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Structural Evolution of Wadi Hudaydun in Wadi Shueib Area, NW Jordan

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Abstract

The study area of Wadi Hudaydun and its surroundings forms part of the 80 km long and NE trending Wadi Shueib Structure in northwestern Jordan. The area is predominated by the Late Cretaceous carbonates with minor bedded cherts and phosphorites of the Ajlun and Belqa Groups. A complex structural style is revealed during the measuring and mapping of the main structural elements. The major area's structures consist of two fold belts; Al Baqr - Hudaydun fold belt and Ath-Thughra fold belt intersected by a complex structural style of fault zones. These faulting systems are normal faults, striking WNW-ESE and N-E, while those trending NW-SE are of the thrusting type. Dextral and sinestral strike-slip faults are also recognized in the area. With the aid of fieldwork observations and the use of "Multiple Inverse Method Software Package", the main stress axes are obtained.

The results of the current study suppose that most of the geological structures in the investigated area follow two tectonic events. The major one is associated with the Late Cretaceous stress pattern, which is presumed to have occurred during the formation of the Shueib Structure, and produced the NNE-SSW folds of Al Baqr-Hudaydun belt. Its maximum and minimum compressive axes ($\sigma1$ and $\sigma3$) are trending towards the WNW-ESE and NNE-SSW, respectively. The minor tectonic phase can be either correlated to a local stress or may even be attached to the primary stresses of the Dead Sea Fault (DSS). Its trend, probably swinging towards the N-S direction, has produced Ath-thughra fold belt. Two distinctive compressional structures are observed in the studied area as well; they are the fault-propagation fold and the strike-slip fault.

Keywords: Fold belt, Structural analysis, Shueib Structure (SHS), fault-propagation fold, duplex structure, Syrian Arc Fold Belt (SAFB), Syrian Arc Stress Field (SAS), Dead Sea Transform Belt (DST), Dead Sea Stress Field (DSS).

1. Introduction

The investigated area, Wadi Hudaydun, which belongs to the SAFB, is located some 25 km from the northeastern tip of the Dead Sea, 20 km WNW of Amman city, within the central part of Wadi Shueib (Fig. 1). It is bounded by longitudes: 35˚ 42' 21.54'' and 35 44' 18.45'' E, and latitudes 31˚ 56' 53.62'' and 31 58' 0.18'' N. The area covers about 5 km^2. It is dissected by three main wadis, namely Wadi Hudaydun, Wadi Ath-Thughra, and Wadi Al Baqr, and is separated by three highlands; Hudaydun highland, AthThughra highland and Al-Baqr highland (Fig. 2).

The objective of this study is to investigate the structural deformations in details and deduce the stress regime affecting the area. It is different from previous studies, in that it shows new evidences of the Mastrichtian-Post Cretaceous (Oligocene-Miocene) activity, and proposed new structural relationships of the tectonic events and evolution of Wadi Shueib structure in the Wadi Hudaydun area, as a whole.

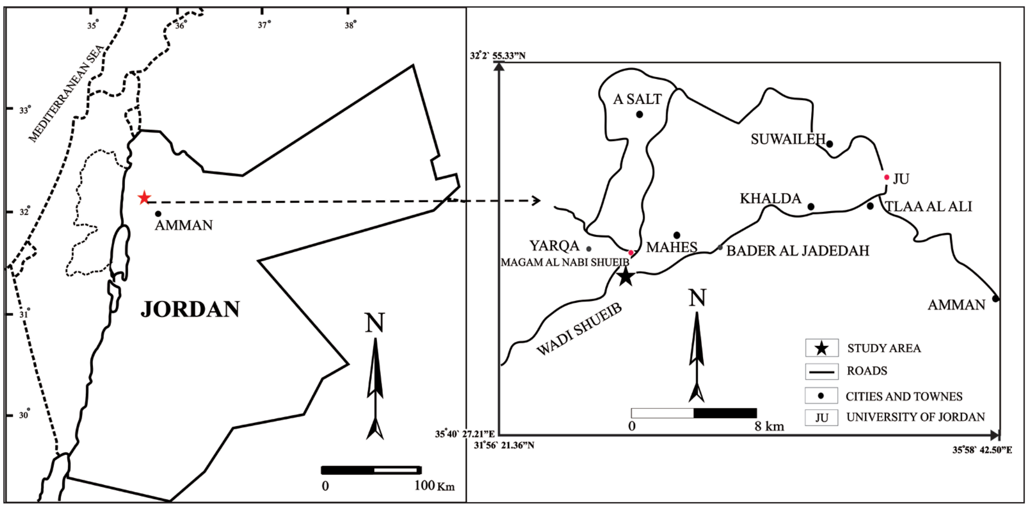

Figure 1. Location map of the study area and the roads leading to it.

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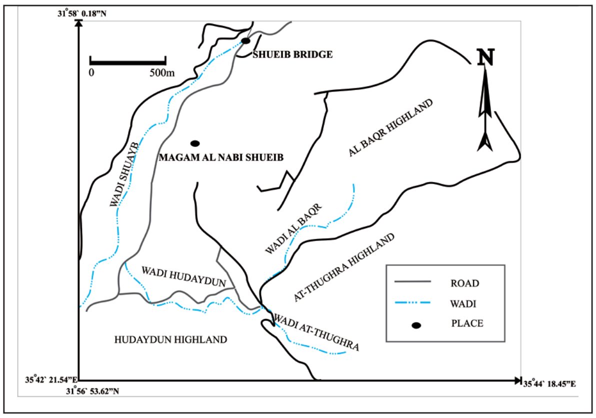

Figure 2. Detailed map of the study area showing the names of wadis and highlands used in the text.

2. Materials and Methods

Extensive field investigations, aerial photographs scales (1:10000 and 1:25000), Google topographical photos, and an accurate contoured topographic map in (1:25000) scale, are used to perform detailed structural map. The map shows the major structural elements investigated with simplified geological map (Fig.3). Multiple Inverse Method Software Package has been used to deduce the major trends of area's stresses.

