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Differential Anticlockwise Rotations of the Crystalline Basement Blocks in the Levant and Their Geologic and Geomorphologic Implications

—Dextral Strike Slip Movements in the Levant

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Abstract

The ±E-W striking vertical faults affecting the eastern Jordan Rift Valley Shoulder Mountains show dextral strike slip movements, which east of these mountains, in the Plateau area die out or turn into the preexisting NW-SE to NNW-SSE depression structures of Jafr, Karak-Fayha, and Sirhan. To form these dextral strike slip movements, the Precambrian stress field portrayed in the faulting of the Crystalline Basement of south Jordan, acting in a ±N-S direction, must have rotated, during the Neogene anti-clockwise, to ±SE-NW-acting. These movements on the Jordanian Block have taken place along a number of major vertical faults striking E-W to SE-NW, whereas, on the Palestinian Block major dextral strike slip movements have taken place only along one main fault, namely the Carmel-Gilboa Fault striking also ±SE-NW with a total strike slip movement of 15 - 25 km. The other manifestations of the stress field are portrayed in folding structures perpendicular to the stress field, striking in a ±NE-SW direction. In Syria, in the Palmyra Mountain Chain, striking ±ENE-WSW, the rotational movement of the Arabian Plate became oriented in a WNW direction, under a ±SE-NW stress field, producing the, towards NW concave bending of the SSW edge of Palmyra Mountain Chain showing local sinistral strike slip movements in places and dextral in others. In Saudi Arabia, the Najd Fault striking NNW-SSE shows also a net major dextral strike slip movement and moderate, but frequent earthquake activity of generally M < 4.5. Because all these faults are of Post Neogene age (affecting Neogene and younger rocks), predating or contemporaneously with the reactivation of faulting and rifting along the Jordan Rift Valley, they must have left their im-

prints on the recent sediments and sedimentary structures of the Jordan Rift Valley. By analyzing all the above mentioned structures, this study concludes that the anti-clockwise rotational of the Arabian Plate around a pole located in north Libya and the Arabian Plate collision with the Anatolian Plate further northwest, have resulted in the following: 1) Differential dextral movements of the crystalline Basement Blocks east of the Jordan Rift Valley. 2) The formation of ±NE-SW striking compressional structures on the Palestinian Block. 3) In the folding of the Palmyra Mountain Chain striking ENE-WSW. 4) In the tilting of the direction of the Jordan and Dead Sea parts of the Jordan Rift Valley anti-clockwise by around 10˚. The author thinks that the sag ponds and ridges along the JRV Depression, including the Dead Sea, Hula, and Lake Tiberias and the salt domes such as Lisan, Grain and Samach are the results of the dextral strike slip movements in combination with the sinistral strike slip movements along the Dead Sea Transform Fault.

Keywords

Levant, Dextral Strike Slip, Sag Ponds, Differential Plate Collisions, Dead Sea Transform Fault, Arabian-Anatolian Plates

1. Introduction

Much has been written about the structural framework of Jordan and the Levant, the existence or nonexistence of a strike slip movement along the Jordan Rift Valley, and the magnitude of that movement [1]-[10] among many others. Some of the workers suggested a sinistral strike slip movement of up to 150 km but most of them agreed on 107 km taking place in 2 stages, the first 62 and the second 45 km. Many of the studies were only concerned with finding new evidence pieces to support the strike slip movement such as [1] [5] and many others. Nonetheless, most workers, who did not agree with the sinistral strike slip movement along the Jordan Rift Valley in its full magnitude, accept a movement of a few tens of kilometers [3] [8].

Detailed mapping and works about the structural framework of Jordan reveal the presence of a series of dextral strike slip movements along faults striking ±E-W found in the eastern Shoulder Mountains of the Jordan Rift Valley (JRV). These faults die out or turn in a NW-SE direction at a few tens of km east of the JRV and merge into the preexisting crystalline basement depressions of Jafr and Sirhan and Karak-Fayha Graben [1] [3] [8] [9] [11]-[16] (**Figure 1**).

In this article, the stress fields producing these faults, their implications to the geology of the area, and the interactions with other main structural elements will be elaborated.

2. Methodology

This article is based on studying and reevaluating existing literature on the geology of the Levant, especially structural geologic works and own fieldwork, map-

ping and experience. The selection of literature depended on the relevance for the present work. Extensive literature exists on the different aspects of the geology of the Levant, which relate to the subject. For example studies on plate tectonics, geomagnetism, paleo-magnetism, gravity anomalies among others, but the present article concentrate on the dextral strike slip faults and their role in the tilting of the Dead Sea Transform Fault and formation of depressions and ridges along the Jordan Rift Valley.

