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Deformed Fossils and Related Structures in Jordan

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Abstract

This study of the deformation of fossils due to tectonic activities is the first study to be carried out in Jordan. Deformed fossils were found in a variety of locations such as Ajlun (Shtafina), Umm Dananier, Wadi Mujib and Jabal Waqf as Suwwan areas.

The different stress fields that produced folding, stylolization and reverse flexuring, are believed to have also produced the deformation of the fossils. Folding, stylolization and reverse flexures are structures, which can unambiguously be referred to defined stress fields. The deformation directions of the fossils are in this study correlated to the structures having unambiguous stress field producing them. The correlation was very clear and accordingly therefore, deformed fossils can be used as very good indicators on the stress fields which produced them irrespective, whether these stress fields have left any macrostructures in the rocks which indicate at them or not.

Deformed fossils from Jabal Waqf as Suwwan area have a different history, because the stress field producing them was a different one. It was a meteoritic impact stress field, which due to the very high velocity of around 18 Km/s caused all rock types to behave in a competent way for a very short time. After which rock block movements of sliding, rotation and tilting took place gradually.

According to the results of the study of deformed fossils, Jordan was during its geologic history exposed to different stress fields; in an ESE-WNW direction which produced the Syrian Arc structure, followed by a SE-NW strong stress field and finally by a NNW-SSE another strong stress field which resulted in the formation of the Dead Sea Transform Fault and accompanying structures.

The deformation of fossils was not always of a ductile type where fossils were compressed in a certain direction and expanded in the other, but some fossils show shear along certain directions, with very prominent shear surfaces.

The study concludes that deformed fossils can be used as excellent indicators of stress fields, even if other structures indicating at them are not found.

Keywords: Deformation of Fossils, Deformation Structures, Paleostress Indicators, Stylolites, Slickenside.

1. Introduction

Deformation of rocks by stress fields whether vertical, horizontal or oblique may be portrayed in the fossil remains and casts. The Upper Cretaceous rocks of Jordan show a variety of deformation structures, such as folding with explicit force plane direction, a complex faulting pattern of less clear stress directions, vertical stylolites because of vertical load and compaction and horizontal stylolites with distinct stress action. Fossils in the Upper Cretaceous rock units in the northern part of the country show vertical, horizontal and oblique deformations. These deformations are categorized in brittle and plastic types.

Although stress fields causing fossil deformation are reversible, the deformation of fossils themselves is irreversible. Therefore, deformed fossils are considered as a historic register of stress fields. The methods of elaborating on the deformational processes depend on how much is known about the original shape and composition of the deformed fossil (Ramsay, 1967; Davis and Reynolds, 1996). Undeformed and deformed fossils may be found in the same general area or in the different parts of the same structures. Therefore, the study of both deformed and undeformed fossils is expected to reveal information on the stress fields, which have affected the different study areas and probably Jordan as a whole.

Deformed fossils are found in several areas in Jordan. For purposes of this study, some of these are selected. The locations of these areas are shown in Figure (1).

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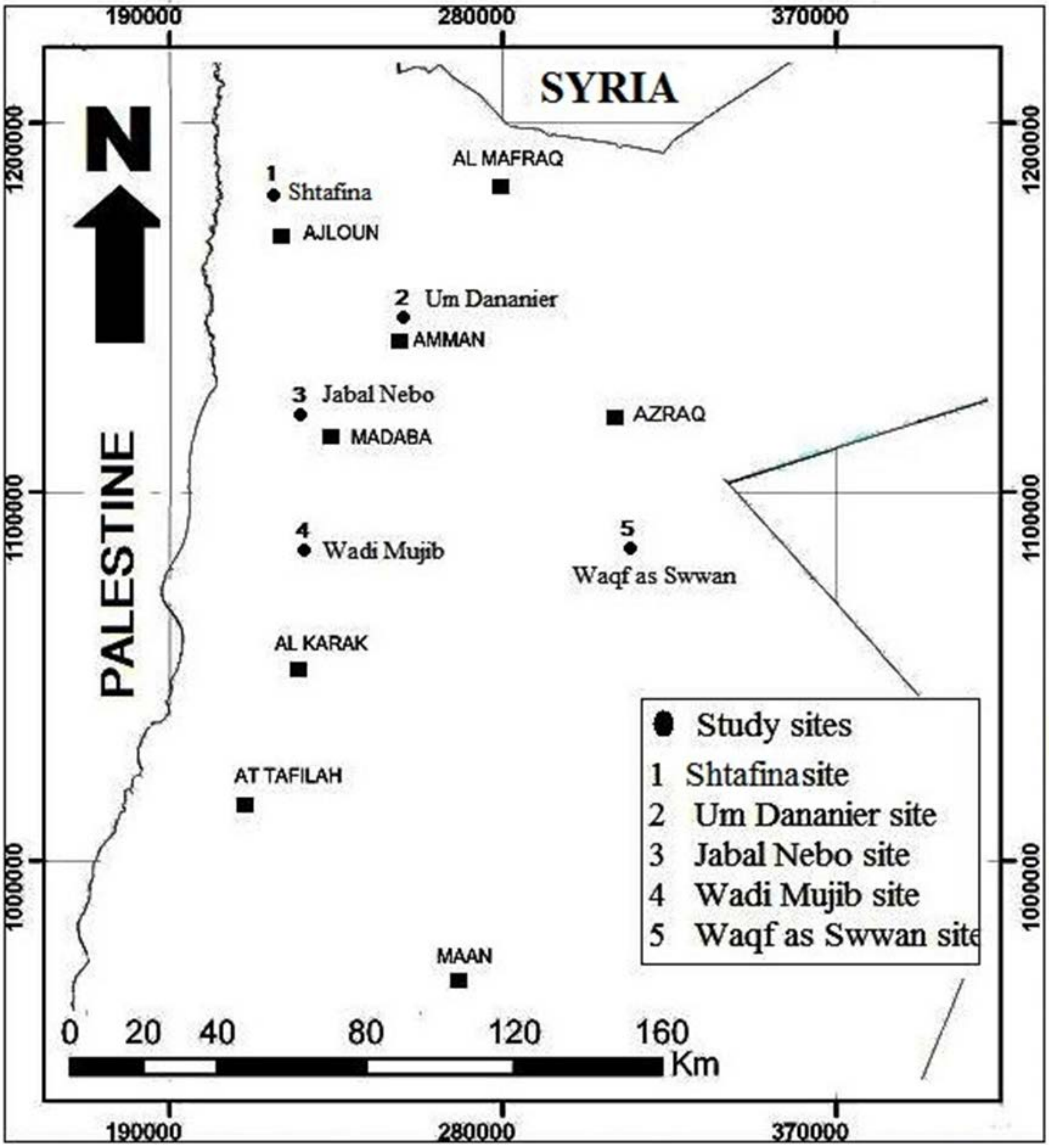

Figure1. Location map of the inspected sites (1, 2 etc... are numbers of studied sites).

