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# MORPHOTECTONIC INDICES OF THE DEAD SEA TRANSFORM, JORDAN

**ABSTRACT:** AL-TAJ M., SHAKOUR F & ATALLAH M., *Morphotectonic indices of the Dead Sea transform, Jordan*. (IT ISSN 1724-4757, 2007).

Two morphotectonic indices (i.e. mountain front sinuosity (Smf) and valley-floor width to height ratio (Vf)) were measured along the eastern margin of the Dead Sea and the Jordan Valley. The area is subdivided into six mountain fronts, three east of the Dead Sea and the other three at the eastern edge of the Jordan Valley. The subdivision was based on the continuity and trend of the mountain fronts. The Smf and Vf values for the six fronts are, low indicating active uplift of the eastern shoulder of the Dead Sea transform. The active uplift is very clear east of the Dead Sea two basins. The variation of the Smf and Vf values of the different fronts are very low. The outcropping rocks forming these fronts are mainly sandstone and limestone and their resistance to erosion is generally similar.

KEY WORDS: Morphotectonic indices, Mountain front sinuosity, Dead Sea, Jordan Valley.

**الدلالات المورفوتكتونية لصدع البحر الميت التحويلي، الأردن**

دليلان تكتونيان (تعرج مقدمة الجبل ونسبة عرض الوادي إلى ارتفاعه) تم قياسهما على طول الجانب الشرقي للبحر الميت وغور الأردن. قسمت المنطقة إلى ست مقدمات جبلية؛ ثلاث منها شرق البحر الميت والثلاث الأخرى على الحافة الشرقية لغور الأردن. التقسيم تم بناء على استمرارية واتجاه مقدمات الجبال. قيم الدليلان السابقان كانت منخفضة، وهذا يدل على عملية الرفع النشطة للجانب الشرقي للصدع التحويلي، وهذا كان واضحا في الجانب الشرقي لحوضي البحر الميت الشمالي والجنوبي. الفروقات بين الدليلين كانت قليلة جدا. عموما، الصخور المتكشفة المكونة لمقدمات الجبال كانت من الحجر الرملي والحجر الجيري ومقاومتهما للتعرية متماثلة تقريبا.

**الكلمات المفتاحية**: الدلالات المورفوتكتونية، تعرج مقدمة الجبل، البحر الميت، غور الأردن.

## INTRODUCTION

Geomorphic indices are useful tools in evaluating tectonic activity. Useful geomorphic indices are the mountain front sinuosity ($S_{mf}$ index) and the ratio of valley-floor width to valley height ($V_f$ index), both developed by Bull & McFadden (1977). Rapid uplift along range boundary faults produces a straight front and narrow valley floors due to down cutting of the streams. When uplift slows or stops, mountain front sinuosity increases with time as the front retreats due to erosional processes, at the same time streams cut laterally producing wide valley floors. These indices have been applied to mountain range in different countries to determine the relative tectonic activity (Keller, 1977; Bull & McFadden, 1977; Keller & Rockwell, 1984; Keller & Pinter, 1996; Silva, 2003; Verrios & *alii*, 2004). In these studies mountain fronts with Smf and Vf values less than 1.6 and 2 respectively were considered to be tectonically active with uplift rate ranging from 1-5 mm per year. The Dead Sea transform (rift) is a prominent geological and geomorphological feature; narrow valley floor and high steep margins characterize it. The difference in elevation between the lowest point in the rift (the Dead Sea) and the adjacent highlands is more than 1500 m. There is evidence of active strike slip movements along the transform since the Miocene (Quennell, 1958; Freund, 1965; Garfunkel & *alii*, 1981; Galli, 1999). Other evidences for vertical movements along boundary faults are also present on the western and eastern margins of the rift (Bender, 1968; Bahat & Rabinovitch, 1983; Picard, 1987). Recent vertical movement is observed on the western margin of the rift (Gardosh & *alii*, 1990; 3 Enzel & *alii*, 1996). Morphotectonic indices were used to describe the uplift east of Wadi Araba, the southern segment of the Dead Sea transform, which provided encouraging results (Atallah, 2002). This work is a continuation of the work in Wadi Araba and aims to apply morphotectonic indices along the eastern margin of the Dead Sea and the Jordan Valley in order to understand and evaluate the dynamics of the Dead Sea transform. These morphotectonic indices are used to discriminate the geomorphic signals of the different fault segments of the transform on the different fronts evolving under different ranges of tectonic activity.

