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Post-Cretaceous Mesostructures and Their Formation Mechanisms, Jordan

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Abstract

In the current work, a variety of deformational mesostructures (tectonic and nontectonic) in the Upper Cretaceous rocks of Jordan are described and attempts have been made to explain their textures, formation and the mechanisms of development. The structures include: undulations, brecciated chert, slickensides, nodules of limestone, deformed fossils, boudinage, geodes, stylolites, flow channels and flowage structures.

These structures have been described in previous studies with no correlation to the factors responsible for their formation. In this article, three types of deformation forces or a combination of them are ascribed for these structures: stress fields acting in ENE-WSW, NW-SE and NNW-SSE directions, shock waves produced by earthquakes or meteoritic impacts, and compaction resulting in density inversion and over-pressurized groundwater.

Keywords: Deformation structures, geodes, undulations, flowage structures, slickensides, stylolites and boudinage structures.

1. Introduction

The Late Cretaceous deposits in Jordan hold different lithological, paleontological and mineralogical layers from detrital to carbonate rocks changing into chalky rocks at the end of this period. The area where these rocks are found has been strongly affected by sea level fluctuations and tectonic movements reflected in the sedimentary deposition and structural geology. The deformation rate of the rocks depends on many factors, including lateral stress fields, confining pressure, temperature, stress rates, and most importantly competence-incompetence behavior of rock materials (Means, 1976; Earle, 2015). The Upper Cretaceous deposits are found distorted in many areas in Jordan and the deformed structures are considered to represent a record of the history of the area related to the paleostress fields that caused the deformation. Rock deformation can develop during deposition or shortly after burial but before the sediment was lithified or cemented. On the other hand, deformation can be the result of post-deposition processes, usually associated with tectonic activity, earthquakes, shock waves, and differential load pressure. The present work is organized to introduce a variety of deformation structures in the Upper Cretaceous rocks in Jordan and study their relationship to tectonic and non-tectonic deformation. Each of the deformation structures is discussed individually below.

1.1. General Geological and Tectonic Overview of Jordan

The history of Mesozoic deposition in Jordan reflects the Tethys Sea level fluctuations and its relation to the geological development of the Arabian Plate. In Jordan, the Cretaceous deposits comprise three lithostratigraphic groups: the Kurnub, the Ajlun and the Balqa Groups which are bound and divided by regional unconformities (Powell 1989; Powell et al., 1996; Flexer et al., 2005).

Generally, most of the deformation structures investigated in this study are found in the Upper Cretaceous rocks from Ajlun and the Balqa Groups. Late Cretaceous sediments are exposed almost all over Jordan from the north of Irbid to the south of Ras en Naqab escarpment (Fig. 1a). During the Cenomanian and Turonian, the Ajlun Group was deposited when Jordan was located at the northwestern margin of the Arabian-Nubian shield, comprising Formations: Na'ur Limestone, Fuheis, Hummar, Shueib, and Wadi (As)-Sir Limestone (Burdon, 1959; Bender, 1974; Powell, 1989) (Fig. 1b). The thickness of this group increases towards the north with maximum reaching about 600 m in Irbid and decreases in the southern part of Jordan (Powell, 1989). The depositional environment of this group is shallow marine mainly depositing limestone with intercalated clay, marl and gypsum beds from Shueib Formation (Powell, 1989; Bandel and Salameh, 2013).

The Ajlun Group is covered by Balqa Group, which is composed of chalk, chert, marls, and phosphorites reflecting changes in the chemistry and temperature of the sea in Coniacian time (Bandel and Salameh, 2013). The Formations included in this Group, from older to younger, are: Umm Ghudran Formation, Amman Silicified Limestone Formation with much chert (Santonian and Campanian), Ruseifa Formation with much phosphatic sand (Campanian), and the Muwaqqar Chalk Marl Formation (Maastrichtian) at the top (Bandel and Salameh, 2013).

Umm Ghudran Formation is characterized by chalk-rich sediments covering most of Jordan's territory. In the south-

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east carbonates grade into fluvial sands and clays. Phosphates were deposited during the Campanian where the Tethys Sea had been rich in organic matter with oyster bioherms (Powell, 1989). The paleo-climate during the Cretaceous according to Francis and Frakes (1993) was characterized by a cold and warm climate as follows: Albian, warm; Cenomanian, cold; Turonian, cold; Coniacian, warm; Santonian, cold; Campanian, cold and Maastrichtian, cold.

Jordan was part of Gondwanaland when that land fragmented into smaller plates one of which is the Arabian- Africa Plate. The Syrian Arc represents a fold-thrust belt which extends from NW Sinai through the Jordan Rift Valley northward to Central Syria, which was active during the Coniacian - Miocene, and is still today (Chaimov et al., 1992; Diabat, 2009). As result of the Syrian Arc compressive stresses with E-W to ESE-WNW, the Shueib Structure and the Amman-Hallabat Structure were formed (Mikbel and Zacher, 1981; Diabat, 2009) (Fig. 2).

Furthermore, a very strong tectonism affected the area creating the Dead Sea transform fault with the N-S/NNE-SSW trending Wadi-Araba-Dead Sea-Rift system. This was initiated with the beginning of the spreading process at the Gulf of Aden during the Late Miocene causing the northward movement of the Arabian Plate, which has been existent since then (Bender 1968, 1974). Along the Dead Sea Transform Fault system, a sequence of pull-apart basins (Gulf of Aqaba, Dead Sea, Lake Tiberias), interrupted partly by transpressional segments, were formed in the consequence of the sinistral transform movement which has caused until today a lateral displacement of Jordan of around 110 km to the north compared to the Sinai-Levant Sub-plate (Quennell, 1959; Freund et al., 1968; Garfunkel, 1981; Bandel, 1981). The rift system is filled by sediments of mid-Miocene to recent ages (Andrews, 1992; Alhejoj, 2013). Regional tectonic and structural elements are studied by Burdon (1959), Salameh and Zacher (1982), Atallah (1992), Diabat et al. (2004), Diabat (2009, 2013, 2015), and others. Eyal and Reches (1983) and Eyal (1996) studied tectonic analysis of the Dead Sea Rift region since the late Cretaceous based on mesostructures in Palestine and Sinai, and identified two tectonic stress fields, each relatively uniformed in both time and space. One stress field, is the Syrian Arc stress with a dominating maximum horizontal compression trending W to WNW, in the Late Cretaceous to Eocene rocks in the folds and plateaus west of the Dead Sea rift. The second field, is the Dead Sea stress with a dominating horizontal extension trending E to ENE.

