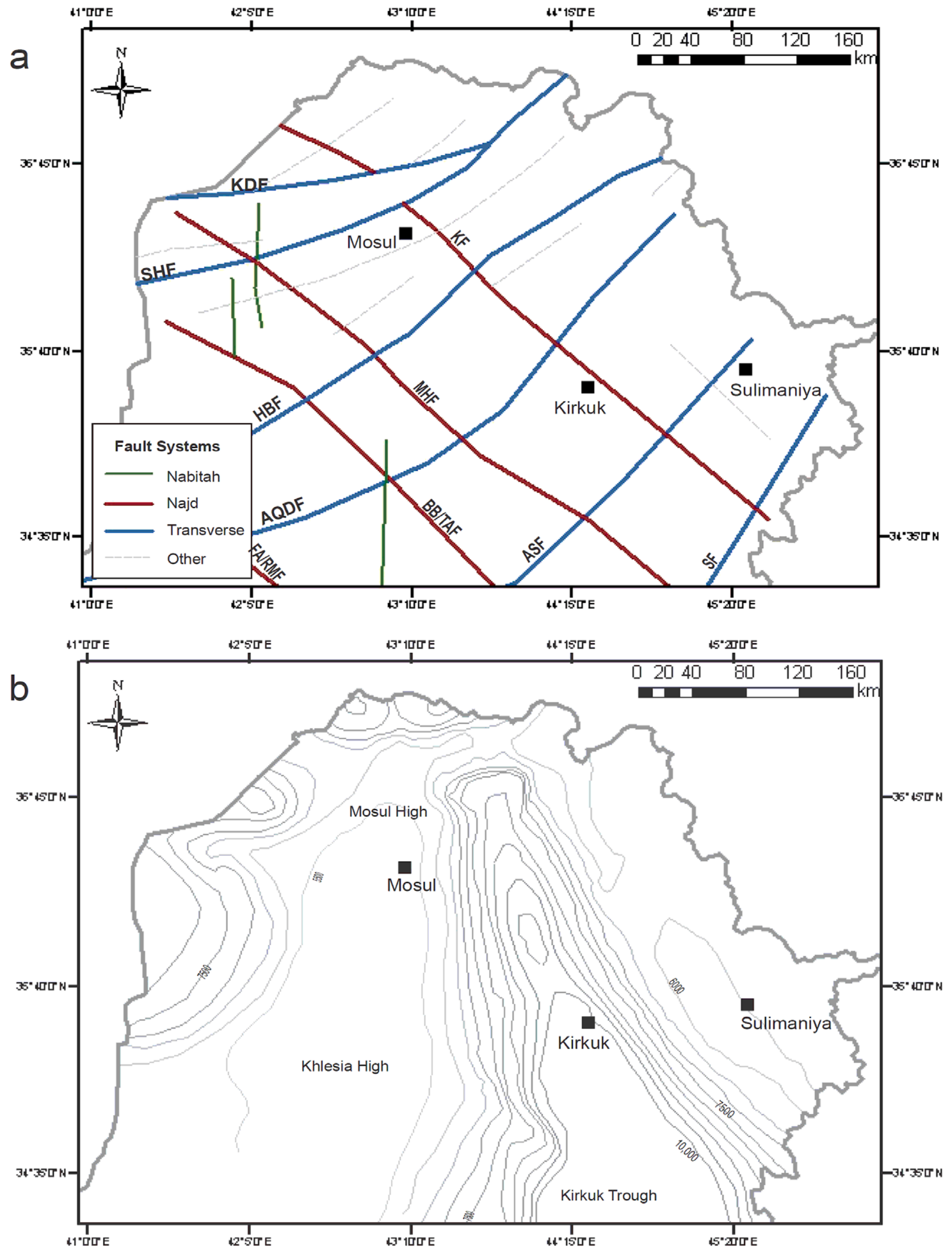

Figure 3. Basement features within the Kirkuk Embayment: (a) basement fault trends, digitized and named after Jassim and Buday (2006a); and (b) basement topography, contoured in meters below sea level, with a contour interval of 500m, after Jassim and Buday (2006a). AQDF, Anah-Qalat-Dizeh fault; ASF, Amij-Samarra Fault; BB/ TA, Tikrit-Amara fault (also known as Balad-Baghdad Fault); FA/ RMF, Ramadi-Musayib Fault (also known as Falluja-Amara Fault); HBF, Hadar-Behkme fault; KDF, Kochuk-Dohuk fault, KKF, Kirkuk fault; MHF, Makhul-Hemrin fault; SHF, Sinjar-Herki fault; SF, Sirwan Fault. Main cities Mosul, Kirkuk and Sulimaniya are marked for reference.

In addition, the influence of basement faults on specific facies changes has not been systematically examined; nor have maps of variations in source rock maturity, or maximum temperature reached during burial, been compared to basement trends. Previous studies in general considered fault sets in isolation, rather than considering the interaction of the complete set of basement fault structures in successive time intervals.

This study relates surface structures, specific, documented facies changes, and recent data on variations in Triassic source rock maturity to a revised basement fault map of the Kirkuk Embayment. It aims to provide a mechanism for understanding the changes in Phanerozoic geology within the study area in the context of the complete multi-trend basement fault system.

Regional Geologic Setting and History

Present-day structures of the Zagros Orogen

The Zagros Orogen formed along the zone of collision between the Arabian Plate and the Central Iran microplate, with ophiolite obduction occurring in the Late Cretaceous (Yilmaz, 1993; Blanc *et al.*, 2003; Ghasemi and Talbot, 2005) and initial thrusting and folding occurring in the Late Paleocene–Early Eocene (Csontos *et al.*, 2012; McQuarrie and Hinsbergen, 2013). The most striking features of the surface geology of the Kirkuk Embayment are the NW-SE trending anticlinal structures of the Zagros Simply Folded Belt (Figure 2). The anticline trend becomes more west-east oriented north of Mosul, similar to the trend

of the Tauride belt in Turkey. The anticlines are often capped by Cenozoic carbonate units, creating obvious carapaces which can be recognized in remotely-sensed datasets. Associated synclines are filled with Cenozoic flysch units, such as the Fars and Bakhtiari Formations, frequently containing progressive unconformities (Hessami *et al.*, 2001b) indicating that the anticlines developed during the deposition of these units. The anticlines range in hinge length from 15 to 70 km and in wavelength from 5 to 10 km (Zebari and Burberry, 2015). Anticlines are doubly plunging and in many cases are found to be fault-cored, generally with a dominant foreland-verging thrust and antithetic thrusts accommodating the remaining displacement (Omar, 2005; Csontos *et al.*, 2012; Zebari and Burberry, 2015). In addition, the geomorphology of the anticlines indicates that some structures show pronounced lateral propagation in one direction only, whereas others show lateral propagation of both fold tips indicating a variation in growth processes across the region (Zebari and Burberry, 2015).

The basement of the Kirkuk Embayment is highly heterogeneous, is cut by many faults (Figure 3a) and thus has a distinct topography (Figure 3b; Abdelsalam and Stern, 1996; Edgell, 1996; Jassim and Buday, 2006a; Kent, 2010). Troughs and high points within the basement topography can be detected by magnetic and gravity anomaly maps, as well as depth-to-basement maps derived from these data (e.g. maps presented in Jassim and Buday, 2006a). Notable topographic features include a distinct high zone trending north-south from Mosul towards central Iraq (Ameen, 1992). This structure is variously known as the Mosul High in the northern part of Iraq and the Khlesia High in central Iraq and can be identified from gravity data (Al-Yasi *et al.*, 2006; Al-Banna *et al.*, 2013). Another significant feature is the NW-SE trending trough in the vicinity of Kirkuk, herein referred to as the Kirkuk Trough, again visible on the depth-to-basement map presented by Jassim and Buday (2006a). However, the resolution of this dataset is not sufficient to show the subtle offsets generated by the fault systems described in the following section. Detailed gravity studies in the Kirkuk Embayment (e.g. Amin *et al.*, 2009; Al-Dawoody, 2013) suggest that the influence of basement faults can be seen in higher resolution gravity datasets (e.g. those contoured in 1mgal intervals).

Both the present-day basement topography and the variation in surface structure across the Kirkuk Embayment hint at a complex geologic history. Prior to the Late Paleocene–Early Eocene deformation, the region underwent a major compressional tectonic episode in the Late Proterozoic, followed by an extensional tectonic phase in the Paleozoic. These events will be described in more detail below.

Late Proterozoic Compressional Tectonics

The Late Proterozoic Pan-African Orogeny lasted from approximately 900 to 610 Ma. A series of major fault structures are thought to have formed in this period, namely the Nabitah, Transverse and Najd fault systems (Figure 3a) which affect much of the Arabian Plate.

The north-south oriented transpressional Nabitah system (Quick, 1991), referred to as the Arabian trend by Edgell (1996), is the earliest fault system preserved from the 680-640 Ma Nabitah Orogeny. The structures originated as a series of compressional faults formed during east-west directed collision. Subsequently, this system underwent extensional reactivation during the Infracambrian. These faults are conspicuous in the basement of southern and western Iraq and less common in northern Iraq (Jassim and Buday, 2006a; Stern and Johnson, 2010). The system is also well-defined in neighboring Iran, forming the major strike-slip faults (e.g. the Kazerun Fault: KF, Figure 1) which separate the salients and embayments (Sadooni, 1995; Sattarzadeh *et al.*, 2000; Sepehr and Cosgrove, 2005).

The NE-SW trending Transverse fault system (Ameen, 1992) also dates from the Late Proterozoic and probably originated as a conjugate fault set to the Najd system. The most significant of the Transverse faults within northern Iraq are the Sinjar-Herki and Kochuk-Dohuk Fault Zones, which extend from the Syrian border to the Mosul area. Some authors include a fault under the Greater Zab River as part of this system (Ameen, 1992, Omar, 2005; Jassim and Buday, 2006a). This fault would be the continuation of the Hadhar-Bekhme Fault identified south of the study area; there is some debate as to whether the structure extends into the study area.

The third major fault system is the NW-SE trending Najd fault system, the dextral Erythaean trend of Edgell (1996), which formed during the NW-SE trending Najd rifting event (610-520 Ma). This system originated as a series of shear zones bounding Precambrian terranes and also appears to have undergone additional extension in the early Cambrian. The Najd system is expected to be present across the entire Zagros Orogen.

Cambrian to Late Cretaceous Extensional Tectonics

Following the Pan-African orogeny, the Arabian Plate formed part of the northern margin of Gondwana. Deposition on the Arabian Plate began with the Infracambrian Hormuz complex (deposits of megasequence AP1: Sharland *et al.*, 2001) which is variably evaporitic or siliciclastic along the strike of the Zagros Orogen. However, units from megasequence AP1 are not found within the Kirkuk Embayment (Figure 4; Jassim, 2006; Aqrawi *et al.*, 2010). Instead, siliciclastic units from megaseqence AP2, including the Khabour and Saq Formations, are found in the study area directly overlying the Precambrian basement.

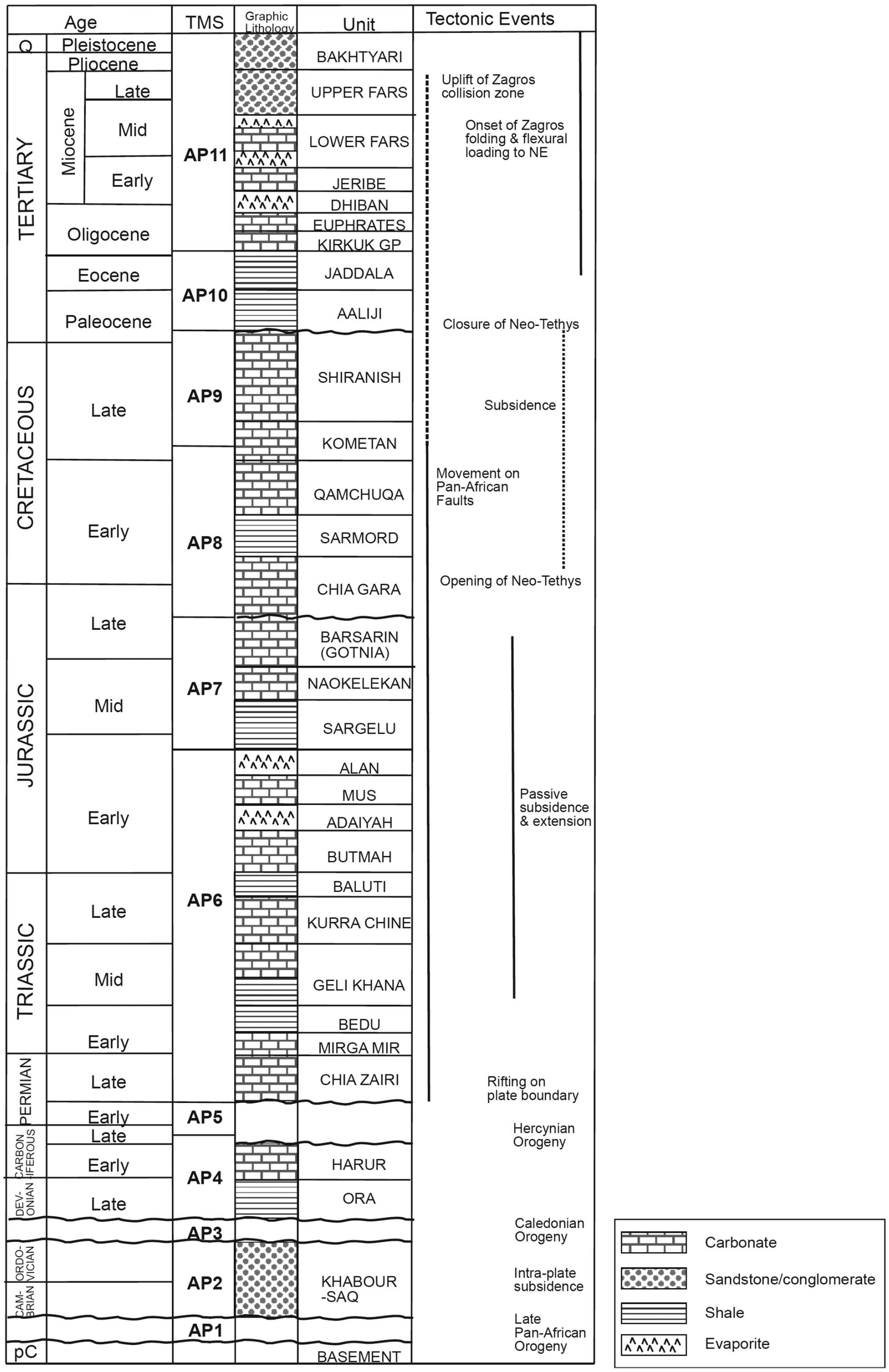

Figure 4. Tectonostratigraphic column for the Kirkuk region of Northern Iraq, based on well-data from Kirkuk-109 and information from van Bellen *et al.* (1959), Grunau (1981), Sharland *et al.* (2001) and Aqrawi *et al.* (2010).

