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Sedimentology and Morphology of Quaternary Alluvial Fans in Wadi Araba, Southwest Jordan

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Abstract

The eastern rim of Wadi Araba in southwest Jordan displays distinct alluvial fans, which were developed since the time of formation of the Dead Sea Transform (DST), initiated in Mid Miocene times. The DST fault system controlled the development of the alluvial fans and their stacking pattern. Siliciclastic sediments were supplied from the east, and dispersed radially forming a stream-flow dominated alluvial fan system. The continuous uplift of the eastern granitic basement and overlying Phanerozoic sedimentary succession, and the active intramontane valleys, whose outlets at the mountain front were elevated continuously above the piedmont plains, resulted in deposition of alluvial fans that coalesced to produce a huge bajada complex comprising several generations of overlapping and superimposed lobes consisting mostly of granitic gravels. Eight lithofacies are identified, comprising three lithofacies associations: proximal fan; medial fan and distal fan. These were deposited in environments ranging from proximal shallow stream and sheet floods, channelized non-cohesive debris flows, medial heterolithic deposits, distal muds and sabkha evaporites.

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

1. Introduction

Alluvial fans are defined by geomorphological features rather than by a characteristic fluvial style. The most distinctive lithofacies components have been considered to be debris-flow deposits, although some fans are sandy (Miall, 1978; Rust, 1978, Harvey *et al*., 2005). Other characteristics of alluvial fans are radiating distributaries and cone-shaped architecture.

This study aims to provide a better understanding of the alluvial fans in southwest Jordan, and the controls on their architecture and the spatial variability of sedimentary associations during their development. Little previous sedimentological study has been carried on the alluvial fans of Wadi Araba. A general description of the alluvial fans has appeared in the bulletins of the Natural Resources Authority (Rabba, 1991; Tarawneh, 1992) and in Bender (1974) and Abed (2000). Galli (1999) discussed the tectonic control on the development of Wadi Araba alluvial fans. Frostick and Reid (1989) studied the alluvial fans exposed at the western side of the Dead Sea.

Owing to the paucity of data concerning the sedimentary record of the alluvial fans in Jordan, the present study provides characterization of the gravel-dominated alluvial fans based on lithofacies analysis, bed architecture and palaeocurrent directions measured in three-dimensional exposures. Wadi Araba alluvial fans are an important local source of groundwater in the prevailing arid region. For instance, the villages of Wadi Rahma and Qatar in Wadi Araba obtain their water supply from wells sunk in distal alluvial fans. The alluvial fans also provide a local source of aggregate. Wadi Araba alluvial fans are a valuable record of neotectonic seismic (earthquake) activities along Wadi Araba- Dead Sea Transform (DST) initiated in middle Miocene (Garfunkel *et al*., 1981), and can be used as indicators of the Dead Sea Transform fault evolution and climatic changes (Atallah and Al-Taj, 2004).

Wadi Araba (Fig. 1) is oriented NNE-SSW, and in the study area is 10-17 km wide in an E-W direction. The elevation of Wadi Araba in the study area, about 45 km north of Aqaba, ranges from zero m above sea level (ASL) in its southern part to about 75 m ASL in its northern part. The southern Wadi Araba is a hot, arid region. Average air temperature range is 17.7^{0}C-30.8^{0}C (Jordan Climatological Handbook, 2000). The daily maximum temperature can reach 48◦C during the summer. Annual rainfall averages 30.4 mm. The eastern mountain range receives up to 200 mm/year rain fall; flood water flows westwards via numerous wadis to Taba Sabkha. The western mountains receive only about 50 mm/year. Annual mean wind speed at the Aqaba airport, south of the study area, is 8.6 knots and 70% of the prevailing winds are northerly and 8% are southerly (Jordan Climatological Handbook, 2000).

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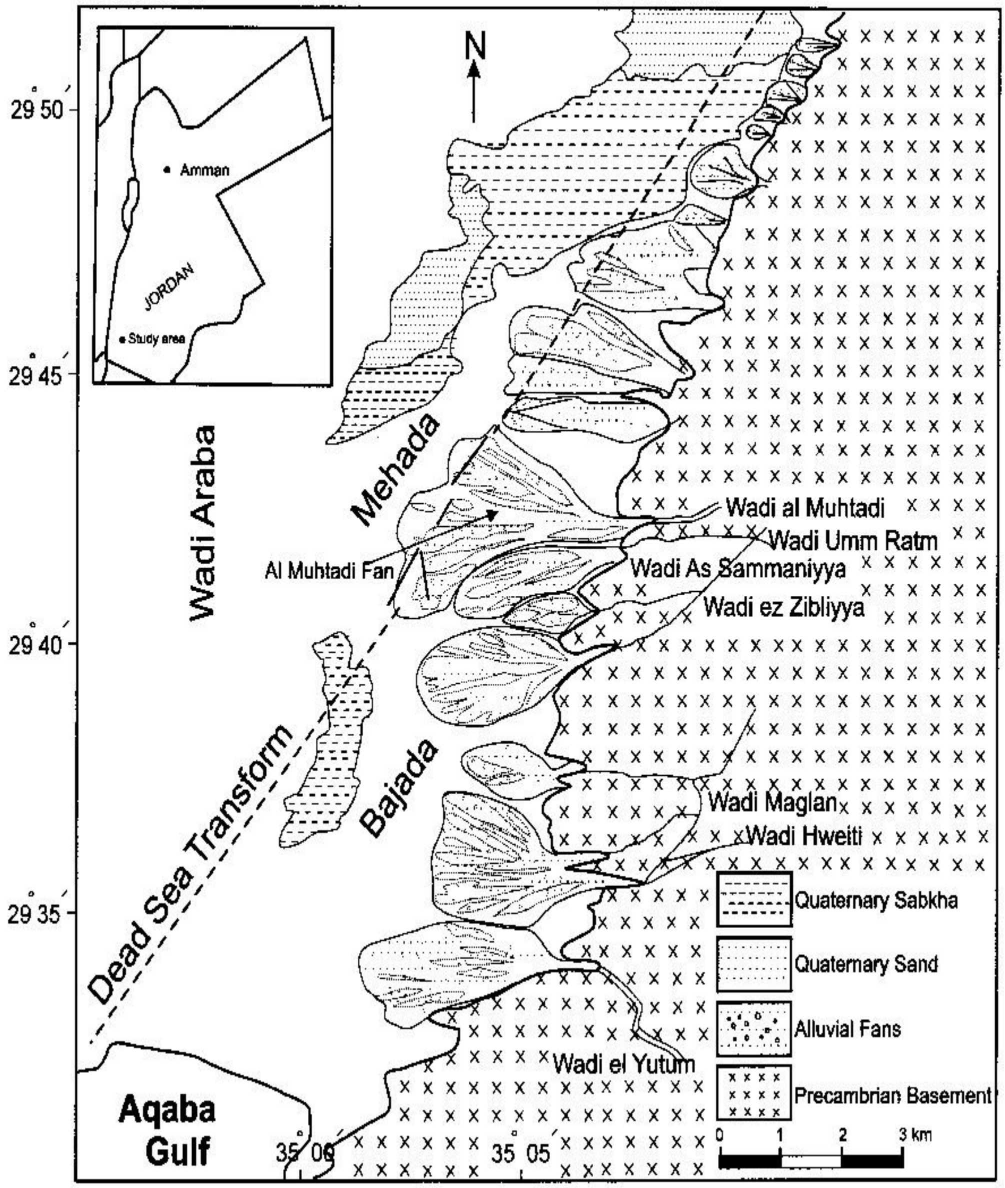

Fig. 1. Location map of the study area showing Wadi Araba, Precambrian Granitoid Basement, Dead Sea Transform (DST), multiple fans and palaeopidmont line. The map is based on satellite image.

2. Geological Setting

The alluvial fans in the study area are situated along the southernmost part of Wadi Araba, at the flanks of its eastern side. They form a series of alluvial fans extending from Aqaba, in the south, up till 45 km to the north (Fig. 1). Wadi Araba forms an important segment of the 1100 km long Red Sea - Dead Sea Transform (DST). The DST started to form in Mid-Miocene times as a plate boundary connecting the spreading regime of the Red Sea in the south with the collision regime in Anatolia in the north (Quennell, 1956; Atallah and Al-Taj, 2004). Jordan, including the eastern margin of the rift (Arabian Plate), is moving NNE along the DST with an average displacement of 5 mm/year, a total displacement, since the Miocene, of 107 km (Quennell, 1956; Amireh, 1997; Abed, 2000; Atallah and Al-Taj, 2004). Since its formation, the floor of the DST has been subsiding while the mountain ranges on both sides are rising. The net difference in elevation, at present, between the eastern mountains and the floor of the DST is in excess of 1000 m. This epeirogenic movement (uplift and subsidence) created several interconnected basins along the DST including Wadi Araba in the south, the Dead Sea basin in Central Jordan and Jordan Valley in northern part of Jordan. These subsiding basins have a huge accommodation space, and they will continue to have it as long as the DST tectonics are active.

The main DST fault runs obliquely in Wadi Araba and it cuts through the lower reaches (medial fan) of the investigated fans. Throughout most of its length the main transform fault is buried by superficial alluvial deposits and its position can only be inferred. However, at the Muhtadi medial fan, the trace of the fault splits into two faults producing a sag pond in between (Galli, 1999). Further north of the same fan a fault escarpment is also clear exposing some 10 m thick of the medial fan material (Fig. 1). The eastern mountain range consists entirely of the granitoids and later dyke rocks of the Aqaba Complex of late Neoproterozoic age (600-630 Ma) (Rashdan, 1988; McCourt, 1990; Ibrahim, 1991). Consequently, the clasts of the fans, at the surface, are almost entirely of igneous origin, although earlier buried fan deposits must include Phanerozoic cover sediments, now eroded. Due to the elevation difference between Wadi Araba and the eastern mountain range, many wadis dissect these mountains and discharge into Wadi Araba as ephemeral flow. The investigated fans are located at the mouth of these wadis; the largest is the Muhtadi Fan at the mouth of Wadi Al Muhtadi, located 25 km north of Aqaba. The coalesced fan complexes at Wadi Araba comprise generations of stacked lithofacies associations of different stages, including older debris flow deposits (some probably Pleistocene in age), and more recent stream flow deposits. Fans become finer-grained in composition towards the medial part of Wadi Araba where three inland sabkhas, separated by mudflats and minor sand dune fields are present. Together, they form the distal part of the alluvial fan complex in the area. The largest of these sabkhas is the Taba Sabkha, located about 35 km north of Aqaba (Fig. 1). It is about 50 km^2 in area, and consists essentially of clay, silt and evaporite deposits with minor aeolian sand horizons (Abed, 1998).