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## GEOLOGIC AND TECTONIC SETTING

The Dead Sea transform (rift) is a plate boundary separating the Arabian plate to the east from the Sinai micro plate to the west. The transform fault was formed as a result of 107 km northward, left lateral, strike slip movement of the Arabian plate, which began in the Miocene (Quennell, 1958; Freund, 1965; Garfunkel & *alii*, 1981). It consists of three morphotectonic segments, the Wadi Araba in the south, the Dead Sea in the middle and the Jordan valley in the north (fig. 1). The Dead Sea consists of two basins; the shallow southern basin extends from the Khunaizira fault scarp in the south to the Lisan Peninsula in the north; the deep northern basin extends from the Lisan Peninsula to the mouth of the Jordan River. The Lisan Peninsula is an active subsurface salt diaper (Garfunkel & *alii*, 1981). The length of the Dead Sea reaches about 80 km; the maximum width reaches 17 km; the deepest point is about 400 m opposite to the Wadi el Mujib. The Jordan Valley extends from the Dead Sea in the south to the Lake Tiberias to the north. It is about 105 km long and 7-25 km wide. The Jordan Valley is below mean sea level; it ranges in elevation from 200 m below mean sea level in the north to about 415 m below mean sea level at the Dead Sea, which is the lowest point on the land surface. The maximum elevation of the highlands east of the Jordan Valley reaches 1200 m in the area of Ajlun (fig. 1). This 4 elevation decreases northwards to reach about 600 m in the area of Um Qais. The maximum highland elevation east of the Dead Sea is about 1200 m