2. Previous Work on Deformed Fossils

Phillips (1843) first studied deformed fossils in his study about slate cleavage, which was later studied by Sharpe (1847). Both indicated that fossils were deformed in the same direction causing the cleavage of slates. Shortening in slates because of the stress field was calculated by Sorby (1853).

Henderson et al. (1986), Jenkins (1987), Wright and Henderson (1992), Goldstein et al. (1995) studied also the percentage of shortening on deformed fossils and concluded that large volume losses accompanied the deformation of fossils in a variety of locations. Hills and Thomas (1944), Cloos (1947), Breddin (1956), Subieta, (1977), Blake (1878), Wright and Platt (1982), Ramsay and Huber (1983), Cooper (1990), Tan et al. (1995), Goldstein et al. (1995), Rocha and Dias (2003), Boyd and Motani (2008) studied the different types of deformations on different types of fossils, such as graptolites, ammonoites, brachiopods etc. Deformed fossils were in addition used as good tools to study the strain using the volume losses.

In Jordan many studies were carried out on fossils and their remains in the different geologic units such as Blake and Lonides (1939), Wetzel and Morton (1959), Quennell (1959), Bender (1968), Basha (1978), Bandel (1981), Bandel and Geys (1985), Dilley (1985), Powell (1989), Mustafa and Bandel (1992), Aqrabawi, (1993), Nazzal, and Mustafa, (1993), Bandel and Mustafa (1996), Neumann, (1999), Abu Hamad (2004). None of the studies dealt with the deformation of fossils.

In this article the deformed fossils found in the Cretaceous rocks of Jordan are studied on deformation types and magnitudes of the causing stress fields and their relation to existing geological structures such as folding, stylolites and slickenside.

The outcropping rocks where the deformed fossils are found consist of Upper Cretaceous sedimentary rocks. These rocks are mainly composed of limestone, marls, chalks, cherts, and dolomites of Cenomanian to

Maaestrichtian ages. The distribution of these sedimentary rocks shows a wide variation in their thickness related to the transgression of the Tethys Ocean to the south and southeast of Jordan where the granitic basement complex (Bender, 1968).

The lithostratgrphic description of the rock units of the Upper Cretaceous are given in Table 1.

Table.1: Stratigraphic nomenclatures and lithology of the Upper Cretaceous rocks in Jordan.

Period	Age	Quennell (1951)	Powell (1989) Formation	Lithology
Upper CRETACEOUS	Maastrichtian	Belqa Group	Muwaqqar Chalk Marl	chalk, marl
			Al Hisa Phosphorite	phosphorite , marl
	Campanian		Amman Silicified Limestone	massive chert limestone
	Coniacian		Wadi Umm Ghudran	chalk, chalky marl
	Turonian	Ajlun Group	Wadi As Sir Limestone	massive limestone , dolomite
			Shueib	marly limestone
	Cenomanian		Hummar	dolomatic limestone
			Fuheis	marl
			Na'ur	marly limestone

3. Tectonic Framework and Effects on the Upper Cretaceous Rocks Sequence.

Quennell (1951 and 1956) suggested that three stress fields were responsible for the formation of the major structures in Jordan (Figure 2). These stress fields have since Upper Cretaceous times rotated in a clockwise direction starting from a direction of ESE-WNW through SE- NW to NNW- SSE directions.

.(A) First stage of deformation started with a compression force acted in a WNW-ESE direction Minor folds resulted from this stage of deformation. The folds trend SSW- NNE such as the folds around Irbid area with axis strikes N15˚ direction.

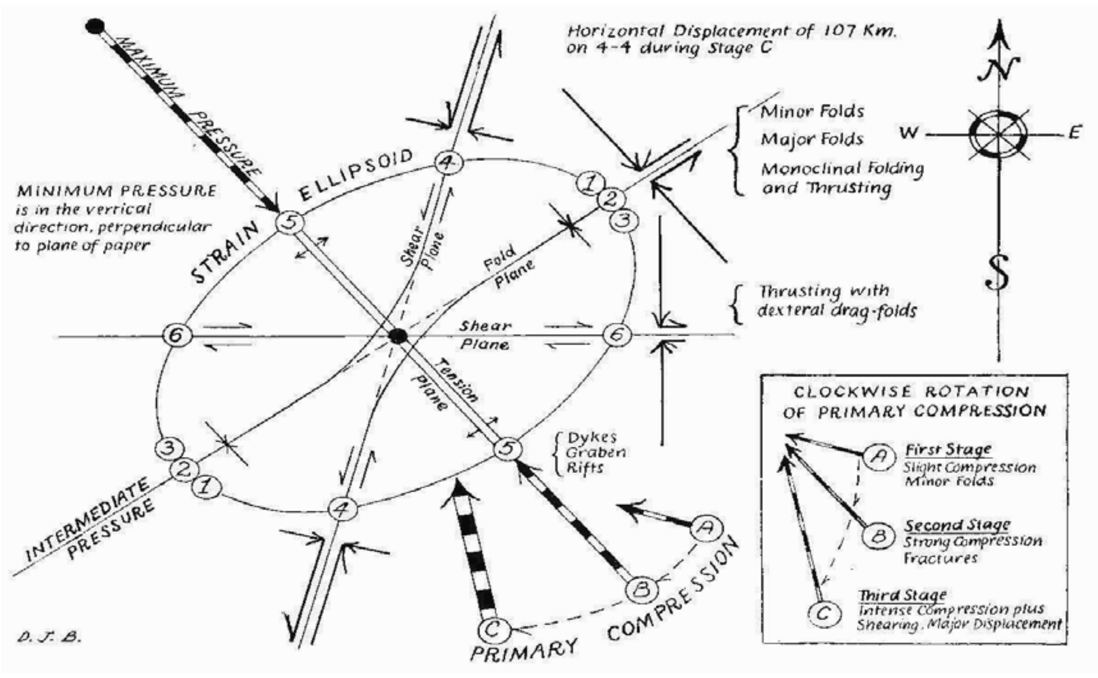

Figure 2. Horizontal Section through the strain Ellipsoid for the Dead Sea Region (QUENNELL 1951).

(B) The Second stage acted in a NW-SE direction. The compressive stress became stronger than during stage A. This stage produced the major folding and fracture system such as, Ajlun Dome, Basalt feeder Dykes, the Wadi Sirhan Graben, the Karak Graben, normal faults of Petra and the Wadi Khuneizira.

(C) The Third stage, which is still acting, has been still more intensive. It has been acting in a NNW-SSE trend, and it is responsible for the formation of the Dead Sea Rift Valley. The sinistral movement along the Dead Sea Transform resulted in a total horizontal movement of 107Km (Quennell, 1959).

Vorman (1961) found that the tensional stresses, which opened the Red Sea, caused also NW- SE normal faults and volcanic activity in the Middle East.

Ruef (1967) studied the undulations, in the Silicified Limestone Unit and the joint systems in Jordan. He concluded that the major fractures trend 170˚ and the minor ones trend 30˚.

Letouzey and Trẻmoliẻres (1980) studied the paleostress fields around the Mediterranean; their measurements of microtectonic elements in Jordan show a shortening zone with a NW-SE trend in the Upper Cretaceous rocks.