2.1 Stress Analysis

To analyze the stress fields, this study uses Multiple Inverse Method Software Package which includes two major parts, namely the main and post processors. The main processor calculates stresses that are consistent with the data. The post processor, not only visualizes the stresses, but also provides various functions to analyze the data and stresses. Because the absolute values of the principal stresses are unachievable in most cases, a relative magnitude of these principal stresses can be estimated from fault population data. For this purpose, the program uses the stress ratio $\Phi = (\sigma2 - \sigma3)/(\sigma1 - \sigma3)$, where σ1, σ2 and σ3 are principal stresses and $\sigma3 \leq \sigma2 \leq \sigma1$. By definition, the value of Φ has the range [0, 1]. The two cases Φ = 0 and 1 represent the stress states $\sigma1 > \sigma2 = \sigma3$ and $\sigma1 = \sigma2 > \sigma3$, respectively.

The parameters of a fault-slip datum consist of the orientation of the fault plane and the slip direction of the hanging-wall block. Since five out of ten major fault attitudes in the study area are measured with their slickenlines recorded accurately, they are used to analyze stresses field by this program. Table 1 shows the dip direction and the dip of the plane, faz and fpl, respectively. The slip direction is denoted by the orientation of slickenside striation and the sense of movement. The former is indicated by the azimuth of plunge of the striation, saz and spl. The letters in the last column represent the first letter of the "Normal," and "Dextral" fault-slip data. The angles are thought to be within the ranges of $0^{\circ} \leq$ faz, saz<360°and $0^{\circ} \leq$ fpl, spl<00°.

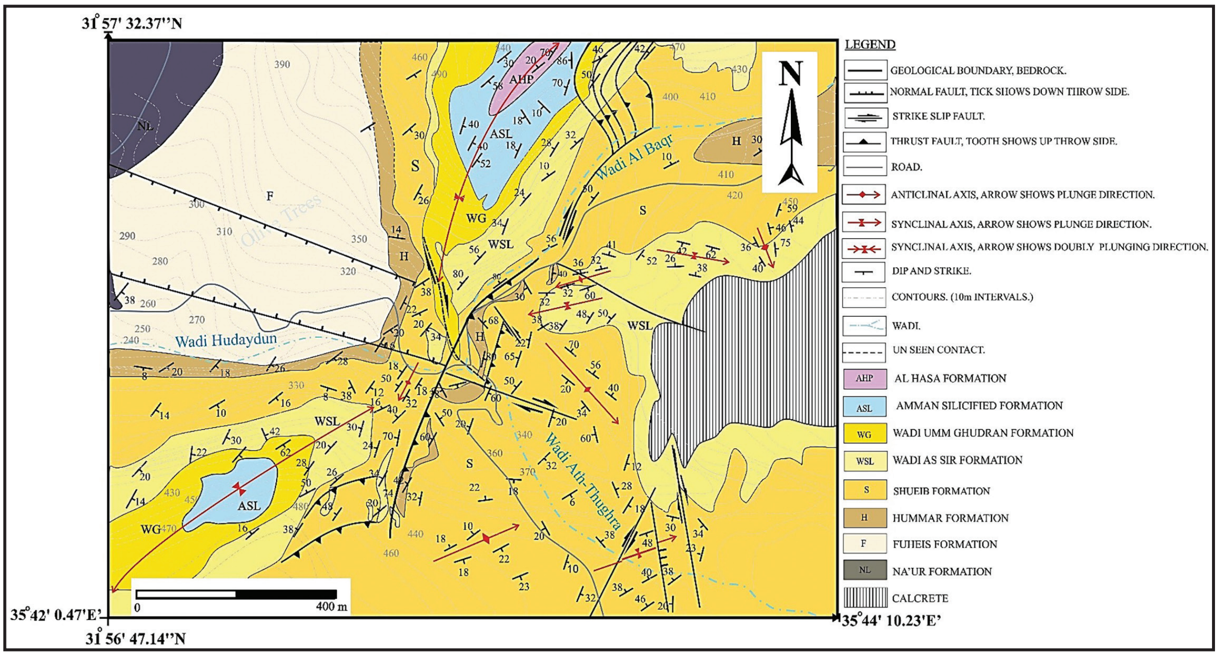

Figure 3. Geological map of study area.

Table 1. Slip data in Wadi Hudaydun area

Fault No.	Strike	Dip	Rake	Faz	Fpl	Saz	Spl	Sense
Fault1	110.0	60.0	-80.0	200.0	60.0	219.4	58.5	N
Fault2	260.0	40.0	-85.0	350.0	40.0	356.5	39.8	N
Fault10	330.0	40.0	-50.0	60.0	40.0	107.6	29.5	N
Fault3	150.0	80.0	150.0	240.0	80.0	326.0	21.6	D
Fault11	140.0	70.0	140.0	230.0	70.0	316.5	9.4	D

Two plotting methods are used in this software package including great-circles and poles or tangent lineation diagram. The first method exhibits the attitudes of faults by great-circles (Fig. 4), and the slip directions of the hanging wall blocks are indicated by arrows attached to the great-circles. In other words, the normal faults are denoted by arrows pointing away from the center of stereogram, and the strike-slip faults are exhibited by paired arrows attached to the great-circles.

The stereograms use a lower-hemisphere, equal-area projection. Each of the symbols that have heads and tails like tadpoles plotted on the stereograms represents a state of stress with the common principal orientations and the common values of stress ratio.

Optimal stress of the five faults, which are depicted by thick lines are shown in Fig. 4. The position of the head of a tadpole symbol on the stereogram indicates the σ1 and σ3 orientations (Fig.5 left and right stereogram); they are 324.5 ˚ trending and 58.5 ˚ plunge and around 130 ˚ trend and 31˚ plunge, respectively. On the whole, it can be concluded that the maximum stress direction trending is towards the N-S.