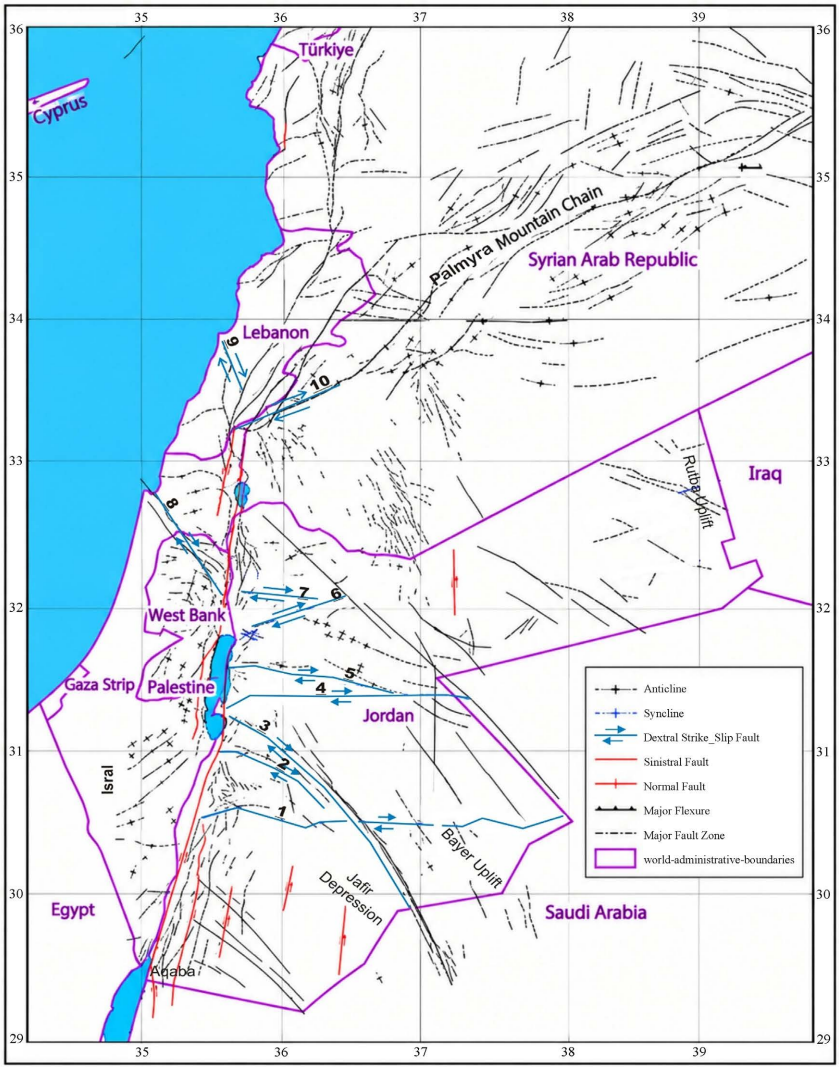

Figure 1. Simplified structural geologic map of the Levant showing the major dextral strike slip faults and other geologic structures (Basic map by [3], updated by [17], and modified by the author). Faults: 1. Salawan, 2. Hasa, 3. Karak-Fayha, 4. Shihan, 5. Zarqa Main, 6. Sweima-Hallabat, 7. Zarqa River, 8. Carmel-Gilboa, 9. Roum, 10. Palmyra.

3. Findings and Discussion

1) Structures in the Study Area

Studies on the eastern and western sides of the Jordan Rift Valley give details of the structural framework of the area, summarize the main structural inventory and

relate structures to force plans [3]-[5] [8] [10] [14] [15] [18] and many others.

According to the different regional studies on Jordan's and the Levant's geology [3] [4] [10] [19]-[23], the Crystalline Basement of Jordan can be subdivided into three main blocks separated from each other by active depressions, namely (**Figure 2**):

- The Southern Block extending from the Gulf of Aqaba in the south to Jafr Depression in the north. It strikes SE-NW with a thick sediment cover of more than 3000 m in Jafr Depression compared to the uplifted areas further SW and NE, where the sediment cover thickness decreases to 600 m (**Figure 2**) Worth mentioning here is that Ras en Naqab fault, striking also SE-NW divides this block in two sub-blocks.
- The Central uplifted Crystalline Basement Block (Bayer Block), striking SE-NW and extending between Jafr Depression in the SW and Wadi Sirhan Depression in the NE. It has a sediment cover of around 1500 m compared to Jafr Depression of 3000 and Sirhan Depression of about 6000 m. This Block contains the down-thrown Karak-Fayha Graben of about 5 km width and a modest, up to 200 m down-throw, striking also in a SE-NW direction parallel to Bayir Block. In the SE, it merges into Jafr Depression southeastern extension.
- The Northeastern Elevated Block (Rutba Block), also striking ±SE-NW, ascending from Sirhan Depression and continuing into Iraq, in the NE, and dipping and descending from there in a NE direction towards the flow course of the Euphrates River oriented there in a SE direction.

