Geomorphic Indicators of Folds Lateral Growth Using Satellite Images: Sulaimaniyah Vicinity in Kurdistan Region of Iraq

Varoujan K. Sissakian[1], Lanja H. Abdullah[2], and Balanbo N. Abdulkareem[3]

[1]Department of Petroleum Engineering, Komar University of Science and Technology, Sulaymaniyah, Kurdistan region – F.R. Iraq

[2]Department of Geology, College of Science, University of Sulaimani, Sulaymaniyah, Kurdistan region – F.R. Iraq

[3]Department of Geological Survey, Kurdistan Regional Government, Ministry of Natural Resources, Sulaimanyah Oil and Mineral Directorate, Sulaymaniyah, Kurdistan region – F.R. Iraq

Abstract—**Visual interpretation of satellite images is a very significant technique to recognize and interpret structural features, which indicate lateral growth of folds, the origin of folds, and dating of folds using the exposure dating method. In this study, Landsat 8 (ESSRI) and Google Earth images are used to recognize structural features at Pira Magroon, Surdash, and Azmar anticlines in the Sulaimaniyah vicinity, Kurdistan Region, north of Iraq. The mentioned anticlines are outstanding geomorphological and structural features in the Sulaimaniyah vicinity. The recognized and interpreted structural features include: en-echelon folding, domes, and Neotectonic indication. All these features are discussed in detail with many images to show the discussed cases, most of the interpreted data and presented figures are never mentioned previously.**

***Index Terms*—Domes, En-echelon fold, Lateral growth, Neotectonic indications.**

I. Introduction

The northeastern part of the Arabian Plate is occupied by the Kurdistan Region of Iraq (KRI). The plate is in collision with the Iranian Plate with convergent tectonic plate boundary (e.g., Alavi, 2004, Allen, et al., 2004; Fouad, 2015). In tectonically active areas, such as the KRI, the lateral growth of anticlines is a very common phenomenon (e.g., Blanc, et al., 2003, Bennett, et al., 2005, Ramsey, Walker and Jackson, 2008). The anticlines in this tectonically active area show different significant geomorphological and structural features which indicate the lateral growth of those folds. The developed landscape and the drainage patterns provide indirect information on the tectonic activity (e.g., Bretis, Bartl and Grasemann, 2011; Burbank and Pinter, 1999; Burbank and Anderson, 2001; Keller, Gurrola and Tierney, 1999; Collignon, et al., 2016).

The mountain building and landscape evolution are controlled by interactions between river dynamics and tectonic forces (Collignon, et al., 2016). The described criteria by Keller, Gurrola and Tierney (1999); Ramsey, Walker and Jackson (2008), Fossen (2020), and Grasemann and Scholholz (2012) can be used to evaluate fold growth, among those criteria are: (1) The deformation of progressively younger deposits or landforms, (2) the development of characteristic asymmetric drainage patterns, (3) the development of domes within folds, and (4) the development of en-echelon plunges withing anticlines.

The Pira Magroon, Surdash–Sara, and Azmar are three main anticlines in the Sulaimaniyah vicinity, located around Sulaimaniyah city, in the northwest, north, and northeast of the city (Fig. 1).

We have reviewed many scientific reports and articles which were published concerning the studied area and the High Folded Zone. Those which dealt with the current work are mentioned briefly hereinafter. Colman-Saad (1978) showed that the simply folded belt of the Zagros Mountains has undergone folding from Miocene to recent time. He added that “Structures in the Competent group are typical of parallel folds formed by buckling and developed by a combination of flexural-slip and neutral-surface mechanisms.”

In the studied area, there is a main competent group formed by the rocks of the Kometan and Qamchuqa formations. Ameen (1991) implied the presence of a decollement horizon at or near the base of the sedimentary cover, the “Infra-Cambrian Hormuz Salt” and a passive role of the Precambrian basement in the tectonic evolution of the folded belt. Structural, stratigraphic, geophysical, and remote sensing evidence suggests that forced folding, due to faulting in the basement, has played a significant role in the development of

ARO-The Scientific Journal of Koya University
Vol. XI, No. 1 (2023), Article ID: ARO.11010. 9 pages
DOI: 10.14500/aro.11010
Received: 22 June 2022; Accepted: 22 February 2023
Regular research paper: Published: 23 March 2023
Corresponding author’s e-mail: varoujan.sissakian@komar.edu.iq

