RESEARCH ARTICLE

Determining the Tectonic Origin of the Gara and Mateen Anticlines Using Geomorphological and Structural Forms, Iraqi Kurdistan Region

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Received: 15-08-2020 **Accepted:** 19-10-2020 **Available online:** 31-12-2020

ABSTRACT

Gara and Mateen are 2 major anticlines in the northern part of the Iraqi Kurdistan Region, located in the vicinity of the town Amadiyah. Both anticlines are oriented in an almost east–west (E–W) trend with a steep southern limb. The length and width of the Gara and Mateen anticlines are 87 km and 63 km, and 11 km and 9.5 km, respectively. The 2 anticlines are separated by a wide and shallow syncline filled by the Tertiary rocks of the Pliocene–Pleistocene age. The oldest exposed rocks in the Gara and Mateen anticlines are from the Triassic age. The carapace of both anticlines is built up by the Bekhme and Qamchuqa formations. The geomorphological and structural features were studied through satellite images and geological maps. Based on these studies, it was found that both anticlines show clear geomorphological and structural features that indicate their lateral growth. Among those features are water and wind gaps, different shapes of valleys that indicate lateral growth, abandoned alluvial fans, whale-back shapes, en-echelon plunges, and multiple dome anticlines. Furthermore, the rate of upward movements was calculated using neotectonic data. In addition, the rate of river and stream incisions was calculated on the basis of the height of the river terrace levels.

Keywords: Lateral growth, Water and wind gaps, Fork-shaped valleys, Abandoned alluvial fans, En-echelon plunges

1. INTRODUCTION

In tectonically active areas, the lateral growth of anticlines is a very common phenomenon (Blanc et al., 2003; Bennett et al., 2005; Ramsey et al., 2008).

Access this article online

DOI: 10.25079/ukhjse.v4n2y2020.pp84-100	E-ISSN: 2520-7792

The Iraqi Kurdistan territory, which forms the northeastern part of the Arabian Plate, is a good example of a tectonically active area. The Arabian Plate collides with the Iranian Plate with a convergent tectonic plate boundary (Alavi, 2004; Allen et al., 2004; Fouad, 2012). Because of the compressional forces exerted by the collision, many anticlines and their associated main faults developed. Mountain building and landscape evolution are controlled by the interactions between river dynamics and tectonic forces. The landscape geomorphology and the drainage patterns provide indirect information about the tectonic activity of the drainage basins and included folds (Oberlander, 1985; Burbank and Pinter, 1999; Keller et al., 1999; Tomkin and Braun, 1999; Burbank and Anderson, 2001; Castelltort and Simpson, 2006; Bretis et al., 2011; Graseman and Schmalholz, 2012; Colligon, et al., 2016). Keller et al. (1999) evaluated fold growth using the following geomorphic criteria: the deformation of progressively younger deposits or landforms, the development of characteristic asymmetric drainage patterns, and the occurrence of a series of wind gaps with decreasing elevation in the propagation direction. The Gara and Mateen anticlines exhibit lateral growth with clear indications of interaction between the existing rivers and tectonic forces, which are indicated by the different geomorphological and structural features that are evaluated in this study. The studied area includes the Gara and Mateen anticlines, which are located north and south of the town of Amadiya, respectively, and about 85 km north of the city of Erbil in the Iraqi Kurdistan Region (Fig. 1).

The aim of this study was to determine the origin of the Gara and Mateen anticlines and identify how they developed to their present morphology. The data were acquired using the geomorphological and structural features that are present in both anticlines. Identification of the features was achieved by the interpretation of high-quality satellite images.

1.1. Previous Studies

Tectonic-geomorphological studies are not common in the Iraqi Kurdistan Region, including the studied area. These types of studies are very rare, although a few studies have been conducted and are described in the following section.

Sissakian (2010) attributed the development of the Derbendi Bazian gorge to neotectonic activity based on a tectonic-geomorphological study in which he confirmed that it was a wind gap. Sissakian and Abdul Jabbar (2010) concluded that the Basara gorge was a water gap that developed because of neotectonic activity based on a study of the transversal gorges in the Iraqi Kurdistan Region. Sissakian et al. (2014) conducted a geomorphological study of the High Folded zone and concluded that the developed gorges in the Handreen, Zozik, and Tanoun anticlines were caused by lateral propagation (growth) of the anticlines. Al-Kubaisi and Abdul Jabbar (2015) indicated a high level of tectonic activity and low maturity of the drainage basins in 3 anticlines in the Kurdistan Region, as determined by a morphotectonic study of 3 folds and presented their effects on the drainage systems. Sissakian et al. (2018) determined the lateral growth of the Qara Dagh anticline by conducting a tectono-geomorphological study. They used the same geomorphological and structural forms that have been used in this study. Ghafur et al. (2019) conducted a tectonic- geomorphological study on the Aqra anticline, confirming its lateral growth using geomorphological and structural forms. Finally, in the latest study conducted by Sissakian et al. (2020), the authors studied the lateral growth of the Handreen, Zozik, and Tanoun anticlines in the Kurdistan Region of Iraq, relying on geomorphological features.

Internationally, several studies have been conducted including the study by Cartwright et al. (1995) who identified fault growth by segment linkage at Canyonlands' Grabens in southeast Utah, United States, by conducting a geomorphological study. Bennett et al. (2005) identified the lateral growth of a ridge along a blind fault in a geomorphological study in South Rough Ridge, Central Otago, New Zealand. They used geomorphological data to confirm the lateral growth. Some of the data of the previous studies have been used in this study. Mumipour and Najad (2011) and Mousavi and Arian (2015) conducted tectonic-geomorphological studies in the Zagros belt, Iran, using geomorphological features to determine the growth of anticlines. Data from these studies have been used in this study to indicate the origin of the Gara and Mateen anticlines.

