JJEES

Volume 5, Number 2, December. 2013
ISSN 1995-6681
Pages 79- 86

Jordan Journal of Earth and Environmental Sciences

Tectonic Geomorphology of Alluvial Fans east of the Wadi Araba Fault (Dead Sea Transform), Jordan

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Received 6 April, 2012; accepted 5 October, 2013

Abstract

This study deals with the development of alluvial fans at the foot of the fault-controlled eastern mountainous chain in Wadi Araba Desert (WAD). The alluvial fans are fed mainly by debris flows of ephemeral streams flowing westward across the eastern highlands to the desert plain and/or inland sabkhas. Morphometric analyses showed that fan surface area (FSA) is directly proportional to drainage basin area (DBA), whereas the fan slope (FS) is inversely proportional to 'FSA' or decreases proportionally as the talus cones evolve into fans. The architecture and evolution of the fan/drainage network are controlled by vigorous tectonic forces that began in the Early Miocene. Bedrock geology, history and rates of sediment supply, and the intensity and duration of surface flow more likely contributed to the progressive changes of fans/drainage basin system. The increment of 'FS' towards fan head pertinent to sediment buildup and the occurrence of steep normal fault scarps at mountain edges may reflect recent uplift in the catchment area. The alluvial fans were dislocated apart from drainage basins as a result of strike-slip movement along the Dead Sea transform (DST) and its subsidiary faults. Fanglomerates are compositionally immature and matrix-supported. The angular-subangular shape of clasts indicates a minimum or non-intensive abrasion has been occurred before sedimentation.

Keywords: Wadi Araba , Jordan, Alluvial Fans, Dead Sea.

1. Introduction

1.1. Previous works

Alluvial fans are among the fascinating geological features, like sand dunes, mud pans and saline inland sabkhas that characterize Wadi Araba desert (WAD). The most recent work describing the sedimentology and morphology of alluvial fans in Wadi Araba is the study of Makhlouf *et al.* (2010). Features, other than alluvial fans, have received considerable attention from researchers in modern decades. For instance, the inland sabkhas and sand dunes in 'WAD' are carefully studied by Abed & Al-Hawari (1991) and Saqqa & Atallah (2004), respectively. Until now, little attention has been paid to studying the development of alluvial fans in 'WAD'. The alluvial fans were occasionally reported as part of geology studies in the area (Bender, 1974; Saqqa, 1998). Klinger *et al.* (2000) and Niemi *et al.* (2001) pointed to fan/drainage basin offsets In the northern part of 'WAD' resulted by 4-5 mm/yr slippages of sinistral movement along the Wadi Araba fault. Klinger *et al.* (2003) attributed the development of alluvial deposits and river entrenchment in the Dead Sea area to lake-level fluctuations, which in turn was as a function of late Quaternary climate changes.

McLaren *et al.* (2004) explained modes of sedimentation and landscape evolution of the Quaternary deposits in Wadi Faynan, to the south of the Dead Sea, in view of tectonic setting and paleoclimate. On the western part of 'WAD', Ginat *et al.* (1998) demonstrated incidence of a 15km left-lateral strike-slip displacement along the Dead Sea Transform (DST) in the Late Pliocene to Early Pleistocene. So, dislocation is very likely of the western highlands alluvial fans system away from its original position. Ben-David *et al.* (2002) described Late Miocene fluvial landscapes evolution in view of the tectonic settings in the Central Naqab Desert (west of study area).

Other studies dealing with alluvial fan evolution were done by several authors in neighboring countries. For instance, the study of Ochugi & Ochugi (2004) dealt with the development of Late Quaternary alluvial fan/drainage basin system in Afrin region inSyria and its relation to Late Quaternary climatic change. The study of Beaumont (1972) evaluated the evolution and hydrological conditions of 26 alluvial fans and their drainage

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basins in the southern margin of Elburz Mountains, SE Tahran. The study of Alçiçek *et al.* (2005) explained the tectonic evolution of the Çameli Basin in SW Anatolia. This basin, which hosts a group of alluvial fans and other fluvial/lacustrine sediments, evolved during three distinct stages of tectonic extensions and resulted in a prominent change in the sedimentation pattern. A recent study on the Quaternary morphotectonics of Wadi Araba by Le Beon *et al*. (2012) identified seven successive morphostratigraphic levels in Wadi Araba. They observed three main phases of alluviation at 102, 163 and 324 ky. Their study estimated the fault slip rate along the Wadi Araba fault to be 5-7 mm/yr.

