Research Article

Fracture Analysis in the Outcrops of the Qara Chauq Anticlines, Zagros Fold and Thrust Belt of Kurdistan Region in Northern Iraq

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Abstract
The Zagros Fold and Thrust belt is one of the world's most prolific petroleum provinces. Most hydrocarbon reserves are stored in naturally fractured reservoirs and such fracture systems can therefore have a significant impact on reservoir performance. Fractures are one of the most important paths for fluid flow in carbonate reservoirs. Fracture data were collected in the outcrops of the Kirkuk Group of Oligocene age around Qara Chauq South and Qara Chauq North anticlines located near the Kirkuk Oil Field. The studied formations outcropping in the Qara Chauq are the main reservoir units in the Kirkuk and Bai Hassan fields. In Kirkuk and surrounding fields, hydrocarbon production comes mainly from primary porosity with assistance from secondary porosity created by dolomitization, karstification, dissolution, vugs and fractures. Fracture attributes collected from outcrops are fracture orientation, density and length. The results show that fractures in the studied reservoir formation are not uniformly distributed due to massive lithologic nature and lack of well bedding. Furthermore, fracture orientations show a clear relationship to the local fold axis in the outcrops. NW-SE fracture set is perpendicular to the NW-SE fold axis. However, some fractures do not show any relation to the local folding. These fractures may have formed in a pre-folding or post folding stage. Other fracture orientations exhibit a symmetrical relation to the maximum horizontal stress direction. The comparative analysis of outcrop data underlines the importance of representative analogue data for reservoir modelling and production strategies.

Keywords: Fracture, Fault, Qara Chauq, Zagros, Kurdistan, Iraq.

1. Introduction
There are numerous outcrop analogue studies of fractured reservoirs in the Zagros Fold and Thrust Belt that have been undertaken, describing fracture patterns in the Zagros Fold and Thrust belt (eg. Sharp et al., 2006, 2010; Wennberg et al., 2006; Stephenson et al., 2007; Ahmadhadi et al., 2008; Casini et al., 2011; Lacombe et al., 2011; Tavani et al., 2011; Awdal et al., 2013, 2016; Massaro et al., 2019; Rashid et al., 2020, 2021). Reservoirs are mainly fractured carbonates developed at a variety of stratigraphic levels. Many studies show that fracture pattern is controlled by mechanical stratigraphy and petrophysical properties such as porosity (eg. McQuillan, 1973; Huang & Angelier, 1989; Underwood et al., 2003; Nemati & Pezeshk, 2005; Wennberg et al., 2006). In a study of folded carbonate units in SW Iran, Wennberg et al. (2006) suggested that the spatial distribution of fractures is a multivariate problem, where fracture attributes such as orientation, length,

spacing and apertures are functions of position within the fold, sedimentary texture and mechanical bed thickness. Fracture patterns could also be controlled by the evolution of fluid pressures during burial and evolution of the stress field during unroofing or uplifting.

Fractures are one of the most important paths for fluid flow in carbonate reservoirs. Natural fracture systems can act as permeable flow conduits or as baffles and seals (Bourne et al., 2000; Agosta, 2008). Outcrop analogue studies can improve understanding of some aspects of fracture distributions and their influence on fluid flow in fractured reservoirs (eg. Antonellini & Mollema, 2000; Aydin, 2000; Nelson, 2001; Stephenson et al., 2007; Lacombe et al., 2011). However, the scaled outcrop data should be used with care in order to improve reservoir modelling and constrain uncertainties (Sharp et al., 2006; Wennberg et al., 2006; Barr et al., 2007; Lapponi et al., 2011).

The fracture attributes of potential carbonate reservoirs are investigated within Kurdistan Region of Iraq, as represented by the Kirkuk Group formations (Oligocene) in Figure (1). The outcrop fracture datasets are mainly collected along the limbs of the Qara Chauq South and Qara Chauq North anticlines. These localities are chosen because of the outcrop exposures of the studied units. These units are making the main reservoirs in Kirkuk and Bai Hassan fields. In this paper, the focus is on the fracture patterns in the Qara Chauq South and Qara Chauq North anticlines.