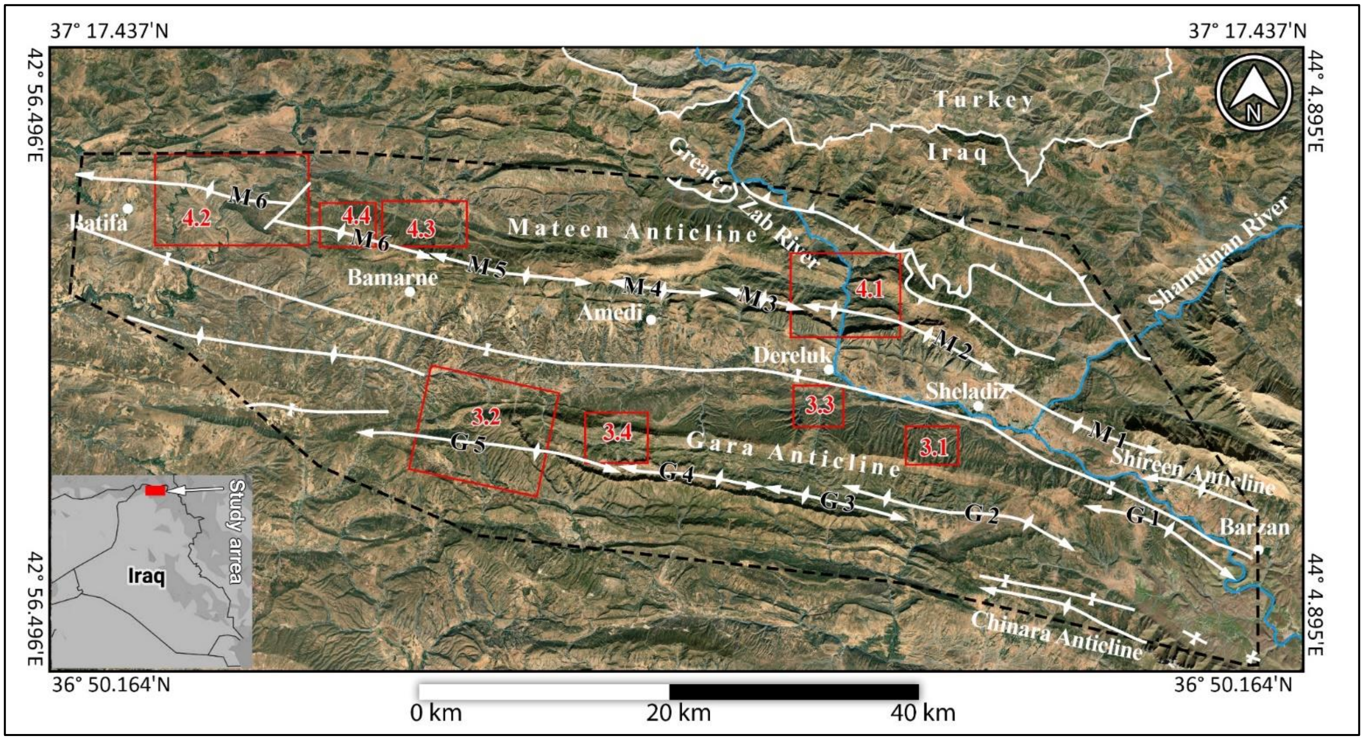

Figure 1. Satellite image showing en-echeon plunges in both the Gara and Mateen anticlines and the Shireen and Chinara anticlines. G1 to G5 are 5 domes within the Gara anticline, whereas M1 to M6 are 6 domes within the Mateen anticline. The red blocks are the locations of Figs. 3 and 4 with their captions mentioned in the text (ESSRI, 2013 satellite image)

2. MATERIALS AND METHODS

To conduct this study and to determine the origins of the Gara and Mateen anticlines, the following materials were used: geological maps at a scale of 1:100,000 and 1:250,000, topographical maps at a scale of 1:100,000, and high resolution satellite images.

The opinions of different researchers were considered in recognizing the geomorphological and structural features, which indicate the origin of the Gara and Mateen anticlines in the study area, including the studies by Keller et al. (1999), Ramsey et al. (2008), Grasemann and Schmalholz (2012), and Collignon et al. (2016). Using available topographical and geological maps of 1:100,000 and 1:250,000 scales with the help of Flash Earth, Global Mapper, a digital elevation model, and other satellite images, different geomorphological and structural features and forms were identified to determine the origin of the Gara and Mateen anticlines. Geomorphological and structural features and forms such as wind and water (river) gaps (or transverse streams), en-echelon plunges, multiple dome folds, and different shapes of valleys like radial, axial, curved, and fork-shaped have been extensively used to define the style of deformation and to quantify both the rate and the direction of propagation (or the lateral growth) of the fault and fold segments (Burbank and Pinter, 1999; Keller et al., 1999; Décallau et al., 2006; Ramsey et al., 2008; Bretis et al., 2011; Grasemann and Schmalholz, 2012). Water gaps represent valleys that were developed by the carving of exposed rocks during fold growth and still host a flowing stream, whereas wind gaps represent similar valleys that are presently dry, but previously hosted water, indicating that the rate of lateral growth of the folds is higher than the rate of stream incision (Ramsey et al., 2008).

In regions affected by low or moderate tectonic deformation rates (as seen in the study area), geomorphological and geological data provide some of the best approaches to detect and characterize active tectonics (Molin et al., 2004; Dumont et al., 2005; Necea et al., 2005).

The rate of upward movement in the Gara and Mateen anticlines was calculated using neotectonic data. The elevation of the contact between the Fatha Formation (Middle Miocene, marine sediments) and the Injana Formation (Upper Miocene, continental sediments) indicates the amount of upward movement since the Upper Miocene, which was during 11.62 Ma (International Commission on Stratigraphy [ICS], 2012). The amount of upward movement at each of the recorded locations could be calculated from the development of the present relief which started from the Pleistocene Epoch (2.588 Ma; ICS, 2012). Accordingly, the rate of the upward movement during the Pleistocene Epoch was calculated. Moreover, the stream rate of river and stream incisions was calculated based on the height difference between the river and/or the stream levels and the base of the terrace levels.

3. GEOLOGICAL SETTING

The geological setting of the study area, including the geomorphology, tectonics, and stratigraphy, is briefly reviewed based on the findings of Sissakian and Fouad (2012, 2014), Fouad (2012), Sissakian and Al-Jiburi (2014), and Sissakian et al. (2014).

3.1. Geomorphology

The following are the main geomorphological units identified in the study area:

(1) Structural units, indicated by anticlinal ridges, are well-developed in both the Gara and Mateen anticlines.

(2) Structural–denudational units are represented by the flat iron topography, cuestas, and hogbacks and are all well-developed in both the Gara and Mateen anticlines.

(3) Fluvial units are represented by valley fillings, flood plains, terraces, and alluvial fans. Many abandoned alluvial fans were recognized, indicating lateral growth of both anticlines.

The geomorphological features that are indicators of lateral growth of the folds include the following: water gaps, wind gaps, axial valleys, curved valleys, radial valleys, inclined valleys, crossed valleys, and fork-shaped valleys. All of these features were recognized in the Gara and Mateen anticlines. The presence of a whale-back shaped anticline is also a good indication of the lateral growth of folds. This was recognized only in the Mateen anticline.

3.2. Tectonics and Structural Geology

The study area is located within the High Folded zone of the Outer Platform, which belongs to the Arabian Plate and is part of the Zagros fold–thrust belt. Both the Gara and Mateen anticlines are double plunging, NW–SE trending, but they change to an E–W trend. Both anticlines exhibit en-echelon plunging and multiple dome folds. It is recognized that both anticlines consist of 2 anticlines. In this study, the authors refer to them as Gara East (with the G1 and G2 domes) and Gara West (with the G3, G4, and G5 domes), and Mateen East (with the M1, M2, and M3 domes) and Mateen West (with the M4, M5, and M6 domes) (Fig. 1). The multiple dome folds and en-echelon plunging are good indicators of the lateral growth of the folds (Cartwright et al., 1995; Dawers and Anders, 1995; Cowie, 1998; Blanc et al., 2003; Bennett et al., 2005) and (Keller and Pinter, 2002; Ramsey et al., 2008), respectively. A long and narrow syncline lies between the 2 anticlines and becomes wider westward where the Bai Hassan Formation of Pliocene–Pleistocene age is exposed in the trough. Many thrust faults run through both anticlines.

