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Dhahrat Al-Qurain Pressure Ridge Structure of the Dead Sea Transform Fault, NW Jordan

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ABSTRACT

Dhahrat Al-Qurain structure is formed after a restraining bend along the active Jordan Valley sinistral strike-slip fault, which is a part of the Dead Sea Transform Fault separating the Arabian plate from the Sinai subplate. The present study aims to understand the volcano-tectonic relationship in the structure. Detailed measurements of the structural elements are done to compare them with modern sandbox models. Also, this study attempts to deduce the mechanisms that led to the formation of the Dhahrat Al-Qurain structure and basalt eruption. The Pleistocene age of Ghor El-Katar Formation in the structure squeezed and experienced upward movement above the stepover, confined by a sinistral, oblique system with an arcuate shape. Later, left-lateral inclined fault planes formed within the main Jordan Valley Fault, connecting through increased displacement to form the principal displacement zones. The uplift evolved into a rhomboidal shape, marked by outer and internal reverse faults. Increasing displacement led to increased amplitude and deformation. A complex system of dextral and sinistral strike-slip faults fractured the rhomboidal pressure ridge structure. The raised blocks exhibited block rotation, synthetic and antithetic movements. Basalt is strongly pushed upward and uplifted Ghor El-Katar Formation causing its tilt at steep to vertical angles.

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تركيب ظهرة القرين الانضغاطي على طول صدع البحر الميت التحويلي، شمال غربي الأردن

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الملخص

تكوّن تركيب ظهرة القرين الانضغاطي بسبب الانحناء الى اليمين على طول صدع وادي الأردن المضربي اليساري النشط، وهو جزء من صدع البحر الميت التحويلي، الذي يفصل الصفيحة العربية عن صفيحة سيناء . تهدف الدراسة الحالية إلى فهم العلاقة البركانية التكتونية في هذا التركيب. تم إجراء قياسات تفصيلية للعناصر التركيبية لمقارنتها مع نماذج الرمل الحديثة. كما حاولت هذه الدراسة استنتاج الآليات التي أدت إلى تكوين تركيب ظهرة القرين وأدت إلى ظهور البازلت. نتيجة انحناء صدع وادي الأردن المضربي اليساري الى اليمين، شهد تكوين غور الكتار المكون للتركيب في عصر البليستوسين حركة ضغط ورفع محصورًا بنظام صدوع مضربية يسارية منحنية على شكل قوس. وفي وقت لاحق، تشكلت عدة صدوع مرافقة لصدع وادي الأردن الرئيس، اتصلت مع بعضها من خلال الإزاحة المتزايدة لتشكل مناطق الإزاحة الرئيسة. تطورت حركات الرفع إلى شكل معيني يتميز بوجود صدوع عكسية خارجية وداخلية. أدت زيادة الإزاحة إلى زيادة سعة التركيب وتشوهه. فيما بعد، تصدع تركيب ظهرة القرين الانضغاطي المعيني بواسطة نظام معقد من صدوع الانزلاق المضربية اليسارية واليمينية. أظهرت الكتل المرتفعة داخل هذا التركيب الضغطي دورانًا داخليًا، مما أدى إلى دوران الصخور وحركتها بعضها مع الحركة العامة للصدوع وبعضها بعكسها. اندفع البازلت بقوة وعمل على دفع التركيب الى أعلى، مما أدى إلى ميله بزوايا شديدة الانحدار إلى عمودية.

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Introduction

Continental strike-slip faults usually show a change in their strikes, or consist of many fault segments. This change in strike is called a bend (Sylvester, 1988; Keller and Pinter, 1996). In some cases, the fault trace is not continuous but comprises fault segments or steps (also arranged en-echelon). Fault bends and steps show local contraction or tension depending on the sense of displacement (right lateral or left lateral) and the direction of bend or step (right bend or step or left bend or step). Contraction is formed due to restraining bend or step, while tension is formed due to releasing bend or step. Areas of contraction are called transpressions, while areas of tension are called transtensions. Transpressions are characterized by shortening, uplift and folding (pressure ridge) (Ramsay and Huber, 1987; Al-Khatony and Al-Azzawi, 2010), while transtensions are characterized by topographic depression (sag ponds) and normal faulting. Bends or step-overs in the Jordan Valley Fault (JVF) had formed a zone of deformation called the principal displacement zone "PDZ".

The Dead Sea Transform Fault (DSTF) like other continental strike-slip faults has many pressure ridges and pull-apart basins, in addition to other morphotectonic features indicating active movement along its trace (Garfunkel *et al.*, 1981; Galli, 1999; Al-Taj, 2000; Klinger *et *al.*, 2000; Niemi *et al.*, 2001; Al-Taj *et al.*, 2003; Al-Taj *et al.*, 2004; Atallah *et al.*, 2005; Ferry *et al.*, 2011; Al Hseinat *et al.*, 2020; Al-Taj, 2023; Atallah *et al.*, 2023). The DSTF is a plate boundary with a sinistral strike-slip movement separating the Arabian plate in the east from the Sinai subplate in the west. It connects the divergent boundary at the Red Sea spreading center with the Taurus collision zone. In Jordan, it consists of three morphotectonic parts; the Wadi Araba in the south, the Dead Sea in the middle and the Jordan Valley in the north. The Jordan Valley is a morphtectonic depression that extends from the Dead Sea in the south to the Tiberias Lake in the north. It is about 104 km long and 7-25 km wide. It ranges in elevation from 200 m below mean sea level (BMSL) in its northern part to 412 m (BMSL) in the Dead Sea.

The DSTF in Jordan consists of two segments, Wadi Araba fault in the south and Jordan Valley fault (JVF) in the north (Fig. 1a). JVF extends about 110 km. It emerges from the NW corner of the Dead Sea to the eastern side of Tiberias Lake (Fig. 1a). It intersects the Jordan Valley in the Dhahrat Al-Qurain area forming the Dhahrat Al-Qurain Structure (DQS).