During the Late Ordovician–Early Devonian, the Zagros area was characterized by a series of north-south trending, potentially transtensional grabens and tilted fault blocks, resulting from the east-west directed back-arc extension of the Caledonian orogeny (435-365 Ma; Sharland *et al.*, 2001) and creating a Silurian hiatus in deposition in the study area. Changing sea levels resulted in the deposition of the shale-rich Ora Formation, followed by the detrital limestones of the Harur Formation, both part of megasequence AP4. The region was subject to further back-arc extension during the 364-295 Ma Hercynian orogeny (Sharland *et al.*, 2001; Ibrahim, 2009), resulting in another marked hiatus (megasequence AP5) in the Pennsylvanian–Permian.

During the Permian, the Arabian Plate underwent an additional phase of broadly NE-SW directed extension, leading to rifting along trends similar to those of the Najd system, the separation of the Iranian and Afghan terranes, and strike-slip motion along faults oriented similarly to the Transverse system (Sharland *et al.*, 2001). During this time interval, the Chia Zairi Formation (the oldest formation in megasequence AP6) was deposited in the shallow-water setting of the

developing passive margin. This initial terrane separation was followed by passive subsidence of the margin during the Triassic and Early Jurassic, and deposition of a sequence of carbonate units including the Kurra Chine and Butmah Formations, interbedded with shale units such as the Bedu, Geli Khana and Baluti Formations. In the region penetrated by the Kirkuk-109 well (Figure 4), the Early Jurassic was characterized by the deposition of evaporite units, the Adaiyah and Alan Formations, followed by an additional shale unit, the Sargelu Formation, overlain by another thick carbonate sequence, the Naokelekan and Barsarin Formations of megasequence AP7. The Barsarin Formation is time-equivalent to the Gotnia Anhydrite unit, which is recorded in wells just south of Kirkuk 109 and is therefore included in parentheses on Figure 4.

This period of subsidence was followed by the opening of the Southern Neo-Tethys Ocean during the Early Cretaceous, again with major transform faults on the rift axis parallel to the older Transverse system (Sharland *et al.*, 2001; Ziegler, 2001). In addition, in the region that is now the Tauride region of northern Iraq and southern Turkey, north-south directed extension defined a rift system oriented east-west and forming the final major structural trend in the region (Edgell, 1996). A basinal carbonate sequence (the Chia Gara Formation) overlain by a thick shale unit (the Sarmord Formation) was deposited during this time. The Sarmord Formation is overlain by another thick carbonate sequence comprising the Qamchuqa, Kometan and Shiranish Formations of megasequences AP8 and AP9.

Paleocene to Recent Compressional Tectonics

Observed deformation in the region is a function of the Paleogene–Recent collision and the reactivation of pre-existing basement faults by this stress field (Sattarzadeh *et al.*, 2000). Ophiolite obduction occurred on the NE margin of the Arabian Plate during the Late Cretaceous (Yilmaz, 1993; Blanc *et al.*, 2003; Ghasemi and Talbot, 2005). Continental collision following the closure of Neo-Tethys started in the Early Miocene and has propagated 250-350 km southwestward since that time (Hessami *et al.*, 2001a, b; Csontos *et al.*, 2012). Convergence between the Eurasian and Arabian Plates has produced basement shortening and vertical escape of basement and cover via NW-SE trending reverse faults together with rotation and internal deformation of basement blocks (Hessami *et al.*, 2001a; Bahroudi and Talbot, 2003; Sepehr and Cosgrove, 2007). NE-SW directed convergence occurs across the greater part of the belt, accommodated by NE-SW compression and dextral transpression (Talebian and Jackson, 2002; Allen *et al.*, 2004). However in the study area, the dominant convergence direction is north-south directed, as a result of margin geometry and plate motions (Sella *et al.*, 2002; Csontos *et al.*, 2012). In the region of well Kirkuk-109, the clastic Aaliji and Jaddala Formations were deposited during the Paleocene and Eocene, followed by the carbonate-dominated Kirkuk Group and Euphrates Formation during the Oligocene.

Miocene deformation of the Zagros was coeval with the opening of the Red Sea and the cessation of Tethyan subduction (Vita-Finzi, 2001). In the region close to well Kirkuk-109, the alternating evaporite and carbonate units of the Dhiban, Jeribe and Lower Fars Formations were deposited. By comparison with the nearby Lurestan region (Iran), where the main phase of folding is dated to the Middle-Late Miocene (Homke *et al.*, 2004; Navabpour *et al.*, 2008), the main deformation period in Northern Iraq is inferred to be Late Miocene–Pliocene, as the sedimentary cover of this age is affected by the deformation (Csontos *et al.*, 2012). The clastic Upper Fars and Bakhtiyari Formations were deposited during this time, and progressive unconformities between beds of these units are documented around the Kirkuk Embayment (Hessami *et al.*, 2001b; Lawa *et al.*, 2013).

A re-organization of the collision may have occurred around 5Ma when deformation intensified in currently active regions. It is also likely that the change from cover deformation only to basement-involved deformation occurred during this reorganization. At the same time, there was rapid exhumation in the Alborz and the initial deposition of the Bakhtyari Formation. This is postulated to be a result of slab break-off with associated isostatic compensation and uplift in the interior (Haynes and McQuillan, 1974; Molinaro *et al.*, 2005). In Iran, recent regional-scale vertical movement is indicated for example by the presence of prominent river terraces and observations of a deflected and upwarped canal across the Shaur anticline (Lees, 1955). Recent earthquakes in Kurdistan and Turkey (e.g. a magnitude 5.1 event close to Erbil on July 18, 2009, as listed in the USGS catalogue) indicate that the area is still tectonically and seismically active. Basement structures, specifically the NW-SE trending set, are considered to be involved in the deformation of the present-day Iraqi Zagros, given that earthquake focal depths appear to be located at depths greater than the total depth of the sedimentary pile (Ameen, 1991; Carruba *et al.*, 2006; De Vera *et al.*, 2009; Kent, 2010). Shortening across different sectors of the Zagros fold-thrust belt is estimated at 16-30 % in Iran (Alavi, 2007), and at 33% in the Kirkuk Embayment (Ibrahim, 2009).

Variations in facies within the Kirkuk Embayment

Well Kirkuk-109, located slightly south of Kirkuk on the Baba Dome structure, is often considered the benchmark for the typical stratigraphy of northern Iraq (Figure 4, see above) given the limited availability

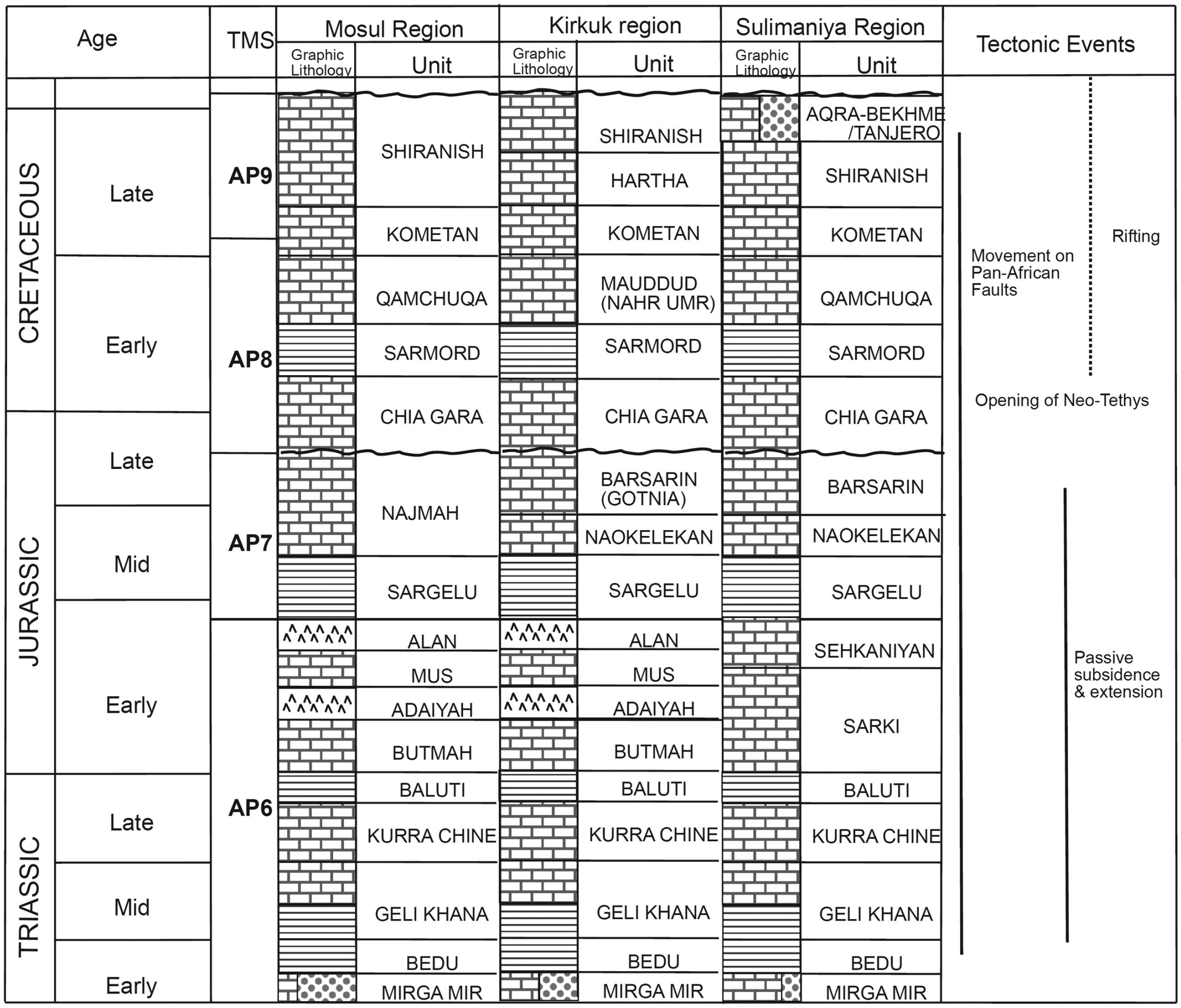

Figure 5. Facies variations within the Triassic–Cretaceous succession in the Mosul, Kirkuk and Sulimaniya regions, showing that the greatest variation occurs in the Early Jurassic facies. Graphic lithology symbols and information sources as in Figure 4.

of data in this area (e.g. Grunau, 1981). However, the facies present in the Mosul and Sulimaniya areas differ from this typical stratigraphy. Facies variations within the Triassic-Recent units will be discussed, given the limited data for deeper parts of the sequence. Figs 5 and 6, and descriptions in this section, are compiled from van Bellen *et al.*, (1959), Grunau (1981), Sharland *et al.* (2001) and Aqrawi *et al.* (2010). The Triassic–Cretaceous passive margin and rifting sequence will be discussed first, followed by the Paleocene–Recent molasse-dominated sequence. Potential reasons for these variations will be discussed in the Results section.

The first change in facies in the Triassic– Cretaceous sequence is within the Triassic Mirga Mir Formation. This formation is an argillaceous limestone and shale unit in which the clastic component increases towards the Mosul area. The lower division of the Triassic Geli Khana Formation also shows an increase in coarse clastic component towards the Mosul area, although this division is dominantly a shale unit as shown on Figure 5. The overlying Kurra Chine Formation is a carbonate unit across the study area, containing a series of evaporite units which are thicker to the NW of Mosul than to the south and east (Aqrawi *et al.*, 2010). Well data also indicates that the proportions of limestone, anhydritic limestone and dolomite vary considerably across the same area, as does the presence of clastic intervals. The greatest abundance of clastic material in this formation is found to the SW of Mosul.