3.3. Stratigraphy

The exposed geological formations in the Gara and Mateen anticlines are briefly described in order, from the oldest to the youngest. The exposed formations are presented in the geological map (Fig. 2).

(1) Baluti and Kura China formations (Upper Triassic): both formations are exposed at the core of both anticlines as very narrow strips. The formations consist of black shale, limestone, and dolomite.

(2) Sehkaniyan and Sarki formations (Lower Jurassic): both formations are exposed at the core of both anticlines. Both formations consist of limestone, dolomite, and black shale.

(3) Chia Gara, Barsarin, Naokelekan, and Sargelu formations (Upper Jurassic): these formations are exposed at the core of both anticlines. The formations consist of limestone, dolomite, and marl.

(4) Qamchuqa Formation (Lower Cretaceous): it forms the carapace of both anticlines and consists of massive limestone and dolomite deposits.

(5) Bekhme Formation (Upper Cretaceous): it forms the outer most part of the carapace of both anticlines and consists of thickly and thinly bedded limestone and dolomite.

(6) Shiranish Formation (Upper Cretaceous): it consists of 2 parts. The lower part consists of white well-bedded marly limestone, whereas the upper part consists of dark blue and olive-green marl. The formation is exposed as a continuous belt surrounding both anticlines.

(7) Tanjero Formation (Upper Cretaceous): it consists of dark olive-green sandstone, shale, and marl. The formation is exposed as a continuous belt surrounding both anticlines in the form of dissected slopes.

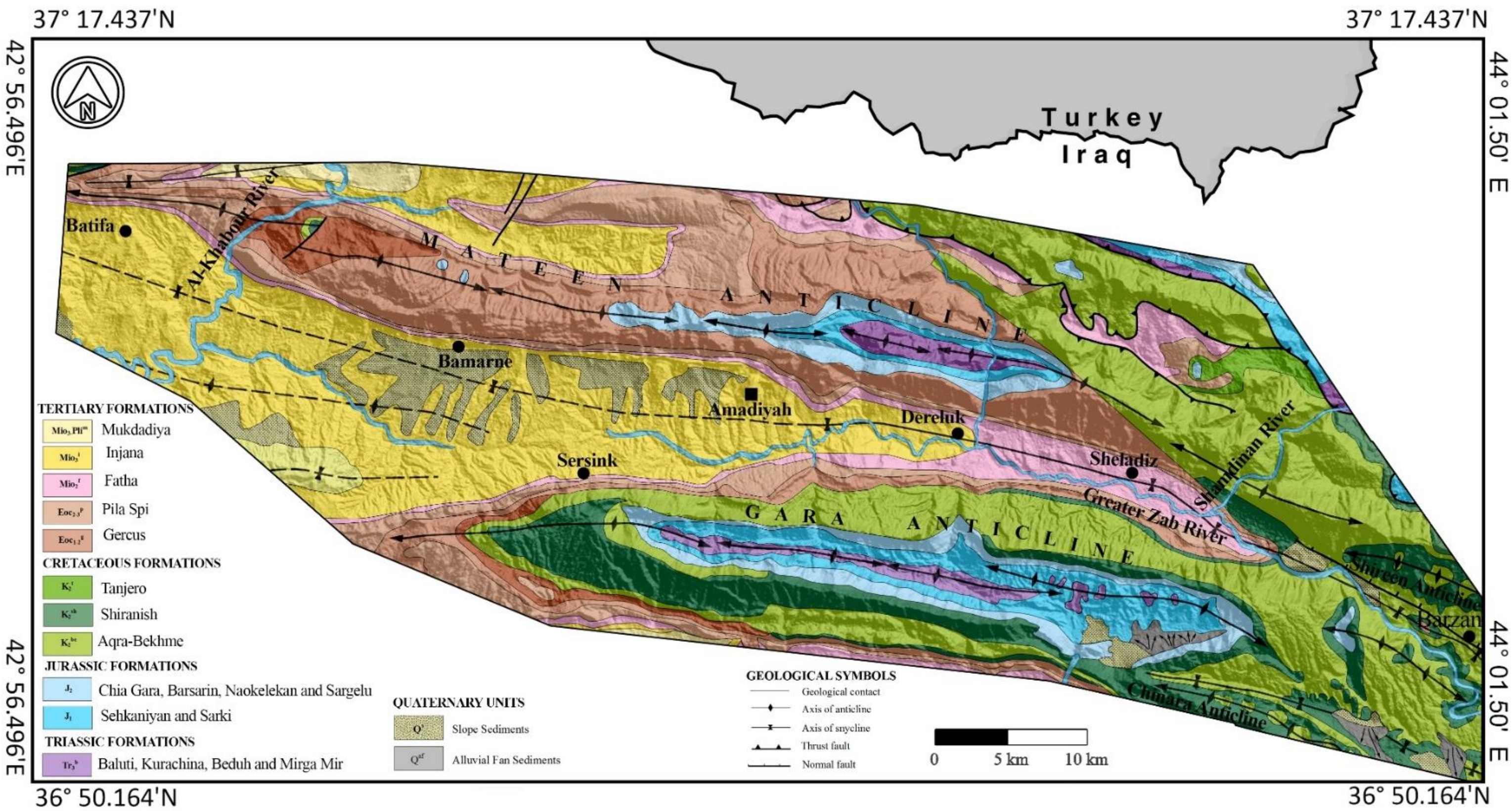

Figure 2. Geological map of the Gara and Mateen anticlines, imposed over the DTM (modified from Sissakian and Fouad, 2012)

(8) Kolosh Formation (Paleocene): it consists of black fine clastics. The formation is exposed as a continuous belt surrounding both anticlines in the form of dissected slopes.

(9) Gercus Formation (Eocene): it consists of reddish brown fine clastics. The formation is exposed as a continuous belt surrounding both anticlines in the form of dissected slopes.

(10) Pila Spi Formation (Upper Eocene): it consists of well-bedded, pale white limestone and dolostone. The formation is exposed as a continuous belt surrounding both anticlines in the form of continuous anticlinal ridges with common flat irons of different sizes.

(11) Fatha Formation (Middle Miocene): it consists of reddish brown fine clastics. The formation is exposed as a continuous belt surrounding both anticlines in the form of anticlinal ridges and dissected slopes.

(12) Injana Formation (Upper Miocene): it consists of reddish brown fine clastics. The formation is exposed as a continuous belt surrounding both anticlines in the form of anticlinal ridges, questas, hogbacks, and dissected slopes.

