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MORPHOGENESIS AND MORPHOMETRY OF ALLUVIAL FANS IN THE HIGH ATLAS, MOROCCO: A GEOMORPHOLOGICAL MODEL OF THE FANS OF THE WADI BENI MHAMMED, SOUSS VALLEY

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Abstract

Morphosedimentary study of alluvial fans formed by the Wadi Beni Mhammed, on the southern piedmont of the western High-Atlas, has indicated three main generations of deposits. Their ages range from ancient (Plio-Pleistocene) to Holocene and recent formations. The first generation, comprising small boundary fans, was deposited prior to lateral migration and subsequent entrenchment of the drainage pattern (the combination of the Wadis Aït Mekhlouf and Ida Ou Merouane). The confluence of these powerful streams gave birth to the principal fan that extends to the Souss valley. The third generation of fans was constructed after the incision of the principal fan, by the re-activation of a high secondary fan that was formed from downstream progradation. The morphological characteristics of the fans, such as their area, shape and gradient, are determined from catchment data and, in particular, from the lithology of their provenance areas, which defines the nature of gravel material, sedimentation processes and, finally, the distribtion of constituent materials. Fan shape also depends on the available accommodation space on the piedmont. The Wadi Beni Mhammed fans are elongated, because they are constrained by the mega fans of Wadis Irguitene and Aoukourta.

Keywords: semi-arid region, piedmont, alluvial fan, Quaternary, morphology, Wadi, High-Atlas

Introduction

The Souss basin is located in Southwestern Morocco between the parallels 30 ° and 31 ° N. It opens wide in the West to the Atlantic Ocean, while in the North and South it is bordered by massive mountains: the High Atlas and Anti-Atlas which adjoin the East by volcanic massif of Siroua (Fig. 1). The southern piedmont of the western High Atlas between Taroudant and the Wadi Aoukourta corresponds with the northern limb of a Cretaceous syncline oriented E–W and filled with detritus eroded from the mountains. This material takes the form of large alluvial fans and coalescing fans (Fig. 2). Together, these form a broad, generally concave slope that progressively shallows towards the Wadi Souss. The Quaternary stratigraphy of the alluvial fans of Taroudant was established by Bhiry (1991), Bhiry *et al*. (1991), Aït Hssaïne (1994) and, Bhiry & Occhietti (2004). The fans of the Wadi Beni Mhammed form a set of narrow successive fans and then differ from those of larger fans of Wadis Irguitene and Louaar (Aït Hssaïne, 1994).

The importance and extent of these alluvial deposits vary according to catchment geology and gradient, the latter controlling stream power. The main contributions were made in the form of successive and much flattened fans. Their varied sedimentological facies reveals a succession from the oldest formations (Plio-Pleistocene?) to the most recent (Holocene) and allows different generations of fans to be distinguished.