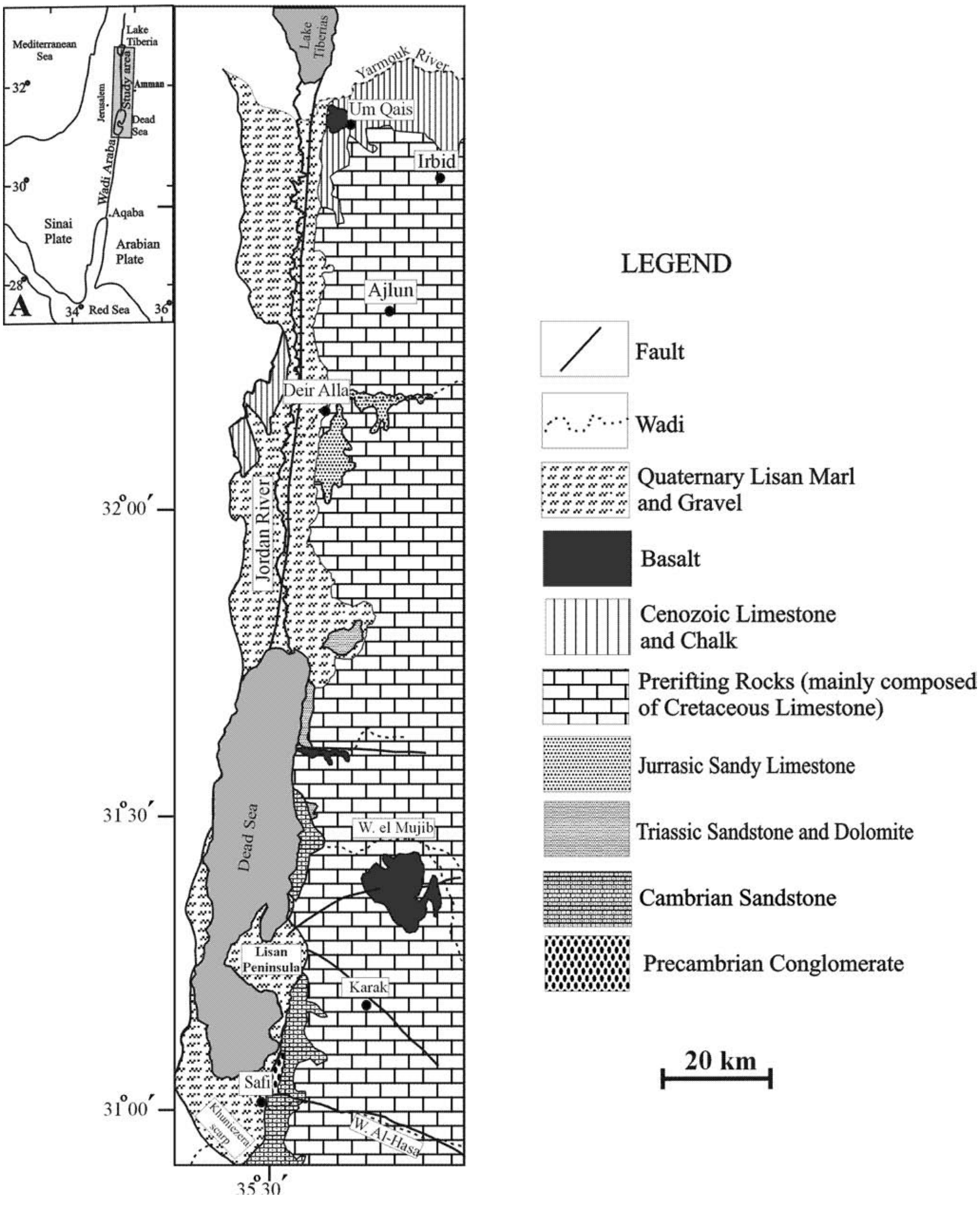


FIG. 1 - Simplified geological map of the area east of the Dead Sea and the Jordan Valley.

east of Safi (fig. 1). East of the Dead Sea, Precambrian conglomerate outcrops are overlain by the Cambrian sandstone and Cretaceous sandstone and limestone (fig. 1). East of the Lisan Peninsula, the area is structurally complex due to the presence of the Edh Dhira monocline. The highlands bordering the eastern margin of the Jordan Valley are composed of the following prerifting beds: the small outcrop of Triassic sandstone and dolomite, located at the southeastern corner of the Valley, the Jurassic sandy limestone beds occupying part of the mountain fronts south of Deir Alla (fig. 1), the Upper Cretaceous limestone that forms the margin south and north of the Jurassic outcrop. Tertiary limestone and chalk and their overlying basalt are found in the northern margin of the Valley. Quaternary Lisan marl and gravel form considerable part of the mountain fronts east of the Jordan Valley. Along the southern part of the rift margin, the beds are folded and faulted, where two SW-NE fold belts are terminated by the rift (Sahawneh, 1991; Sahawneh & Atallah, 2002). Further to the north, the mountain front is characterized by the presence of short extended step faults, narrow tilted blocks and flexures (Atallah, 1992).

The major structural element in the Jordan Valley is the Jordan Valley active strike slip fault (JVF), it extends from the northwestern corner of the Dead Sea to the southeastern corner of Lake Tiberias. The general strike of the JVF zone is N-S. The active movement along the fault produced several morphological features as pressure ridges, sag ponds, stream offsets, and fault scarps (Al-Taj, 2000).

## GEOMORPHIC INDICES

Two geomorphic indices were used to evaluate the activity of the eastern side of Wadi Araba; mountain front sinuosity ($S_{mf}$) and the ratio of valley-floor to valley height ($V_f$). The combination 5 of these indices can provide quantitative information on the relative degree of tectonic activity of the segmented Dead Sea transform and allows individual mountain fronts to be assigned in different tectonic activity classes.