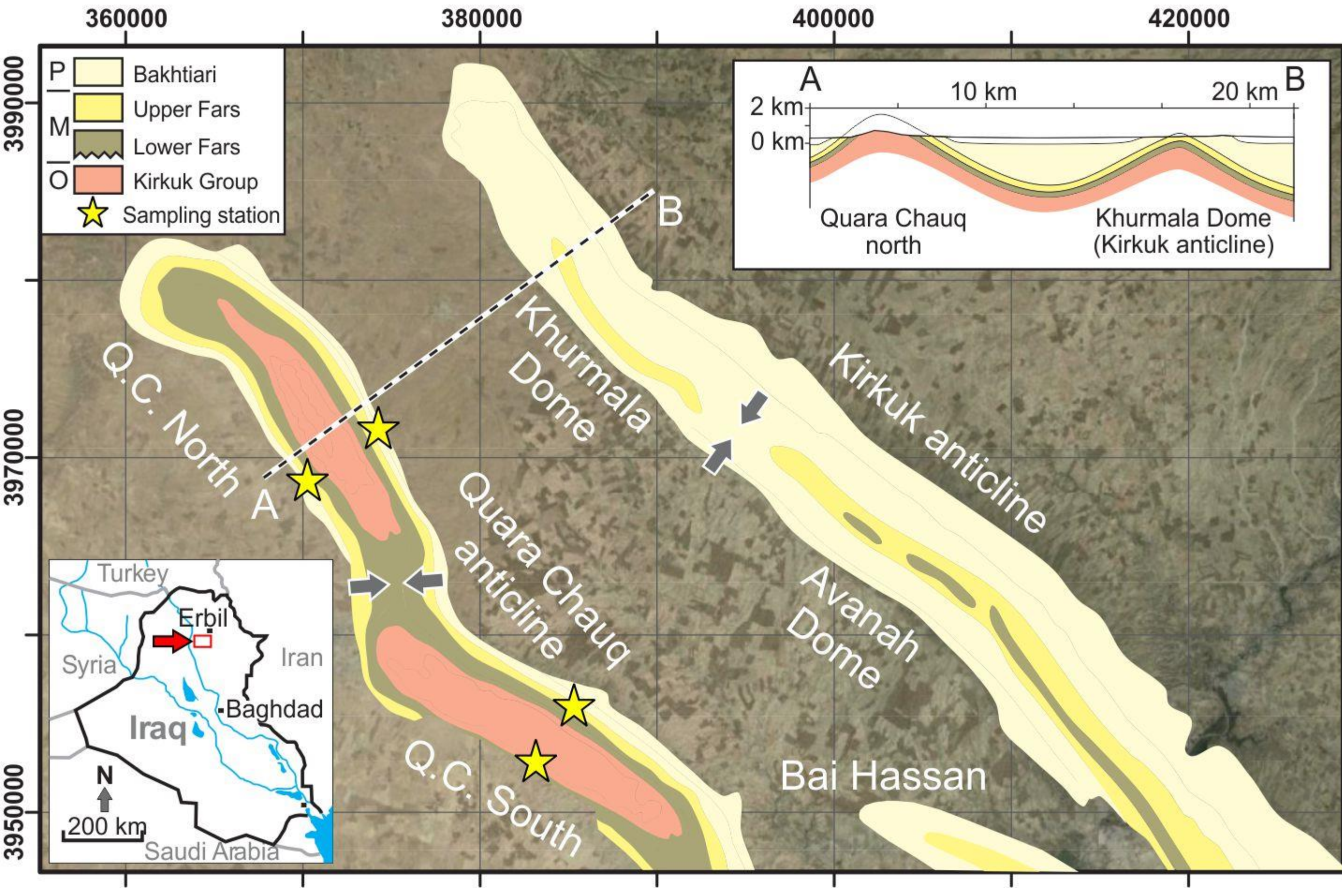


Figure 2. Geological map of the Qara Chauq South and Qara Chauq North anticlines. The cross section run across the Qara Chauq North and Khurmala Dome (Grasemann & Schmalholz, 2012).

2. Geological Setting

2.1. Tectonics

The Zagros Orogenic Belt in Kurdistan Region of Iraq can be divided into five distinct structural zones, that distributed from the NE hinterland to the SW foreland, and are named the: Zagros Suture, Imbricated Zone, Highly Folded Zone, Low Folded Zone and Mesopotamian Foreland Basin (Jassim & Goff, 2006; Fouad, 2015). The Imbricated and Highly Folded zones are characterised by major surface-breaching, mainly SW-verging thrust-related anticlines, whereas major folds above blind thrusts characterise the Foothill Zone (Awdal et al., 2013). The orientation of fold axes in the study area is NW-SE, parallel to NW-SE-trending tectonic domains, and sub-parallel to the fold and thrust belt itself.

The study area is located in the Foothill Zone and includes several anticlines such as Kirkuk and Qara Chauq anticlines. Qara Chauq South and Qara Chauq North are double-plunging anticlines and NW-SE orientated fold axes. The Qara Chauq North near the Upper Zab River Fault shows a clear deflection in the trend of fold axis when approaching transverse faults (Fouad, 1983; Fouad, 2012). In addition, the geometric relationship between transverse faults and the local fold structures such as the Upper Zab River Fault against Qara Chauq anticlines is indicated by the distinguished linearity of their traces and the sharp angular (almost perpendicular) geometry against fold structures (Fouad, 2012). The Qara Chauq anticline consists of the Qara Chauq North, which trends NW-SE, and the Qara Chauq South, which trends WNW-ESE (Dunnington, 1958) in Figure (1). Both segments are linked by an antiformal saddle that trends north-south. It is suggested that this structure formed by a linear linkage of individual segments (Grasemann & Schmalholz, 2012). Although the Kirkuk and Qara Chauq anticlines are affected by fluviatile erosion, the saddle points and the initial fold segments can be easily recognized (Grasemann & Schmalholz, 2012). The Qara Chauq anticline is segmented into Qara Chauq North and Qara Chauq South which appear to be influenced by basement faults in the Nabitah or Transverse systems (Burberry, 2015).

Qara Chauq outcrops consists of Tertiary layers thought to be correlative with the reservoir interval at Bai Hassan Field in a 16-18 km long sigmoidal fold (Sadeq et al., 2016). The analysis of the surface exposure of reservoir analogy strata at Qara Chauq may provide insight into the fractures present at reservoir depths in Kirkuk and Bai Hassan oil fields. Fault-line scarps noted on the crest of Qara Chauq, also lead to the interpretation of normal displacement faults sub-parallel to the fold axis. These faults are mainly limited to the axial region, but a few of them move down the limb. None of the faults extend beyond the edges of the structure indicating that (1) they are not regional faults, and (2) they formed in response to folding (Sadeq et al., 2016).

2.2. Stratigraphy

The Kirkuk Group (Oligocene) is cropping out along the core of Qara Chauq South and North anticlines. A couple of hydrocarbon exploration wells have been drilled in the Qara Chauq South and both wells have penetrated the Tertiary, Cretaceous and Jurassic units as demonstrated in Figure (2). No hydrocarbon well has been drilled in the Qara Chauq North yet. The reservoir Kirkuk Group (Oligocene) is observed to be vuggy at both limbs of the Qara Chauq South and North structures. The dip of stratigraphic units in the Qara Chauq South and North anticlines increases gradually towards the higher stratigraphic levels. In order to study the petrography, outcrop rock samples were collected from the interested section in the crest of the Qara Chauq South. The location of the outcrop is about 4 km southeast of well QC-2 along the axis of the anticline close to the anticline maximum crest point. Five rock samples were selected, and a set of thin sections were prepared for a petrography description. The samples show mainly carbonate mud with a few miliolids, forams, peloids. Most likely the Anah Formation, is indicating Back-reef and lagoonal depositional environment. According to stratigraphic records from outcrops of the Qara Chauq South, the Anah Formation within the Kirkuk Group is thinner in the NE limb (back-limb) and thicker in the SW limb (forelimb), probably due to a variation in the accommodation space of the depositional basin.