3. Methods

Wadi Al Muhtadi fan was chosen for a detailed sedimentary logging as it is one of the largest alluvial fans in the area, and is well exposed (Fig. 2). Measurements of maximum particle size and bed thickness were made for specific lithofacies. Maximum particle size was calculated as an average of the long axis of the 10 largest clasts in a bed. The orientation of the a-b planes of a representative selection of clasts ranges from 10 to 15 readings. Palaeocurrents were measured from clast imbrication and occasional cross-beds.

Stratigraphic sections were measured from the main exposures in Wadi Al Muhtadi. Lithofacies associations are laterally distributed in the order of FP, FM and FD from east to west. Five sections were measured along the axial length of Al Muhtadi fan, from the fan apex eastward to the fan toe westward (Fig. 2).

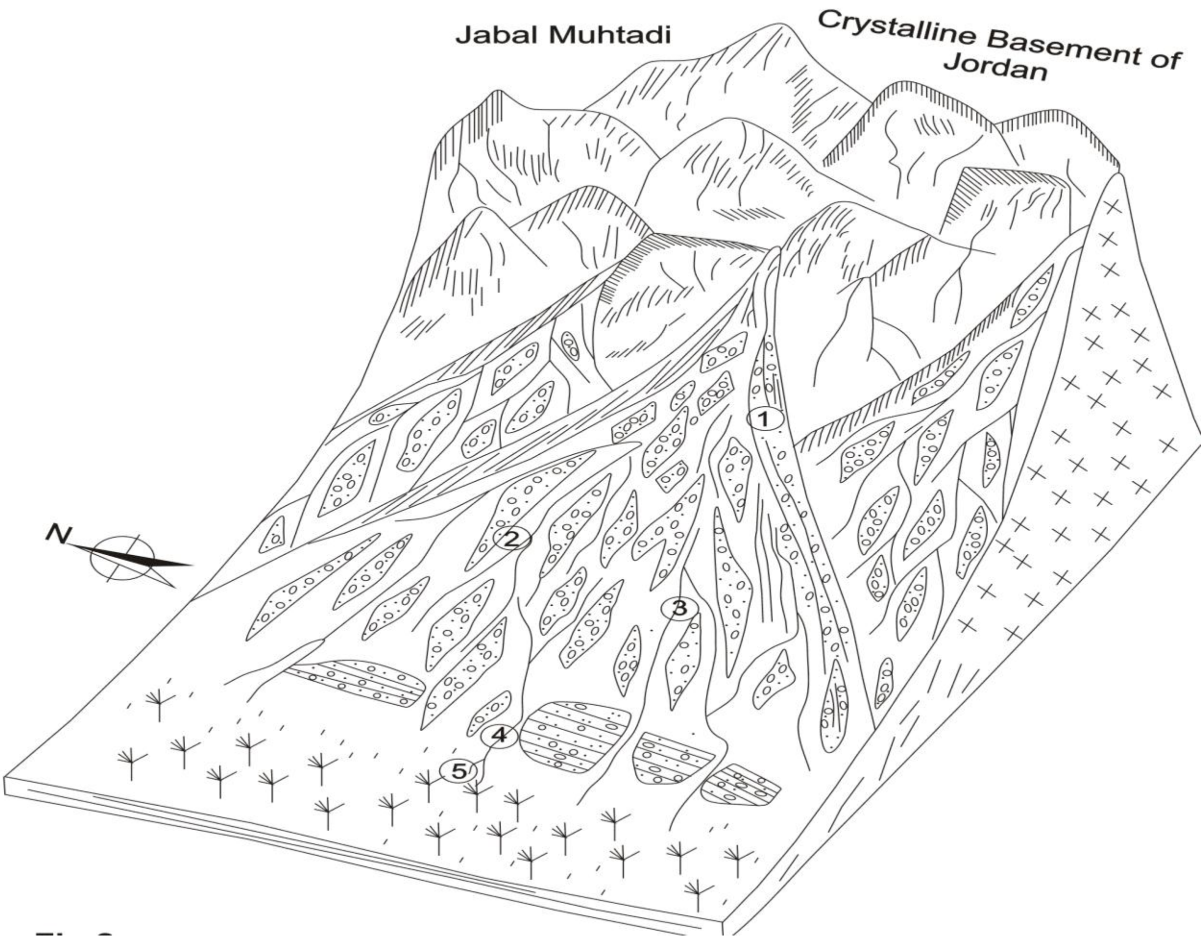

Fig. 2. Schematic block diagram showing the depositional system of the Muhtadi Fan and it's section locations: (1) proximal fan, (2, 3, and 4) midfan, (5) distal fan.

4. Morphological Description

The spatial extent of the Al Muhtadi fan can be estimated based on distribution of lithofacies associations. The axial length of the fan is about 5 km displaying thin alluvial sheet appearance in the distal area, passing westward into a flat lowland sabkha area. The fan surface has a low gradient to the west (260°N) (Fig. 3A). Numerous alluvial fans have been recognized at palaeo-piedmont zones in front of the Wadi Araba-Dead Sea Transform fault escarpment (Fig. 1). The overlapping pattern of adjacent alluvial fans forms a proximal bajada along the southern part of Wadi Araba (Figs. 1, 3B). The fan system is related to palaeo-piedmont lines, which are inferred from the basin-margin faults (Fig. 1). The fan system in this study area is rich in gravel-size clasts as they are derived from granitoid source areas located nearby (Fig. 3C, D).

The intermontane valleys are V-shaped (Fig. 3E) with maximum widths of around 200 m (Fig. 3F). The apical parts of the fans are at altitudes of 100- 200 m ASL. They have been affected by subsequent braided fluvial processes that reworked abandoned fan sectors, and deposited recent alluvium (Fig. 3F). Fan-head segments slope at 13° from the horizontal and decrease to 5°- 8° at about 800 m westward from the apex (Fig. 3A).

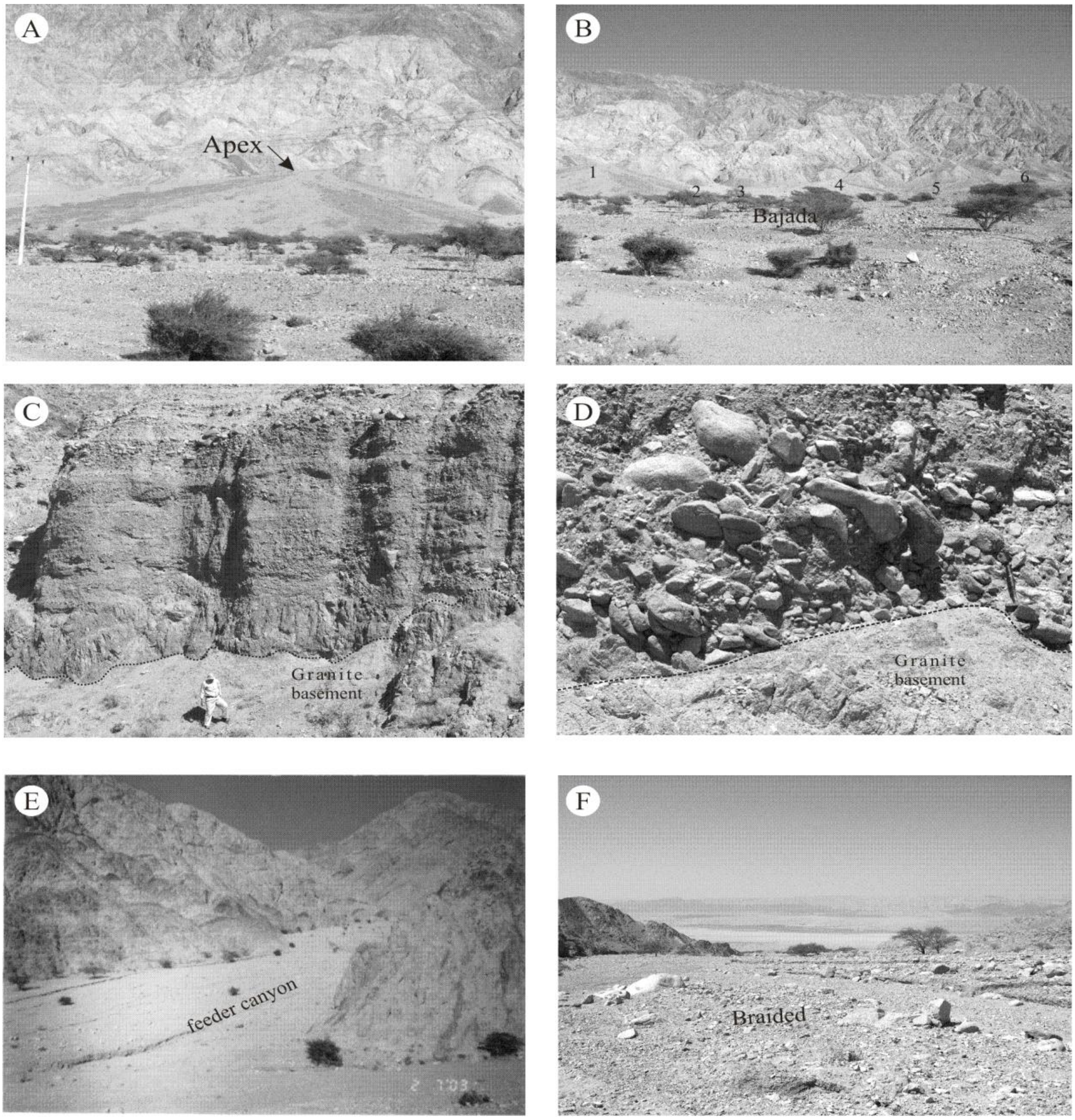

Fig. 3. Field photographs of the alluvial fans in Wadi Araba showing: (A) general view of Al Muhtadi alluvial fan, Wadi Araba, showing its apex, proximal and medial parts; the active lobe is modified by surface flow; (B) adjacent distal fans at the piedmont of the mountains producing a bajada; (C) the fan deposits resting unconformably on the basement granitic rocks.; (D) close-up of C to showing details of the boundary; note the eastward imbricated cobbles; (E) general view showing the fan apex and feeder canyon in the proximal part of Al Muhtadi alluvial fan; (F) braided channel displaying longitudinal bars at the fan-head trench.

Close to the apex of Al Muhtadi fan an abandoned ancient tributary fan trending NE-SW overrides the primary fan, building a huge cone of gravels including boulders and blocks, made of granitic and other igneous clasts (Figs. 4, 5A). This fan is 100 m wide and more than 10 m thick and is superimposed by a small more recent fan (Fig. 5B). It is truncated by the present braided channel which is trending westward (260°N).