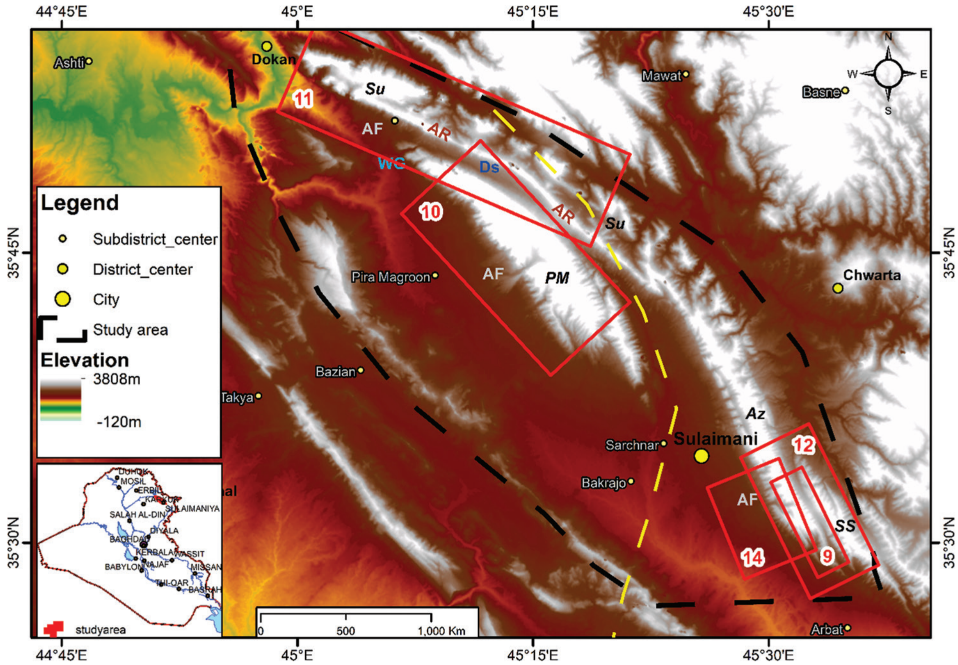

Fig. 1. Satellite image showing the location of the studied area; approximately limited by the black dashed line. Anticlines, PM=Pira Magroon, Su=Surdash, Az=Azmar, SS=Said Sadiq, AF=Alluvial fan, DS=Dissected slopes, AR=Anticlinal ridges, WG=Water gap, the yellow dashed line represents the approximate location of a paleo ridge.

many of the folds in this region. No comment can be added to this study since it is a surface study that mainly dealt with the acquired data from the interpretation of satellite images and field check. Blanc, et al. (2003) showed that the NW – SE-trending folds and thrusts in the Simple Folded Zone are shortened by right-lateral strike-slip fault on the NW – SE-trending main recent fault. The geometries of exposed structures suggest both basement thrusts and thin-skinned decollement levels, with major folds possibly nucleated above basement faults. Since the present study deals with the surface structural expressions; therefore, we cannot assure or otherwise the presented data. Bretis, Bartl and Grasemann (2011) focused on the interaction of the transient development of drainage patterns along growing antiforms, as this directly reflects the kinematics of progressive fold growth. We have interpreted many water and wind gaps along the studied anticlines, which confirm the growth of the anticlines under consideration. Omar (2011) studied the minor fold in the Azmar Anticlinorum and showed that the process involved both buckling and homogeneous flattening mechanisms. We also have interpreted such data, especially along the Azmar anticline, this is mainly due to the exposed homogeneous rocks of the Kometan and Balambo formations. A semi-detailed geological mapping was conducted for an area northwest of Sulaimaniyah covering Pira Magroon anticlines and part of the Surdash anticline (Sissakian and Al-Jiburi, 2014; Sissakian and Al-Jiburi, 2014). Zebari (2013) studied the geometry and evolution of the fold structures within the HFZ, he suggested that the folds are transitional between fault-bend folds and fault propagation folds. Karim, Bety and Khanaqa (2015) described the actual structural setting of the Azmar–Goizha anticline, they changed the previous piggy-back thrust imbricated fan to a nearly isoclinal detachment fold. We have recognized many small double plunging folds with the en-echelon pattern within the main Azmar and Goizah anticlines, some of them are isoclinal. Burberry (2015) defined the relationship between the basement faults and surface structures, facies, and source-rock maturity through time. Omar, Lawa and Sulaiman (2015) found an imprint between tectonostratigraphic and structural with balanced sections in the studied area. Karim and Khanaqa (2017) studied the southeastern part of Pira Magroon anticline stratigraphically and structurally, they used nannofossils for the aging of intervals, and they showed that it is an asymmetrical anticline with a southwest plunge mainly in a few places, while it changes to overturned fold in others and is deformed by reverse fault. We also have recognized different fault types within the Pira Magroon anticline. Mohammed, Al-Kubaisi and Bety (2018) estimated the tectonic activity of the Pira Magroon anticline by calculating three geomorphic indices of three-sub-basins which were identified as very high, high, and moderate levels. Ahmed (2019) classified the anticlines in Zagros Fold Belt according to the orientation of compression stress, among these are Azmar, Pira Magroon, and Surdash anticlines. Karim, Khanaqa and Ismail (2020) mentioned the role of facies changes in shifting the trend of the anticlines in Zagros Fold-Thrust Belt (ZFTB).

The present study aims to describe the recognized significant structural features which are developed within the Pira Magroon, Surdash–Sara, and Azmar anticlines. Moreover, the present study aims to shed light on the relationship between the surface and subsurface tectonic and structural styles and the role of the basement depth and existing faults in the basement on the developed surface anticlines. The visually interpreted and presented data can be used in similar studies, which use the visual interpretation of satellite images to recognize geomorphological and structural forms.

II. Materials and Methods

The studied area is one of the most studied parts of the Iraqi Kurdistan Region; therefore, there are tens of published scientific articles, post graduate theses, which dealt with different geological aspects; some of those articles are reviewed and relevant data are acquired to confirm the visually interpreted data from the satellite images, some of them were confirmed by field check. Besides those articles, we have interpreted different satellite images (Google Earth, and Esri satellite image) to elucidate different geological features; mainly structural and some geomorphological. Most of the recently elucidated features were checked in the field by continuous field inspections through 2018–2021.

III. Geological Setting

The geological setting of the studied area is briefly described. We have used the best available data in the description of Geomorphology, Structural geology, Tectonics, and Stratigraphy.

A. Geomorphology

The studied area is located physiographically in the High Mountainous Province which is characterized by rugged mountains and narrow valleys (Sissakian, Kadhum and Abdul Jab'bar, 2014). The main geomorphological units in the studied area are as follows:

Units of alluvial origin

Different types of alluvial fans were recognized, like old, and dormant (Fig. 2a), usually covered by a mantle of calcrete (Fig. 2b), others are small and still active; coalesced together forming bajada (Fig. 3). Valley fill and flood plain sediments (Fig. 4a) are well developed along the mainstream and valleys, such as Qash Qooly, Charmaga, Merga Pan (Shadala), Tabin, and Zewe, the size of the pebbles may reach 1 m or even more.

Units of structural

Denudational Origin: Among these units are anticlinal ridges (Fig. 1), which extend for a few kilometers. Flat Irons are well developed in Kometan and Qamchuqa formations, they reach a few hundred meters in height (Fig. 4b), and dissected slopes (Fig. 3) are developed in soft rocks, such as the Shiranish, Tanjero, Kolosh, and Gercus formations.