Also, they are useful in tectonic studies because they can be used for rapid evaluation of large areas, and the necessary data are often obtained easily from topographic maps and aerial photographs that are available in different scales. Mountain front sinuosity is determined by measuring the length of the mountain front along the foot of the mountain $L_{mf}$ and the straight line length of the mountain $L_s$. Successively, the mountain front sinuosity $S_{mf} = L_{mf}/L_s$ is obtained (Bull & McFadden, 1977). Mountain front sinuosity reflects the balance between erosional forces that tend to cut embayment into a mountain front and tectonic forces that tend to produce a straight mountain front coincident with an active range-bounding fault. Those mountain fronts associated with active tectonics and uplift are relatively straight, with low values of Smf. Another factor which influences the sinuosity of the mountain fronts is the type of exposing rocks at these fronts; high erosion-resistant rocks tend to show straighter mountain fronts while low resistant rocks show more sinuous fronts. Table (1) shows the values of Smf for the different fronts east of the Dead Sea and the Jordan Valley.

The $V_f$ index reflects the difference between V-shaped valleys that are down cut in response to active uplift (low values of $V_f$) and broad-floored valleys that are eroding laterally into adjacent hill slopes in response to base level stability (high values of $V_f$) (Bull, 1978). The ratio of valley-floor width to valley height (Vf) may be expressed as:

$$V_f = 2V_{fw} / ((E_{ld}-E_{sc}) + (E_{rd}-E_{sc}))$$

Where $V_{fw}$ is the width of valley floor, $E_{ld}$ and $E_{rd}$ are elevations of the left and right valley divides, respectively, and $E_{sc}$ is the elevation of the valley floor (Bull & McFadden, 1977). In this study, as in previous studies (Bull, 1978; Atallah, 2002), these parameters are measured upstream from the front, at a distance of 0.1 of the drainage basin length. Table (1) shows the values of $V_f$ for the major valleys east of the Dead Sea and the Jordan Valley and the average $V_f$ value for the valleys in each front. There are no big variation in the Smf and $V_f$ values for the different fronts and valleys, the lowest measured $S_{mf}$ is 1.03 and the largest is 1.66, while $V_f$ values range from 0.20 to 2.60.

## MOUNTAIN FRONTS

The area is divided into 6 fronts, depending on continuity and trend. The escarpment bounding the eastern margin of the Dead Sea is divided into three continuous segments (fronts), the southern segment extends from the Khunaizira scarp in the south to the southern boundary of the Lisan Peninsula (fig. 2), trending N15ºE. It borders the southern basin of the Dead Sea. The second front extends from Wadi Edh Dhira in the south to Wadi Abu ed Darat in the north; it borders the Lisan Peninsula with a general trend of N-S. The third front borders the northern basin of the Dead Sea, it trends N7ºE. To the north, east of the Jordan Valley, three fronts also can be recognized: two short fronts in the southern Jordan Valley and the third long front representing most of the Jordan Valley eastern border. The southern front (front IV) coincides with the northeast striking fault. The northern front (front VI) coincides with the general trend of the transform, while front V was formed as a connection between the two previous fronts (fig. 3).

### *Front I*

It is about 60 km long (fig. 2). The exposed rocks along this front are Cambrian sandstone at the bottom of the escarpment covered by the Cretaceous sandstone and limestone. North of Wadi el Hasa fault, the Precambrian Saramuj conglomerates are exposed, they form the bottom of the escarpment for about 10 km before they plunge to the north under the Cambrian sandstone. The measured $S_{mf}$ value of this front is 1.15, while the average value for $V_f$ is 0.50±0.*37*. 7