The correspondence between the length of the tail and plunge is shown by the ten gray tadpole symbols plotted between the stereograms; they indicate the plunges at 0˚, 10˚, 20˚, and 90˚. Φ values are digitized with the intervals of every 0.1 on the color bars just under the stereograms. Violet and red indicate Φ = 0 and 1, respectively. Therefore, the color of tadpoles (green to yellow) in Fig.5 is assigned to a moderate stress ratio, it is around 0.4.

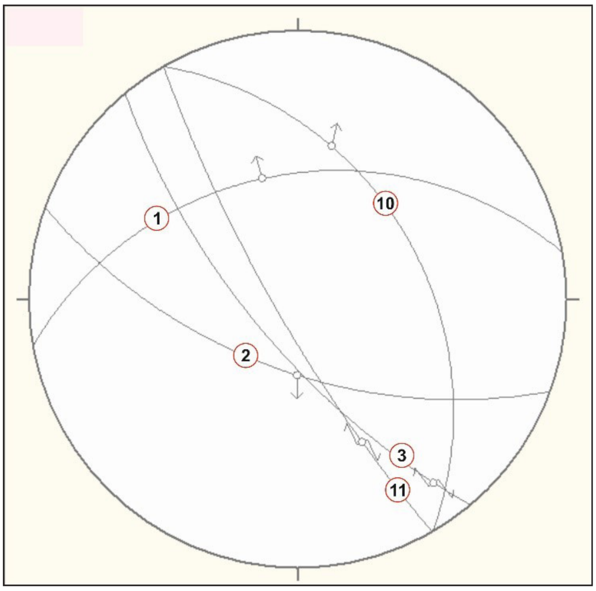

Figure 4. Lower-hemisphere, equal-angle projection. Numbers in open circles indicate the fault numbers in the map.

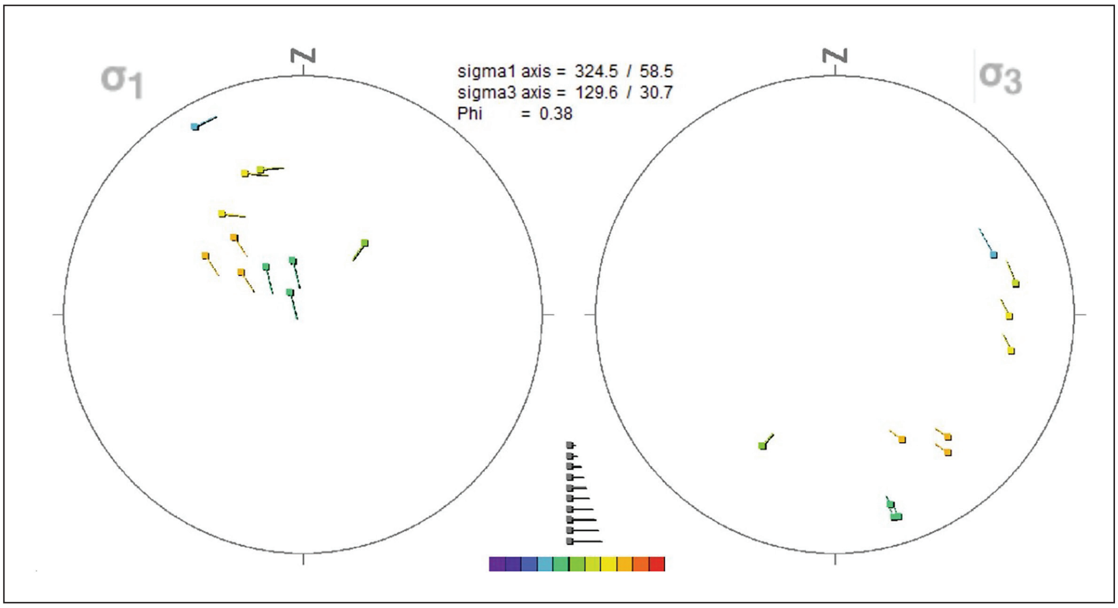

Figure 5. The position of the tadpole symbol on the stereogram indicates the major σ1 orientation and minor σ3. Phi~0.4.

3. Geological Setting

3.1 Stratigraphy

The present work deals with late Cretaceous carbonate facies. thick sequence of predominantly carbonate rocks of Cenomanian–Coniacian age, which represents the Ajlun and Belqa Groups, are exposed in the area of study. The formations that are measured and observed over there have been shaded in Table 2.

The Amman Silicified and Al-Hisa Formations are well-preserved in the cores of the major synclines at the northern and southern corners of the study area. However, the complete sequence of Ajlun Group (Na'ur, Fuheis, Hummar, Shueib and Wadi As Sir formations) is exposed at the eastern, central, and western borders of the study area. The most complicated and deformed part of the study area is its central part near the three wadis' intersection.

Table 2. Nomenclature of the Ajlun – Belqa Groups in the study area, Jordan.

Age		Group	Formation	Member
Tertiary	Eocene		Shallala	
			Umm Rijam Chert Limestone	
	Paleocene		Muwaqqar Chalk Marl (MCM)	
	Paleocene-Mastrichtian	Balqa	Al-Hisa Phosphorite (AHP)	Qatrana Phosphorite
				Bahiyya Coquina
Late Cretaceous				Sultani Phosphorite
	Campanian-Santonian		Amman Silicified Limestone	
	Coniacian		Wadi Umm Ghadran	Dhiban Chalk
				Tafila
				Mujib Chalk
	Turonian	Ajlun	Wadi As Sir Limestone	
	Cenomanian		Shueib	
			Hummar	
			Fuheis	
			Na'ur	
Early Cretaceous	Aptian-Albian		Kurnub (Hathira)Sandstone Group	

3.2 Tectonic setting

Coinciding with the contractional tectonic style, the closure of the Neo-Tethys, and the convergence of the African-Arabian Plate with the Eurasian Plate, a new NW-oriented horizontal compressive stress was generated (e.g. Ricou, 1995; Abd El Motaal and Kusky, 2003; Bumby and Giraud, 2005). This stress regime caused the flexturing of the preexisting strata forming a number of folds frequently associated with reverse and thrust faults, known as the Syrian Arc Fold Belt (SAFB) (Krenkel, 1924; Reches et al., 1981; Burek; 1981; Chaimov and Barazangi, 1990; Chaimov et al., 1992; Shahar, 1994; Reilinger and Mc Clusky, 2011). The largest structures in NW Jordan are the Amman-Hallabat Structure (AHS) and Shueib Structure (SHS); interpreted as part of the SAFB (e.g. Abed, 1989). The SAS is perhaps still active up to the present time (Awabdeh et al., 2015). The SHS was first coined by Mikbel and Zakher (1981) who gave a general description to the deformations along its length; a description which remained with little or no additions since then.

