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Sinjar Anticline Northwest of Iraq: A Tectonic Geomorphological Study

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The Sinjar Anticline (Mountain) is an outstanding structural and geomorphic feature in the northwestern part of Iraq. The anticline is a double plunging with almost E – W trend dividing the gently rolling plain in which it is developed into two parts, Al-Jazira Plain in the south and Rabi'a Plain in the north. The Sinjar anticline is asymmetrical with steeper northern limb (45 – 80)° and gentler southern limb (15 – 25)°, its length is about 80 km, whereas the width ranges between (9.25 – 12. 5) km. The oldest exposed rocks belong to the Shiranish Formation, whereas the youngest rocks belong to the Fatha Formation. Different geomorphological and structural forms were observed through interpretation of satellite images, geological and topographical maps of different scales, beside field observations. Among those forms are: Abandoned alluvial fans, radial, inclined, and cross-shaped valleys, whale-back shape, wind gaps, and parasitic folds. All these forms are good indications about the lateral growth of the anticline. Neotectonic measurements were carried to estimate the rates of upward and downward movements. These estimations were performed by measuring the elevation of the contact between the Fatha (Middle Miocene) and Injana (Late Miocene) formations at different selected locations on both sides of the anticline.

Keywords: *Sinjar anticline, lateral growth, neotectonic movements, wind gap, abandoned alluvial fans*

Introduction

The Sinjar anticline is in the Low Folded Zone (LFZ), which is a part of the Zagros Fold – Thrust Belt (ZFTB). This in turn is a part of the Zagros Foreland Basin, which is developed due to the collision of the Arabian and Eurasian plates (Alavi 2004, Jassim and Goff 2006, Fouad 2015).

The Sinjar anticline (mountain) is an outstanding structural and geomorphological form; developed within a wide and gently rolling plain in the central northwestern part of Iraq. Towards the north is the Rabi'a Plain with elevation ranges between (460 – 515) m, and towards the south is Al-Jazira Plain with elevation ranges between (380 – 440) m. The height of the ground surface decreases westwards in the Rabi'a Plain, whereas in Al-Jazira Plain it decreases eastwards. The Sinjar anticline is about 80 km long and 9.25 km wide in the western part and 12.5 km in

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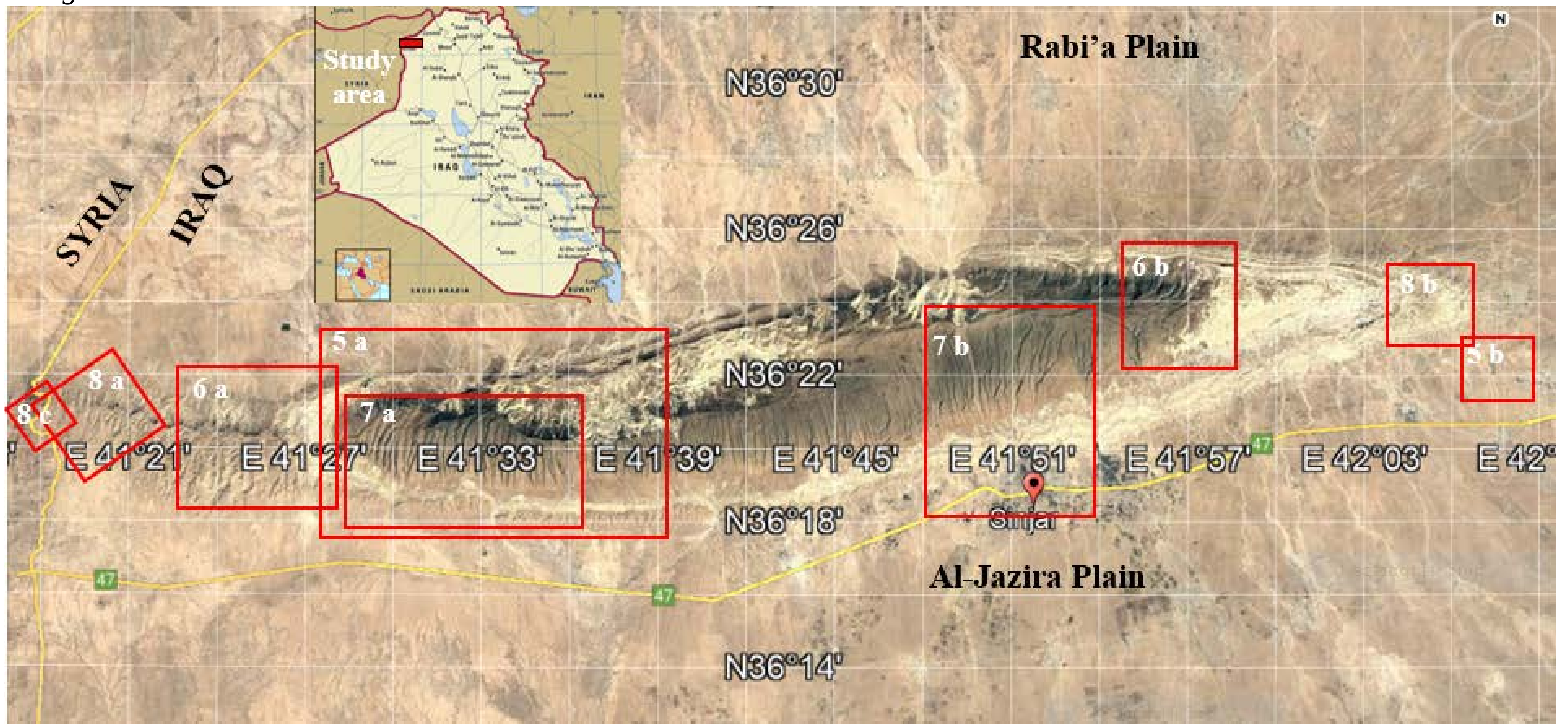
the eastern part. The highest peak is 1421 m (a.s.l.) it is located north of the Sinjar town along the southern limb that extends like a whale-back shape along the whole southern limb of the anticline (Figure 1).