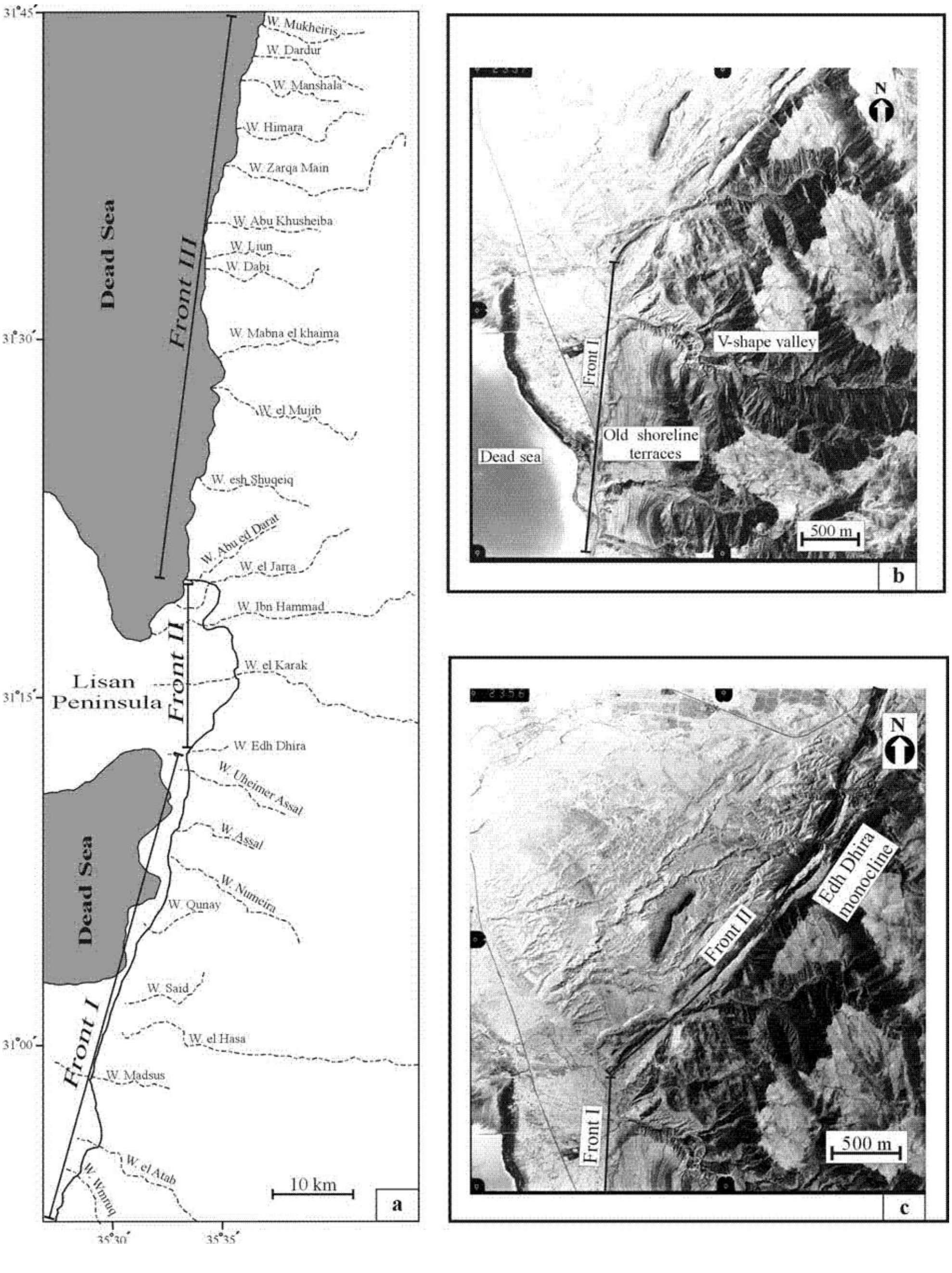


FIG. 2 - The major valleys and mountain fronts east of the Dead Sea (a). Aerial photograph shows straight mountain front and V-shaped valleys (front I), the old shore line terraces of the Lisan lake are clear on the mountain slope (b). Aerial photograph shows the curved Edh Dhira monocline (front II) (c).

*Front II*

This front borders the Lisan Peninsula. The Lisan Peninsula divides the Dead Sea into two basins; it is underlain by an active salt dome (Garfunkel, 1981). This N-S trending front extends from Wadi Edh Dhira in the south to Wadi Abu ed Darat in the north (fig. 2). The mountain front east of the Lisan Peninsula has a bow shape, it follows the shape of the Edh Dhira monocline (fig. 2), where the hard Upper Cretaceous limestone beds are steeply dipping to the west, and in some places they are vertical (Powell, 1988). The value of the $S_{mf}$ of this front is 1.60, while the average value for $V_f$ is 1.10±0.73.