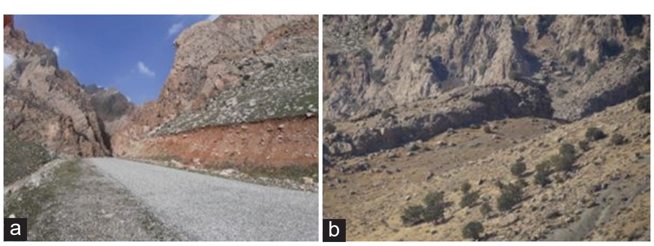

Fig. 2. (a) Old alluvial fan at Jasana gorge in Surdash anticline and (b) calcrete cover of an old alluvial fan in Surdash anticline.

Units of karstification origin

The most common units are the caves (Fig. 5a) and solution holes (Fig. 5b). Both are developed in rocks of the Qamchuqa and Pila Spi formations.

B. Stratigraphy

The exposed geological formations in the studied area range in age from Jurassic to Eocene, they are presented in the geological map (Fig. 6) and a columnar stratigraphic section (Fig. 7), based on Sissakian and Al-Jiburi (2014).

C. Tectonic and Structural Geology

The studied area is located in the high folded zone of the outer platform which belongs to the Arabian Plate (Fouad, 2015). Moreover, it is part of the ZFTB which is developed within the Zagros Foreland Basin (Alavi, 2004, and Fouad, 2015).

The High Folded Zone is characterized by long anticlines and narrow synclines (Jassim and Goff, 2006). Three main anticlines exist in the studied area: Pera Magroon, Surdash (Sara), and Azmar. Although some local names are used by many researchers; however, we will call them as aforementioned. They all are oriented in NW – SE direction and the southwestern limb is steeper. Tens of faults of different types are developed along the three main anticlines with different displacements. The beds are highly deformed and crushed (Fig. 8). Among the faults are those which have formed Zewe gorge; in the Pera Magroon anticline and Jasana and Qamchuqa gorges in the Surdash anticline. The displacements are around a few tens of meters.

IV. Results

From the interpretation of different types of satellite images, geological maps, and field investigations in the studied area, we found the following structural and Neotectonic forms. Besides the presence of anticlines, synclines, and different types of faults, we have recognized the following structural features, they all confirm the lateral growth of the anticlines in the study area.

A. Domes

The presence of dome(s) in an anticline is a good indication of its lateral growth (Blanc, et al., 2003; Bennett, et al., 2005). In the studied area, all anticlines show doming; some of them are already grouped due to the lateral growth of the anticline (Figs. 9-11). Grasemann and Schmalholz (2012) mentioned that growing folds can join each other forming one single fold, and this is the case in Pira Magroon and Surdash anticlines. In the Azmar anticline, the domes and successive anticlines and synclines are common (Fig. 9).

B. En-echelon Plunges

Anticlines showing en-echelon plunges are exhibiting lateral growth (Keller and Pinter, 2002; Ramsey, Walker

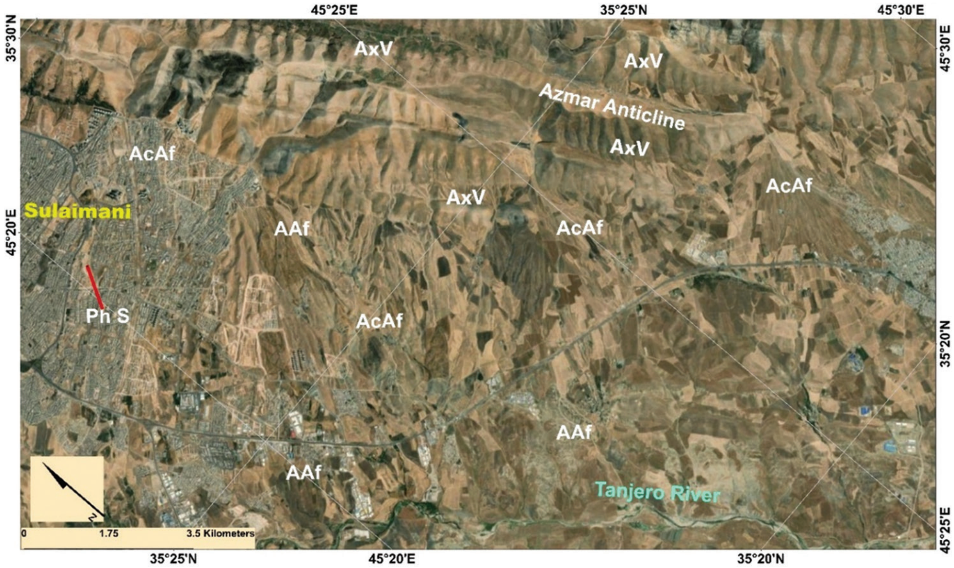

Fig. 3. Esri satellite image of alluvial fans in Azmar anticline for abandoned (AAf) and active (recent) fans (AcAf), AxV=Axial valley, PhS=Approximate site of the field photos (Fig. 15).

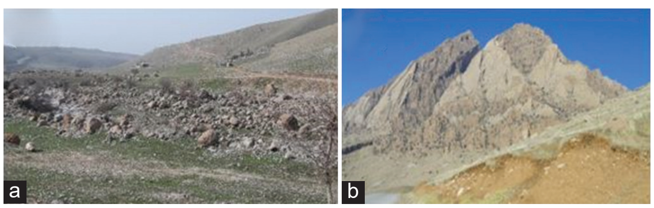

Fig. 4. (a) Valley fill sediments in Zewe Valley, Pira Magroon anticline and (b) Flat irons in the Qamchuqa Formation, Surdash anticline.