Few studies on paleostress were carried in the eastern side of the Dead Sea Transform (DST). The first study was carried out by Zaineldeen et al. (2002). Eight paleostress tensor groups (stages) have been identified from their study, ranging from the Late Neoproterozoic to the Holocene period, and have been correlated with the tectonic evolution of the Dead Sea Rift. Diabat et al. (2004) studied the paleostresses at the eastern rim of the DST. Their results summarize the stress field east of the DST in two compression stress systems, namely the NNW-SSE Dead Sea System (DSS), and the Syrian Arc System (SAS) with a stress field in NW-SE direction (Fig. 2). Al Khatib et al. (2010) measured fault slip data in the Upper Cretaceous (Turonian) rocks of Northern Jordan. The orientation of the studied paleostress showed E-W to WNW-ESE compression, and N-S to NNE –SSW extension associated with the formation of the Syrian Arc fold belt which started in the Turonian. Another paleostress has NW-SE to NNW-SSE compression and NE-SW to ENE-WSW extension related to the Dead Sea transform system. Recently, Al Hseinat (2009) has studied the relationship between the formation of the Wadi Shueib fold-belt and the Dead Sea Transform based on anticlines, synclines, monoclines, flower structure, and thrust fault structures. He stated that the formation of the Wadi Shueib Structure is a contraction horsetail formed due to the termination of the Wadi Araba sinistral strike-slip fault.

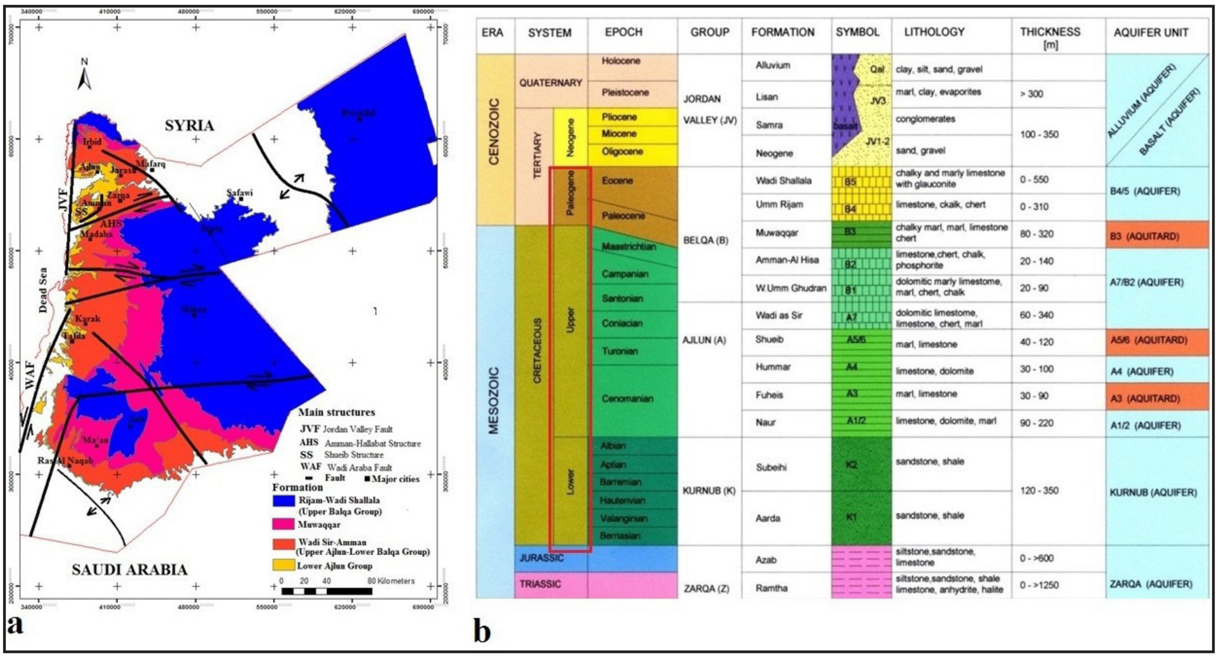

Figure 1. a, Simplified geological map showing the outcrops of Upper Cretaceous Formations and the main structural features in Jordan based on NRA maps (NRA open files) (Jordan Transverse Mercator Projection, JTM). **b**, Sequences of Triassic to Recent lithostratigraphic units in Jordan (Mc Donald and Partners, 1965; Bender, 1968; NRA open files).

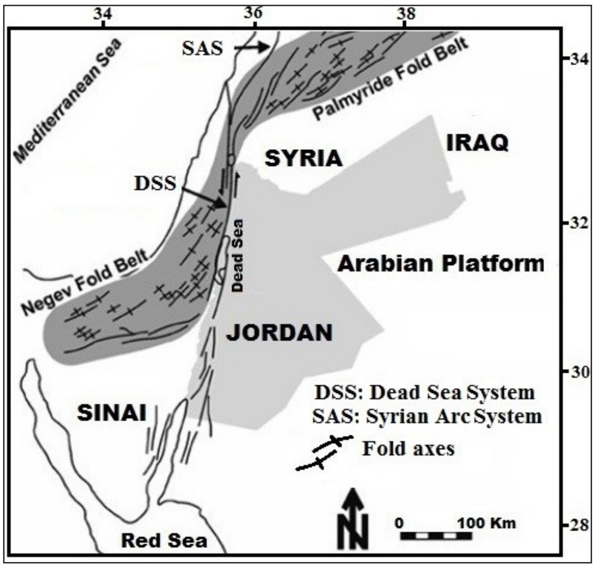

Figure 2. Major tectonic setting of the Dead Sea Transform and the Syrian Arc, in the north-western part of the Arabian plate (modified after Chaimov et al., 1992).

2. Methodology

This work is based on field observation, measurements, and literature review of mesostructures and their formation mechanisms in general and data in the literature about their presence in Jordan. The stress fields which have been active in Jordan since the Upper Cretaceous times are well-known and documented in the geologic literature on Jordan, especially in Burdon (1959), Quennell (1959), Bender (1968), Zaineldeen et al. (2002), and Diabat (2004).

The interpretation of the mechanisms and forces leading to the formation of the different structures is based on field mapping (Fig. 3), measurements of structure and advances in tectonic explanations of deformation.