4. Results

4.1 Description of the Structures

The folds are divided into two belts; Al Baqr -Hudaydun highlands fold belt and Ath-Thughra highlands fold belt. The first fold belt includes three folds, namely Al Baqr doubly plunging syncline, Hudaydun anticline, and the doubly plunging Hudaydun syncline, which are present along Wadi Al Baqr and Wadi Hudaydun, respectively. The axis of Al Baqr syncline plunges 2˚ to N24˚E and 5˚ to the S24˚W (Fig.6a), whereas the axis of the Hudaydun syncline plunges 10˚ to the N42˚E and 20˚ to the S30˚W (Fig.6b). The Hudaydun anticline, which separates the two abovementioned doubly-plunging synclines, strikes towards S12˚W (Fig.6c).

The second belt, Ath-Thughra fold belt, extends along the eastern side of the study area between Wadi Al Baqr and Wadi Ath-Thughra. It includes seven folds, mostly asymmetrical; their plunging varies from 5˚ to 29˚ in different directions (Fig. 7). The folding is affecting the Mastrichtian phosphorite limestones (Al Hisa Formation) in Al-Baqr syncline and Hudaydun folds, while Ath-Thughra fold belt has affected the older carbonates of the Hummar and Shueib Formations.

Different types of faults are recognized in the study area (Fig. 8). Two major trends of a normal fault are measured, WNW-ESE, and NNW-SSE (e.g. fault10/Fig. 9b). The first two strikes, which are almost parallel but with an opposite downthrow, form a small graben (e.g. faults 1 and 2 /Fig. 9). Thrust faults are mainly striking towards the NNW-SSE (fault 4 and 6 in Fig. 9). Two types of strike-slip faults are also recognized in the area: dextral faults which are the dominant faults (e.g. faults 8 and 3 in Fig. 9/Fig. 9a, /Fig.9c, and fault 9), and the less abundant sinistral faults (e.g. Fig.9/d). The highly deformed fold limbs have resulted from faults passing through folded rocks that left some relicts on fault planes.

4.2 Distinctive Structural Features

Two distinctive structures are documented in the area, namely the fault-propagation fold and the strike-slip fault. These structures are used by some authors (e.g Al-Hseinat, et al., 2015) as a convenient evidence of the horsetail model theory that considered Wadi Shueib Structure a subsidiary feature splaying from the DST.

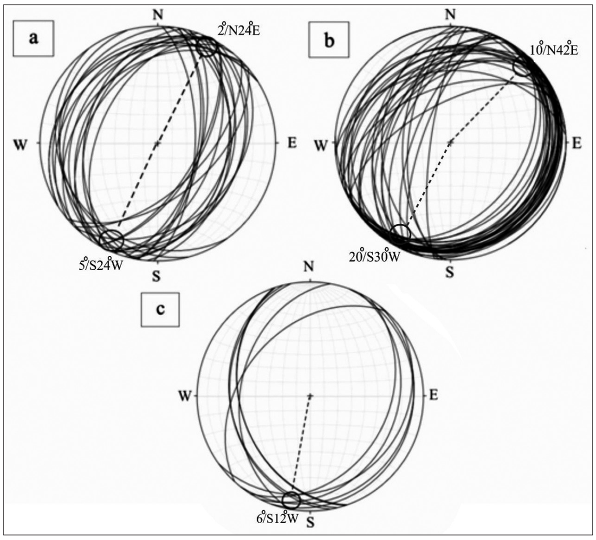

Figure 6. Stereographic projection of Al Baqr and Hudaydun fold belts.

4.2.1 Fault-propagation Fold

This type of fold is formed in association with thrust faults; as the fault tip propagates, the overlying beds are folded. By continuing propagation, the forelimb and the backlimb of the fold lengthen and form an asymmetric anticline. In the study area, this fold is located within the lower side of the eastern limb of Al-Baqr syncline (Fig. 10). The flat segment of the fault follows the soft marl beds of the Shueib Formation, while the ramp segment transects the hard limestone beds of the Wadi As Sir Formation. The fault and the overlying fold are verging to the southwest direction.

4.2.2 Strike-Slip Duplex

This structure is formed due to the bending of strike-slip faults. Depending on the type of bending (right or left) and the fault type (sinistral or dextral), either transpressive or transtensile duplexes are formed. Towards the uppermost part of the eastern limb of Al Baqr syncline, a duplex structure is formed. It consists of an array of several thrust faults that parallel a bend in a strike-slip fault (Fig.11a) passing through Wadi As Sir, Ghudran and Amman Silicified Formations (Fig.11b). Contractional thrust faults bounded by the two dextral strike-slip segments (fault5) generate a "contractional strike-slip duplex". It is recognized as a positive relief comprised of a series of juxtaposed areas, resulting in stacked S shape fault blocks.