The high topography and distinctive basaltic eruption throughout the whole rift floor of Dhahrat Al-Qurain (Fig. 1b) attracted the interest of several researchers. Bender (1974) attributed the uplift to the intrusion of basaltic rocks. Belitzky and Mimran (1996) characterized the elevation as a result of active salt diapirism. Other perspectives classify it as a pressure ridge (Garfunkel *et al.,* 1981; Galli, 1999; Al-Taj, 2000; Abu Hayeh, 2014).

This study aims to determine the origin of the DQS by analyzing the different structural characteristics of pressure ridges and determining the relationship between the basaltic eruption that exists in the area and the local tectonic settings. The research relies on extensive field investigation, analysis of aerial photographs, and interpretation of the available geophysical data.

The study area “Dhahrat Al-Qurain” is a small domal uplift located in the southern part of the Jordan Valley. It is located between longitudes 35.52° and 35.56° E and latitudes 32.00° and 32.04° N. It is an asymmetric domal shape uplifted about 42 m (-258 m BMSL) above the surrounding ground level (about -300 m BMSL) (Figs. 1b and 2b).

According to Al-Taj (2000), The Jordan Valley consists of two physiographic provinces: The Jordan Valley Floor and the Eastern Jordan Valley Escarpment provinces. The study area “Dhahrat Al-Qurain” is a part of the Jordan Valley Floor province, which in turn can be subdivided into three sub-provinces as follows:

1. Flat Floor Sub-province: It represents a flat area mainly covered by soil and highly cultivated lands. The study area represents an example of this sub-province disturbed by hills.
2. *Katar Sub-province*: “Katar” is a local term that means bad land topography. It comprises Pleistocene soft deposits of the Lisan Marl Formation that are highly dissected by a dense drainage system and directly flank the Jordan River in the west. Such morphology indicates the role of scattered rainfall and fluvial processes in shaping the weak and easily eroded Lisan Formation. The width of this sub-province near the study area reaches about 3 km.
3. *Az Zor Sub-province*: “Az Zor” is another local term, which refers to the flood plains created by the Jordan River. The Jordan River is a recent geomorphic feature that develops a meandering system formed within its floodplain and the surrounding terraces. These terraces range from 6-8 m in height and consist of red-brown loams, coarse clastics and black humus soil (Bender, 1974). In some parts, the Jordan River cuts into the sediments to a depth of 50 m on the floor of the Jordan Valley.

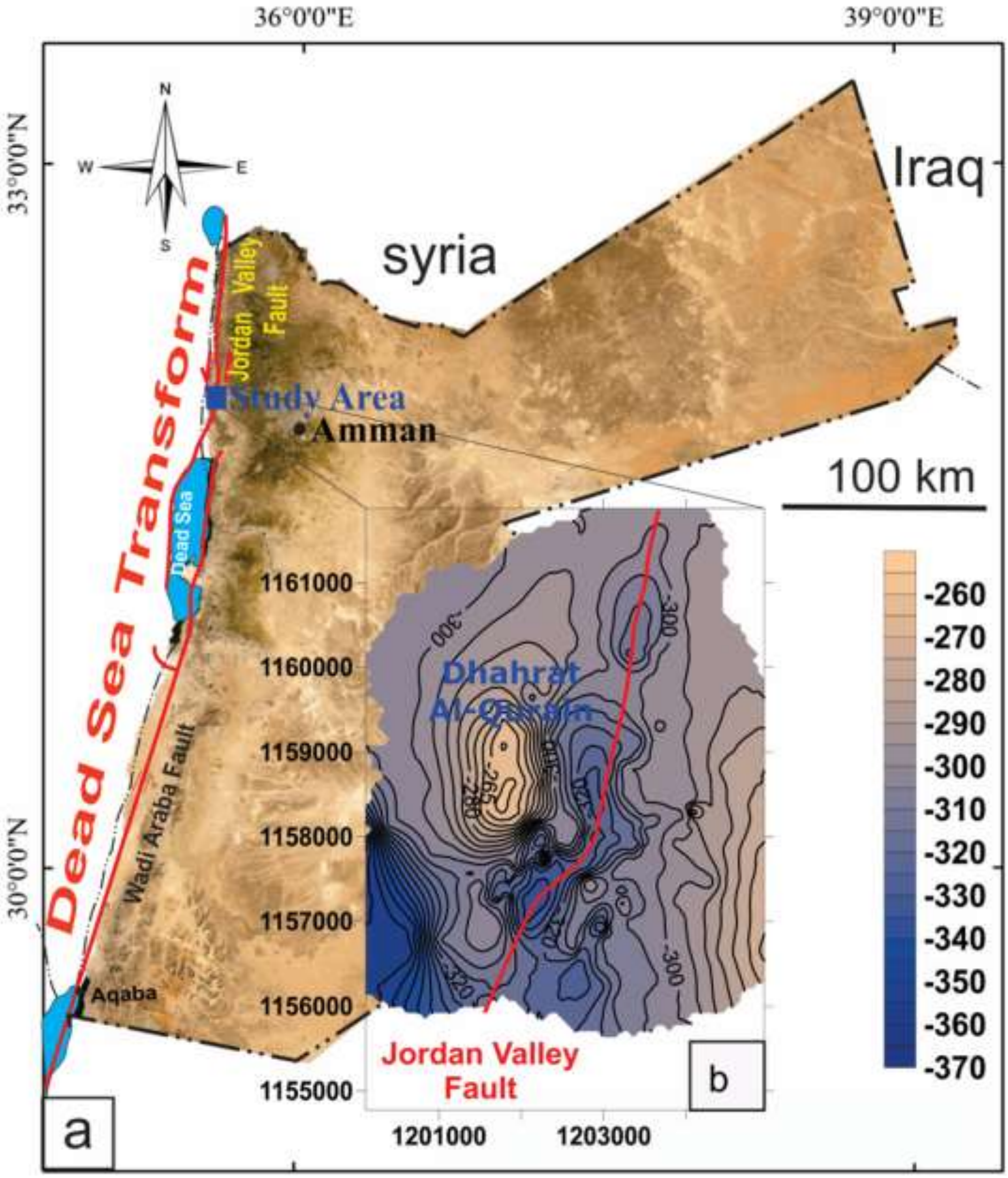


Fig. 1. (a) Location map of the study area. (b) Topographic map of Dhahrat Al-Qurain.