Salameh and Zacher (1982) studied the stylolites in the Uppermost Cretaceous rocks of northern Jordan and east of the Dead Sea as paleostress indicators and concluded that the stress field affecting Jordan had two dominant directions namely 130˚ to 140˚ and 170˚. Recently, Salameh (personal communication) measured weak horizontal peak stylolization is found in the Upper Cretaceous rocks in an ENE- WSW direction; 70˚. Field evidence shows that this weak horizontal stylolization in older rocks than those affecting the most Upper Cretaceous rocks. Figure 3 shows the main structural features in Jordan

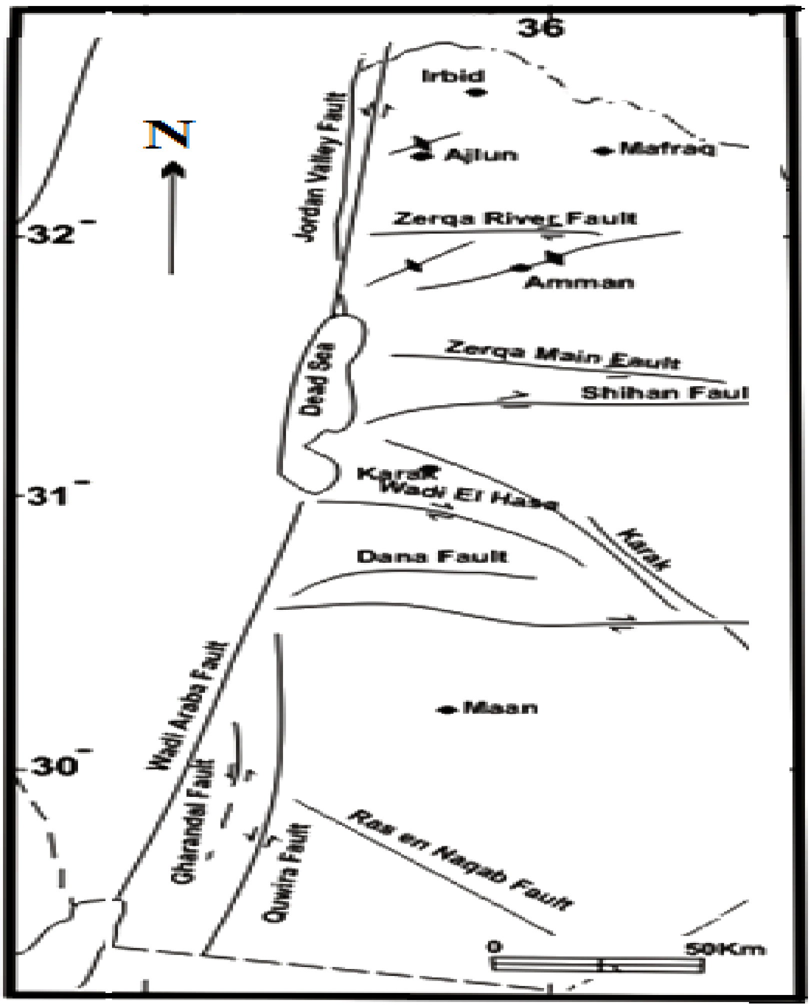

Figure 3: Major geologic structures map of Jordan (Al Diabat 2004).

4. Main Deformation Structures In The Upper Cretaceous Rocks In Jordan

The Upper Cretaceous rocks in Jordan show several types of deformation features, including; Fractures, faults, fold, slickenside, stylolites and deformed fossils. These deformation elements give good indicators on paleostress orientation, and allow interpreting stress conditions of the past.

4.1.Fractures

Field observations, measurements of joint trends in outcrop and also data collected from previous work on the structural evolution of Jordan (Burdon, 1959; Bender, 1968; Beicip, 1981; Barjous, 1986; Sahawneh, 1991; Atallah, 1992; Ibrahim, 1993; and Al Diabat, 1999) are used to represent the major orientation of fractures in Jordan, where Upper Cretaceous rocks crop out (Figures 4 and 5).

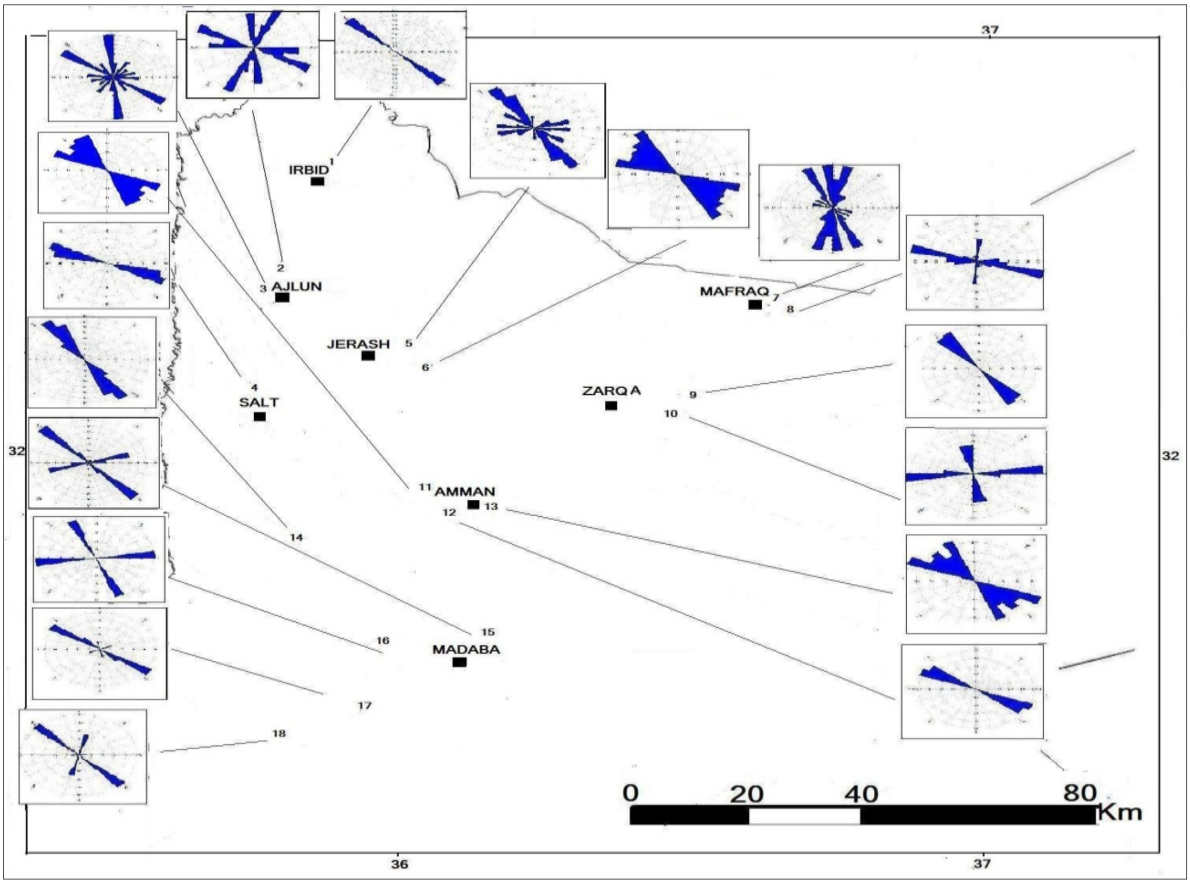

Figure 4. Fractures systems in the Upper Cretaceous rocks of northern Jordan. (Obtained from field observations, Burdon 1959, Bender 1968, Beicip 1981, Barjous 1986, Sahawneh 1991, Atallah 1992, Ibrahim 1993, and Al Diabat 1999.