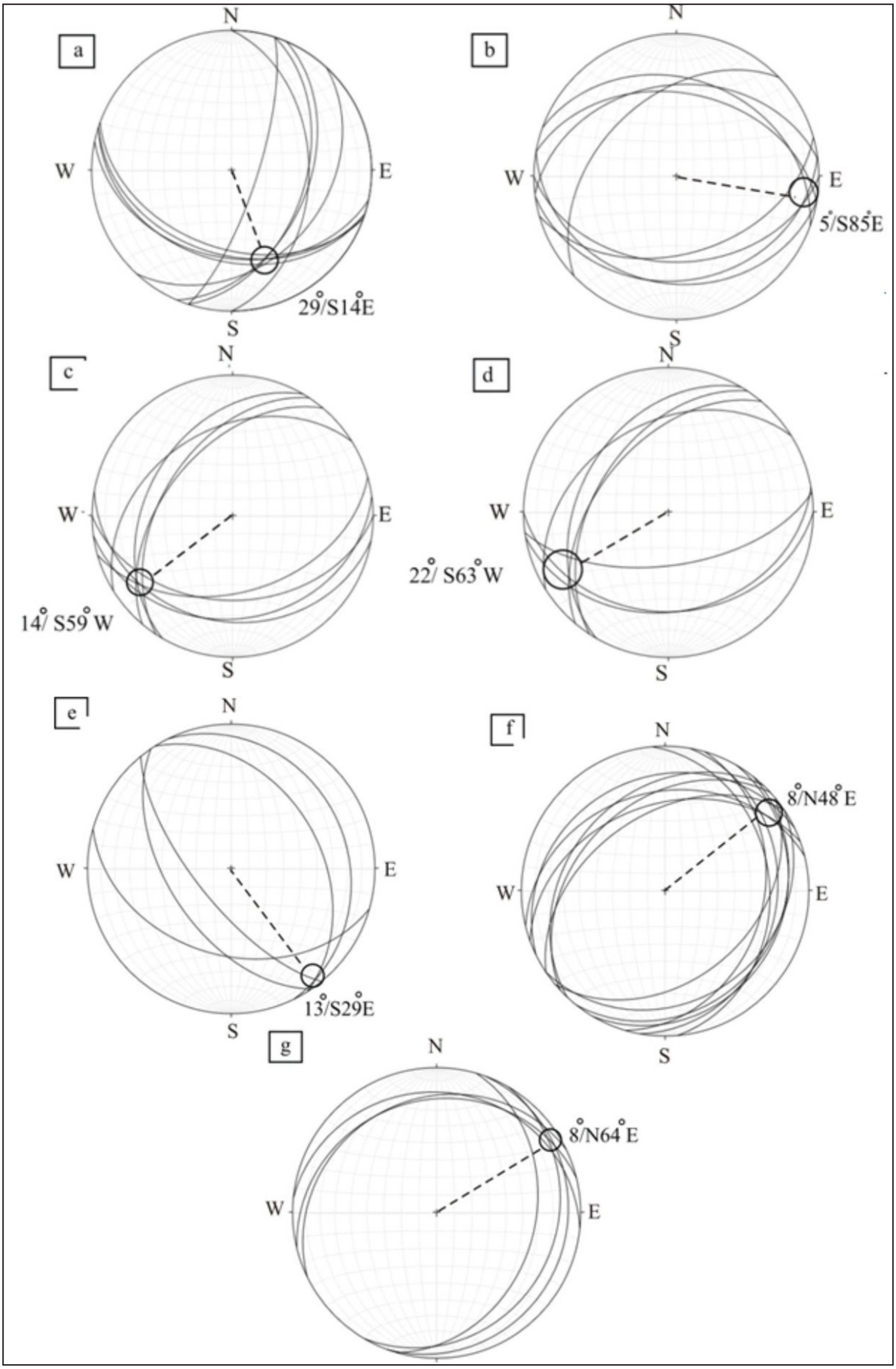

Figure 7. Stereographic projection of Ath-Thughra folds.

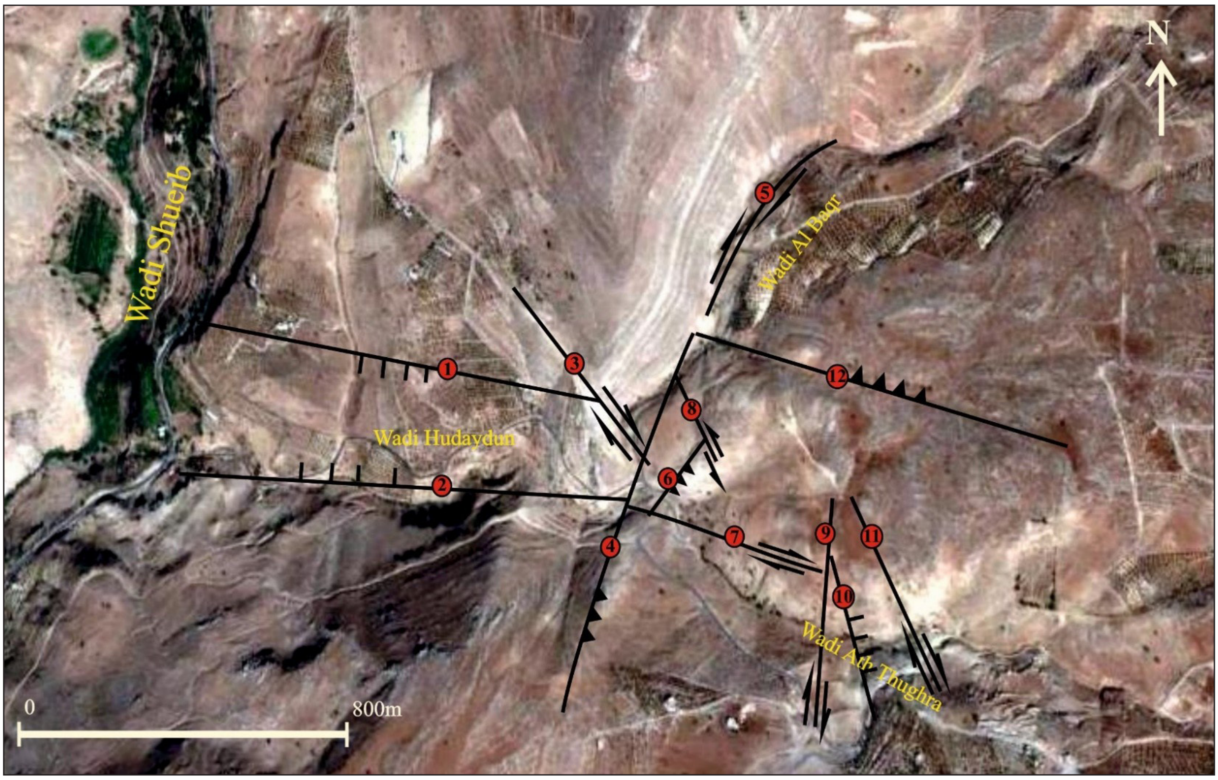

Figure 8. Google map of the major faults in the study area.

