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Original Article

Types of Folding of Some Anticlines from the North of Iraq. A Critical Discussion

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ABSTRACT

The Kurdistan Region of Iraq (KRI) is a mountainous territory that occupies the northern and northeastern parts of Iraq, which is a part of the Arabian Plate. The Arabian and Iranian plates are colliding with a convergent boundary. The collision has initiated anticlines with different shapes and types. Some of the anticlines are associated with thrust faults. The common orientation of the anticlines is northwest-southeast, changing westwards to E-W. To indicate the structural type of the developed anticlines, we have selected 60 anticlines in different parts of the central and northern parts of Iraq, including the Kurdistan Region. Using satellite images (Google Earth Pro), the length, hinge length, width, fold front sinuosity (FFS), and width of the shorter limb were measured. After that, we calculated the Aspect ratio (AR), Fold Symmetry Index (IFS or FSI), and Length of the Mountain Front (FS) of the anticlines. Consequently, we have indicated the structural type of those studied anticlines. Moreover, we didn't recognize any difference in the type of anticlines in the three tectonic zones (Low Folded, High Folded, and Imbricate). We also studied the lateral growth of the concerned anticlines based on geomorphological and structural forms and we have found that the majority of them exhibit lateral growth as indicated by the presence of the following form: en-echelon plunge (32 folds), Domes (38 folds), Abandoned alluvial fans (49 folds), Water gaps (35 folds), Wind gaps (29 folds), and Different valleys' forms (60 folds). From the studied 60 anticlines, we have found that 34 folds are Detachment Folds, 15 are Asymmetric Detachment Folds, and 11 are Fault-Bend Folds. This means that the type of folds can be known without the help of seismic sections.

Keywords: Development of anticlines, Aspect ratio, Fold symmetry index, Fault-bend fold, Detachment fold, Lateral growth.

1 Introduction

The topography of the Iraqi territory has a large diversity, which is attributed to the diversity of tectonic effects on the topography. Iraq occupies the northeastern part of the Arabian Plate (Figure 1), which is in collision with the Eurasian Plate [1–4]. The collision has initiated different types of folds and, accordingly, different terrains. The central parts of the territory are hilly terrain representing folds of low amplitude, which form the Low Folded Zone [4].

More north and northeastwards from the Low Folded Zone, the terrain changes to a mountainous area with cliffs and deeply incised gulleys including tens of anticlines of different sizes, shapes, and origins, the common orientation of the anticlines is northwest-southeast, which changes westwards of Longitude 43° 30' to E – W [5]. The amplitudes of the folds increase north and northeastwards, representing the High Folded and Imbricate zones, respectively [4,5]. Many of the anticlines in the Low Folded, High Folded, and Imbricate zones (Figure 2) are associated with large thrust faults and are affected by different types of faults leading to different shapes of anticlines, which increase in their complexity as much as the area becomes close to the collision zone between the two plates [4].

Formerly, the Fold-Thrust belt was considered to include detachment folds (D.F.) only [6,7]. However, "the interaction of surface drainage systems and growing folds and measurement of geomorphic indices shows that fault-bend folds (F.B.F.) are also present, as well as a continuum of geometries between these end-member fold" [8]. Following the opinion of Burberry et al. [9], we extended our study area to include the High Folded and Imbricate zones, which are near the Zagros Suture Zone, where the collision of both plates is still ongoing [1–4].

Studies indicating the type of folds using structural and geomorphological forms are not very common in KRI, so we have reviewed the following studies: Champel et al. [11] studied geomorphological attributes and drainage evolution in Nepal and concluded that the models provide a good indication for the fault-

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related fold propagation. Burberry et al. [8,9] studied different surface folds in the Simply Folded Belt of Zagros in Iran and indicated that the types of folds can be indicated by studying different structural and geomorphological indices. We have used the results of their study in the current study and benefited from their results. Sissakian and Al-Ansari [12] indicated the type of Sinjar anticline based on the Aspect ratio and hinge line and concluded that the Sinjar anticline is of fault-bend fold type. Sissakian and Abdullah [13] used the same opinion as Burberry et al. [9] and deduced the origin of the Qara Chough South anticline to be a detachment fold. Sissakian et al. [14] studied Korek and Pirat anticlines and concluded that both of them are of detachment fold type, based on the data used by Burberry et al. [8,9].

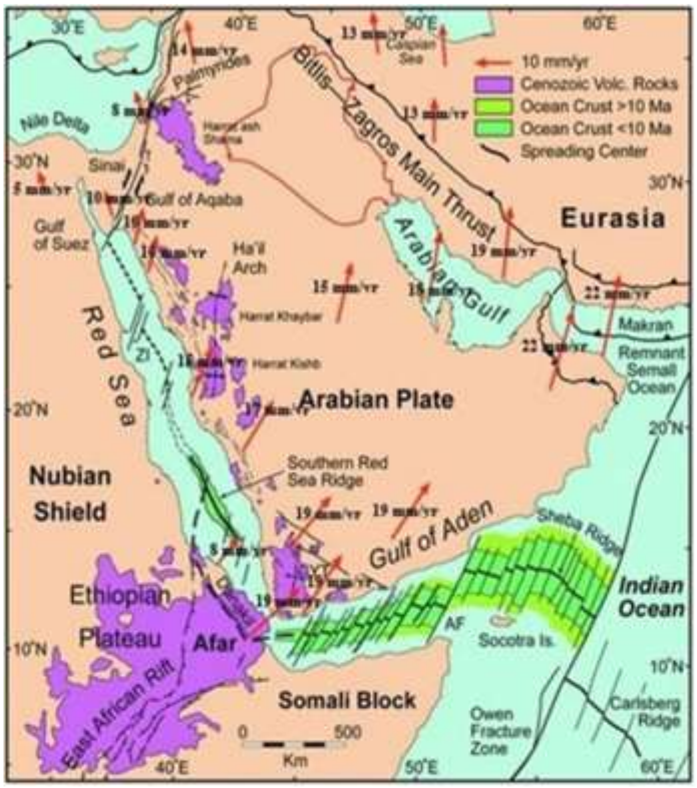

Figure 1: Tectonic Map of Saudi Arabia and surroundings showing the rates of plates' movements [10].

For indicating the growth of folds using structural and geomorphological data in the northern part of Iraq (KRI), many studies have been published; they all have used the opinions of Burbank and Pinter [15], Burbank and Anderson [16], Keller et al.[17], Ramsey et al. [18]. Among those studies are: Zebari [19] studied the geometry and evolution of fold structures within the High Folded Zone: Zagros fold-thrust belt, Kurdistan Region-Iraq; Shihab and Obaidi [20], Ma'amar and Obaidi [21] studied the geometrical and structural analysis in the High Folded Zone between Harir and Bradost, and Bekhme anticlines. Ghafur et al. [22] studied the Aqra anticline and concluded that it is a laterally growing anticline. Sissakian et al. [23] studied three anticlines in the KRI using also structural and geomorphological aspects and concluded that the three anticlines are exhibiting lateral growth. Zebari et al. [24] studied the structural style of the NW Zagros Mountains and the role of basement thrusting for its Mountain Front Flexure, Kurdistan Region of Iraq. Doski and McClay [25] studied the tectonostratigraphic evolution in the Duhok region, Kurdistan, north Iraq.