These three Blocks can be easily recognized in the structural contour map of the basement complex of Jordan (**Figure 2**) and in the shorelines map of the Tethys throughout geologic times [3] (**Figure 3**).

Worth mentioning here is that these main blocks are subdivided into smaller sub-blocks by faults and weakness zones trending in the same ±NW-SE direction but turning near the Jordan Rift Valley into ±E-W direction.

The main structures, which developed during the Paleozoic Era, are faulting along NNW-NNE lines associated with sinistral strike slip movements, E-W compressional faults and NW-SE extensional faults, which separated the afore mentioned blocks.

In Saudi Arabia, a prominent example of the ±SE-NW-NNW-SSE striking faults is the Najd Fault with both sinistral and dextral strike slip movements [24], but a net dextral movement.

Geologic mapping on the Palestinian Block [20] [21] does not show this block differentiation because the Jordan Rift Valley structure striking N-S seems to have separated the Jordanian and the Palestinian Blocks in their early geologic history; since Precambrian times (The Precambrian Geosuture or weakness zone according to Bender 1968). Another reason for the absence or obscure of these structures on the Palestinian Block is the very thick sediment package there, which overlies the Crystalline Basement measuring several km and reacting to rapturing tectonism in the Crystalline Basement by the elastic deformation of the overlying ductile sedimentary cover rather than by fracturing (**Figure 1**).

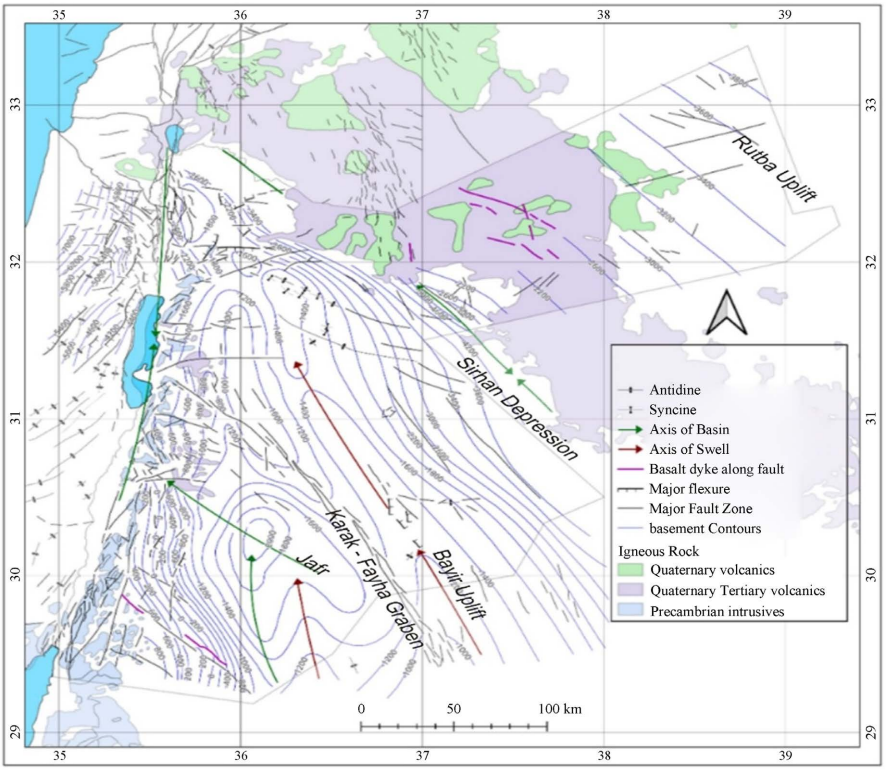

Figure 2. Structural contour map of the Crystalline Basement Complex of Jordan and immediate surroundings. It shows the Depressions of Jafr and Sirhan, borded in the SW by Ras en Naqab Uplift, in the NE by Rutba Uplift and in between the two depressions by Bayir Upift after [3].

Fault, dike, and joint systems in the Crystalline Basement Complex in southern Jordan strike in a ±NNE-SSW and ±NE-SW direction, these indicate at a stress field, during Paleozoic time acting in a NNW-SSE direction [3] [10].