The following works were carried out concerning the Sinjar anticline, majority of the carried-out works have emphasized on the developed alluvial fans on both sides of the anticline: Ma'ala (1977) in Sissakian and Al-Jibouri (2012) performed regional geological mapping of Sinjar anticline and surrounding plains, he described the tectonic, structure, stratigraphy, and geomorphology of the concerned area. Al-Daghastani (1989) mapped Sinjar Anticline and the alluvial fans by means of remote sensing technique. His study was emphasized on the developed alluvial fans along both sides of the anticline. Al-Daghastani et al. (2004) in an attempt of rainwater harvesting have mapped the Sinjar alluvial fans using remote sensing techniques. They have analyzed and classified the landforms to obtain the details about rainwater harvesting, they also prepared a geomorphological map with emphasizing on the alluvial fans. Al-Daghastani and Al-Dewachi (2009) performed a comprehensive geomorphological study of the Rabi'a Plain north of the Sinjar Mountain using remote sensing technique. They concluded that the development of the alluvial fans is related to different episodes of Neotectonic movements. Sissakian (2011) studied the alluvial fans of Sinjar anticline, which are developed along both sides of the anticline, he recognized five stages of alluvial fans, the fifth being in Syria. He also confirmed that the five stages are separated from each other due to Neotectonic activities. Fouad (2012) studied tectonically the Low Folded Zone where the Sinjar anticline is developed. He mentioned that most of the folds are structural highs above earlier structural lows, and consequently they are considered as inversion structures. Moreover, he added that structural analysis of tectono-stratigraphic sequences in Mosul region indicate that the folds have had formed in two distinct episodes; an early Campanian – Maastrichtian episode of extension and rift formation, followed by Pliocene – Pleistocene episode of compression and fold formation.

Figure 1. *Satellite Image of the Sinjar Anticline, Note the Whale-back Shape and the Developed Alluvial Fans, Especially Along the Northern Limb*



Note: The red rectangles are the locations of the presented figures in the text with their serial numbers.

The studied area is in the northwestern part of Iraq. It includes the whole Sinjar anticline and parts of the surrounding plains (Figure 1). The coverage area is about 200 km^2.

This study aims in describing the tectonic and geomorphological development and existing forms of the Sinjar anticline. Moreover, to estimate the rates of upward and downward Neotectonic movements in the concerned area.

Materials and Methods

Geological and topographical maps of different scales and satellite images were used to conduct the current study. From the visual interpretation of satellite images, different geomorphological forms were recognized, such as abandoned alluvial fans, radial, inclined, cross-shaped, and fork-shaped valleys, wind gaps, all these forms are indications for the lateral growth of anticlines (Burbank and Anderson 2001, Keller and Pinter 2002, Ramsey et al. 2008, Fossen 2010, Collingnon et al. 2016).

For estimating the rates of the upward and downward movements as Neotectonic movements, we have used the method, which depends on the elevation and/ or the depth of the contact between Middle and Late Miocene rocks from the present topography (above the sea level), which is the same concept of Obruchev (1948) and adopted by ATOMENERGOEXPORT (1985) and is confirmed by Pavlides (1989) and Koster (2005). The upwards and downwards movements were presented by means of contour lines, which mark the up warded and down warded areas as the Neotectonic Phase has started from the Upper Miocene Period (Obruchev 1948). The elevation of the contact between the Middle Miocene Fatha Formation (Marine sediments) and the Upper Miocene Injana Formation (Clastic continental sediments) represents the beginning of the Neotectonic Phase in Iraq (ATOMENERGOEXPORT 1985). This is attributed to the change of the marine environment to continental, due to the collision of the Arabian and Eurasian plates. The elevations of the concerned contact (above sea level) were indicated either from topographic maps (at a scale of 1:100000) or from the Google Earth images. The indicated elevations represent the amount of the upwards Neotectonic movements. In areas covered by the Injana Formation, the depths of the contact (below the surface) were indicated either from existing wells, cross sections and/ or by subtracting the average thickness of the Injana Formation from the height of a certain point from the surface elevation at the concerned point. The result is the depth of the contact between the Fatha and Injana formations; accordingly, will represent the downward amount of the Neotectonic movement.

For recognizing Neotectonic evidences and lateral growth of the Sinjar anticline we have used the opinions of many researchers: Rockwell et al. (1985), Pavlides (1989), Becker (1993), Cartwright et al. (1995), Dawers and Anders (1995), Kumanan (2001), Cloetingh et al. (2002), Blanc et al. (2003), Décallau et al. (2006), Koster (2005), Bretis et al. (2011), Mumipour and Najad (2011), Skilodimou et al. (2014), Burberry (2015) Gurpuz and Saein (2019).

Geological Setting

The geological setting of the studied area is briefed including tectonics and structural geology (Fouad 2015), Geomorphology (Yacoub et al. 2012), and Stratigraphy (Sissakian and Al-Jibouri 2012), and Neotectonics. The geological map of the Sinjar anticline is presented in Figure 2.

Tectonics and Structural Geology

The studied area is in the Low Folded Zone (LFZ), which belongs to Outer Platform of Iraq (Fouad 2015). The LFZ is a pert of the Zagros Fold – Thrust Belt, which is developed due the collision of the Arabian and Eurasian plates (Alavi 2004, Fouad 2015). The Sinjar anticline is 80 km long and 20 km wide, almost trending E – W, with steeper northern limb (45 – 80)° and gentler southern limb (15 – 25)°. A normal fault trending E – W runs along the northern limb; many other small faults occur too (Figure 2). Locally, along the southern limb a low amplitude anticline occurs, it is developed within the Sinjar Formation with a length of about 15 km and separated from the main axis of the Sinjar anticline with a shallow syncline (Figure 2).