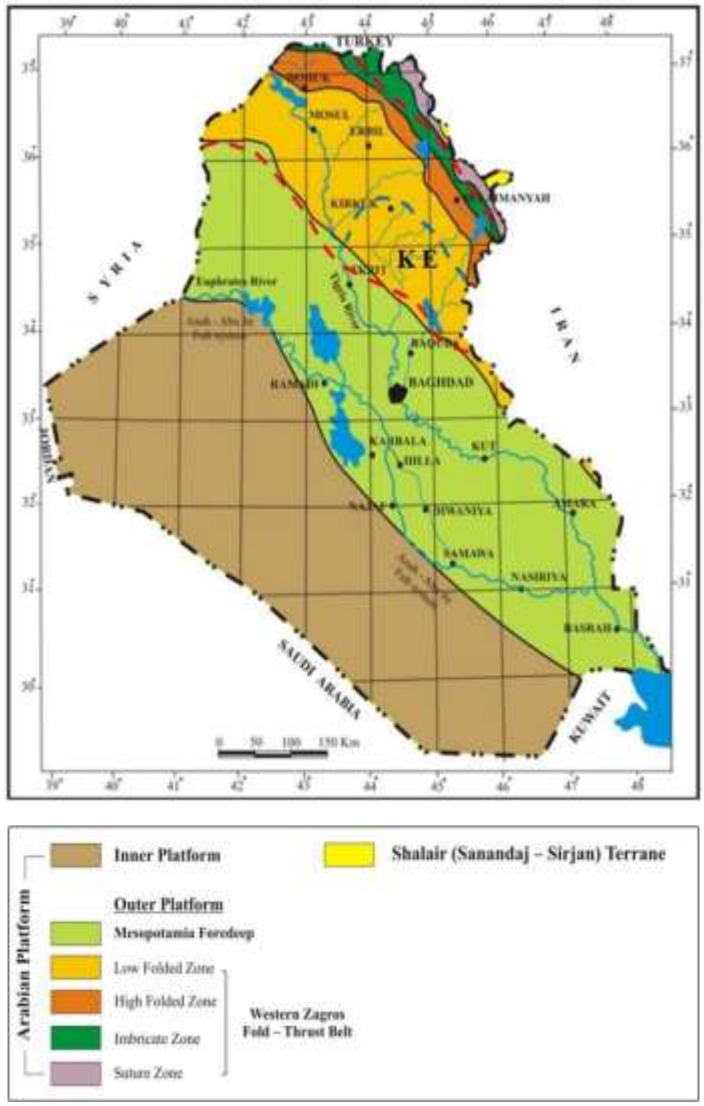

Figure 2: Tectonic map of Iraq (Modified from [1]) showing the studied area (In between the red lines), KE= Kirkuk Embayment.

This study aims to indicate and discuss the types of folds only on the surface in the three tectonic zones of Iraq, which belong to the Zagros Fold–Thrust Belt. The three zones, Low Folded, High Folded, and Imbricate, include tens of surface folds; we have studied 60 anticlines. Moreover, to discuss those folds that showed clear deviations from the used opinion of Berberry et al. [9], which shows three types of folds (Figure 3) based on four measured parameters (Figure 4).

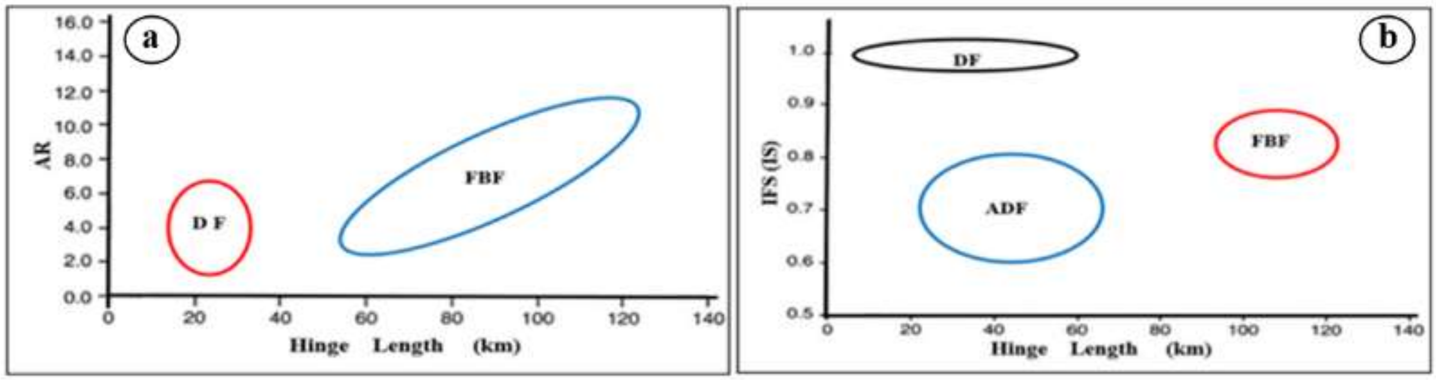

Figure 3: Fold type indicating diagrams, a) IFS versus hinge length, b) AR versus hinge length. DF= Detachment fold, ADF= Asymmetric Detachment fold, FBF= Faul-bend fold (After Barberry et al. [9]).

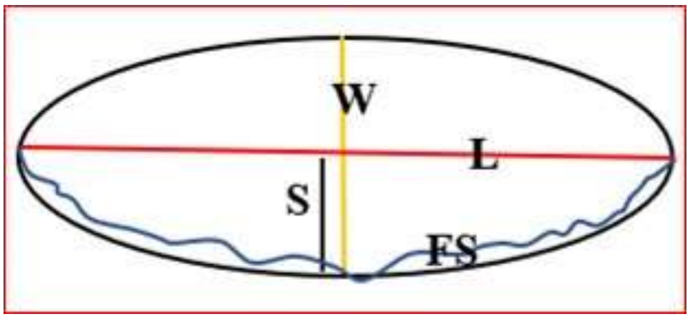

Figure 4: Diagrammatic presentation of the measured parameters. W= Width, L= Length, S= Width of the fore limb, and FS= Length of the mountain front (Modified from Barberry et al. [9]).

2 Materials and Methods

Used data: We studied geological and topographical maps and satellite images to indicate relevant data, which indicates the type of folding within the studied 60 folds. The topographical maps were used to indicate the names of the mountains (anticlines) and the presence of water and wind gaps, both were checked in the satellite images and geological maps. The satellite images are of Google Earth Pro type with a resolution of about 15 m. Also, we have reviewed different scientific articles dealing with the concern of this study, and we have compared the acquired results with those achieved by Burberry et al. [9]. We have used the same technique as Burberry et al. [8,9] to determine the type of folding of the studied anticlines. We used the geometry and geomorphological forms of the studied folds to indicate the type of folding [8,9] in the studied area.

Measurements: We have measured and indicated different structural elements of 60 folds using satellite images, the elements are: 1) fold length, 2) fold hinge length, 3) width of the fold, 4) width of the forelimb, 5) presence of en-echelon fold, and 6) presence of domes, and 7) axial thrust faults. We compared some of the measured aspects from the satellite images and those measured in the field and found an excellent coincidence, about 85- 90%.

Calculations: We calculated and indicated different geomorphological aspects and forms; these are: 1) fold front sinuosity (FS), domes, 3) abandoned alluvial fans, 4) water gaps, 5) wind gaps, 6) different valley shapes.