3. Methods and Data

Field work was conducted in outcrops around the Qara Chauq South and Qara Chauq North anticlines. The outcrop localities were carefully chosen in order to collect representative data from different structural positions in each fold, i.e., the forelimb and backlimb of each fold (Figure 1). The collected data includes bedding strike and dip, fracture strike and dip and fracture type. In order to compare fracture orientations to the local fold axis and investigate if there is a prefolding fracture family, fractures are back-tilted until associated bedding is restored to the horizontal, using Stereonet software. Bedding dip removal is required to determine the original set of fractures that could have been subjected to a later regional folding event. It is also required to study the relation between pre-folded fracture orientation and the incipient compression or shortening direction of a later formed fold. Fracture orientation data were graphically presented by using stereograms to describe the fracture surface as planes in three dimensions and rose diagrams to illustrate the trend of the fracture strikes in two dimensions.

Furthermore, fractures and faults were interpreted from high resolution satellite images using ESRI ArcMap software (ESRI, 2015). Fracture and fault orientations were plotted as Rose Diagram and fracture and fault lengths were plotted against their cumulative frequency. Fractures interpreted from satellite images were classified into three groups: (1) hinge parallel fractures; (2) hinge perpendicular fractures; and (3) oblique factures. The fracture length interpreted from satellite images is ranged from 30 meters up to 1000 meters; and fault length is ranged from 300 meters up to 4000 meters.

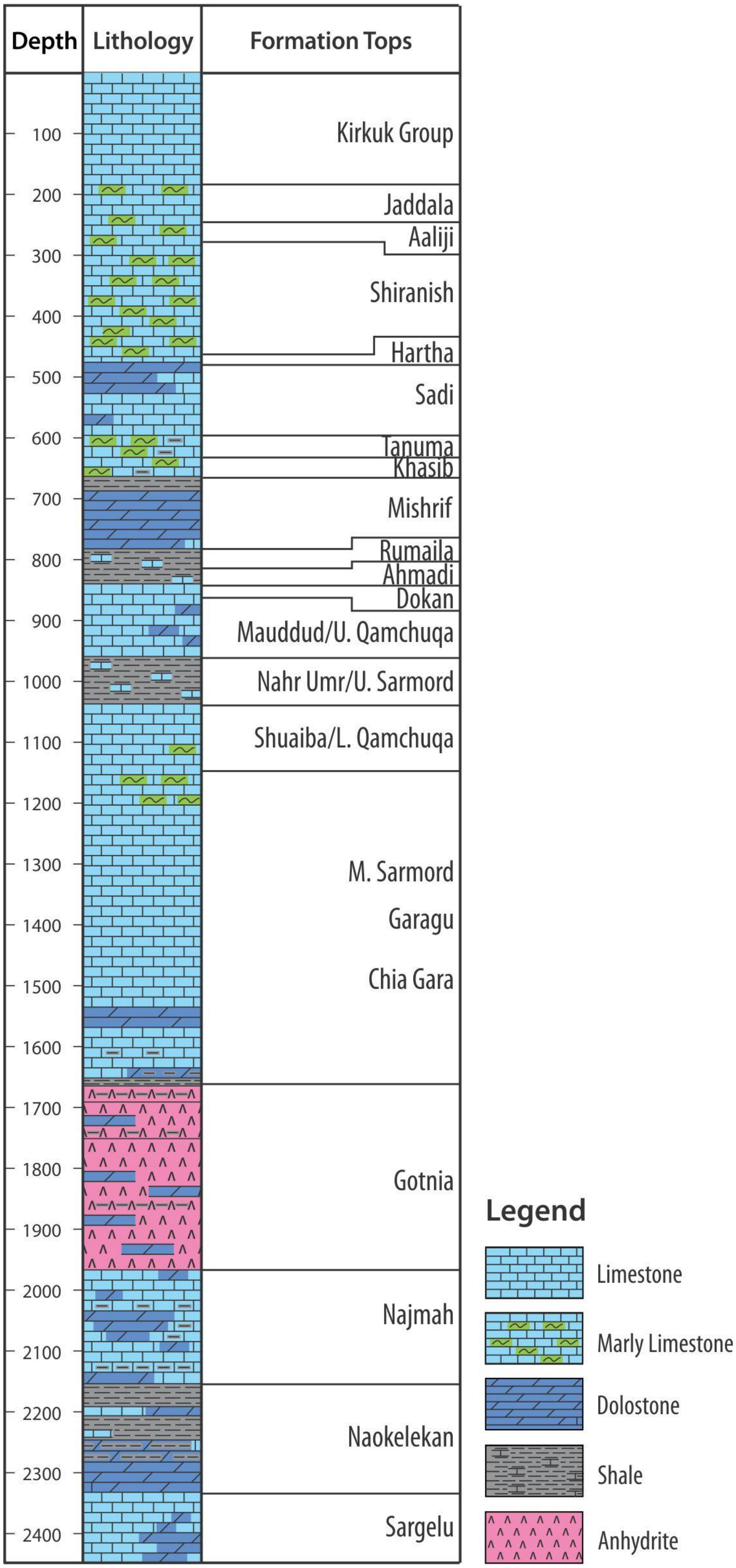


Figure 2. Stratigraphic column of well QC-X in the Qara Chauq South Anticline. Kirkuk Group (Oligocene) are the studied fractured reservoir units (GeoDesign, 2015).