Small scale colluvial fans are well developed along the recent valley margin faces incising the pre-existing fans (first generation), some of which are coalesced and others are solitary (Fig 5C). Clastic sediments are supplied to the colluvial fans as rock-fall and dry debris flow. Some colluvial fans were developed along the truncated face of the abandoned fan (Fig. 5D).

5. Facies, Lithofacies and Facies Associations

Wadi Al Muhtadi fan is described in terms of three lithofacies associations comprised of eight lithofacies (Table 1), which were identified on the basis of sediment texture, clast fabric, matrix type, lithology and clast composition. Three representative lithofacies have been recognised in proximal fan (FP), three lithofacies in the medial fan (FM) and two lithofacies in the distal fan (FD). This subdivision serves as the basis for the interpretation of depositional processes.

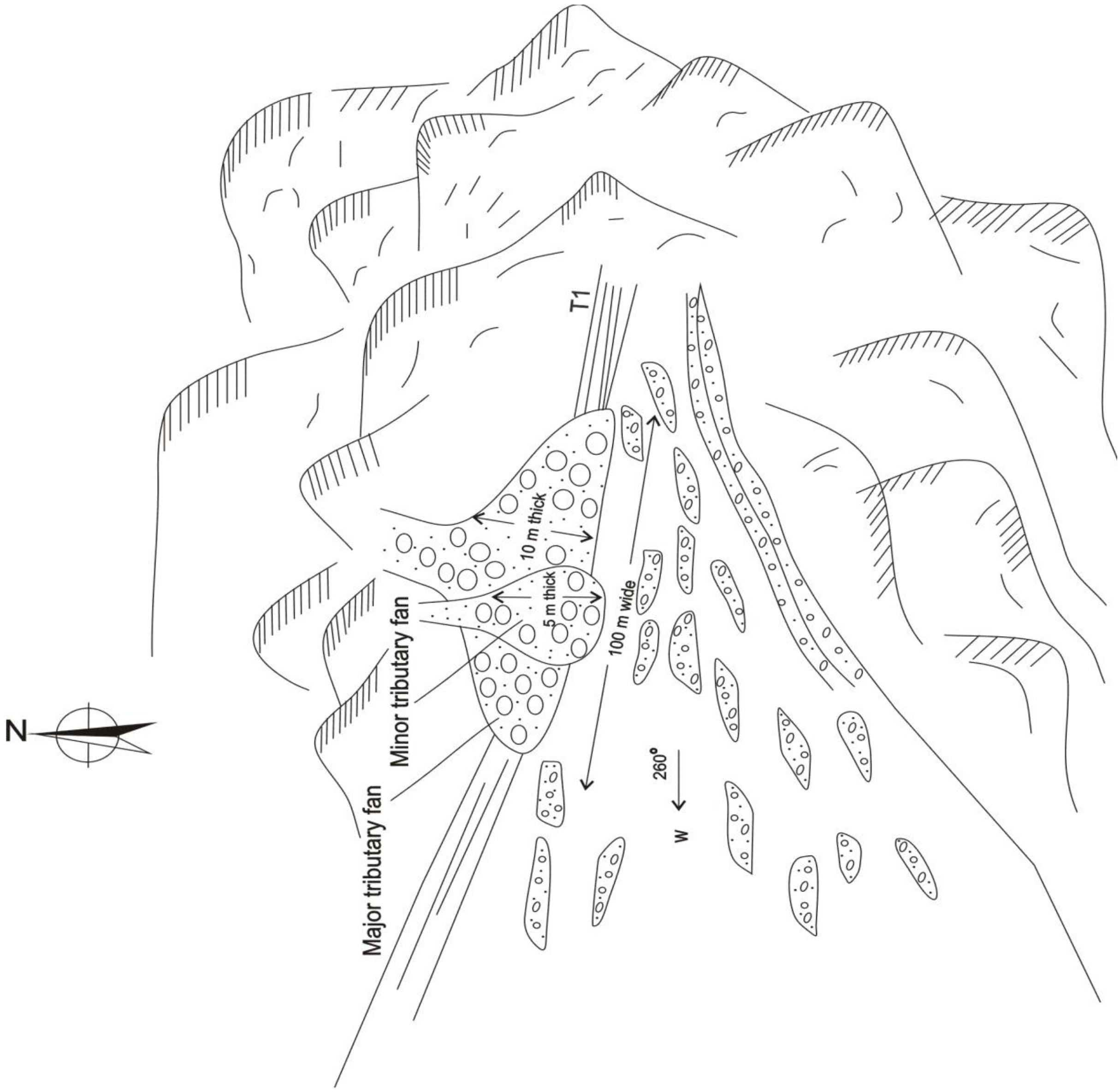

Fig. 4. Sketch showing an ancient abandoned alluvial fan overriding the primary fan, which in turn, is truncated by the present braided channel. The abandoned fan is superimposed by a small recent fan (T1 refers to channel terrace).

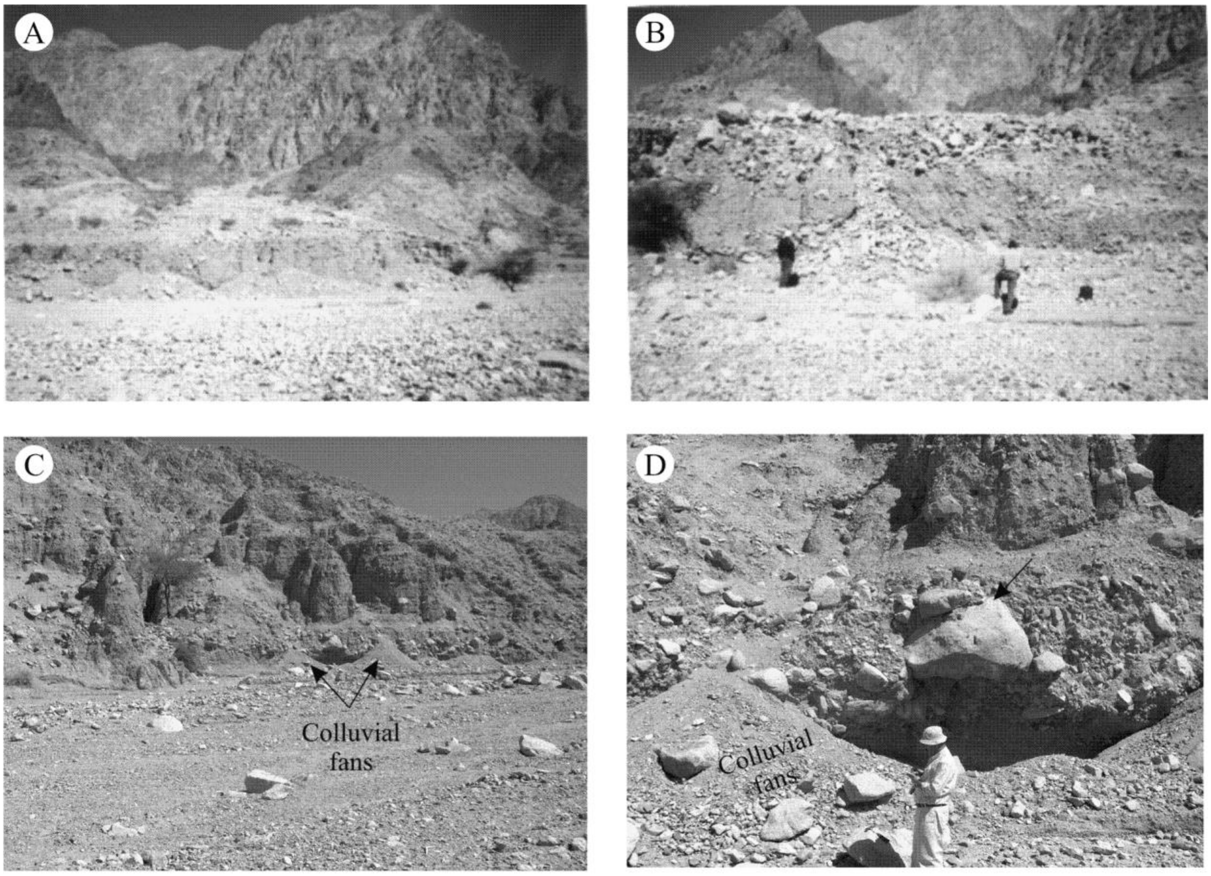

Fig. 5. Field photographs showing the channels at the apex: (A) abandoned tributary alluvial fan overridden by the primary fan and truncated by the present braided channel; (B) the abandoned fan is superimposed by a small recent fan; (C) small colluvial fans perpendicular to the present course of the channel, developed along the truncated face of the abandoned fan; (D) close-up of a colluvial fan overriding the ancient fan; note the large boulder.

Tabel 1. Lithofacies associations of Al Muhtadi fan.

Alluvial Fan Facies		
Proximal Fan Lithofacies (FP) Lithofacies Associations	Medial Fan Lithofacies (FM) Lithofacies Associations	Distal Fan Lithofacies (FD) Lithofacies Associations
1. Clast-supported, disorganized conglomerate lithofacies (Gcd). *2. Clast-supported, organized conglomerate lithofacies (Gco).* 3. *Matrix-supported, disorganized conglomerate lithofacies (Gmd).*	*Trough- filling conglomerate lithofacies (Gt).* *Horizontally stratified conglomerate lithofacies (Gh).* *Heterolithic lithofacies (Htr).*	*Massive mudstone lithofacies (Mm).* *Evaporite lithofacies (Ev).* *Gypsum-Anhydrite sublithofacies (Evgyp).* *Halite sublithofacies (Evhal)*

5.1. Lithofacies Associations of Proximal fan (FP)

Not far from the apex of Al Muhtadi fan; two vertical sections were measured at the proximal part of the fan (Figs. 6, 7). The bedding is poorly developed in the upper settings and becomes more pronounced down-channel (Fig. 8A, B). Lithofacies association (FP) comprises poorly sorted boulder beds, horizontally stratified pebble to block beds (Fig. 8C) and clast-supported conglomerates (Fig. 3C). Boulders are subrounded to subangular, and are occasionally imbricated (Fig. 3D). Several huge fallen boulders of granitoid basement (up to 150 cm) were identified (Fig. 5D).

Well defined imbrication is present to some degree in most of the beds of the gravelly lithofacies (Fig. 8D). It appears as general inclination of the clasts (a-b planes dipping upstream) relative to bedding as shown in Fig. 8D. Imbrication is best developed in the finer grained, stratified conglomerates where clast long axes (a) are orientated transverse to flow (Fig. 8D). In the more poorly sorted, coarser grained deposits, there is no preferred orientation of clast long axes (Fig. 8A). Clast imbrication was used to determine palaeocurrent orientation (Fig. 9) which is unidirectional to the west (250°N).