We also calculated the following aspects with the mentioned equation:

$$AR = \frac{L}{W} \text{ [9]} \quad (1)$$

Where: AR is the aspect ratio. L and W are the length and width of the fold, respectively.

$$IFS = \frac{S}{(\frac{W}{2})} \text{ [9]} \quad (2)$$

Where the fold symmetry index is IFS. S is the width of the forelimb, and W is the width of the fold.

$$\text{Smf} = \frac{\text{FS}}{L} \text{ [26]} \quad (3)$$

Where Smf is the mountain front sinuosity index, FS is the length of the mountain front along the foot of the mountain at the pronounced break in slope, and L is the straight-line length of the mountain front.

3 Geology of the Studied Area

3.1 Stratigraphy

The exposed stratigraphic section (Table 1) in the studied area starts with the Khabour Formation of the Ordovician age and ends with the rocks of the Bai Hassan Formation of the Pliocene – Pleistocene age. In the Low Folded Zone (Figure 2), the Neogene formations are exposed in the majority of the anticlines. In the High Folded Zone (Figure 2), the Paleogene formations are exposed in the anticlines, and more northwards, the Cretaceous formations are widely exposed in almost all anticlines. Whereas, the rocks of the Jurassic formations and locally even the rocks of the Triassic formations are exposed in the cores of some anticlines. In the Imbricate Zone, the Paleozoic formations are exposed, especially in the northwestern parts; however, in the northern and northeastern parts of the zone, only the Triassic, Jurassic, and Cretaceous formations are exposed. The Quaternary sediments are developed in restricted areas in the three tectonic zones [5].

3.2 Geomorphology

Within the studied area, different geomorphological units are developed with a wide diversity of forms. Among them are:

Alluvial Units, among them are alluvial fans (Figure 5a), and river terraces (Figure 5b).

Structural-Denudational Units, among them, are anticlinal ridges, hogbacks, and questas.

Table 1: Columnar stratigraphic section of the studied area. The colors of the stratigraphic time units are from [27] and Geological data from [5].

Era	Period	Epoch		Formations/ Sediments	General Lithology
CENOZOIC	Quaternary	Holocene		Flood plain, Valley fill	Silt, clay, and sand with rare pebbles
		Pleistocene		Slope, River terraces, Alluvial fans	Rock fragments, fairly cemented Pebbles and/ or rock fragments cemented
	Neogene	Pliocene		Bai Hassan	Conglomerate and red-brown claystone
		Miocene	U	Mukdadiya, Injana	
			M	Fatha	Marl, gypsum, limestone/ red fine clastics
			L	Euphrates, Serikagni, Jeribe	Mainly limestone and dolostone
	Paleocene	Oligocene	U	Azkand, Anah, Ibrahim	Mainly limestone
			M	Tarjil, Baba, Bajwan	
			L	Palani, Shurau, Sheikh Alas	
		Eocene	U	Pila Spi, Jaddala, Avanah	Mainly limestone and dolostone
			M	Gercus	Red fine clastics
			L		
		Paleo cene	U	Khurmala, Sinjar	Mainly limestone
			L	Kolosh/ Aaliji	Black fine clastics/ Marl, limestone, shale
MESOZOIC	Cretaceous		U	Tanjero/Shiranish/ Bekhme	Clastics/ Marly limestone/ Limestone
			L	Kometan, Gulneri, Dokan, Qamchuqa, Balambo, Sarmord	Mainly carbonates with rare marl and shale
	Jurassic		U	Chia Gara, Barsarin, Naokelekan	Mainly carbonates
			M	Sargelu	
			L	Sehkaniyan, Sarki	
	Triassic		U	Baluti/ Kurra Chine	Shale/ Limestone
			M	Geli Khana, Bedu, Merga Mir	Black dolostone
			L		
	Permian			No rocks are exposed	
	Carboniferous		U		
			L	Harur, Ora	Black limestone and shale
	Devonian		U	Kaista/ Chalki/ Pirispeki Red Beds	Limestone/ Basalt and clastics/ Quartzite, sandstone, red sandstone, conglomerate with igneous pebbles
			M		
			L		
	Silurian			No rocks of the Silurian are exposed	
	Ordovician			Khabour	Sandstone, quartzite, shale,

Denudational Units, among them, are slope sediments and badlands, which are developed only in the lower parts of the Low Folded Zone.

Solution Forms, then the main forms are caves and sinkholes.

Mass movement forms are landslides, some of them are very old (Figure 6a), others are recent (Figure 6b), rock fall, toppling, creep, and flow.

In all developed units and forms, different types can be seen with different compositions, shapes, sizes, and thicknesses. However, the intensity of their occurrence increases northwards within the studied area.

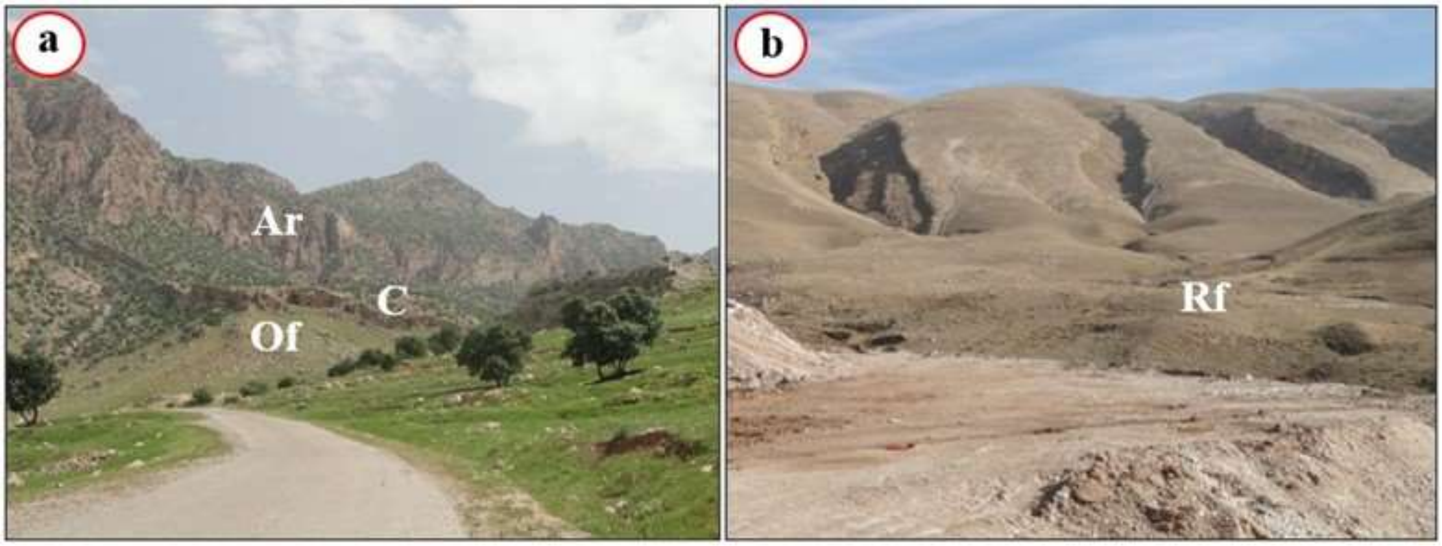

Figure 5: Alluvial fans, a) Old alluvial fan (Of) capped by calcrete (C), note the anticlinal ridge (Ar) in the background, b) Recent alluvial fan (Rf).

