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

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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
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

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**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.
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.
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; Abdel-salam 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 NE-SW 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 Nabihat, Transverse and Najd fault systems (Figure 3a) which affect much of the Arabian Plate.

The north-south oriented transpressional Nabihat system (Quick, 1991), referred to as the Arabian trend by Edgell (1996), is the earliest fault system preserved from the 680-640 Ma Nabihat 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; Sattar-zadeh 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 megasequence AP2, including the Khabour and Saq Formations, are found in the study area directly overlying the Precambrian basement.
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

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**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).**

![Tectonostratigraphic column](image)
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 (Taleb 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 Aaliyi 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 Lures 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.

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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 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.](image-url)
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 Naokelakan 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 terrestrial 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...
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, Shaqalawa 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...
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 Agrawi 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
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 Nabita 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

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**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.
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
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 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–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 Makhlul-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 Kobuk-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, Makhlul-Hemrin and Tikrit-Amara faults (Najd) and the Kobuk-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.
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 $T_{\text{max}}$ 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 source-rock 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).
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 Karkuk 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. 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 Nabītah 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 Nabītah 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.
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