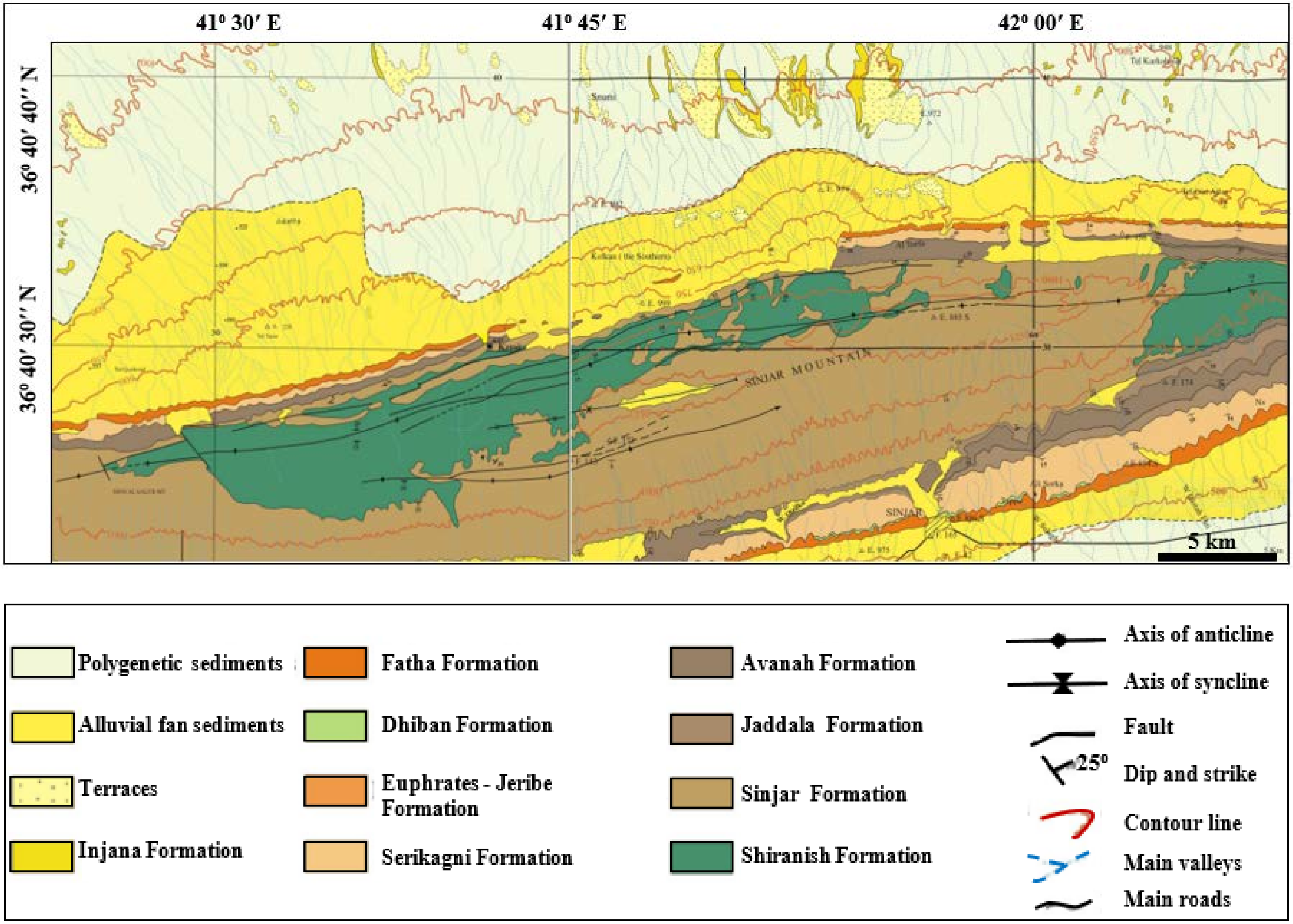
Stratigraphy

The exposed rocks in the studied area range in age from the Late Cretaceous, represented by the Sinjar Formation up to Late Miocene, represented by the Injana Formation (Sissakian and Al-Jibouri 2012). A generalized columnar section of the exposed formations is represented in Table 1.

Table 1. *Generalized Columnar Section of the Exposed Formations in the Studied Area (Red Line Represent Unconformity) (After Sissakian and Al-Jibouri 2012)*

Formation	Age	Thickness (m)	General Description
Injana	**Late Miocene**	**900 – 100**	Sandstone interbedded with siltstone and claystone in rhythmic cycles, all rocks are reddish-brown in color
Fatha	**Middle Miocene**	**550 – 630**	Green marl interbedded with limestone and gypsum in rhythmic cycles, in the upper cycles, reddish brown claystone occurs.
Jeribe		**100 – 125**	Well bedded greyish white limestone
Dhiban	**Early Miocene**	**5 – 100**	Mainly limestone with rare limestone
Serikagni		**65 – 300**	Well bedded white limestone with some marl intercalations
Avanah	**Middle Eocene**	**85**	Marly limestone interbedded with marl
Jaddala		**500 – 550**	Marl interbedded with marly limestone
Sinjar	**Early Eocene-Late Paleocene**	**170**	Well bedded, white and very hard limestone
Aaliji		**50**	Shale and marl
Shiranish	**Late Cretaceous**	**565**	**Bluish green, papery marl, in the upper part well bedded greyish white limestone in the lower part**

Figure 2. *Geological Map of the Sinjar Anticline (Modified from Sissakian and Fouad 2015)*



Geomorphology

The study area is within the Low Amplitude Mountainous Province (Sissakian and Fouad 2015). Apart from the Sinjar Mountain (anticline), the surrounding areas form flat terrain dissected by dense valleys, which flow dong from the mountain. The highest point is 1462 m, on the top of Sinjar Mountain, whereas the lowest point is about 300 m, in the southeastern part of the study area.