4. Qara Chauq South Anticline

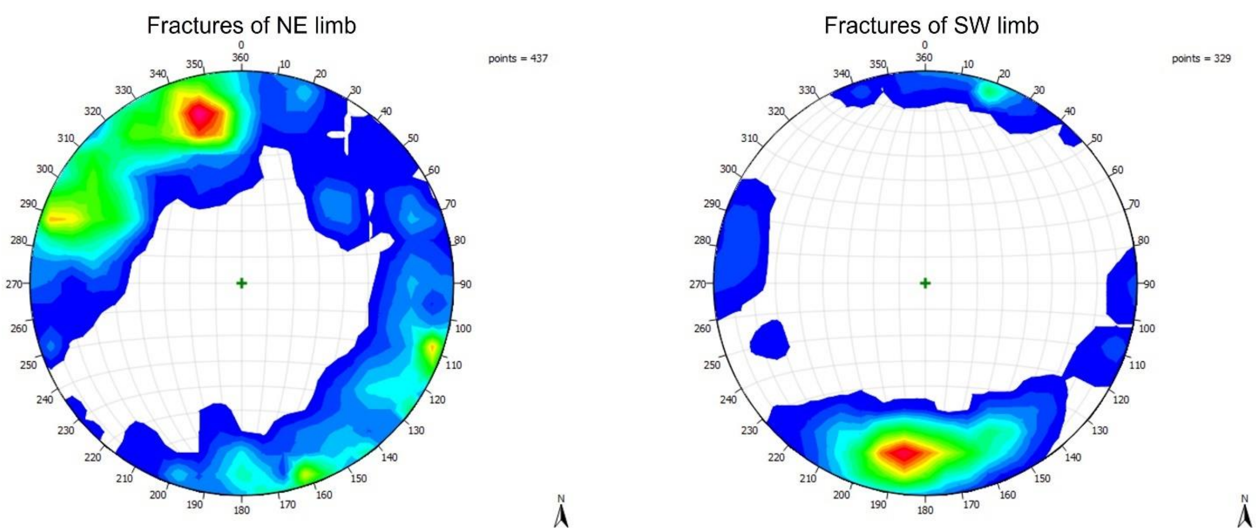
The Qara Chauq South Anticline is located about 60 km south-southwest from Erbil City within the Foothills of the Zagros Fold and Thrust belt (Figure 1). It is a NW-SE trending asymmetrical and double-plunging anticline. The Qara Chauq South Anticline is traceable for 22 km along its length, and it is up to 3 km in width as marked by the closure of competent Kirkuk Group formations. The Qara Chauq South cut by E-W trending normal faults which are mainly limited to the axial region, but a few of them move down the limb. Faulting has resulted in a collapse of the crestal area of the Qara Chauq South. Azkand cirque is a deep valley that cut through stratigraphic units where the Avanah, Jaddala and Shiranish formations are exposed in the southern limb of the Qara Chauq South. The core of the anticline is accessible through the paved road through its southeast nose and cement factory road in its NE flank. The dip of stratigraphic units in the Qara Chauq South increases gradually towards the higher stratigraphic levels.

4.1. Fracture and fault characteristics

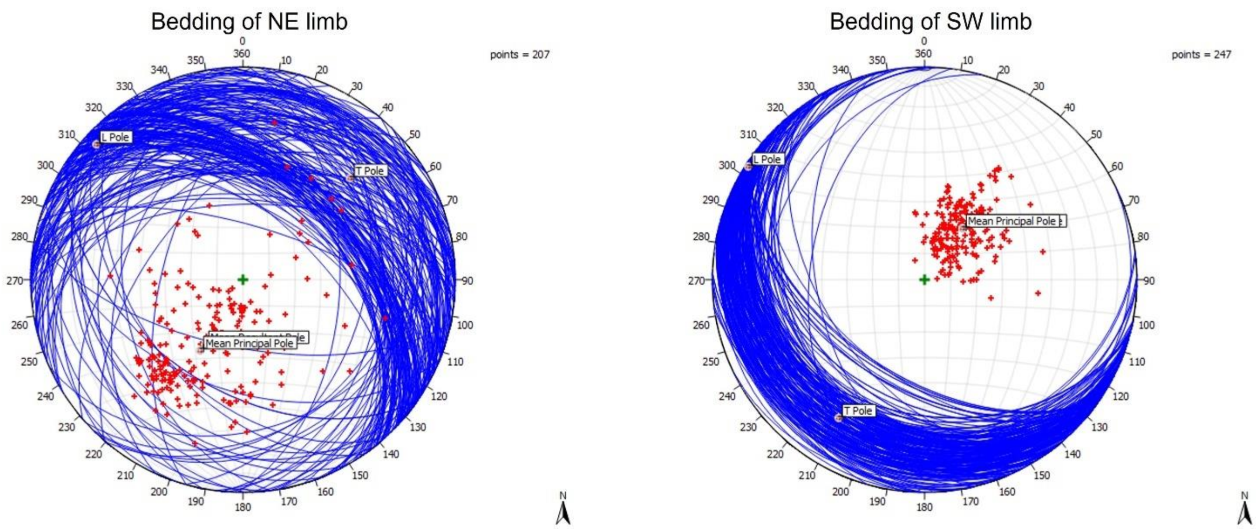
Based on detailed mapping from remote sensing data (satellite images and aerial photos) and outcrop fracture data from the Qara Chauq South anticline, three dominant fracture sets are identified: Set 1 is fold-axis-parallel represented by NW-SE trending fractures; Set 2 is fold-axis-perpendicular represented by NE-SW oriented fractures; and Set 3 is normal-fault-parallel represented by E-W fractures. Fracture sets 1 and 2 are dominantly strata-bound extension fractures, and therefore influence transmissivity and lateral anisotropy within reservoir layers. In contrast, fracture set 3 may include small-scale normal faults that cut multiple layers and systems of related smaller faults and extension fractures that form an interconnected fracture network that can provide reservoir communication vertically between layers. Similar results were reported in another study by Sadeq et al. (2016).

NE-SW fracture set 2 is dominant in the NE limb of the Qara Chauq South whereas E-W fracture set 3 is dominant in the SW limb. NE-SW fracture set 2 is perpendicular to the fold axis while E-W fracture set 3 is parallel to the fault network exposed on surface. E-W trending normal faults have been observed in the Qara Chauq South. These faults are mainly limited to the axial region, but a few of them move down the limb. Faulting has resulted in a collapse of the crestal area of the Qara Chauq South. Furthermore, 766 fracture measurements were recorded from both limbs of the Qara Chauq South (Figure 3a). In addition, 454 bedding measurements were recorded from both limbs of the Qara Chauq South (Figure 3b).

In the Qara Chauq South, the E-W oriented faults do not show symmetry with fold geometry (Figure 4a and b). Faults interpreted from satellite images are statistically longer than fracture data collected in the outcrops. Fractures generally show symmetry with fold geometry. Hinge-perpendicular fractures (set 2) are longer than hinge-parallel fractures (set 1) and oblique fractures (set 3) (Figure 4c). Fault and fracture length may be biased by sampling window size (censoring and truncation effects).