*Front III*

This front borders the northern basin of the Dead Sea and extends to the northeastern corner of the Dead Sea (fig. 2). This front represents a steep cliff composed of generally horizontal beds of Cambrian, Triassic, and Cretaceous rocks. Triassic rocks outcrop north of Wadi el Mujib. A major fault in this front is the E-W Zarqa Main right lateral fault, along which basalt extruded along the southern downthrown block of the fault plane. The length of this front is about 73 km. The value of $S_{mf}$ is 1.05, while the average value for $V_f$ is 0.56±0.31.

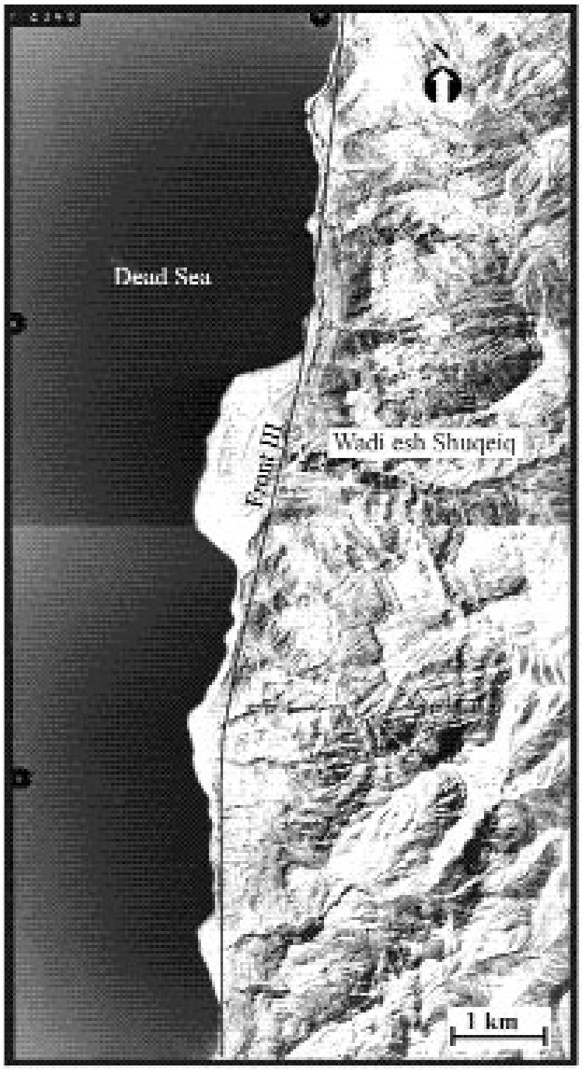


FIG. 3 - Aerial photograph shows (front III), the mountain front coincides with the Dead Sea shore line. Highly jointed Cambrian sandstone is clear south of Wadi el esh Shuqeiq.

*Front IV*

At the northeastern corner of the Dead Sea, the very steep escarpment bordering the northern basin of the Dead Sea gradually degrades and changes its orientation to a more NE trend. The change in the front orientation is due to the deflection of the east intrabasinal fault (Ben-Avraham, 1997). The outcropping rocks along this front are formed of Triassic sandstone and limestone. The length of this front is 10 km and it extends to Wadi Hisban (fig. 3). The $S_{mf}$ value for this front is 1.03, while the average value for $V_f$ is 0.59±0.06.

*Front V*

The length of this trend is 15 km (fig. 3). The highlands east of the Jordan Valley in this area consist of Upper Cretaceous carbonate rocks. The fold belt of Shuíib structure commences in this area and extends in a NE direction (Mikbel & Zacher, 1981). The value of $S_{mf}$ for this front is 1.66, while the average value for $V_f$ is 0.81±0.38.

*Front VI*

This 85-km long front was considered one front because the trend does not change and the boundary structures are similar (fig. 3). It represents most of the highlands east of the Jordan Valley from Wadi En Nuqra in the south to the Yarmouk River in the north and separates the highland east of the rift from the rift floor (fig. 3). The outcropping rocks in this front are composed of Jurassic limestone and sandstone, Cretaceous sandstone and limestone, Tertiary limestone, and Quaternary gravel. The major structural features in this area are short extended step faults, narrow tilted blocks, and westward dipping flexures (Atallah, 1992). $S_{mf}$ index for front VI equals 1.47, while the average value for $V_f$ is 1.09±0.51.