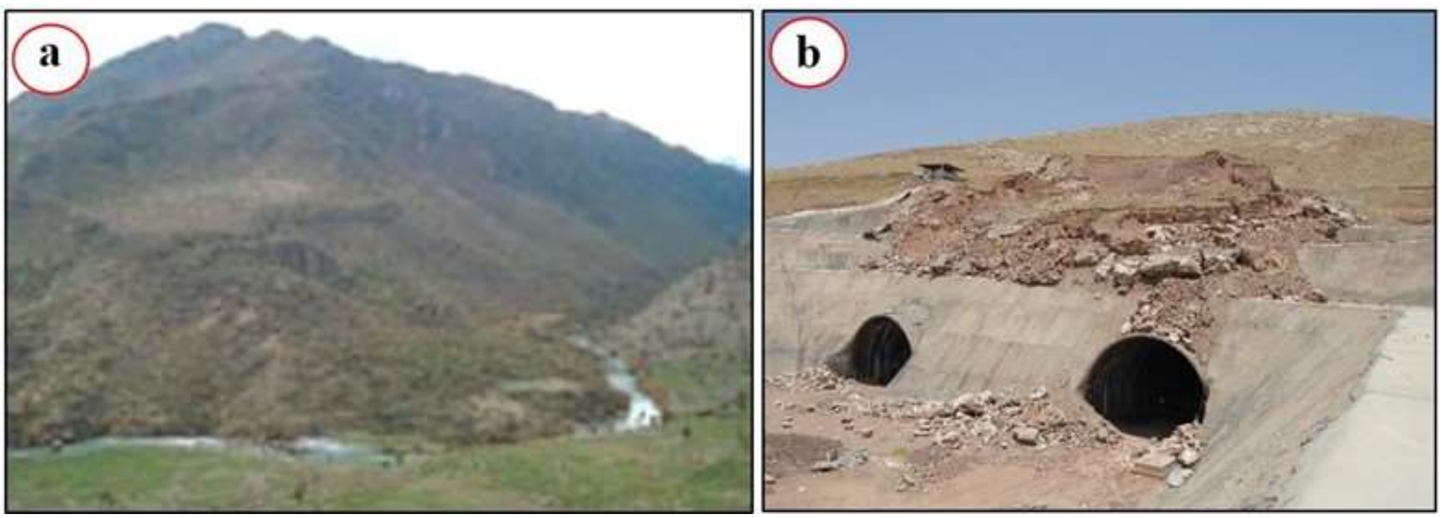

Figure 6: Landslides, a) Very old landslide along the Khabour River, not the shifted course of the river due to the landslide, b) Recent landslide (May 2015) on top of the abandoned Koya tunnel.

3.3 Structural Geology and Tectonics

The studied area includes three tectonic zones, which are shown in Figure (2). The zones belong to the Outer Platform (Unstable Shelf), which is included within the Zagros Fold-Thrust Belt [4,28]. Moreover, the Outer Platform forms the northeastern part of the Arabian Plate, which is in collision with the Eurasian Plate with a convergent contact [1–4,28]. The released forces by the collision have developed tens of anticlines in the northern part of Iraq, including the studied area [2–4,28]. The anticlines are usually long and narrow; their amplitudes increase towards the north. In Kirkuk Embayment (Figure 2), the southwestern limb of the anticlines is usually overridden by the northeastern limb, causing total or partial disappearance of the fold axis[5]. Good examples are the following anticlines: Himreen North (No. 6), Pulkhana (No. 17), Kirkuk (No. 20), and Jambour (No. 21). For details, refer to Table (2).

The same character can be seen in some of the anticlines in the Imbricate Zone (Figure 2), using satellite images, good examples are the following anticlines Tanoon (No. 48), Endiza (No. 52), Ora (No. 53). Some of the studied anticlines; apart from the Low Folded Zone exhibit en-echelon plunges and multi domes;

whereas in the Low Folded Zone, very rarely these characters can be seen (Table 2). Moreover, mainly the anticlines in the studied area show lateral growth with indications of structural and geomorphological characters; however, not all the characters are developed in all anticlines to confirm the lateral growth (Table 2).

4 Results

Two main aspects are dealt with in the current work; we have presented the details hereinafter.

4.1 Structural Type

To indicate the structural type of the studied 60 anticlines, we used the opinion of Burberry et al. [9], which is based on AR and the FSI (Figure 3). The results of all performed measurements, calculations, and identification of structural and geomorphological forms are shown in Table (2).
The achieved data from the calculation of AR and IFS of the studied 60 anticlines are imposed versus the hinge length of the anticlines, which represents the acquired three main types of folds by Burberry et al. [9]. Accordingly, the types of the studied 60 folds were indicated (Figure 7).

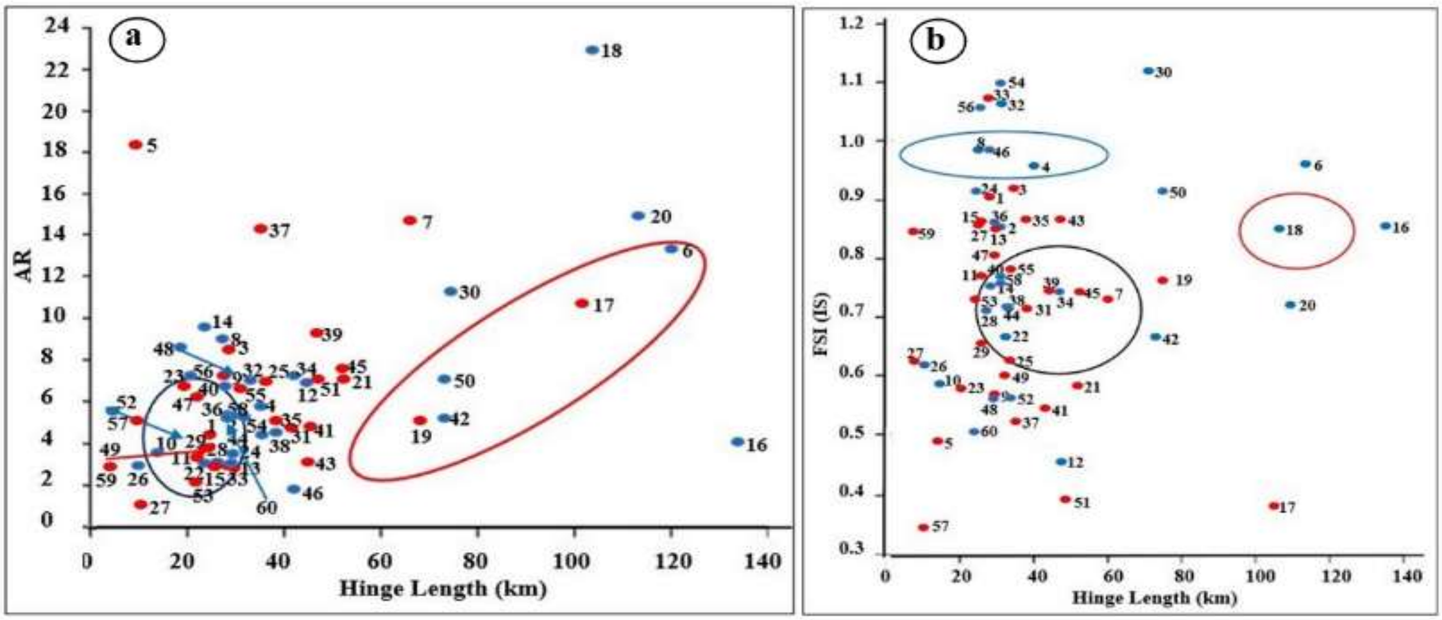

Figure 7: Locations of 60 studied anticlines, a) Aspect Ration (AR) versus hinge length. The black and red clusters indicate the Detachment folds and Fault-bend folds, respectively. b) Fold Symmetry Index (FSI) versus hinge length. The blue, black, and red clusters indicate Detachment folds, Asymmetric Detachment folds, and Fault-bend folds, respectively.

