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MORPHOTECTONIC INDICES OF THE EASTERN WADI ARABA (DEAD SEA RIFT, JORDAN)

ABSTRACT: ATALLAH M., *Morphotectonic indices of the Eastern Wadi Araba (Dead Sea Rift, Jordan)*. (IT ISSN 0391-9838, 2002).

Two morphotectonic indices, i,e, mountain front sinuosity (S_{mf}), valley width to height ratio (V_f) were measured along the eastern rim of Wadi Araba, which represents the southern segment of the Dead Sea transform in Jordan. The area can be divided into three mountain fronts based on trend and continuity of the escarpment. The southern two fronts are controlled by two eroded boundary normal faults, while the northern front is controlled by the Dead Sea transform fault. Generally the values of these indices are low and characteristic to active mountain fronts with high uplift rate. The effect of rock type variations on the index values is clear on rocks of the same front; highly resistant igneous rocks show very low S_{mf} and V_f values, whereas low resistant Lower Cretaceous sandstone show high index values.

KEY WORDS: Morphotectonic indices, Mountain front sinuosity, Dead Sea transform, Wadi Araba.

المؤشرات المورفوتكتونية لشرق وادي عربة (انهدام البحر الميت، الاردن)

ملخص

تم قياس مؤشرين مورفوتكتوينين(تعرج مقدمات الجبال ونسبة عرض الوادي الى ارتفاع) على طول الحافة الشرقية لوادي عربه والذي يمثل الجزء الجنوبي لصدع البحر الميت التحويلي .قسمت المنطقة الى ثلاث مقدمات جبلية اعتمادا على اتجاه واستمرارية الجروف .المقدمان الجنوبيان ينطبقان على صدعين عاديين يحدان الانهدام، بينما ينطبق المقدم الثالث على صدع البحر الميت التحويلي .عموما، قيم هذه المؤشرات منخفضة وتميز المناطق ذات معدلات الرفع العالية .تأثير اختلاف نوعية الصخور على قيم المؤشرات واضحا على الصخور في نفس المقدم حيث تكون قيم مؤشر التعرج الجبلي وموؤشر نسبة عرض الوادي الى ارتفاعه قليلة في الصخور النارية ذات المقاومة العالية بينما تكون قيم هذه المؤشرات كبيرة في صخور الكريتاسي الاسفل الرملية ذات المقاومة المنخفضة.

الكلمات الرئيسية :المؤشرات المورفونكتونية، تعرج مقدمات الجبال، صدع البحر الميت التحويلي، وادي عربه.

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INTRODUCTION

The geomorphology of an area is determined by the interaction of many variables, the most important being base level change, climate, rock type and tectonics. Base level tectonic fall partly determines the relief of a fluvial system, and a pulse of uplift along a mountain front will cause adjustment in the systems that flow across the front (Bull & McFadden, 1977). Uplift can influence stream dynamics and favour down cutting with respect to lateral erosion. 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 ranges in the western United States to determine the relative activity (Keller, 1977; Bull & McFadden, 1977; Keller & Rockwell, 1984; Keller & Pinter, 1996). In these studies, mountain fronts with S_{mf} and V_f values less than 1.6 and 2 respectively are considered to be tectonically active with uplift rate ranges from 1-5 mm per year. Geomorphic indices are useful in tectonic studies because they can be used for rapid evaluation of large areas, and the necessary data often are obtained easily from topographic maps and aerial photographs.

The Dead Sea transform (rift) is a prominent geological and geomorpholgical 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 1500m. There is evidence of active strike slip movements along the transform since the Miocene (Quennell, 1958; Freund, 1965; Garfunkel & *alii*, 1981; Galli, 1999). Other evidence for vertical movements along boundary faults is also present on the western and eastern margins of the rift (Bender, 1968; Bahat &

Rabinovitch, 1983; Picard, 1987). Garfunkel & *alii* (1981) described recent vertical offset in eastern Wadi Araba. Recent vertical movement is also described on the western margin of the rift (Gardosh and *alii*, 1990; Enzel & *alii*, 1996). The aim of this paper is to use morphotectonic indices to understand the dynamics of the Dead Sea transform. The study area extends from Aqaba in the south, to the southern boundary of the Dead Sea basin represented by Khunaizira scarp in the north (fig. 1). Topographic maps at a scale of 1:50,000 produced by the Jordanian Geographic Center were used to obtain the values of the geomorphic indices. The small scale of these maps produces certain measurement error in the values of the indices. There are no maps with larger scale available for the study area, but for such reconnaissance study, these errors are considered acceptable.