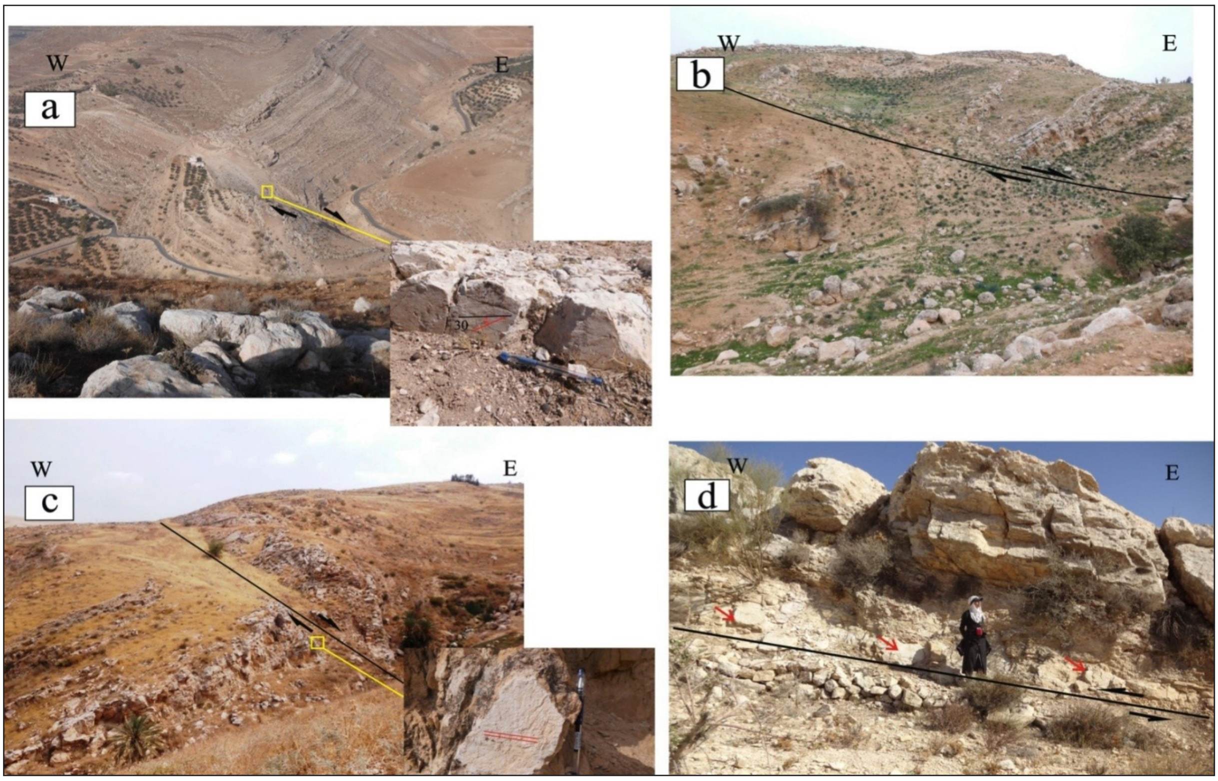

Figure 9. a) Fault 3; rake 30W, oblique dextral type; **b)** Fault 10; vertical section of normal fault / Ath-Thughra fold belt; **c)** Fault 11; dextral slip fault with horizontal slickenlines; **d)** A left lateral minor fault crossing the Al Baqr syncline, it is recognized by tracing slickenside "red arrows" in the Shueib layers.

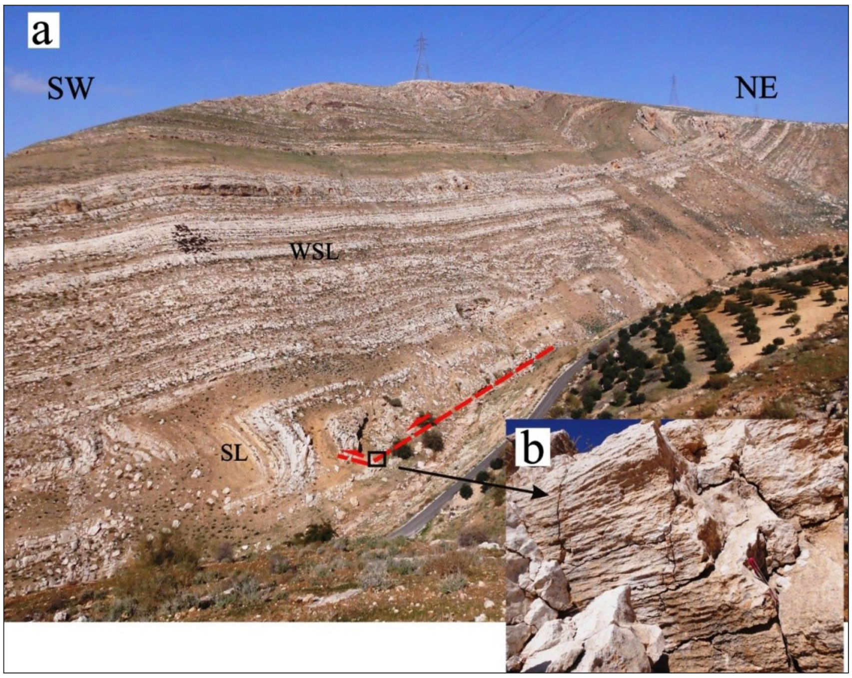

Figure 10. shows **a)** Fault-propagation fold feature in the western limb of Al Baqr syncline **b)** Horizontal slickenlines assigning sinistral strike-slip fault. (WSL=Wadi As Sir Limestone formation, SL= Shueib Limestone formation).