Most of the beds show sheet-like geometries without apparent basal scour, although a few beds show irregular erosional bases with variable relief (about tens of centimetres) (Fig. 8A, B). Sharp bounding surfaces separating boulder beds from the underlying pebble-rich beds indicate distinct ephemeral flow (Fig. 8B). Some bedding planes are fairly distinct and locally show scour and fill features. Clast-size grading is obvious at different levels of bedding (Fig. 8C). Bed thicknesses vary between 0.2 m and 1m (average 0.6 m). The conglomerates have a loose to moderately tight packing and commonly comprise normally graded, cobble- to pebble-size clasts (Fig. 8A, B). Matrix (up to granule grade) is abundant in most of the units (Fig. 8C). The conglomerates are commonly capped by medium- to coarse-grained sandstones up to 0.30 m thick, which drape the irregular topography of the underlying clasts (Fig. 8B). They are usually parallel laminated or display low angle (5°) bedding planes. Planar cross-stratification often parallel to the fabric in the conglomerates, and faint medium-scale trough cross-bedding is present. Two types of upward-fining cycles are present; firstly from cobble-pebble size to sand size fraction; and secondly from boulder size to pebble size fraction.

5.1.1. Clast-supported, disorganized conglomerate lithofacies (Gcd)

This lithofacies reveals erosional surfaces in the form of two troughs truncating the underlying matrix-supported gravel lithofacies, and is characterized by planar, wedging cross-bedding directed westwards. Bedding is gently undulating, and appears as troughs of low amplitude. The first trough is filled with clast-supported, ungraded, disorganized, and very poorly sorted gravel. The lithofacies comprises subrounded to rounded, granule-, pebble-, cobble- to small boulder-gravels. The mean size of the ten largest clasts is 0.45 m. The second trough is filled with a clast-supported, ungraded, disorganized, poorly sorted, subangular to subrounded, sandy, granular, pebbly coarse cobble lithofacies (Fig. 8A, B). Laterally eastward, a channel of 20 m width, and a maximum height of 1.85 m occurs, filled with boulder-sized clasts that are randomly oriented. This channel-fill lithofacies is characterized by a clast-supported fabric, and a random orientation for the large clasts, and faint imbrication for the smaller clasts. The mean size of the ten largest clasts is 65.5 cm. This lithofacies represents deposits of gravel sheets or low-relief longitudinal bars (Boothroyd and Ashley, 1975; Hein and Walker, 1977; Nemec and Postma, 1993), emplaced by high-velocity flood flows (Allen, 1981; Todd, 1989; Maizels, 1993).

5.1.2. Clast-supported, organized conglomerate lithofacies (Gco)

This lithofacies is a thickly bedded, clast-supported, ungraded, organized, horizontally orientated, well stratified (Figs. 8C, 9), very poorly sorted, subrounded, sandy, granule, pebble, cobble and boulder-gravel lithofacies. Excluding one outsized clast of 0.95 m, the mean size of the ten largest clasts is 0.21 m. This unit is characterized by remarkable lateral variation, and imbrication (Fig. 8C). The clast size increases vertically, and the mean size of the ten largest clasts is 0.70 m. This lithofacies occurs as deposits of sheet bars/longitudinal bars or diffuse gravel sheets (Boothroyd and Ashley, 1975; Hein and Walker, 1977), formed by grain-by-grain bedload sedimentation (Harms et al., 1982).

5.1.3. Matrix-supported, disorganized conglomerate lithofacies (Gmd)

This lithofacies is thickly bedded, very poorly sorted, matrix-supported, muddy, sandy ungraded, very poorly sorted, pebble to cobble gravels. Large clasts are occasionally present randomly floating in the mud matrix. Clasts are subrounded to rounded. The mean size of the ten largest clasts is 0.20 m (Fig. 8A). The interparticle matrix consists mostly of very small pebbles and granules similar in composition to the larger clasts. The shape of clasts is mainly spherical to discoidal, with rare prolate and tabular clasts. Clasts are mainly granite with less common basalt and rare rhyolite. The larger clasts commonly occur in local concentrations or small clusters, but are scattered without apparent order throughout the beds (Brayshaw, 1984; Went, 2005). Deposition of this lithofacies took place from visco-plastic debris flows (Shultz, 1984; Costa, 1988).

5.2. Lithofacies Associations of Medial fan (FM)

Part of the medial fan outcrops about 3km westward of the fan-head, and very close to Aqaba-Amman highway at the eastern side (Fig. 10). The exposed scarp is produced due to uplift, which took place along the Wadi Araba-Dead Sea Transform. The section strikes north-south, which is normal to the general dispersal of the fan deposits. The fan fault scarp is exposed due vertical displacement along the fault.

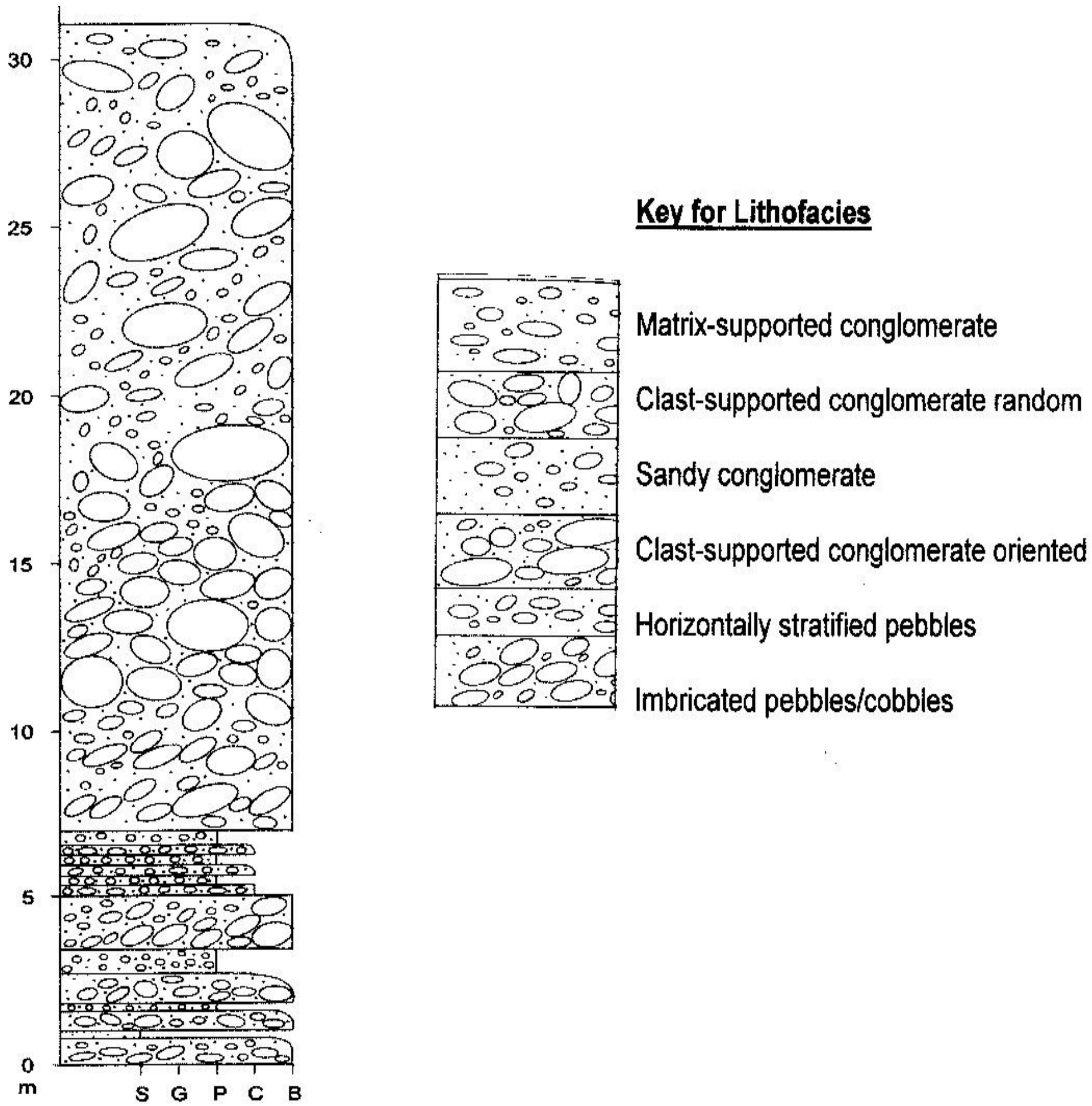

Fig. 6. Columnar section showing the thickness and lithofacies distribution at the southern side of the proximal part of Al Muhtadi alluvial fan (section 1, see Fig. 2 for location). Ancient fan deposits eroded by the stream.