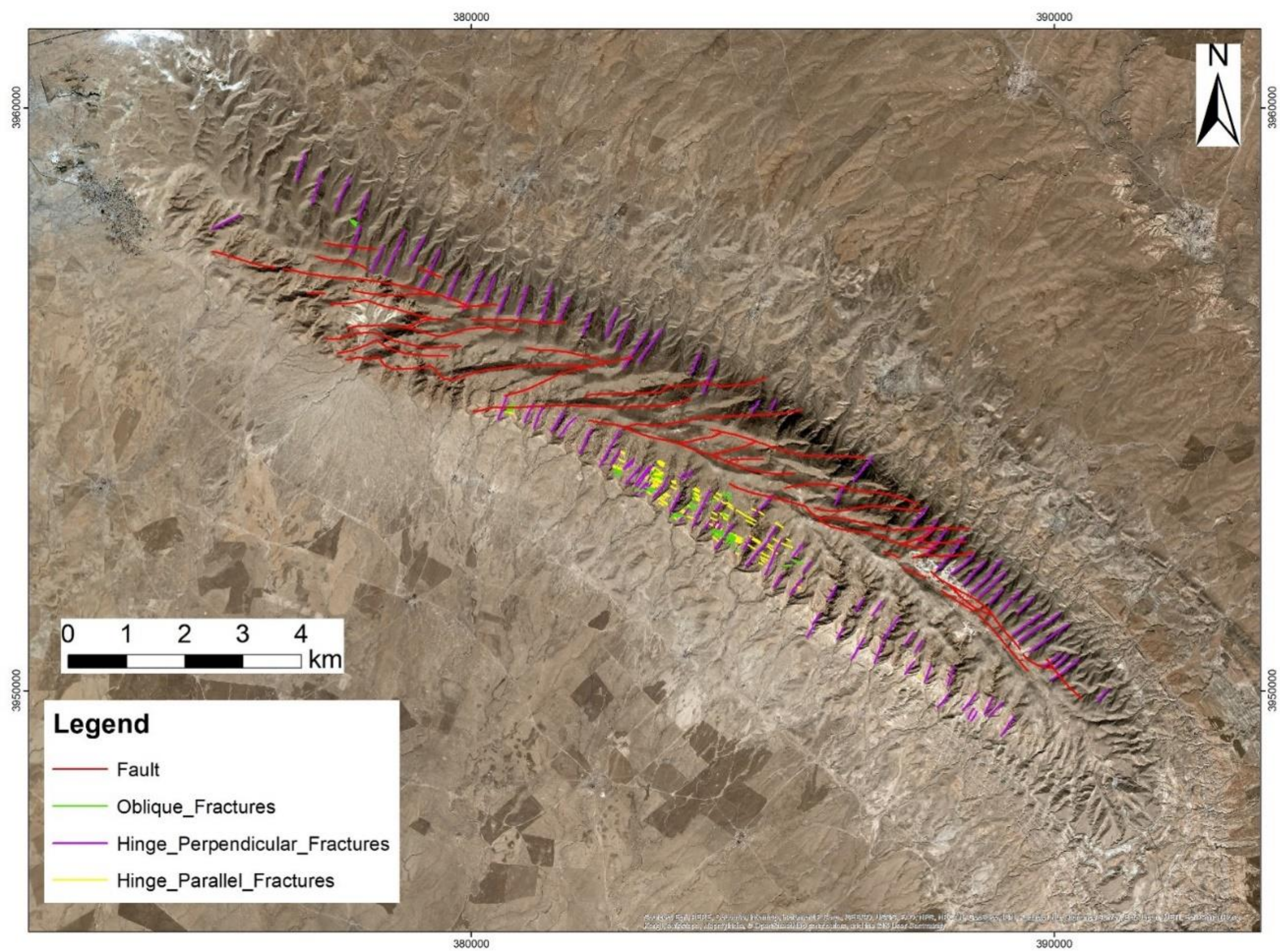


(a)

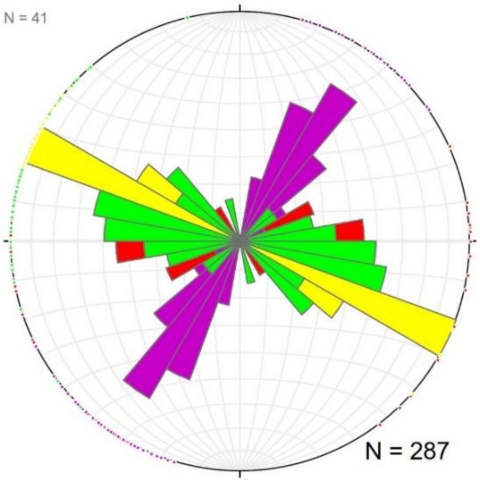


(b)

Figure 3. (a) Stereograms showing density contours for fracture poles. Red colours represent high density, (b) Lower hemisphere equal area stereograms for bedding planes. Bedding planes plotted as great circles in blue and poles to bedding planes in red.



(a)



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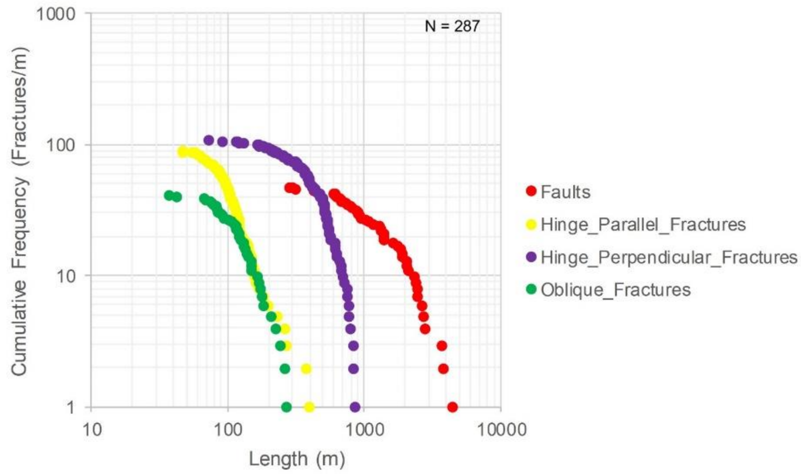


(c)