On the Palestinian Block, many ±NE-SW striking compressional structures affecting the entire sedimentary column are present (**Figure 1**). They indicate at a stress field acting in a ±NW-SE direction. Such structures are missing in Jordan or are only very weakly portrayed in the thin sedimentary cover of the Crystalline Basement. Worth mentioning here is that the axes of the folding structures rotate slightly anticlockwise when moving north in coincidence with the rotational field of the Arabian Plate. In Syria, the Palmyra Mountain Chain exposes a series of compressional structures striking ±WSW-ENE indicating at the same ±SE-NW stress field affecting the Levant.

The above details allow us to conclude that all recent major structures in the Levant indicate at a stress field acting in a ±SE-NW direction.

The sediment package thickness overlying the Crystalline Basement where it is present in Jordan is very thin (**Figure 2**) with the exception of Jafr and Sirhan Depressions, which throughout their geologic history formed boundaries of basement blocks (**Figure 3**). The reaction of these blocks to more recent stress fields acting in a different direction than the one leading to their formation of ±NNW-SSE direction, expresses itself in rotational movements of the blocks against each

other as portrayed in the dextral strike slip movements, rather than by the formation of new faulting systems. Only in northwest Jordan where the sediment package is thick (Ajlun) slight folding striking SW-NE is present. Here it is worth mentioning that the collision of the Levant Plate with the Anatolian and Cyprus Plates must not have been uniform along the collision front but differential along block boundaries striking ±NW-SE and with different magnitudes.

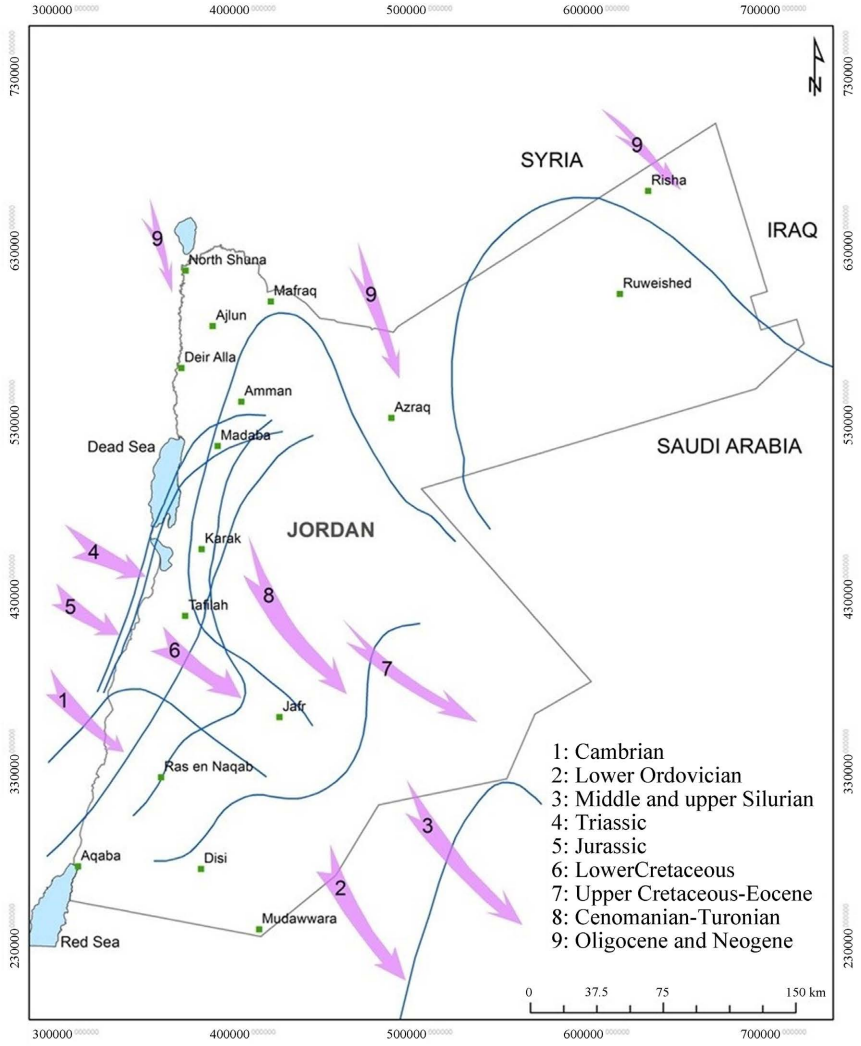

Figure 3. Tethys shorelines during the different geologic eras indicating the transgressions of the Tethys Sea, especially in the Gulfs' areas of the Precambrian Jafr and Sirhan (Azraq) depressions redrawn after [3].