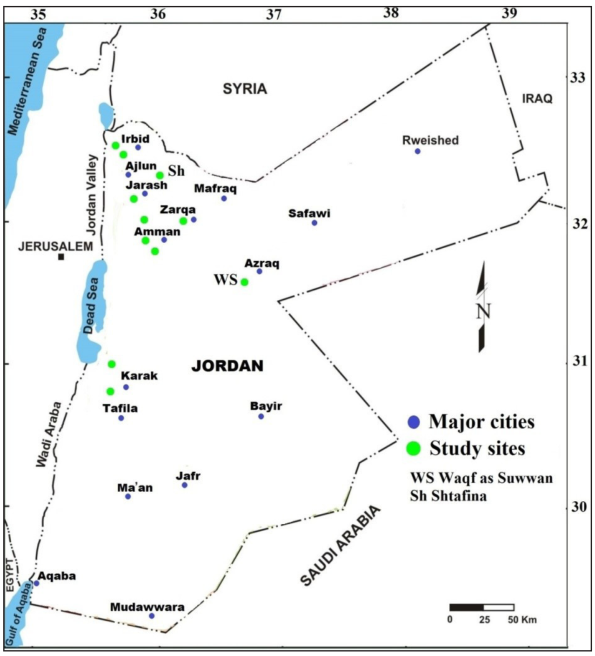

Figure 3. Location map of sampling and measurement sites.

3. Description of the Deformation Structures

3.1. Silica Geode Structures

Geods have a spherical to oval shape with varying diameters between 2cm- 50 cm and are often found in limestone or dolomite beds. In a dolomite bed of the Na'ur Formation at a distance of about 3 km to the north of the University of Jordan, silica geodes were found. Geods are restricted in distribution to an area of about 5000 m² , and are present in one dolomite bed of 1m thick in the middle part of the Formation which is 230 m thick. In a lateral extension, chert lenses and layers are distributed vertically in a range of a few meters in the underlying and overlying limestone beds of the dolomite bed. This structure observed in the south of Ma'an area is chalky limestone and sandstone layers from Wadi Umm Ghudran Formation. They are usually filled with fine- grained quartz crystals (Fig. 4a).

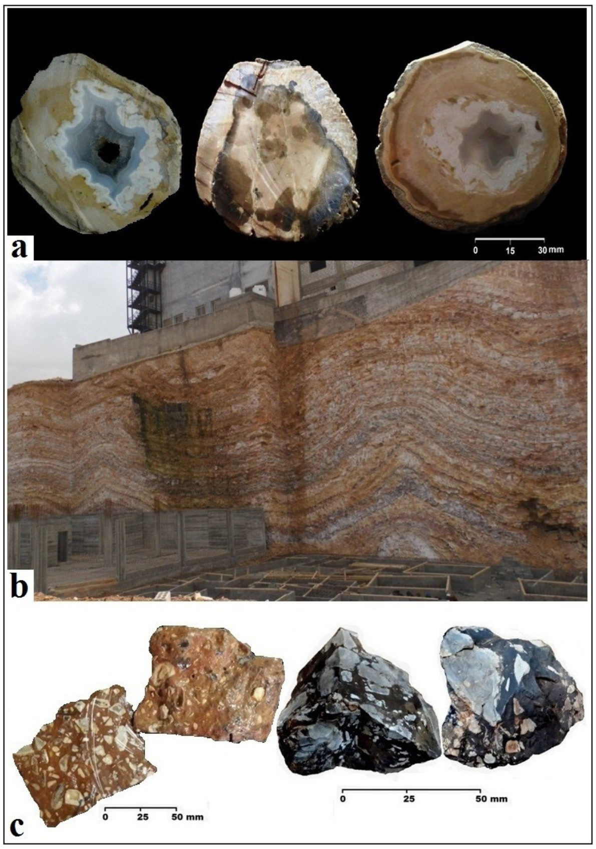

Figure 4. Different deformation structures from the study area, **a**. Spherical and semi-spherical silica geods filled with quartz crystals from Na'ur Formation, North of Amman area, 3km north of the University of Jordan, **b**. Undulations in the Amman Silicified Limestone Formation exposed along Amman – Zarqa, **c**. Chert breccias rocks from Amman Silicified Limestone Formation, Ajlun, Shtafina area.

3.2. Undulation Structure

In the highlands of Jordan extending from Irbid in the north to Karak in the south, the Amman Silicified Limestone Formation shows undulations (folding, disharmonic folding) (Fig. 4b). This Unit, of the Campanian– Maastrichtian age, is composed of chert beds, each a few mm to one meter of thickness. They alternate with silicified limestone, marl, and silicified phosphate beds, the latter increase upward. The thickness of the Unit can reach 140 m, but in average it is 60 – 70 m (Ruef, 1967). The different chert beds show generally no change in their thicknesses on a scale of kms. But the chalk and marl beds thicken in the fold troughs, and are thin along the flanks. According to Ruef (1967), the cherts are composed of 93 % SiO_2 and about 2 % H_2O. All the chert layers show internal brecciation with very sharp grain edges embedded in a very fine groundmass composed of SiO_2.

The number of undulation reaches thousands, while the overlying and underlying marl and marly limestone rocks of the Amman Silicified Limestone Formation show no undulations at all. The amplitudes of undulations range from decimeter to about 10 m. Undulations are generally convex structures. Concave undulations are very rare. The areal distribution of the undulation is irregular. The strike direction of the undulation axes range from 150˚ to 210˚ (330˚ - 30˚) fluctuating around the N–S direction. Generally, the undulation axes plunge to the north with small varying degrees of up to 15˚ (Table.1).

The verging of undulations (inclination axial surfaces) is generally towards the west. Thickening and thinning of folded beds are present in the less competent, gliding-mobile beds of chalk marl and are almost absent in the chert beds. Thickening is, as expected, found in fold troughs and crests, and thinning along the fold flanks.

Table 1. Field measurements of strikes of horizontal stylolite's peaks, slickensides surfaces with horizontal movements, undulations folding axis and shortening directions in fossils in the different sites in Jordan. In addition hundreds of measurements are found in the literature e.g. Ruef (1967), Salameh and Zacher (1981). For locations refer to Fig. 3. (NF, not found)