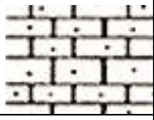
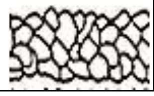
Stratigraphy

The structure of Dhahrat Al-Qurain is one of the few places in the Jordan Valley, where the Ghor El Katar Formation is outcropped. It is exposed here due to the squeeze-up of the rocks after the formation of the Dhahrat Al-Qurain pressure ridge. The age of this formation is suggested to be of Middle Pleistocene (Bender, 1974). It consists of steeply dipping layers of alternating conglomerate, gravel, sand and silt (Fig. 2a). The Lisan Formation unconformably overlies the steeply dipping Ghor El Katar beds with a clear angular unconformity (Fig. 2b). The beds of the Lisan Formation are generally horizontal and consist of an alternating thin laminae of calcite, aragonite, gypsum, and anhydrite (Abed, 2017). The age of the Lisan beds ranges from 65 ka to 15 ka before Present. These beds are overlain by the calcareous siltstone and silty limestone of the freshwater Damya Formation (Abed, 2017). They represent the uppermost Pleistocene rocks (15-11 ka before Present). The top of Ghor Al-Katar Formation is uplifted to the level (-258 m BMSL) over the erosional flat Jordan Vally floor (-300 m BMSL) at the top of the Lisan and Damya Formations (Fig. 2b).

Ghor El Katar beds are intruded by basalt. Outcropping of the basaltic rocks in the Jordan Valley floor only occurs in this area, 30 km north of the Dead Sea. The basalt had intruded the

Ghor El Katar Formation, and the basaltic rocks are assigned to the middle Pleistocene age (Bender, 1974). The chemical composition of the basalt has been studied by Saffarini et al. (1985).

Table 1: Stratigraphic column of Dhahrat Al-Qurain area (Abed, 2017).

Group	Period	Epoch	Formation	Log	Lithology
Jordan	Quaternary	Holocene			Soil and Alluvial fans
		Uppermost Pleistocene	Damya		Calcareous siltstone and silty limestone
		Upper Pleistocene	Lisan Marl		Thin lamina of calcite, aragonite, gypsum, and anhydrite
		Middle Pleistocene	Ghor El Katar		Conglomerate, gravel, sand, and silt

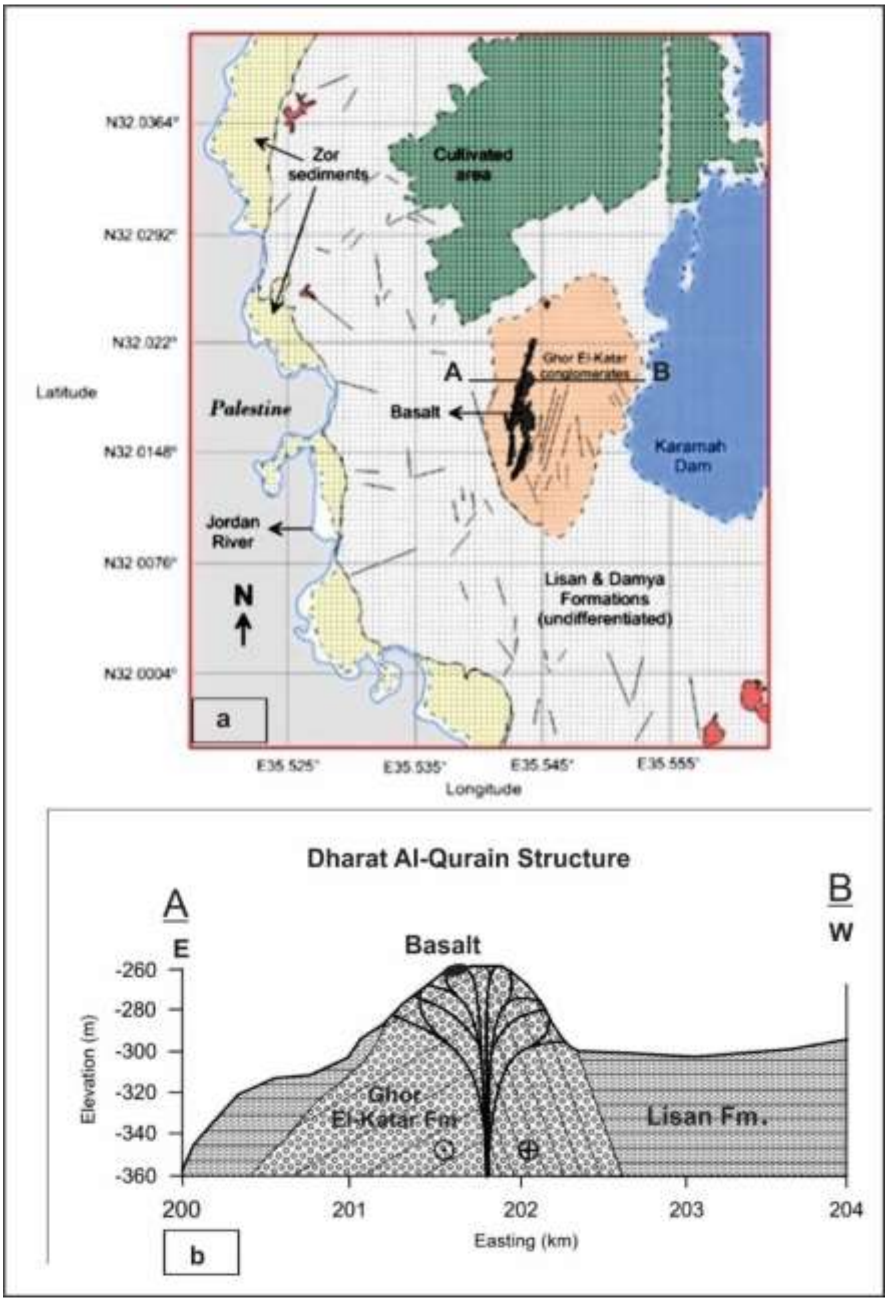


Fig. 2. (a) Geological map of the Dhahrat Al-Qurain area (Moh'd and Muneizel, 1988). (b) A-B cross-section through the DQS.