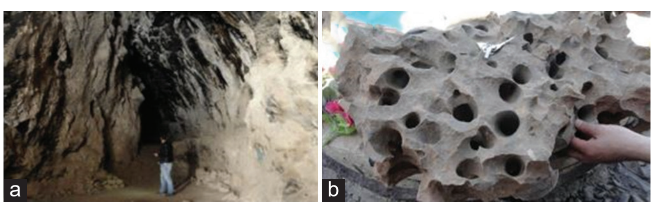

Fig. 5. (a) Jasana Cave, Surdash anticline, and (b) Solution holes in the carbonates of the Pila Spi Formation at the southwestern limb of Pera Magroon anticline.

and Jackson, 2008; Fossen, 2010). In the studied area, all anticlines exhibit en-echelon plunges; either totally separated from the neighboring anticline, as Pira Magroon and Sulaymaniyah anticlines (Fig. 6), Surdash and Khalakan anticlines, within the same anticline as in the Azmar anticline (Fig. 12), and within the same range; as Azmar and Surdash anticlines (Fig. 13).

C. Neotectonic Indications

Indications for neotectonic activities in the studied area are very common; however, we have selected a very clear indication from the east of Sulaimaniyah city within the old and recent alluvial fans (Fig. 14). The directions of old alluvial fans are different from the recent and active alluvial fans, and even they are dissecting indicating titling of the slopes of the main foothills. Furthermore, the tilting of old alluvial fans' sediments was seen at a construction site (Fig. 15).

The recent and abandoned old alluvial fans are distinguished based on the outcrop dating method (Burbank and Anderson, 2001). The feeder channels are used to distinguish between both types since the abandoned feeder channels (Fig. 14) are not following the regional gradient, which means that there is tilting in the area after the deposition of the old alluvial fans, accordingly, they were abandoned. In Fig. 12, the semestral fault is older than the developed alluvial fan. This is indicated by the location of the feeder channel which runs through the fault.

V. Discussion

The anticlines in the Iraqi Kurdistan Region are still active and exhibit later growth (propagation) as witnessed by the presence of different geomorphological and structural forms; some of those indications are presented in the current research. The anticlines accompanied by synclines in the study area are developed due to the clockwise movement of the Arabian Plate and its collision with the Eurasian Plate forming a convergent tectonic plate boundary (Alavi, 2004, Allen, et al., 2004).

The exerted forces due to the collision of the plates have developed regional thrust faults and another local thrust, reverse, normal, and strike-slip faults. The structural style of the studied area and indications for the lateral growth mentioned in the present study is discussed hereinafter.

A. Structural Style

The studied area is a part of the High Folded Zone that belongs to the ZFTB; therefore, the folds are oriented generally in NW – SE trend with minor deviation to NWW – SEE trend (Figs. 1 and 6). Karim, Khanaqa and Ismail (2020) mentioned that the deviations in the folds

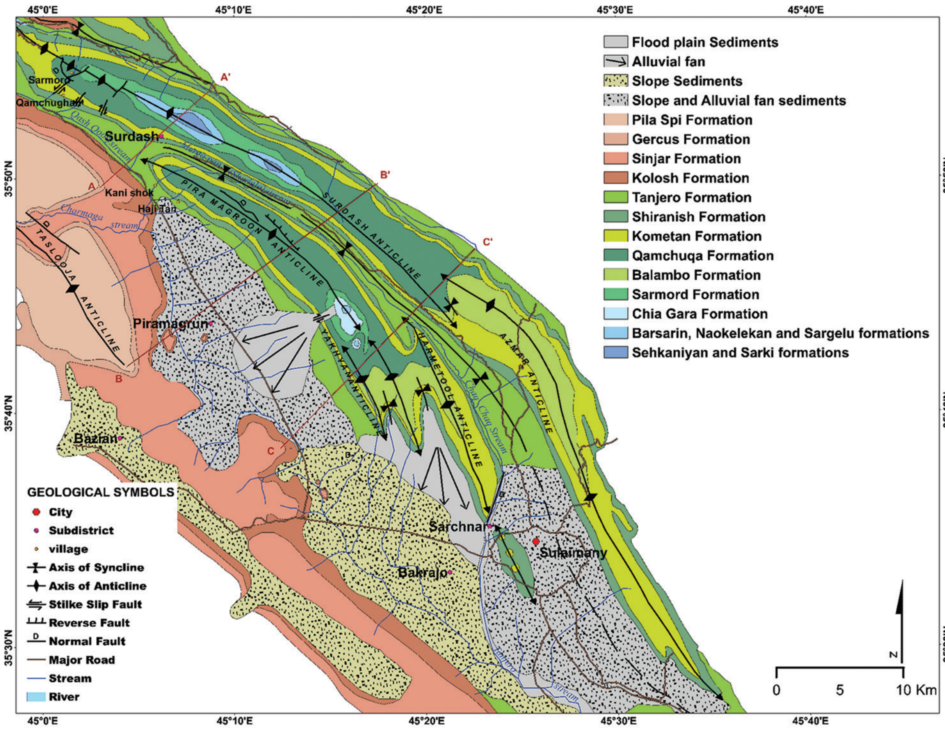

Fig. 6. Geological Map of the studied area (Modified from Sissakian and Fouad, 2015).

Formations	Age	Thickness (m)	Lithology	Lithologic description
Pila Spi	U.Eocene	60		Well bedded limestone and dolostone with rare marl.
Gercus	Eocene	110		Red clastic including clay stone, siltstone, sandstone and rare pebbles.
Sinjar	L.Eocen U.Paleocene	80		Well bedded limestone and very rarely dolomitic.
Kolosh	Paleocene	70		Black clastic including shale, sandstone and rare conglomerate
Tanjero	Upper Cretaceous	350		Olive green clastic including claystone, sandstone, shale and conglomerate occasionally with pillow like structure.
Shiranish		200		Bluish grey soft papery marle underlain by thinly bedded of marly limestone.
Kometan	Lower Cretaceous	170		Well thinly bedded marly limestone.
Qamchuqa		650		Massive and thickly bedded limestone and dolostone.
Balambo		330		Interbedding of crystalline limestone and dark blue papery shale.
Sarmord		300		Interbedding of soft marl and hard limestone and dolostone.
Chia Gara	L.Cretaceous U.Jurrasic	160		Thinly bedded of limestone and dolostone with black bituminous shale.
Bersarin	Jurrasic	16		Thickly bedded limestone and dolostone with stromatolite.