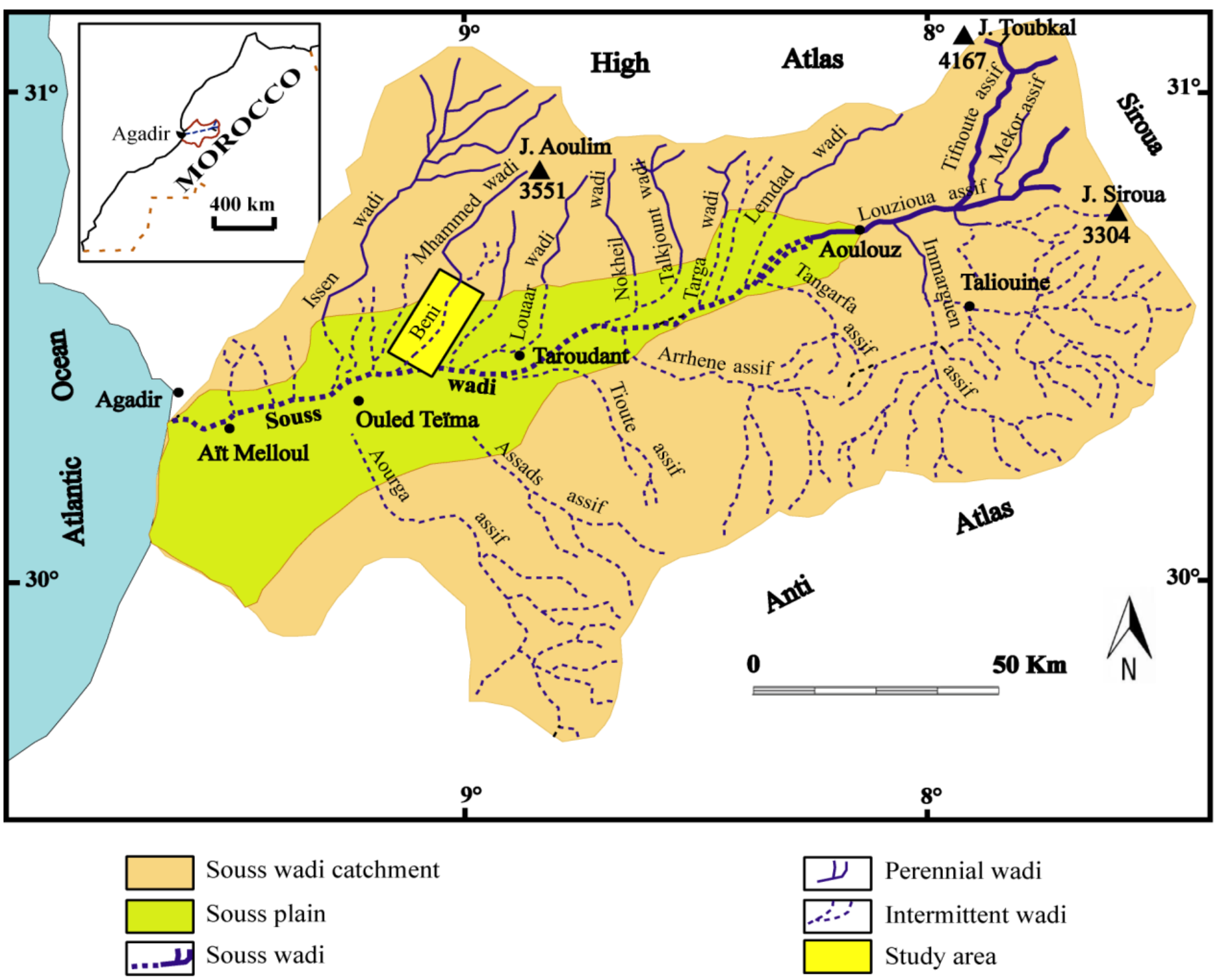
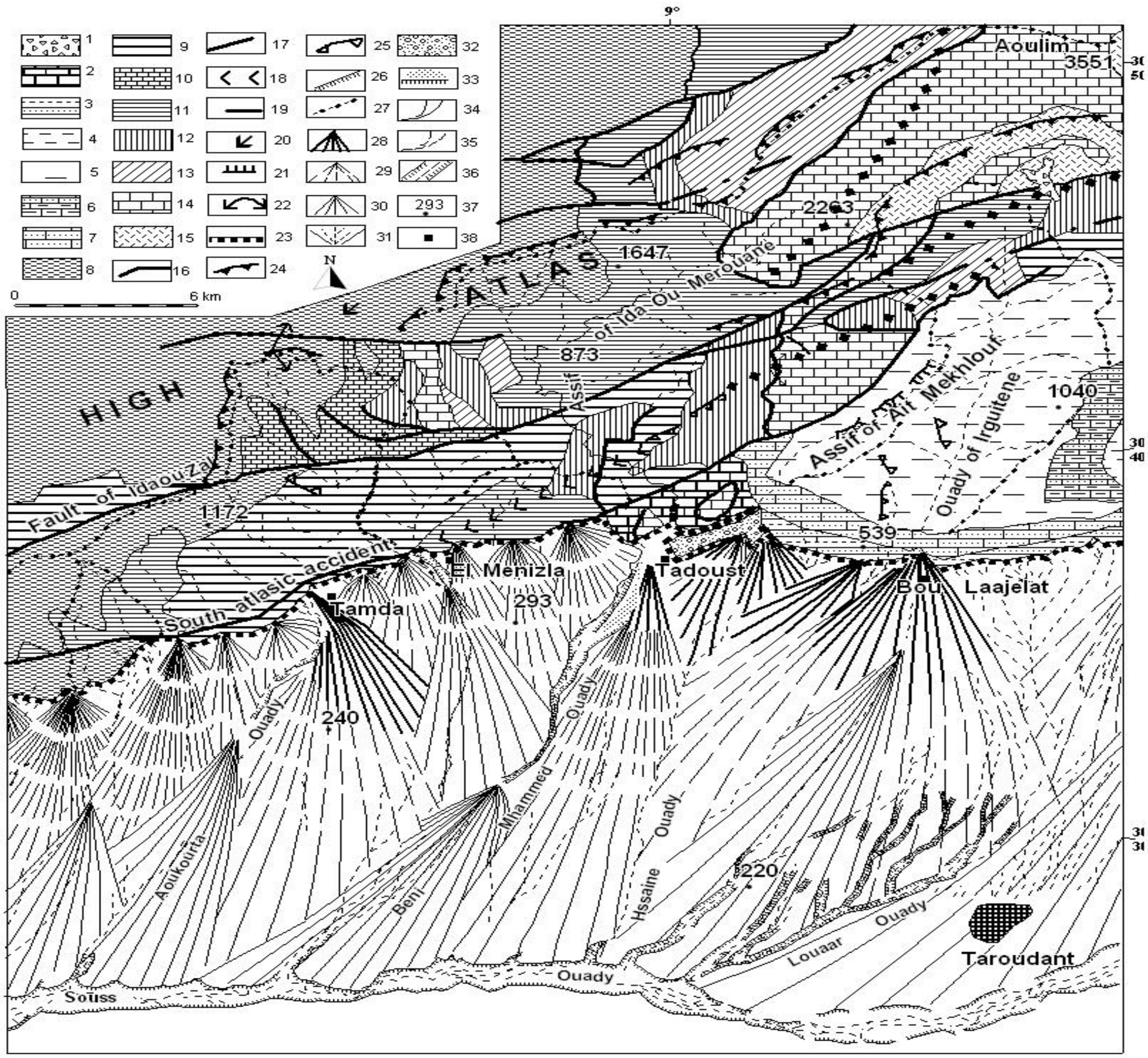