TABLE 1 - Values of geomorphological indices for mountain fronts

| Front No. | Front location | Bounding rocks | Front trend | Front length (km) | $S_{mf}$ | Average $V_f$ |
|---|---|---|---|---|---|---|
| I | East of the southern basin of the Dead Sea, from Wadi Khuneizira to Wadi Edh Dhira | Conglomerate, sandstone and limestone | N15°E | 60 | 1.15 | 0.50±0.37 |
| II | East of the Lisan Peninsula, from Wadi Edh Dhira to Wadi Abu ed Darat | Limestone | N-S | 20 | 1.60 | 1.10±0.73 |
| III | East of the northern basin of the Dead Sea, from Wadi Abu ed Darat to Wadi Mukheiris | Sandstone | N7°E | 73 | 1.05 | 0.56±0.31 |
| IV | From Wadi Mukheiris to Wadi Hisban | Sandstone and limestone | N40°E | 10 | 1.03 | 0.59±0.06 |
| V | From Wadi Hisban to Wadi En Nuqra | Limestone | N30°W | 15 | 1.66 | 0.81±0.38 |
| VI | From Wadi En Nuqra to the Yarmouk River | Limestone, sandstone and gravel | N8°E | 85 | 1.47 | 1.09±0.51 |

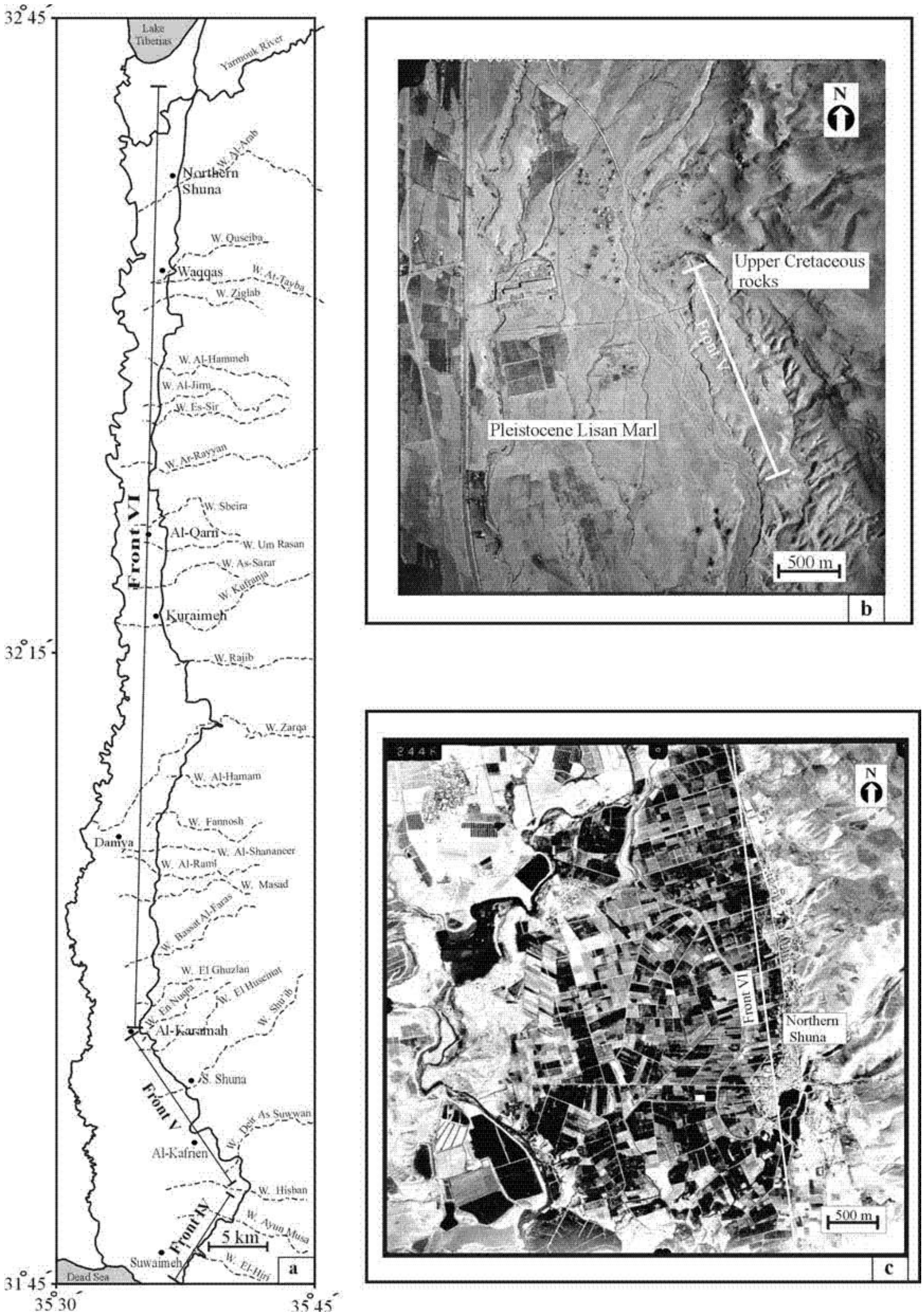


FIG. 4 - The major valleys and mountain fronts east of the Jordan Valley (a). Aerial photograph shows the NE-SW trend of front IV and NW-SE trend of front V, the fronts separate the Triassic rocks from the Pleistocene Lisan marl (b). Aerial photograph shows part of front VI that separates the highland east of the rift from the rift floor (the cultivated area). The settlements are concentrated along the front (c).

DISCUSSION AND CONCLUSIONS

Mountain front sinuosity and valley width to height ratio were used to evaluate the tectonic activity of the eastern margin of the Dead Sea and the Jordan valley. The outcropping rocks in these fronts are mainly sandstone and limestone. Precambrian hard conglomerate and Tertiary indurated conglomerate are exposed in fronts I and VI, respectively. The resistance of these rock types to erosion is generally similar, which is different from the mountain fronts east of Wadi Araba, where the lithological differences play a role in the morphotectonic indices variation (Atallah, 2002). $S_{mf}$ values for front I and III are extremely low (1.15 and 1.05, respectively), while the $S_{mf}$ value for front II is larger (1.60). The