Within the Early Jurassic sequence, the facies variation is more marked, with the presence of thick evaporite intervals (the Alan and Adaiyah Formations) in the Mosul and Kirkuk regions which are absent in the Sulimaniya region. In addition, the carbonate units in the Sulimaniya area differ from those in the remainder of the study area, being rich in dolomite and deposited in a restricted lagoonal setting as opposed to the limestone-rich shelf deposits of the Butmah and Mus Formations. This interpretation of differing lithology and therefore formation is based on van Bellen *et al.* (1959) but recent data (Jassim, *pers. comm.)* indicates that wells reaching the Triassic in this area also

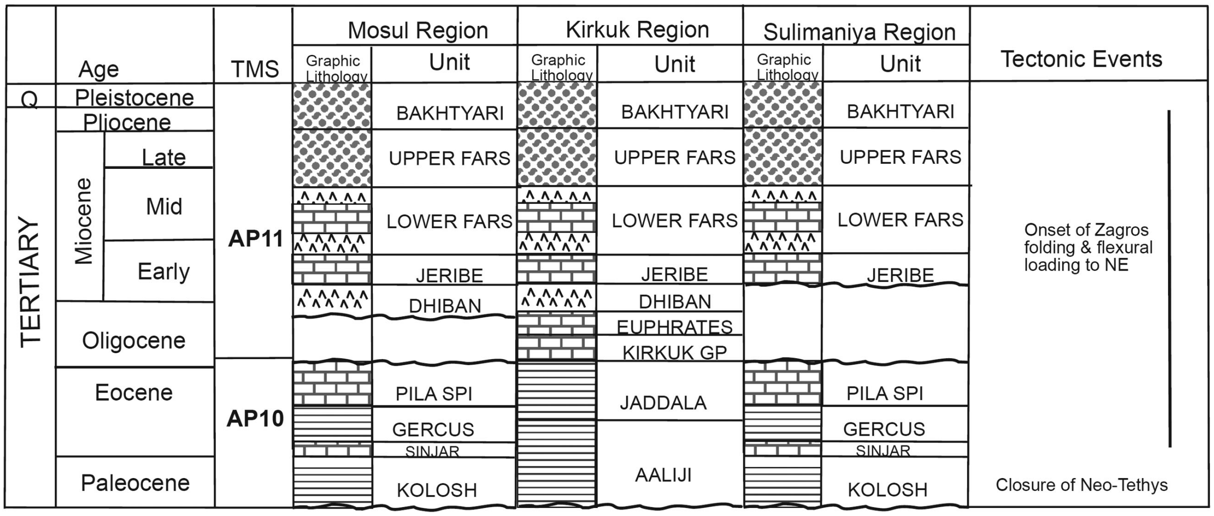

Figure 6. Facies variations within the Paleocene–Oligocene succession in the Mosul, Kirkuk and Sulimaniya regions. Marked variation is noted in the Paleocene–Oligocene sequence, whereas the Miocene–Recent stratigraphy is the same across the study area. Graphic lithology symbols and information sources as in Figure 4.

penetrate the Alan and Adaiyah Formations. The terminology may reflect dissolution of the major anhydrites in the surface layers (Jassim, *pers. comm.*).

A different pattern is observed in the Mid-Late Jurassic carbonate sequences, where the shelf deposits of the Najmah Formation, observed around Mosul, pass into the dolomite-rich Naokelekan and Barsarin Formations in the Kirkuk and Sulimaniya regions. In addition, the Gotnia Formation is observed in some wells to the south of Kirkuk, but not in the Mosul or Sulimaniya regions. In the Early Cretaceous, the Qamchuqa Formation is recognized in the Mosul and Sulimaniya regions, but the Mauddud Formation, which is equivalent to the Upper Qamchuqa (Jassim and Buday, 2006b) is recognized in the Kirkuk region. Descriptions of the Upper Qamchuqa and the Mauddud Formation indicate that both are organodetrital limestone units deposited on a carbonate ramp; therefore this may be a variation in naming convention only, and not a true facies variation.

Lastly, the Late Cretaceous sequence varies across the three areas being discussed, with increasing clastic units in the Sulimaniya region and the presence of the Aqra-Bekhme carbonate units in this area also. The thickness and age of the Shiranish Formation also varies, with the Hartha Formation present in Kirkuk but not in the other two regions.

Within the Paleocene–Eocene sequence, the time-equivalent facies become more terrestrially influenced from the Kirkuk region towards the Mosul and Sulimaniya regions (Figure 6). The Paleocene–lower Eocene carbonate-rich marls and limestone units from the Kirkuk region (the Aaliji and Jaddala Formations) pass into increasingly clastic units (the Kolosh and Gercus Formations, with minor carbonates—the Sinjar Formation) towards the hinterland (Mosul and Sulimaniya). In the far northern part of the Sulimaniya region, the Paleocene–lower Eocene units consist of an entirely terrestrial "red bed" sequence (not shown on Figure 6). The upper Eocene sequence in the hinterland area is capped by the lagoonal, cherty facies of the Pila Spi Formation, which is not present in the Kirkuk region. Basinal limestone units appear in the lower Oligocene in the Kirkuk region, with a time-equivalent erosional hiatus in the hinterland. However, by the late Oligocene–Miocene, deposition was restored across the three regions with the same formations recorded in the stratigraphic column (Figure 6).

Variation in source rock maturity within the Kirkuk Embayment

Geochemical analyses suggest that there are three distinct families of oils in the Kirkuk Embayment, corresponding to a Triassic source rock, a Jurassic source rock, and a mixed Jurassic-Cretaceous source system (Al-Ameri and Zumberge, 2012; Al-Ameri, 2014). Triassic oils are clearly distinguishable from Jurassic-Cretaceous oils, as the Triassic oil family has lower δ13C values than the Jurassic and Cretaceous oil families. This lower δ13C value is apparent whether saturated or aromatic hydrocarbon compounds are considered (Al-Ameri and Zumberge, 2012; Al-Ameri, 2014). The Jurassic and Jurassic–Cretaceous source units are mature across the majority of the region (Pitman *et al.*, 2004; Al-Ameri and Zumberge, 2012; Mohialdeen *et al.*, *in press*; Al-Ameri *et al.*, 2014) and charge Jurassic, Cretaceous and Paleogene reservoirs by vertical migration (Al-Ameri *et al.*, 2011). However, the Triassic oil family, and mature source rocks within the Triassic Kurra Chine Formation, are only found in the NW of the Kirkuk Embayment (Figure 7; Sadooni and

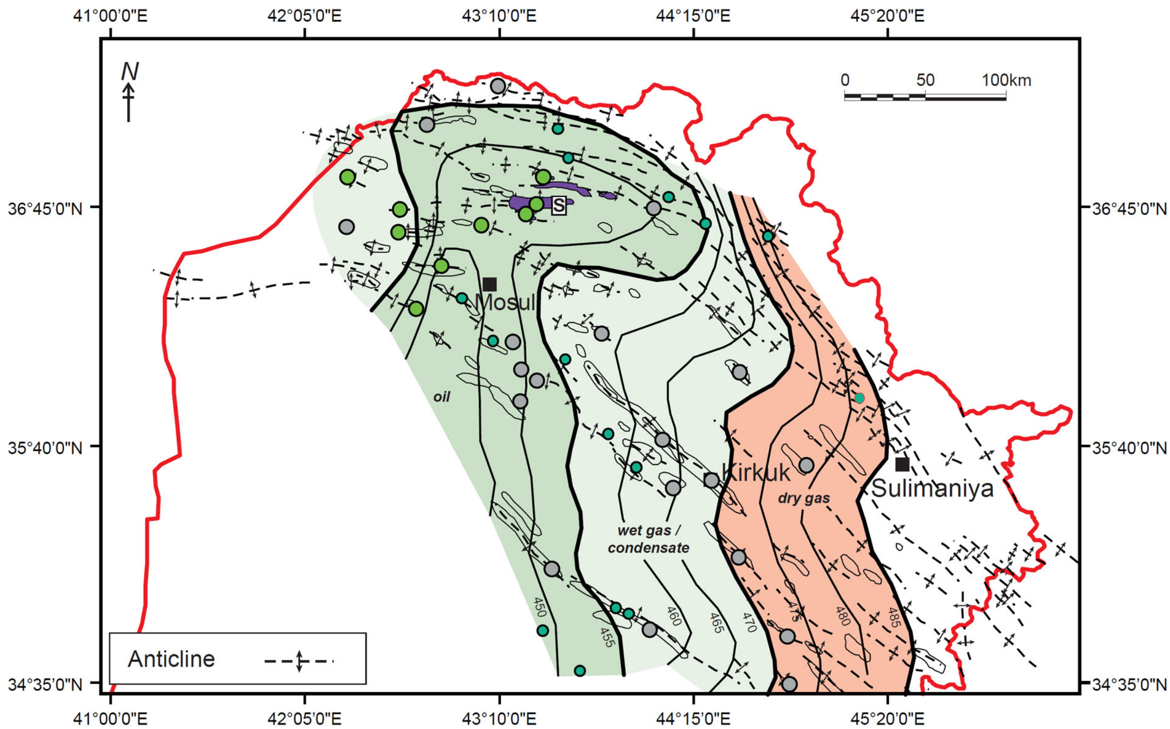

Figure 7. Map showing maturity of the Triassic source rocks within the Kirkuk Embayment. Known Triassic reservoirs are shown in purple, with *Shaikan* field marked with a letter "S". Large green dots show data points from wells where the Triassic source rocks are within the oil window; grey dots show data points where the Triassic source rocks are not within the oil window (Al-Ameri *et al.*, 2009; Al-Ameri and Zumberge, 2012; Naqishbandi *et al.*, *in press*). Contours show calculated T_{max} for the Triassic Kurra Chine Formation, and small teal-colored dots indicate data points used for T_{max} contours (English *et al.*, 2015).

Alsharhan, 2004; Al-Ameri *et al.*, 2009; Aqrawi *et al.*, 2010, Al-Ameri and Zumberge, 2012; Al-Ameri 2014). In addition, the Middle Triassic Geli Khana Formation is overmature in this area (Naqishbandi *et al.*, *in press*). Lastly, analysis of maturity of the Triassic systems indicates that only the Mosul High region falls within the oil window, whereas the remainder of the Kirkuk Embayment falls either in the condensate or dry gas zone (Figure 7; English *et al.*, 2015). Recent discoveries and exploration programs in the Mosul area are targeting the Triassic system. This is in part related to the success of the *Shaikan* field and nearby discoveries (English *et al.*, *ibid.*) to the north of Mosul. *Shaikan* field produces from the Jurassic system and wells have tested the Triassic system; nearby drilling reports also document hydrocarbon shows in the Jurassic and Triassic systems (English *et al.*, *ibid.*).

Materials and Methods

This study was carried out using remote sensing data and with extensive use of previously published maps and stratigraphic information. The primary remote sensing dataset used was a series of Landsat Thematic Mapper images obtained from NASA and processed under the MrSID algorithm (Tucker *et al.*, 2004). This algorithm combines Band 7 (mid-infrared) as red, Band 4 (near-infrared) as green, and Band 2 (visible green light) as blue. This produces a false color image in which bare rock surfaces are colored in shades of pink and brown (clastic units are darker than carbonate units) and vegetation appears in shades of green. These images have a ground resolution of 28.5 m. An additional remote sensing dataset was a digital elevation model (DEM) sourced from the Shuttle Radar Topography Mission (SRTM) that has a ground resolution of 3-Arc/sec (90 m) and a vertical resolution of approximately 10m. Voids in the data were filled using STRMFill, available from 3D Nature LLC. Since the DEM data were primarily used to identify surface anticlines and major lineaments, the vertical and horizontal resolution of the DEM and the use of SRTMFill do not compromise the results.

The surface structure and lithology were mapped from a DEM and from satellite data, and ground-truthed in a series of field excursions in the Dohuk, Shaqlawa and Sulimaniya regions during the period 2008-2010. In addition, detailed field mapping (Zebari and Burberry, 2015) was used to constrain surface maps and structural interpretations. The DEM and satellite data were also used to create a lineament map of the area. Lineaments were picked based on abrupt changes

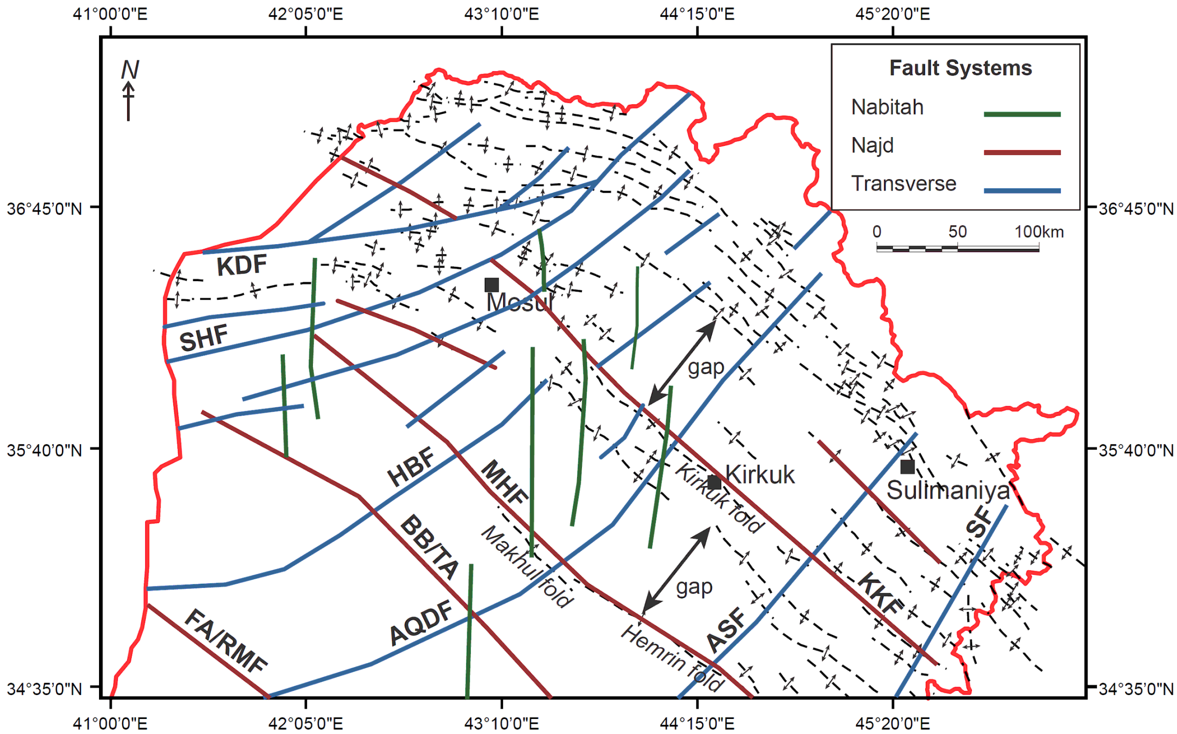

Figure 8. Basement fault trends within the Kirkuk Embayment, derived by the present author, using pre-existing fault maps (e.g. Jassim and Buday, 2006a) and lineament mapping. The surface anticlines are superimposed for reference. AQDF, Anah-Qalat-Dizeh fault; ASF, Amij-Samarra fault; BB/TA, Tikrit-Amara fault (also known as Balad-Baghdad fault); FA/RMF, Ramadi-Musayib fault (also known as Falluja-Amara fault); HBF, Hadar-Behkme fault; KDF, Kochuk-Dohuk fault, KKF, Kirkuk fault; MHF, Makhul-Hemrin fault; SHF, Sinjar-Herki fault; SF, Sirwan fault. Mosul, Kirkuk and Sulimaniya cities are marked for reference.

in topography, lithology and geomorphological features such as abrupt diversions in stream channels. Where these lineaments formed a pronounced trend they were considered to be surface markers of a deeper-seated fault, hereafter referred to as "basement faults". These putative basement faults were then categorized into those already named as part of the three major fault trends (described above) by comparison with Jassim and Buday (2006a), and remaining fault structures which were classified as "other". Thus, the basement fault maps presented in this contribution form a significant part of the new data generated in this study.