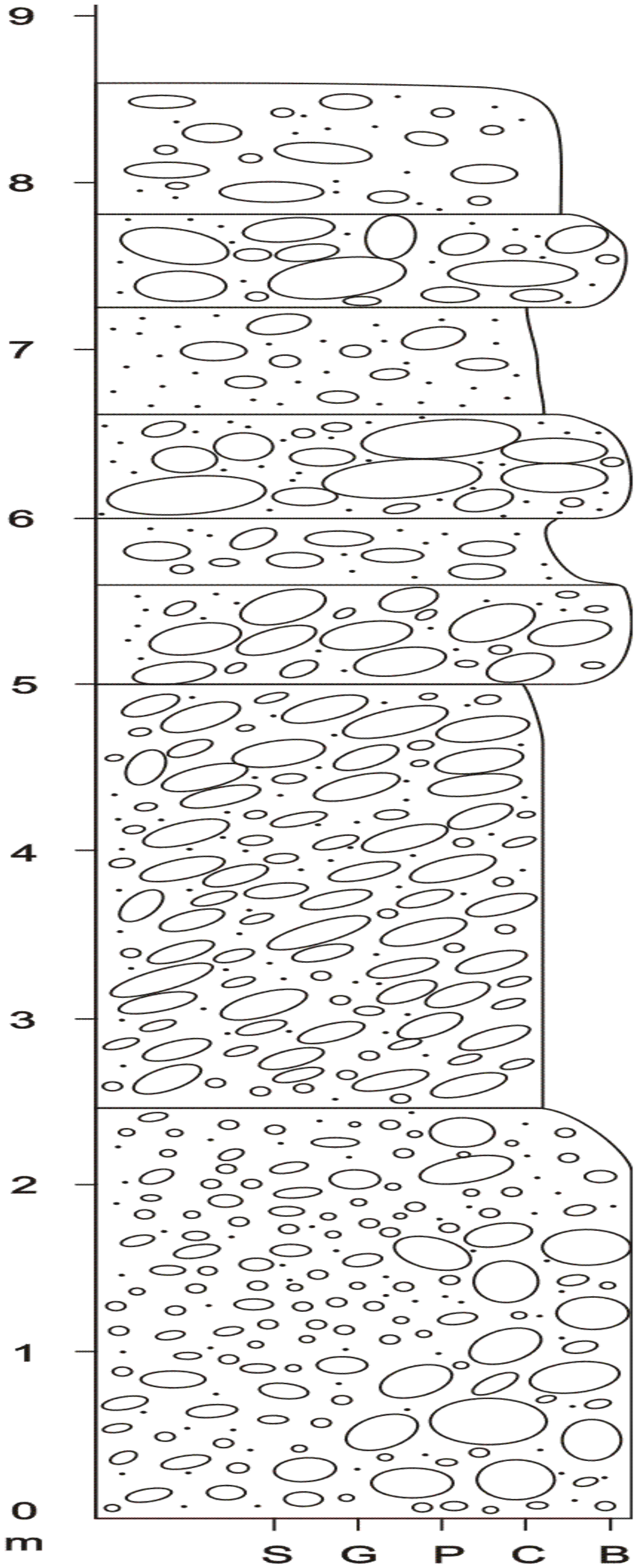

Fig. 7. Columnar section showing the thickness and lithofacies distribution at the northern side of the proximal to midfan part of Al Muhtadi alluvial fan (section 2; see Fig. 2 for location, and Fig. 6 for lithofacies key).

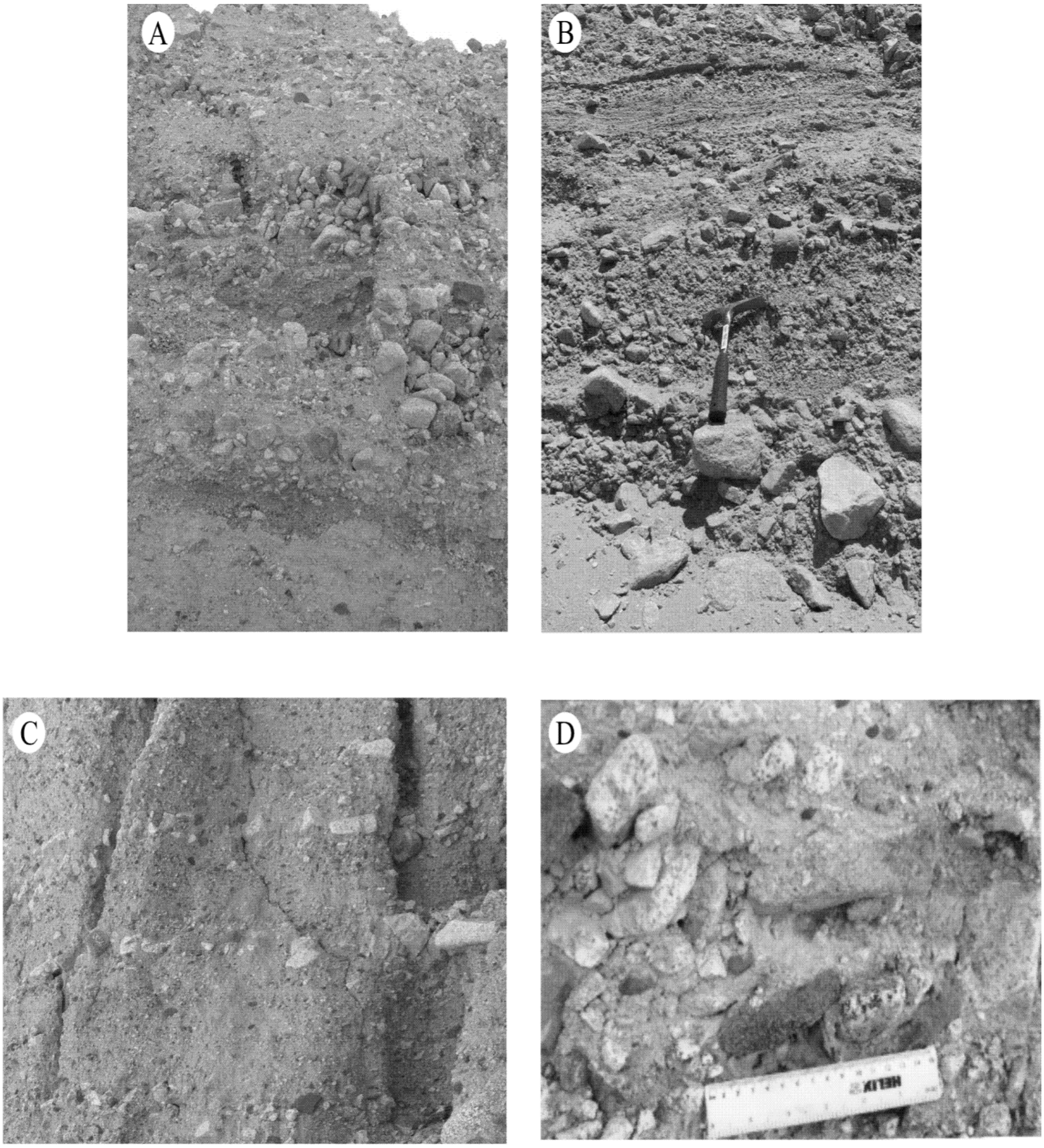

Fig. 8. Field photographs showing the proximal lithofacies associations: (A) lithofacies association (FP) comprises poorly-sorted, clast-supported boulder beds with horizontally stratified pebble- to boulder-size clasts, some showing clusters (Gcd); (B) fining upward cycle starting with disorganized boulders and terminating with thinly bedded sandstones (Gcd), which drape the irregular topography of the underlying clasts. (C) graded beds with matrix (up to granule size are abundant in most of the units supporting clasts; here arranged as multiple cycles of horizontally bedded conglomerates (Gco) commonly capped by granular sandstones; (D) boulders are subrounded to subangular, and are well imbricated (Gco).

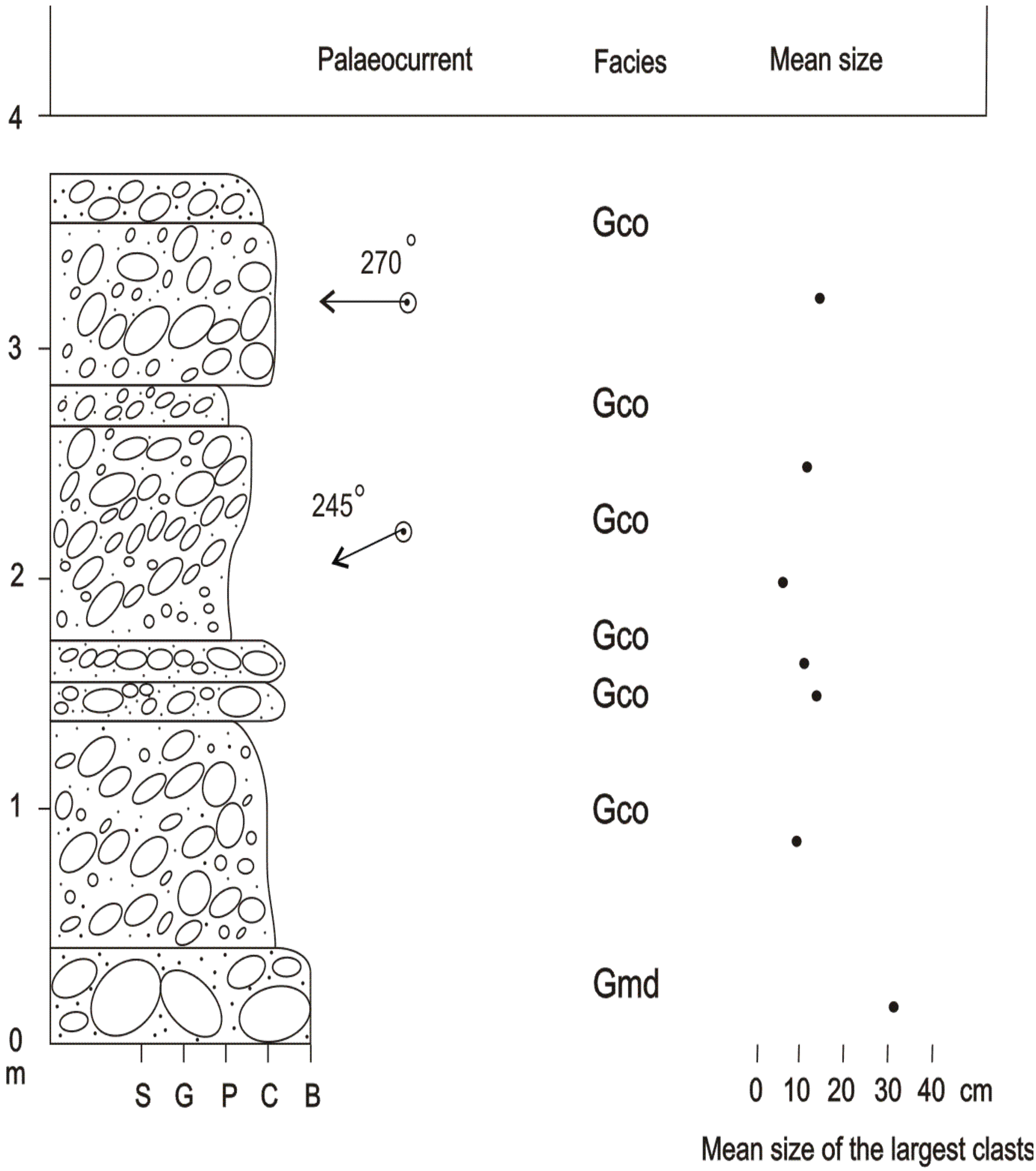

Fig. 9. Columnar section showing the thickness and lithofacies distribution at the southern side of the proximal to midfan part of Al Muhtadi alluvial fan (section 3, see Fig. 2 for location, and Fig. 6 for lithofacies key).