average $V_f$ values for the valleys in front I and III are low (0.50 and 0.56, respectively) and relatively high in front II. The higher $S_{mf}$ and $V_f$ for front II relative to front I and III is attributed to two factors: the curved shape of the front, which causes a higher $S_{mf}$, and the uplift of the base level (the Lisan Peninsula, which is underlain by an active salt diaper). The lower value of $S_{mf}$ and $V_f$ for front I and III is due to the relative subsidence of the Dead Sea's two basins especially the northern deeper basin. The highlands east of the Jordan Valley form three mountain fronts. The southern short one (front IV) coincides with the northeastern bending of the east intrabasinal fault. The lowest $S_{mf}$ and $V_f$ value for the fronts east of the Jordan Valley were measured in this front (1.03 and 0.59, respectively). Fault VI, which is the longest front east of the Jordan Valley and the Dead Sea shows relatively higher $S_{mf}$ and $V_f$ (1.47 and 1.09, respectively), which could be attributed to the less resistant sediments in this front especially the Tertiary limestone and conglomerate. The higher value of $S_{mf}$ in this front could be attributed to the large bay made by the retrogressive erosion of Wadi Zarqa (Zarqa River), which is the largest valley east of the Jordan Valley. The trend of front V (N30ºW) is different from the trends of the other fronts and the main trend of the Dead Sea 11 transform, this difference in trend is because this front connects front IV and front VI. It shows also relative higher $S_{mf}$ and $V_f$ (1.66 and 0.81, respectively).

It can be concluded that the mountain fronts east of the Dead Sea and the Jordan Valley have low $S_{mf}$ and $V_f$ values, which indicates active uplift of the eastern margin of the Dead sea and the Jordan valley. The variations of the $S_{mf}$ and $V_f$ values for the different fronts are small. The uplift is clearer east of the two basins of the Dead Sea. The sedimentary rocks forming the different fronts are generally similar in their resistance to erosion.

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