Fig. 1: Location map of the Souss basin and the studied territory



A) Lithology: 1- recent Quaternary: Alluviums, 2- Pliocene: Limestone, 3- Oligocene: Sandstone and conglomerate, 4- Eocene: Limestone and pink marls, 5- Maastrichtian-Sénonien: Marls, 6- Cenomanian-Turonian: Marls and dolomite limestone, 7- Lower Cretaceous: Marly calcareous, 8- Permo-Trias: Sandy clay, 9- Stephanian-Autunian: Sandstone and red conglomerate, 10- Devonian: Limestone, 11- Cambro-Ordovician: Schist, 12- Acadian: Sandstone, 13- Georgian terminal: Tuff, 14- Georgian s.s.: Limestone, 15- Precambrian: Crystalline block. **B) Morphostructure:** 16- Faults, 17- Flexures, 18- Anticlinal axis, 19- Synclinal axis, 20- Layer dips, 21- Layers very rectify, 22- Anticlinal crest. **C) Morphology:** 23- Main ridges, 24- secondary ridges, 25- Cliffs, 26- Watershed limits. **D) Accumulation forms:** 27- Plio-Pleistocene fans, 28- Pleistocene fans, 29- Holocene fans, 30- Interfans, 31- Terrace-fans, 31- Alluvial Terraces. **E) Hydrography:** 33- Perennial wadi, 34- Intermittent wadi, 35- Encased bed. **F) Altitude and Habitat:** 36- Height spot, 37- Village.

Fig. 2: Morphologic map of Atlasic fans and their drainage basin between Louaar and Aoukourta wadis

Fan morphometry

The Wadi Beni Mhammed is formed by the confluence of the Wadis Ida Ou Merouane and Aït Mekhlouf wadi. Four main successive fans have been constructed between the mountain edge and the Wadi Souss, dissected by the Wadi Beni Mhammed (Fig. 3). These fans are limited to the east by the Wadi Irguitene fan and to the west by a zone of four coalescent fans, associated with the Wadi Aoukourta. Their altitude varies between 230 m at the foot of the mountain slope and 130 m in their distal part, where their truncated margins stand 2–2.5 m above the channel floor of the Wadi Souss. Thus they decline by 100 m over a length of 23 km, an average gradient of 4.35% (Table 1). Fans 1 and 2 have much steeper slopes because they have been deposited at the foot of the mountain by the Wadi Aït Mekhlouf upstream of its confluence capture and they are have also been affected by uplift of the Atlas. These two successive fans, building westward, led the formerly separate Wadi Aït Mekhlouf to form a confluence with the Wadi Ida Ou Merouane, thus forming the main fan (N°. 3). This main fan is spread over a length of 19 km and an average width of 4 km, thus occupying an area of 56 km^2. Fan 4 is parasitic on fan 3 and is much more recent than the other fans (Fig. 3), with a triangular form and an area of 34 km^2 (Table 1).