1.2. Aim of Study

The present work seeks to understand the morphogenesis and tectonic evolution of the alluvial fans system on the eastern rim of Wadi Araba Desert 'WAD', south of the Dead Sea.

1.3. Methods of Study

Aerial photographs (1:10000) and topographic sheets (1:50000) were used to find out the relationship between fan surface area (FSA), drainage basin area (DBA), and fan slope (FS). Areas were measured by dividing the fan surface and basins into polygons. Fan slopes were measured from the contour lines of the 1:50 000 topographic sheets Computations of 'FSA', 'DBA', and 'FS' are essential means for describing morphotectonic evolution of alluvial fans. Lithotype of fanglomerates were described and gravel shapes were analyzed (Zingg method, 1935). Grain size analysis, particularly of the distal part of Wadi Rahma alluvial fan sediments, was carried out using Retsch-type sieve automated shaker.

2. Location and Geological Setting

The investigated alluvial fans rest upon the foot of the eastern mountainous chain in 'WAD'. The fans emerge at about 10 km away from the northern shorelines of the Gulf of Aqaba and stretch out north along the Dead Sea Rift to the district of Rahma (Fig.1). The bedrock of alluvial fans system and its catchment is the granitic rocks of the Precambrian Aqaba complex and the acidic & mafic dikes and metasediment associations. Thick sequences of Paleozoic–Mesozoic sediments rest non-conformably upon the Precambrian igneous rocks (Jarrar, 1984; Rashdan, 1988; Ibrahim, 1991). Late Quaternary sand dunes, inland sabkhas and mud flats cover extensive areas of 'WAD'.

Wadi Araba-Dead Sea-Jordan Rift Valley province is a narrow depression between Gulf of Aqaba in the south to Lake Tiberias "The Sea of Galilee" in the north. It is about 375 km long and 9-25km width. The Rift is a part of a large-scale fracture zone extending between the East African Rift and southeast Turkey. The Jordanian Rift aligns the Dead Sea Transform (DST), which is a major left lateral strike slip fault, which runs parallel to the eastern escarpment (Fig.1). The fault has been active since the Miocene and has caused cumulative displacements of about 107km.

The Jordanian Rift is tectonically and seismological active dry region that witnessed several past earthquakes (Garfunkel *et al*., 1981) and is still active.

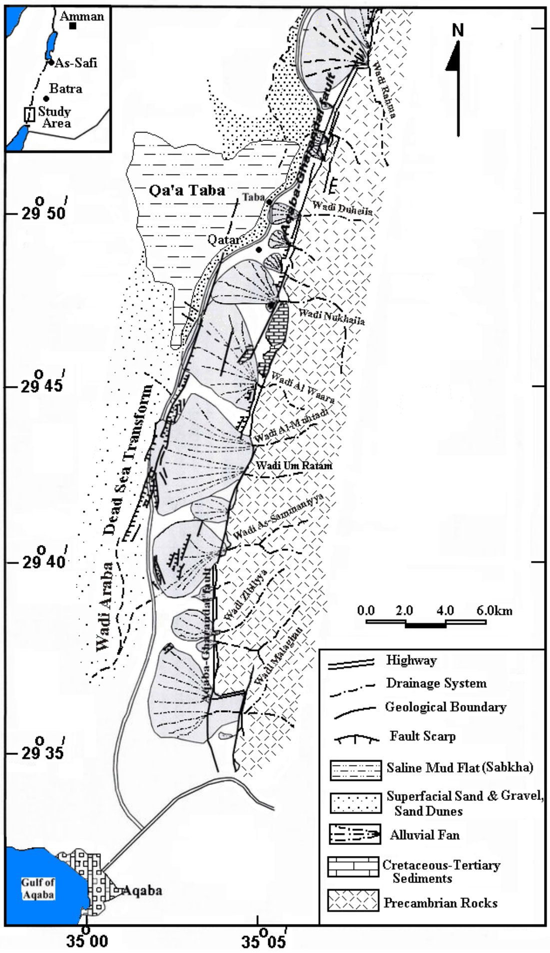

Figure 1. Geologic map of alluvial fans, south of Wadi Araba. Dead Sea Transform (DST) cuts the western parts of some fans forming pull apart basins. Secondary faults of DST cut also fan surfaces.