Additional maps, used for facies analysis and analysis of source rock maturity, were taken from both published, peer-reviewed literature and from recent presentations of new discoveries and recent oil-related activity, generated by operators and consultants working in Kurdistan. Key facies maps (chosen by availability of unbiased contoured maps) were taken from Aqrawi *et al.* (2010); many of these maps were compiled by co-author Andrew Horbury (Cambridge Carbonates Ltd). The maps were contoured from well data and were not created with a basement fault pattern in mind (A. Horbury, *pers. comm.*). Data on Triassic source rock maturity are taken from Al-Ameri *et al.* (2009), Al-Ameri and Zumberge (2012), English *et al.* (2015), and Naqishbandi *et al.* (*in press*).

Results

New basement fault map

Figure 8 shows the basement fault map generated from the remote sensing analyses in this study. The faults generated fall into three major orientation classes: faults trending NW-SE, faults trending N-S and faults trending broadly NE-SW. These faults match the categories described above, i.e. the NW-SE trending Najd system, the north-south trending Nabitah system, and the NE-SW trending Transverse system. Transverse system faults are the most abundant in the study area, and the Nabitah system is the least prominent. By comparison with Figure 3, it is apparent that this study has both assigned faults previously marked as "other" to the three major trends, and has recognized structures in addition to those currently known, particularly when considering the Nabitah and Transverse trends. This process has created a more detailed fault map of the Kirkuk Embayment than previous work (Figure 8), and the map has been used as the input for the following analyses.

Distribution of surface structures with respect to basement faults

As well as the new basement faults, Figure 8 includes the surface anticlines (shown in Figure 2) such

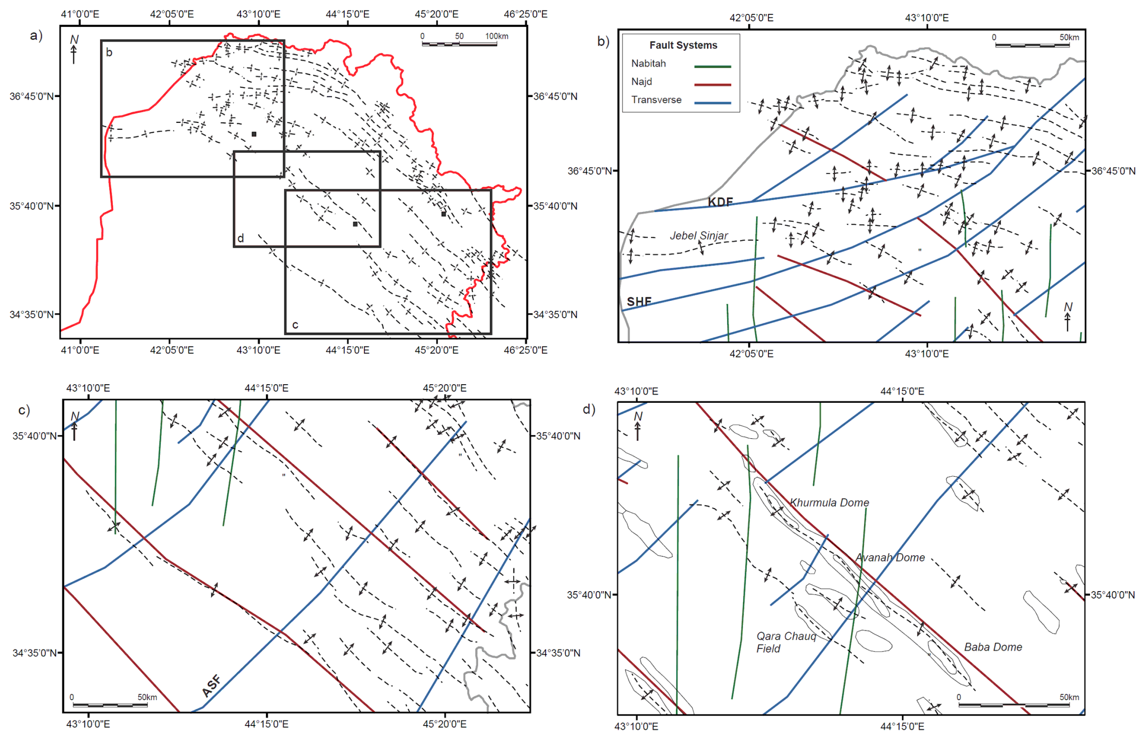

Figure 9. Specific examples of variation in anticline orientation with respect to basement fault location. (a) reference map (Figure 2); (b) variation in anticline trend in the Kochuk-Dohuk/Sinjar-Herki fault (KDF-SHF) region where the anticlines are oriented parallel to the faults; (c) close-up of anticlines terminating at the Amij-Samarra fault (ASF); and (d) close-up of anticlines in the Kirkuk region, showing the separation of the Kirkuk structure into the Khurmula, Avanah and Baba Domes and the separation of the *Qara Chauq* field from the on-trend linked structures.

that the relationship between the surface anticlines and the basement faults can be examined. On a large scale, a number of observations can be made concerning anticline location and orientation. For example, the Kirkuk and Makhul-Hemrin surface anticlines are located just to the SW of the major basement faults of the same name, and have the same orientation. There is also a deformation gap between surface anticlines close to the Kirkuk fault and surface anticlines close to the Makhul-Hemrin fault. This gap extends from the Sinjar-Herki fault in the NW to the Amij-Samarra fault in the SE. A similar but smaller gap in surface anticlines exists to the NE of the Kirkuk fault. Anticline orientation generally parallels the basement faults of the Najd trend, i.e. oriented NW-SE, but the overall anticline trend in the hinterland appears to change from NW-SE to an orientation closer to the Tauride belt, i.e. generally east-west, in the region where the Kochuk-Dohuk and Sinjar-Herki faults join (Figs 8, 9a). In addition, anticlines are oriented generally east-west in the zone created by the Kochuk-Dohuk fault and the Sinjar-Herki fault (Figure 9b). An example of this trend is Jebel Sinjar, parallel to the nearby Sinjar-Herki fault.

In the SE of the study area, many surface anticlines appear to terminate at the Amij-Samarra fault (Figure 9c) creating an apparent deformation gap (i.e. an area where there are fewer surface anticlines) between this fault and the Mosul area (Figure 8). On a smaller scale, the Kirkuk anticline structure is segmented into a series of domes — the Khurmula, Avanah and Baba domes (Figure 9d) which appear to be influenced by basement faults in the Nabitah or Transverse systems. The same pattern is noted in the *Qara Chauq* field and the two on-trend anticlines to the NW (Figure 9d).

These observations imply that the basement faults have affected deformation in the Zagros orogen between the Eocene and the present day at a number of scales. The presence of Najd faults appears to influence the location of major surface anticlines in the Foothill Zone, although this relationship cannot be identified as clearly in the High Folded Zone. This is likely to be because the NW-SE orientation of the surface anticlines and the Najd faults is the orientation expected from present-day plate motions and thus the influence of the pre-existing structures is masked. However, the presence of major anticlines separated by deformation gaps associated with the Kirkuk and Makhul-Hemrin faults indicates that the Najd faults may have influenced the location of long, potentially fault-related anticlines at the surface by the model of footwall collapse proposed by Burberry *et al.* (2010) for Iran. Cover deformation is assumed to be somewhat

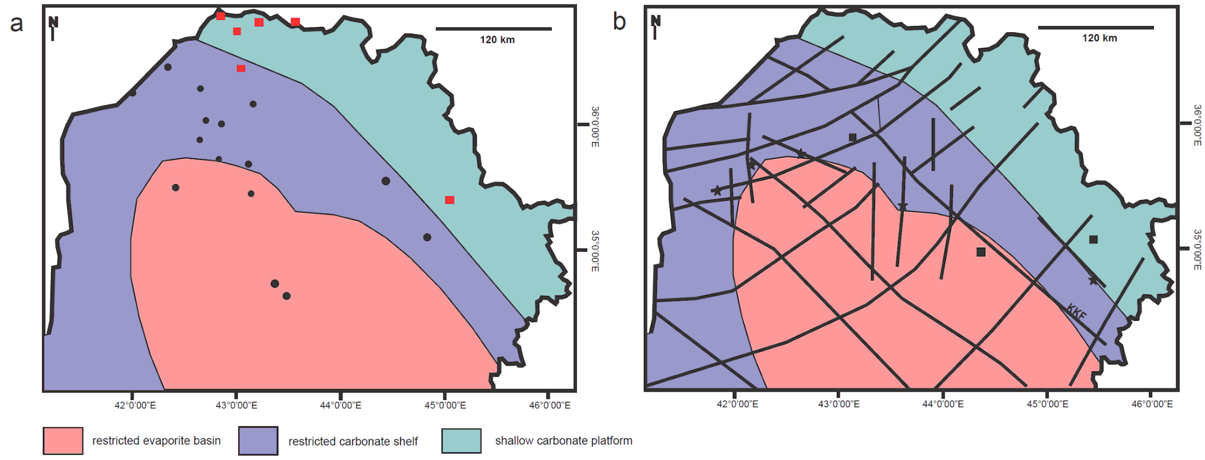

Figure 10. Carnian facies map compared to basement fault trends. (a) Lower Kurra Chine paleogeography, base map from Aqrawi *et al.* (2010). Data points used are marked with black dots (wells) or red squares (outcrop). (b) Map from (a) with basement faults superimposed. The faults mentioned in the text are either starred or named, if there is a commonly accepted name for the structure. KKF, Kirkuk fault.

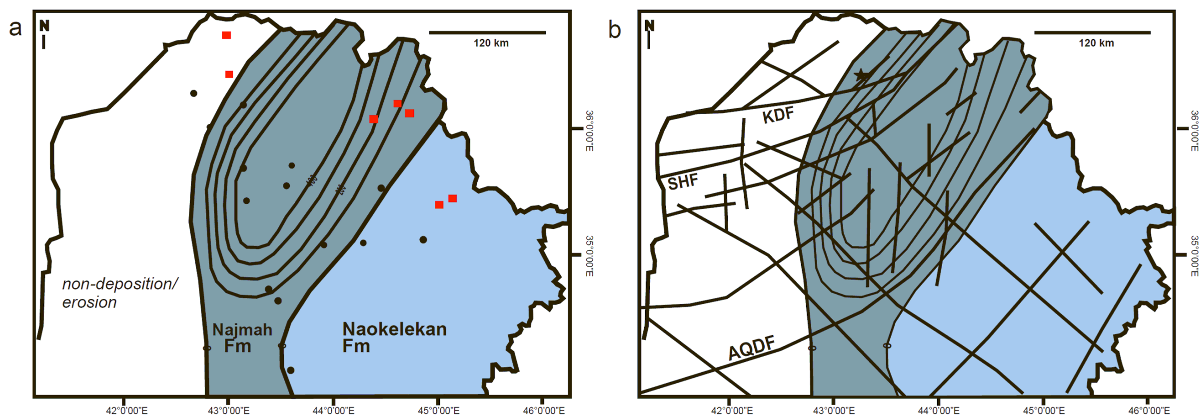

Figure 11. Late Jurassic facies map compared to basement fault trends. (a) Callovian-Oxfordian paleogeography, base map from Aqrawi *et al.* (2010). Data points used are marked with black dots (wells) or red squares (outcrop). (b) Map from (a) with basement faults superimposed. The faults mentioned in the text are either starred or named, if there is a commonly accepted name for the structure. AQDF, Anah-Qalat-Dizeh fault; KDF, Kochuk-Dohuk fault; SHF, Sinjar-Herki fault.

decoupled or separated from basement deformation, as indicated for the Lurestan Salient (Farzipour-Saein *et al.*, 2009a), and discussed for the region by Molinaro *et al.* (2005), such that the Kirkuk and Makhul-Hemrin faults are located slightly to the NE of the anticlines of the same names.

In addition the Transverse fault system appears to influence both location and orientation of the anticlines. The large-scale change in orientation from the Zagros trend to the Tauride trend may be affected by the Sinjar-Herki and Kochuk-Dohuk faults, but may also be the result of large-scale plate motions (see below). However, Jebel Sinjar is so far from the plate boundary that a basement fault has probably controlled both this anticline and other anticlines between the two major faults.

Lastly, segmentation of some anticlines is likely to be the result of a NE-SW directed principal stress interacting with basement faults that are somewhat oblique to that direction, whether subtly as in the case of the Transverse faults, or with a greater obliquity as in the case of the Nabitah faults.

Distribution of facies changes with respect to basement faults

Figure 10a shows the distribution of different facies within the Lower Kurra Chine Formation, during Carnian time. The facies map in this figure is taken from Aqrawi *et al.* (2010) and the faults superimposed in Figure 10b are those in Figure 8. At this time, the depositional environment varied from a shallow platform to a restricted basin (carbonate, carbonate-evaporite, and evaporite).