Geomorphological Units

The following geomorphologic units are developed in the studied area:

A. Units of Denudational Origin

- **Pediments:** These units are well developed on both sides of the Sinjar Mountain and along the main scarps. The thickness ranging from (1 – 5)m.
- **Dissected Slopes:** These are developed around the Sinjar Mountain; near both flanks with thickness ranging from (1 – 12) m.
- **Polygenetic Sediments:** These sediments are mainly of fine clastics and cover vast parts of the flat areas of Al-Jazira and the Rabee'a plains.

B. Units of Structural – Denudational Origin

- **Hogbacks and Cuestas:** These are developed on both sides of the Sinjar anticline, within the exposures of the Sinjar and Serikagni – Jeribe formations.
- **Anticlinal Ridges:** These are well developed around Sinjar anticline, especially within the Sinjar Formation; especially in the southern limb.

C. Units of fluvial Origin

- **Alluvial Fans:** These are well developed around Sinjar anticline; in (2 – 5) stages. The older stage rests directly on the Fatha and Injana formations (Figure 2). They cover many square kilometres (each one) and are composed of limestone gravels; up to 1 m in size, the size decreases in the younger stages. The thickness of each stage ranges from (3 – 10) m. Locally, they interfere with the dissected slopes and terraces.

D. Forms of Solution Origin

- The main form of solution origin is the sinkholes, which are developed in Sinjar Mountain, within limestone and gypsum. They are of different shapes, forms and dimensions, some caves also are present in the Sinjar Mountain.

Mass Movements

The main phenomenon in the study area is the toppling, where blocks of hard carbonate rocks of different formations are toppled on the back slopes. The blocks range in size from less than one cubic meter up to 3 m^3. Landslides are rare, they are developed along the southern limb of the Sinjar anticline due to steep deep, especially along the Sinjar Formations. Rock fall, flow, and other mass wasting phenomena can be seen at different parts of the anticline.

Neotectonic Movements

We have constructed a Neotectonic map (Figure 3), which shows the up-warded and down-warded areas, as Neotectonic activities are concerned. The presentation is in form of contour lines, the contours are drawn as mentioned in Section "Materials and Methods". Such presentation is confirmed by ATOMENERGOEXPORT (1985), Pavlides (1989), Koster (2005), and in Iraq by Deikran and Sissakian (2008) and Sissakian and Deikran (2009).

Results

From manual interpretation of satellite images, and geological and topographical maps, we have recognized the following forms. All interpreted forms are excellent indications of the lateral growth (Rockwell et al. 1985, Burbank and Pinter 1999, Burbank and Anderson 2001, Keller and Pinter 2002, Ramsey et al. 2008, Decallau et al. 2006, Bretis et al. 2011, Burtscher et al. 2012, Grasemann and Schmalholz 2012, Collingnon et al. 2016).

Abandoned Alluvial Fans

The Sinjar anticline is a very well known to have tens of alluvial fans developed along its both limbs. However, many of them are abandoned and the recent valleys are already dissecting them (Figure 4b). The dissected alluvial fans are good indications that they are abandoned, and no more sediments are supplied; therefore, indicate the lateral and vertical growth of anticlines (Burbank and Anderson 2001, Keller and Pinter 2002, Ramsey et al. 2008).

Wind Gaps

At many parts of the Sinjar anticline, wind gaps are developed (Figure 4a). They indicate the lateral and upward growth of the anticline (Burbank and Anderson 2001, Keller and Pinter 2002, Ramsey et al. 2008).

Figure 3. *Satellite Image of Sinjar Anticline Showing the Locations of the Points Where up-ward and Down-ward Movements were Measured, and the Constructed Contour Lines*