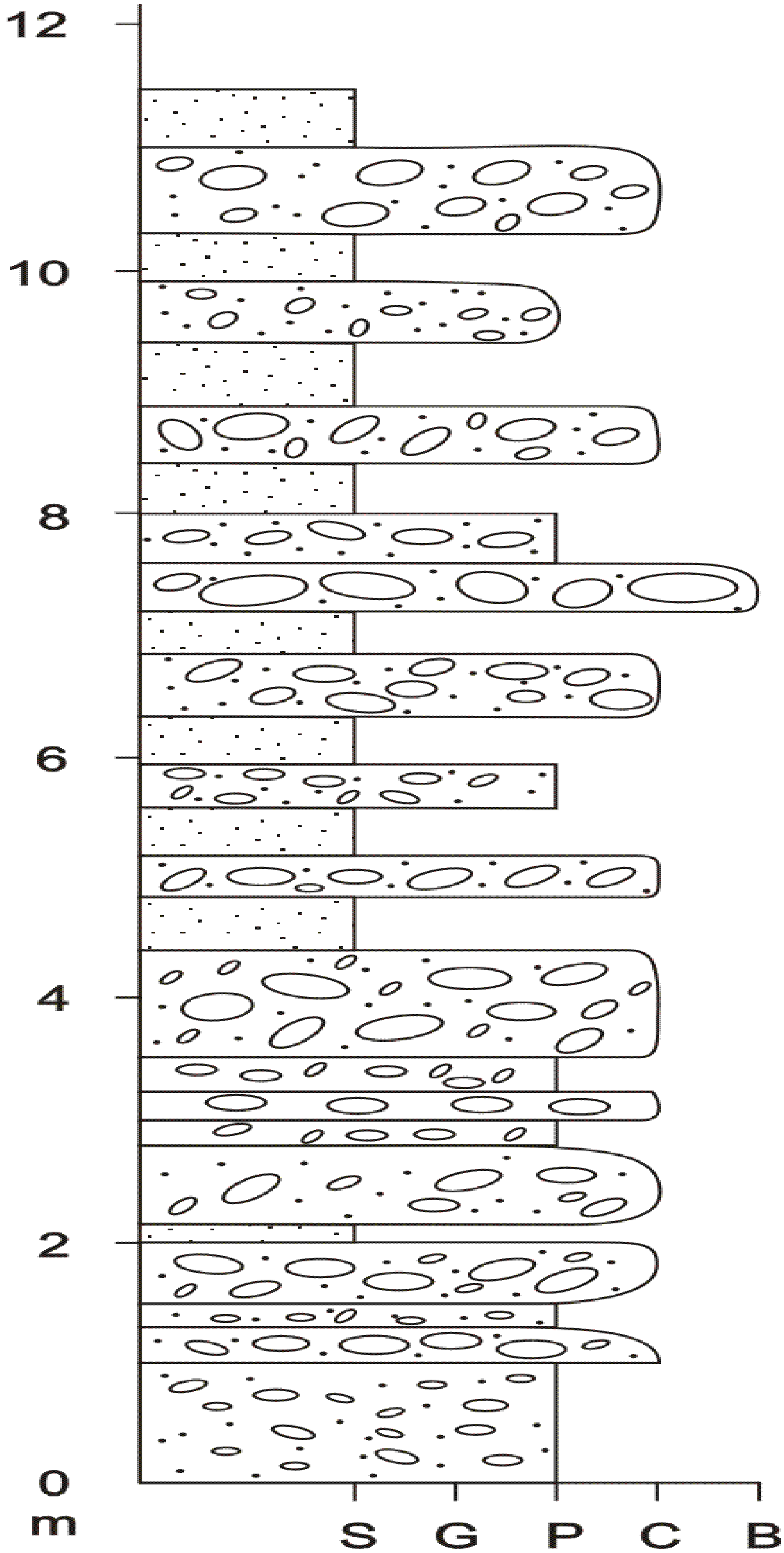

Fig. 10. Columnar section showing the thickness and lithofacies distribution of the midfan of Al Muhtadi alluvial fan (section 4, see Fig. 2 for location, and Fig. 6 for lithofacies key).

The measured section at the fault escarpment facing west attains a thickness of 12 m (Fig. 11A-D). The medial fan lithology consists of fine cobbles, pebbles and large amounts of sand arranged in several fining-upward cycles (Fig. 11A). Beds are inclined toward the upstream (eastward) as a result of fault tilting.

The lower reaches of the medial fan at about 300 m elevation, located to the west of the highway; the medial fan crops out due to the western fault scarp facing SE. The exposed fan lithofacies attains a thickness of 10 m, and is generally fine grained. Unfortunately, much of the outcrop is covered with talus. The gravel component decreases, and the beds become thin and laminated. Sedimentary structures are well pronounced (Fig. 12A, D). Parallel laminated granular sandstones alternate with pebbly horizons that pass upward into structureless granular sandstones (Fig. 12A-D). Small-scale cross-bedding, ripple marks and cross lamination are common. The following three lithofacies were recognized:

5.2.1. Trough- filling conglomerate lithofacies (Gt)

Two units of this lithofacies are encountered; the first one consists of horizontally bedded, clast-supported, ungraded, organized, imbricated to horizontally orientated, poorly sorted, muddy, sandy, granular, coarse pebble gravel. The mean size of the ten largest clasts is 0.57 m. The second unit is a thick bedded, clast-supported, ungraded, slightly to well-imbricated, subrounded to rounded, poorly sorted, clayey, pebbly, fine cobble conglomerate lithofacies. The mean size of the ten largest clasts is 0.88 m, disregarding two outsized clasts that attain a diameter of 0.29 and 0.34 m. The upper part of this unit is characterized by almost horizontal orientation of the clasts leading to horizontal stratification. This unit constitutes a bed of 1 m thickness that persists laterally for 12 m before dying out below base of the outcrop. This lithofacies was deposited as infills of minor channels, scours and channel pools (Miall, 1977).

5.2.2. Horizontally stratified conglomerate lithofacies (Gh)

This lithofacies consists of a horizontally bedded, matrix- supported, ungraded, organized, subrounded to subangular, poorly sorted, clayey, silty, sandy, coarse pebble gravel lithofacies. The mean size of the ten largest clasts is 0.27 m (Fig. 11D). The lithofacies constitutes the fine-grained component of the fining-upward cycles which start with lithofacies (Gt). Thicknesses of the upward-fining cycles vary from 0.10 to 0.12 m (Fig. 11A). The lower half to two thirds of each cycle is usually of gravel size. Cross-bedded sandstones are rarely present. Flame structures were observed at certain levels at the boundaries separating the sandstones from gravelly beds, where differential loading has taken place. Upper plane bed sedimentation was suggested for the deposition of this lithofacies (Boothroyd and Ashley, 1975; Allen, 1981; Harms *et al*., 1982; Todd, 1989; Maizels, 1993).

5.2.3. Heterolithic lithofacies (Htr)

This is an assemblage of relatively fine grained sediments. The best exposures are at the western side of the Aqaba Highway. This lithofacies consists of silty sandstones, granular sandstone and small-pebble conglomerate (Fig. 12A- D). The sandstones show parallel and wavy laminations alternating with pebbly horizons. Others are structureless granular sands. Some of them show fining upward cycles, graded bedding, ripple marks and cross lamination (Fig.12B, C). Beds of laminated sandstones and intercalated mudstone show normal grading. Parts of the sand deposits are certainly aeolian, derived from the dune field located to the north (Fig. 13).

5.3. Lithofacies Associations of Distal fan (FD)

The distal fan (FD) forms a flat area "Mehada" (Fig. 13 B, C) trending north-south, a result of the coalescence of the distal part of adjacent and overlapping alluvial fans (the term Mehada in Arabic best expresses this definition). An inland sabkha, known as Taba Sabkha (Fig. 14A-C), also occurs to the north.

The Taba Sabkha represents part of the distal fan setting (FD), situated in the southern part of the Dead Sea - Wadi Araba rift, 32 km north of the Gulf of Aqaba. It occupies an area of about 55 square km west of the Precambrian granitic basement. It is drained by E-W wadis that have their alluvial fans on the eastern side of Wadi Araba. The surface inclination of the sabkha is only a few seconds to the west and south-west (Fig. 14 A-C). It forms the distal lithofacies of several alluvial fans emerging from the eastern basement mountains. The sabkha sediments are mainly the result of ephemeral deposition from these wadis. Twenty shallow pits (1-1.5 m deep) and 9 boreholes up to 17 m depth were drilled into the sabkha during detailed studies by Abed (1998). Samples and cores were obtained, and a few groundwater samples were collected during these earlier studies, which showed zonation in the sabkha reflected in both plant habitat and evaporite minerals as a function of increasing salinity of groundwater towards the centre. Brown clays dominate its centre, grading eastwards into more sandy lithofacies. The following lithofacies are recognized:

5.3.1. Massive mudstone lithofacies (Mm)

These massive mudstones occur at the distal part of the fan composing the centre of the sabkha (Fig. 14 A-C). Petrographic study (Abed, 1998) has shown that the detrital minerals include quartz, feldspar, chlorite, mica, kaolinite, illite, smectite and illite / smectite mixed layers. Calcite, though partly authigenic, is dominantly detrital and aeolian in origin. Bedding surfaces show desiccation cracks up to 1 m in diameter (Fig. 14 B, C) and rain prints.

5.3.2. Evaporite lithofacies (Ev)

The barren interior of the sabkha consists of two colours: (a) whitish involving the relatively low areas with a salt crust and desiccation cracks (Fig. 14 B, C), and (b) brownish, a little higher in elevation, with older desiccation cracks (Abed, 1998). The former areas are the currently active areas of sedimentation. Geochemical analyses (Abed, 1998) indicate that the main evaporite minerals are gypsum, anhydrite and halite.