The evaporite basin appears to be partly bounded by the Kirkuk fault and a series of un-named faults in the Transverse and Nabitah systems, marked by black stars. The boundary between the restricted

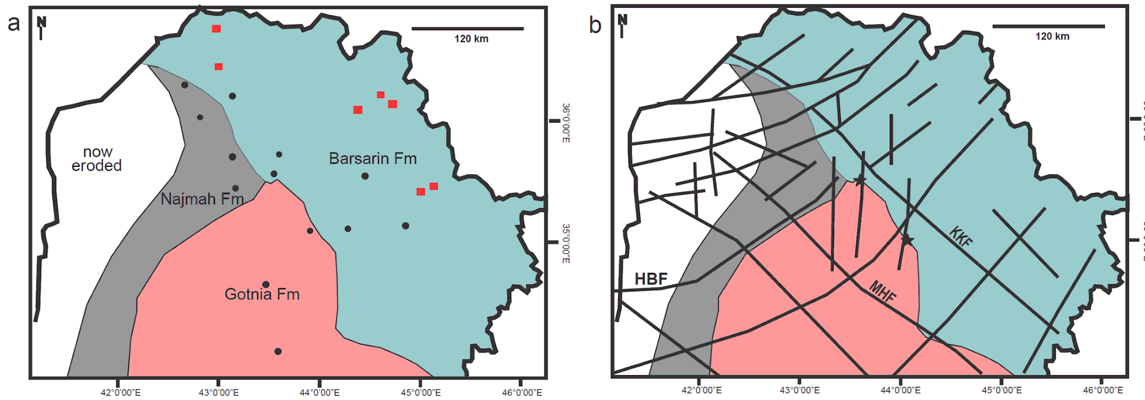

Figure 12. Late Jurassic facies map compared to basement fault trends for the Gotnia Basin. (a) Kimmeridgian paleogeography, modified after Jassim and Buday, (2006b) and Aqrawi *et al.* (2010). Data points used are marked with black dots (wells) or red squares (outcrop); (b) map from (a) with basement faults superimposed. The faults mentioned in the text are either starred or named, if there is a commonly accepted name for the structures. HBF, Hadar-Bekhme fault; KKF, Kirkuk fault; MHF, Makhul-Hemrin fault.

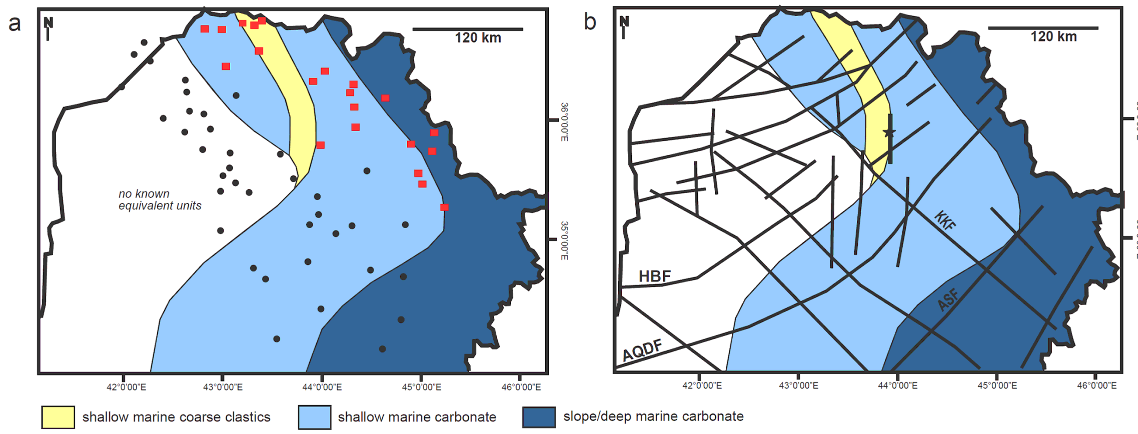

Figure 13. Early Cretaceous facies map compared to basement fault trends. (a) Tithonian-Valanginian paleogeography, base map from Aqrawi *et al.* (2010); (b) map from (a) with basement faults superimposed. The faults mentioned in the text are either starred or named, if there is a commonly accepted name for the structures. AQDF, Anah-Qalat-Dizeh fault; ASF, Amij-Samarra fault; HBF, Hadar-Bekhme fault; KKF, Kirkuk fault.

carbonate basin and the carbonate platform appears to be controlled by an un-named Najd system fault, also marked with a black star.

Figure 11a shows the distribution of different formations and the varying thickness of the Najmah Formation during Callovian-Oxfordian time. The facies map in this figure is from Aqrawi *et al.* (2010), and the faults superimposed in Figure 11b are those from Figure 8. At this time, the Najmah Formation passed laterally into the Naokelekan Formation to the SE, and there was an area of non-deposition over the present-day Mosul High (Figure 3b). The boundary between the Najmah and Naokelekan Formations appears to be influenced by the location of the Anah-Qalat-Dizeh fault. In addition, the thickness changes in the Najmah Formation appear to be influenced by the Kochuk-Dohuk/Sinjar-Herki fault and an un-named parallel fault, marked with a black star. All of these faults are within the Transverse system. The uplifted zone (the area of non-deposition or erosion) may be bounded by north-south trending faults in the Nabitah system, but there are presently no mapped faults that precisely correspond to them. Nonetheless, the north-south trend of the boundary between this zone and the Najmah Formation merits further investigation.

Figure 12a shows the distribution of facies within the Late Jurassic, during the deposition of the Gotnia Formation. The facies map is modified from Jassim and Buday (2006b) and Aqrawi *et al.* (2010), and the faults superimposed in Figure 12b are those from Figure 8. Carbonate facies vary from the Barsarin Formation to the Najmah Formation, and the Gotnia Formation (a restricted evaporite basin) is present in the south of the study area. The Gotnia Basin appears to be bounded by the Kirkuk and Hadar-Bekhme faults, and the southern limit of the Barsarin Formation appears to be bounded by the Kirkuk fault. Additional un-named structures within the Nabitah trend (starred on Figure 12b) appear to modify the shape of the Gotnia Basin. These facies patterns may also have been partially influenced by contemporaneous sea level changes (Sadooni, 1997; Hallam, 2001).

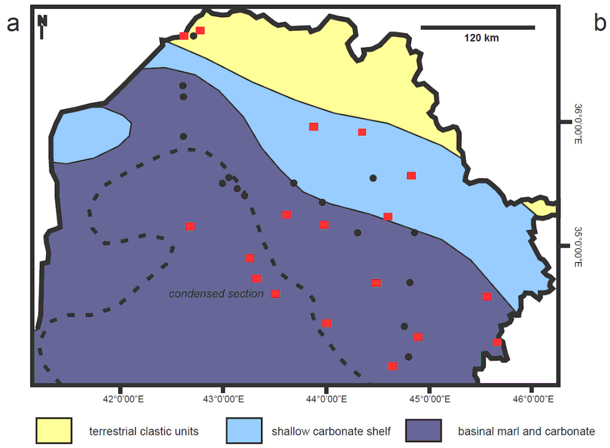

Figure 14. Paleogene facies map compared to basement fault trends. (a) Paleocene–Eocene paleogeography, base map from Aqrawi *et al.* (2010); (b) map from (a) with basement faults superimposed. The dashed line represents the boundary of a condensed stratigraphic section (see text). The faults mentioned in the text are either starred or named, if there is a commonly accepted name for the structures. HBF, Hadar-Bekhme fault; KDF, Kochuk-Dohuk fault; KKF, Kirkuk fault; MHF, Makhul-Hemrin fault; SHF, Sinjar-Herki fault; TAF, Tikrit-Amara fault.

Figure 13a shows the distribution of facies from the Late Tithonian to Middle Valangian, i.e. deposition of the Chia Gara Formation. The facies is taken from Aqrawi *et al.* (2010) and the faults superimposed in Figure 13b are those from Figure 8. The Chia Gara Formation is dominated by carbonates; the clastic belt shown in the figure marks an inner ramp sandy facies. The boundary between the shallow- and deeper-marine carbonates appears to be influenced by the Amij-Samarra Fault. The boundary between the area of no known equivalent units and the shallow carbonate facies appears to follow the Kirkuk fault in part, and run parallel to, but lie between, the Hadar-Bekhme and Anah-Qalat-Dizeh faults. In addition, the sandy facies appears to be bounded by a fault in the Nabitah system (starred).

Finally, Figure 14a shows the Paleocene–Early Eocene paleogeography of the study area, during deposition of the Kolosh and Sinjar Formations in the Mosul and Sulimaniya regions, and the deposition of the Aaliji Formation in the Kirkuk region. The facies map in this figure is taken from Aqrawi *et al.* (2010) and the faults superimposed in Figure 14b are those from Figure 8. There is a zone of terrestrial clastic material in the NE bounded by a shallow carbonate shelf, which passes to the SW into basinal carbonates and marls. The boundary between the clastic material and the shallow shelf environment is not correlated to any known fault, but the boundary between the shallow shelf and the deeper carbonate facies is influenced by the Kirkuk fault and an additional, un-named Najd fault (starred). The dashed line marking the condensed section within the basinal carbonate succession appears to be influenced by the location of the Makhul-Hemrin fault to the NE, the Tikrit-Amara fault to the SW, and the Hadar-Bekhme and an un-named Transverse fault (starred) to the NW. In addition, a second, small-scale carbonate shelf is present between the Kochuk-Dohuk and Sinjar-Herki faults in the west of the study area.

These observations imply that the basement faults have intermittently affected sedimentation in the area since the Triassic. During Carnian time, a subset of a few faults within each system, including the Kirkuk fault (Najd), appears to have affected the sedimentation patterns. During Callovian-Oxfordian time, the most influential faults are those within the Transverse system, primarily the Anah-Qalat-Dizeh fault. During the Latest Jurassic (deposition of the Gotnia Formation), the Kirkuk fault (Najd) and the Hadar-Bekhme fault (Transverse) influenced the position of the Gotnia Basin and Najmah-Barsarin boundary. A few unnamed Nabitah faults also seem to have influenced this system, but the effect is minor compared to the effects of the previously-named faults. During Tithonian-Valangian time, the Kirkuk fault (Najd) again influenced the facies patterns, as did a series of structures in the Transverse trend (the Hadar-Bekhme, Anah-Qalat-Dizeh and Amij-Samarra faults).

Finally, during the Paleocene–Eocene, the paleogeography was affected by the Kirkuk, Makhul-Hemrin and Tikrit-Amara faults (Najd) and the Kochuk-Dohuk, Sinjar-Herki and Hadar-Bekhme faults (Transverse). Again, the apparent Najd influence may also be attributed to large-scale plate motions, which will be discussed later.

The Najd and Transverse fault trends appear to have been reactivated from the Triassic to the Recent, with different faults active at different times as the relative orientations of the principal stresses and pre-existing faults changed. The Nabitah trend faults appear to have had a minor impact on the sedimentation patterns through time in this area.

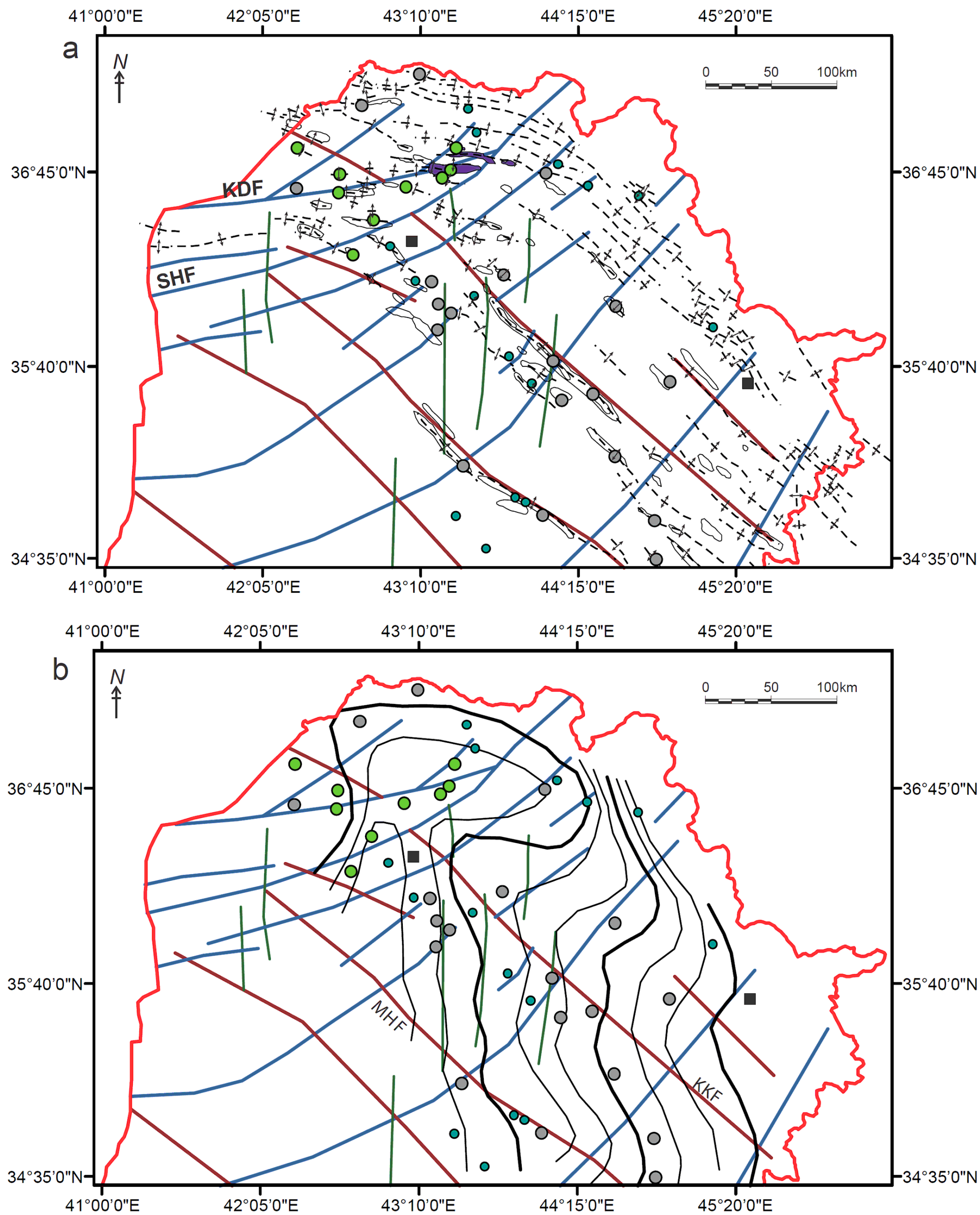

Figure 15. Maturity of the Triassic source rocks within the Kirkuk Embayment, related to basement faults. The original base map is from Figure 7 and has been separated into two parts for clarity. (a) Locations where Triassic source rocks are in the oil window (green dots), together with locations of Triassic-age discoveries; and (b) T_{max} contours for the Triassic Kurra Chine Formation. These maps indicate that the basement faults that form the Mosul High have had a significant influence on the distribution of T_{max} and where the Triassic source rocks are in the oil window. The faults mentioned in the text are named. KDF, Kochuk-Dohuk fault; KKF, Kirkuk fault; MHF, Makhul-Hemrin fault; SHF, Sinjar-Herki fault.