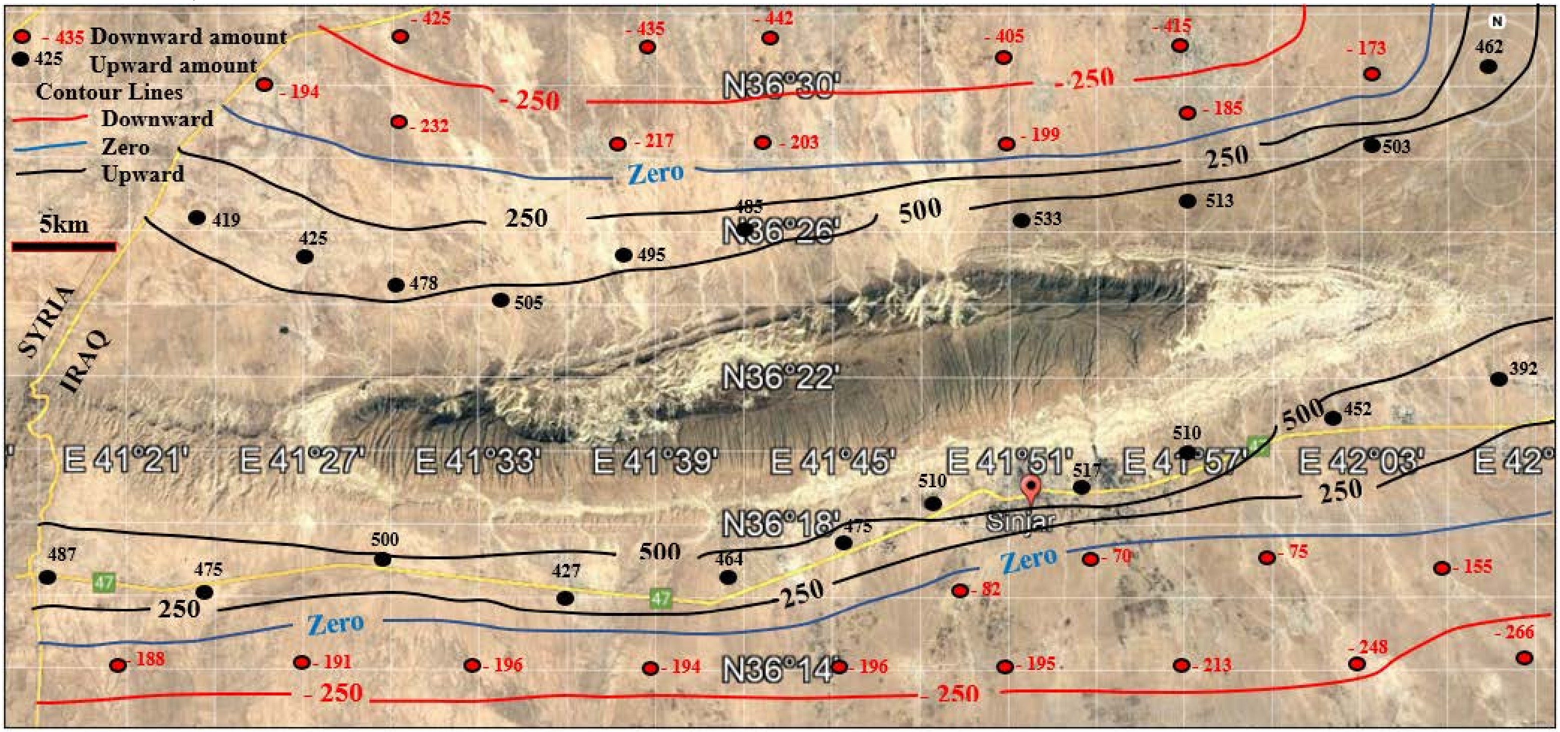
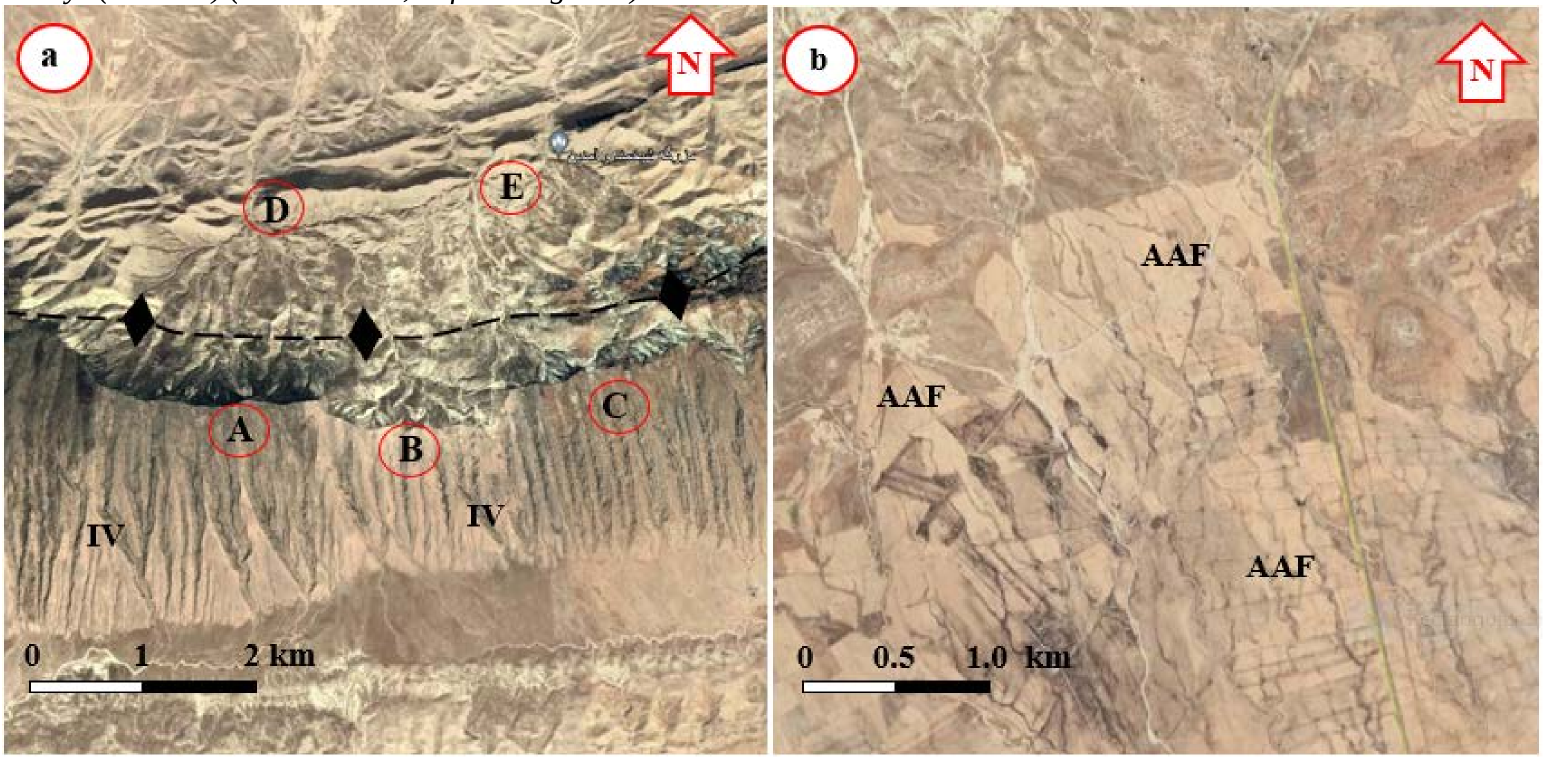


Figure 4. *Satellite Images of Interpreted Forms, a) Wind Gaps, Note the Valleys which Run from A, B,C to D and E, Inclined Valleys (IV), b) Abandoned Alluvial Fans (AAF), Note the Abandoned Feeder Channels (in Black) and the Recently Dissecting Valleys (in White) (For Location, Refer to Figure 1)*



Different Shaped Valleys

Different shaped valleys are developed within the Sinjar anticline, like radial, axial, cross, inclined (Figures 5 and 6). They all are good indications for the lateral growth of the Sinjar anticline (Burbank and Anderson 2001, Keller and Pinter 2002, Ramsey et al. 2008).