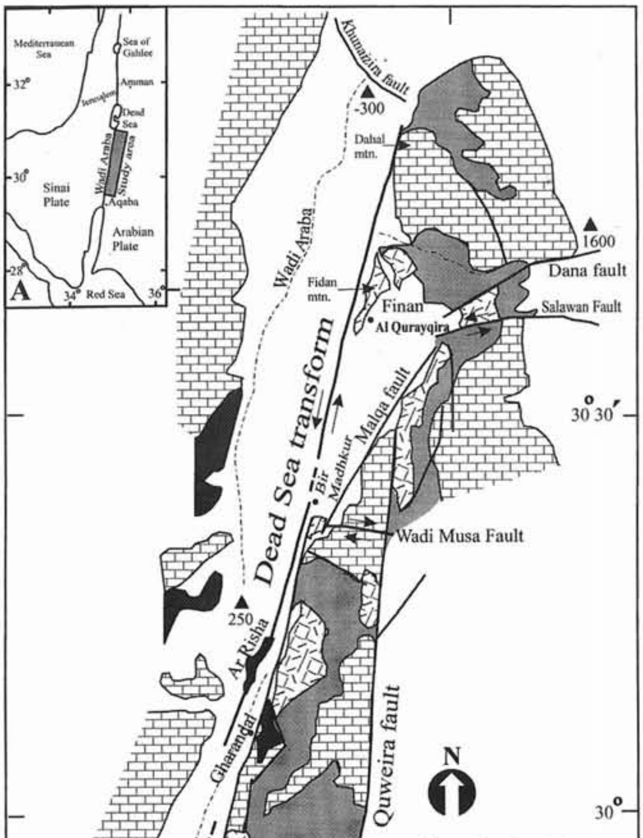

FIG. 1 - Generalized geological map of Wadi Araba area.

GEOLOGIC SETTING

Wadi Araba is part of the 1000 km Dead Sea Transform (DST) which separates the Arabian micro plate from the Sinai micro plate (fig. 1). The transform fault was formed as a result of north-south, left lateral, strike slip movement of the Arabian micro-plate relative to the Sinai micro-plate, which began in the Miocene (Quennell, 1958; Freund, 1965; Garfunkel & *alii*, 1981).

The study area consists of two major geomorphological units: the highlands to the east and the Wadi Araba rift valley to the west. The former consists of uplifted blocks that are asymmetric, with steep western fronts and gently dipping eastern slopes. Mainly E-W trending valleys dissect them. The highest mountains are more than 1600 m above sea level and more than 2000 m above local base level (the base level is below sea level).

The Wadi Araba rift valley is an elongated depression (10-15 km wide) extending from the Gulf of Aqaba to the Dead Sea. The rift floor is a nearly flat area covered mainly by unconsolidated Quaternary gravel, sand dunes, mud flats and lake deposits. Wadi Araba itself contains two drainage basins, separated by the watershed of Ar Risha Mountain; the southern basin drains to the Gulf of Aqaba and the northern basin drains north to the Dead Sea (fig. 1). The maximum elevation of the rift floor is the Ar Risha Mountain, which is 250 m above sea level. It drops to zero in the Gulf of Aqaba and to 300 m below sea level at the top of Kunaizira fault scarp and to 412 m below sea level at the Dead Sea, which is the lowest point on the continental earth surface.

The mean annual precipitation in the highlands ranges between 100-400 mm. Wadi Araba is an extremely arid area, the mean annual rainfall is less than 50 mm, occurring as a few isolated storms during late Autumn and Winter.