(13) Mukdadiya Formation (Upper Miocene–Pliocene): it consists of gray fine clastics, and some of the sandstone beds are pebbly. The formation is exposed as a continuous belt surrounding both anticlines in the form of anticlinal ridges, questas, hogbacks, and dissected slopes.

(14) Bia Hassan Formation (Pliocene–Pleistocene): it consists of coarse conglomerate alternated with reddish brown claystone. The formation is exposed as a continuous belt surrounding both anticlines

in the form of anticlinal ridges, questas, hogbacks, and dissected slopes.

(15) Quaternary sediments are represented by terraces, alluvial fans, slope sediments, valley fill sediments, and flood plain sediments.

4. RESULTS

The recognized structural and geomorphological features in the Gara and Mateen anticlines are summarized in Table 1. The geomorphological and structural features that were recognized and interpreted from satellite images with the aid of topographical and geological maps, are briefly mentioned below. The rates of upward movements were calculated in the Gara and Mateen anticlines using neotectonic data. Moreover, the rates of river incisions were calculated based on the height differences between the levels of the rivers and terraces at different locations in both anticlines.

Table 1: The recognized geomorphological features in the Gara and Mateen anticlines

Anticline	Structural and Geomorphological Features											
	En-echelon plunges	Multiple dome folds	Water gap	Wind gap	Abandoned alluvial fans	Whale-back shaped anticline	Valleys					
							Inclined	Fork-shaped	Axial	Cross-shaped	Radial	Asymmetrical
Gara	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Mateen	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

(1) **En-echelon plunges**: the presence of en-echelon plunges in a fold is an indication of the lateral growth of the fold (Keller and Pinter, 2002; Ramsey et al., 2008). En-echelon plunges can be recognized easily from the existing geological maps and by interpretation of satellite images. The Gara East and Gara West anticlines form an en-echelon plunge (Fig. 1). There is an en-echelon plunge between the Mateen East and Mateen West anticlines (Fig. 1). Moreover, the Gara and Mateen anticlines show en-echelon plunges with the Chinara and Shireen anticlines, respectively (Fig. 1). The northwestern plunges of both the Gara and Mateen anticlines have narrow and long shapes (Figs. 1 and 2).

(2) **Multiple dome folds:** The presence of multiple domes in folds is another indication of the lateral growth of folds (Cartwright et al., 1995; Dawers and Anders, 1995; Cowie, 1998; Blanc et al., 2003; Bennett et al., 2005). Multiple dome folds can be identified by using available geological maps and through the interpretation of satellite images; however, the available geological maps are at a scale of 1:250,000 and therefore not all of the existing domes are present on the geological maps. Moreover, Grasemann and Schmalholz (2012) have mentioned that multiple domes in a fold can join together to form 1 single fold. In the Gara anticline, 5 domes (G1, G2, G3, G4, and G5) have developed but not along a straight line, with an extensive lineament separating domes G2 and G3 (Fig. 1). In the Mateen anticline, 6 domes (M1, M2, M3, M4, M5, and M6) have developed but they are not aligned in a straight line, and the same extensive lineament, which runs through the Gara anticlines, extends to the Mateen anticlines and cuts through dome M2 (Fig. 1).

(3) **Abandoned alluvial fans:** the presence of an abandoned alluvial fan along a fold is an indication of the lateral growth of the fold (Keller and Pinter, 2002; Ramsey et al., 2008). The alluvial fans can be easily interpreted from satellite images; moreover, some of them are also present on the geological maps. Abandoned alluvial fans can be seen along the Gara

anticline (Fig. 3-3) and the Mateen anticline (Fig. 4-3). In both anticlines, the alluvial fans are very old and inactive. In the Mateen anticline, they are capped by calcrete (Fig. 4-3).

(4) **Whale-back shaped anticline:** when an anticline exhibits a whale-back outer shape or part of it, it is an indication that the anticline is experiencing lateral growth (Keller and Pinter, 2002 and Ramsey et al., 2008). The whale-back shape can be easily interpreted from satellite images and even from detailed topographical maps. Only in the northwestern part of the Mateen West anticline can the whale-back shape be seen (Fig. 4-4), whereas in the remaining parts of the anticline, the whale-back shape has vanished because of extensive erosion and the exposure of the soft-to-fairly-hard rocks of the Triassic age. However, along both limbs of the anticline, the remnants of the whale-back shape can still be seen (Figs. 4-4 and 5). In the Gara anticline, the whale-back shape was not recognized (Fig. 3-2), although the exposed rocks on both limbs of the anticline are the same as those in the Mateen anticline. This can be attributed to the widely exposed soft-to-fairly-hard rocks of the Triassic age in the core of the anticline.