Materials and Methods

The investigation methods include office work and field investigation through several field trips. In office work, we construct a lineaments map using aerial photographs and satellite imagery to find the relation between these lineaments and other features and or structural elements. Also, the geological, topographic and Bouguer anomaly maps are very important and useful for obtaining surface and subsurface data. On the other hand, field investigation and mapping give more details than those deduced from satellite imagery and aerial photographs.

Lineaments:

Depending on aerial photographs (scale of 1:30000 and 1:6250) and satellite imagery, a lineament map is constructed to study the relation between these lineaments and other structural elements or features such as (the trends of joints, faults, outcropped basalt, pressure ridge, and the DSTF). The diagram shows that the major trend is N5°E. This trend is in good agreement with the trend of the DSTF, and also the trend of the basalt and the elongating direction of the pressure ridge (Fig. 3).

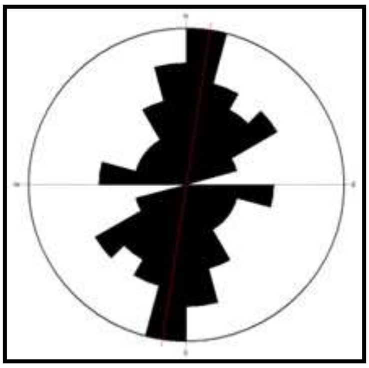
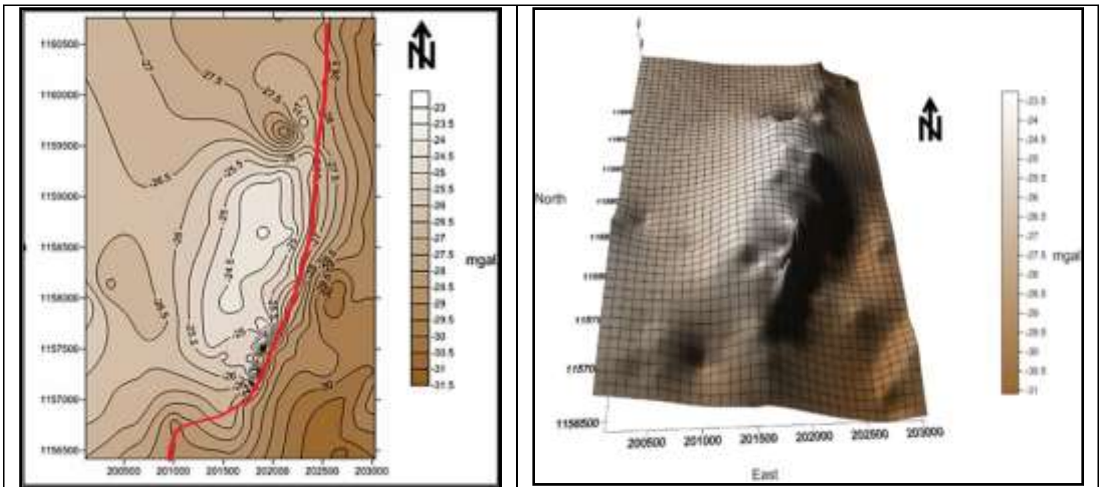


Fig. 3. Rose diagram of lineaments in the study area.

Bouguer anomaly map

2D and 3D Bouguer anomaly maps (Fig. 4) reflect the surface morphology (Fig. 1b). This means that the active Quaternary morphtectonic features are reflected also in the sub-surface. The 3-D Bouguer map gives a clear picture of the right bending of the JVF which had formed the Dhahrat Al-Qurain pressure ridge.

Note that the presence of the positive gravity anomaly (8 mgal) is interpreted by the presence of the Ghor El-Katar Conglomerates Formation sediments. Its density is higher than the surrounding Lisan and Damya Formations.



(a) (b)

Fig. 4. (a) 2-D and (b) 3-D Bouguer anomaly diagram of Dhahrat Al-Qurain (modified from Batayneh and Hassouneh, 1990). The red line is the location of the interpreted JVF.

Results

The field investigations are performed in several locations that cover the whole area of the structure (Fig. 5). In these locations, wadi incisions and trenches allow detailed measurements of stratigraphic and structural features. The other locations are covered with soil and wadi sediments or are not accessible.