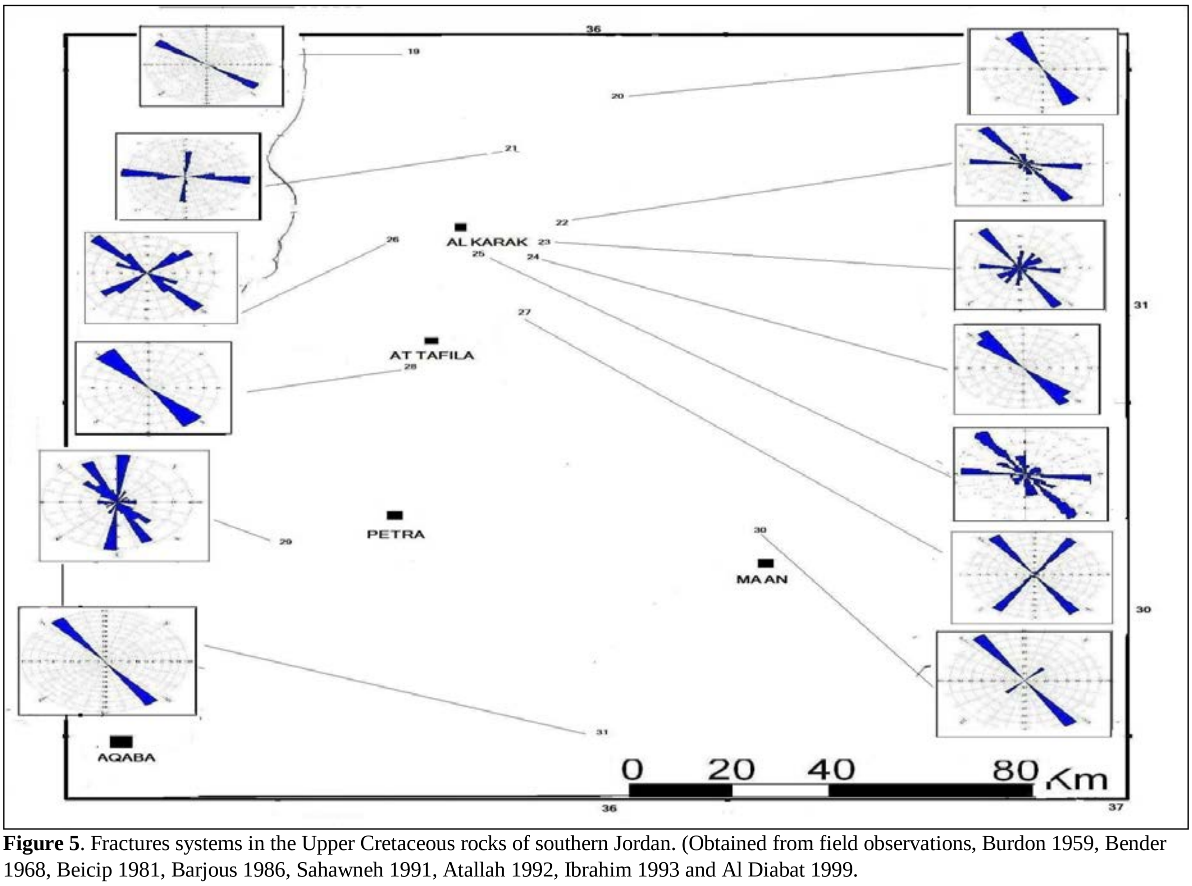

Figure 5. Fractures systems in the Upper Cretaceous rocks of southern Jordan. (Obtained from field observations, Burdon 1959, Bender 1968, Beicip 1981, Barjous 1986, Sahawneh 1991, Atallah 1992, Ibrahim 1993 and Al Diabat 1999.

According to Figures 4 and 5 four directions of joint orientations are recognized; NNW± SSE, WNW±ESE, NW±SE and NE-SW.

Depending on the work of Quennell and own measurements and observations of joint trends which are given in Figures 4 and 5, the stages of stress can be classified as:

1. First stage WNW-ESE direction.
2. Second stage NW-SE direction.
3. Third stage NNW-SSE direction.

These observations in addition to other structures such as folds, faults, flexures indicate that the same stress field systems produced all these structures. The fractures trend WNW±ESE may be associated with the Syrian Arc fold system that affected the area in Turonian, and the NNW±SSE trending fractures sets are compatible with Dead Sea Stress Field System which is the youngest stress field system which started in Early Miocene, and was responsible for the major deformation process and structural elements in Jordan (Quennell 1956).

4.2.Slickensides

Slickenside's were very clearly observed during the field investigations, their trends and relative directions of movement between the block were measured. Table 2 lists that the NW-SE and NE-SW directions of slickenside are Riedel shear of the first stress field acting in a WNW-ESE direction.

Table 2: Different trends and directions of movement along the slickenside in several locations of Jordan.

Location name	Type of movement	Trend
Ras El-Ain (Naur road), Amman	Dextral	110˚
El Sarrow, (Amman- Salt road).	Dextral	115˚
Kufr Huda , Amman	Sense of movement not clear	180 ˚ and 80˚
Ain Al Basha , Amman	The movement along the inclined layers surfaces with dip 65°	180˚
Anjarah, Ajlun.	Sinistral	20˚
Wadi Mujib	Sense of movement not clear	145˚
	Dextral	90˚
	Sinistral	170˚
Wadi Al Karak	Sinistral	110˚
Ain Sara, Al Karak	Sinistral	20 ˚ and 330˚
Al Hallabat, east of Zarqa	Dextral	135˚
Dhuleil, east of Zarqa	Dextral	100˚
	Sinistral	160˚
East of Jarash about 20 Km	Sinistral	40˚
Zenah, South of Mafraq	Sinistral	180˚
Jebel Nebo area, Madaba	Dextral	120˚ – 135˚
	Dextral	70˚- 80˚
Wadi Himarah, NE of Dead Sea.	Dextral	135˚
Makawer area	Dextral	90˚
Wadi Safsaf near Karak	Dextral	140˚
	Sinistral	45˚
Wadi Al-Hasa	Dextral	125˚ -145˚
	Sinistral	35˚
Umm Dananier, Amman	Dextral	100˚-145˚
Ras En Naqb	Sinistral	10˚
	Dextral	110˚

4.3.Stylolites

The stylolites described here are found mainly in the carbonate rocks of Upper Cretaceous age, with various types and amplitudes. Stylolites characterization in this study depends on the direction of their peaks (teeth) which allows their easy recognition without confusion. Vertical peak stylolites are defined where the peak (teeth) direction is vertical, and perpendicular to bedding planes. Horizontal peak stylolites are defined where the peaks (teeth) direction is horizontal and parallel to bedding planes. Inclined peak stylolites where the oblique peak direction, is between vertical and horizontal peak stylolites (Figure 6).