Fig. 7. Columnar stratigraphic section of the exposed formations in the study area (After Sissakian and Fouad, 2015).

are mainly due to facial changes. Although their study area is larger than the present study area and the minor folds are out of the studied area; however, we are in full accordance with them about the role of the facial changes in the deviations of the folds from the main trend. A good example is at the plunge area between Azmar and Surdash anticlines (Figs. 1, 6, 13), where the main facial change occurs between the Balambo (Basinal environment) and the Qamchuqa (Neritic environment) formations and the hardness of their rocks and thickness changes. However, the main deviation is slightly west of the concerned location. The type of the rocks also has contributed to the development of M-shaped parasitic Azmar anticline with many minor successive anticlines and synclines (Fig. 14) which have mainly very tight hinge lines (Points A and S, Fig. 14). The compressional forces exerted from the collision of the Arabian and Eurasian plates, besides the thrusting of the ophiolite bodies at Mawat Massif (20 km NE wards) have played a big role in the development of the parasitic fold system in the Azmar anticline, especially with the exposed monotonous ductile and incompetent rock types of marly limestone and marl.

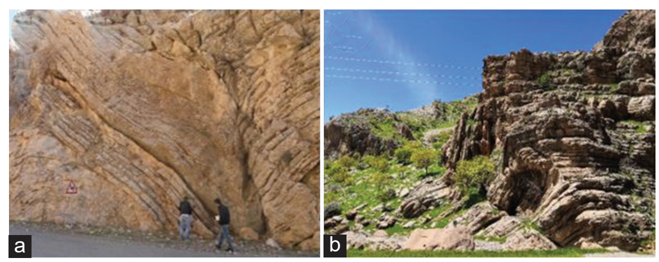

Fig. 8. Disturbed beds due to folding and faulting, (a) Pira Magroon anticline and (b) Surdash anticline.

The width of the anticlines of the studied area is also an interesting feature, especially the southwestern limb of the Pira Magroon anticline (Figs. 1, 6, 16). This is attributed to the minor folding within the Shiranish, Tanjero, Kolosh, Sinjar, and Gercus formations, besides the retreating of the main cliff of the Sinjar Formation due to continuous sliding (Fig. 17a).

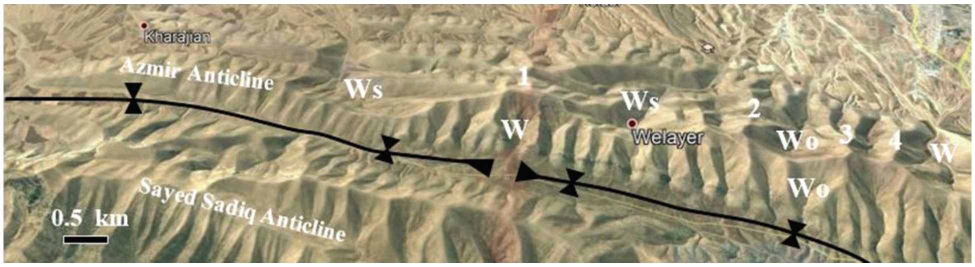

Fig. 9. Satellite images of Azmar anticline facing southeast showing possible domes at points 1, 2, 3, and 4 and many wine glasses (W), Wo=Opposite wine glass, and Ws=Successive wine glass, which are indications for the lateral growth of the anticline.

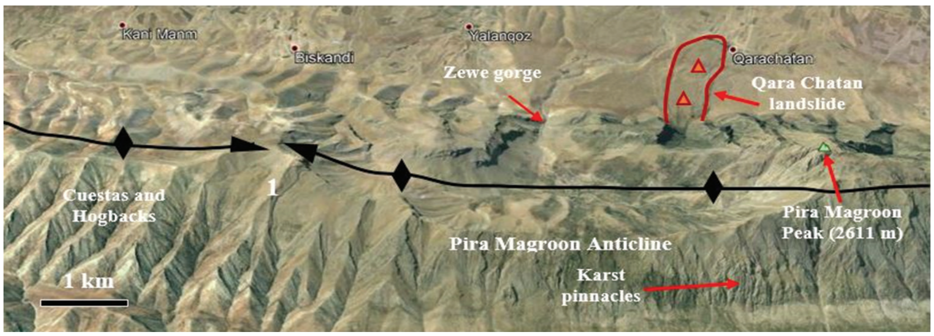

Fig. 10. Satellite image of Pira Magroon anticline facing SE. Note the domes of Pira Magroon anticline. Also note the absence of the Qamchuqa Formation left of point 1.

Fig. 11. Satellite image of Surdash anticline facing SE. Note the domes of the Surdash anticline. Also, note overturned beds at points 1 and 2.

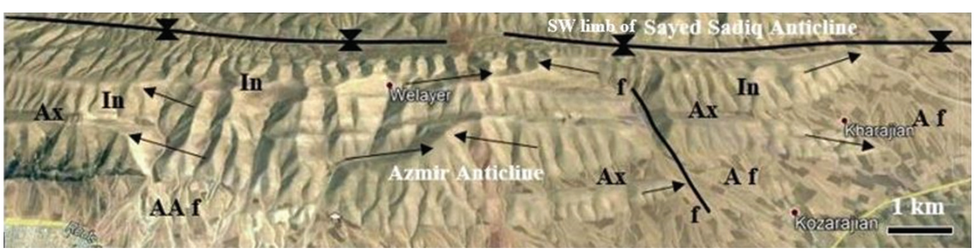

Fig. 12. Satellite image of Azmar anticline facing NE. The arrows point to plunges of minor folds, f – f is a sinistral fault. Different valleys: In=Inclined, Ax=Axial, AAf=Abandoned alluvial fan, Af=Active alluvial fan, all are indications of lateral growth of the anticline.