Basement rocks of Precambrian age outcrop along the mountain range that borders the eastern margin of the rift from Aqaba to the South to Wadi Nukhaila to the North (figs. 1, 2). Further to the north, Paleozoic and Mesozoic sandstone and Mesozoic carbonates are exposed along the rift margin. Tertiary limestone and conglomerate outcrop in highly faulted areas (fig. 1). North of Bir Madhkur (fig. 1), the rift is bounded by a NNE trending elongated porphyritic body covered by Paleozoic and Mesozoic rocks. In this area the rift rim is located further to the East, especially in Finan area, where the horst of Dana forms a prominent bay in the rift boundary (fig. 1). North of the village of Al-Qurayqira, the bounding mountains of the rift have less steep slopes than the previously described mountains. The outcropping rocks are mainly Cambrian sandstone and Cretaceous sandstone and carbonate.

The area east of Wadi Araba is characterized by intensive faulting. Among the major faults is the Quweira N-S sinistral fault. Other E-W faults are the Salawan dextral fault and the Dana fault (fig. 1). The Dana horst is restricted between these two faults. Block rotation was recorded along the major strike slip faults east of Wadi Araba (Atallah, 1988). The overlap of strike slip faults east of Wadi Araba produced some pull apart basins as the Gharandal pull apart basin, where Cretaceous and Tertiary rocks outcrop in an area of dominating Precambrian and Paleozoic rocks.

GEOPHYSICAL REVIEW

The detailed anatomy of the Dead Sea transform, based on gravity, seismic and well data show that the transform consists of a string of subsurface basins of varying size, shape and depth along the plate boundary and relatively short and discontinuous fault segments (Ten Brink & *alii*, 1999). An estimated slip rate of 6-10 mm/yr is based on a cumulative offset of 107 km of Miocene and older rocks (Garfunkel & *alii*, 1981). Late Pleistocene slip rate depending on dated geomorphic features in northern Wadi Araba was calculated to be 4 mm/year (Klinger & *alii*, 2000) and 4.7 mm/year (Niemi & *alii*, 2001). The seismic, historical and archeological records of the DST region show that past strong earthquakes have caused widespread destruction (Ben-Menahem, 1991; Poirier & Taher, 1980). However, the recent seismic activity has been relatively low, especially in Wadi Araba (Shapira, 1981). From the distribution of the earthquake epicenters in Wadi Araba, it can be concluded that there is no visible spatial clustering of epicenters along the transform faults but the clusters are related to the tensional basins (Van Eck & Hofstetter, 1990; Kovach & *alii*, 1990).

GEOMORPHIC INDICES

Wadi Araba consists of two geomorpholigical units: The southern Wadi Araba, which extends from the Gulf of Aqaba to the south to Ar Risha mountain in central Wadi Araba to the north. The major morhological features in this part are the alluvial fans on the mountain fronts east of Wadi Araba, especially the mountains of the Precambrian basement. Another morphological feature is the Taba sabkha, which is a large salty flat formed at the edges of the alluvial fans. The third feature is the sand dunes, which extends north of Taba Sabkha to Ar Risha mountain. The northern morphological unit in Wadi Araba extends from Ar Risha mountain to the South to Kunaizira fault scarp to the North. In this part, the Wadi Araba floor is wider than the southern part, it reaches 25 km in the area of Finan (fig. 1). In the northern part, there is no sabkhas and the sand dunes are less than the southern part. The alluvial fans still exist, but they are not well developed as in the southern part. In addition to the above mentioned features, the Wadi Araba floor is disected by many E-W ephemeral streams.

The following 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).