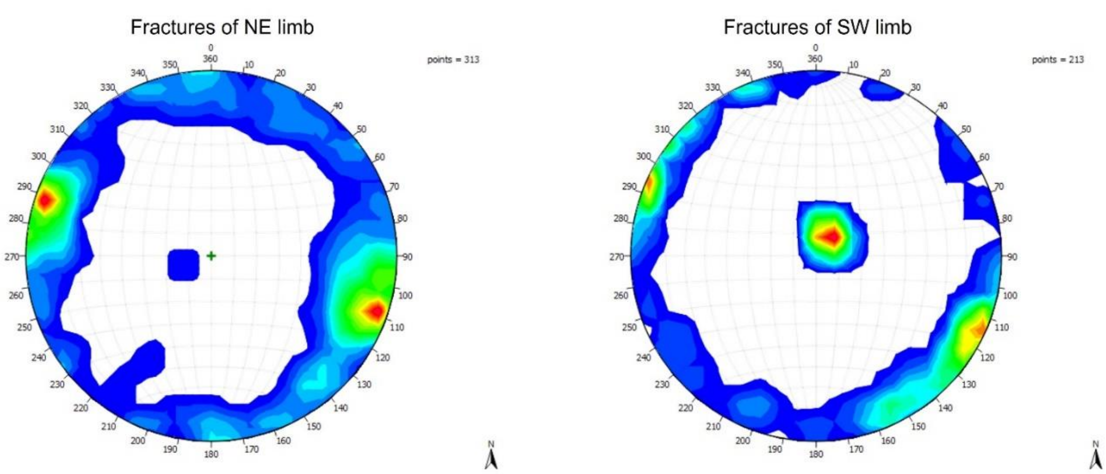
Figure 4. (a) Satellite image (QuickBird) of the Qara Chauq South with interpreted faults and fractures, (b) Rose diagram showing orientation of interpreted faults and fractures, and (c) Cumulative frequency diagram of the fault and fracture lengths in the Qara Chauq South.

5. Qara Chauq North Anticline

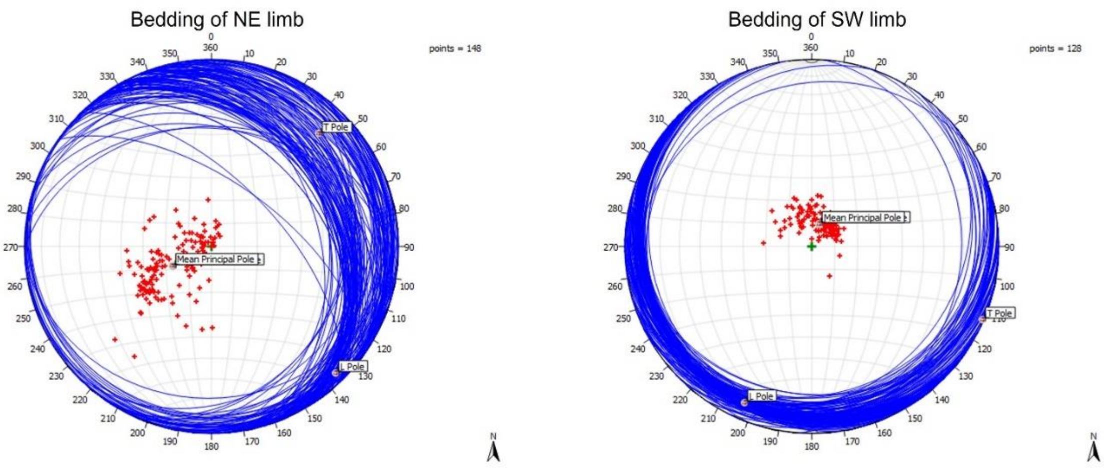
The Qara Chauq North Anticline is located about 55 km south-southwest from Erbil City within the Foothills of the Zagros Fold and Thrust Belt (Figure 1). It is a NW-SE trending slightly asymmetrical and double-plunging anticline. The Qara Chauq North Anticline is traceable for 24 km along its length and is 3 km in width as marked by the closure of competent Kirkuk Group formations. The structure does not show a clear vergency. The Qara Chauq North cut by N-S and E-W trending normal faults which are mainly limited to the axial region. The faults exposed at the Qara Chauq North are less abundant and more localized compared to the Qara Chauq South. The core of the anticline is accessible through the road through its south-east nose. The dip of stratigraphic units in the Qara Chauq South increases gradually towards the higher stratigraphic levels.

5.1. Fracture and fault characteristics

NE-SW fracture set is dominant in both limbs of the Qara Chauq North anticline. In addition, bed-parallel shear fractures are recorded at the SW limb of the anticline, and N-S and E-W trending normal faults are exposed on the surface of the anticline. Furthermore, 526 fracture measurements were recorded from both limbs of the anticline (Figure 5a). In addition, 276 bedding measurements were recorded from both limbs of the anticline (Figure 5b). Fractures observed and sampled in the Qara Chauq North outcrops show layer parallel shearing as indicated by bedding-parallel shear fractures.



(a)



(b)

Figure 5. (a) Stereograms showing density contours for fracture poles. Red colours represent high density, (b) Lower hemisphere equal area stereograms for bedding planes.

Bedding planes plotted as great circles in blue and poles to planes in red.

Fractures and faults were interpreted from satellite images using ESRI ArcMap software (ESRI, 2015) (Figure 6a). Fracture orientations were plotted as Rose Diagram (Figure 6b) and fracture and fault lengths were plotted as their cumulative frequency (Figure 6c). In the Qara Chauq North, N-S and E-W oriented faults do not show symmetry with fold geometry (Figure 6a). Faults interpreted from satellite images are statistically longer than fractures. Fractures generally show symmetry with fold geometry. Hinge-perpendicular fractures are longer than hinge-parallel and oblique fractures (Figure 6c). Fault and fracture length may be influenced by sampling window size (censoring and truncation effects).