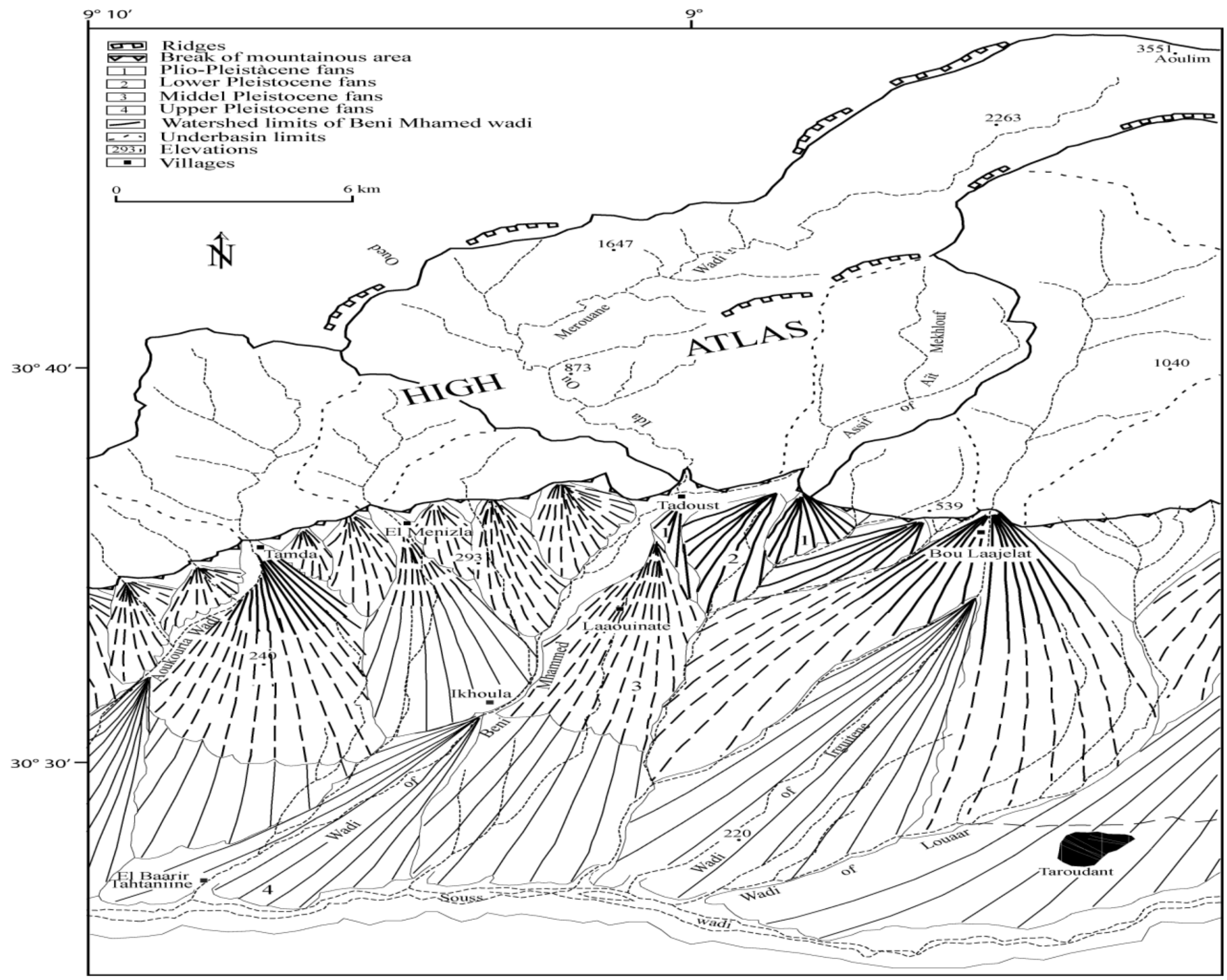
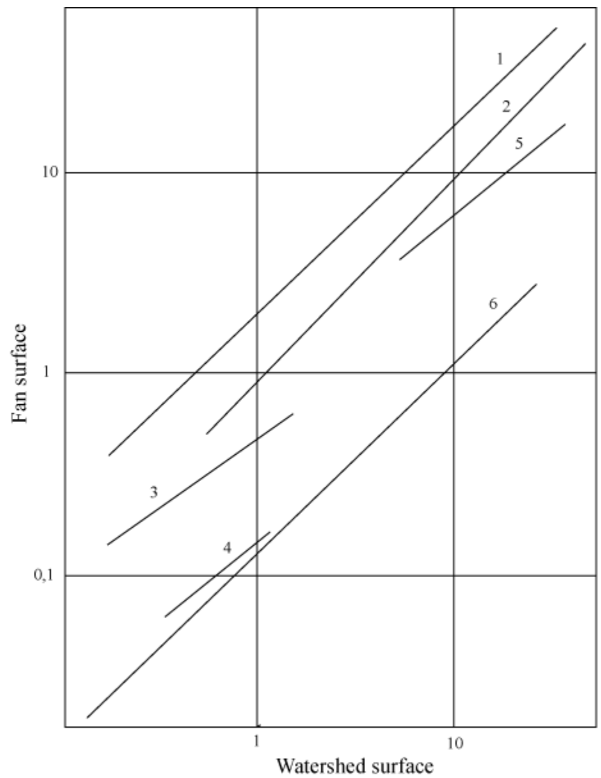