Site	Stylolite	Slickensides	Undulations	Deformed fossils
Maan	NF	340˚-20˚ (16) 60˚-75˚ (11)	340˚-10˚ (8) 80˚-90˚ (3)	NF
Karak	352˚-10˚ (25) 115˚-140˚ (12)	330˚-10˚ (27) 70˚-80˚ (12)	350˚-40˚ (25) 70˚-80˚ (10)	N-S
Mujib	350˚-360˚ (3) 110˚-118˚ (12)	350˚-20˚ (24) 65˚-80˚ (12)	0-26˚ (21) 70˚-82˚ (12)	N-S and E-W
Jiza	NF	350˚-10˚ (22) 80˚-85˚ (9)	350˚-112˚ (18) 70˚-72˚ (6)	10˚-20˚ and 70˚
Madaba	350˚-10˚ (17) 115˚-120˚ (8)	350˚-18˚ (33) 70˚-88˚ (8)	15˚-26˚ (17) 90˚-0(6)	N-S and 115˚
Amman	360˚-15˚ (6) 115˚-125˚ (13)	355˚-22˚ (28) 74˚-86˚ (17)	10˚-25˚ (61) 75˚-84(12)	N-S and 120˚
Ajlun	355˚-10˚ (21) 110˚-140˚ (8)	330˚-10˚ (26) 70˚-80˚ (6)	10˚-18˚ (12) 80˚-83˚ (6)	N-S and 115˚
Irbid	350˚-6˚ (16) 120˚-125˚ (3)	350˚-30˚ (18) 70˚-83˚ (6)	5˚-20˚ (32) 80˚-85˚ (8)	N-S and 125˚
Azraq, Hallabat & Waqaf as Suwwan	10˚-12˚ (3) 120˚-130˚ (4)	10˚-20˚ (8) 90˚-100˚ (4)	NF	N-S and 120˚-125˚

3.3. Brecciated Chert

The Amman Silicified Limestone formation does not only show undulations (disharmonic folding), but in addition, its chert beds are strongly brecciated (Fig. 4c). Angular fragments of chert which range in size from a few mm up to 10 cm are sharp – edged without any sign of roundness or even weathering and with no special spatial orientation.

The brecciation is strictly confined to chert beds, and it is evenly distributed between troughs and flanks of folds and along not folded chert layers. The brecciated chert lies in a groundmass of silica SiO_2 of a supposedly younger formation age.

3.4. Deformed Fossils

For a long time, the deformation of fossils has been considered as a significant structural geologic tool, caused by tectonic activity. Such deformation can give important clues on paleo-stress fields and their directions (Sharp, 1847; Breddin, 1956). The comparison of deformed and non-deformed fossils gives evidence about the type of stresses responsible for the deformation, the directions in which these stresses were acting, and the magnitude of the stresses causing them.

In Jordan, different groups of fossils are found deformed in the Upper Cretaceous rocks (Figs. 5a, b). These are widely distributed in Ajlun (Shtafina) (Fig. 5c), Umm Dananier, Wadi Mujib and Jabal Waqf as Suwwan areas as discussed by Alhejoj et al. (2013). Two types of deformation are noticed in the fossils of these areas: ductile and brittle. In the ductile deformations, fossils are found compressed in one direction and expanded in the other direction perpendicular to the first with different shortening or expansion ratios based on the composition of the fossils, the stress field type, its strength, and the relative rheological behavior of the embedding rock and fossil materials. The brittle types of deformation are also present with some fossils showing shear with very prominent shear surfaces as can be seen on the deformed fossils of Jabal Waqf as Suwwan which are also rewelded along the shear planes.

3.5. Slickenside Structures

Slickensides refer to striated, polished rock surfaces of deformation structures along the shear zone movement. They are developed on vertical and inclined to horizontal rock discontinuity surface, and are very common in the Late Cretaceous rocks in Jordan (Fig.6). On a vertical and inclined rock surface, horizontal slickenside movements are both sinistral and dextral. Sinistral slickensides are generally found on rock discontinuity surfaces striking NNW –NNE (330˚ – 30˚) mostly (350˚ – 20˚), whereas dextral slickensides developed on surface strikings ENE – ESE (60˚ -120˚) but mostly (70˚ -100˚)(Table 1).

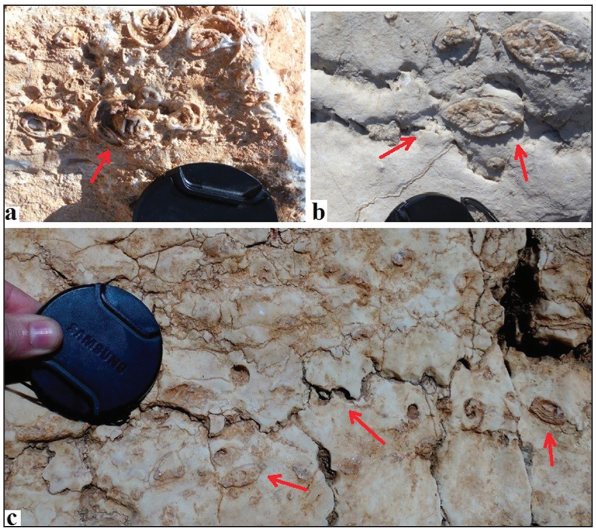

Figure 5. a. Broken fossils from Ajlun area, **b**. Deformed fossils of gastropods (original shape rounded) associated with vertical peak stylolites in Ajlun area, **c**. Deformation of gastropod fossils found together with stylolites from Wadi-Sir Formation in Shtafina area, Ajlun. (Arrows refer to the deformed fossils and stylolites structures).

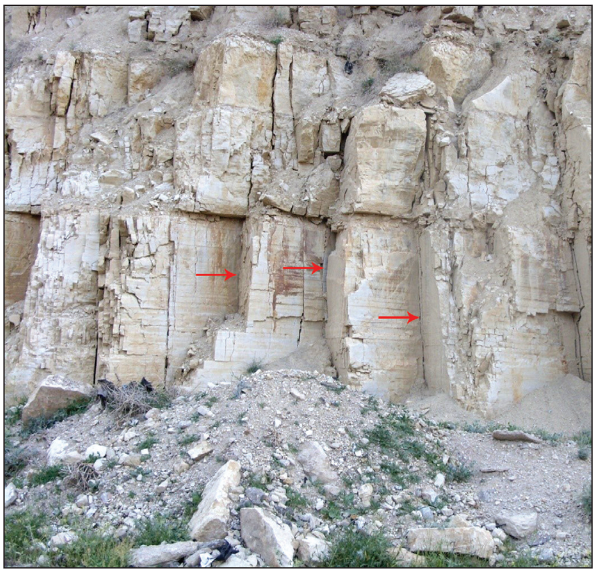

Figure 5. Slickensides in the Upper Cretaceous rocks in Zarqa-Hallabt area (arrows indicate the movement direction).

3.6. Stylolite Structures

Stylolites are secondary structures with a tooth-like shape. They form due to a pressure–solution process affecting mainly sedimentary rocks (Park and Schot, 1968). Stylolites can be classified into sedimentary stylolites and tectonic stylolites. Sedimentary stylolites (Vertical– peak stylolites) are overload structure thought of to be formed during the rock diagenesis (lithostatic pressure), while tectonic stylolites are produced by tectonic processes, and can be used as indicator of paleostress directions (Fabricius and Borre, 2007; Ebner et al., 2010).