In general, the post Neogene structures manifest themselves in differential rotational movements of the old Crystalline Basement blocks against each other in Jordan, Sinai, and along the dextral strike slip faults in Palestine, Lebanon, the Syrial Arc and the Najd Fault in Saudi Arabia all associated with dextral strike slip movements. In addition to the folding structures on the Palestinian block and the Syrian Arc.

2) Horizontal Stylolites

The dominant horizontal stylolite-peaks in the Upper Cretaceous limestone and dolomite beds in Jordan strike in a SE-NW direction indicating at a persistent stress field acting for long times in this same direction during post-Cretaceous time. In addition, stylolites striking 170˚ are common and those striking 110 - 120˚ are rare [13] [25] indicating an early stress field acting NNW-SSE and another weak one acting in ESE-WSW directions. We assume that they reflect the collision of the Arabian Plate with the Eurasian Plates at times. The different orientations of these stylolites and the affected rocks indicate also at the anti-clockwise rotation of the stress field postulated by [10].

3) Deformed Fossils

Alhejoj *et al.* 2013 [26] found that macro fossils in the Upper Cretaceous rocks in Jordan were deformed by a persistent stress field acting in a SE-NW direction causing their main horizontal deformation. Other stress fields had also been active but their effects on fossils had been weak.

4) Dextral Strike Slip Faults

Considering the many specific studies on the structural geologic framework of Jordan (**Figure 1**), one can recognize that most E-W striking faults in the Eastern Shoulder Mountains of the Rift Valley show dextral strike slip movements, each of a few kms of sliding [8] [10] [13] [15] [16] [18] [27]-[34], and many others. Such faults in Jordan are those with latitudes: Salawan (30˚37'), Dana (30˚38') Hasa (31˚00'), Karak-Fayha Graben (31˚16'), Ibn Hammad (31˚18'), Shihan (31˚24'), Swaqa, Zarqa Ma'in (31˚36'), Sweima-Hallabat (31˚49'), and Zarqa River (32˚11') (**Figure 1**). In the Plateau area, they die out gradually or deflect into a southeasterly direction and merge into Jafr, Karak-Fayha, and Sirhan pre-existing depressions and their offspring faults, with these depressions possessing thick sedimentary covers overlying the Crystalline Basement.

In Syria, the Palmyra Mountain Chain shows local sinistral and dextral strike slip movements, which strike ENE-WSW. In Lebanon, the Roum Fault striking SSE-NNW shows also dextral strike slip movement of several kilometers [35] (**Figure 1**).

On the Palestinian Block, dextral strike slip movements took and are still taking place along the Carmel-Gilboa Fault striking ±NW-SE with an estimated 15 - 25 km net dextral horizontal movement [36]-[38]. All other manifestations of a NW-SE stress field express themselves there in folding structures striking SSW-NNE to SW-NE.

In Sinai, where the sediment cover of the Crystalline Basement Complex is thin, E-W dextral strike slip movements are also present [39].

The above indicates the different reactions of the Crystalline Basement sedimentary cover on the eastern side of the JRV compared to its western side and to areas covered by thick sedimentary rocks such as southwestern Syria and Lebanon. The sedimentary cover of the western side of the Rift Valley in Palestine, Israel, Lebanon and the Palmyra Mountains in Syria is thick and sediments of more than 5.500 m cover the Crystalline Basement reacting elastically to stress

fields. Whereas in Jordan and Sinai the sedimentary cover is thinner in north Jordan less than 1200 m and in central Jordan 1200 - 400 m (**Figure 2**) [4] [40], and therefore, the sedimentary cover reacts to brittle faulting in the Crystalline Basement Complex by breaking (faulting) rather than by elastic deformation (folding or flexuring).

All the dextral strike slip movements in Jordan, Palestine, Israel, Syria, and Lebanon and structures such as the intensive folding on the Palestinian Block and the Palmyra Mountain Chain folding can tectonically be produced only by a stress field acting in a ±NW-SE direction. The stress field that produced the NNE-SSW to NNW-SSE striking transtentional faults during Precambrian to Paleozoic times, including the geosuture along the JRV, must had acted in a ±N-S direction [3] [4]. This stress field seems to have reactivated during Early Neogene time to turn gradually anti-clockwise to become strong acting in a ±SE-NW direction, reflecting the collision of the Arabian Plate with the Anatolian Plate lying further in the NW rather than colliding with the Turkish and Iranian Plates in the north and east.

The effects of the ±NW-SE stress field components on the preexisting geosuture along the JRV are sinistral shear in N-S direction, which certainly has produced the sinistral strike slip movement along the JRV and the dextral strike slip movements along the E-W faults of the eastern Shoulder Mountains.