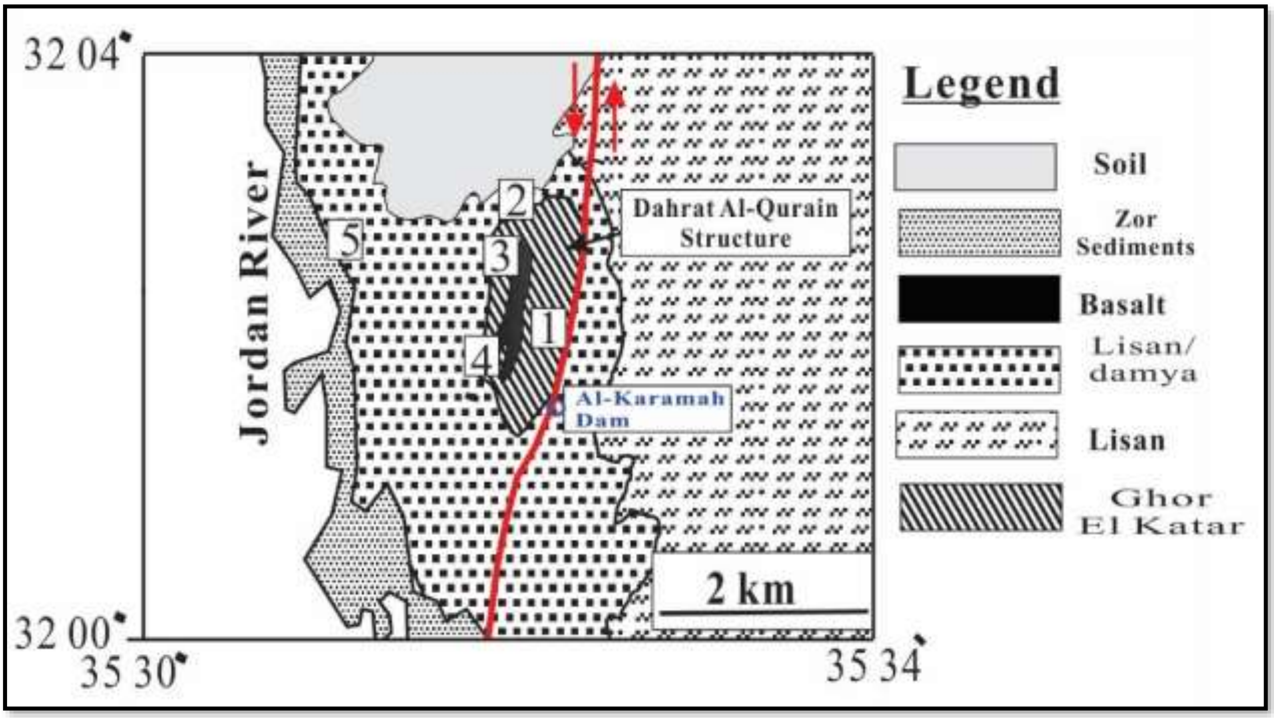


Fig. 5. Location of field stations in the Dhahrat Al-Qurain area. The red line is the Jordan Valey Fault. Numbers (1,2,3,4,5) are stations of measurement.

Station 1

This station is along the asphalted road between Dhahrat Al-Qurain and Al-Karamah Dam. The attitude of faults and layers (strike direction, dip angle and dip direction) are measured. The outcropping rocks in this area are conglomerates of the Ghor El-Katar Formation and the Lisan Marl Formation.

A clear oblique fault (Strike-slip and reverse) can be easily seen at the western side of the road, whose strike is N32°E and the dip angle is about 70° to the west (Fig. 6a). The rake on the slicken lines is 70° due south. The predominant sense of movement along this fault is reversed. Also, in this station, a clear sinistral strike-slip fault located at the eastern side of the road is observed; about 7 m of strike separation along this fault has been measured, the strike of this fault is 150° and the dip angle is about 85° (Fig. 6b).

The layers of Ghor El-Katar and Lisan Formation are highly tilted, uplifted and fractured. The dip angles of these layers in this site generally range from 30 to 50° dipping to the east (Fig. 6 a). Ghor El-Katar Formation is overlain by Lisan and Damya Formations at its flanks with clear angular unconformity.

This area in general represents a part of the eastern limb of the Dhahrat Al-Qurain structure. The dip angle of sediments increases by getting closer to the basalt in the central region of the structure.

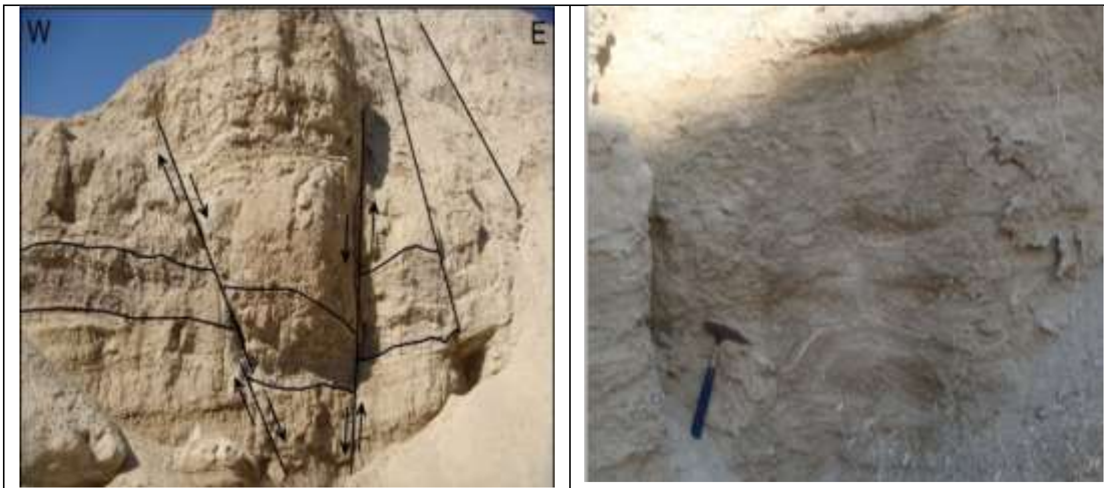
(a) (b)

Fig. 6. (a) Oblique-reverse and strike-slip fault in Ghor El-Katar Formation, the fault attitude is 32°/70° W. (b) About 7 m of horizontal displacement along a sinistral strike-slip fault in Ghor El-Katar Formation.

Station 2

The outcropping rocks in this area are of Ghor El-Katar, Lisan, and Damya formations. The layers of these formations are highly tilted and dissected by several faults. Here, the measured dip angle of the strata is about 30° to the west.