3. Climate and Geomorphology

Wadi Araba desert 'WAD' and the adjacent Naqab Desert to the west form rain shadow zone between the eastern and western topographic highs. Present-day climate represents seasons of short dry-cold winter and lengthy dry-hot summer. The maximum temperature may rise up to 50°C in summer and drops to 0.0°C in winter. The diurnal temperature variations are large enough (>30°C) to restrict plant growth. Annual rainfall is normally less than 100mm. Eastern highlands may receive over 200 mm/a. The mean potential evapotranspiration is very high (ca. 2200-2500mm/a) resulted in a rapid loss of soil moisture. Relative humidity fluctuates between 53%-62% in winter and 30%-40% in summer. Localized storms occur mainly in conjunction with active Red Sea troughs or low-pressures centered over the southern parts of Jordan and adjacent regions. Dust storms are principally developed in spring-early summer times (Saqqa and Atallah, 2004).

Several authors stated that universal high rainfalls and fluvial erosions were much more effective during the warm interglacial periods in Late Pleistocene-Early Holocene (Gasse *et al.*, 1987; Glennie, 1987; Petit-Maire and Guo, 1997; El-Baz, 1998; Zhuo *et al.*, 1998).

The western and eastern mountainous chains vary greatly in elevations. The eastern chain has an elevation in excess of 1000m.a.s.l. whereas the western chain is much less (around 300m.a.s.l.) (Abed and Al-Hawari, 1991). The higher elevation of eastern chain referred to as an immediate upwarping along the DST fault during NNE horizontal movement of the Arabian plate (Abed and Al-Hawari, 1991). The eastern mountain range is mainly characterized by the existence of structurally controlled scarps exerted by normal faulting. The eastern highlands are deeply dissected into east-west steep-sided valleys or gorges. The average width: height ratio of the developed valleys is 0.54 (Atallah, 2002). These valleys are practically the catchment of alluvial fans. Stream courses in catchment areas follow, at most, fracture systems. We believe that the configuration of drainage basins and streams was affected by net expansions during active tectonic uplifts.

4. Alluvial Fans Settings

Alluvial fans trap sediments delivered from mountain source areas and affect sediment dynamics downstream, either in relation to distal fluvial systems or to sedimentary basin environments (Harvey *et al.*, 2005 and other references therein). Alluvial fans are common in arid-semi arid regions, but they may occur in arctic, alpine, humid temperate and humid tropical regions (Harvey *et al*., 2005 and other references therein). Alluvial fans of arid environments are usually developed when streams depart the mountainous summits and debouche over desert plains and drop straight away most of their sediments. Alluvial fans indicate periods of heavy rains or flashfloods with a resultant debris-flow and stream-flood deposition. Produced fans range in size from small debris cones (< 50m in length) to fluvially dominated megafans up to 60km in length (Harvey *et al*., 2005 and other references therein). The sizes of alluvial fans which depend basically on rates of sediment supply may be a question of climatic changes (Bull, 1991; Harvey, 1997; Harvey *et al*., 1999; Klinger *et al*., 2003). Oguchi and Oguchi (2004) claimed that a rapid geomorphic response to climatic changes is in the form of talus dissection, debris flow, and fan deposition. Klinger *et al*., (2003) stated that changes of geomorphic systems in arid regions exerted by external variables are slow. Besides climate, a number of factors may also influence aggradations/incision processes and alluvial fan geometry. Among these factors are base-level changes caused by sea-level or lake-level fluctuations and/or tectonics (Merritts *et al*., 1994; Klinger *et al*., 2003), variations in sedimentary processes of fluvial systems (Tucker and Slingerland, 1996) geomorphic adjustment of catchment area and fan systems (Bull, 1991), and temporal as well as spatial extents of aggradations/incision processes in response to vegetation growth and climatic changes (Knox, 1984; Bull,1991). Drainage basins respond very differently to climatic changes. A slightly different climatic change may cause a very different geomorphic response. Such a complexity obscures a clear vision about climatic controls on timing and extent of aggradations/incision episodes (Klinger *et al*., 2003).

Stanistreet and McCarthy (1993) recognized three kinds of subaerial fans. These are expressed in terms of debris flow dominated fans, braided fluvial fans, and low-sinuosity/meandering fluvial fans. This triangular scheme can be compared with the classification of Collinson (1996) expressed in terms of gravity flow, fluvial and terminal fans. Blair and McPherson (1994) recommended limiting the term alluvial fan to steep systems with a slope range of 1.5° - 25° in which debris flow and sheet-floods are common. This has been criticized by others who distinguished alluvial fans based on radial sediment dispersal and their cone shape from fluvial systems with linear-elongated patterns. They stated that alluvial fans are a type of fluvial depositional system in which their geomorphic character is much more important than their fluvial style (Harvey *et al*., 2005, among other references).