Fig. 3: Morphology of fans of Beni Mhammed and Aït Mekhlouf wadis and their watershed

Relationship between fan and catchment area (Table 1)

The dimensions, shapes and locations of the fans are controlled by the characteristics of their catchments (cf. Bull, 1962; Denny, 1965; Hooke, 1967, 1968; Guzzetti *et al.*, 1977; Cooke *et al.*, 1993a). Bull (1962) expressed this relationship by the equation $Af = cAd^n$, where ***Af*** is the area of the fan. ***Ad*** refers to the catchment, ***c*** to the surface area of a fan which has a drainage area of 1 km^2, and ***n*** to the slope of the regression line. Therefore, this relationship illustrates the basic concepts of fan geomorphology and catchment characteristics (Fig. 4).



1: Schistic drainage basin ($Af = 2{,}1\ Ad^{0{,}91}$)
2: Sandstone rocks drainage basin ($Af = 0{,}79\ Ad^{0{,}98}$)
3: Quartziferous and dolimitic drainage basin ($Af = 0{,}44\ Ad^{0{,}62}$)
4: Quartziferous drainage basin ($Af = 0{,}16\ Ad^{0{,}75}$)
5: Drainage basin of the west side of Death Valley ($Af = 1{,}05\ Ad^{0{,}76}$)
6: Drainage basin of the east side of Death Valley ($Af = 0{,}15\ Ad^{0{,}9}$)

Fig. 4: Lithology of the drainage basin: its role in the relation between the alluvial fan and drainage basin surfaces (surfaces are given in mi^2 (Mile)), (After HERAIL, 1984)

The application of this relationship ***($Af = cAd^n$)*** to the fans of the Aït Mekhlouf–Beni Mhammed wadi system ($Af = 0.18\ Ad^{1.2}$) and to neighboring fans; namely, Irguitene to the east and Aoukourta to the west ($Af = 14Ad^{0.5}$), shows that the value of ***n*** is very different. It is about 1.2 for the Aït Mekhlouf–Beni Mhammed fans. This is comparable with equivalent data from fans on the eastern slopes of Death Valley, USA, from a study by Denny (1965). Thus abundant material was transported from the mountain area to the head of the wadi-fan thanks to the strong catchment gradient, in the order of 180 ‰ (Table 1). In contrast, the value of ***n*** (0.5) of the Aoukourta and Irguitene fans is always less than 0.9 (cf. Denny, 1965).

Table1: Morphometry of the fans of Beni Mhammed wadi, Aoukourta wadi, and Irguitene wadi

	Fans						**River Basin**			
Fans	Length in km	Width in km	Surface of fan in km^2	Altitude up/down	Fane dislevelment	∑ fane slope ‰	Surface of R.B. km^2	Altitude up/down	River Basin dislevelment	∑ R.B. slope ‰
Aït Mekhlouf Fan 1 old Fan 2 old	2 ,7 6	1,8 2,7	3 8	529/364 361/265	165 96	61 16	{44}	2612/404	2208	{180}
Beni Mhammed Fan 3 main Fan 4 secondary	19 12	4,5 8	56 34	233/150 206/121	83 95	4,3 8	{199}	3551/233	3318	
Aoukourta Fan 1 main Fan 2 secondary	15 12	6 6	60 35	340/120 214/104	220 110	14,6 9	{40}	1976/336	1640	{156}
Irguitene Fan 1 main Fan 2 secondary	16 17	12 7	85 58	463/233 353/160	230 193	15,3 12	{73}	2982/480	2502	{168}