Distribution of source rock maturity with respect to basement faults

As noted above, there is variation in the maturity of Triassic source rocks across the Kirkuk Embayment. Figure 15a illustrates that samples which show oil potential, or discoveries and producing fields within the Triassic Kurra Chine Formation, are clustered around the Mosul High. The Mosul High is bounded by both the Sinjar-Herki and Kochuk-Dohuk faults, and by additional structures within the Nabitah system. Figure 15b superimposes the T_{max} contours from Figure 7 (English *et al.*, 2015) on the basement fault map from Figure 8, indicating that the contours follow the basement faults and basement topography (Figure 3b) in the northern part of the Kirkuk Embayment and that the contours are influenced by the Najd fault system in the southern part. Significant faults within the Najd system are the Kirkuk fault and the Makhul-Hemrin

fault, affecting the shape of the contours in the Kirkuk Trough.

These observations imply that the maturity of the Triassic source rocks has some relationship to large-scale basement structure and topography. These source rocks are mature over the Mosul High and over-mature in the rest of the Kirkuk Embayment. The factor that links basement topography to source-rock maturity is the thickness of the sedimentary column overlying the basement. Where the basement forms a high, the sedimentary cover is in general thinner, and burial depths are such that the Triassic source rocks are mature. Where the basement forms a pronounced trough, sedimentary thicknesses are greater and Triassic units are over-mature. Thus it appears that the large-scale basement topography rather than the specific reactivation of individual faults may in this case have been the main factor controlling in distribution of source-rock maturity.

Taken together, these results indicate that the three basement fault trends have periodically been reactivated to influence facies changes from the Triassic to the Recent. Different fault sets have been most influential at particular times, as indicated by the facies maps, but the Transverse system was influential throughout the Jurassic and Cretaceous and into the Cenozoic. In addition, all three fault trends influenced the location and orientation of surface structures, whether subtly, as in the case of the Nabitah system, or more dramatically, as in the case of the Transverse and Najd systems. Finally, the large-scale basement topography influenced cover sediment thickness, affecting the maturity of the Triassic source rocks across the Kirkuk Embayment.

Discussion

The preceding examples demonstrate that surface structure, facies variations and distribution of sourcerock maturity in northern Iraq are all influenced by basement configuration, whether it be via the potential reactivation of specific fault structures in the basement from the Triassic to Recent, or the large-scale topography generated by these faults. These results need to be understood within the correct plate tectonic context, however, as some changes in facies or in surface structure orientation may be the result of changes in large-scale plate motions.

The Najd trend, noted above as being a key influence on facies and structural variation, was oriented perpendicular to the main extension direction during rifting and passive margin subsidence in the Triassic and Late-Mid Jurassic. In addition, the trend was perpendicular to the main compression direction during Eocene-Recent compression. The former observation means that it may be difficult to separate facies changes due to fault movement from facies changes due to increasing water depth on a subsiding margin. However, it is reasonable to suppose that the two effects will interact, as the Najd trend is favorably oriented to have been reactivated as normal faults during rifting and subsidence, thus enhancing the effects of changing water depths and therefore facies distribution. The latter observation implies that anticlines influenced by the Najd trend will be difficult to separate from anticlines formed as a result of the regional compression direction without basement influence.

However, the observation that the anticlines in the foreland, the Kirkuk and Makhul-Hemrin structures, are located above the faults of the same name, with a major deformation gap between them, suggests that the location of these long anticlines is indeed governed by the presence of the basement faults. This type of relationship, where long hinge-length, fault-related anticlines are spatially related to inherited faults and present-day thrusts, with either a deformation gap or a series of shorter hinge-length, less strongly-faulted anticlines, has been demonstrated for part of the Fars Zone in Iran by Burberry *et al.* (2010). Thus, although the effect of large scale plate motions is not negligible, there is a reasonable expectation that there will be a contribution from the presence of the basement faults.

The Najd system is favorably oriented to be reactivated during Eocene-Recent deformation as a series of thrust faults and indeed, other authors (Sepehr and Cosgrove, 2004, 2005; Jassim and Buday, 2006c; Carruba *et al.*, 2006; Aqrawi *et al.*, 2010) invoke the involvement of these structures in creating valid cross-sections. These concerns do not apply to the Transverse and Nabitah systems, as these fault systems are both oriented oblique to the present-day compression direction and are reactivated as transpressional systems. Major zone-bounding thrust faults such as the Main Zagros Thrust (Figure 1) are interpreted to be the surface expressions of reactivated basement faults from this system (Ameen, 1992; Jassim and Buday, 2006c; De Vera *et al.*, 2009).

The effects of this reactivation on facies and surface structure can mostly be separated from large-scale plate motion effects. One exception to this is the apparent spatial coincidence of the change in the overall trend of the surface anticlines with the Kochuk-Dohuk and Sinjar-Herki faults. This change may also be accounted for by the change in large-scale plate motion. NE-SW directed convergence occurs across the SE part of the study area, accommodated by NE-SW compression and dextral transpression (Talebian and Jackson, 2002; Allen *et al.*,2004). However in the northern part of the study area, the dominant convergence direction is north-south directed, as a result of margin geometry and plate motions (Sella *et al.*, 2002).

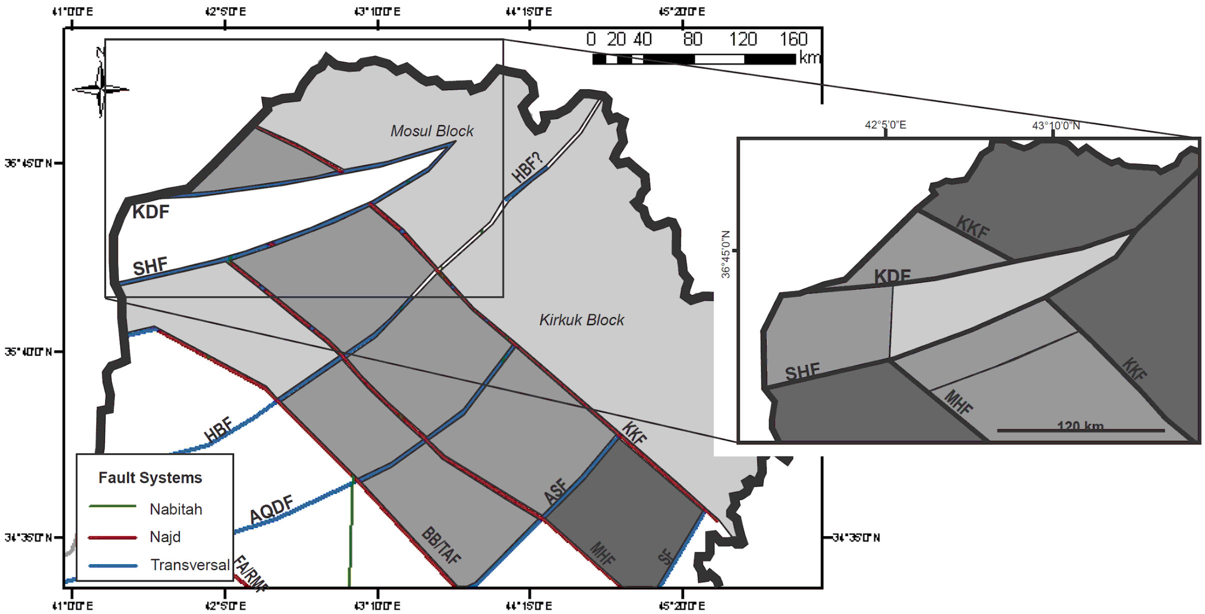

Figure 16. Map of the eleven large-scale basement blocks in the Kirkuk Embayment, each with a geologic history that is linked to that of the other blocks and yet distinct. AQDF, Anah-Qalat-Dizeh fault; ASF, Amij-Samarra fault; BB/TAF, Tikrit-Amara fault (also known as Balad-Baghdad fault); FA/RMF, Ramadi-Musayib fault (also known as Falluja-Amara fault); HBF, Hadar-Behkme fault; KDF, Kochuk-Dohuk fault, KKF, Kirkuk fault; MHF, Makhul-Hemrin fault; SHF, Sinjar-Herki fault; SF, Sirwan fault. The inset map shows detail of the potential sub-blocks around the Mosul High. Deeper shading represents deeper-lying basement blocks. Each block or sub-block has a subtly different tectonic and burial history, indicating that variations in structure, facies and hydrocarbon maturity may be understood in terms of basement blocks.

Therefore, it can be stated with a high degree of confidence that the original Precambrian structures have periodically been reactivated as the stress regime changed over time, and that all three Precambrian fault systems (the Najd, Nabitah and Transverse trends) have influenced facies distributions and structures at various times from the Triassic to the present day. All three trends are considered to have been active during the Zagros Orogeny, with the Najd and Transverse systems having had the greatest effect on the surface geometry, facies changes and hydrocarbon potential. This is related to the favorable orientation of the Transverse and Najd trends relative to the overall plate motion.

In Recent time, based on the angular velocities calculated from the NUVEL-1A model (DeMets *et al.*, 1994), the Arabian Plate has moved NNW relative to the Eurasian Plate in the study area. Given this movement direction, Transverse faults like the Sinjar-Herki and Kochuk-Dohuk faults, oriented nearly orthogonal to the plate motion vector, have been reactivated as reverse faults to create the Mosul High. This reactivation appears to be limited to the region closest to the Zagros deformation front. In contrast, the basement structures in neighboring Syria still show a trough zone at depth (Jamal *et al.*, 2000) although there may be partial inversion of some cover structures. The importance of structures on the Transverse trend was also described by Ameen (1992), separating the study area into two distinct areas with different tectonic histories—the Mosul and Kirkuk areas—corresponding to the Mosul High and Kirkuk Trough nomenclature of the present contribution.

Similar relationships are discussed by other authors for the Iranian part of the Simply Folded Belt. Surface structures in the Iranian Zagros are partitioned into distinct zones, such as the Dezful Embayment and the Fars zone, by the presence of reactivated faults in the Nabitah system—most notably the Kazerun fault (Figure 1). Seismic data from the nearby Persian Gulf (Burberry *et al.*, 2011) indicates that the Kazerun fault was reactivated during the Cretaceous and the Miocene. This result is consistent with other studies in the area (e.g. Sherkati *et al.*, 2005; Fard *et al.*, 2006; Ahmadhadi *et al.*, 2007; Lacombe *et al.*, 2011) describing a basement influence on the generation, orientation and detailed geometry of structures forming during the Zagros Orogeny. Facies variations similar to those described in this contribution, i.e. relating to the position of basement faults, may also control the distribution of the Hormuz salt within the Persian Gulf. The salt unit is absent in the Dezful Embayment in Iran, potentially present in the Lurestan Salient, and present in the Fars Salient (Ameen, 1991; Casciello *et al.*, 2009). Diapirs within the Persian Gulf indicate that the Hormuz salt was remobilized along Nabitahsystem faults (Alsharhan and Kendall, 1986; Edgell, 1996) during the Cretaceous. Again, the Kazerun fault, part of the Nabitah system, influences regions where natural gas is found

in Iran. Gas is found in the Fars zone to the east of the Kazerun fault, but has not been reported in the Dezful Embayment to the NW (Beydoun *et al.*, 1992).

These observations from the wider Zagros belt further indicate that different fault systems have been reactivated preferentially in different parts of the belt. The Nabitah system is considerably more influential in the SE Persian Gulf than in the present study area. Correspondingly, the Transverse system is more influential in the study area than in the Gulf, reflecting the change in local plate motion and the partitioning of deformation as a result of the large-scale plate rotation. The only major structure in the Persian Gulf which may be related to Transverse system faults is the Qatar–South Fars Arch (Perotti *et al.*, 2011).

Considering all three basement fault trends as a single interacting system, the basement of the study area in Northern Iraq can be divided into a series of mobile blocks, which have moved semi-independently throughout the geologic history of the area. The overall effect of these three interacting fault trends is that the basement within Northern Iraq has behaved over time as a "continuum rubble" of interacting blocks, with multiple phases of movement on each fault involved in the cover deformation, rather than as a coherent mass (c.f. Dewey *et al.*, 2008; Taylor *et al.*, 2008). Each basement block and the sediments thereon therefore have a discrete and distinct geologic history. The idea that basement may be fragmented into discrete blocks that interact in predictable ways in subsequent stress regimes has been demonstrated for the Coso region in southern California by Dewey *et al.* (2008) and Taylor *et al.* (2008) and is frequently invoked to explain the large-scale geometry of the California Transverse Ranges (e.g. Namson and Davis, 1988).

In the study area, eleven large basement blocks can be defined north of the Tikrit-Amara (also known as the Balad-Baghdad) fault (Figure 16). These blocks are bounded by faults in the Najd and Transverse systems and are typically subdivided by additional faults in these systems or by Nabitah faults (inset map, Figure 16). The basement blocks are delimited based on the faults affecting facies distribution or surface structure, as described above, indicating that these structures are the dominant reactivated structures. This map differs from previous maps (e.g. Buday and Jassim, 1984; Jassim and Buday, 2006a) in the number of small-scale basement blocks in this area, representing the interaction of all pre-existing fault trends over time. Many faults appear not to be active NE of the Kirkuk fault; one exception to this is the Hadar-Bekhme fault (Zebari and Burberry, 2015) which separates the Mosul Block and the Kirkuk Block (Ameen, 1992) in the hinterland of the belt.