Whale-back Shape

The Sinjar anticline exhibits typical whale-shape (Figures 1, 3 and 6). Although parts of the anticline are eroded, especially along the northern limb; however large parts of the anticline still exhibit whale-back shape with clear erosional ridges (Figure 6). According to Burbank and Anderson (2001), Blanc et al. (2003), Fossen (2010) some anticlines can exhibit anomalous structural shapes, among those shapes is the whale-back, which is also a good indication for the lateral growth of the Sinjar anticline. The presence of whaleback anticlines is a good indication that the decollement is shallow (Sepehr and Cosgrove 2005, Burberry et al. 2010).

En-echelon Plunge

The en-echelon plunges are good indication for the lateral growth of anticlines (Keller and Pinter 2002, Ramsey et al. 2008, Fossen 2010). In the bulk of the Sinjar anticline (Figure 2), many en-echelon plunges can be observed indicating the lateral growth of the anticline.

Domes

In the bulk of the Sinjar anticline many small domes along the axial part can be observed (Figure 2). The presence of domes along any anticline may indicate that previously each dome was a distinct anticline and due to the lateral growth, they are joined together (Campbell 1958, Fossen 2010, Grasemann and Schmalholz 2012).

Neotectonic Movements

The constructed Neotectonic map of the studied area (Figure 3) shows that all the contour lines run almost parallel to the Sinjar anticline. However, there are slight deviations, these are attributed to the accuracy of the measured height of the point where the upward and/or downward calculations were done. Moreover, the used thickness of the Injana Formation and the overlying Quaternary sediments also contributes to such abnormalities.

Figure 5. *Satellite Images of the Sinjar Anticline, a) The Western Plunge, b) The Eastern Plunge. Valleys: AV= Axial, RV= Radial, CV= Curved, IV= Inclined, F – F is a Normal Fault, the Plunge Direction is the Down Thrown Side (For Location, Refer to Figure 1)*

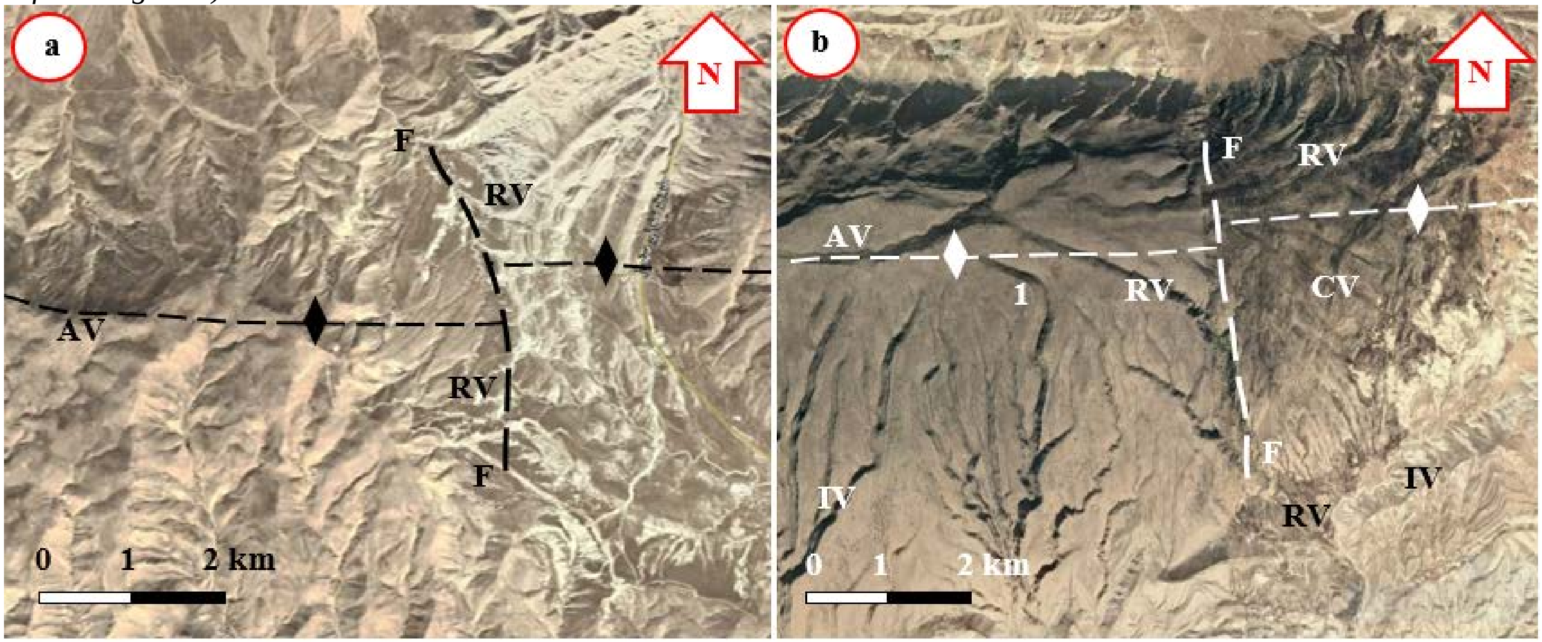
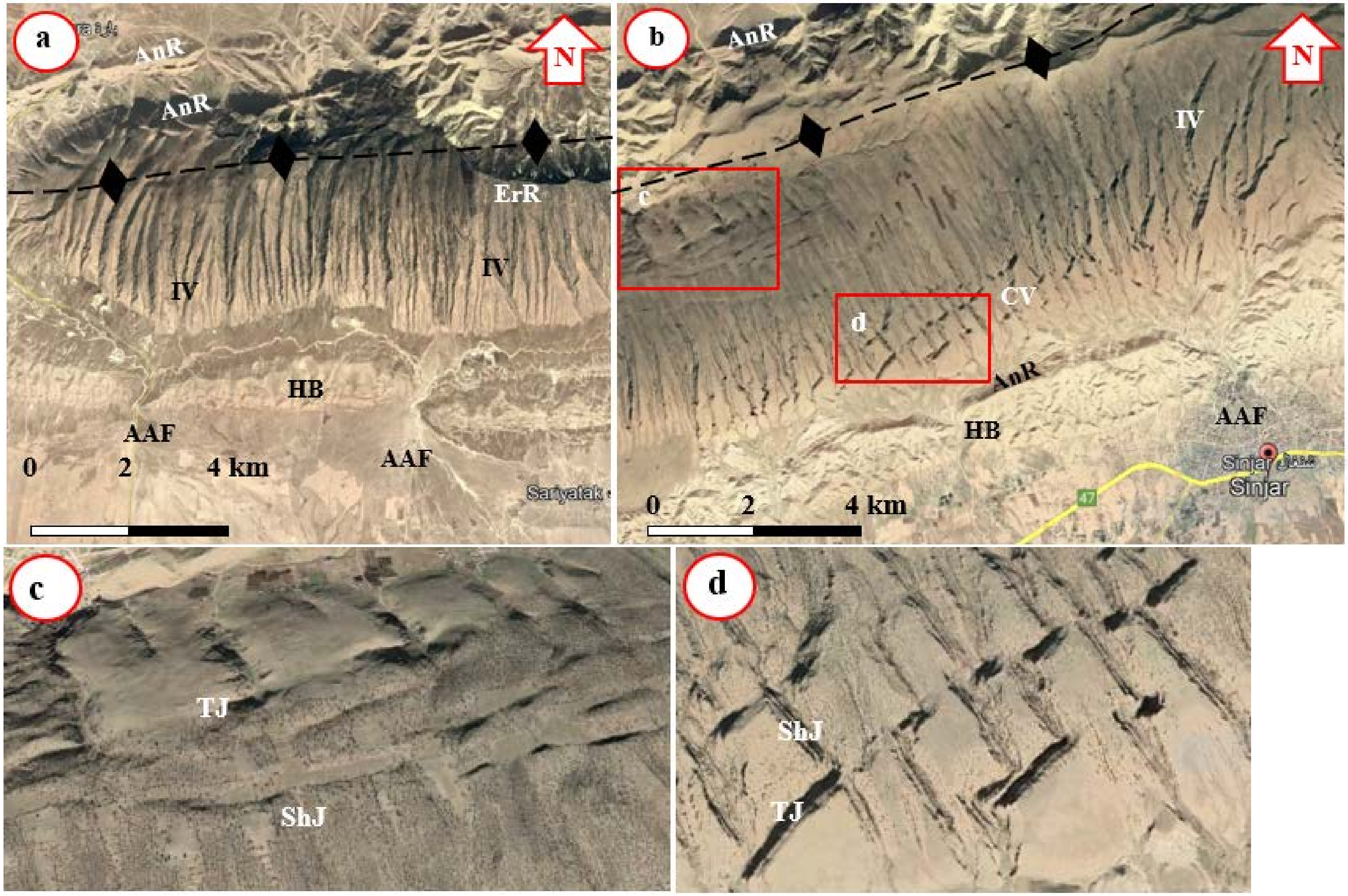