Two main types of stylolites are found in the Upper Cretaceous carbonate rocks in Jordan in the form of: horizontal peak stylolites (H–peak stylolites), and vertical peak stylolites (V–peak stylolites) (Fig. 7 and 8a). Oblique stylolites are also observed in the Ajlun area (Fig. 8b).

Stylolites are mainly observed in Wadi-Sir and Hummar Formations which are, to a great extent, composed of almost pure limestone (Fig. 8c). These stylolites are well- developed in the above-mentioned rock Formations, and their peaks may reach a few centimeters in height (Figs. 8d,e).

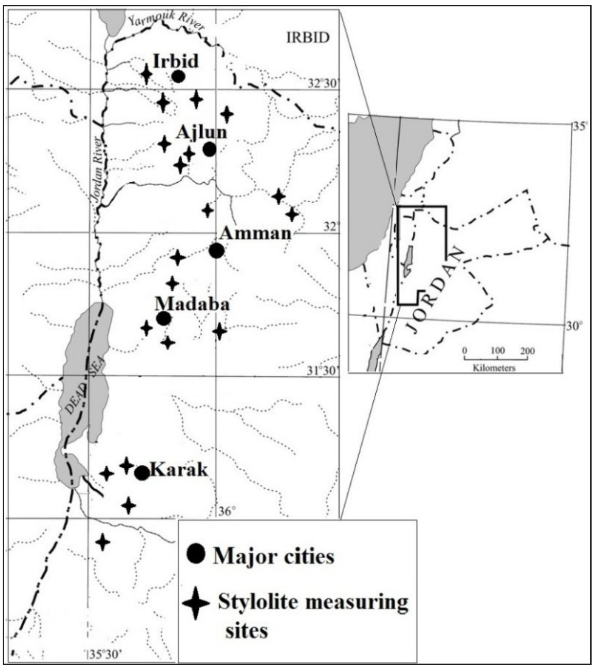

Figure 7. Stylolite measuring locations.

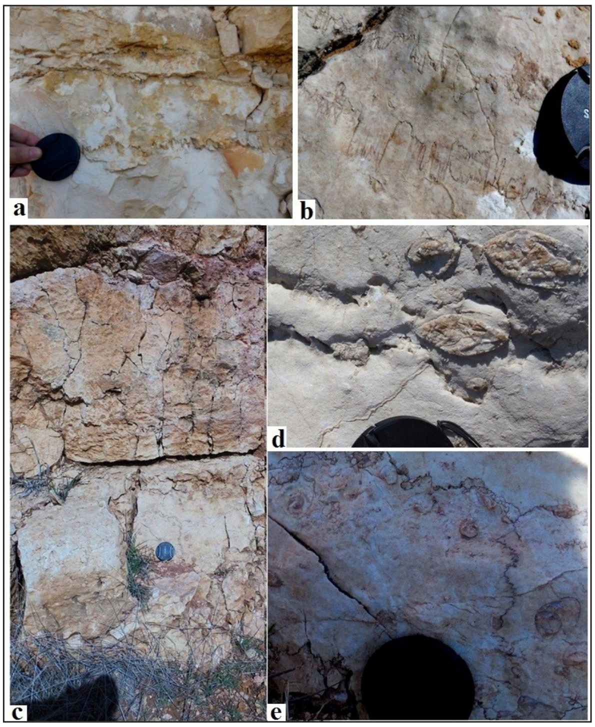

Figure 8. Studied stylolites from Ajlun area, **a**. Vertical-peak stylolite in Wadi-Sir Limestone Formation, Ajlun, **b**. Oblique stylolite in Wadi-Sir Limestone Formation, Ajlun, **c**. Horizontal- peak stylolites in Wadi-Sir Limestone Formation, **d**. Deformed fossils and the stylolites have the same stress field, Wadi-Sir Limestone Formation in Ajlun area, **e**. Close-up of figure (8c) showing tectonic stylolites associated with deformed fossils, Ajlun.

3.7. Flowage Structures

Early Cretaceous sandstones underlie the calcareous Late Cretaceous rock sequences in Jordan (Fig. 9a, b). The transition beds between them are about 10 m thick and consist of marls, clays and silty marls with a density of about 2.30 g/cm^3 and a permeability of about 10^{-7} to 10^{-8} m/s compared to that of the underlying almost pure sandstone (about 1.92 g/cm^3 and 5x 10^{-5} m/s) (Salameh and Udluft, 1985). The transition zone shows a variety of density inversion structures such as the boulders of sandstone which have moved a few meters upward into the marly clayey higher density rocks and vertical flow channels that are up to 20 cm wide and filled with sand, along which the friable to semi-consolidated sand of the Early Cretaceous had moved upwards through the transition zone into the Late Cretaceous rocks or through them to the ground surface (Al-Saqarat, 2009). This structure is clearly exposed in Ajlun area and along Irbid road (Fig. 9c,d).

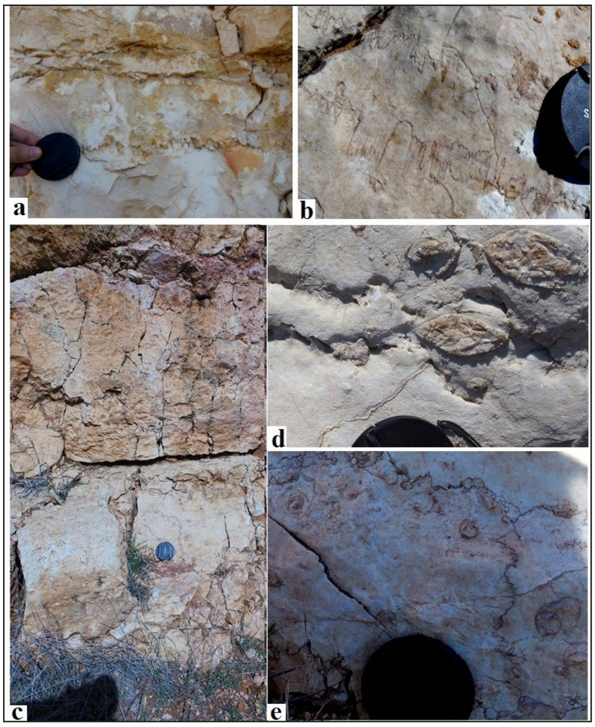

Figure 9. a, Horizontal clay flowage structure in between two hard rock beds of limestone; Ajlun, **b**. Close- up of clay flowage structure between hard blocks of Wadi- Sir Limeston Formation, **c**. General view of clay flowage from Wadi-Sir Limestone Formation in Ajlun area, **d**. Horizontal clay Flowage appears at Irbid city main road.