5. Methodology

Fieldwork, including geological mapping and lithologic description of alluvial fans system at the foot of the eastern mountainous chain in the southern part of Wadi Araba Desert, was carried out. Aerial photographs were used to delineate depositional patterns, tectonic uplift and dislocations of alluvial fans. Size of alluvial fans and slopes of their surfaces in addition to drainage basin areas were determined, and the relationships between these parameters were identified.

6. Results

6.1. Source of Alluvial Fans Sediments

The main source of alluvial fan sediments is the Precambrian granites of Aqaba complex and the associated volcanic materials and meta-sediments. Eight different types, at least, of clasts were recognized; the most common are granite, granodiorite, rhyolite, schist, and gneiss. Diorite and trachytes are less common.

6.2. Morphometric Analyses and Depositional Pattern of Fanglomerates

Debris flow and stream flood facies are responsible for the formation of alluvial fans. Debris flow facies consist of chaotic mixture of fine-coarse clastic sediments. Clasts are supported with sand-clay matrix, which makes about 40% of the original size, and their sizes vary between granules to very large boulders or blocks. The grain-supported stream flood facies is confined to braided channels cut into fan surface and radiate out down slope from fan apex. The channels may go through periods of down cutting, infilling, and channels migration (Fig. 2).

Grain size analysis of 13 samples along a horizontal transect in the distal part of Wadi Rahma fan is shown in Fig. (3). The percentages of gravel, sand and mud are between 47%-84%, 13%-43%, and 3%-10% with averages as 61%, 33% and 6%, respectively. The low percent of fines (mud size) is more likely attributed to down slope washout by surface running waters, and the washed-out fines discharge into the nearby inland sabkhas or desert plain. The great variation in grain size distribution indicates a wide range of hydrodynamic processes acting during deposition of the fans. Grain size gradation from coarse to fine is from fanhead to fantoe.

Grain shape analysis (Zingg, 1935) demonstrates the lack of actual clustering of any type of clasts to a certain shape regardless the differences in grain size (Fig. 4), but they are randomly distributed between equant (spheroid), oblate (disc), bladed and prolate grain shapes without an aspect of preference.

Concerning the roundness, clasts are mainly angular-subangular being experienced low rates of abrasion through transport. The depositional features and textural attributes of fanglomerates give an impression that the sediments traveled only short distances from the source area and have experienced little modifications before deposition.

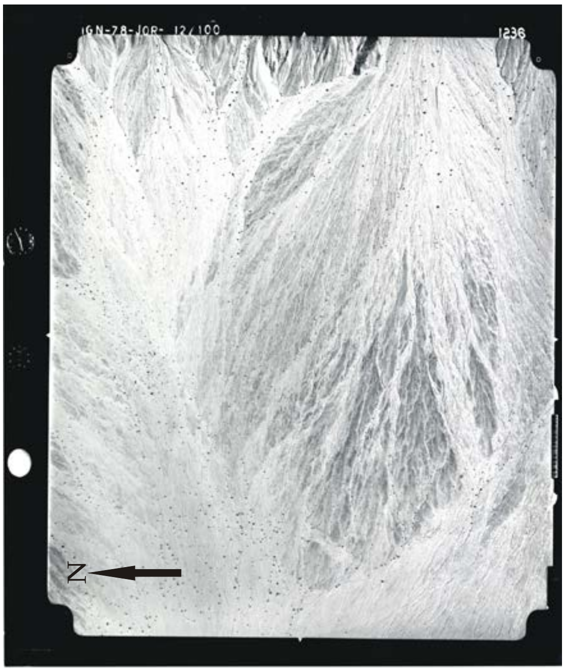

Figure 2. Aerial photograph of Wadi Zibliyya alluvial fan showing color contrast (light-dark) of fan surface due to tectonic uplift.

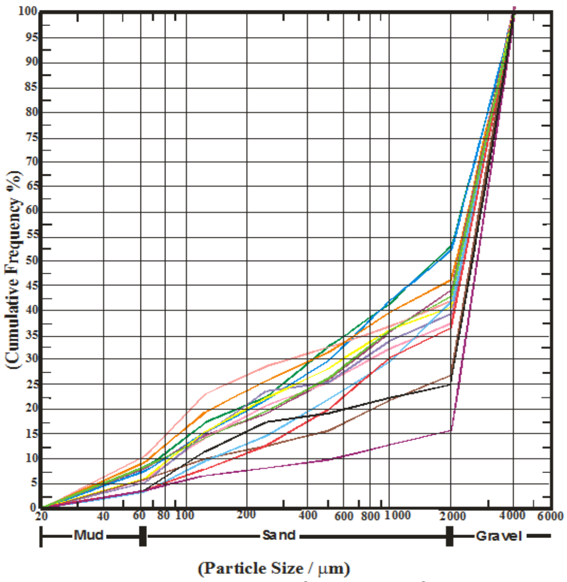

Figure 3. Grain size analysis of sediments from distal part of Wadi Rahma fan.