The distribution of recent earthquakes in the Levant area (**Figure 4**) shows that the main earthquakes distribute around the Jordan Rift Valley Fault and along the dextral structures in Jordan, Palestine, and southern Syria reflecting the continuous activities of these structures.

5) Evolution of the E-W striking faults

The separation of the Arabian Plate from the African Plate and its migration in a ±N direction have caused its collision with the Iranian (Zagros), Turkish (Taurus), and Anatolian plates (Eurasian Plate). The almost total missing of ±NW-SE and E-W striking folding structures in the Levant indicates that since Neogene times the area has not been subjected to any appreciable stress fields acting NE-SW to N-S to produce folding in the sediment package. This can be interpreted by the assumption that the collision and subduction of the Arabian Plate under the Iranian and Turkish Plates has not produced the necessary stress in the Levant to form compressional structures striking ±NW-SE to E-W. Contrary to that, the continuing collision of the Arabian Plate with the Anatolian Plate since Neogene time seems to have produced the necessary stress field to form:

a) The folding structures striking SSW-NNE to SW-NE on the Palestinian Block.

b) The dextral strike slip movements along the many E-W to SE-NW striking structures in Jordan, the Carmel-Gilboa Fault on the Palestinian Block, the Roum Fault in Lebanon [35], and the ENE-WSW striking Palmyra Mountain Chain in Syria.

c) In addition, it had produced the horizontal peak stylolites and the deformed fossils in Jordan as mentioned above.

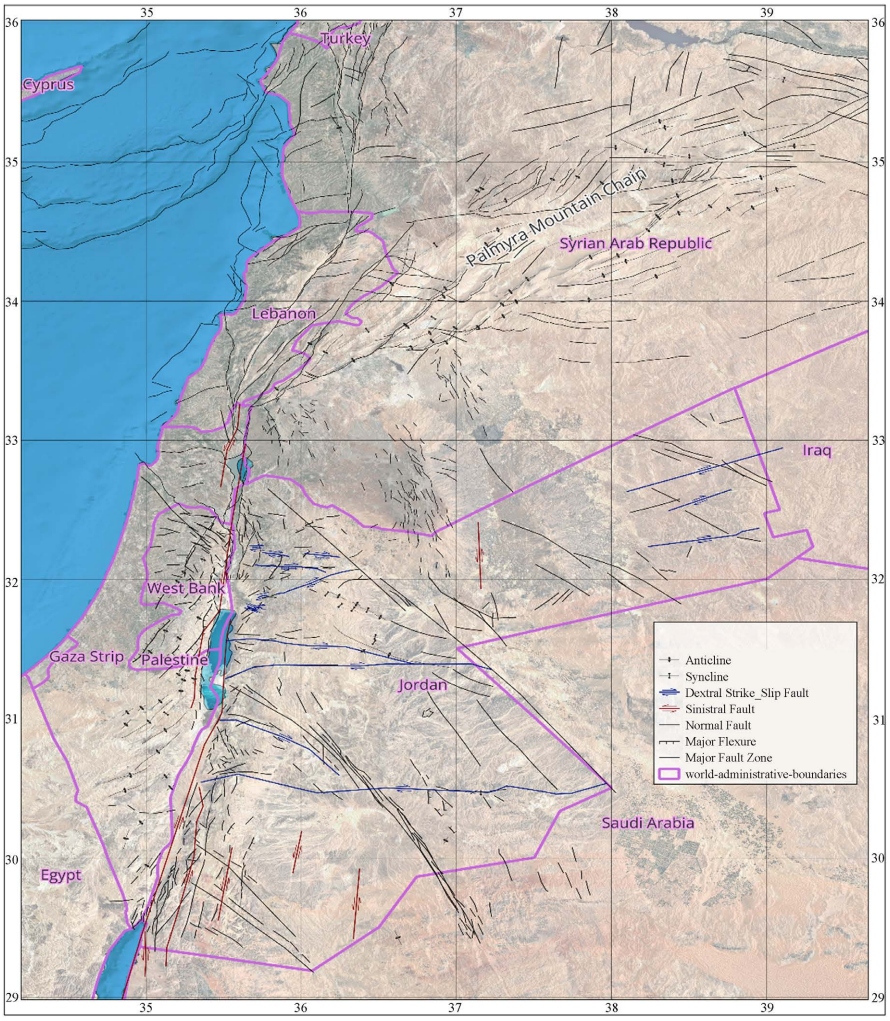

Figure 4. Locations of all magnitudes earthquakes > 3, which took place in Jordan from 1918 to 2023 showing that they concentrated along the Jordan Rift Valley [41] (ISC, 2023).