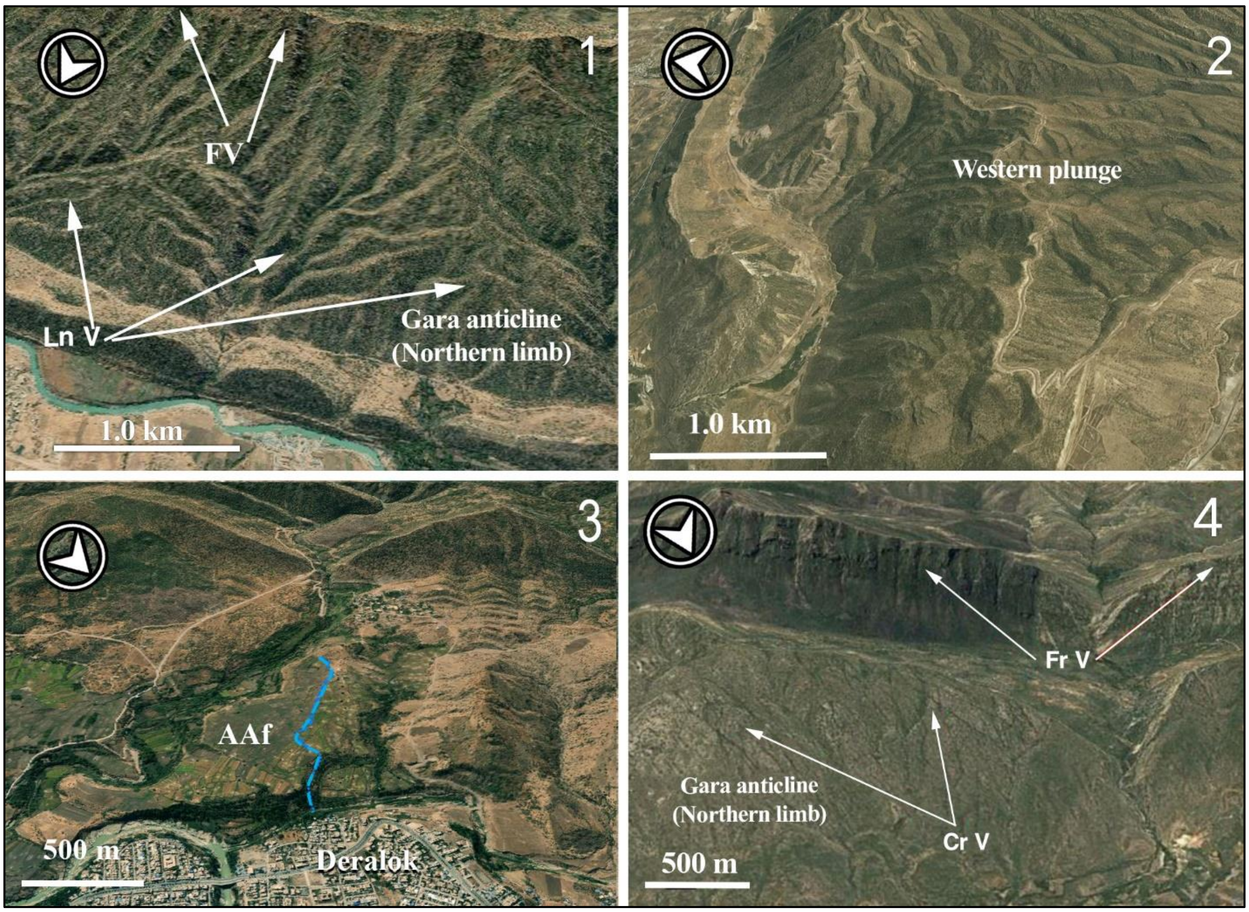

Figure 3. Satellite images of the Gara anticline indicating the **(1)** inclined and fork-shaped valleys, **(2)** radial valleys, **(3)** abandoned alluvial fan (the blue dashed line represents the abandoned feeder channel), and **(4)** cross-shaped and fork-shaped valleys. For locations, refer to Figure 1.

(5) **Different valley shapes:** the presence of different valley shapes in a fold such as axial, curved, inclined, cross-shaped, or radial, is a good indication that the fold exhibits lateral growth (Keller and Pinter, 2002; Ramsey et al., 2008). In the Gara and Mateen anticlines, all types of valleys can be seen (Figs. 3 and 4) such as fork-shaped valleys, crossed valleys, inclined valleys, axial valleys, and radial valleys. However, a radial valley did not develop in the Mateen anticline. Accordingly, the presence of such valleys is a good indication of the lateral growth of the Gara and Mateen anticlines. It is worth mentioning that

asymmetrical valleys are recognized in both anticlines, however, they are not present in the interpreted satellite images.

(6) **Water gaps**: the presence of water gaps in folds is a good indication of the lateral growth of the anticlines (Ramsey et al., 2008). In the Mateen anticline, 4 water gaps have developed (Fig. 1) because the anticline is crossed by the Al-Khabour, Greater Zab, and Shamdinan rivers. No streams and/or valleys cross the anticline to form more water gaps. This is attributed to the exposure of very hard and thick carbonate rocks of the Bekhme and Qamchuqa formations along both limbs of the anticline. A longitudinal cross section along the anticline shows that the depth of the water gaps increases to the southeast (Fig. 6, bottom), indicating the direction of the lateral growth. No water gap developed in the Gara anticline (Fig. 1). This can be attributed to the same reasons as mentioned for the Mateen anticline.

(7) **Wind gaps**: the presence of wind gaps in folds is a good indication of the lateral growth of the anticlines (Ramsey et al., 2008). No wind gap was recognized in the Gara or Mateen anticlines. However, in the Mateen anticline (Fig. 4-4), 2 valleys show the same alignment, crossing the anticline in opposite sides as a single valley, and possibly indicate the existence of a previous wind gap that is no longer present because of the upward growth of the anticline. Nevertheless, the position of both valleys at the highest part of the anticline decreases the possibility of the existence of a wind gap. The absence of wind gaps is attributed to the absence of water gaps apart from the 3 main rivers (Al-Khabour, Greater Zab and Shamdinan) that cross the Mateen anticline.

(8) **Rates of upward movements:** using neotectonic data, the rates of upward movements along the Gara and Mateen anticlines were calculated in certain areas where the Fatha and Injana formations are exposed; the elevation of the contact point represents the amount of uplift (when exposed) or downward movements (when in the subsurface) from the Miocene sea level. The calculated rates during the Pleistocene Epoch are presented as mm/100 years in Table 2.

(9) **Stream incisions:** through careful inspection of satellite images, with the help of geological maps at a scale of 1:100,000, the river terrace of the Greater Zab and Al-Khabour rivers were recognized. Locally, 3 levels were preserved, and the height differences between the river and terrace levels are indicated on Google Earth images. Accordingly, the incision rates were calculated during the Lower, Middle, and Upper Pleistocene periods.

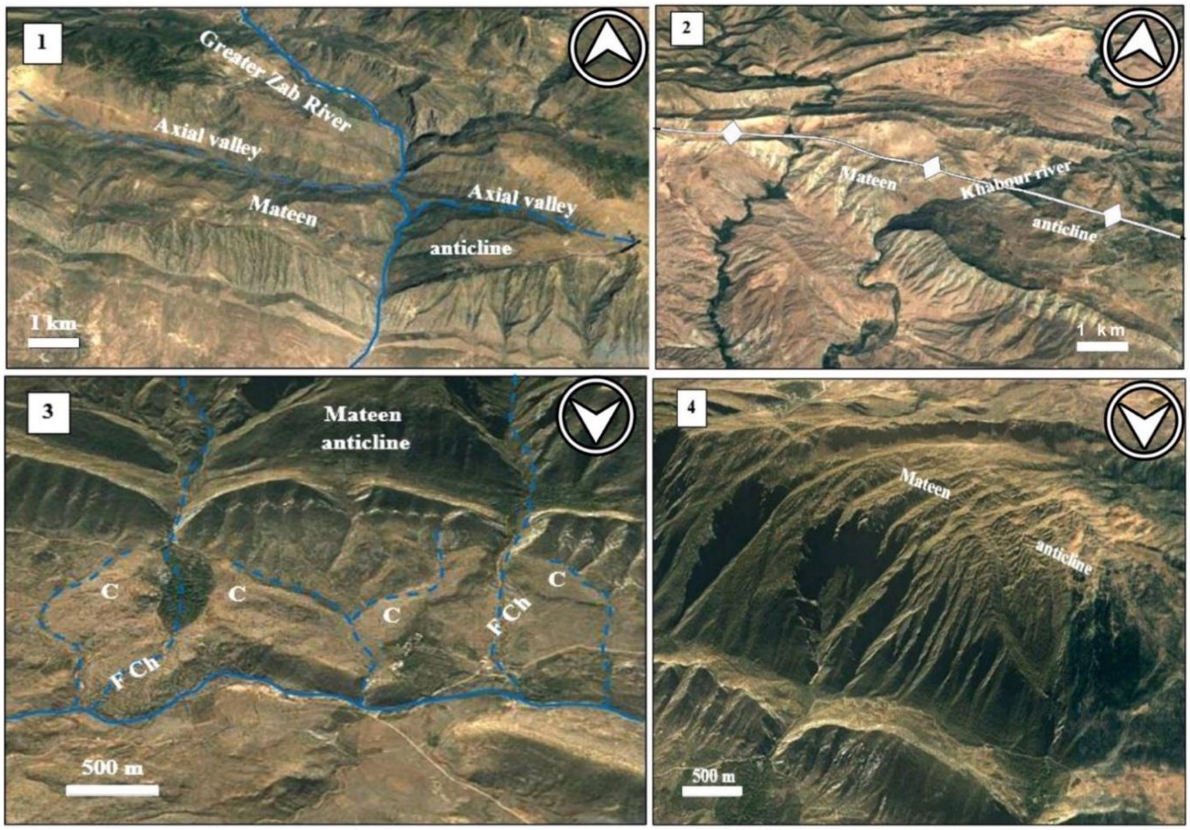

Figure 4. Satellite images of the Mateen anticline indicating **(1)** an axial valley, **(2)** 2 water gaps, **(3)** 2 abandoned alluvial fans, and **(4)** an eroded whale-back shape. For locations, refer to Figure 1; C, calcrete; FCh, new feeder channel.