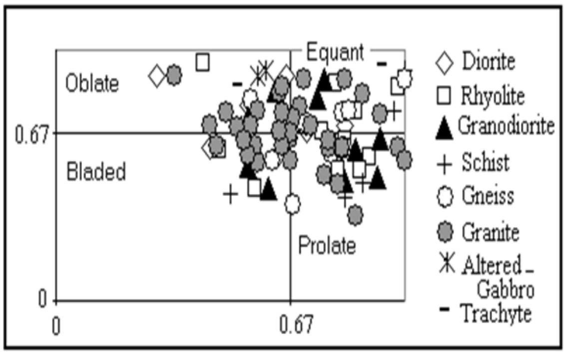

Figure 4. Grain shape analysis Wadi Rahma fanglomerates.

6.3. Geometry of Fans/Drainage Basins

The shape of alluvial fans is generally conical. They concave-up radially (head-to-toe) and concave-down laterally (margin-to-margin. Feeding drainage basins have no definite shapes. They are somewhat elongated in larger drainage basins to semicircular in smaller drainage basins (Fig. 5)..Measurements of fan surface area (FSA), drainage basin area (DBA) and fan slope (FS) pointed to variations in size and slope of the investigated alluvial fans (Table 1). FSA values are between 1.94 km^2 (Wadi Duhaila alluvial fan 'F8, and 13.81 km^2 (Wadi al-Muhtadi alluvial fan 'F5,). DBA values are between 5.7 km^2 (Wadi Zibliyya, 'D2,) and 73.09 km^2 (Wadi Rahma basin 'D9,). It seems that DBA for all fans with the exception of Wadi Um Ratam fan (F4) is larger than FSA. A direct relationship between DBA and FSA is demonstrated in Fig. (6). The size of the alluvial fans is related to the size of drainage basins, available accommodation space, rates of sediment delivery and style of sediment production in the catchment areas.

Classic alluvial fans of arid regions are usually laid down in tectonically active basins. The available capacity of such basins will be increased if the drainage basins enlarge. Smaller drainage basins deliver sediments to alluvial fans in every transport event more effectively than larger drainage basins can do (Blair and McPherson, 1994; Ritter *et al*., 1995). This can be visualized in the increase of FSA relevant to DBA as it is the case in Wadi Um Ratam fan (Table 1). Fan slope (FS) is a function of lithology in the source area, particle size of debris material, drainage basin area (DBA), rates of discharge (Bull, 1978; Bull and McFadden, 1977) and size of alluvial fan (Bull, 1964; Hooke, 1965). The results of the present study (Table 1) showed that alluvial fans slopes are between 2.6° (Wadi Rahma alluvial fan " F9") and 6.3°(Wadi Duheila alluvial fan "F8"). A modest inverse relationship is more likely between FS and FSA (Fig. 6) . This is consistent with the findings of Bull (1964) and Hooke (1965): sizeable alluvial fan surfaces are characterized by low slope angles and vice versa. A decrease in FS may be attributed to systematic variations in debris caliber, depositional processes or an increase of discharge (Hooke, 1965). The alluvial fans of Wadi Al-Muhtadi (F5) and Wadi Rahma (F9) are mainly produced by relatively large discharges resulted in gentler slope fan surfaces. Whereas Wadi Duheila alluvial fan (F8) is more likely produced by a lower discharge and it has a higher-slope fan surface.

Table 1. Fan/Drainage basin areas ((km^2) and fan slope (degrees).

Fan number (F_{1-9})	Name of fan	*Fan area (FA) (km^2)	** Drainage basin area (DBA) (km^2)	Fan slope (degree)
F_1	Wadi Malghan fan.	6.48	21.22	3.2
F_2	Wadi Zibliyya fan.	3.90	5.70	4.6
F_3	Wadi As-Sammaniyya fan.	8.84	11.50	4.3
F_4	Wadi Um Ratam fan.	10.24	5.84	4.3
F_5	Wadi Al Muhtadi fan.	13.81	30.96	3.2
F_6	Wadi Al Waara fan.	5.80	6.31	4.1
F_7	Wadi Nukhaila fan.	7.33	12.07	4.5
F_8	Wadi Duhaila	1.94	7.63	6.3
F_9	Wadi Rahma	11.61	73.09	2.6