A trench clearly shows a special style of deformation in this area. Figure (7a) shows a horst and graben structures formed due to tensional stresses. This structure may be formed due to the rotation of the blocks on a sinistral strike-slip fault trending N-S. Also, a vertical dextral strike-slip fault is measured in this structure; the general strike of these dextral faults is E-W. Along this trench, seismites are also observed in the Lisan Formation (Fig. 7b). Seismites are beds disturbed by seismic shaking; they describe a variety of penecontemporaneous structures that resulted from seismic shocks on unconsolidated sediments.



(a) (b)

Fig. 7. (a) Horst and graben structure observed along an outcrop that cuts the Lisan and Damya Formation at the northwestern side of the Dhahrat Al-Qurain structure. (b) Seismites in Lisan Formation, north of the DQS.

Station 3

It is located near the northwestern corner of the basalt extrusion, the general outcropping rocks are Ghor El-Katar and Damya formations, in addition to basalt. The layers of the Ghor El-Katar Conglomerate are highly tilted and become relatively vertical, especially in places close to the basalt extrusion (Fig. 8a). In other places, to the west, away from the basalt, these layers are moderately dipping, about 50°-60° due west (Fig. 8b). The layers were displaced by a NW-SE striking sinistral strike-slip fault (Fig. 9).

Fig. 8. (a) Vertical layers of Ghor El-Katar Conglomerate close to the basalt. (b) Moderately west dipping layers of Ghor El Katar Conglomerate, away from the basalt.

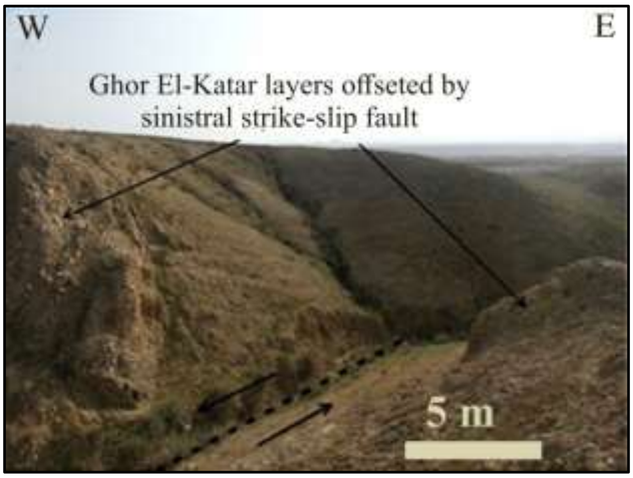


Fig. 9. Ghor El Katar layers displaced by a NW-SE sinistral strike-slip fault.

Station 4

Several valleys are observed cutting through this station, they are relatively parallel to the measured fractures. The general trend of these valleys is N-S. Some valleys, especially those at the western side, represent the contact region between basalt and Ghor El-Katar Conglomerates Formation.

Many vertical faults dissect the basalt in this area; the general attitudes of these faults are 160°/84°NE, 146°/86°SW and 140°/86°SW, while other faults are 40°/80° SE, 66°/74° NW, 84°/76° S, 132°/74° NE and 40°/70° NW (Fig. 10). The upper surface of the basalt flows shows polygonal cracks of different sizes and shapes.

Fig. 10. Sinistral strike-slip fault cutting the basalt, the attitude of this fault is 146°/86°SW.

Station 5

It is located to the west of the Dhahrat Al-Qurain pressure ridge. The rocks exposed in this region consist of the Lisan Marl Formation, which is covered by the Damya Formation. The beds of these formations are horizontal (Fig. 11). They do not display any signs of deformation. This indicates that the JVF and the corresponding PDZ don't extend in a straight line toward the north, but instead, they bend to the right.

Fig. 11. Horizontal beds of Lisan Marl and Damya Formations on the western side of the area, near the Jordan River.

Discussion and Conclusions

Many pressure ridges of variable sizes were formed along the JVF trace, such as Dhahrat Al-Qurain in the south, Tall Al-Qarn in the middle, and Tall Al-Arba'een in the north. This research focuses on the Dhahrat Al-Qurain pressure ridge because of its distinctiveness as a site that experienced not just tectonic activity but also the eruption of related basalt, differentiating it apart from similar sites in the Jordan Valley.

The area also is of certain interest because of the construction of the "Al-Karama Dam" at the southern edge of the structure, and there is a large debate about the suitability of the dam site in this area in the light of seismic risk as the area is located on the active JVF. Stratigraphically, the area is mainly covered by the Lisan Formation, which is very susceptible to erosion.

Extensive mapping of this formation is conducted to make analogies with modern sandbox models. Strike-slip "pop-up" structures form when oblique-reverse fault segments link over a basement step-over resulting in a rhomboidal uplift in the overlying layers (McClay and Bonora, 2001).

The Jordan Valley Fault is a part of the Dead Sea Transform Fault, that acts to split the Sinai-Palestine subplate from the Arabian Plate. The JVF is not a single continuous fault. Instead, it is made up of several fault segments forming a complex fault zone (Abu Hayeh, 2014).

A pressure ridge is a morphotectonic structure that developed due to the rightward bending of the sinistral strike-slip JVF. It often occurs when a strike-slip fault changes direction or orientation. Dhahrat A1-Qurain is the prominent pressure ridge that has developed due to this rightward bending of the JVF. It is recognized as the greatest pressure ridge along the JVF. This suggests that the rate at which slips occur in the study area (Dhahrat Al-Qurain) is higher compared to other sections of the JVF. As a result, there is a greater amount of elevated material or the distance between the bends is larger than in other regions.