These basement zones are not identical to the surface longitudinal segments of the Zagros belt, as the High Folded Zone–Foothill Zone boundary is located to the NE of the Kirkuk fault. However, it is plausible that the shorter Najd fault identified in Figure 8 to the NE of the Kirkuk fault, continues across Kurdistan and influences the boundary of the High Folded Zone. Independent evidence to confirm this has not yet been produced, as the gravity data used by Jassim and Buday (2006a) to delineate other basement faults do not extend reliably into this region, and the surface signature of the Najd fault interactions in the hinterland is obscured by the effect of recent plate motions.

The ability to delineate basement blocks with specific geologic histories and specific facies and deformation patterns becomes an important tool in predicting hydrocarbon presence and maturity in an exploration setting. An example is given for the region around the Mosul High in the inset map in Figure 16, where the Mosul High is represented by the highest basement block, resulting in source rock maturation in an isolated shallow depocenter, tending to produce sulfur-rich heavy oil in the Triassic system. Thus, a knowledge of the basement geometry and its probable effect on burial depths, maturity and structural development during subsequent deformation becomes an important tool in understanding why apparently on-trend surface structures may have very different hydrocarbon signatures.

Conclusions

This paper has presented examples of basement fault reactivation affecting both structural style and facies variations in the northern portion of the Zagros Simply Folded Belt in northern Iraq. Surface structures, Triassic–Recent facies changes and Triassic source rock maturity in this area are constrained by the interaction of three major basement fault trends, which have been reactivated throughout the time period under consideration (Triassic–Recent). The Transverse and Najd trends have had the greatest influence on tectonics and sedimentation in the study area. These faults partition the basement into a series of basement blocks, each with a separate geologic history which is distinct from but linked to that of the surrounding blocks.

These main basement blocks and the Najd and Transverse basement fault trends have affected subsequent sedimentation and deformation patterns and hydrocarbon pool locations and maturity within northern Iraq and the rest of the Zagros region. This distinct geologic histories of the basement blocks cause local but predictable differences in sediment thickness and structural style across the Zagros belt.

This has also controlled the locations where specific source-rocks are mature. During exploration procedures, therefore, the basement in the study area should be considered as a "rubble" rather than a coherent unit. An understanding of the location and behavior of basement blocks and the related faults thus becomes a valuable predictive tool in exploration.

Acknowledgments — Mjahid Zebari is thanked for contributing field data to verify maps in this contribution. Reviewers S. Sherkati and S. Z. Jassim are thanked for careful and constructive reviews of this manuscript. JPG staff are thanked for editorial suggestions which improved the text.

References

ABDELSALAM, M.G., and STERN, R.J., 1996. Sutures and shear zones in the Arabian-Nubian Shield. *Journal of African Earth Sciences*, **23** (3) 289-310.

AHMADHADI, F., LACOMBE, O., and DANIEL, J. M., 2007. Early reactivation of basement faults in Central Zagros (SW Iran): evidence from pre-folding fracture populations in the Asmari Formation and Lower Tertiary paleogeography. In: Thrust Belts and Foreland Basins; From Fold Kinematics to Hydrocarbon Systems. Frontiers in Earth Sciences. O. Lacombe, J. Lavé, J. Verges, and F. Roure (eds.), Springer Verlag, Chapter 11, 205–208.

AL-AMERI, T.K., 2014. Oil biomarkers, isotopes and palynofacies are used for petroleum system type and migration pathway assessments of Iraqi oil fields. *Arabian Journal of Geosciences* DOI 10.1007/s12517-014-1606-5

AL-AMERI, T. K., and ZUMBERGE, J., 2012. Middle and Upper Jurassic hydrocarbon potential of the Zagros Fold Belt, North Iraq. *Marine and Petroleum Geology*, **36,** 13-34.

AL-AMERI, T.K., AL-DOLAIMY, Q.H., and AL-KHAFAJI, A.J., 2009. Palynofacies and hydrocarbon generation potential of the upper Triassic Kurrachine Formation and lower part of the Baluti Formation, Mosul Block, Northwest Iraq. *Arabian Journal of Geosciences*, **2**, 273-283. DOI 10.007/s12517-009-0041-5

AL-AMERI, T.K., ZUMBERGE, J., and MARKARIAN, Z. M., 2011. Hydrocarbons in the middle Miocene Jeribe Formation, Dyala region, NE Iraq. *Journal of Petroleum Geology*, **34** (2) 199-216.

AL-AMERI, T.K., NAJAF, A.A., AL-KHAFAJI, A.S., ZUMBERGE, J., and PITMAN, J., 2014. Hydrocarbon potential of the Sargelu Formation, North Iraq. *Arabian Journal of Geosciences,* **7,** 987-1000. DOI 10.1007/s12517-013-0875-8.

AL-BANNA, A. S., AL-SAGRI, K. E., and HUMIDE, L.Z., 2013. The boundary between stable and unstable shelf in Iraq as inferred from using ideal gravity to elevation ratio. *Arabian Journal of Geoscience*, **6**, 187-191.

AL-DAWOODY, A.N., 2013. A gravity survey and data interpretation of Tawke structure (Iraqi Kurdistan region). *Kirkuk University Journal – Scientific Studies* **8** (4) 26-37.

AL-YASI, AL-KHERSAN and AL-KASHAN, add initials 2006. Construction of basement depth map in Al-Jezira area Northwestern Iraq, using two dimensional spectral analysis technique. *Basrah Journal of Science*, **24** (1) 82-91.

ALAVI, M., 2004. Regional stratigraphy of the Zagros Fold-Thrust Belt of Iran and its pro-foreland evolution. *American Journal of Science*, **304,** 1-20.

ALAVI, M., 2007. Structures of the Zagros fold-thrust belt in Iran. *American Journal of Science*, **307**, 1064–1095.

ALLEN, M. B., J. JACKSON and R. WALKER, 2004. Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of the short term and long term deformation rates. *Tectonics*, **23**, TC2008.

ALSHARHAN, A. S., 2014. Petroleum Systems in the Middle East. In: Rollinson, H. R., Searle, M. P., Abbasi, I. A. , Al-Lazki, A. I., and Al Kindi, M. H., (eds.), Tectonic Evolution of the Oman Mountains. *Geol. Soc. Lond., Spec. Publ.* **392**, 361-408

ALSHARHAN, A.S., and KENDALL, C. G. St C., 1986. Precambrian to Jurassic Rocks of Arabian Gulf and adjacent areas: their facies, depositional setting and hydrocarbon habitat. *AAPG Bulletin*, **70** (8) 977-1002.

AMEEN, M. A., 1991. Possible forced folding in the Taurus-Zagros Belt of northern Iraq. *Geological Magazine*, **128** (6) 561-584.

AMEEN, M.A., 1992. Effect of Basement Tectonics on Hydrocarbon Generation, Migration, and Accumulation in Northern Iraq. *AAPG Bulletin*, **76** (3), 356-370.

AMIN, G.F., YASS, A.M., and YOUSIF, M.A. 2009. Gravity and Magnetic Study in Wadi Shalgha, east of Erbil, North Iraq. *Iraqi Bulletin of Geology and Mining*, **5** (1), 101-117.

AQRAWI, A.A.M., GOFF, J.C., HORBURY, A.D., and SADOONI, F. N., 2010. The Petroleum Geology of Iraq. Scientific Press, Beaconsfield, UK. 424pp.

AUDET, P., and BURGMANN, R., 2011. Dominant role of tectonic inheritance in supercontinent cycles. *Nature Geoscience* **4**, 184–187 doi:10.1038/ngeo1080.

BAHROUDI, A., and TALBOT, C. J., 2003. The configuration of the basement beneath the Zagros Basin. *Journal of Petroleum Geology* **26**(3), 257-282.

BAYONA, G., and THOMAS, W. A., 2006. Influence of preexisting plate-margin structures on foredeep filling: Insights from the Taconian (Blountian) clastic wedge, Southeastern USA. *Sedimentary Geology* **191**(1-2), 115-133.

BERBERIAN, M., 1981. Active Faulting and Tectonics of Iran. *AGU/GSA Geodynamics series* Vol **3**, 33-69.

BERBERIAN, M., 1995. Master "blind" thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics* **241**, 193-224.

BEYDOUN, Z. R., HUGHES CLARKE, M. W., and STONELEY, R., 1992. Petroleum in the Zagros Basin: A Late Tertiary Foreland Basin overprinted onto the outer edge of a vast hydrocarbon-rich Paleozoic-Mesozoic passive-margin shelf. In: MacQueen, R. W., and Leckie, D.A. (eds.), Foreland Basins and Fold Belts. *AAPG Memoir* **55**, 309-339.

BLANC, E. J. P., M. B. ALLEN, S. INGER and H. HASSANI, 2003. Structural styles in the Zagros Simple Folded Zone, Iran. *Journ. Geol. Soc., Lond.*, **160**, 401–412.

BRETIS, B., N. BARTL and B. GRASEMANN, 2011. Lateral fold growth and linkage in the Zagros fold and thrust belt (Kurdistan, NE Iraq). *Basin Research*, **23**, 615-630.

BUDAY, T., and JASSIM, S.Z., 1984. Geological map of Iraq, 1:1,000,000 Scale Series, sheet No. 2, Tectonic Map of Iraq. Publication of Geological Survey of Iraq, Baghdad.

BURBERRY, C. M., J. W. COSGROVE and J. G. LIU, 2010. A study of fold characteristics and deformation style using the evolution of the land surface: Zagros Simply Folded Belt, Iran. In: Leturmy, P., and C. Robin, C. (eds.), Tectonic and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic. *Geol. Soc. Lond., Spec. Publ.* **330**, 139–154.

BURBERRY, C.M., JACKSON, C. A-L., and COSGROVE, J.W.C., 2011. Late Cretaceous to Recent deformation related to inherited structures and subsequent compression within the Persian Gulf: A 2D seismic case study. *Journ. Geol. Soc.*, **168**, 485-498. doi: 10.1144/0016-76492010-022

BUTLER, R.W.H., HOLDSWORTH, R.E., and LLOYD, G.E., 1997. The role of basement reactivation in continental deformation. *Journ.*