3.8. Nodular Limestone

The term nodular limestone has been used to include several types of textures that are of genetically different origins. In general, nodular limestone forms by the precipitation of amorphous silica, in the case at hand from spicules of sponges or debris of radiolaria and the post depositional replacement of either the enclosing limestone or chalk by this silica (Boggs, 2009).

Small, irregular rounded and sub-rounded pieces of chert nodules are found within some limestone beds of the Upper Cretaceous rocks of Jordan (Fig. 10).

Figure 10. Nodular limestone in Wadi-Sir Formation as exposed along the Dead Sea road, near Na'ur town.

3.9. Boudinage Structures

Boudinage structures are found in the Upper Cretaceous chert rocks of Jordan. The structure consists of cylinder-shaped pieces of rocks building together thin to thick layers mostly found in the chalky limestone of the Umm Rijam and Shallala Formations, but also in other formations, such as Al-Hisa Phosphorite Formation.

The chert pieces, over- and underlain by the soft rocks of chalky limestone, must originally have built continuous beds of chert, which were then disintegrated into pillow-like pieces. It seems that the incompetent chalky limestone beds reacted to the overburden vertical pressure by flowage, and the rigid competent chert beds reacted by disintegration into pieces. Dissolution of the edges of the chert pieces and borders took place afterwards by the descending water, and their real location changed by pressure and flowage of the chalky limestone components.

Field observation shows that boudinage affects a single layer of chert as a result of its extension in a direction parallel to itself. The boudinage breaks up the layer into a series of discrete segments, each showing a barrel-shaped cross-section, separated from one another by a narrow neck of rock (Fig. 11).

This structure is also found in phosphorite deposits of Al-Hisa Phosphorite Formation, especially in the southern part of Jordan (Fig. 12). The Formation is given Campanian to Maastrichtian age (Bender, 1974). Muwaqqar Formation is of Maastrichtian to Paleocene age (Bender, 1974; Bandel and Salameh, 2013).

Figure 11. Boudinage chert layer bounded by soft chalk layers from Muwaqqar Formation in northwestern Irbid near Al Maqarin area.

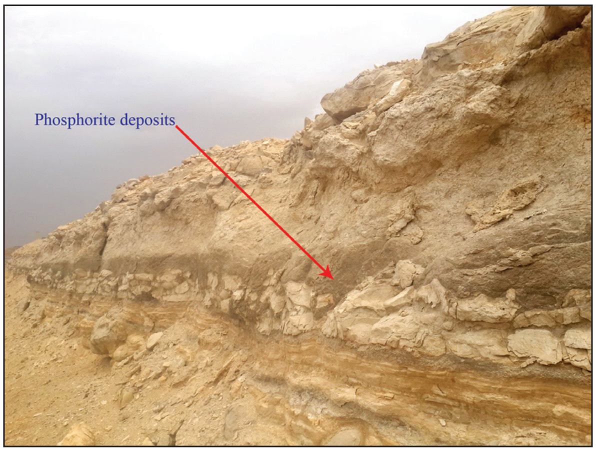

Figure 12. Deformation of phosphorite layer of Al-Hisa Phosphorite Formation is exposed along the Kings Highway, south of the Karak area.

2. Discussion of the Deformation Mechanisms

In the calcareous Late Cretaceous rock sequence in Jordan, a variety of meso structures are present, such as vertical, horizontal and network stylolites, horizontally deformed fossils, slickensides, flow channels, density inversion, undulations among others.

Such structures of tectonic and non-tectonic origins may be used to define the stress fields affecting the rock sequences as well as the type and nature of the stress fields.

Silica geode structures were studied by Salameh and Schneider (1980). The external diameter of the concentrically structured geodes ranges from 8 – 18 cm. Generally, the outer layer is 1 – 3 cm thick, and is composed of silicified dolomite like the host rock. Inwards follow several layers composed of chalcedony, in some geodes alternating with quartz layers. Well crystallized quartz is frequently found inside the geodes.

The structure of the geodes indicates an organic origin, most probably sponges. Hence, the organic matter had influenced the chemical condition of silica precipitation in the geodes. These formations are considered a result of the embedding of the organic matter of sponges in the carbonate sediments of a shallow marine environment to be followed by early diagenetic dolomitization of the carbonate by magnesium – rich pore water in the intertidal environment. After that, opal precipitated from the pore water around the skeleton of organisms. In some cases, the soft silica shrank, and was brecciated (Bandel and Salameh, 2013).

The formation of these geodes and their partially fragmented (brecciated) inner rings are referred to early diagenetic processes accompanied by shrinkage of the still soft silica gel as a result of crystallization and aging.

Because the brecciation of the geods only affects the intermediate and outer chert layers, it can be concluded that a shockwave, during that stage of silica deposition, affected the rocks. After that shockwave, the precipitation of quartz continued filling the geods. Geods totally filled at the time of the shockwaves are, as a whole, brecciated.

In southern Jordan, Makhlouf et al. (2015) studied the quartz geods from the Upper Cretaceous Wadi Umm-Ghudran Formation and stated that their silica composition comes from the weathering of the Amman Silicified Limestone Formation and the infiltration of chemical products by the action of groundwater.

The undulation structure of Amman Silicified Formation was discussed by Ruef (1967). After a rigorous study of the undulations in the Amman Silicified Limestone Formation, he concluded that tectonic forces have to be excluded as initiators of the folding. He favors E-W directed gravity movements (syn-sedimentary gliding) of the mobile sediments, where silica and limy layers served as a means of gliding. According to Ruef , the gravitational movements were intensified by seismic impetus and other non – tectonic factors. Schneider and Salameh (2014) have attributed the triggering of the formation of the undulation to the meteoritic impact event of Jabal Waqf as Suwwan (Salameh et al., 2006 and 2008) which took place in an area lying E and SE of the area of undulation. Here, within the rock sequence, the chert beds played the role of competent beds, and the marl beds the role of incompetent beds which reacted by gliding as well as by the flow of the ductile material collected in folding troughs and crests.

The Suffield Tests explosive TNT experiments (Price, 2001) showed that the maximum principal stress during explosions acted radically generating a series of peripheral folds of small-wave lengths and amplitudes. The stress acted perpendicular to the folding axis. This test supports the hypothesis that a meteoritic impact has caused the undulation in the Amman Silicified Limestone Formation, and that the impact site should lie to the east or west of the Dead Sea area at a few tens to one hundred kms: Waqf as Suwwan lies 80-100 km east of the undulating beds. The general verging of the folding axial planes to the west supports an impact site at around 100 km east of the Dead Sea.