The red and blue colored dots (Fig. 7) represent odd and even numbers of anticlines, respectively. The red and blue arrows are used to represent the locations of odd and even numbers of some anticlines, respectively, because Figure (7) is very crowded; therefore, by coloring them, the locations (dots) will be clearer.

After imposing the calculated results of AR and FSI (Table 2) in Figure (7) we indicated the types of the 60 anticlines. For each anticline, we have two possibilities, either based on AR (Figure 7 a) or FSI (Figure 7 b). We considered the best fit one to indicate the type of each anticline; however, some of them showed deviation from the mentioned domains by Burberry et al. (2010) (Figure 7). In such cases, we have considered the nearest domain to the location of the anticline in Figure (7). Some of the anticlines; however, showed large deviations, such as Sinjar anticline (No. 16, Figure 7). Such cases are discussed in the section of Discussion.

4.2 Lateral Growth

In tectonically active areas like those nearby to collision zones, the majority of the anticlines exhibit lateral growth with clear structural and geomorphological indications [18,29,30]. Since the studied area forms the northeastern part of the Arabian Plate, therefore, the majority of the studied anticlines exhibit lateral growth.

We recognized six characters that indicate lateral growth of anticlines, two of them are structural forms and the other four are geomorphological (Table 2 and Figure 8). However, not all the six characters were recognized in all studied 60 anticlines, few of the studied anticlines exhibit all six characters, others exhibit less, and only the Bedu anticline (No. 59) exhibits only one character (Table 3). The existing characters at each anticline and the type of the folds are presented in Table (3). Moreover, we recognized from the interpretation of satellite images, field trips, and existing geological maps, of axial thrust faults in some of the studied anticlines (Tables 2 and 3) that, locally, the thrusted northeastern limb has covered totally or partially the southwestern limb. Very rarely, the majority of the southwestern limb is covered, which has caused incorrect measurements of the width of the anticline and the width of the forelimb. Such cases are discussed in the section of Discussion.

Table 2: Main calculated parameters and recognized structural and geomorphological forms within the studied anticlines.

Number and Name of anticline	Length (km)		W (km)	S (km)	FS (km)	AR	FSI (IS)	Smf (FFS)	Tectonic Zone	Structural form	Indications of Lateral Growth							Thrust Fault
	Normal	Hinge									Forms							
	L	Hl									Structural		Geomorphological					
											1	2	3	4	5	6		7
1- Qara Chough South	22.0	24.0	5.33	2.4	26.3	4.15	0.90	1.19	Low Folded	DF	–	+	+	–	+	+		–
2- Qara Chough North	27.4	29.5	5.69	1.89	32.3	5.14	0.84	1.18		ADF	–	–	+	+	–	+		–
3- Bai Hassan	19.7	20.8	2.43	1.11	20.6	8.11	0.92	1.04		DF	–	–	+	+	–	+		+
4- Qara Boutaq	37.9	38.1	6.68	3.17	40.9	5.67	0.95	1.08		DF*	–	+	+	+	–	+		–
5- Damir Dagh East	16.9	18.2	0.93	0.21	19.1	18.17	0.45	1.12		ADF	–	–	+	–	+	+		+
6- Himreen North	118.0	119.1	8.51	4.10	121.0	13.86	0.96	1.03		FBF	+	+	+	+	+	+		+
7- Makhoul	59.9	61.5	4.31	1.55	86.6	14.27	0.72	1.45		DF*	+	+	+	–	–	+		–
8- Khanooqa	25.9	27.3	2.92	1.45	26.8	8.87	0.99	1.03		DF*	–	–	+	–	+	+		–
9- Badoush	27.8	28.3	4.11	1.17	30.1	6.76	0.57	1.08		DF	+	–	+	+	+	+		–
10- Qusair	13.2	13.9	4.45	1.31	16.6	2.97	0.59	1.26		DF*	+	+	–	–	–	+		–
11- Ba'shiqa	22.4	24.2	5.67	2.19	27.3	3.95	0.77	1.21		DF*	–	+	+	+	+	+		–