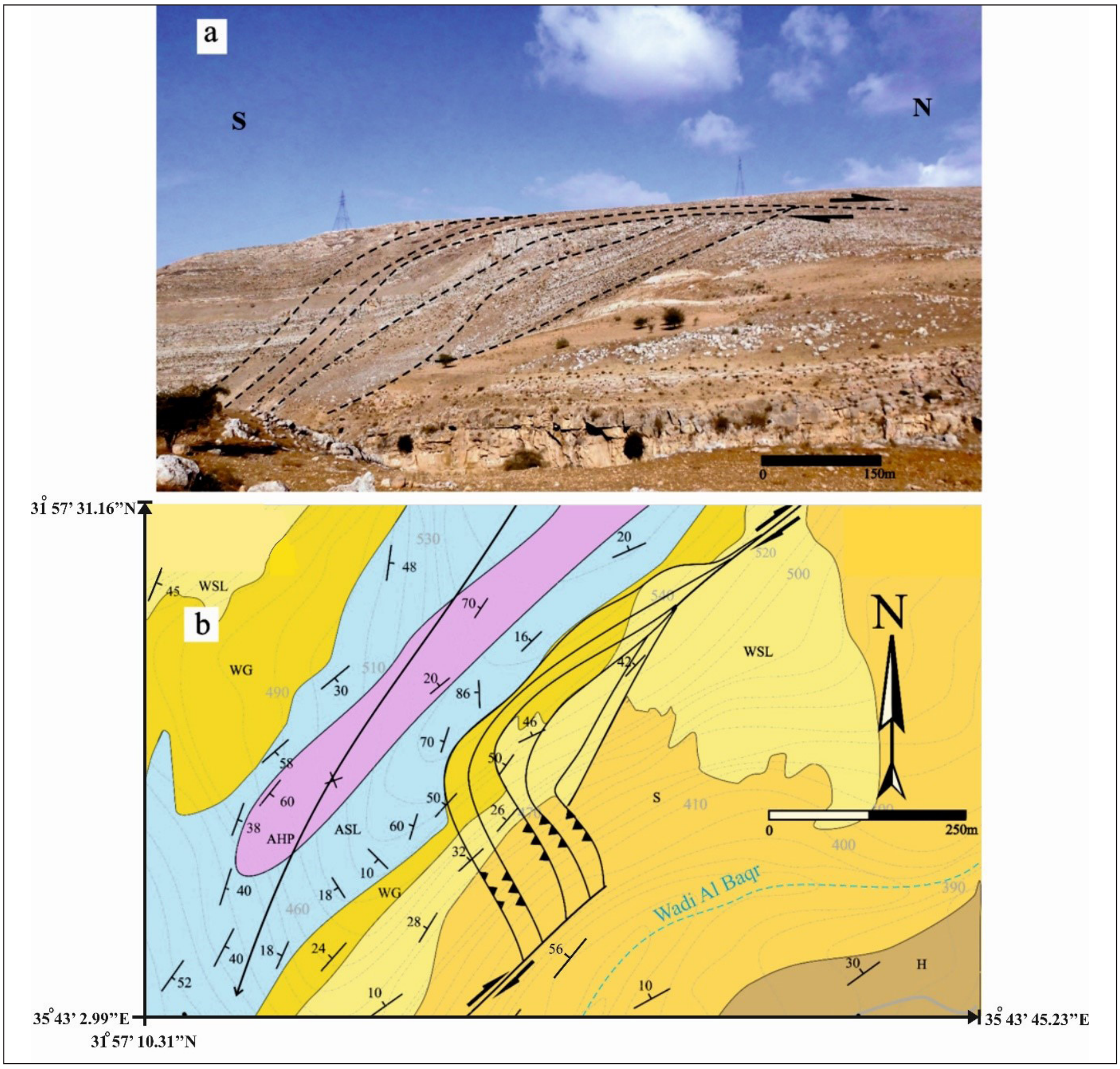

Figure 11. Strike-slip duplex a) Thrust fault system along juxtaposed horse of the strike-slip duplexes structure in the study area. The dashed line illustrates the contractional thrust fault at Wadi Al Baqr, b) the geological map shows the strike-slip duplex structure in the study area. For legend, see Fig. 3.

5. Discussion

Several authors indicated that two main stress fields have been affecting central and northern Jordan. The first field is characterized by ESE-WNW compression and NNE–SSW extension (Burden, 1959; Diabat et al., 2004; Diabat, 2009) These are: The Wadi Shueib and Amman Hallabat structures trending towards the NNE-SSW and NE-SW, respectively (Mikbel and Zacher, 1981, 1986). The latter structures are associated with the (SAS) (e.g. Abed; 1989). The second paleostress regime, which is a NNW–SSE compression and ESE–WNW extension is related to the (DSS) (Qassem, 1997; Zain Eldeen et. al., 2002; Sahawneh and Atallah, 2002; Al khatib et al., 2010, Al Tarawneh; 2011). Amman Hallabat Structure and Shueib Structure are redefined as active structures since the Neogene (Diabat, 2009; Al Awabdeh et al., 2015, and 2016), and are receiving a direct transference of tectonic stress through the Wadi Araba Fault (Awabdeh et al., 2015).

The main trends of the fold axes in the study area, based on measuring 10 axes of the folds, are: NNE-SSW and ENE-WNW of Al Baqr-Hudaydun fold belt and Ath-Thughra fold belt, respectively. The first fold belt trend N30°E of Al Baqr-Hudaydun structure is supposed to be the result of the ESE-WNW stress (Fig.12a). The youngest sediments of Al Baqr-Hudaydun structure that have been affected by a folding process are related to the Mastrichtian Period, which means that the folded deformations' stress is much younger than the folded sediments itself. In other words, the compressional folding force could have occurred beyond the Mastrichtian period (post Cretaceous). Many authors proved that the activity of the SAS has started in Turonian (Davies, 1984; Chaimov et al., 1992; De Ruiter et al., 1994; Guiraud and Bosworth, 1999; Diabat et al., 2004; Diabat, 2007, Giana et al., 2013) and it still active till now (Al Awabdeh et al., 2016). Hence, the area of study is considered as part of the Wadi Shueib structure, and the Wadi Shueib structure is considered part of the SATB (Zacher and Mikbel, 1981). Accordingly, it could be mentioned assertively that the investigated area must have been deformed by the SAS as well.