MOUNTAIN FRONT SINUOSITY (S_{mf})

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. Thus, 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 embayments into a mountain front and tectonic forces that tend to produce a straight mountain fronts coincident with an active range-bounding fault. Those mountain fronts associated with active tectonics and uplift are relatively straight, with low values of S_{mf}. If the rate of uplift is reduced or ceases, then erosional processes will carve a more irregular mountain front, and S_{mf} will increase. Another factor which influence the sinuosity of the mountain fronts is the type of exposing rocks at these fronts; highly resistant rocks tend to show more straight mountain front while low resistant rocks show more sinuous fronts. The escarpment bounding the eastern margin of Wadi Araba can be divided into three continuos segments (fronts), depending on continuity and trend. The southern segment extends from the southern end of Wadi Araba to Wadi Musa fault (fig. 1), trending N10E. The second front extends from Wadi Musa fault in the south to the Salawan fault in the north, trending N30E. The northern segment extends from the Dana fault in the south to the Khunaizira fault scarp in the north, trending N20E.The base for the escarpment partition is the change in trend. The fronts terminate mainly against E-W faults.

Front 1

This front represents the major eastern boundary of Wadi Araba, extending from Wadi el Yutum in the south to the Wadi Musa E-W trending dextral strike slip fault (fig. 2). The orientation of this front is N10E, mostly parallel to the Dead Sea Transform fault. The lithologies along this front are varied; they are Precambrian basement crystalline rocks in the south, in the Gharandal area (fig. 1) Cretaceous and Tertiary rocks outcrop in a pull- apart basin. Farther to the north Precambrian rocks outcrop again east of Ar Risha Mountain. Cambrian sandstone overlain by Cretaceous sandstone and limestone forms the northern part of this front. The drainage area of this front has a complex structural pattern. The area is dissected by a network of intersecting faults especially in its northern part, where the outcrop pattern of the sedimentary and igneous rocks is also very complex. At some places, younger rocks outcrop in a structurally subsided block surrounded by