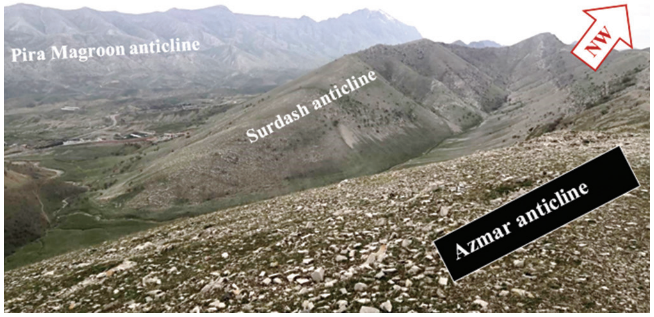

Fig. 13. Field photo, southeastern plunge of the Surdash anticline. Note the local syncline between the Surdash and Azmar anticlines. In the background is the Pira Magroon anticline.

The presence of isolated hills (which may attain 60 m in height) caped by the hard limestone of the Sinjar Formation (Fig. 6) is a good indication of the aforementioned two reasons for the widening of the Pira Magroon anticline. On contrary, the syncline between the Pira Magroon and Surdash anticlines is very narrow, although the rocks in the northeastern limb of the Pira Magroon anticline suffer from severe karstification (Fig. 17b) and many landslides (Fig. 10).

B. Domes

Domes are a good indication of the lateral growth of anticlines (Blanc, et al., 2003 and Bennett, et al., 2005). One dome form was interpreted in the Pira Magroon anticline

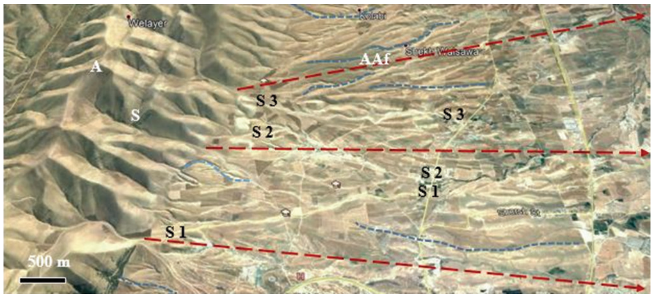

Fig. 14. Satellite image of Azmar anticline facing SW. The drown arrows indicate the direction of old alluvial fans. Note the direction of the recent feeder channels (S1 – S1, S2 – S2, and S3 – S3) of active alluvial fans. Furthermore, note the very tight anticline (A) and syncline (S). AAf is an old alluvial fan. Blue dotted lines are scars of old feeder channels.

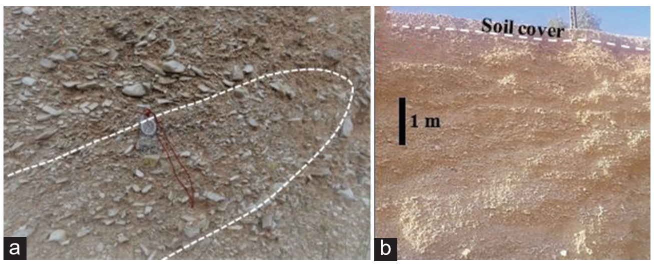

Fig. 15. Field photos for an old fan, (a) tilted sediments of old alluvial fan, note the tilted orientation of the pebbles and (b) hard soil cover. Both photos are toward SE.

(Fig. 10); it occupies a very large wine glass that is growing due to erosion and most probably due to lateral growth.

A good indication can be seen in point 1 (Fig. 10). This is most probably due to the absence of the exposures of the very hard and massive beds of the Qamchuqa Formation. In the Surdash anticline, five domes were interpreted, they also are occupied by wine glasses (Fig. 11), which are also growing due to erosion and lateral growth of the anticline. However, in the Surdash anticline, the shapes of the domes are thinner and shorter; as compared to those developed in the Pira Magroon anticline, this is attributed to the thinning of the Qamchuqa Formation eastwards; and accordingly, the core is occupied mainly by fairly hard rocks of the Sarmord Formation (Fig. 11), besides being subjected to more compressional forces; as can be seen from the overturned beds (Points 1 and 2, Fig. 11). In the Azmar anticline, however, no domes are developed. This can be attributed to the exposed monotonous rock types (marly limestone and marl) within the Kometan and Balambo formations (Figs. 12 and 14). Both marl and marly limestone are more incompetent and ductile as compared to the massive and very hard limestone and dolomite beds of the Qamchuqa Formation.

C. En-echelon Plunges

The presence of an en-echelon plunge within an anticline is also a good indication of the lateral growth of the