12- Barda Rash	43.4	45.7	6.20	2.47	49.1	7.00	0.45	1.13		DF	+	+	+	+	+	+		–
13- Taq Taq	26.5	28.2	9.71	4.10	29.0	2.73	0.85	1.09		DF*	+	–	+	+	+	+		–
14- Qand	24.6	24.8	2.71	1.00	28.3	9.07	0.74	1.15		DF	+	+	+	+	+	+		–
15- Shaikh Ibrahim	25.6	26.2	7.58	3.24	28.2	3.38	0.85	1.10		DF*	+	+	+	–	–	+		–
16- Sinjar	133	137.5	31.3	13.5	141	4.26	0.86	1.06		FBF	–	–	+	–	+	+		–
17- Pulkhana	104	107	10.1	1.97	109	10.29	0.39	1.05		FBF	+	+	+	+	+	+		+
18- Qara Dagh	108	109	4.66	2.16	111.8	23.18	0.85	1.04		FBF*	+	+	+	+	+	+		–
19- Aj Dagh	64.5	68.2	12.6	4.87	77.6	5.12	0.77	1.20		FBF*	+	+	+	+	+	+		–
20- Kirkuk	108	110	7.4	2.61	126	14.59	0.71	1.17		FBF	+	+	+	+	+	+		+
21- Jambour	51.3	52.2	7.21	2.12	55.0	7.12	0.59	1.09		FBF	–	–	+	+	+	+		+
22- ChamChamal N.	22.2	22.8	7.02	2.36	24.2	3.17	0.67	1.09		DF*	–	–	–	–	+	+		–
23- Ad'dayah	19.8	20.2	3.16	0.92	22.7	6.27	0.58	1.15		DF*	+	+	+	–	–	+		–
24- Sasan	24.3	26.3	7.77	3.52	26.6	3.13	0.91	1.09		DF*	+	+	+	+	+	+		–
25- Shkaft	37.1	37.9	6.11	1.88	41.0	6.08	0.62	1.11		DF	+	+	+	–	–	+		–
26- Nuwaiqeet	12.3	13.0	4.11	1.26	15.2	2.99	0.61	1.24		DF	–	–	–	–	–	+		–
27- Butmah West	10.9	11.1	4.16	1.29	12.8	1.33	0.62	1.17		DF	–	–	+	–	–	+		–
28- Tawqe	24.6	24.8	8.17	2.91	28.2	3.04	0.71	1.15		DF*	–	–	+	+	+	+		–
29- Pirmam	27.1	27.4	8.51	2.73	32.4	3.17	0.64	1.20	High Folded	ADF	+	+	+	–	–	+		–
30- Safeen	74.2	76.4	6.57	3.31	82.4	11.92	1.01	1.11		FBF	+	+	+	+	–	+		–
31- Bana Bawai	41.6	42.1	9.32	6.59	46.8	4.46	1.41	1.13		ADF	+	+	+	+	+	+		–
32- Hareer	36.7	37.3	5.32	2.82	37.3	6.89	10.6	1.02		DF	–	–	+	+	+	+		–
33- Korek	27.3	27.97	7.10	3.00	28.9	3.85	1.07	1.06		DF*	–	+	+	+	+	+		–
34- Pirat	34.8	35.4	5.50	2.00	44.0	6.33	0.73	1.26		ADF	–	+	+	+	+	+		–
35- Peris	39.1	39.3	7.13	3.10	41.0	5.48	0.87	1.05		ADF	+	+	+	+	+	+		–
36- Aqra	29.9	30.1	5.10	2.10	32.1	5.86	0.84	1.07		DF*	–	–	+	+	+	+		–
37- Azmir	35.5	35.8	2.51	0.91	36.7	14.14	0.52	1.03		ADF	+	+	+	–	–	+		–
38- Pera Magroon	37.6	38.4	8.25	2.94	40.9	4.56	0.36	1.09		ADF*	–	–	+	+	–	+		–
39- Surdash	45.4	46.5	4.77	1.75	47.4	9.52	0.74	1.04		ADF*	–	–	+	–	–	+		–
40- Khalikan	27.7	28.0	4.24	1.84	29.1	6.53	0.87	1.05		ADF*	+	+	+	–	–	+		–
41- Bradost	42.5	43.1	9.51	2.51	46.1	4.47	0.53	1.08		ADF	+	+	+	–	–	+		+
42- Gara	71.8	72.1	12.4	4.10	73.6	5.79	0.66	1.03		FBF*	+	+	+	–	–	+		–
43- Zawita	43.4	46.4	12.0	5.24	48.8	3.62	0.72	1.12		ADF	+	+	+	+	–	+		–
44- Bekhair	32.2	32.9	8.12	2.91	35.9	3.96	0.72	1.11		DF*	+	+	+	–	–	+		–
45- Chinara	50.5	51.1	6.85	2.51	54.0	7.37	0.73	1.07		ADF*	+	+	+	–	–	+		–
46- Handreen	27.5	27.8	9.49	4.74	30.6	2.9	0.99	1.11		DF*	+	+	+	+	+	+		–
47- Zozic	26.6	26.8	4.37	1.74	28.7	6.09	0.80	1.08		DF*	+	+	+	–	–	+		–
48- Tanoon	32.2	32.9	4.96	1.40	34.6	6.50	0.56	1.07	Imbricate	DF	+	+	+	+	+	+		+
49- Shireen	31.8	32.0	14.1	4.22	35.6	2.26	0.60	1.12		DF*	–	–	+	+	+	+		–
50- Mateen	76.3	77.6	11.3	5.12	82.3	6.75	0.99	1.07		FBF*	+	+	+	+	+	+		–
51- Ranya	43.4	43.6	5.92	1.13	47.9	7.33	0.38	1.10		FBF	–	–	+	–	+	+		–
52- Endiza	22.1	23.4	4.37	1.22	24.4	5.06	0.56	1.10		ADF	+	+	+	+	–	+		–
53- Ora	22.7	22.9	9.69	3.49	26.7	2.34	0.72	1.17		DF*	–	–	+	+	–	+		+
54- Halabja	32.4	32.6	7.00	3.86	45.4	4.63	1.10	1.09		DF*	–	–	+	–	–	+		–
55- Waraska	28.9	29.1	4.59	1.82	32.8	6.30	0.79	1.13		ADF*	+	+	–	–	–	+		–
56- Baibu	22.6	22.8	3.10	1.63	26.7	7.29	1.05	1.18		DF*	–	+	–	+	–	+		+
57- Darkar	10.5	10.7	2.1	0.36	12.00	5.00	0.34	1.14		DF*	–	+	–	+	–	+		+
58- Merga Sur	28.4	29.1	5.16	2.00	31.2	5.50	0.77	1.10		DF*	–	–	–	+	–	+		+
59- Bedu	3.69	3.91	1.46	0.61	4.35	2.53	0.84	1.18		DF	–	–	–	–	–	+		+
60- Warta	25.0	25.90	5.27	1.33	28.8	4.74	0.50	1.15		DF*	–	–	–	+	+	+		+