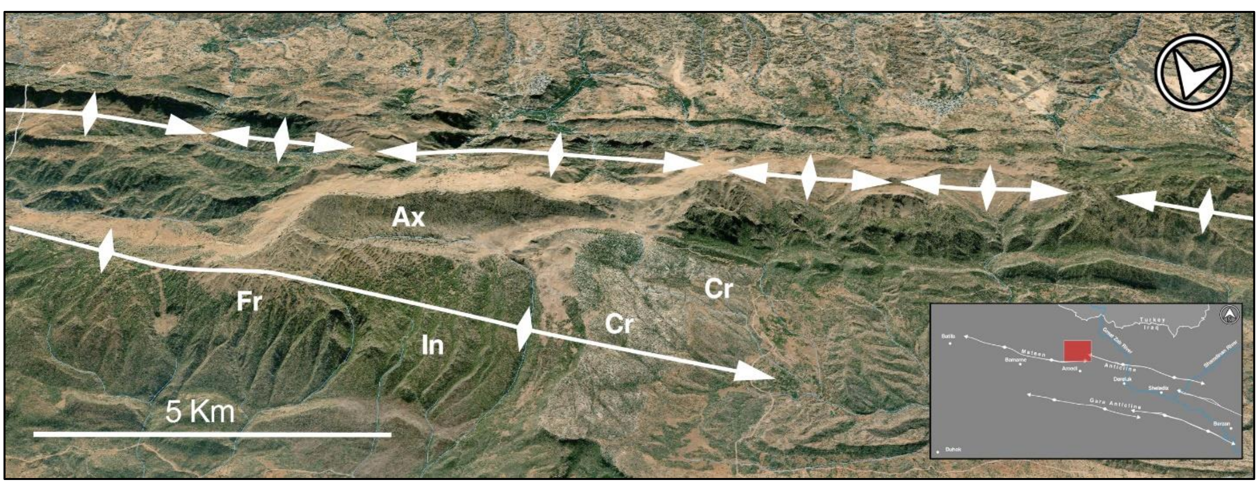

Figure 5. Satellite image showing the en-echelon plunge between the East and West Mateen anticlines (on the left and right of the image, respectively); Ax, axial valley; Cr, cross-shaped valleys; In, inclined valleys; Fr, fork-shape valleys

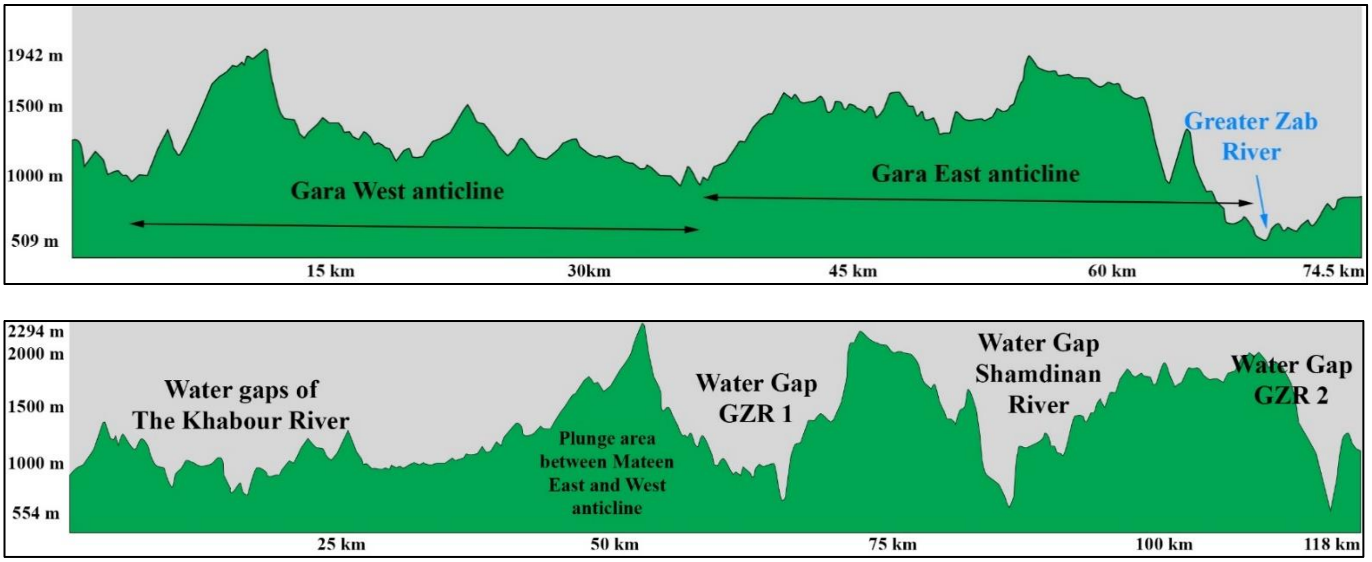

Figure 6. Longitudinal cross section through the **(top)** Gara anticline and **(bottom)** the Mateen anticline

5. DISCUSSION

The results obtained from the interpretation of satellite images clearly show that both the Gara and Mateen anticlines are exhibiting lateral growth (Figs. 3, 4, and 5). The presence of the various structural and geomorphological forms (Table 1) is a good indication of the lateral growth of both anticlines. However, the rate of growth and the incision of the streams in both anticlines are not the same. In the Gara anticline where no wind gaps and/or water gaps have developed (Figs. 1, 3 and 6), it is clear that the rate of uplift is greater than the rate of incision of streams and valleys (Ramsey et al., 2008). In contrast, in the Mateen anticline, the presence of many water gaps and the absence of any wind gap (Figs. 1 and 4) is a good indication that the rate of stream incision is higher than the rate of uplift, otherwise some wind gaps would be present, which is a good indication that the original water gaps changed to wind gaps because of a higher rate of uplift.