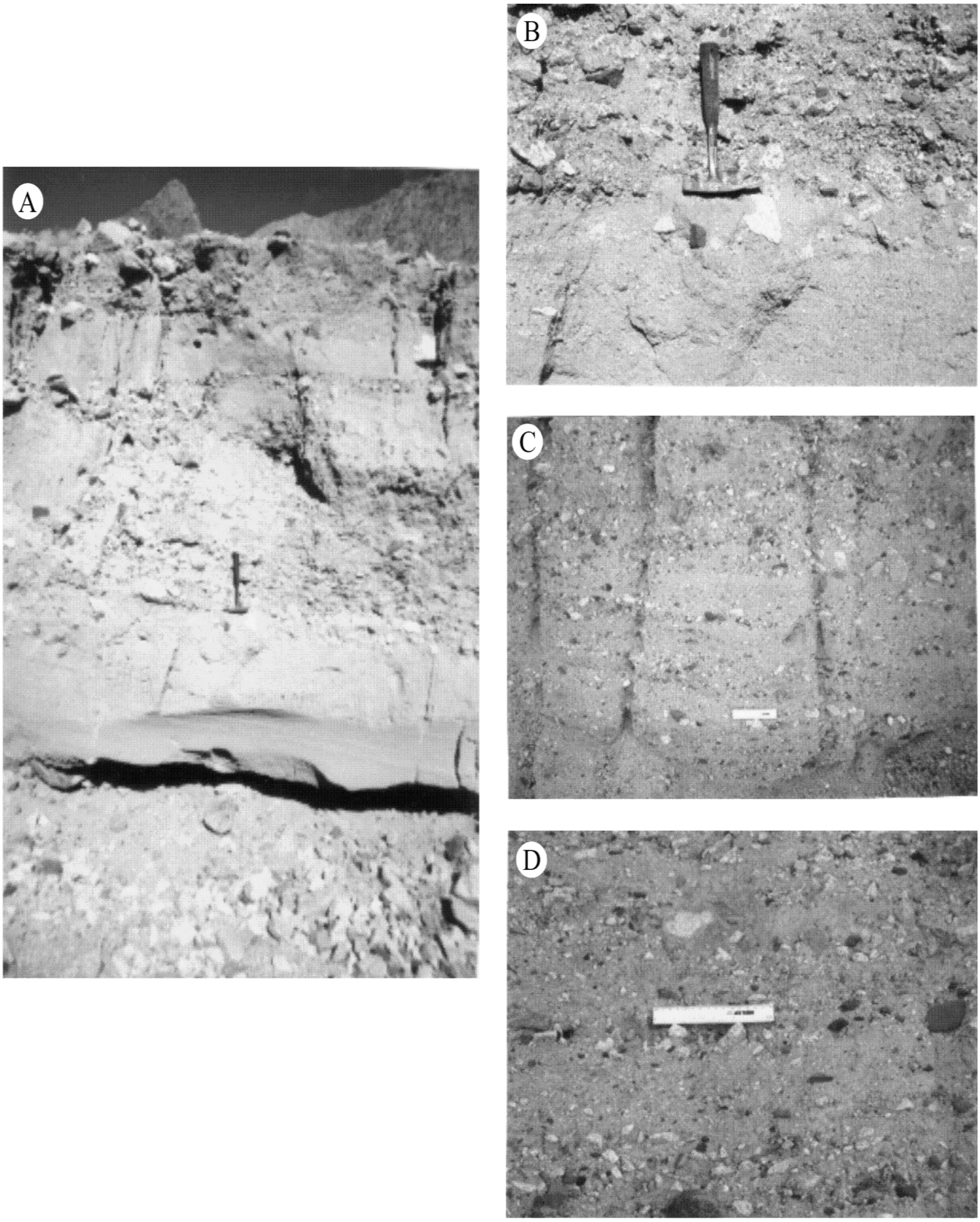

Fig. 11. Field photographs showing lithofacies associations of the medial fan (FM): (A) graded beds comprising three thick upward fining cycles terminated by thick bedded sandstones (Sh); (B) sharp bounding surfaces separating cobbly beds (Gt) from the underlying granular sandstone beds (Sh) indicate abrupt termination; (C) faint medium-scale trough cross-bedded conglomerates (Gt); (D) thin multiple cycles of conglomerates (Gt) (up to 30cm thick each) commonly capped by coarse-grained sandstones (Sh) which drape the irregular topography of the underlying conglomerates.

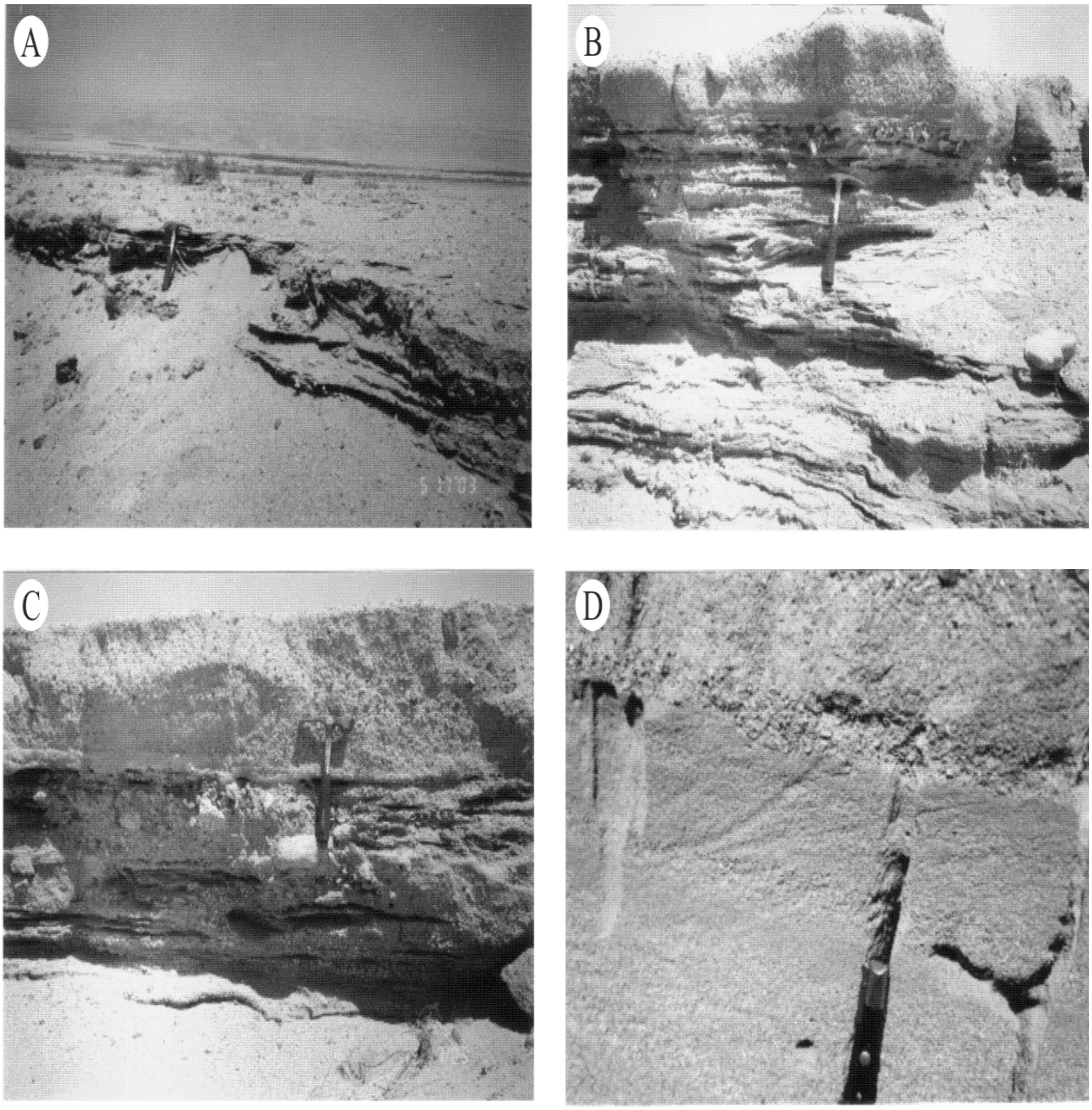

Fig. 12. Field photographs of the lowermost reaches of Al-Muhtadi medial fan facing west and passing gradually to the distal fan (Htr): (A) laterally persistent, thin bedded, pebbly sandstones; ripple marks and small scale cross-bedding are present; (B) the medial fan (FM) consists of trough cross-bedded, rippled and cross-laminated granular sandstone passing upward into coarser structureless granular sandstone; (C) the medial fan (FM) displaying parallel lamination of granular sandstone with occasional pebbly horizons passing upward into a structureless bed; (D) planar and trough cross-stratification often parallel to the fabric in the conglomerates.

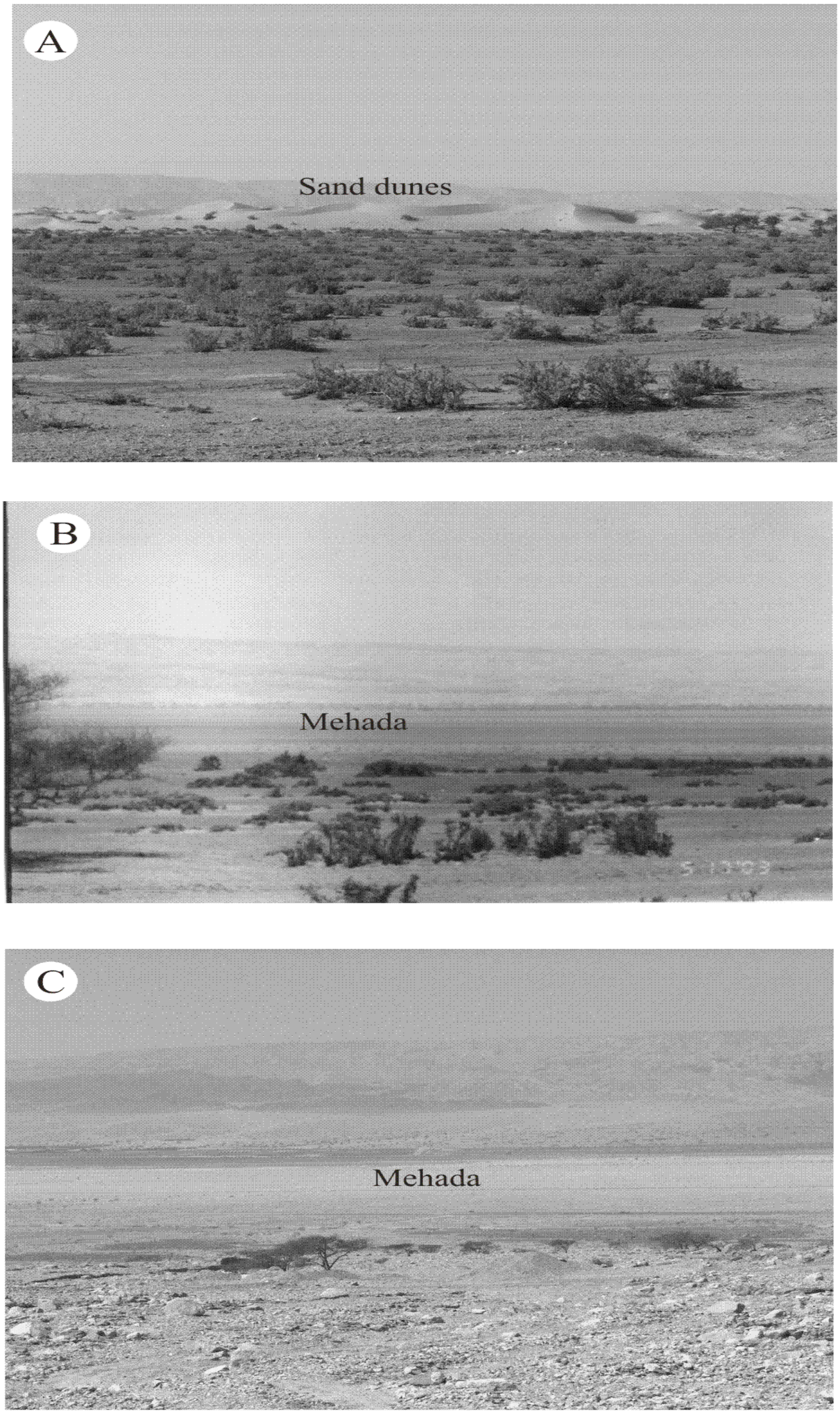

Fig. 13. (A) aeolian sand dunes advancing from the north and covering parts of the medial and distal fan zones; (B) lower reaches of the medial fan (FM) grading into the distal fan (FD); (C) the toe of the fan appears as a flat strip trending north-south as a result of coalescence of the distal part of adjacent and overlapping alluvial fans. Sabkha is also present locally.