Figure 6. *Satellite Images of the Sinjar Anticline Showing Whale-back Shape, a) Western Part, b) Eastern Part, c and d) Tension Joints (TJ) and Shear Joints (ShJ). AAF= Abandoned Alluvial Fan, HB= Hogback, AnR= Anticlinal Ridge, ErR= Erosional Ridge. Valleys: CV= Cross-shaped, IV= Inclined (For Location, Refer to Figure 1)*



Discussion

The Sinjar anticline is an outstanding high amplitude anticline in the Low Folded Zone of the Outer Platform of the Arabian Plate, it is also part of the Zagros Fold Thrust Belt (Alavi 2004, Fouad 2015). The oldest exposed rocks in the core of the anticline belong to the Shiranish Formation of the Upper Cretaceous age (Sissakian and Fouad 2015); it is the second anticline (after Qara Chough anticline) within the Low Folded Zone with the Cretaceous rocks in the core.

The Sinjar anticline is an inverted graben (Fouad 2009, 2015) as many other southerly existing subsurface folds in the Jazira Plain, like Tayarat anticline (Fouad 2009). The inversion process has increased the deformation of the anticline, besides the lateral growth, which is a characteristic feature of most of the anticlines in the IKR (Ghafur et al. 2019, Sissakian et al. 2018 2020, 2021). Moreover, it has caused the Cretaceous rocks to be exposed in the core of the Sinjar anticline.

The intense structural deformation is clear along the southern limb of the Sinjar anticline (Figure 6), where the thick carbonate rocks of the Sinjar Formation form most of the limb. Although the northern limb is steeper than the southern limb, but the deformation is not clear. This is attributed to the type of the exposed rocks on both limbs and relief differences.

The long (2.6 – 3 km) steep, narrow and vertical valleys cross the anticlinal axis of the Sinjar anticline (Figure 6a) and run southwards. These valleys are most probably shear joints (Figure 6c and d), which are enlarged by gulley erosion and weathering. However, some of them, which run southwards directly crossing the anticlinal axis, they may represent water gaps which are abandoned due to the lateral and upward movements of the anticline.