The rotational migration movement of the Arabian Plate around a pole located in northeastern Libya [24], has a component, oriented in a NW direction, around Latitude 31˚61' and longitude 24˚22' (which is the most northern Jordan Valley and the Southern Beqa'a Valley area). This movement has produced the anti-clock bending of the Rift Valley from striking 14˚ - 20˚ NE in Beqa'a to 4˚ NE in the Jordan Valley (**Figure 5**). This bending is thought of to be a result of differential resistance of the collision between the Arabian Plate and the different parts of the Anatolian-Cyprus Plate.

6) Implications to the regional geology

The total of a few tens of km of dextral strike slip movements manifest themselves on the Palestinian Block in the many folding structures striking NE-SW to NNE-SSW and in the net dextral strike slip movement along the Carmel-Gilboa Fault. In Lebanon, the net dextral movement along the Roum Fault and other faults can be easily explained by the same stress field.

Along the JRV eastern mountains in the part extending from about 45 km south

of the southern end of the Dead Sea (Latitude 30˚30') to the headwaters of the Jordan River in Hermon Mountains (Latitude 33˚20'), the dextral strike slip movements have taken place along many, mostly ±E-W striking faults, which die out or turn, in the east to striking ±SE-NW. The main playground of these movements are Sirhan Depression and its NW extension under Harrat esh Sham Basalts towards the JRV ±NW-SE arrangement of basaltic necks along extensional faults [3], along Hasa Fault, Zarqa Ma'in Fault, Karak-Fayha Graben (offsprings of Jafr Depression) and all the other ±E-W striking dextral strike slip faults in between.

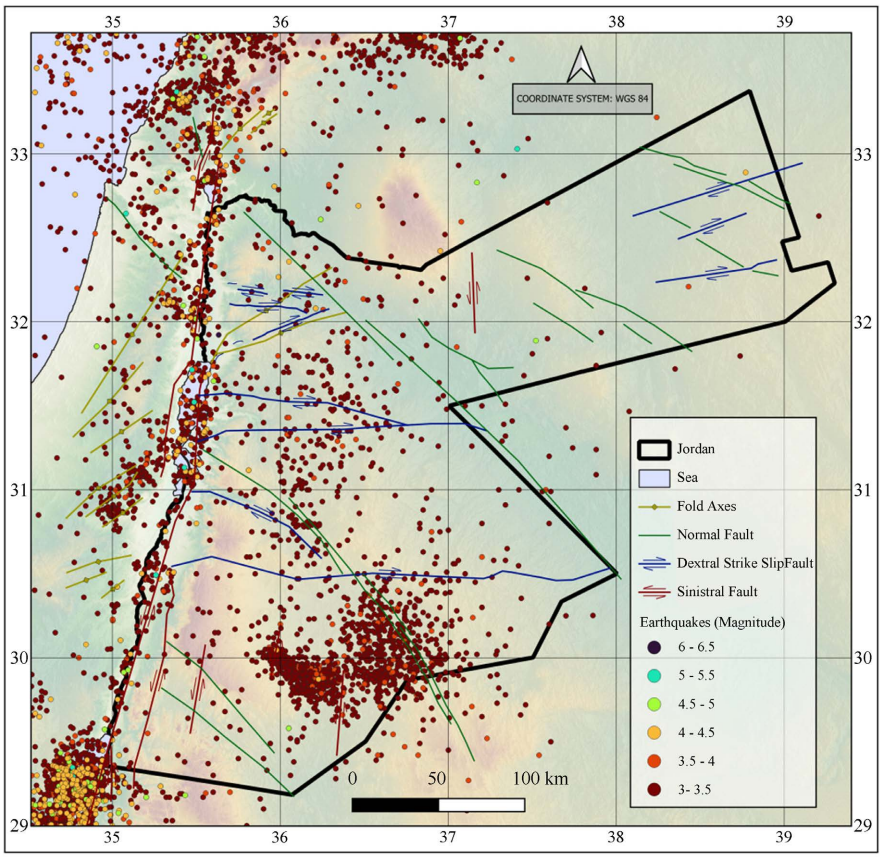

Figure 5. Bending of the JRV structure in Jabal El Shekh area (Hermon Mountains) as a result of the accomodation of the rotational movement of that northern most part of the Arabian Plare (Palmyra Mountains and nort of it) with the Anatolian Plate. South of the Hermon mMuntains the accomodation of the rotational movement was compensated by dextral strile slip movements in the area east of the JRV, and by folding in its western area.

The dextral strike slip movements along the ±E-W faults have taken place because of differential movements of dextral slipping of the southern blocks parts separated from each other by Precambrian N-S striking faults in the Crystalline Basement.