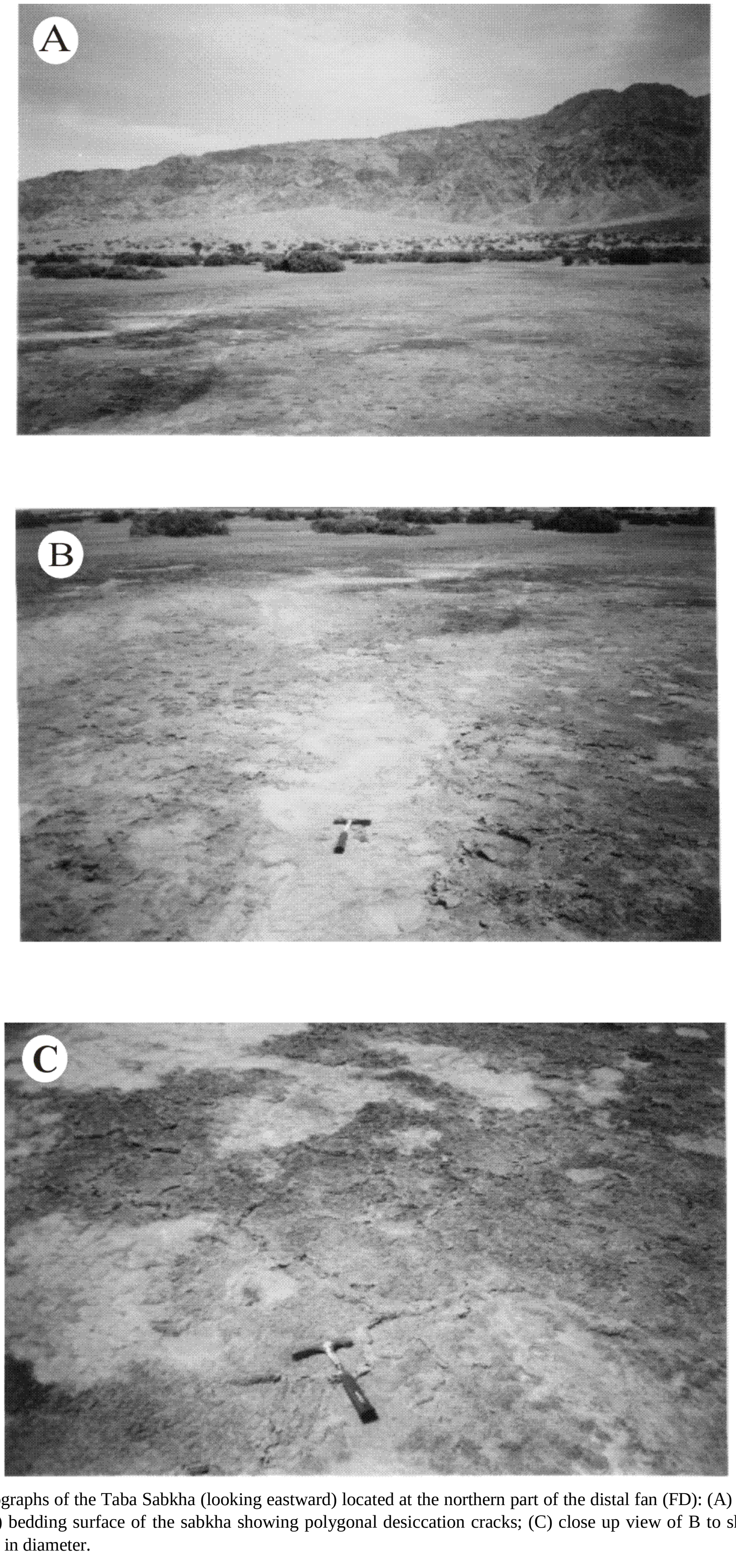

Fig. 14. Field photographs of the Taba Sabkha (looking eastward) located at the northern part of the distal fan (FD): (A) general view of the fan and sabkha; (B) bedding surface of the sabkha showing polygonal desiccation cracks; (C) close up view of B to show the large-scale polygons, up to 1 m in diameter.

i) Gypsum-Anhydrite sublithofacies (Evgyp)

Gypsum (sometimes present as the hydrated salts anhydrite and/or basanite in summer) is found in two settings: (a) at the surface or near surface, as concretionary and powdery deposits, especially around the plants. This type is due to direct precipitation from the groundwater and (b) at a deeper horizon, overlain by halite, towards the centre of the sabkha (Abed, 1998). This type is precipitated by the rising groundwater due to capillary action. The presence of overlying halite supports this interpretation (Schreiber and El-Tabakh, 2000).

ii) Halite sublithofacies (Evhal)

Halite predominates towards the inner parts of the sabkha and is also present in two settings: (a) as a desiccated whitish crust, about 0.01m thick, precipitated from the highly saline surface water noted above. In the older, reddish parts of the sabkha "salt-rich cakes" are found underlying "dissolution holes" at the centre of the shrinkage polygons indicating downward movement of the surface salt, and (b) as a subsurface horizon 0.15-0.40 m thick, several centimetres below the surface and underlain by gypsum in the centre of the sabkha. It is composed of discrete crystals, a few mm in diameter, scattered within the red clay matrix. This type has a similar origin like the underlying gypsum (Abed, 1998).

1. Interpretation

Lithofacies Gcd and Gco largely show characteristics of streamflow deposits that are similar to those of gravel-bed streams in alluvial fans and outwash fans (Boothroyd and Ashley, 1975). The poor sorting of lithofacies may be due to clast interactions in flood flows that were hyperconcentrated to some degree (Costa, 1988; Went, 2005, Harvey *et al*., 2005), deposited in deep, high velocity, sediment-concentrated floods, either within the fan head trench, at the mouth of the fan head trench or in other major fan channels (Went, 2005). The absence of the finer sand and gravel components indicates that they were winnowed from between many of the larger clasts. The Gcd and Gco lithofacies are interpreted as cobble- and boulder-clogged stream channels and surface lags, such as those commonly found on the surface of modern fans (Blair, 1999; Went, 2005, Harvey *et al*., 2005).

Lithofacies Gcd and Gco are interpreted as waterlain deposits, resulting from sheet flood, stream flood and stream flow processes. Palaeocurrents indicate unidirectional flow. Moderately organized textures and fabrics, including clast imbrication and horizontal stratification, point to the selective deposition of clasts, from an energetic flashy or bedload-dominated braided fluvial system (Went, 2005). The locally preserved undulating surfaces and locally cross-cutting strata are interpreted as channel-forms. The lack of any foreset beds indicates that they were not generated from migration of gravelly dune bed-forms. They may be produced by rapidly shifting narrow channels. The lenticular beds of cobble and boulder conglomerates are interpreted as stream channel deposits (Fig. 11C).

The erosive base to many of the deposits might suggest an earlier phase of more turbulent flow. The imbrication of clasts with a-b planes dipping upstream is typical of water lain gravels. Clasts where the long axis (a) is perpendicular to flow suggest rolling of the clast along the stream bed. The heterolithic lithofacies of sandstones and small pebble conglomerate is interpreted as representing the deposits of relatively low energy streams (Fig. 12A-D). The occurrence of ripple cross-lamination grading into wavy lamination suggests deposition by low energy bedload and suspended processes. The finer conglomerate layers are consistent with deposition from stream flows.

The mudcracks and rain prints of the massive mudstone lithofacies (Mm) confirm periodic exposure. These features point to streams that were of much lower velocity than any other streamflow operating on the fan surface. The fine-grained sediments are possibly the products of low energy stream reworking of an abandoned fan sector at the distal fan setting. The thicker intervals of structureless, clay-dominated mudstone suggest prolonged periods of deposition from suspension in a standing body of water at the toe of the fan, when the abandoned sector of the fan was inundated by a marginal playa lake (sabkha). The presence of the evaporite lithofacies (Ev), including the Gypsum-Anhydrite (Evgyp) and the Halite sublithofacies (Evhal), strongly support the existence of the playa lake at the marginal toe of the fan.

2. Discussion and Conclusions

The fan system in this study fully illustrates the criteria for piedmont alluvial fans given by McPherson and Blair (1993), Blair and McPherson (1994) and Harvey *et al*. (2005), such as the large amount of gravelly debris flow deposits and high slope gradient. The poorly sorted boulder beds are interpreted as the deposits of debris flows, as suggested by their extreme large size (up to 150 cm), clast shape (angular to sub-angular), scarce erosional surfaces, and abrupt lateral termination of beds. The cross-bedded, pebbly sandstone beds were produced by the bed load transportation by streams. The abundance of angular clasts in these gravel beds indicates the proximal setting in relation to the granitoid basement rocks to the east, which supplied the clasts (Figs. 2, 3A). Clast compositions and fabric clearly indicates that they were derived chiefly from *in situ* weathered and fractured granitic basement rocks as large blocks (up to 1.50 m).

Interpretation of lithofacies associations and other sedimentological characteristics indicate the depositional processes of the alluvial system in the area. Lithofacies association FP (large-scale debris flow) represents proximal fan deposits. MF (mixed pebble, sand) corresponds to medial-fan deposits, and FD (sand, silt, clay) corresponds to distal fan deposits. Faulting processes and the associated subsidence of the floor of Wadi Araba, and the uplift of the adjacent mountains in the study area took place prior to the deposition of alluvial fans which were likely formed on palaeo-piedmont fronts.

The upward-coarsening sequences are interpreted as representing episodes of alluvial fan progradation, probably formed under a tectonic control (Heward, 1978). Perhaps, during periods of source area uplift and basin floor subsidence, the fan would have abandoned its former position to fill the newly created space adjacent to the mountain front.

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