The previous studies on stylolites in Jordan, concentrated mainly on the tectonically more interesting horizontal peak stylolites caused by horizontal stress.

Beicip (1981) studied the horizontal peak stylolites in the Upper Cretaceous rocks in several areas in Jordan and concluded that there is a relationship between the horizontal peak stylolites and the orientation of stress affecting their areas.

Salameh and Zacher (1982) studied also the horizontal peak stylolites, east of the Jordan Valley and the Dead Sea, they concluded that the area was affected by two stress fields an old system : 130˚ to 140˚ and a younger system 170˚

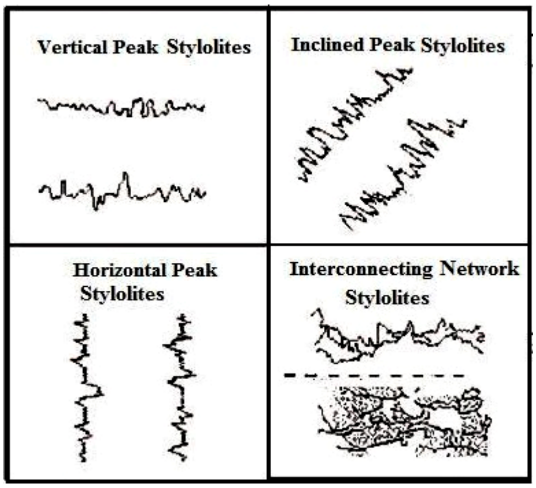

Figure 6. Stylolites classification depending on the direction of the stylolites peak as used in the present study.

The stylolitization of a sedimentary body causes deformation of rocks which changes the shape and reduces the thickness so stylolites accommodate volume reductions of up to 50% in some rocks (Stockdale, 1922). To estimate shortening percentages of deformed rocks due to vertical peak stylolization calculations were made by measuring and adding stylolites amplitudes of peaks and dividing the result by the thickness of the whole rock x100 %. For example in the sample in Figure 7, the sum of stylolite peaks is 8mm while the whole rock measures about 70mm. The vertical shortening ratio is around 11%. About 40 measurements were carried out in several locations near Ajlun and Jarash areas (Figure 8).

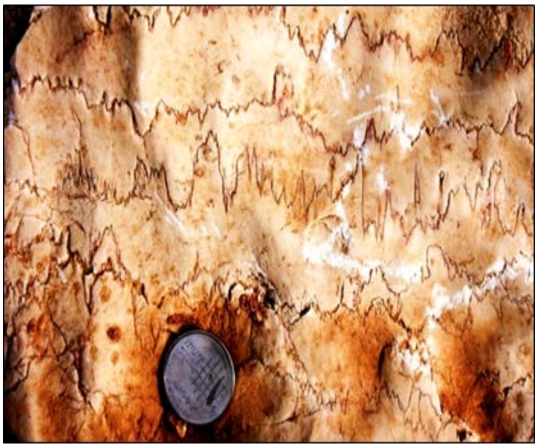

Figure 7. Vertical peak stylolite, sharp peak with high amplitudes, the shortening ratio in this sample is 11% as a result of stylolization (Shtafina area).

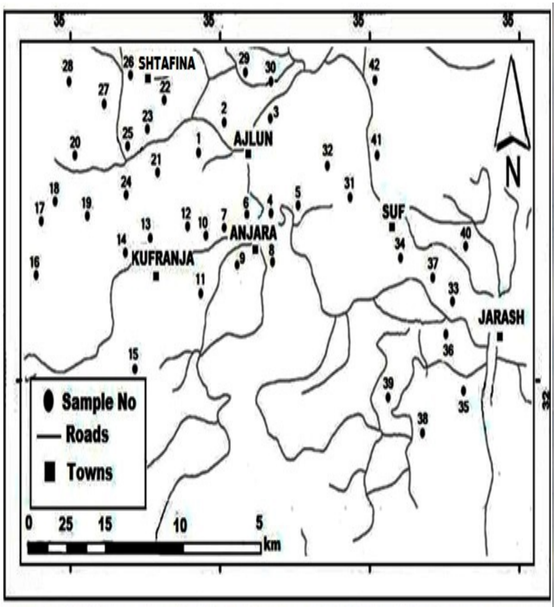

Figure 8. Differentiate stations according of stylolite types, see Table 3 for more explanation.

The results of shortening ratio were calculated in the same way as mentioned in Table 3.

During the field investigation numerous stylolites; vertical, horizontal, interconnected network and inclined, were observed especially, in Shtafina area (Figures 9 and 10).

Figure 9. Interconnected network of stylolites (in Wadi Es Sir Formation Shtafina area).

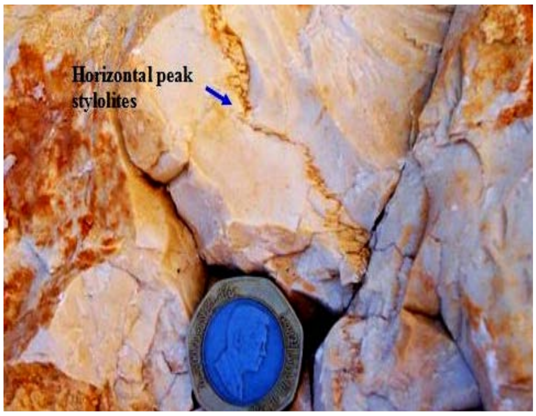

Figure 10. Tectonic (horizontal peak) stylolites cross- cut the bedding surface in the Upper Cretaceous Limestone rocks in Shtafina area. (Bedding is horizontal).

5. Deformed Fossils

The fieldwork revealed several locations were deformed fossils are found in Jordan. These locations show different; lithologies, structural and tectonic elements. Deformed fossils showing brittle and ductile deformation types were collected and described to analyze the forces that affected them. The sites where distorted fossils are found in the Upper Cretaceous rocks in Jordan are described below.

5.1. Site 1 : Shtafina Site

The field observations show vertical, horizontal and oblique deformation of fossils and fossil remains or casts (Figures 11, 12 and 13). Two behaviors of deformation namely, ductile and brittle were observed. Figure 11 shows highly deformed rudists in a limestone rock with crack marks.

Figure 11. Broken and deformed fossils from Wadi Es Sir Limestone Formation (Shtafina site).

These deformed fossils indicate that the deformation affected the fossils and led to the formation of crack marks, which can only take place after the consolidation and lithification processes. This means that deformation in these fossils took place during post lithification stages because of tectonic deformation.