Assuming that an impact was the source of shock waves causing the disharmonic folding, then the internal brecciation of chert beds must be restricted to the consolidated brittle pre-existing chert beds, which is the case in the Jordanian Silicified Limestone Unit. Therefore, the assumption of the impact of shockwaves contradicts and challenges the gravitational gliding which assumes that the rocks were still unconsolidated, and could gravitatively flow. Field evidence does not support gravitational gliding, because of the very low variability in the forms and geometry of the undulation and in the strike and plunge of their axes.

Regarding the brecciated Chert formation mechanism, until now no satisfactory explanation has been provided to clarify the brecciation of the chert beds. Disharmonic folding as a cause of the brecciation is discarded by the fact that not folded chert layers are brecciated.

Agitation during digenesis can also be discarded because chert nodules do not show brecciation. It seems that after hardening, the chert beds were exposed to sudden stresses, which due to their brittle nature had led to their brecciation. Such sudden stress can be referred to the shockwaves of an impact event. Shockwaves of impacts produce love waves, which create horizontal differential rock movements with a reflection of waves within the rock itself and energy remaining in the rock (Hiller and Schneider, 1967). Such mechanism may well lead to brecciation and agitation of the brittle chert beds.

Studied slickensides structures occur on preexisting joint surfaces representing Riedel joints of a tectonic stress field in a general N–S direction (Burdon, 1959), which is the most recent stress field that has been affecting the Arabian Shield area east of the Mediterranean (Zaineldeen et al., 2002). Some folding structures show also slickensides as a result of differential interlayer movements in the direction of the a-fold axis. These are classified as tectonic slickensides. Tectonic as well as non-tectonic slickensides are found developed on vertical and inclined rock discontinuity surfaces with movements resulting from the overload of the overlying rocks and gravitational sliding. Such Slickensides accompany fault and flexure structures. Tectonic slickensides on inclined surfaces are also present along the major flexures of Suweima – Hallabat and Shueib – Suweileh.

One other studied deformation structure is deformed fossils which were observed, firstly by Alhejoj et al, (2013). They stated that the deformation directions of fossils in the Late Cretaceous rocks of Jordan correlate to the structures produced as a result of unambiguous stress fields. These authors, and formerly Quennell (Burdon, 1959), concluded that Jordan was exposed during its geologic history, in Tertiary and Quaternary times, to different stress fields in an ENE-WSW direction, followed by a NW-SE strong stress field which produced the Syrian Arc, Sweima-Hallabat and Shueib-Suweilih structures. It was finally followed by another strong stress field in a NNW-SSE direction which resulted in the formation of the Dead Sea Transform Fault and the accompanying structures. The studied deformed fossils in the Ajlun area were found horizontally deformed in the same directions of the formerly well-known stress fields producing other structures in the area such as folds, stylolites, reverse faults and flexures. This unambiguously shows that even if other structures indicating stress fields are not found, deformed fossils can well be used as paleostress indicators.

Although, the deformation of Late Cretaceous fossils indicates the three above- mentioned stress fields well-known before namely, ENE-WSW, NW-SE and NNW-SSE, it has not been attempted to obtain information on the history of the stress field evolution from the deformed fossils themselves. Furthermore, deformed fossils in Waqf as Suwwan impact area shows deformation stress directions originating from the center of the impact.

It is worth mentioning that not all deformation of fossils result from tectonic activates, but compaction process can cause deformation of fossils such as the deformed gastropod fossils in the Wadi Mujib area, Jordan (Alhejoj et al., 2013).

An important deformation structures discussed in this work are stylolites especially, horizontal – peak stylolites striking in three directions with trending peaks mainly in 140˚–160˚, rarely in 70˚–80˚ and common in 170˚–190˚. These stylolites are of tectonic origin and reflect the well-known three consecutive stress fields Jordan was exposed to during the Late Tertiary to Recent times. According to Quennell (1959), the first stage of stress was in an ENE – SWS direction, while the second was in NW-SE, and the third was NNW – WSW direction reflected in the formation of the above-mentioned stylolite directions (Fig. 13). The rarely occurring stylolites (Network stylolites) resulted from a combination of tectonic H–peak stylolites and diagenetic V–peak stylolites, and are found accompanying the other two types of stylolites.

Schneider and Salameh (2014) attributed the 140˚-160˚ striking horizontal stylolites and the network stylolites to Waqf as-Suwwan meteoritic impact event which hit the area lying SE of Ajlun and Amman, where most of the 140˚-160˚ striking stylolites are found (Table.1). The stress fields obtained from the interpretation of horizontal–peak stylolites of ENE-WSW, NW-SE, and NNW-SSE are the same which have been obtained from the interpretation of stresses producing the deformed fossils (this study).

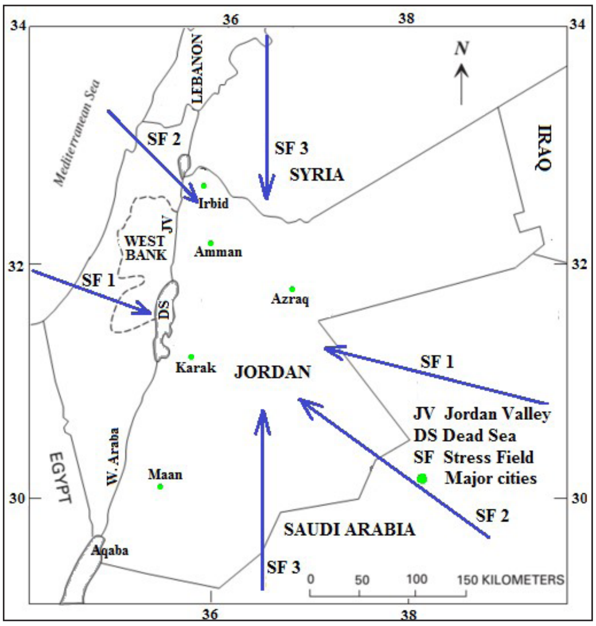

Figure 13. Stress fields affecting Jordan during Neogene to recent times (based on Quennell 1959).

Flowage Structures are also a good example of soft deformation structures. The flow channels seem to have served as escape paths for the over-pressurized Lower Cretaceous semi-consolidated sands caused by the withdrawal (regression) of the Tethys and the very slow process of water pressure releases controlled by very low permeability of 10^{-8}-10^{-9} m/s . The factors which resulted in the upward flow of the sand are: a) the friable nature of the sand b) the increasing pressure in the sand caused by the retreat of the Tethys and the epirogenic upward land movement resulting in lower water pressures in the overlying rock units of Upper Cretaceous age compared to those of Lower Cretaceous age c) a triggering factor causing liquefaction of the over-pressurized friable sands. The triggering factor can be a very strong earthquake, may be > 8 on the Richter Scale, or it could be the result of shock waves like those produced by Waqf as-Suwwan meteoritic impact (Schneider and Salameh, 2014).