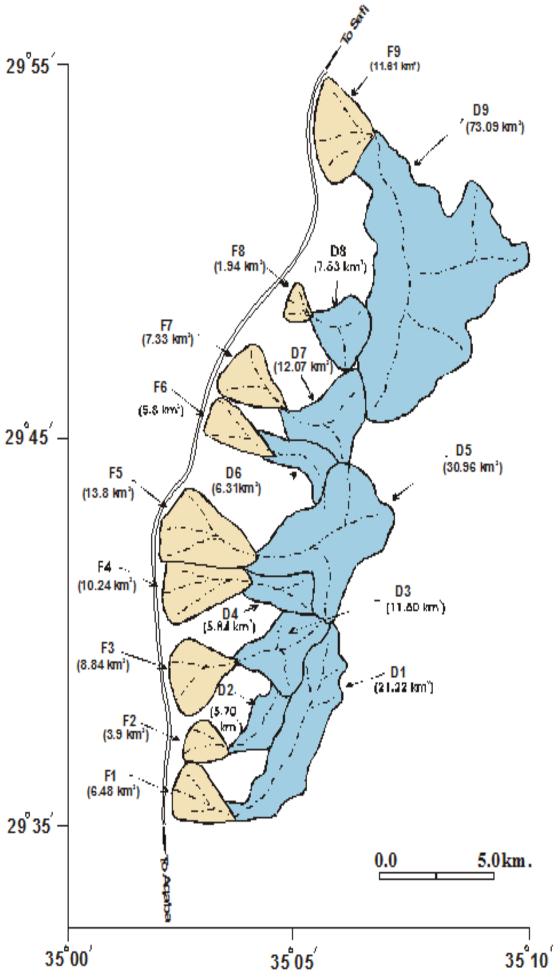

Figure 5. Geometry and surface area of fan/drainage basin system.

(A)

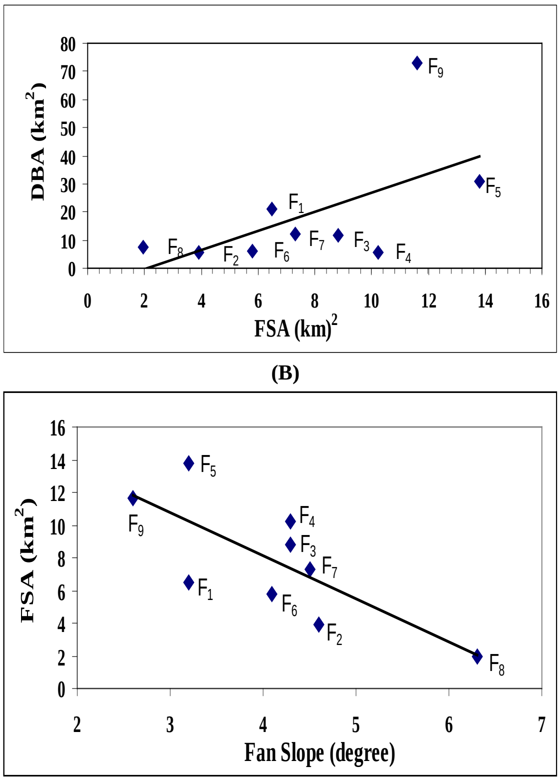

Figure 6. (**A**) Scatter plot of fan surface area (FSA) vs. drainage basin area (DBA). (**B**) Scatter plot of fan surface area (FSA) vs. fan slope (FS).

6.4. Fans Evolution as a Function of Tectonic Setting

Field observations and aerial-photographs analyses show a direct relationship between alluvial fans development and tectonic setting. Active faulting along the DST and its subsidiary faults control strongly sedimentation patterns and evolution of alluvial fans. The Aqaba-Gharandal fault (Fig. 7) is a typical example of an active faulting and scarp development. Fault-controlled scarps, pull-apart basins and narrow grabens hosted talus deposits and fanglomerates are very common in Wadi Ratam, Wadi Al Muhtadi, Wadi Malghan and Wadi As-Sammaniyya in the study area (Atallah and Al Taj, 2004). Mountain-front sinuosity was measured along the mountain front east of Wadi Araba (Atallah, 2002). It is the ratio between the length of the mountain front and the straight- line length of the front (Bull, 1978). The low sinuosity index (1.08) of the adjacent eastern mountain front is a sign for a strong uplift, which was responsible for the development of alluvial fans in the Pleistocene time (Atallah, 2002; Atallah and Al-Taj, 2004). Aerial photographs display color contrasts between younger sediments (light-colored) laid down in alluvial fans proximities and older sediments (dark-colored) in distal parts (Fig. 2). The contrast in colors has been explained by Bull (1978) as a sign of an active uplift in highland regions and fanhead entrenchment. Tectonic forces not only influences the geomorphic setting of alluvial fans, but slopes of alluvial fans surfaces will be affected through uplift and changes in base levels (Calvache *et al.*, 1997; Harvey, 2002).