The presence of domes (Cartwright et al., 1995; Dawers and Anders, 1995; Cowie, 1998; Blanc et al., 2003 and Bennett et al., 2005) and en-echelon plunges (Keller and Pinter, 2002; Ramsey et al., 2008) are good indications of the lateral growth of both anticlines. Both the Gara and Mateen anticlines (Figs. 1, 2, 3, and 5) have domes and en-echelon plunges, implying that they are growing laterally (Campbell, 1958). Moreover, the continuous growth of a fold that includes many domes may lead to the merging of the domes and the formation of 1 large fold (Grasemann and Schmalholz, 2012). In both the Gara and Mateen anticlines, it is clearly observed that some of the domes do not show clear closures in their plunges (Figs. 1 and 5). This is another indication that the folds are growing and that the domes will merge together over time.

It is well-studied and well-known that the intensity of folding and deformation decreases to the southwest because of the continuous collision of the Arabian and Iranian plates (Alavi, 1994; Berberian, 1995; Jassim and Goff, 2006; Burberry, 2015; Obaid and Allen, 2017). However, the Gara anticline shows a higher rate of uplift than that of the Mateen anticline, although the Mateen anticline is closer to the deformational front compared with the Gara anticline and it shows a higher peak of 2294 m (above sea level) (Fig. 6, bottom). In contrast, the highest peak in the Gara anticline is 1942 m (above sea level) (Fig. 6, top). This can be attributed to 4 factors. The first factor is the presence of a large lineament in the middle part of the Mateen anticline (Fig. 1 and 4-1), which forms a water gap to allow the passage of the Greater Zab river. This lineament has contributed and facilitated the crossing of the Greater Zab river to the Mateen anticline. In addtion, it has accelerated the rate of incision because of the weakness zone initiated by the lineament. Second, the big difference in the thickness of the Qamchuqa Formation in the Gara and Mateen anticlines (Fig. 7), where it is thicker in the Gara anticline, has played an important role in resisting the incision of the streams at the anticline.

Third, the steepness of the dip in the beds of the Qamchuqa Formation in the Gara anticline when compared with those in the Mateen anticline (Fig. 7) indicates that in the Gara anticline, the upward movement is greater than in the Mateen anticline. Finally, the Mateen anticline is the last fold within the High Folded zone, which faces the Imbricate Zone (Fouad, 2012), and therefore it has received more pressure from the imbrication and accordingly, there is a decreased rate of upward warping and lateral growth.
Apart from the presence of multiple domes in both the Mateen and Gara anticlines, the presence of sharp en-echelon plunges in both is good indication that both anticlines originally consisted of many domes that were all aligned at each anticline in a single axial line (Campbell, 1958; Fossen, 2010). However, because of the continuous lateral growth of the folds, the domes at each anticline started losing their separate dome shapes. Moreover, both folds started exhibiting en-echelon plunges, especially the Mateen anticline (Figs. 4-2 and 5), with different indications being present in the plunge area as the different shapes of the valleys developed, accompanied by the en-echelon plunges (Fig. 5).

The presence of abandoned alluvial fans in both the Gara and Mateen anticlines (Figs. 3-3 and 4-3, respectively) is a good indication of the lateral growth of both anticlines.

This means that the gradients at different places in both anticlines have changed and accordingly, the sediment supply for the development of the alluvial fans has changed too. However, climatic change during the Holocene period and its role in the abandoning of the alluvial fans cannot be ignored.

The constructed longitudinal topographical cross sections along both the Gara and Mateen anticlines (Fig. 6) indicate that the lateral growth of both anticlines is toward the southeast. This is confirmed by the depth of the water gaps in the Mateen anticline, which is deeper at the southeast, and in the southeastern plunge of the Gara anticline, which is deeper than the northwestern plunge. The rates of upward growth at both the Gara and Mateen anticlines have been estimated using neotectonic data. The Neotectonic period started in Iraq during the Upper Miocene period (Atomenergeoexport, 1985). Sissakian and Diekran (1998) adopted this idea and constructed the neotectonic map of Iraq based on the elevations of the contact between the Fatha Formation (Middle Miocene, marine sediments) and the Injana Formation (Upper Miocene, continental sediments). The elevation of the mentioned contact was recorded at different locations along both the Gara and Mateen anticlines (Table 2).

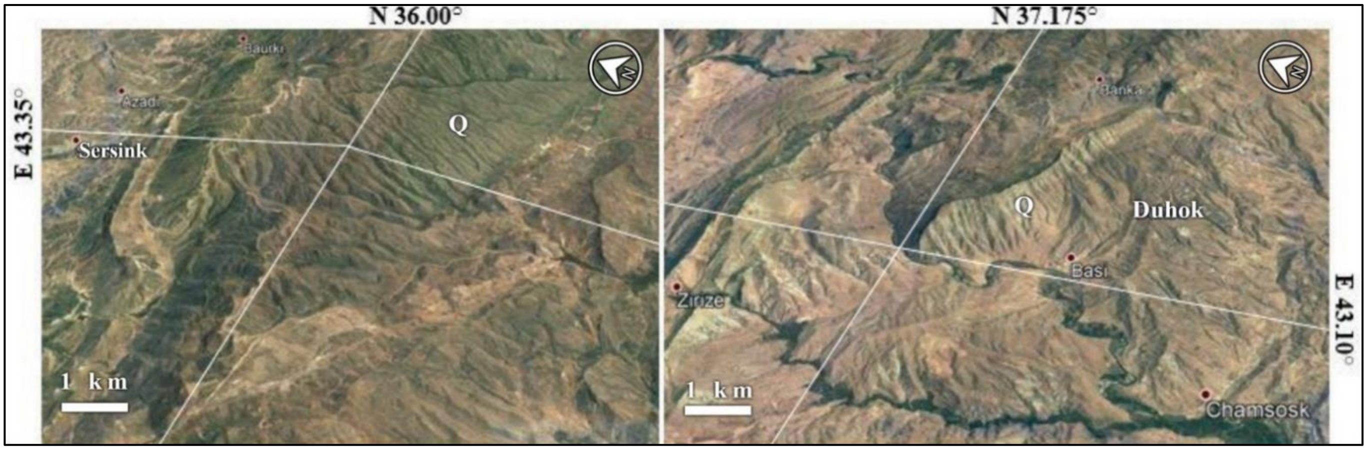

Figure 7. Satellite images of the northwestern plunges of the **(left)** Gara anticline, and **(right)** Mateen anticline. Note the differences in thickness and steepness of the beds of the Qamchuqa Formation (**Q**) in both anticlines

Table 2: Recorded elevations of the contact between the Fatha and Injana formations

Anticline	Geographic Location	Elevation of the contact between the Fatha and Injana Formations (m, a.s.l.)		Amount of upward movement during the Pleistocene (2.588 Ma) (m)	Rate of upward movement during the Pleistocene (mm/100 year)
Gara	Near Sarsang town	NE Limb	1035	230.51	8.907
	NE of Chamange village	SW Limb	1028	228.96	8.847
	South of Al-Khabour river	NW Plunge	910	202.68	7.832
		SE Plunge	--------	---------	--------
	Average				8.529
Mateen	Near Khash'khashe village (25 km NW Amadiya town)	NE Limb	1352	301.12	11.635
	Near Amadiya town	SW Limb	1048	233.41	9.019
	Near Al-Khabour river	NW Plunge	926	206.24	7.969
		SE Plunge	-------	----------	----------
	Average				9.541