Two hypotheses were proposed to explain the elevated status of the Dhahrat Al-Qurain. Belitzky and Mimran (1996) explained that the rise of Ghor E1-Katar Formation, which forms the elevated region, was caused by a salt diaper that is now active. On the other hand, Bender (1974) suggested that the uplift occurred due to the intrusion of (basic) basaltic rock. The first idea proposed by Belitzky and Mimran (1996) is rejected based on:

1- Corrected gravity data (Batayneh and Hassouneh, 1990) and borehole data from the Dhahrat A1-Qurain area (Sir Alexander Gibb and Partners, 1984) have shown the existence of a positive anomaly with a magnitude of 8 (mgal). The presence of the positive gravity anomaly (8 mgal) is interpreted by the authors to indicate the presence of Ghor El-Katar Formation, whose rocks densities are higher than the surrounding Lisan and Damya formations.

2- The borehole data does not indicate the presence of salt at a particular depth (Sir Alexander Gibb and Partners, 1984).

The second hypothesis proposed by Bender (1974) fits with the knowledge of both regional and local settings of the area. Our field investigations and geophysical surveys (Sir Alexander Gibb and Partners, 1984; Batayneh and Hassouneh, 1990; Abu Hayeh, 2014) provide evidence for possible uplift caused by the intrusion of the basaltic rocks and the existence of a feeder dyke structure. However, no contact surface between the basalt and Ghor El-Katar conglomerates has been identified that supports this idea.

Nevertheless, our research shows that DQS is a geological feature known as a pressure ridge, which has evolved because of a restraining bend within the JVF. Hence, it is proposed that the uplift is mostly attributed to the presence of Ghor El-Katar Formation at the bend. Consequently, it is believed that the basalt extrusion resulted from a weaker region that developed due to tilting and rotation causing certain extensions of the underlying rocks. Additionally, the region showed indications of expansion (Fig. 7a).

Most of the Quaternary rocks in the Jordan Valley are deformed due to structural activity in different phases that most probably were connected by major tectonic activities.

Four distinct phases of structural activity and movements are noted from field investigation and geological mapping. The first phase of activity was very strong and active during the middle Pleistocene. The Ghor El-Katar Formation is more affected by this structural movement than other overlying formations. During this phase, the basalt extruded. It raised and tilted the Ghor El-Katar Formation. The second phase of activity affected the Lisan Formation, which overlies all older formations with a visible angular unconformity. The presence of seismites indicates a strong phase of activity (Fig. 7b). This phase dates to the post-late Pleistocene. The third phase of activity had affected the Damya Formation, which is the youngest formation in the study area. In some localities, it overlies the Lisan Formation with angular unconformity. This phase dates to the sub-Holocene. The fourth phase of activity is continuing till present days and is indicated by historical and instrumental earthquakes. These earthquakes also reflect the recent movement along the JVF. A list of documented historical and instrumental events related to the Jordan Valley Fault (JVF) is listed in Table (2) (Abou Karaki, 1987; Meghraoui, 2014; JNBC, 2022).

Table 2: Large historical and instrumental earthquakes on the JVF (Abou Karaki, 1987; Meghraoui, 2014; JNBC, 2022).

Year (A. D.)	Intensity (MMI)	Ms (Magnitude)
19	X	7
33	IX	7
419	VIII	6
634	IX	7
748	XI	8
835	IX	6.5
1034	XI	7
1105	VIII	6
1160	VIII	6
1287	IX	6.5
1546	XI	7.5
1759	XI	6.5
1834	IX	6.5
1927	IX	7.3

Evolution of Dhahrat Al-Qurain structure

This structure represents a well-formed pressure ridge structure resulted after the bending in the sinistral strike-slip movement of the Jordan Valley Fault in Jordan. The rocks that dominate this structure include reddish conglomerates, gravel, sand, and silt, in addition to basalt extrusions. The Ghor El-Katar Formation is situated under the Lisan Formation with a distinct angular unconformity (Fig. 2b).

The following gradual progression is suggested to provide an in-depth picture of the genesis of this structure. At first, a lengthy and wide area of upward movement emerged above the stepover. The uplift is constrained by a sinistral, oblique (strike-slip and reverse faults) system with an arcuate shape. Subsequently, several left-lateral with inclined fault planes formed above the main JVF. The shears are connected via increased displacement forming a network of faults known as principal displacement zones (PDZs). Subsequently, the uplift figured out a rhomboidal shape delineated by two sets of faults. The outer reverse faults have marked the boundaries of the uplift, while the inside zone of the uplift was characterized by internal reverse faults. Increasing displacement leads to an increase in both the amplitude and deformation, particularly in the center region of the uplift. Oblique-slip of sinistral strike-slip and reverse faults transect the central area of the uplift and connect the PDZs. The rhomboidal pop-up structure is extensively fractured by a complex system of dextral and sinistral strike-slip faults. The raised blocks exhibited varying degrees of internal rotation resulting in both block rotation and synthetic and antithetic extension (horst and graben) that accommodated the rotation of the uplifted blocks. During this phase, basalt strongly pushed upward and uplifted Ghor El-Katar Formation causing its tilting at steep to vertical angles. This interpretation coincides completely with other pop-up structures worldwide. Similar structures have been observed in various locations including West Netherlands (Racero-Baema and Drake, 1996), Mongolia (Cunningham *et al.*, 1996), Tunisia (Richard *et al.*, 1995), the southern Baltic Sea (Deeks and Thomas, 1995), and Nevada, USA (Campagna and Ayden, 1991). Additionally, it is consistent with three-dimensional sandbox models as supported by McClay and Dooley (1995), Dooley et al. (1999), and McClay and Banora (2001).

Many natural examples of pop-ups from various strike-slip terranes around the world show comparable morphologies and structures to analog experimental models (Naylor *et al.*, 1986; Mandl, 1988; Richard *et al.*, 1989; Richard and Cobbold, 1990; Richard, 1991; Schreurs, 1994; McClay and Dooley, 1995; Dooley and McClay, 1997; McClay and Banora, 2001). One of the best experiments is that of McClay and Banora (2001), which may provide guidelines and structural templates for the interpretation of sections across restraining stepovers in a strike-slip system (Fig. 12).