6. Discussion

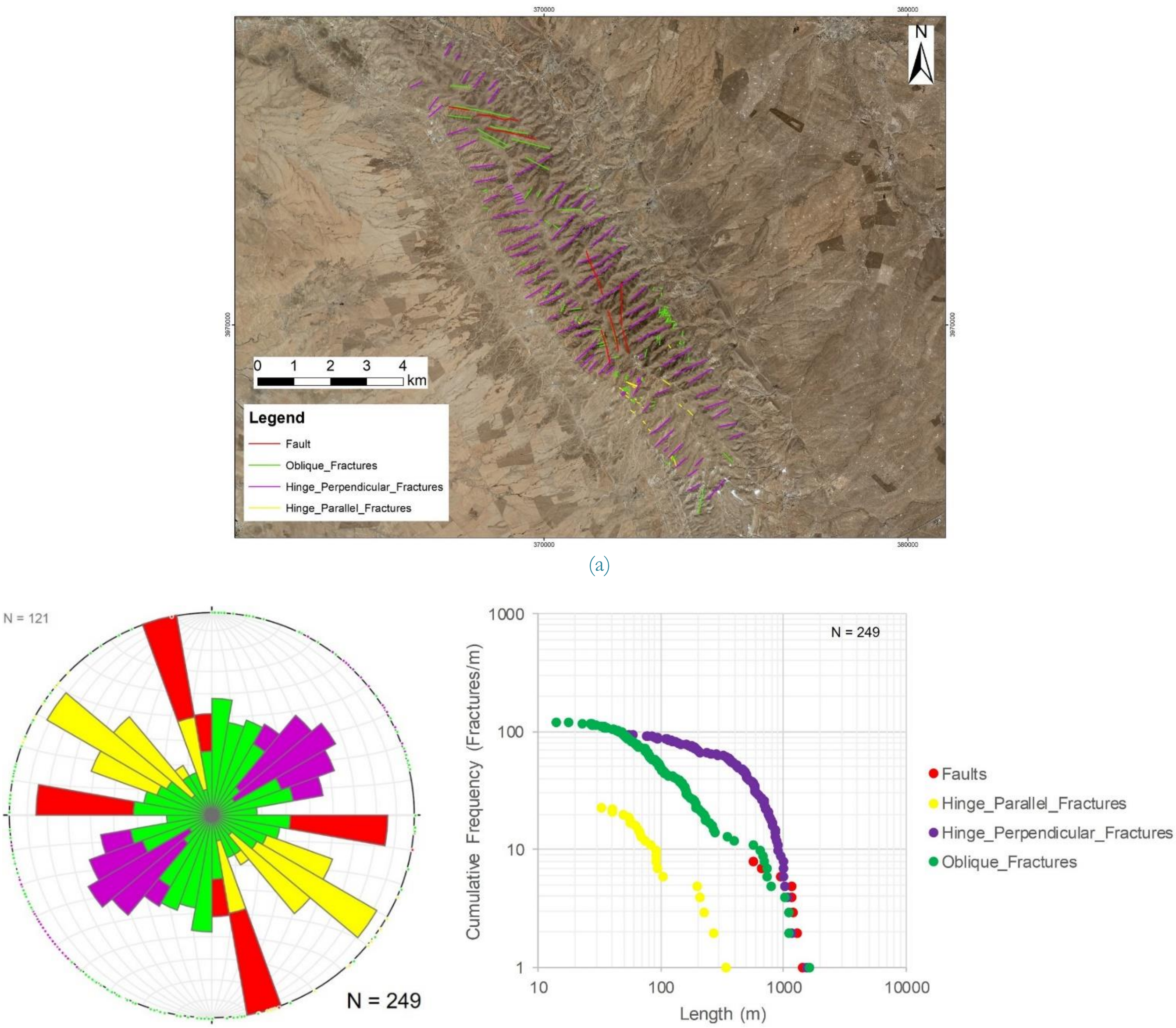
6.1. Development of faults and fractures

The results show that fractures in the studied reservoir formation are not uniformly distributed due to massive lithologic nature and lack of well bedding. Vugs and karsts are dominant within the studied Kirkuk Group in the outcrop due to its massive lithologic nature. Fractures, on the other hand, are not very well developed in these massive units compared to well bedded units. The Qara Chauq South anticline is cut by E-W trending normal faults which are mainly limited to the axial region, but a few of them move down the limb. None of the faults extend beyond the edges of the structure indicating that (1) they are not regional faults, and (2) they formed in response to folding (Sadeq et al., 2016). Fractures observed and sampled in the Qara Chauq North outcrops show layer parallel shearing. Bedding-parallel shear fractures have been observed in the forelimb (SW limb) of the anticline. Hence, flexural slip folding is the possible mechanism of folding which is characterised by bedding parallel slip striation and bending (Reif et al., 2012). In addition, fracture orientations show a clear relationship to the local fold axis in the outcrops. NE-SW fracture set is perpendicular to the NW-SE fold axis. However, some fractures do not show any relation to the local folding. These fractures may have formed in a pre-folding or post folding stage. Other fracture orientations exhibit a symmetrical relation to the maximum horizontal stress direction. The present in-situ maximum horizontal tectonic stress direction in the study area is oriented NNE-SSW, according to the world stress data (Heidbach et al., 2016).

6.2. Implications for reservoir connectivity and production

The Kirkuk Group formations are equivalent to the prolific Asmari Formation in Iran. Despite their high matrix porosity and permeability, the formations are to some degree fractured which are considered as type 3 where fractures provide a permeability assist to an already producible reservoir, according to classification of fractured reservoirs (Nelson, 2001; Narr, 2006). The prediction of the permeability and connectivity is challenging, as indicated by initial high flow rates from discoveries followed by a dramatic drop off during production. Furthermore, the occurrence of highly permeable fracture zones in wells are of concern because they may cause early water breakthrough, as demonstrated by numerical analysis (Jonoud et al., 2013). Therefore, a careful use of scaled outcrop data can, to some extent, improve reservoir modelling and constrain uncertainties (Sharp et al., 2006; Wennberg et al., 2006). In terms of geometry, the dominant NE-SW open and part-open fracture strike orientation is perpendicular to the fold axes, which indicates anisotropic permeability with the maximum fracture permeability aligning in the NE-SW direction. In terms of drilling dynamics, the total mud losses and hydrocarbon shows at reservoir intervals confirm the presence of various scales of conductive fractures and faults.