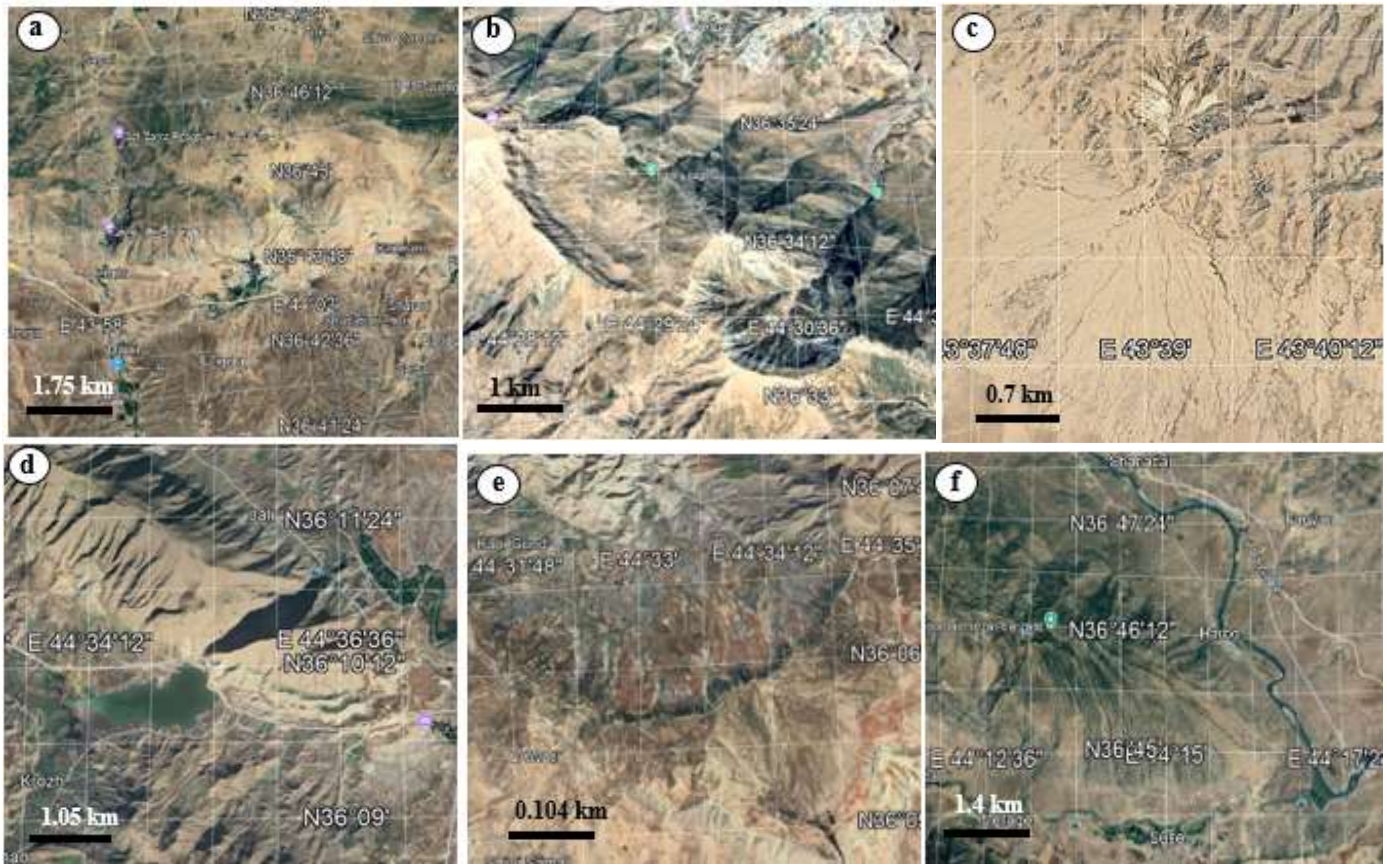

Figure 8: Satellite images, a) En-echelon plunge, Pirat and Aqra anticlines, b) Dome, Korek Anticline, c) Abandoned alluvial fan, Qara Cough South anticline, d) Water gap, Safeen anticline, e) Wind gap, Bana Bawi anticline, and f) Radial valley, Chinara anticline.

5 Discussion

The type of the studied folds is discussed based on Burberry et al.[9] (Figs. 3, 4, and 5). Accordingly, we indicated the types of the studied 60 anticlines (Table 2 and Figure 9).
The recognized three types of folds recognized in the current study are: 1) Detachment Fold (DF), 2) Asymmetric Detachment Fold (ADF), and 3) Fault Bend Fold (FBF). We found among the studied 60 anticlines (Figure 7) that 34 anticlines are Detachment Folds, 15 are Asymmetric Detachment Folds, and 11 are Fault-bend Folds.

We checked the role of the tectonic zone on the type of folding and found that all three types of folds occur in the three tectonic zones, where the studied anticlines occur, which means the tectonic zone, not the tectonic forces, has no role in the type of folding.

For those folds that point in the three domains (clusters) (Figure 7), we considered them as typical fold types based on which of the three domains they are located in. For those anticlines that point near the three domains, we considered the type to belong to the nearest domain. However, some anticlines point in the domain of certain fold types in Aspect ratio versus Hinge length (Figure 7a), whereas point large deviations in the Fold Symmetry index versus Hinge length (Figure 7 b), and the reverse case occurs too. In all such cases, we considered the type of folds to which the domain they have pointed (Figure 7).

We found many strange cases where anticlines do not coincide with each other in both considered aspects, the AR and FSI versus their hinge lengths (Figure 7). We have discussed many cases hereinafter.

The Damir Dagh East anticline (No. 5, Figure 7), points a large deviation in both cases, this is attributed most probably to the disappearance of the southwestern limb due to the thrusting of the northeastern limb, accordingly, hindering the true width of the anticline and the mountain front length (FS).

The Makhoul anticline (No. 7, Figure 7) points to a large deviation in the AR versus the HL (Figure 7 a), whereas it points to a typical Asymmetric Detachment fold (Figure 7 b). This is most probably attributed to the developed thick gypcrete deposit along the southwestern limb[31]; accordingly, hindering the true widths of both the anticline and the fore limb. In all such cases

(Figure 7), we have repeated the measurements and calculations of all those anticlines that have shown such ambiguities and found that all measurements and calculations were correct.

We have compared our results with many researchers who have studied the structural style in the IKR. All indicated results by Sissakian and Al-Ansari [12], Sissakian and Abdullah[13], Sissakian et al. [14,23], and Ghafur et al. [22]. Fouad [4] compiled the Tectonic map of Iraq at a scale of 1:1000000 and didn't mention the type of folds at each tectonic zone. Ma'amar and Obaidi[21] performed a geological and morphometric study to indicate the properties of the High Folded Zone of Iraq to identify the tectonic activity of Pirat and Bradost anticlines without mentioning the type of folding. Shihab and Obaidi [20] performed geometrical and structural analysis for the area between Harir and Bradost anticlines, but never referred to the type of the studied folds. Doski and McClay [25] studied the tectonostratigraphic evolution in the Duhok vicinity (IKR), and they didn't mention the type of existing folds in the studied area. Zebari et al. [24] studied the role of the basement thrust on the developed folds in IKR, but didn't refer to the type of folding. He also studied the evolution of the folds in the IKR and concluded that fault-bend folds and fault propagation folds are the main types of existing folds. Some of their conclusions meet our conclusions, which is attributed to the data used by Zebari et al. [24] since they used seismic data, besides some geomorphological data. Zebari [19,24] studied the structural style of the Zagros Mountains and the role of the basement faults on the developed anticlines in IKR, but they didn't refer to the type of folding. The main reason for these discrepancies is that the aims of those studies were not the aim of the current study.

We also indicated and discussed the lateral growth of the studied 60 anticlines depending on two structural and four geomorphological forms (Table 2). The six recognized structural and geomorphological forms are based on Burbank and Pinter [15], Burbank and Anderson [16], and Ramsey et al. [18]. However, not all the studied anticlines showed the six mentioned forms (Table 3); therefore, not all the studied anticlines exhibit lateral growth. The number of recognized forms in the studied 60 anticlines ranges from 1 to 6 forms (Table 4).