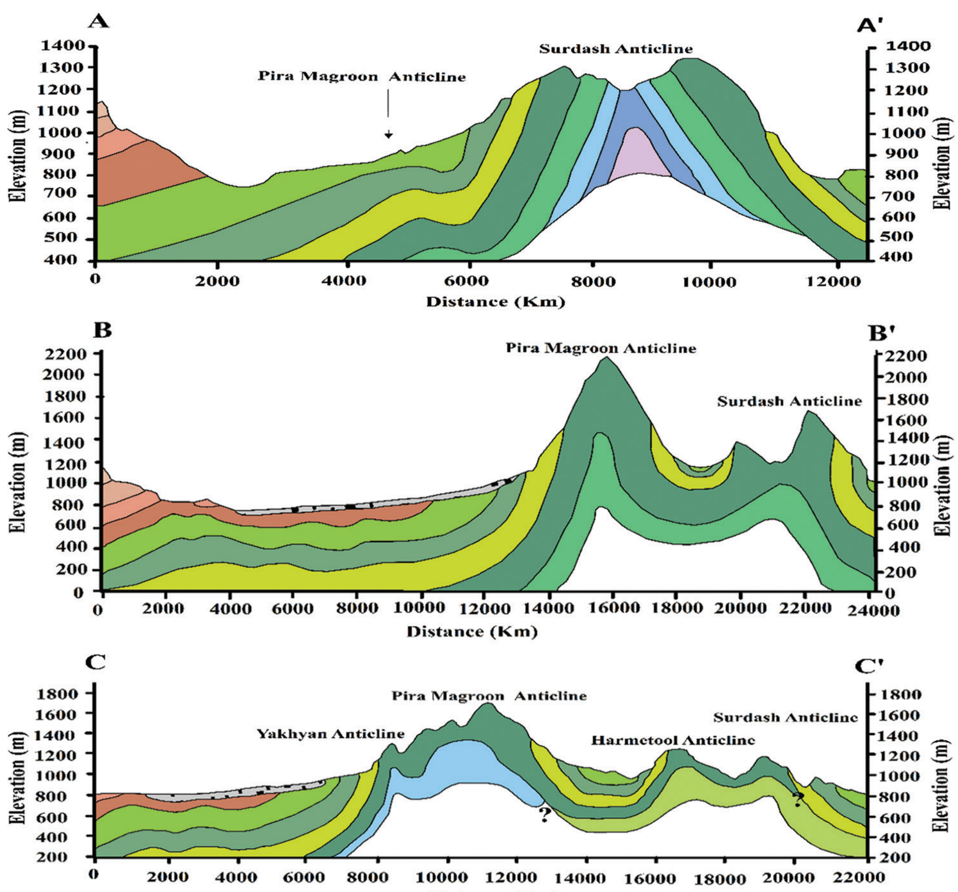

Fig. 16. Three cross-sections showing folding harmony in the studied anticlines (for the location of the cross-sections see Fig. 6).

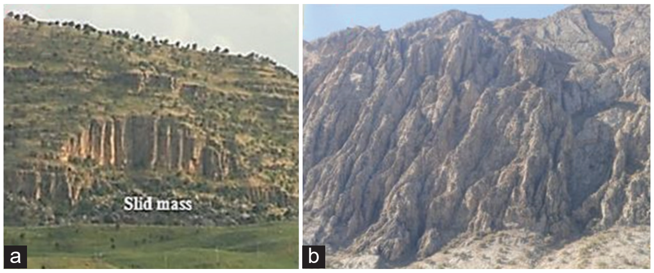

Fig. 17. Pira Magroon anticline, (a) large landslide along the southwestern limb (The height is about 50 m) and (b) Karstified rocks along the northeastern limb (The height of the cliff is about 700 m).

anticline (Keller and Pinter, 2002; Ramsey, Walker and Jackson, 2008; Fossen, 2010). The Surdash and Azmar anticlines exhibit a right-hand en-echelon plunge (Fig. 13). The en-echelon plunge is developed at the areas where the Qamchuqa Formation pinches out; eastwards, the thickness of the formation at the plunge area is only 12 m (Sissakian and Al-Jiburi, 2014; Sissakian and Al-Jiburi, 2014), and at the type locality, which is at the northwestern part of the anticline is 792 m, whereas the thickness of the Balambo Formation is 320 m (Sissakian and Al-Jiburi, 2014; Sissakian and Al-Jiburi, 2014; Sissakian and Al-Jiburi, 2014). This great change in the thickness is the reason for the change in the width of the Surdash anticline and its plunge area, as compared to that of the Azmar anticline (Fig. 13). Due to this big change in the thickness of the anticlines, and the difference in the hardness of the rocks on both plunge areas, the northwestern plunge of the Azmar anticline is moved out of the range; northwestwards (Fig. 6). The plunge area also coincides with a paleo-ridge (at NW – SE direction) that has separated the depositional basins of the Qamchuqa Formation (toward west) and that of the Balambo Formation (toward east) (Buday and Jassim, 1987; Jassim and Goff, 2006). The location of the paleo-high also coincides with the southeastern plunge of the Pira Magroon anticline (Fig. 1). In the Azmar anticline, however, many en-echelon plunges were interpreted within the anticline (Fig. 13), this is attributed to the presence of many minor anticlines successive to each other in both directions (NE – SW and EW), which form the main Azmar anticlines as M-shaped parasitic anticlines. The thick rock succession of the Balambo and Kometan formations (about 800 m of marly limestone and marl) has also contributed to the development of this type of anticline with the main Azmar anticline since they are cert ductile and incompetent.

VI. Conclusions

From the interpreted data and field investigations, the following can be concluded: The studied anticlines exhibit different structural features which indicate their lateral growth. Different structural features are recognized as an indication for the lateral growth of the anticlines in the study area, among them are domes, en-echelon plunges, and Neotectonic indications. Besides, geomorphological indications of the lateral among them are different-shaped valleys (Radial, Fork-shaped, Axial, and Inclined), water and wind gaps, and abandoned alluvial fans. We also can conclude that the fold's thickness varies along its axis, some of the folds are parasitic types like the Azmar anticline. Some of the gorges in the Pira Magroon and Surdash anticlines are developed due to strike-slip faults.

Acknowledgments

The authors would like to pass their sincere thanks to the authorities at the Komar University of Science and Technology, and the University of Sulaimani for their encouragement during this research work.

References

Ahmed, S.H., 2019. Designation and study of anticlines-Kurdistan region-NE Iraq. *Journal of Physics Conference Series*, 1294, p.082001.

Alavi, M., 2004. Regional stratigraphy of the Zagros fold-Thrust Belt of Iran and its proforeland evolution. *American Journal of Science*, 304, pp.1-20.

Allen, M., Jackson, J., and Walker, R., 2004. Late cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates. *Tectonics*, 23, p.TC2008.