Type of bedrock, geomorphic adjustment, and geometry of drainage basins as well as the rates and history of sediment supply may all contribute in alluvial fan development. The geomorphic response to climate change in the Quaternary was more likely in the form of fanhead entrenchment or talus dissection. We believe that any excess of stream power relative to sediment load enhances fan entrenchment.

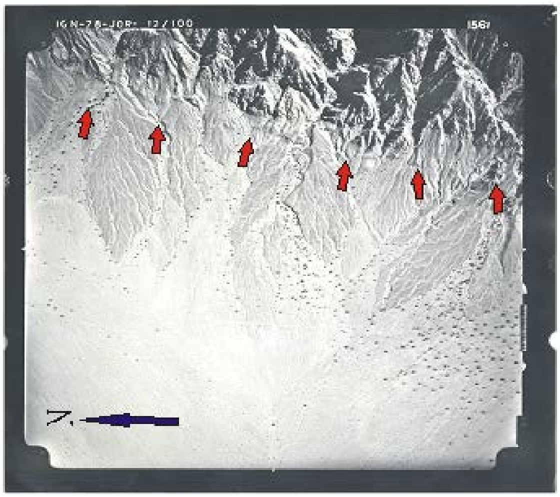

Figure 7. Aerial photograph showing an active fault scarp produced by Aqaba-Gharandal fault (arrows) north of Wadi Rahma.

7. Discussion and Conclusions

The present study relies primarily on the tectonic uplift, and the initiation of the Dead Sea Transform (DST) to explain the geomorphic evolution of alluvial fans at the foot of eastern mountains, south of Wadi Araba Desert (WAD). The results showed that the fan surface area (FSA) is generally proportional to the drainage basin area (DBA) because of greater sediment inputs delivered to the site of deposition. Concerning the inverse relationship between fan surface area (FSA) and fan slope (FS), we intimately know that sediment transport in large drainage basins is for longer distances, comparative to short transport in smaller drainage basins. Because of this, the longer transport of sediments leads to the development of relatively larger alluvial fans having more fine sediments and with lower slope angles and vice versa (Bull, 1964; Hooke, 1965). In addition, tectonic uplift and sediment accretion at mouths of streams produce steep-slope and smaller alluvial fans relative to larger alluvial fans with more gentle-slope surfaces. The occurrence of Aqaba-Ghrarandal fault-scarps at the base of the eastern mountains front of Wadi Araba, the tilting of fans due west and the deposition of younger sediments at the proximal part of alluvial fans (e.g .Wadi Zibliyya fan) are all strong pieces of evidence on the tectonic uplift in the catchment areas.

The strike slip movement along the DST (Ginat *et al.*, 1998) caused some dislocations to alluvial fans off their original sites (Fig. 8). Some of the fans were subjected to differential uplift (Fig. 9). In view of the tectonic setting, we may infer to the occurrence of some sequential development of drainage basins through stream capture. Any modification in catchment area affects dramatically the routings and sediment supply to the sedimentary basin. Therefore, the surface area and size of an alluvial fan adjusts to accommodate any change in the catchment area. Tectonic uplift may raise the upper portion of a drainage basin relative to the base level of a stream system. The net effect is to increase the overall gradient of stream and rates of down cutting toward the base level. Therefore, high rates of erosion in catchment area is expected, which is more likely exceed the rates of sedimentation in site of deposition. This conclusion agrees fairly with the obtained results, where DBA is greater than FSA (Table 1). However, the case in Wadi Um Ratam alluvial fan (F4) is dissimilar, where FSA value is nearly twice that of DBA (Table 1, Fig. 6). The reason behind this may refer to a sort of net expansion and stream capture. The capturing in catchment area of Wadi Um Ratam left behind an abandoned drainage basin, which was previously the feeding source of the related alluvial fan. The new-developed smaller drainage basin incorporated within the expanded drainage basin of Wadi Al Muhtadi fan (F5) and drained by the catchy stream is no doubt the new supplier for Wadi Um Ratam alluvial fan (F4) sediments. Therefore, we believe that Wadi Um Ratam alluvial fan (F4) developed prior to the stream capture. A similar approach was introduced by Mather *et al*. (2000) who studied three modern mountain catchment areas in SE Spain affected by a river capture. Later, other authors found that the catchment areas were effected by a regional tectonic uplift, most significantly by drainage net expansion and river capture rather than by a lowering of surface relief. Variables other than tectonic uplift may also interact to produce progressive changes in alluvial fan/drainage basin system; these are: the history and rates of sediment supply and the intense and duration of surface flow as a function of climate at time of deposition. Such variables need further assessment. In northern Wadi Araba (Dead Sea area), the story of alluvial fans development might be a little bit different. Klinger *et al*. (2003) looked for better understanding of the late Quaternary climatic changes and active tectonic impacts on morphogenesis of alluvial fans that have been deposited before lake transgression (Lisan period) which started at about 70 KY B.P. The said authors presumed that relative high-stand lake-water levels were interrupted by time periods of fans aggradations. Therefore, the climate change factor seems to have a priority to explain alluvial fans development in northern WAD.