These anticlockwise differential movements of the Arabian Plate and the Levant resulted in deflecting the direction of the JRV structure into 4˚ NNE-SSW direction from its original strike in the southern Wadi Araba area of 14˚N and the

Beqa'a part in Lebanon and Syria of 14˚ - 20˚ NNE-SSW (**Figure 5**). Hence, the net dextral strike slip movements produced a total anti-clockwise rotation of the area extending from the Middle of Wadi Araba (Latitude 30˚25') to the headwaters of the Jordan River (Latitude 33˚20') of about 35 km in total, taking place along all major NW-SE and E-W faults in the area, each displaced dextrally by a few kms.

The ±NW-SE oriented stress field have a sinistral strike slip component on the preexisting JRV geosuture [3]. This, together with the differential dextral ±E-W oriented movements on the eastern side of the JRV are thought of to have produced the depressions along the JRV (Sag-ponds or lakes). Some of them are merely depressions, some filled by salt deposits and some others form salt domes such as the well-recognizable Tiberias, Hula, the Dead Sea, Grain, and Lisan Lakes, and the El Qarn Ridge in the central part of the Lower Jordan Valley [24] [42].

Although they are concentrated along the DST (Dead SeaTransform Fault), the Shoulder Mountain ±E-W compressional dextral strike slip faults show some activity that rapidly attenuate when these faults start turning ±SE-NW and become tensional.

Two of the ±E-W striking dextral strike slip scissor faults, namely El-Hasa and Sweima Hallabat delineate a down-thrown Eastern Mountains block in between them, which seems to have its western extension bounding the depression of the Dead Sea in the north and south. This allows classifying the Depression of the Dead Sea as geologically belonging to the eastern side of the Jordan Graben structure.

4. Conclusions

The stress field that had created the NNE–SSW to NNW-SSE striking faults and the ±N-S geosuture along the JRV in the Levant area during Precambrian and Cambrian times must had acted in a ±N-S direction [3] [9]. This stress field seems to have reactivated during Early Neogene time to turn gradually anti-clockwise to become acting in a ±SE-NW direction, reflecting the collision of the Arabian Plate with the Anatolian Plate, rather than with the Turkish and Iranian Plates during Precambrian and Cambrian times. The playground of the reoriented stress field is the deep-basement vertical fault system striking ±E-W in the eastern JRV Shoulders Mountains, which east of these mountains gradually turn to strike ±SE-NW into the old basement block faults directions (Jafr, Sirhan. Karak-Fayha). This ±SE-NW stress field produced dextral strike slip movements along these ±E-W oriented faults on the eastern side of the JRV, folding structures on the Palestinian Block, in addition to a major net dextral strike slip fault namely, the Gilboa (Carmel) Fault. In southern Syria, the stress field and the rotation of the Arabian Plate around a pole located in north Libya produced the folding of the Palmyra Mountain Chain and the concave bending of its WSW edge in a NW direction with local sinistral and dextral strike slip movement along the ENE-WSW b-c faults.

The dextral strike slip movements along the E-W striking eastern Mountain

Shoulders' faults resulted in an anti-clockwise rotation of the Jordanian Block, in the area extending from the Middle of Wadi Araba (30˚30') to the WSW edge of the Palmyra Mountain Chain (headwaters of the Jordan River) (33˚20'), by a net total of about 35 km. This explains the anti-clockwise deflection of the Jordan Rift Valley orientation from ±14˚ - 20˚ NNE to ±4˚ NNE relative to the orientation of the southern area extending from the Gulf of Aqaba to the middle of Wadi Araba (14˚N) and of the northern Beqa'a Depression in Lebanon oriented ±20˚ NNE.

The dextral strike slip movement of the eastern side of the JRV can be made responsible for the development of the sag ponds and ridges along the Rift Valley such as Lisan, Dead Sea, Grain, Al-Qarn, Samakh, Lakes Tiberias, and Hula, and the formation of salt accumulations and salt domes in most of them.

In terms of regional tectonism, it seems that the differential collision of the Arabian Plate with the Anatolian plate in its northern and northwestern parts has become very resistive and stresses accumulate to be released in the form of vehement tectonic movements accompanied by strong earthquakes. Whereas, in the southwestern parts of the Anatolian Plate (Cyprus and the Southeastern Mediterranean), the collision is smooth and the Levant Sub-plate rotates and easily subdues under the latter. These differential movements of the Levant Sub-plate parts take place along the dextral faults in the Levant. It is noted here that the movements along the (dextral) faults have throughout their history been only dextral, but in accordance with the collision and differential partial movements of blocks, in times the movement must have been sinistral. But the net balance is a total dextral movement and anti-clockwise of the area between the middle of Wadi Araba and the WSW end of the Palmyra mountain chain measures around 35 km.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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