Ameen, M.S., 1991. Possible forced folding in the Taurus-Zagros Belt of Northern Iraq. *Geological Magazine*, 128(6), pp.561-584.

Bennett, E.R., Youngson, J., Jackson, J.A., Norris, R.J., Raisbeck, G.M., Yiou, F. and Fielding, E.J., 2005. Growth of South Rough Ridge, Central Otago, New Zealand: Using *in situ* cosmogenic isotopes and geomorphology to study an active, blind reverse fault. *Journal of Geophysical Research Atmospheres*, 110, p.B02404.

Blanc, E.J.P., Allen, M.B., Inger, S. and Hassani, H., 2003. Structural styles in the Zagros simple folded zone, Iran. *Journal of the Geological Society*, 160, pp.401-412.

Bretis, B., Bartl, N. and Grasemann, B., 2011. Lateral fold growth and linkage in the Zagros fold and Thrust belt (Kurdistan, NE Iraq). *Basin Research*, 23, pp.615-630.

Buday, T., and Jassim, S.Z., 1987. Tectonic Map of Iraq, scale 1:1000000. 1st ed. Iraq Geological Survey Publications, Baghdad, Iraq.

Burbank, D.W. and Anderson, R.S., 2001. *Tectonic Geomorphology*. Blackwell Science Malden, United States of America.

Burbank, D.W. and Pinter, N., 1999. Landscape evolution: The interactions of tectonics and surface processes. *Basin Research*, 11, pp.1-6.

Burberry, C.M., 2015. The effect of basement fault reactivation on the Triassic-recent geology of Kurdistan, North Iraq. *Journal of Petroleum Geology*, 38(1), pp.37-58.

Collignon, M., Yamato, P., Castelltort, S. and Kaus, B.J.P., 2016. Modelling of wind gap formation and development of sedimentary basins during fold growth: Application to the Zagros fold belt, Iran. *Earth Surface Processes and Landforms*, 41(11), pp.1521-1535.

Colman-Saad, S.P., 1978. Fold development in Zagros simply folded belt, Southwest Iran. *AAPG Bulletin*, 62, pp.984-1003.

Fossen, H., 2010. *Structural Geology*. Cambridge University Press, United Kingdom, p.463.

Fouad, S.F, 2015. Tectonic map of Iraq, scale 1: 1000 000, 3rd edition. *Iraqi Bulletin of Geology and Mining*, 11(1), pp.1-8.

Grasemann, B. and Schmalholz, S.M., 2012. Lateral fold growth and fold linage. *Geology*, 40(11), pp.1039-1042.

Jassim, S.Z. and Goff, J.C., 2006. *Geology of Iraq*. Dolin, Prague and Moravian Museum, Brno, p.334.

Karim, K.H. and Khanaqa, P.A., 2017. Stratigraphy and structure of the southeastern part of Piramagroon anticline, Sulaimani area, Northeast Iraq. *Bulletin of the Mineral Research and Exploration*, 154, pp.27-39.

Karim, K.H., Bety, A. and Khanaqa, P.A., 2015. Geomorphology of the Piramagroon-Kanikhan valley, Sulaimani governorate, Kurdistan region, North Iraq. *International Journal of Geography and Geology*, 4(12), pp.183-195.

Karim, K.H., Khanaqa, P.A. and Ismail, K.M., 2020. Role of facies changes in shifting trends of anticlines in the Zagros fold-Thrust belt: Examples from Sulaimaniyah area, Kurdistan Region, Northeastern Iraq. *Journal of Zankoy Sulaimani*, 22(1), pp.1-13.

Keller, E.A., and Pinter N., 2002. *Active Tectonics: Earthquakes, Uplift, and Landscape*. 2nd ed., Prentice Hall, Upper Saddle River, New Jersey, p.359.

Keller, E.A., Gurrola, L. and Tierney, T. E., 1999. Geomorphic criteria to determine direction of lateral propagation of reverse faulting and folding. *Geology*, 27(6), pp.515-518.

Mohammed, S.K., Al-Kubaisi, M.S. and Bety, A.K., 2018. Geomorphic indices of tectonic activity through the analysis of the drainage systems in Pera Magroon anticline, Northeastern Iraq. *Iraq National Journal of Earth Sciences*, 18(2), pp.99-112.

Omar, A.A., 2011. Analysis and interpretation of minor folds developed in the cretaceous formations within Azmar anticlinorium, in a part of Iraqi Zagros fold and Thrust belt, Suliyamania district, Northeastern Iraq. *Journal of Basic Applied Science Research*, 1(10), pp.1490-1497.

Omar, A.A., Lawa, F.A. and Sulaiman, S.H., 2015. Tectonostratigraphic and structural imprints from balanced sections across the north-western Zagros fold-Thrust belt, Kurdistan region, NE Iraq. *Arabian Journal of Geosciences*, 8(10), pp.8107-8129.

Ramsey, L.A, Walker, R.T., and Jackson, J., 2008. Fold evolution and drainage development in the Zagros mountains of Fars Province, SE Iran. *Basin Research*, 20, pp.23-48.

Sissakian, V.K. and Al-Jiburi, B.S.M., 2014. Stratigraphy, geology of the high folded zone. *Iraqi Bulletin Geology and Mineral*, 6, pp.73-161.

Sissakian, V.K. and Fouad, S.F., 2015. Geological map of Iraq, scale 1: 1000 000, 4th edition. *Iraqi Bulletin Geology and Mineral*, 11(1), pp. 9-18.

Sissakian, V.K., Kadhum, T.H. and Abdul Jab'bar, M.F., 2014. Geomorphology. The geology of the high folded zone. *Iraqi Bulletin Geology and Mineral*, 6, pp.7-56.

Zebari, M., 2013. *Geometry and Evolution of Fold Structures within the High Folded Zone: Zagros Fold-Thrust Belt, Kurdistan Region, Iraq*. Unpublished Master Thesis, Department of Earth and Atmospheric Sciences, University of Nebraska, Lincoln.