--------- Means not present

The recorded elevation of the contact between the Fatha and Injana formations, represents the amount of upward movement since the Upper Miocene period at the recorded location along both the Gara and Mateen anticlines. The amount of the upward movement at each of the recorded locations could be calculated (Table 2) because the present relief developed from the Pleistocene Epoch (2.588 Ma, ICS, 2012). Subsequently, the rate of the upward movement during the Pleistocene Epoch was calculated (Table 2). The maximum rate of upward movement (11.635 mm/100 year) was recorded along the northeastern limb of the Mateen anticline, near Khash'khashe village (25 km NW of Amadiya town), whereas the minimum rate of upward movement (7.832 mm/100 year) was recorded along the northwestern plunge of the Gara anticline near the Al-Khabour river (Table 2). It is clear that the rate of the upward movement decreases southward, as recorded along the northeastern and southwestern limbs of both the Mateen and Gara anticlines (Table 2). The same decrease in the rate was recorded in the northwestern plunges of the Mateen and Gara anticlines, respectively (Table 2). The average rate of upward movement at both anticlines is 8.529 and 9.541 mm/100 years, respectively.

The rate of river incision is also calculated along the courses of the Greater Zab and Al-Khabour rivers. Locally, 3 levels of terraces were recognized. These are dated as Lower, Middle, and Upper Pleistocene as determined by Sissakian et al. (2014) and by using an exposure dating method (Keller and Pinter, 2002). Terraces were recognized at 10 different locations, with 8 along the Greater Zab river and 2 along the Al-Khabour river, , each with 3 levels of terraces; however, at some locations only 1 or 2 levels of terraces were recognized (Table 3).

Table 3 Incision rates of the Greater Zab and Al-Khabour rivers at different geographical locations

River	Location		Terrace level		Age	Height difference between the terrace and river level (m, a.s.l.)	Rate of incision (mm/100 years)	Comments
Greater Zab	Iraqi – Turkish borders	North of Mateen anticline	1	L	Pleistocene	164	6.337	There may be an older terrace level than Level 1
			2	M		92	11.779	
			3	U		13	11.111	
	Deralok	Mateen anticline	3	U		18	15.385	Along the syncline between the 2 anticlines
	Sheladiz		3	U		15	12.821	
	Balinda		2	M		67	8.579	
	Baze		1	L		151	5.835	These are along the south western limb of the Mateen anticline
			2	M		97	12.419	
			3	U		21	17.949	
	Barzan		1	L		148	5.719	
			2	M		57	7.298	
	Bele		2	M		54	6.914	Southeast of the Gara and Mateen anticlines
	Zibar		3	U		17	14.529	
						Average	8.265	Average of 3 levels
Al-Khabour	Basi	Mateen Anticline	3	U		23	19.658	
	NW Plunge Area (East of Batifa)		1	L		117	4.521	Crossing of Al-Khabour river to the plunge area of the Mateen anticline
			2	M		67	8.579	
			3	U		22	18.803	
						Average	10.312	Average of 3 levels

Pleistocene, L, Lower = 2.588 Ma; M, Middle =0.781 Ma; U, Upper = 0.0117 Ma.

The height differences between the river level and the terrace level at each of the recognized 10 points were calculated using Google Earth images. The time spans of the 3 parts of the Pleistocene Epoch were used to calculate the incision rates. For the Lower, Middle, and Upper Pleistocene periods, the following time spans were used: 2.588 Ma, 0.781 Ma, and 0.126 Ma, respectively.

The minimum rates of the upper, middle, and lower levels along the Greater Zab river are: 4.521, 6.914, and 11.111 mm/100 year, respectively, whereas the maximum rates of the upper, middle, and lower levels are 6.337, 12.419, and 17.949 mm/100 years, respectively (Table 3). However, the average rates of incision of the 3 levels along the Greater Zab river are 5.964, 9.398, 14.359 mm/100 years, respectively. Moreover, the average rate of the 3 levels along the Greater Zab river is 8.265 mm/100 years, whereas the average rate of the 3 levels along the Al-Khabour river is 10.312/100 years.

6. CONCLUSIONS

The Gara and Mateen anticlines are exhibiting lateral growth as indicated by different structural features (e.g., multiple dome folds and en-echelon plunges) and geomorphological features (e.g., water gaps, abandoned alluvial fans, and different valley shapes). The rate of uplift in the Gara anticline is higher than the rate of stream incision as indicated by the absence of water and wind gaps. In contrast, in the Mateen anticline, the rate of stream incisi on is higher than the rate of uplift as indicated by the presence of 3 water gaps. The absence of wind gaps in the Mateen anticline is another indication that the rate of stream incision is higher than the rate of uplift.

The presence of en-echelon plunges in both the Gara and Mateen anticlines is a good indication that each anticline was on a single alignment but because of lateral growth, each anticline was divided into 2 parts (East and West). This is also confirmed by the presence of many domes in each anticline and by the observation that the domes have already started losing their dome shape and will merge together into a single double-plunging fold. However, the development of en-echelon plunge between the already existing domes is highly possible after a certain geological time.

The maximum and minimum rates of upward movement at the Mateen anticline are 11.635 mm/100 years and 7.969 mm/100 years, respectively, whereas for the Gara anticline they are 8.907 mm/100 years and 7.832 mm/100 years, respectively. In both anticlines, the maximum rate was recorded along the northeastern limb, whereas the minimum rate was near the north western limb. The maximum rates of incision of the Greater Zab river were recorded at the lower (younger, no. 3) terrace level, (17.949 mm/100 years), whereas the minimum rates were recorded at the upper (oldest, no. 1) terrace level (5.719 mm/100 years).

The average rate of incision of the Al-Kabour river (10.312 mm/100 years) is higher than the average rate of upward movement of the Mateen anticline (9.541 mm/100 years). In contrast, the average rate of incision of the Greater Zab river (8.265 mm/100 years) is lower than the average rate of upward movement of the Gara anticline (8.529 mm/100 years). Therefore, the river runs around the southeastern plunge and does not dissect the anticline. Although the average rate of incision of the Greater Zab river (8.265 mm/100 years) is lower than the average rate of upward movement of the Mateen anticline (9.541 mm/100 years), the river still dissects the anticline. This is attributed to the presence of deep and straight lineaments along which the river dissects the anticline.

ACKNOWLEDGMENTS

This study is the result of research work carried out at the University of Kurdistan Hewler (UKH). The authors also highly appreciate the support of the university authorities. The authors would also like to extend their appreciation to Mr Paul Dirk Embery (lecturer at the English language Center at UKH) for proofreading the manuscript.

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