Geol. Soc., **154**, 69-71. doi: 10.1144/gsjgs.154.1.0069
BUTLER, R.W. H., TAVARNELLI, E., and GRASSO, M. 2006. Structural inheritance in mountain belts: An Alpine-Apennine perspective. *Journal of Structural Geology* **28**, 1893-1908.
CARRUBA, S., PEROTTI, C.R., BUONAGURO, R., CALABRO, R., CARPI, R., and NAINI, M., 2006. Structural Pattern of the Zagros fold-and-thrust belt in the Dezful Embayment (SW Iran). *GSA Special Paper* **414**, p11-32
CASCIELLO, E., VERGES, J., SUARA, E., CASINI, G., FERNANDEZ, N., BLANC, E., HOMKE, S., and HUNT, D.W., 2009. Fold patterns and multilayer rheology of the Lurestan Province, Zagros Simply Folded Belt (Iran). *Journ. Geol. Soc. Lond.*, **166**, 947-959. doi: 10.1144/1106-76492008-138
CSONTOS, L., Á. SASVÁRI, T. POCSAI, L. KÓSA, A. T. SALAE and A. ALI, 2012. Structural evolution of the northwestern Zagros, Kurdistan Region, Iraq: Implications on oil migration. *GeoArabia*, **17**, 2, 81-116.
DEMETS, C., GORDON, R.G., ARGUS, D.F., and STEIN, S., 1994. Effect of recent revisions to the geomagnetic reversal timescale on estimates of current plate motion. *Geophysical Research Letters*, **21** (20) 2191-2194.
DE VERA, J., GINES, J., OEHLERS, M., McCLAY, K., and DOSKI, J., 2009. Structure of the Zagros fold and thrust belt in Kurdistan Region, northern Iraq. *Trabajos de Geologia* **29**, 213-217.
DEWEY, J. F., TAYLOR, T., and MONASTERO, F. C., 2008. Transtension in the brittle field: the Coso region, Southern California. *International Geology Review*, **50**, 193-217.
EDGELL, H.S., 1996. Salt Tectonism in the Persian Gulf. In: G. I. Alsop, Blundell, D. J., and Davison, I. (eds.), Salt Tectonics. *Geol. Soc. Lond., Spec. Publ.* **100**, 129-151.
ENGLISH, J. M., LUNN, G. A., FERREIRA, L., and YACU, G., 2015. Geologic Evolution of the Iraqi Zagros, and its Influence on the Distribution of Hydrocarbons in the Kurdistan Region. *AAPG Bulletin,* doi:10.1306/06271413205.
FARD, I. A., A. BRAATHEN, M. MOKHTARI and S. A. ALAVI, 2006. Interaction of the Zagros Fold–Thrust Belt and the Arabian-type, deep-seated folds in the Abadan Plain and the Dezful Embayment, SW Iran. *Petroleum Geoscience*, 12, 347–362.
FARZIPOUR-SAEIN, A., YASSAGHI, A., SHERKATI, S., and KOYI, H., 2009a. Mechanical stratigraphy and folding style of the Lurestan region in the Zagros Fold-Thrust Belt, Iran. *Journ. Geol. Soc.*, **166**, 1101-1115. doi: 10.1144/0016-76492008-162.
FARZIPOUR-SAEIN, A., YASSAGHI, A., SHERKATI, S., and KOYI, H., 2009b. Basin evolution of the Lurestan Region in the Zagros Fold-and-Thrust Belt, Iran. *Journal of Petroleum Geology* **32** (1), 5-20.
FREHNER, M., D. REIF, D., and GRASEMANN, B., 2012. Mechanical versus kinematical shortening reconstructions of the Zagros High Folded Zone (Kurdistan Region of Iraq). *Tectonics*, doi:10.1029/2011TC003010.
GHASEMI, A., and C.J. TALBOT, 2005. A new tectonic scenario for the Sanandaj-Sirjan Zone (Iran). *Journal of Asian Earth Sciences*, **26**(6), 1-11.
GRUNAU, H.R., 1981. Overview of source rocks for oil and gas; a worldwide survey. V3, Source Rocks of the Middle East. Dublin, Petroconsultants, 295pp.
HALLAM, A., 2001. A review of the broad pattern of Jurassic sea-level changes and their possible causes in the light of current knowledge. *Palaeogeography, Palaeoclimatology, Palaeoecology* **167** (1-2) 23-37
HANDFORD, C.R., and R.G. LOUCKS 1993. Carbonate depositional sequences and systems tracts—Responses of carbonate platforms to relative sea-level changes. In: R.G. Loucks and G.F. Sarg (Eds.), Carbonate Sequence Stratigraphy. *AAPG Memoir* **57**, 3-41.
HAYNES, S. J., and McQUILLAN, H. 1974. Evolution of Zagros Suture Zone, Southern Iran. *Geological Society of America Bulletin* **85**(5), 739-744.
HESSAMI, K., KOYI, H. A., and TALBOT, C. J. 2001a. The significance of strike-slip faulting in the basement of the Zagros fold and thrust belt. *Journal of Petroleum Geology* **24**(1), 5-28.
HESSAMI, K., KOYI, H. A., TALBOT, C. J., TABASI, H., and SHABANIAN, E. 2001b. Progressive unconformities within an evolving foreland fold-thrust belt, Zagros Mountains. *Journal of the Geological Society* **158,** 969-981.
HOMKE, S., VERGES, J., GARCES, M., EMAMI, H., and KARPUZ, R., 2004. Magnetostratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Push-e Kush Arc (Lurestan Province, Iran). *Earth and Planetary Science Letters*, **225** (3-4) 397-410.
HUERTA, A.D., and HARRY, D.L. 2012. Wilson cycles, tectonic inheritance, and rifting of the North American Gulf of Mexico continental margin. *Geosphere*, **8**, 374-385.
IBRAHIM, A. O., 2009. Tectonic Style and Evolution of the NW Segment of the Zagros Fold-Thrust Belt, Sulaimani Governorate, Kurdistan Region, NE Iraq. Ph.D. thesis, University of Sulaimani, Sulaimani.
JAMAL, M., BIZRA, Y., and CARON, C., 2000. Palaeogeography and hydrocarbon habitat of the Triassic series in Syria. *Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science*, **331** (2) 133-139
JASSIM, S. Z., 2006. Paleozoic Megasequences (AP1-AP5). In: Jassim, S., and Goff, J. (eds.), The Geology of Iraq. Dolin (Prague) and Moravian Museum (Brno), pp. 91-103.
JASSIM, S. Z., and BUDAY, T., 2006a. Tectonic Framework. In: Jassim, S., and Goff, J. (eds.), The Geology of Iraq. Dolin (Prague) and Moravian Museum (Brno), pp. 45-56.
JASSIM, S. Z., and BUDAY, T., 2006b. Late Tithonian-early Turonian Megasequence AP8. In: Jassim, S., and Goff, J. (eds.), The Geology of Iraq. Dolin (Prague) and Moravian Museum (Brno), pp. 124-140.
JASSIM, S. Z., and BUDAY, T., 2006c. Units of the Unstable Shelf and the Zagros Suture. In: Jassim, S., and Goff, J. (eds.), The Geology of Iraq. Dolin (Prague) and Moravian Museum (Brno), pp. 71-83.
KENT, W.N., 2010. Structures of the Kirkuk Embayment, northern Iraq: Foreland structures of Zagros Fold Belt Structures? *GeoArabia*, **15** (4) 147-188.
LACOMBE, O., BELLAHSEN, N., and MOUTHEREAU, F., 2011. Fracture patterns in the Zagros Simply Folded Belt (Fars, Iran): constraints on early collisional tectonic history and role of basement faults. *Geological Magazine*, **148**(5-6), 940-963.
LAWA, FA, KOYI, H., and IBRAHIM, A., 2013. Tectonostratigraphic evolution of the NW segment of the Zagros fold-thrust belt, Kurdistan, NE Iraq. *Journal of Petroleum Geology***, 36**, 75–96. doi: 10.1111/jpg. 12543.
LEES, G. M., 1955. Recent earth movements in the Middle East. *Geologische Rundschau* **43**, 221-226.
MARSHAK, S., 2004. Salients, Recesses, Arcs, Oroclines and Syntaxes – A review of ideas concerning the formation of map-view curves in fold-thrust belts. In: McClay, K.R. (Ed.), Thrust tectonics and hydrocarbon systems. *AAPG Memoir* **82**, 131-156.
McCLAY, K., WHITEHOUSE, P.S., DOOLEY, T., and RICHARDS, M., 2004. 3D evolution of fold and thrust belts formed by oblique convergence. *Marine and Petroleum Geology*, **21** (7) 857-877.
McQUARRIE, N., 2004. Crustal scale geometry of the Zagros Fold-Thrust Belt, Iran. *Journal of Structural Geology*, **26**, 519-535.
McQUARRIE, N., and VAN HINSBERGEN, D.J.J., 2013. Retrodeforming the Arabia-Eurasia Collision zone: Age of collision versus magnitude of continental subduction. *Geology* **41** (3) 315-318.
MOHIALDEEN, I.M.J., HAKIMI, M.H., and AL-BEYATI, F.M., *in press*. Biomarker characteristics of certain crude oils and the

oil-source rock correlation for the Kurdistan oilfields, Northern Iraq. *Arabian Journal of Geosciences*. Published online 2013. doi: 10.1007/s12517-013-1228-3.

MOLINARO, M., ZEYEN, H., and LAURENCIN, X. 2005. Lithospheric structure beneath the south-eastern Zagros Mountains, Iran: recent slab break-off? *Terra Nova* **17**(1), 1-6.

NAMSON, J., and DAVIS, T., 1988. Structural transect of the western Transverse Ranges, California: Implications for lithospheric kinematics and seismic risk evaluation. *Geology*, **16** (8) 675-679. doi: 10.1130/0091-7613(1988)016<0675:STOTWT>2.3.CO;2

NAQISHBANDI, S.F., JABBAR, W.J., and AL-JUBOURY, A.I., *in press*. Hydrocarbon potential and porosity types of the Geli Khana Formation (Middle Triassic), Northern Iraq. *Arabian Journal of Geosciences* 10.1007/s12517-013-1258-x.

NAVABPOUR, P., BARRIER, E., and MCQUILLAN, H., 2014. Oblique oceanic opening and passive margin irregularity, as inherited in the Zagros fold-and-thrust belt. *Terra Nova*, **26** (3) 208-215.

OMAR, A. A., 2005. An integrated structural and tectonic study of the Bina Bawi-Safin-Bradost Region. Ph.D. thesis, Salahaddin University, Erbil.

PAULSEN, T and MARSHAK, S., 1998. Charleston transverse zone, Wasatch Mountains, Utah: Structure of the Provo salient's northern margin, Sevier fold-thrust belt. *GSA Bulletin*, **110** (4) 512-522. doi: 10.1130/0016-7606(1998)110<0512:CTZWMU>2.3.CO;2

PAULSEN, T and MARSHAK, S., 1999. Origin of the Uninta recess, Sevier fold-thrust belt, Utah: influence of basin architecture on fold-thrust belt geometry. *Tectonophysics* **312** (2-4) 203-216.

PEROTTI, C. R., CARRUBA, S., RINALDI, M., BERTOZZI, G., FELTRE, L., and RAHIMI, M.,2011. The Qatar–South Fars Arch Development (Arabian Platform, Persian Gulf): Insights from Seismic Interpretation and Analogue Modelling. New Frontiers in Tectonic Research-At the Midst of Plate Convergence, ISBN 978-953. InTech, Croatia.

PITMAN, J.K., STEINSHOUER, D., and LEWAN, M.D., 2004. Petroleum generation and migration in the Mesopotamian Basin and Zagros fold belt of Iraq: Results from a basin-modeling study. *GeoArabia* **9** (4) 41-72.

POMAR, L., 2001. Types of carbonate platforms: a genetic approach. *Basin Research* **13** (3) 313-334.

QUICK, J. E., 1991. Late Proterozoic transpression on the Nabitah fault system – implications for the assembly of the Arabian Shield. *Precambrian Research*, **53,** 119-147.

REIF, D., K. DECKER, B. GRASEMANN and H. PERESSON, 2012. Fracture patterns in the Zagros fold-and-thrust belt, Kurdistan Region of Iraq. *Tectonophysics*, **576–577**, 46–62.

SADOONI, F. N., 1995. Petroleum prospects of the Upper Triassic carbonates in northern Iraq: *Journal of Petroleum Geology*, **18**, 171-190.

SADOONI, F. N., 1997. Stratigraphy and petroleum prospects of upper Jurassic carbonates in Iraq. *Petroleum Geoscience* **3**, 233-243.

SADOONI, F. N., and ALSHARHAN, A.S., 2004. Stratigraphy, lithofacies distribution, and petroleum potential of the Triassic strata of the northern Arabian plate. *AAPG Bulletin* **88**, 4, 515-538.

SATTARZADEH, Y., COSGROVE, J., and VITA-FINZI, C., 2000. The Interplay of faulting and folding during the evolution of the Zagros deformation belt. In: Forced Folds and Fractures. Cosgrove, J.W., and Ameen, M.S. (eds.), *Geol. Soc. Lond. Spec. Publ*. **169**, 187-196.

SELLA, G. F., T. H. DIXON and A. MAO, 2002. REVEL: A model for Recent plate velocities from space geodesy. *Journal of Geophysical Research*, **107**, B4, 2081, 30.

SEPEHR, M., and COSGROVE, J. W., 2004. Structural framework of the Zagros fold–thrust belt, Iran. *Marine and Petroleum Geology,* **21**(7), 829-843.

SEPEHR, M., and COSGROVE, J.W., 2005. Role of the Kazerun Fault in the formation and deformation of the Zagros Fold-thrust belt, Iran. *Tectonics* **24**, TC5005, doi:10.1029/2004TC001725.

SEPHER, M., J. COSGROVE and M. MOIENI, 2006. The impact of cover rock rheology on the style of folding in the Zagros fold-thrust belt. *Tectonophysics,* **427**, 265–281.

SEPEHR, M., and COSGROVE, J.W. , 2007. The role of major fault zones in controlling the geometry and spatial organisation of structures in the Zagros Fold-Thrust Belt. In: Deformation of the continental crust. Ries, A. C., Butler, R.W.H., and Graham, R. H. (eds.), *Geol. Soc. Lond. Spec. Publ.,* **272**, 419-436.

SHARLAND, P. R., ARCHER, R., CASEY, D. M., DAVIES, R. B., HALL, S. H., HEWARD, A. P., HORBURY, A. D., and SIMMONS, M. D., 2001. Arabian Plate Sequence Stratigraphy. *GeoArabia Special Publication* **2**, Manama, Bahrain.

SHERKATI, S., M. MOLINARO, D. F. DE LAMOTTE and J. LETOUZEY, 2005. Detachment folding in the central and eastern Zagros folded-belt (Iran): salt mobility, multiple detachments and late basement control. *Journal of Structural Geology,* **27**, 1680–1696.

STERN, R.J., and JOHNSON, P., 2010. Continental lithosphere of the Arabian Plate: A geologic, petrologic, and geophysical synthesis. *Earth-Science Reviews*, **101** (1-2), 29-67.

TALEBIAN, M., and J. JACKSON, 2002. Offset on the main recent fault of NW Iran and implications for the late Cenozoic tectonics of the Arabia-Eurasia collision zone. *Geophys. J. Int*., **150**, 422-439.

TAYLOR, T., DEWEY, J. F., and MONASTERO, F. C., 2008. Transtensional deformation of the brittle crust: Field observations and theoretical applications in the Coso-China Lake region, eastern margin of the Sierra Nevada Microplate, southeastern California. *International Geology Review* **50**, 218-244.

THOMAS, W.A. 1977. Evolution of Appalachian-Ouachita Salients and Recesses from Re-Entrants and Promontories in Continental-Margin. *American Journal of Science* **277** (10), 1233-1278.

THOMAS, W.A. , 2004. Genetic relationship of rift-stage crustal structure, terrane accretion, and foreland tectonics along the southern Appalachian-Ouachita orogen. *Journal of Geodynamics* **37**(3-5), 549-563.

TISSOT, B.P., PELET, R., and UNGERER, Ph., 1987. Thermal History of Sedimentary Basins, Maturation Indices, and Kinetics of Oil and Gas Generation. *AAPG Bulletin* **71** (12) 1445-1466.

TUCKER, C. J., D. M. GRANT and J. D. DYKSTRA, 2004. NASA's global ortho-rectified Landsat data set. *Photogrammetric Engineering and Remote Sensing*, **70**, 3, 313–322.

VAN BELLEN, R.C., DUNNINGTON, H.V., WETZEL, R., MORTON, D.M., and DUBERTRET, L., 1959. Stratigraphic Lexicon of Iraq. Lexique stratigraphique International III, Asie, fasc 10a, Iraq. CNRS Paris, pp. 333.

VITA-FINZI, C., 2001. Neotectonics at the Arabian Plate Margin. *Journal of Structural Geology*, **23** (2-3), 521-530.

YILMAZ, Y., 1993. New evidence and model on the evolution of the southeast Anatolian Orogen. *Geological Society of America Bulletin*, **105**, 251–271.

ZEBARI, M., and BURBERRY, C.M., 2015. 4D evolution of anticlines and implications for hydrocarbon exploration within the Zagros Fold Thrust Belt, Kurdistan Region, Iraq. *GeoArabia* **20** (1) 161-188.

ZIEGLER, M.A., 2001. Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences. *GeoArabia*, **6** (3) 445-504.