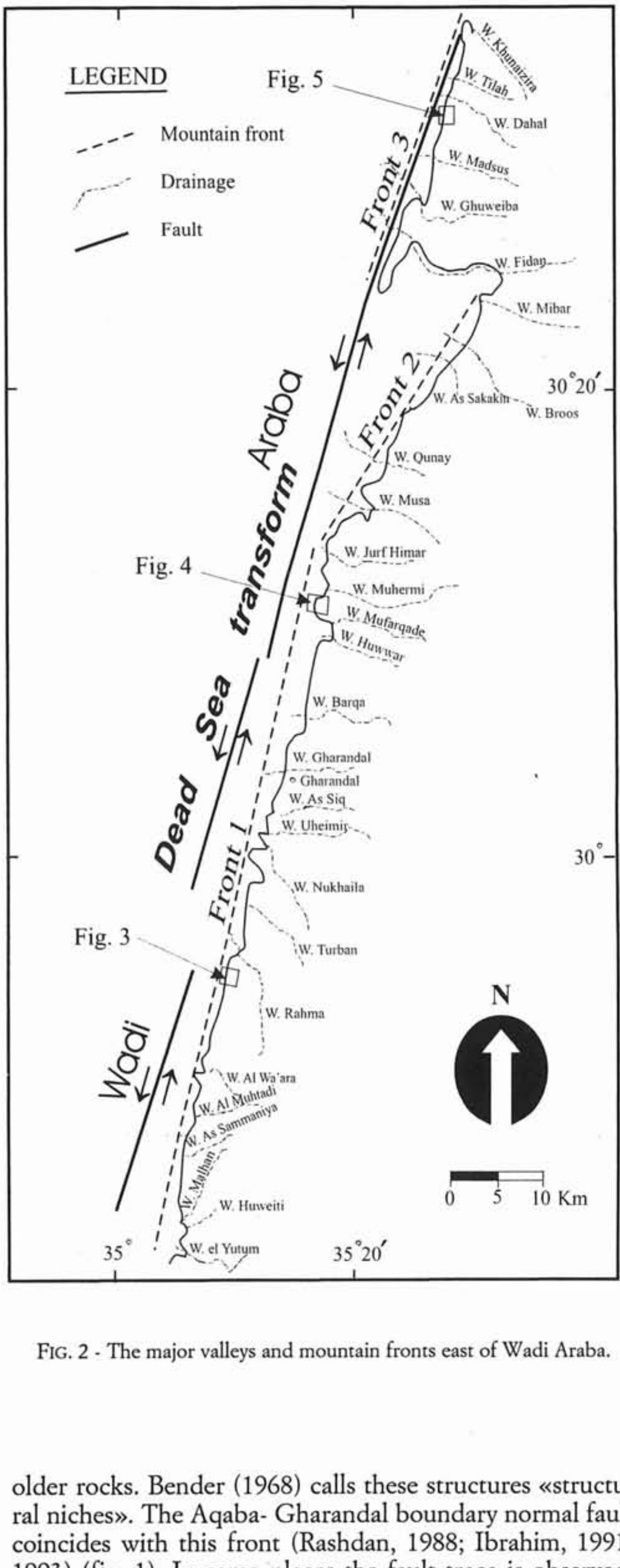

FIG. 2 - The major valleys and mountain fronts east of Wadi Araba.

older rocks. Bender (1968) calls these structures «structural niches». The Aqaba- Gharandal boundary normal fault coincides with this front (Rashdan, 1988; Ibrahim, 1991, 1993) (fig. 1). In some places the fault trace is observed, but along most of its trace it is eroded. In front of the basement granitic rocks, alluvial fans are more prominent than the sedimentary rocks. The value of the S_{mf} for this front is 1.6. The S_{mf} was calculated for the section of the front where basement rocks crops out and was found to be 1.08, and for the sedimentary rocks 2.6. (fig. 3) shows a straight mountain front on Precambrian basement, and (fig. 4) shows a more sinuous front composed of Cambrian sandstone.

Front 2

North of Wadi Musa fault (fig. 1), the width of the Wadi Araba floor increases gradually due to the change of the escarpment orientation from N10E to N30E. The geology of this front is controlled by the Quweira fault (fig. 1). This fault is one of the major sinistral faults east of the Dead Sea rift. It strikes almost N-S, extending from the southern border of Jordan to Wadi Araba. In Wadi Araba it shows vertical throw of about 700 m. The western downthrown block is composed of highly faulted Cretaceous rocks, while the upthrown block is composed of Precambrian-Cambrian porphyrites (Bender, 1968). This front composed of Cretaceous rocks south of the intersection of the Quweira fault with Wadi Araba and composed of porphyrite between this intersection to Salawan fault. This front coincides with the Malqa fault (Rabba, 1991). The S_{mf} index for this front equals 1.3. This front is truncated in the north by the E-W striking Salawan fault, which forms the southern boundary of the Dana horst, where the mountain front retreats further to the east. The Wadi Araba floor reaches its maximum width in the area of Al Qurayqira (fig. 1).

Front 3

The southern boundary of this front begins at the southern end of Fidan Precambrian granitic massif. It is truncated by the western extension of the Dana E- W fault, which forms the northern boundary of the Dana horst (fig. 1). This front extends to the Khunaizira transverse fault, which represents the southern boundary of the Dead Sea basin and the northern end of Wadi Araba. South of Wadi Ghuwaiba, the mountain front consists of Precambrian basement, and north of this valley it consists of Cretaceous and Tertiary calcareous rocks. The mountains east of this front are different from those east of the other fronts by their low elevations close to the rift, which increase gradually eastwards. The value of S_{mf} index = 1.2. Alluvial fans were formed in front of the Fidan basement massif and in front of Dhahal calcareous mountains (fig. 5). In these two areas, the Dead Sea transform fault trace is close to the mountain front. S_{mf} index for the Dhahal Mountains is 1.09.

RATIO OF VALLEY-FLOOR WIDTH TO VALLEY HEIGHT (V_f)

This index reflects the difference between V-shaped valleys that are downcut in response to active uplift (low values of V_f) and broad-floored valleys that are eroding lat-