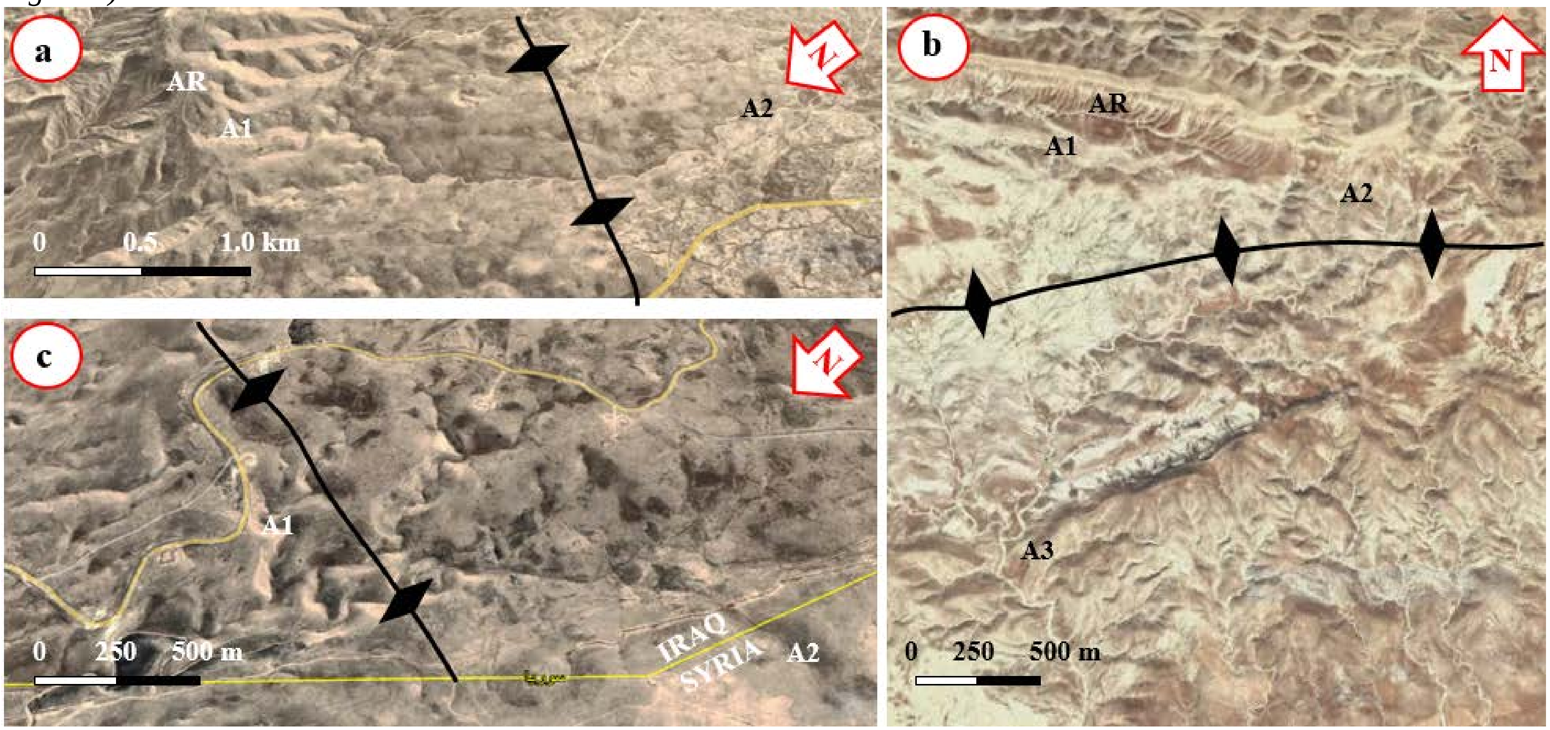
The constructed Neotectonic map (Figure 3) shows that the maximum upward amounts along the northern and southern limbs of the Sinjar anticline are 533 m and 517 m, respectively. Whereas the maximum downward amounts along the northern and southern limbs are - 405 m and - 266 m, respectively. The downward amounts along the northern limb are higher than those along the southern limb, this is attributed to: 1) Northern limb is steeper than the southern one, 2) There are many normal step faults parallel to the northern limb (Sissakian 2011), which increased the depth to the contact between the Fatha and Injana formations, and 3) The normal faults are active and continuously increasing the depth of the down thrown block; as indicated from the developed five stages alluvial fans (Sissakian 2011).

The interpreted geomorphological forms like different shaped valleys, abandoned alluvial fans, hogbacks are recognized only along the southern limb (Figures 4 and 5). This is attributed to the exposures of the hard carbonate rocks of the Sinjar Formation, and gentler dip as compared with the steep dipping beds along the northern limb.

Water gaps are also recognized along the western and eastern parts of the anticline only (Figure 7). This attributed to the exposure of the very hard carbonate rocks of the Sinjar Formation along the southern limb, where they form the bulk of the Sinjar Mountain, which is in whale-shape (Figure 6a and b). Moreover, the valleys run southwards just at the beginning of the anti-dip slopes of the northern limb (Figure 7a, b and c, Points A1 – A2 – A3). This attributed to the steeply dipping hard rocks, which form anticlinal ridges (Figure 7a and b, Point AR), where the valleys cannot cross the ridges. However, by continuous erosion and lateral growth of the Sinjar anticline, the valleys will be able to cross the developed anticlinal ridges.

The last recognized geomorphological form is the intense karstification of the exposed rocks of the Fatha Formation at the extreme western part of the Sinjar anticline within the study area (Figure 7c). This is attributed to the exposures of the gypsum and limestone beds within the Fatha Formation, which is characterized by intense karstification (Yacoub et al. 2012).

Figure 7. *Satellite Images of the Sinjar Anticline, a and c) The Western Plunge Area, b) The Eastern Plunge Area. Note the Water Gaps and the Intense Karstification in the Extreme Western Part of the Anticline (Caption c) (For Location, Refer to Figure 1)*



Conclusions

The Sinjar anticline shows clear structural and geomorphological indications for its lateral growth. Among those indications are water gaps, wind gaps, abandoned alluvial fans, different-shaped valleys, domes, plunges. The calculated Neotectonic movements indicate that the amount of the maximum upward movement along the northern and southern limbs of the anticline are 533 m and 512 m, respectfully. Whereas the maximum downward movements along the northern and southern limbs are – 405 and – 266 m, respectfully.

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