The formation mechanisms of Nodular Limestone are interpreted by Abed and Schneider (1980) saying that this structure may have originated by the activities of burrowing organisms such as *ThaIassinoides, Cauianassa or Ophiomorpha*. On the other hand, the origin of this structure also appears to be caused by digenetic processes of highly fractured, disintegrated limestone of about one decimeter in side length. Because crustacean burrows are common in all Cenomanian and Turonian_limestones in Jordan and not restricted to those of the lagoons.The nodules are generally composed in their core part of limestone or dolomitic limestone surrounded by a veneer of silicified limestone. This shows that after fracturing, solutions infiltrated and caused the deposition of the veneers. Such solutions can be the result of silicate dissolution by acidic water and deposition when the pH of the infiltrating water rises. Fracturing in small pieces can be brought about by shock waves, and dissolution of silicates can be the result of acid rain (e.g. of meteoritic impacts). But it is also likely that these nodules resulted from the general bioturbation in the original sea floor mud of that time. Crab burrows helped in keeping the water of the sediment oxygen-loaded, but that must have ended when digenesis began to transform the mud and sand into nodules. Also the depth of sediment needed for the change from aragonite to calcite and limestone is vital.

The last structure to be discussed is the boudinage structure. Geologic field observation allows this structure to be interpreted as post-deposition process resulting from tectonics causing the formation of the Syrian Arc (Coniacian–Miocene). This produced load pressure and lateral expansion of the soft and gliding-mobile over- and underlying sediments and breaking of the rigid chert into pieces and deforming the phosphorite deposition in Jordan.

Field observation, measurements, previous work and the results of the current work show that the brittle deformed and smashed fossils in soft materials and finely smashed and brecciated chert beds underlain and overlain by less competent limestone rocks indicate the rapidly-acting stress fields (shock waves), which did not allow for the slow accommodation of stresses by ductile deformation.

Stylolites, slickensides and ductile deformed fossils in horizontal direction seem to have developed as a result of gradually developing, long lasting stress fields.

The deep burial of rocks lead to stronger compaction of clays and marls than sandstone. According to Wunderlich (1966) a burial depth of about 500m results in a density inversion between the sandstones with their higher density when deposited at the ground surface, compared to clays and marls under the same conditions. This seems to be the case at the interface of the Lower Cretaceous sandstone and the Upper Cretaceous calcareous rocks where the interface is composed of about 10 m of clays and marls (Bandel and Salameh, 2013). The burial thickness before eroding the top layers covering the Upper Cretaceous rocks which crop out at the ground surface at the present was estimated by Wiesemann (1969) to be at least 1000m. Under this load pressure, the density of the sandstone becomes 2.10 g/cm^3 and that of the clays and marls 2.35 g/cm^3. When adding to this situation the condition that the sandstones are only very weakly cemented in many parts, or even friable, and the groundwater in most parts of them is still confined or over-pressurized, it becomes clear that the layering conditions are label and the system is prune to density inversion and even to releases of over-pressure in them. Actually, density inversion and upward flow channels are very clearly found in the transition zone from the Lower to the Upper Cretaceous. Density inversion and flow along channels may require a triggering factor (activation energy) to liquefy the sandstone. But this is easily provided by earthquakes or meteoritic impact shock waves, such as Waqf as-Suwwan impact (Salameh et al, 2008 and Schneider and Salameh, 2014).

Undulations in the silicified limestone and chert beds without any corresponding undulations in the overlying and underlying limestone sequences and even without any macro or micro structures in them, which might indicate gradually developing regional stress fields, open the door for other interpretations. In addition, the very strongly brecciated chert beds, in fragments up to a few cm, cannot be explained by gradual application of stress fields. Most probably, the undulations and the brecciation of the chert beds are the result of shock waves and the reaction of the competent chert beds relative to the over- and under- lying incompetent limestone beds to these shock waves. Shock waves of a magnitude to produce the wide spread phenomena of brecciation and undulation in an area of 50 by 200 km can only be produced by meteoritic impacts (Schnneider and Salameh, 2014).

Furthermore, the formation of the nodular limestone remains a riddle in spite of the advanced ideas about its origin as a result of crap borrows or biogenic origin. However, looking in details at its outcrops with the very narrow joint spacing of less than 10 cm, it seems that strong sudden forces must have affected this thin bedded limestone that is approximately of a 10 cm layer thicknesses. Thus, these rock pieces moved against each other under shear and torque forces, which had led to the breaking of the edges of rock, composed of almost cubic pieces. These forces acted among others horizontally and affected specific rock types functioning as competent beds represented by the nodular limestone which is generally composed of dolomitic limestone. The shock waves producing the shear and torque stresses resulting in the rounded edges of the nodules and most probably in shattering the beds into pieces might be a very strong earthquake, or more probably a meteoritic impact event.

Finally, boudinage of chert and the phosphorite structure of Upper Cretaceous rocks is mainly a result of the stress field causing the formation of the Syrian- Arc.

Conclusion

Mesostructures in the Upper Cretaceous rocks of Jordan are interpreted to have been produced by a variety of mechanisms:

1. Tectonic stress fields acting in ESE - WSW, NW - SE and NNW-SSE in a sequence producing, in addition to faults and folds, also ductile deformed fossils in horizontal directions, stylolites, boudinage and slickensides. These deformation structures took place contemporaneously with the Syrian Arc and Dead Sea Transform Fault and the stress fields causing them.
2. Shock waves of very strong earthquakes or meteoritic impacts produced brittle deformed fossils embedded in soft materials, very strongly smashed chert beds, undulations in the competent chert beds with no undulations whatsoever in the incompetent over and underlying limestone beds and slickensides.
3. Compaction resulted in density inversions, and hence upward migration of less dense sandstone blocks into the overlying denser but very wet clay and mud layers.

4. Over-pressurized groundwater in the Lower Cretaceous sandstone aquifer caused by the retreat of the Tethys, where the over- pressurized groundwater was triggered by shock waves to cause liquefaction in the friable or very weakly cemented sandstone, ended in the upward migration of its groundwater transporting sand grains into and through the overlying clay and marl layers.
5. Chemical precipitation and replacement of organic matter by silicates produced silica geodes.

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