However, this conclusion does not exactly mean that the tectonic forces did not have a role at that time. Whereas, the geometry and location of these alluvial fans were constrained to some extent, by tectonic forces since they formed at the base of cumulative normal fault scarps similar to the alluvial fans system, south of Wadi Araba. However, Klinger *et al*. (2003) believed that the tectonic control on episodes of alluvial fan aggradations and river entrenchment seems doubtful for the period of interest, since a 10m vertical movement along the Dead Sea shorelines was estimated in the post-Lisan period. Another correlation between alluvial fans and Quaternary climatic change (Le Beon, *et al*., 2012) shows that two of the three periods of alluviation are correlated with wet periods that are regionally well documented.

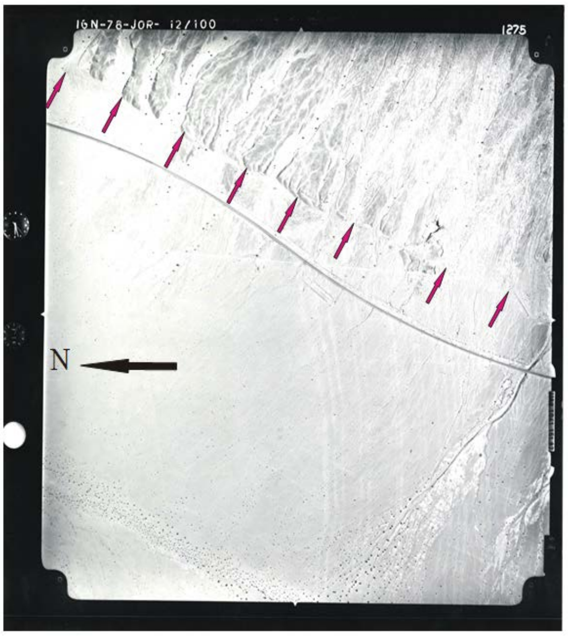

Figure 8. Aerial photograph showing dislocations in the western edge of Wadi Al Muhtadi fan caused by Wadi Araba strike slip fault. The fault is expressed by a prominent westward facing scarp and a horizontal offset of the fan surface.

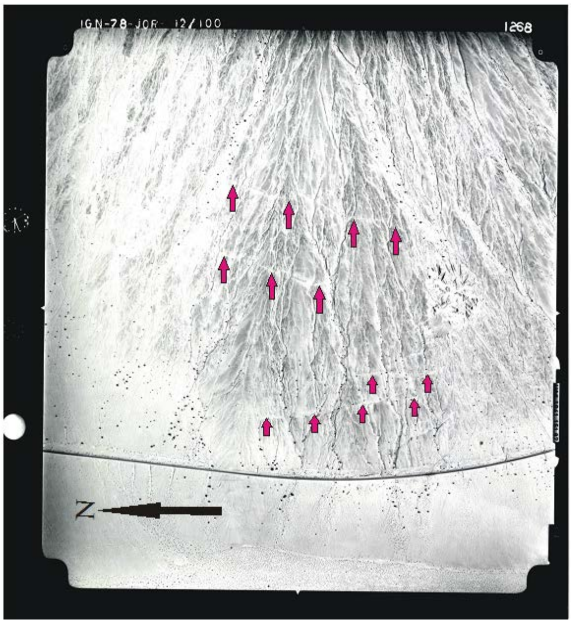

Figure 9. Aerial photograph of fault scarps affecting Wadi As Sammaniyya alluvial fan and causing some differential uplift of fan surface.

Acknowledgments

This work received financial support from Yarmouk University Research Council (Grant No. 1/2003). The authors would like to thank the two reviewers for their constructive comments on this paper.

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