Bitumen stains have been observed at the base of the Euphrates Limestone at Darmanawa locality at NE limb and at Ali Rash locality at SW limb (Figure 7). Bitumen seeps out from pores and fractures. No active oil seepages were found in the area. Previous workers have reported traces of bitumen in the Upper Cretaceous limestones exposed in the Azkand cirque. The low angle thrust faults detaching from the Fatha Formation could act as conduits for hydrocarbon migrating upwards to the surface in the form of biodegraded oil or bitumen. In addition, the occurrence of several diffuse sulfur springs along the outcrops of the Fatha Formation were reported in the Qara Chauq South anticline (Sahib et al., 2016). A similar sulfur spring was observed in the northeastern flank of the Qara Chauq South anticline. This underlines that the Fatha Formation acts at least partly as a hydraulic barrier, due to the low matrix permeability (Sahib et al., 2016).

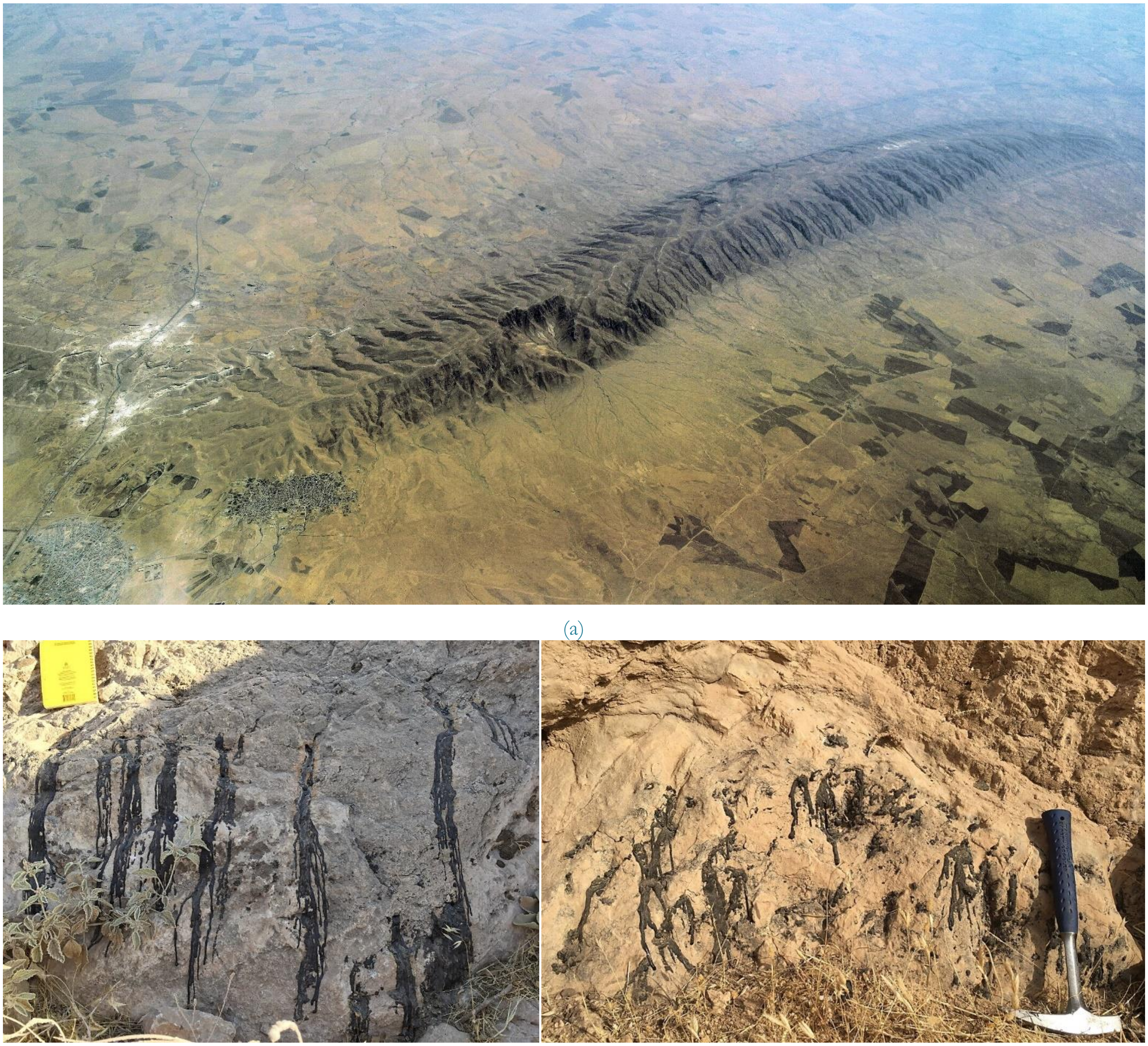


(b) (c)

Figure 6. (a) Satellite image (QuickBird) of the Qara Chauq North with interpreted faults and fractures, (b) Rose diagram showing orientation of interpreted faults and fractures, (c) Cumulative frequency diagram of the fault and fracture lengths in the Qara Chauq North.

7. Summary and Conclusions

The studied fracture attributes in the outcrops of the Kirkuk Group in the Qara Chauq anticlines provide insight into the fractures present at subsurface reservoir in Kirkuk and Bai Hassan fields. Faults interpreted from outcrops and satellite images are statistically longer than fracture data collected in the outcrops, due to the difference in the fracture sampling windows. Furthermore, fractures generally show symmetry with fold geometry. However, faults do not show a direct relation with fold geometry. The Qara Chauq South cut by E-W trending normal faults which are mainly limited to the axial region, but a few of them move down the limb. Faulting has resulted in a collapse of the crestal area of the Qara Chauq South. Fracture attributes such as length and spacing along the reservoir units measured in the outcrops are difficult to quantify from subsurface borehole image log data and therefore pose as important fracture input for fracture modelling.



(a)

(b) (c)

Figure 7. (a) Aerial photograph of the Qara Chauq South anticline. Photo looking east, (b) Euphrates limestone (Lower Miocene) at the NE limb of the Qara Chauq South with bitumen seeping out of vugs and fractures, (c) Euphrates limestone (Miocene) at the SW limb of the Qara Chauq South with bitumen seeping out of vugs and fractures.

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