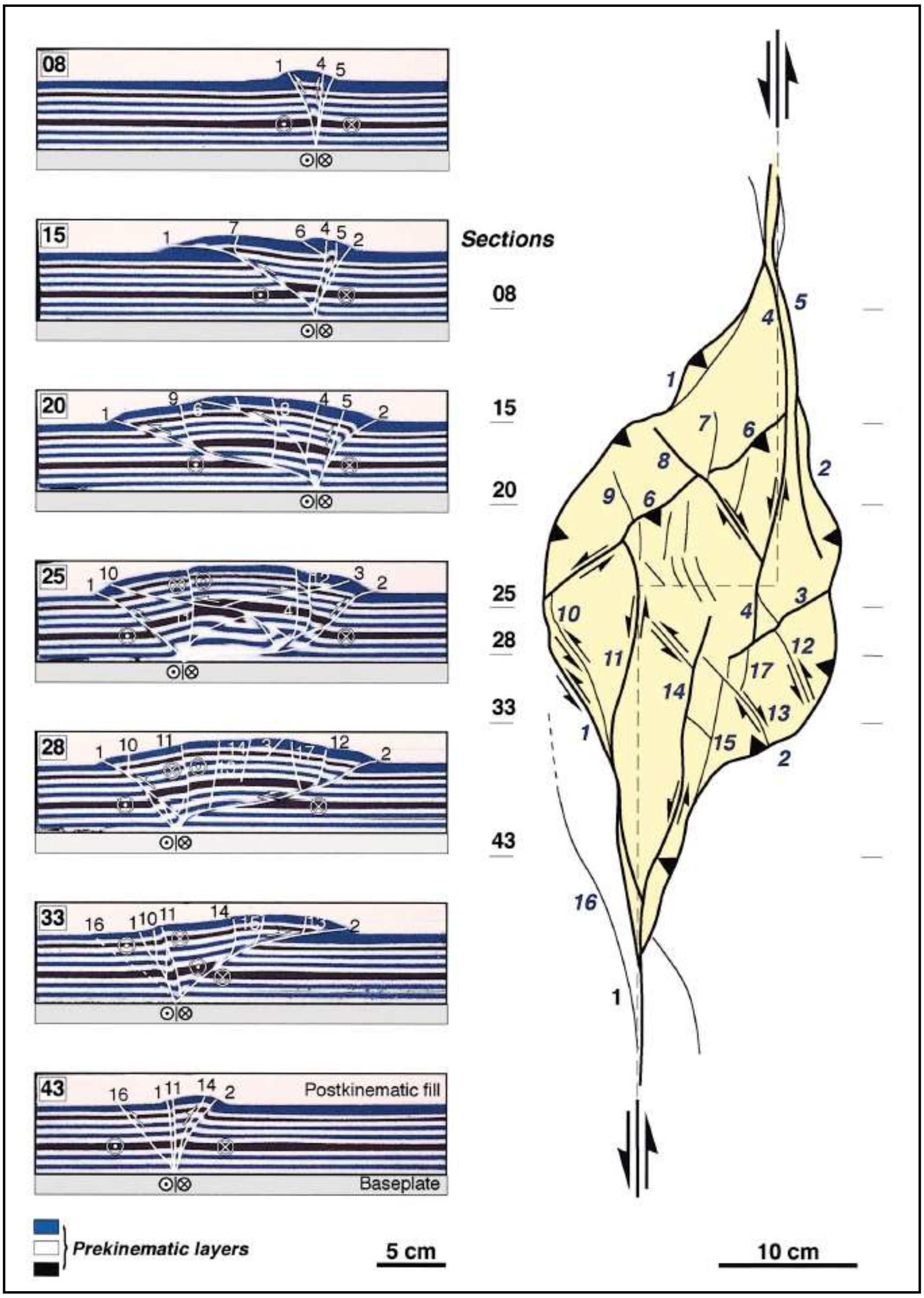


Fig. 12. Sequential vertical sections and a line diagram illustrating the surface of a restraining bend experiment after sinistral strike-slip displacement on the basement fault system. Faults are assigned numbers to facilitate linkage between the plan view diagram and the vertical sections (McClay and Bonora 2001).

In sandbox cross sections, the pop-up structure has a significant asymmetry with the bounding faults inclined inward towards the underlying basement fault system, particularly at both ends of the pop-up. Pop-up geometries that are almost symmetrical only exist above the central parts of the basement stepover.

However, sandbox models demonstrate several parallel faults that are oriented in the same direction as in the field resulting from the fault bending. This observation provides evidence to support the suggestion that the basalt did not flow, but rather forced out via one of these deep lithospheric faults that slide in a left-lateral strike-slip motion, generated on the right bend of the JVF. Segev and Schattner (2023) demonstrated that the dominant pattern within the DSF architecture inhibited magma ascent; therefore, preventing the formation of on-transform volcanism. Weinstein et al. (2020) believed that the relationship between volcanic activity and transpression, such as basalt intrusion and enhanced strike-slip activity, indicates that transform activity may both inhibit and facilitate magmatic activity. Intensive trans-pressure may lead to the development of compressional structures like the Dhahrat Al-Qurain Transpression Structure by concentrating on the width of the slip zone. This prevents the upward movement of molten material in the highly stressed section by redirecting it to the less squeezed fault zone areas (e.g., Weinstein *et al.*, 2020). Ghor El-Katar beds have experienced tilting and rotation to accommodate this deformation and permitted the basalt to extrude. The conglomerate layers near the basalt display a semi-vertical dip (Fig. 8a). Once we go further from the basalt, the inclination of the layers gradually decreases at the edge of the Structure. Lisan and Damya layers, that overlain the Ghor El-Kater, are roughly horizontal near the Jordan River in the west (Fig. 11). The true significance of this structure can be derived from the vertical and horizontal sectioning of the analogue sandbox models.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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