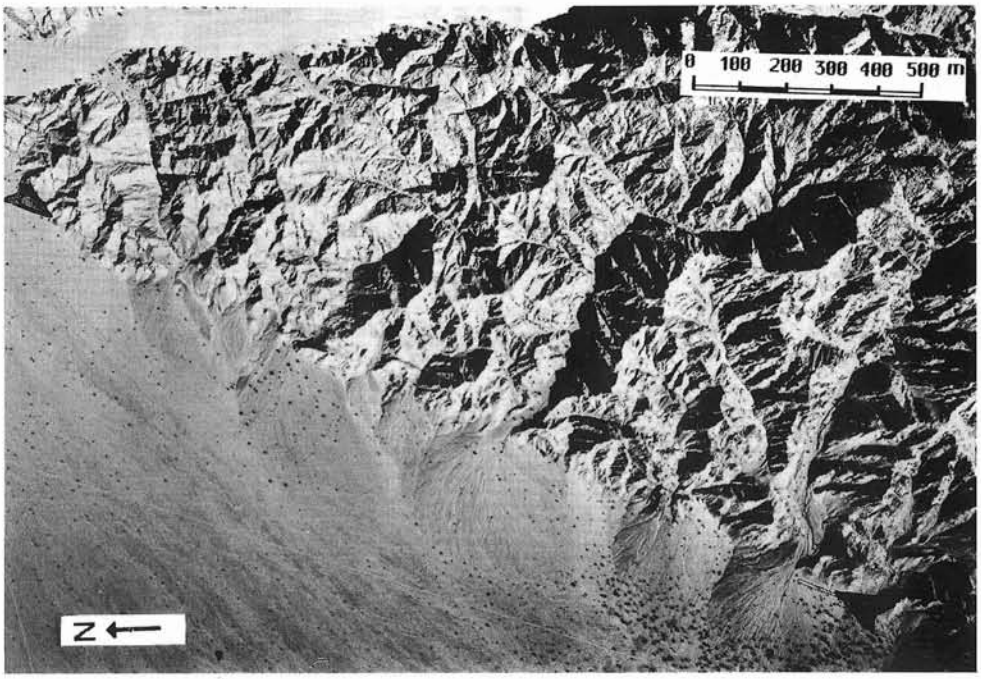

FIG. 3 - Aerial photograph showing straight mountain front (low S_{mf} index) in granitic rocks east of southern Wadi Araba. Different sizes of alluvial fans were formed at the granitic mountain front (location is shown in fig. 1).

erally 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 (V_f)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 Esc is the elevation of the valley floor (Bull & McFadden, 1977). In this study, as in previous studies (Bull, 1978), these parameters are measured upstream from the front, at a distance of 0.1 of the drainage basin