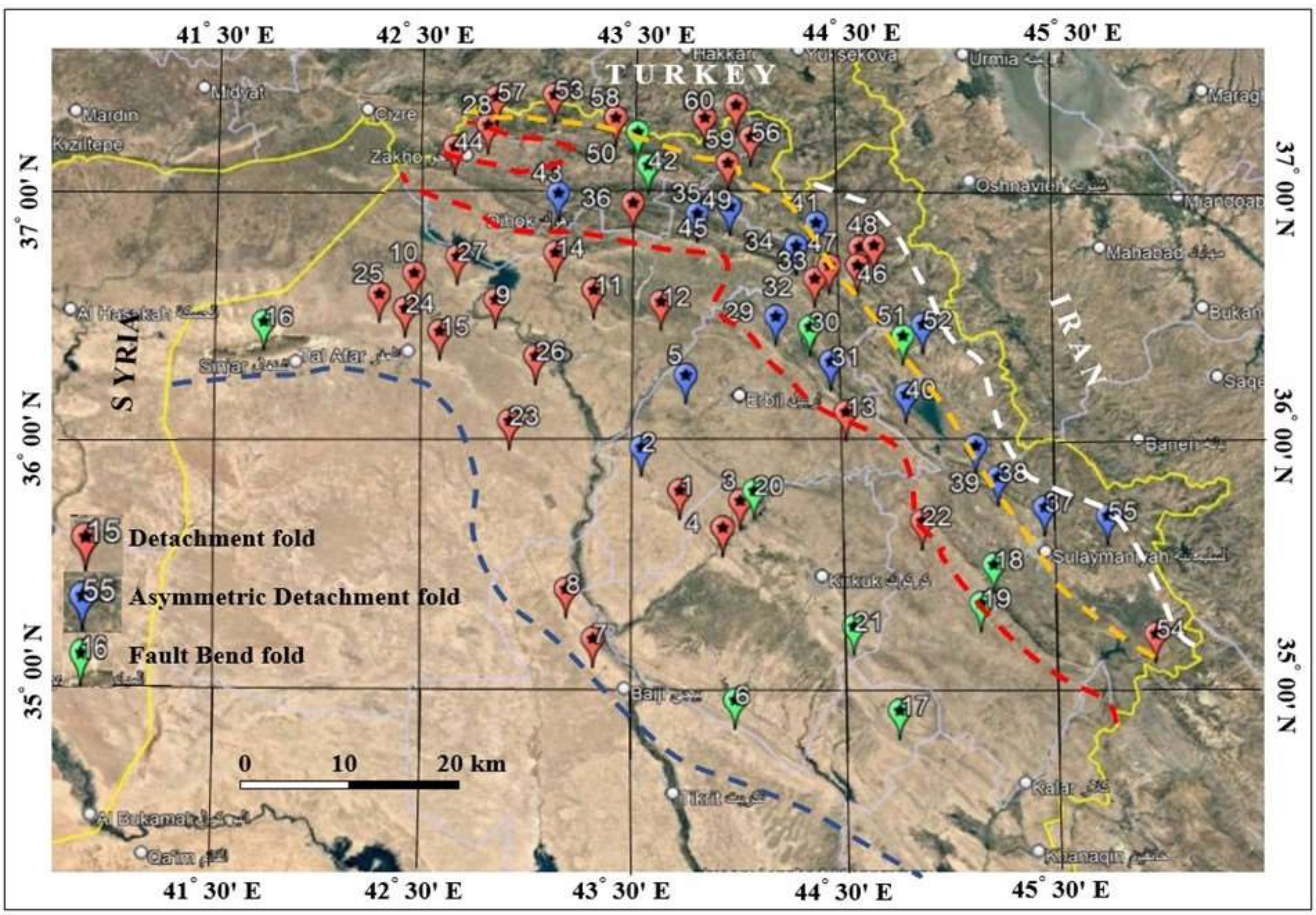

Figure 9: Satellite image showing the locations of the studied 60 anticlines. The blue, red, orange, and white dashed lines represent the lower limits of the Low Folded, High Folded, Imbricate, and Zagros Suture zones.

Table 3: Structural and geomorphological characters of the studied 60 anticlines **FT**= Folding type, **SZ**= Structural Zone.

	1	2	3	4	5	6	7	FT	SZ
Anticlinal Number	—	1	1	—	1	1	—	DF	Low Folded Zone
	—	—	2	2	—	2	—	ADF	
	—	—	3	3	—	3	3	DF	
	—	4	4	4	—	4	—	DF*	
	—	—	5	—	5	5	5	ADF	
	6	6	6	6	6	6	6	FBF	
	7	7	7	—	—	7	—	DF*	
	—	—	8	—	8	8	—	DF*	
	9	—	9	9	9	9	—	DF	
	10	10	—	—	—	10	—	DF*	
	—	11	11	11	11	11	—	DF*	
	12	12	12	12	12	12	12	DF	
	13	—	13	13	13	13	—	DF*	
	14	14	14	14	14	14	—	DF	
	15	15	15	—	—	15	—	DF*	
	—	—	16	—	16	16	—	FBF	
	17	17	17	17	17	17	17	FBF	
	18	18	18	18	18	18	—	FBF*	
	19	19	19	19	19	19	—	FBF*	
	20	20	20	20	20	20	20	FBF	
	—	—	21	21	21	21	21	FDF	
	—	—	—	—	—	22	22	DF*	
	23	23	23	—	—	23	—	DF*	
	24	24	24	24	24	24	—	DF*	
	25	25	25	—	—	25	—	DF	
	—	—	—	—	—	26	—	DF	
	—	—	27	—	—	27	—	DF	
	—	—	28	28	28	28	—	DF*	
	29	29	29	—	—	29	—	ADF	High Folded Zone
	30	30	30	30	—	30	—	FBF	
	31	31	31	31	31	31	—	ADF	
	—	—	32	32	32	32	—	DF	
	—	33	33	33	33	33	—	DF*	
	—	34	34	34	34	34	—	ADF	
	35	35	35	35	35	35	—	ADF	
	—	—	36	36	36	36	—	DF*	
	37	37	37	—	—	37	—	ADF	
	—	—	38	38	—	38	—	ADF*	
	—	—	39	—	—	39	—	ADF*	
	40	40	40	—	—	40	—	ADF*	
	41	41	41	—	—	41	41	ADF	
	42	42	42	—	—	42	—	FBF*	
	43	43	43	43	—	43	—	ADF	
	44	44	44	—	—	44	—	DF*	
	45	45	45	—	—	45	—	ADF*	
	46	46	46	46	46	46	—	DF*	
	47	47	47	—	—	47	—	DF*	
	48	48	48	48	—	48	48	DF*	Imbricate Zone
	—	—	49	49	—	49	—	DF*	
	50	50	50	50	50	50	—	FBF	
	—	—	51	—	51	51	—	FBF	
	52	52	52	52	—	52	—	ADF	
	—	—	53	53	—	53	53	DF*	
	—	—	54	—	—	54	—	DF*	
	55	55	—	—	—	56	—	ADF*	
	—	56	—	56	—	56	56	DF*	
	—	57	—	57	—	57	57	DF*	
	—	—	—	58	—	58	58	DF*	
	—	—	—	—	—	59	59	DF	
	—	—	—	60	60	60	60		

Table 4: Number of recorded forms of lateral growth in the studied 60 anticlines.

Number of forms	6	5	4	3	2	1
Recorded cases	12	8	18	15	4	3

We considered those anticlines, which showed three forms and more, anticlines exhibiting lateral growth. Accordingly, seven anticlines among the studied 60 anticlines are considered anticlines without lateral growth (Table 5).

Table 5: Anticlines in the studied area without lateral growth.

Serial No.	**Anticline No.**	**Anticline Name**	**Type of fold**	**Tectonic Zone**	**Number of forms**	**Recognized forms**
1	22	Cham Chamal North	Detachment Fold	Low Folded	1	Different valley shapes
2	26	Nuwaiqeet			1	
3	27	Butmah West			2	Abandoned alluvial fans + Different valley shapes
4	39	Surdash	Asymmetrical Detachment Fold	High Folded	2	
5	54	Halabja	Detachment Fold	Imbricate	2	
6	58	Merga Sur			2	Water gap + Different valley shapes
7	59	Bedu			1	Different valley shapes

Conclusions

We selected and studied 60 anticlines in different parts of Iraq to elucidate their types based on structural elements, Aspect ratio, and fold symmetry index. Accordingly, we found that 34 are Detachment folds, 15 are Asymmetrical Detachment folds, and 11 are Fault-bend folds. We checked the influence of the tectonic zone on the type of folds and found that the tectonic zone (not the tectonic forces) almost does not affect the developed type of folds. However, we don't mean the exerted forces due to the collision of the Arabian and Eurasian plates, but the characteristics of each tectonic zone in Iraq. Moreover, we studied the lateral growth of the 60 studied anticlines depending on two structural and six geomorphological aspects and we found that 53 anticlines showed 3 or more aspects and 7 anticlines showed only 2 or 1 of the structural and/ or geomorphological aspects; therefore, we have considered those anticlines (Nos. 22, 26, 27, 39, 54, 58, and 59) as anticlines without indications for lateral growth. Based on the achieved results in the current study, we highly recommend using the mentioned six characters to indicate the structural type of folds, especially when seismic sections are not available and the anticlines are not easily accessible.

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