The formation of "mis-shape" of rudists in Shtafina is resulted from compaction loading (Figure 12). Field observation shows also horizontal tectonic deformations in the same site. In this case the maximum compressive stress was parallel to bedding planes.

Oblique deformation can also be observed on deformed fossils in Shtafina site. The deformation of fossils is observed in a NNE-SSW and NE-SW directions (Figure 13).

From the field observations similarity between stylolites peak directions and deformation directions of fossils is recorded. Therefore, it is concluded that the stress field producing the stylolites must be the same one that produced the deformation of fossils. Shtafina site was affected by a WNW- ESE compression stress and NNE-SSW tension stress direction (Al Diabat, 1999 and Al Diabat *et al.*, 2004).

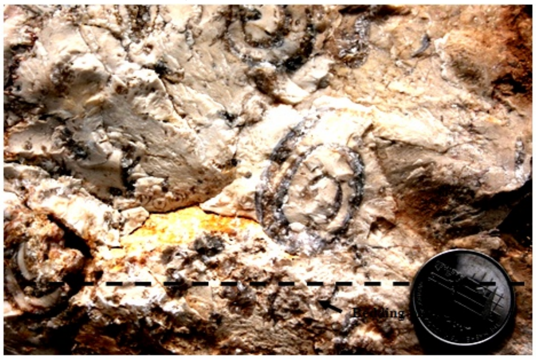

Figure 12. Deformed rudist in Wadi Es Sir Formation (Shtafina site) as a result of compaction processes.

The oblique compression forces between vertical and horizontal as indicated by the oblique stylolites and obliquely deformed fossils are the result of tectonic stresses directed SE- NW or ESE- WNW and vertical stresses due to overburden pressure or to transverse expansion.

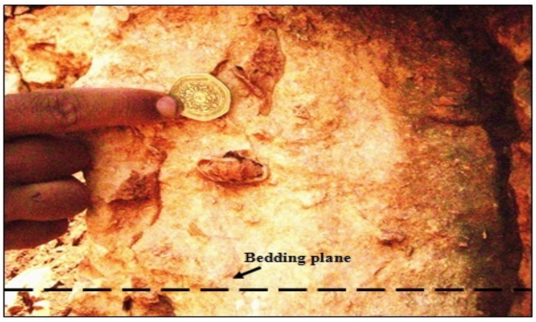

Figure 13. Oblique deformation of fossils in Wadi Es Sir Formation (Shtafina site).

5.2. Site 2: Umm Dananier Site

During the field investigation, the highly flattened and squeezed ammonites resulted from compaction processes and vertical load pressures which are responsible of distortion in their shape. Another field observation is that

the deformed echinoids were affected by ductile deformation, which clearly appeared in change in their shapes as it's observed at Umm Dananier area (Figures 15 and 16,).

Figure 15. Deformed and undeformed regular echinoids (Umm Dananier, near Amman).

Figure 16. Ductile deformation appears on deformed echinoids fossils (Umm Dananier site).

Umm Dananier area was affected by tectonic deformation which is reflected in the deformation of rocks. The major geologic structure in this area is Umm Dananier flexure trending in a NNE- SSW direction. The deformed echinoid fossils have the same composition of the rock matrix. But the deformed rocks do not show their original shapes, contrary to echinoids fossils affected by the same tectonic events.

The deformation of echinoids is observed in a WNW-ESE direction parallel to the WNW- ESE stress field and perpendicular to the trend of Umm Dananier flexure, NNE – SSW.

5.3. Site 3: Jabal Nebo

In Jebel Nebo site different types of distorted fossils such as; bivalves, echinoids, gastropods and corals are found. Field observations show that fossils were subjected to plastic deformation especially bivalves, which is reflected in the change in their shapes (Figure 17).

Figure 17. Deformed bivalves fossils show the movement of a horizontal shear component (shear movement direction represented by arrows) Jabal Nebo site.

During the field work at Jabal Nebo site other deformation elements such as; Fractures, slickenside and horizontal peak stylolites were observed.

The deformed fossils, as mentioned before show shear deformation. This type of deformation indicates that strike slip movements had affected the area.

The major joint set in this site strikes 120˚ – 135˚ and the minor set strikes 70˚- 80˚. Horizontal slikensides trend 120˚-135˚ with dextral movements and 70˚- 80˚ with sinistral movement. Deformed fossils in Jabal Nebo site were affected by the same shear stress fields producing the shear deformation elements within the Upper Cretaceous rocks.

5.4. Site 4: Wadi Mujib Site

The deformed fossils in the area show different directions of deformation in the different types of fossils such as gastropods and echinoids. During the field investigation gastropod fossils from Amman Silicified Limestone Formation were found deformed in Mujib Site. The initial aragonite composition of shells changed and was substituted by silica composition during early diagenesis processes (Bandel *et al.*, 1999). The conical shape of turritella was distorted and became more flattened compared to the original shape of this family of gastropods (Figure 18).

Figure 18. Highly deformed gastropods fossils in the Upper Cretaceous rocks. The fossil impressions are extended horizontally, due to compaction or vertical pressure (Wadi Mujib Site).

The field observations indicate that the deformation of gastropods in Mujib site is the result of vertical load or compaction processes. Consequently, the overburden loading or maximum compression stresses are orientated perpendicular to layering (Figure 18). Irregular echinoids were also found in this site they are deformed in different directions (Figure 19). In Wadi Mujib and Shtafina areas fossils are highly deformed, as a result of the embedding limestone rocks, which are also rigid and competent similar to the fossils material itself.

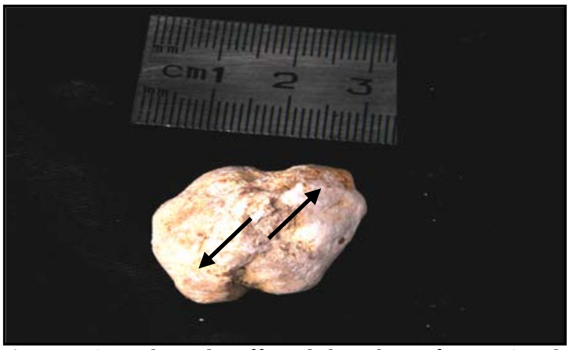

Figure 19: Echinoids affected by shear forces (Wadi Mujib site).

The Mujib area was affected by NW – SE compression forces (Beicip 1981). This force caused two deformation zones and two types of strike slip movements that were recognized in the field as Riedel shear (Table 3).

Table 3. Shortening ratio as measured from stylolization in the different locations of Ajlun and Jarash.