The short longitudinal extension of the Ath-Thughra folds (meso scale folds) and the major trend of its axes N70°E (Fig.12b), presuppose more than one scenario to interpret Ath-thughra structure. Firstly, the NNW-SSE maximum compressional stress is introduced as a local confined stress force that has affected the Cenomanian-Turonian sediments (Hummar and Shueib Formations), or based on the kinamatic analysis of the area's faults, it could have been affected by the DSS.

To sum up the whole former discussion, it can be said that the paleostress analysis of the study area's faults indicates one paleostress regime belonging to one major phase; the major tensor of the maximum compressive stress axis trends toward the NNW-SSE direction, and since Al Baqr-Hudaydun and Ath-Thughra folds' limbs are cut by these faults, they must have been younger than the youngest folding phase of the Al Baqr-Hudaydun belt. They were developed in the post-Cretaceous period, perhaps during the Early Paleocene-Miocene, or they could be related to the Dead Sea Stress Field and the opening of the Red Sea (Freuend et al., 1970; Diabat, 2007). Ath-Thughra belt folding seems to be corresponded with the faulting activities because of the consistency of the maximum compressional force of the Ath-Thughra folds and the maximum compressive stress axis of the area's faults that had, approximately, the same attitudes ~N30°W (Fig.12b). The only evidence for relating Ath-Thughra and fault events to the Dead Sea stress is the absence of the Quaternary deposits in the study area; under other circumstances this theory remains in doubt.

The strike-slip duplex structure occurred in competent beds (Wadi As Sir Limestone and Amman Silicified Limestone formations) that are separated by thin incompetent layers of Ghudran chalk Formation. Meanwhile, the flat segment of the fault-propagation fold structure took place in a weaker incompetent soft marl beds of the Shueib Formation, and its ramp segment transects the hard limestone beds of the Wadi As Sir Limestone formation (competent). Moreover, because they cut the eastern limb of Al-Baqr syncline, they must be younger than Al-Baqr folding phase. Therefore, the strike-slip duplex and fault-propagation folds are generated by northern trends of dextral and sinistral strike-slip faults; respectively, assigning a north trend of the maximum compressive stress that could be also associated with the formation of Ath-Thughra fold belt structure. Moreover, the strike-slip duplex compressional structure is one of the clues to explain and detect the relationship between Wadi Araba fault terminus, which represents the eastern border of the Dead Sea shore, and Shueib-Hallabat structures. They are considered as a subsidiary features splaying from the Dead Sea Transform fault (Al- Hseinat et al., 2015; Al Awabdeh et al., 2015). Accordingly these distinctive structural features could be regarded as extra proof to consider the DSS as a major stress field for the Wadi Hudaydun deformations.

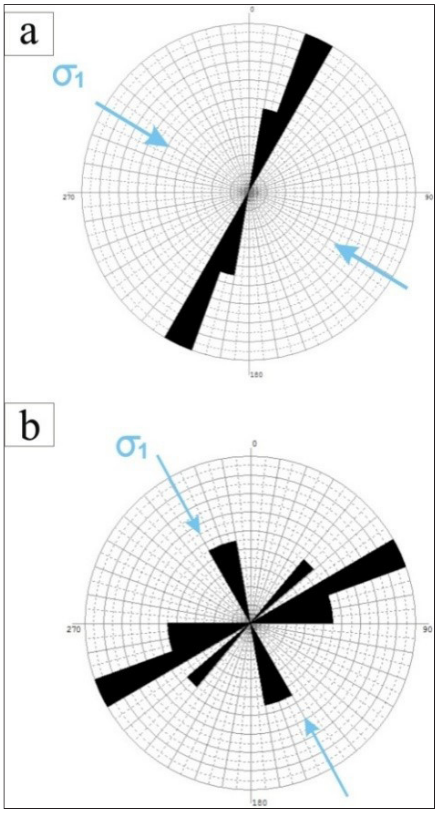

Figure 12. Rose diagrams show a) The major trends of fold axes in Al Baqr-Hudaydun fold belt. Blue arrows indicate the maximum horizontal compression axis. b) The major trends of fold axes in Ath-Thughra fold belt. Blue arrows indicate the Maximum horizontal compression axis.

6. Conclusions

The Wadi Hudaydun area is subjected to two phases of folding that are different in type, trending, and scale. The first phase of Al Baqr-Hudaydun fold belt produced asymmetrical large longitudinal extension folds (exceeds 1 Km), striking NNE-SSW, and is supposed to be the result of ESE-WNW compressional forces. It occurred through the accumulation of the horizontal stresses in the Arabian plate as a consequence of the northward movement and the rotation of the Arabian plate in the Late Cretaceous period. This stress pattern is similar to the one associated with the Shueib Structure which is a branch of the Syrian Arc Fold Belt. The second phase of the Ath-Thughra belt, trending to the ENE-WSW direction, is assumed to have occurred as a result of NNW-SSE maximum compressional stress. The maximum compressive stress of the fault slip data, striking to the NNW-SSE, and the compressional structure features (the duplex structure and the fault propagation fold) could have been produced either by local stress or by the Dead Sea transform fault stress.

Inaccuracy in detecting the reason behind Ath-Thughra's folding and the faulting time is due to the absence of the Quaternary deposits in Wadi Hudaydun area. However, because the faults are cutting through Al Baqr-Hudaydun and Ath-Thughra fold limbs, they must have been younger than the youngest folding phase of the Al Baqr-Hudaydun belt, and thus the age of the area's deformation could be between the Maastrichtian and post- Cretaceous period; perhaps during the Early Paleocene-Oligo-Miocene).

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