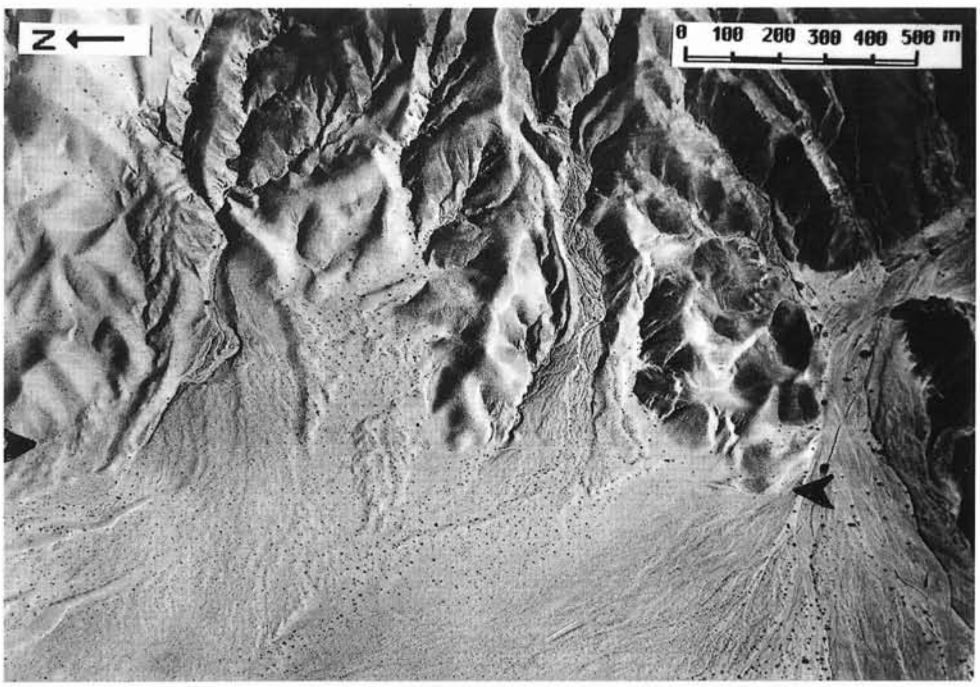

FIG. 4 - Arial photograph showing sinuous mountain front (high S_{mf} idex) east of central Wadi Araba in Cambrian sandstone. Wide valley floors are also clear on the photograph (location is shown in fig. 1).

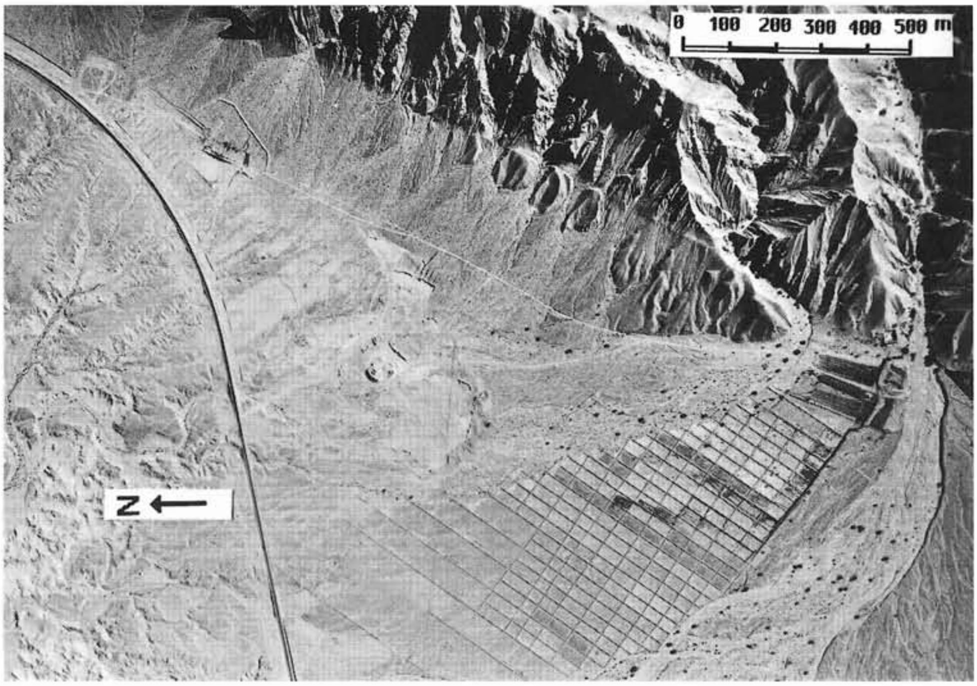

FIG. 5 - Arial photograph showing straight mountain front in calcareous Upper Cretaceous rocks in Dhahal area in northern Wadi Araba.In this area, the Dead Sea transform fault coincides with the mountain front. Different generations of alluvial fan surfaces are clear on the photograph (location is shown in fig. 1).

TABLE 1 - Values of V_f index

Front Number	Name of Wadi	V_f value for wadi	V_f average for front
	Wadi el Yutum	0.54	
	Wadi Huweiti	0.30	
	Wadi Malghan	0.71	
	Wadi As - Sammaniyah	0.32	
	Wadi Al-Muhtadi	0.75	
	Wadi Al Waara	0.42	
	Wadi Rahma	0.75	
1	Wadi Turban	0.42	2.21
	Wadi Nukhaila	1.38	
	Wadi Uheimir	8.31	
	Wadi As Siq	1.66	
	Wadi Barqa	0.26	
	Wadi Huwwar	1.25	
	Wadi Mufarqade	5.0	
	Wadi Muhermi	11.5	
	Wadi Jurf Himar	1.8	
	Wadi Musa	5.5	
	Wadi Qunay	1.3	
2	Wadi As Sakakin	0.27	1.59
	Wadi Broos	0.37	
	Wadi Mibar	0.52	
	Wadi Fidan	1.9	
	Wadi Ghuweiba	2.7	
3	Wadi Madsus	1.1	1.35
	Wadi Dhahal	1.0	
	Wadi Tilah	1.2	
	Wadi Khunaizira	0.2	