Location	Number Of samples	Shortening %	Maximum amplitudes (mm)	Formation
1	8	3.3	4	A5-6
2	56	3.2	6	A5-6
3	34	3.4	4	A5-6
4	5	1.9	10	A5-6
5	31	3.5	14	A4
6	28	3.8	8	A7
7	17	5.3	5	A5-6
8	4	3.6	14	A5-6
9	5	5.2	5	A5-6
10	23	0.8	2	A5-6
11	9	0.8	2	A4
12	12	0.6	1	A5-6
13	9	3.9	2	A5-6
14	8	1.4	1	A5-6
15	60	11.5	10	A7
16	50	4.7	7	A7
17	38	1.4	5	A7
18	44	3.7	20	A7
19	44	3.1	20	A7
20	14	0.9	4	A7

21	67	3.3	8	A7
22	75	3.6	10	A7
23	31	1.4	5	A7
24	6	3.6	5	A7
25	60	8.8	15	A7
26	5	3.0	5	A5-6
27	7	5.0	3	A7
28	10	0.85	3	A7
29	43	6.5	15	A7
30	3	9.4	7	A7
31	7	4.0	3	A5-6
32	24	4.5	2	A7
33	8	3.5	12	A7
34	40	3.2	2	A5-6
35	3	3.4	6	A1-2
36	11	3.2	2	A7
37	16	2	15	A1-2
38	14	13.0	5	A7
39	17	9.0	4	A7
40	22	1.0	2	A5-6
41	50	3.6	3	A7
42	30	4.0	8	A5-6

The deformation of fossils in Mujib site appears to be a result of shear stress and compaction stress. The vertically compressed gastropods, with expansion in the horizontal direction are certainly the result of compaction or vertical stress. The rock matrix is composed of silicified and crystalline limestone and not much difference are found in the competence behavior of rocks and fossils. Therefore, fossils show partly brittle deformation.

The horizontally compressed and sheared echinoids must be the result of horizontal forces causing the slickensides, strike slip movements and even horizontal peak stylolization in the area.

5.5. Site 5: Jabal Waqf as Suwwan

Different types of deformed fossils and different forms of deformation were found. The more interesting field observations are evidenced on echinoids which originally have circular shapes but were found having elliptical or flattened shape. This allowed the easy recognition of deformation in these fossils and forces direction which produced the deformation of fossils (Figures 20 and 21).

Figure 20. Distorted echinoids in the F/H/S Formation (Waqf as Suwwan site).

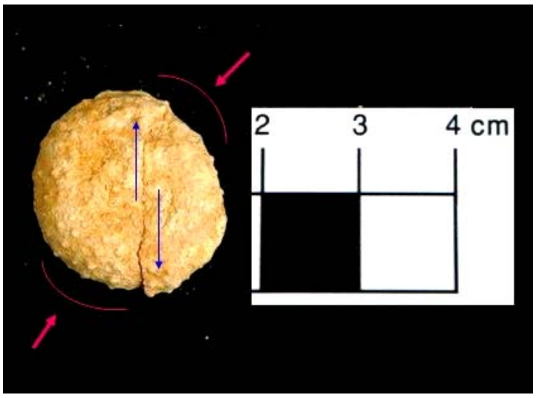

Figure 21. Deformed echinoids showing the displacement (blue arrows) and the shear stresses (pink arrows) that produced them, in F/H/S Formation (Waqf as Suwwan site).

Figure (22) shows the circular shape of a regular echinoid which due to lateral deformation became elliptical. To measure the change in shape it is assumed that no change in volume during deformation of this fossil has taken place (Davis and Reynolds, 1996). So the percent lengthening and shortening of this sample was calculated. The percent lengthening parallel to line A makes approximately 21% and the shortening parallel to line B, or the short axis of the ellipse makes approximately 17%.

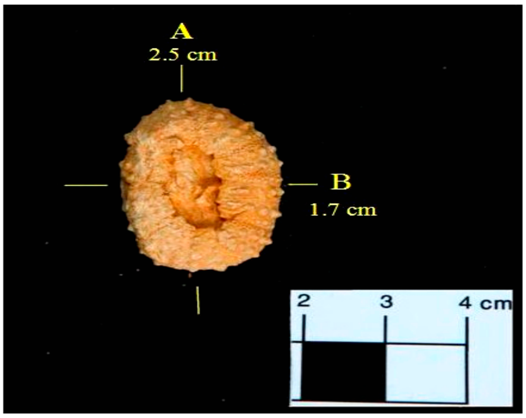

Figure 22. Ductile deformation of an originally regular echinoid in the F/H/S Formation (Waqf as Suwwan site).

Other filed observations reveal brittle deformation evidenced by cracking of samples, Figure (23) shows a deformed fossil with distinguished crack and fractures along the edges of this fossils.

Figure 23. Deformed fossils with crack marks on the surface in F/H/S Formation (Jabal Waqf as Suwwan site).

In Jabal Waqf as Suwwan site strongly deformed rocks were also observed. This originally circular concretion was deformed by the shock wave of the impact. It shows strong brittle deformation and rewelding along shear planes (Figure 24).

Figure 24. Highly deformed chert indicating shear stresses. Fragments were welded (Jabal Waqf as Suwwan impact structure).

The deformation of the fossils mentioned above, is the result of different processes, but mainly because of horizontal stresses affecting the area, which are also responsible for the formation of other structural features.

In Jabal Waqf as Suwwan area, the deformation of fossils is mainly of the brittle type and is referred to the recently discovered meteorite impact structure of the Jabal Waqf as Suwwan (Salameh et *al.*, 2008).

The impact is also made responsible for the shear stresses and crack marks found not only in regular echinoids but also in the area's rocks (Salameh et al. 2008).

As an example of rock deformation by shear stresses, Figure 24 shows the brittle deformation of chert concretion in the area. The same stress field also affected the fossils with distinguished cracks and fractures (Figure 23).

The distorted fossils of Jebel Waqf as Suwwan area are a special case of deformation that is different from those in other areas in their genesis and type of deformation.

Ductile types of deformation appear on bivalves fossils found in this site.

The reduction in thickness of the fossils was caused by the meteorite impact. An overburden of rocks of less than 500 m in that area will surely not cause lithified fossils to deform vertically.

6. Discussion

The Upper Cretaceous rocks of Jordan show a variety of deformation structures, such as folds, faults, Fractures, undulations and stylolites. Most of these structures were studied by authors such as: Quennell, 1951, 1956a, and 1959; Burden, 1959; Ruef, 1967; Bender, 1968; Beicip, 1981; Mikbel and Zacher, 1981**;** Salameh and Zacher, 1982; Atallah 1986; Bender, 1974; Andrews, 1991; Atallah, 1992; Abed, 2000; Al Diabat and Masri, 2002; and others.

As mentioned previously, none of these studies dealt with the deformed fossils in Jordan. Deformation of fossils resulting from tectonic activity can give important clues to be used as a structural geologic tool. The comparison of deformed and non-deformed fossils gives evidence about the type of forces responsible for the deformation, and the directions in which these forces were acting.

The study of deformation depends on how much is known about the original shape and composition of the deformed fossils. The deformations of fossils may be of brittle or ductile types.

The deformation of fossils in the Upper Cretaceous rocks of Jordan is generally the result of two processes:

- Tectonic processes; Represented by horizontally or obliquely distorted fossils. These in themselves are a historic register of stress fields, indicating the type of forces and their direction that lead to the deformation of rocks and fossils.
- Compaction processes due to overburden stress result in loss of volume, as fossils are initially buried, the weight of the overlying sediments linearly compacts the fossils vertically.