length. Table (1) shows the values of V_f for the major valleys east of Wadi Araba, the index values varied from 0.27 to 11.5. The values less than 1 are mostly measured in the hard igneous rocks, while the values range from 1-2 are mostly in the hard Cambrian sandstone or Upper Cretaceous and Tertiary limestone. Higher index values (more than 5) are measured in the soft Lower Cretaceous sandstone. Fig. 2 shows the valleys, where the V_f were measured.

DISCUSSION AND CONCLUSIONS

Mountain front sinuosity and valley width to height ratio were used to evaluate the tectonic activity of the mountain ranges bounding the eastern side of Wadi Araba, which is part of the Dead Sea Transform. Indications of active strike slip movement along the transform are abundant, but evidence of uplift along the boundary faults is also present. The escarpment east of Wadi Araba was divided into three fronts based on the orientation and the continuity of the escarpment. Mountain fronts 1 and 2 are bounded and controlled by eroded normal faults (Aqaba-Gharandal and Malqa faults respectively), while the Dead Sea Transform fault control the escarpment of front 3. The three fronts are characterized by low, mountain front sinuosity indices (table 2).

Front 1 has the highest S_{mf} value due to the exposure of the more erodible rocks along the northern half of the front (S_{mf} =2.6). The southern half, where granitic base-

TABLE 2 - Values of geomorphological indices for mountain fronts

Front No	Front location	Bounding rocks	Front orientation	Front length (km)	S_{mf} V_f	Average
1	Between Wadi el-Yutum and Wadi Jurf Himar.	Precambrian basement, sandstone and Carbonates.	N10E	67	1.6	2.21
2	Between Wadi Musa and Wadi Mibar	Sandstone, rhyolite and carbonates	N30E	22	1.3	1.59
3	Between Wadi Fidan and Wadi Khunaizira	Precambrian basement and carbonates	N20E	33	1.2	1.35

ment outcrops, the S_{mf} is extremely low (1.08). The average V_f values for the valleys crossing this front is 2.21 (table 1). Values less than 1 are measured in the valleys cutting the hard granitic rocks, while higher values are measured in less resistance sedimentary rocks, especially those cutting the Lower Cretaceous, Kurnub sandstone like Wadi Uheimir and Wadi Muhermi (table 1). S_{mf} value for front 2 is very low (1.3), because most of this front is composed of hard porphyritic rocks, the sedimentary rocks show also a straight mountain front. The average value of the V_f for the valleys crossing this front is very low (1.59). A high value is observed in Wadi Musa, which cuts less resistive sandstone, while other valleys, which have values less than 1 cut through hard porphyritic rocks. Front 3, has the lowest S_{mf} index (1.2), although the exposed rocks are mainly sedimentary. The average V_f index for the valleys crossing this front is 1.35, which is the lowest for the three fronts. V_f indices were measured in sedimentary rocks. Fronts 1 and 2 coincide with boundary normal faults (Aqaba- Gharandal fault and Malqa fault respectively), while the Dead Sea transform passes close to front 3, especially in the northern part of the front in Dhahal mountains, where the mountain front is a straight line (fig. 5).

From the previous discussion, it can be concluded that the S_{mf} and V_f indices for the three fronts east of Wadi Araba are low and indicate active mountain fronts, as compared with the work of Bull & McFadden (1977) and Bull (1978). In this study the effect of the lithological changes is clear on the index values within the same front. Extreme low values of S_{mf} and V_f indices are observed in the hard igneous rocks and extreme low values are observed in the soft Lower Cretaceous sandstone. Very low indices are also observed in the Cambrian sandstone and Upper Cretaceous calcareous rocks, which support the idea of active mountain fronts.

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