The deformation of fossils depends on many factors, including confining pressure, strain rate, and most importantly on the composition of these fossils and their competence relative to the embedding rocks.

Different sites were investigated in the course of this study where deformed fossils were found in the Upper Cretaceous rocks. The field investigations revealed that the deformation of fossils was caused by different forces and directions.

Shtafina study site was affected by tectonic stresses trending WNW- ESE and SE- NW (Quennell, 1959; Al Diabat 1999). The deformation of fossils is also in NNE-SSW and NE-SW directions. So the tectonic deformation of fossils in Shtafina site resulted also from WNW- ESE and NW- SE compression forces.

The field investigation of vertical and horizontal stylolites in association with the deformed fossils gives the evidence that the stress fields, which caused the deformation of fossils, are the same that produced the stylolites.

Highly deformed rudist fossils from Wadi Es Sir Limestone Formation were also observed in this area. They show brittle and ductile deformation types indicating that these deformations occur in post lithification stage, because of tectonic deformation.

Another field observation shows that some deformed rudists in Shtafina area are deformed because of the overburden pressure of the overlying sediments.

The vertically deformed fossils are accompanied with vertical peak stylolites affecting the rocks, indicating the overburden load as a cause of deformations and stylolization.

Horizontal stylolitic peaks serve as an excellent indicator of the stress field causing stylolization. The deformed fossils in Shtafina area show shortenings trends in the same directions of stylolitic peaks. This means that deformed fossils can also be used as a very good indicator on the prevailing stress field.

In Shtafina area where both vertical and horizontal stylolites were found in the same rock, even crossing each other at right angles, the rudists were deformed obliquely in a direction in between that of vertical and horizontal stylolization. Some of these rudists were even deformed beyond their plastic limit and show breakage in their shells in directions corresponding to the resultant vertical and horizontal stresses.

Umm Dananier area was also included in this study, with different forms of deformed fossils. A flatted ammonites fossil in the Upper Cretaceous rocks is believed to have been caused by vertical pressure or compaction processes.

In contrast, the distorted regular echinoids fossils indicate that Umm Dananier area was affected by horizontal tectonic deformation in a WNW- ESE direction perpendicular to the reverse flexure trending in a NNE-SSW direction.

In Jabal Nebo site tectonic deformation was found to affect bivalve and echinoids fossils and to deform them by shear stresses.

The major fractures trend in this site is 120˚-135˚ and the minor trends 70˚- 80˚. Horizontal slikensides indicate that the types of movement were in 120˚-135˚ with dextral movement and 70˚- 80˚, sinistral movement.

Horizontal stresses in the area were responsible for the formation of the structural features and it is the same causing the deformed fossils also.

In Jabal Waqf as Suwwan area; East Jordan, where the meteoric impact structure was found (Salameh et *al.*, 2008), deformed fossils were found in the Upper Cretaceous rocks. Both vertical and horizontal deformations were observed.

These deformed fossils show also distinguished cracks and shears, because of the meteoric impact. These distorted fossils gave good evidence that the area was affected by shear stresses resulting from the shock waves leading to horizontal compression.

Vertically the deformed fossils in the central uplift of the impact site indicate high vertical pressure resulting from the impact event with vertical to subvertical pressure.

Horizontally deformed echinoids are mainly found on the eastern outside of the inner ring. As mentioned above they show both change in shape from circular to ellipsoidal and shear along cracks.

Finally, in Wadi Mujib area silicified gastropods fossils from the Amman Silicified Limestone Formation, are found squeezed, flattened and deformed vertically.

The deformation seems to be the result of gravitational loading during last stages of diagentic compaction which could lead to deformation of non-tectonics origin, where the maximum shortening occur perpendicular to the bedding plane. In this location here rocks and fossils are composed of the same minerals and hence the same competence behavior of both.

Tectonically, deformed fossils are found as irregular echinoids in Wadi Es Sir Formation. The tectonic event that affected Wadi Mujib area, responsible for the deformation of the Upper Cretaceous rocks must have also deformed the fossils found there. The deformation is the result of the compression and the deformed echinoids show compression and shear fractures. Beicip (1981) concluded that the area was affected by NW – SE compression. This compression is reflected in the deformation of echinoids, resulting in their change in shape and distortion.

7. Conclusions

- The results of this study show that deformed fossils form very good indicators on the deformation stress affecting the rocks they are embedded in.
- The deformed fossils with a merely change in shape can be used as a very good indicator of the stress fields leading to the deformation of rocks and fossils contained in these rocks.
- Sheared fossils with relative movements indicate to the prevailing stress and the type of horizontal movement, sinistral or dextral.
- Rocks, especially when homogenous do not always show deformation features or horizontal peak stylolites, but if these rocks contain fossils, the deformation appears on the fossils, especially when the rock matrix is competent and transfers stresses to the fossils.
- Echinoids which originally have circular shapes show elliptical shapes after deformation indicating the prevailing stress field directions which led to the deformation.
- The original circle shape of regular echinoid fossils, which due to deformation became elliptical makes it easy to calculate the percent lengthening and shortening when as commonly assumed that no change in volume during deformation had taken place.
- Deformation of fossils in Shtafina site was parallel, oblique and perpendicular to bedding planes indicating at horizontal and vertical pressures and their resultants.
- In Shtafina area, the fossils were tectonically deformed with NNE-SSW and NE-SW directions, which indicate to stress fields in WNW- ESE and NW-SE directions. These are the same directions of horizontal stylolitic peaks.
- Vertical peak stylolites are used to calculate the shortening ratio of rocks, and the fossils contained in them.
- Deformation of bivalve's fossils in Wadi Mujib and Jabal Nebo shows horizontal displacement of the two valves, which indicate to shear stress.
- Highly deformed and squeezed gastropoda fossils in Wadi Mujib site show that the maximum

compressional stresses were perpendicular to bedding planes which is resulted from loading pressure.

- The meteoritic impact in Jabal Waqf as Suwwan is made responsible for the shear stresses, compressional stress and crack marks which appear on the deformed fossils in this area.
- The deformation ratio of the fossils depends on the relative competence properties of fossils and rocks.
- Ductile and brittle deformations were recognized in the different studied sites and in different fossils types indicating the relative behavior of rocks and fossils and their relative competence to deformational stresses.

8. Recommendations

For our case in Jordan, a well-studied area in the context of its structural geological features and the stress fields causing the structures, fossil deformation seems to form an integrative evidence to stress field recognition.

Therefore, it is highly recommended to study older geological formations than Upper Cretaceous on their deformed fossils, to shed light on the stress fields, which must have prevailed during the Pre-Cretaceous periods, especially, because the tectonic forces affecting Jordan in Pre-Cretaceous periods are not well established.

Deformed fossils can contribute to the understanding of the tectonic forces and the prevailing stress field during the different geologic eras not only in Jordan but also elsewhere. The study of deformed fossils in the other parts of the country as well as the other types of deformed fossils present in the different geologic sediments may reveal important information on the development of stress field and their evolution. The inner structures of deformed and undeformed fossils are of utmost importance for the completion of the accomplished study and other related studies.

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