The value of ***c*** also varies from one catchment to another, mainly for lithological and tectonic reasons. Table 1 shows the existence of very large and very narrow fans relative to the surface area of their current catchment. By way of comparison, the Aoukourta and Irguitene fans, derived mainly from Mesozoic and Cenozoic rocks (Fig. 2), have extensive surfaces relative to their catchment areas. Hence, the value of ***c*** is 14 km^2. In contrast, the Wadi Beni Mhammed system has several narrow fans, deposited in successive episodes, each fan showing different morphological characteristics, related to a number of factors. Initially, the durability of catchment rocks and the role of climatic conditions and tectonic activity in liberating material for incorporation in wadi bedloads are important and related influences. The less resistant sandstone outcrops of the Tertiary have given rise to widespread accumulations >10 km wide, whereas the Palaeozoic limestone and sandstone have delivered a more restricted plume of material. Also important is the accommodation space available for the build up of fan material. Nonetheless the value of ***c*** is always very low and does not exceed 0.18 km^2. As noted already, the main fan (3) of the Wadi Beni Mhammed is constricted to the east and west by other (larger) fans, which have limited its development, such that it is very long but very narrow (19 km) compared with other adjacent fans.

Relationship between fan and catchment gradient

Bull (1964b) suggested that the slope of an alluvial fan is related to the size of its catchment. However, it is clear from the present study that catchment lithology is the main factor influencing fan slope, since this controls the nature of the debris, sedimentation processes, and the volume of deposited material (Chakir, 1997). Hooke (1968) suggested (following Eckis, 1928; Melton, 1965) that the slope of the fan decreases as its area increases. Fans formed by torrential flows (debris flow) are characterized by steep slopes, particularly in their apical area. On the other hand, the Wadi Beni Mhammed has a low gradient because it of its abundant sediment supply and the large extent of its catchment; this can be explained in part by the catchment geology and the high rate of weathering of these rocks.

Relationship between fan gradient and catchment area (Table 1)

Like its surface area, the slope of a fan is also controlled by several factors such as the characteristics of its component material, sediment load, the morphology of the catchment area, and the alternation of several phases of accumulation. Bull (1964a) noted that the slope of a fan tended to decrease with increasing catchment area. This is in agreement with the morphological characteristics of the fans of the Wadi Beni Mhammed, which have shallow slopes compared with the Aoukourta and Irguitene fans. In a laboratory simulation, Hooke (1968) showed that fan slope is generally proportional to catchment surface area, to the radius of the fan, and to the alluvial discharge. The last is particularly important because a large discharge can carry debris even on a gentle slope and with a high flow viscosity.

The three generations of Wadi Beni Mhammed fans

The first generation of fans

At the exit from the mountains, the deposits of the oldest fans are almost completely obliterated by the sediments of nested terrace fans. The former are seen in outcrop only where the surface is ravined. The material from the Wadi Aït Mekhlouf is dominantly very coarse, with rounded blocks >1 m long, mainly of limestone, sealing the surface of fans 1 and 2. In the case of the Wadi Beni Mhammed, this has supplied large accumulations of gravel composed of limestone and sandstone, generally embedded in a matrix of poorly consolidated coarse sand. These are capped by a thick (>2 m) conglomeratic ‘slab’ comprising medium gravel (8-15 cm), predominantly rounded, set in a reddened and calcreted matrix. It seems that this formation is identical to that described by Weisrock (1980) at El Maasser and by Aït Hssaïne (1994) at Irguitene. Weisrock hypothesized that this type of formation is characteristic of Pliocene-Villafranchian fans. The origin of the calcareous cement may be related to the dissolution of limestone in the catchment. Aït Hssaïne (1994, 2009) suggested that the enrichment of this facies in carbonate arises from its proximity to the essentially calcareous sub-Atlas zone (the zone interposed immediately before the Atlas foothills).

The main fan of the Wadi Beni Mhammed

At Laaouinate, ~10 km downstream from the confluence where it is formed (by the confluence of the Ida Ou Merouane and Aït Mekhlouf wadis), the Wadi Beni Mhammed has incised its bed ~10 m into the alluvial fan deposits (Fig. 3). The sediments are markedly different from those in the earlier fans, being formed by a sequence of four coarse gravel sheets (Fig. 5).

Petrographic study of these deposits has been performed in the coarse lenses of the main fan. In an attempt to reconstruct the various morphological steps of the construction of the fan, a comparative study has been conducted between the complex alluvial petrography and the lithology of the corresponding catchment.

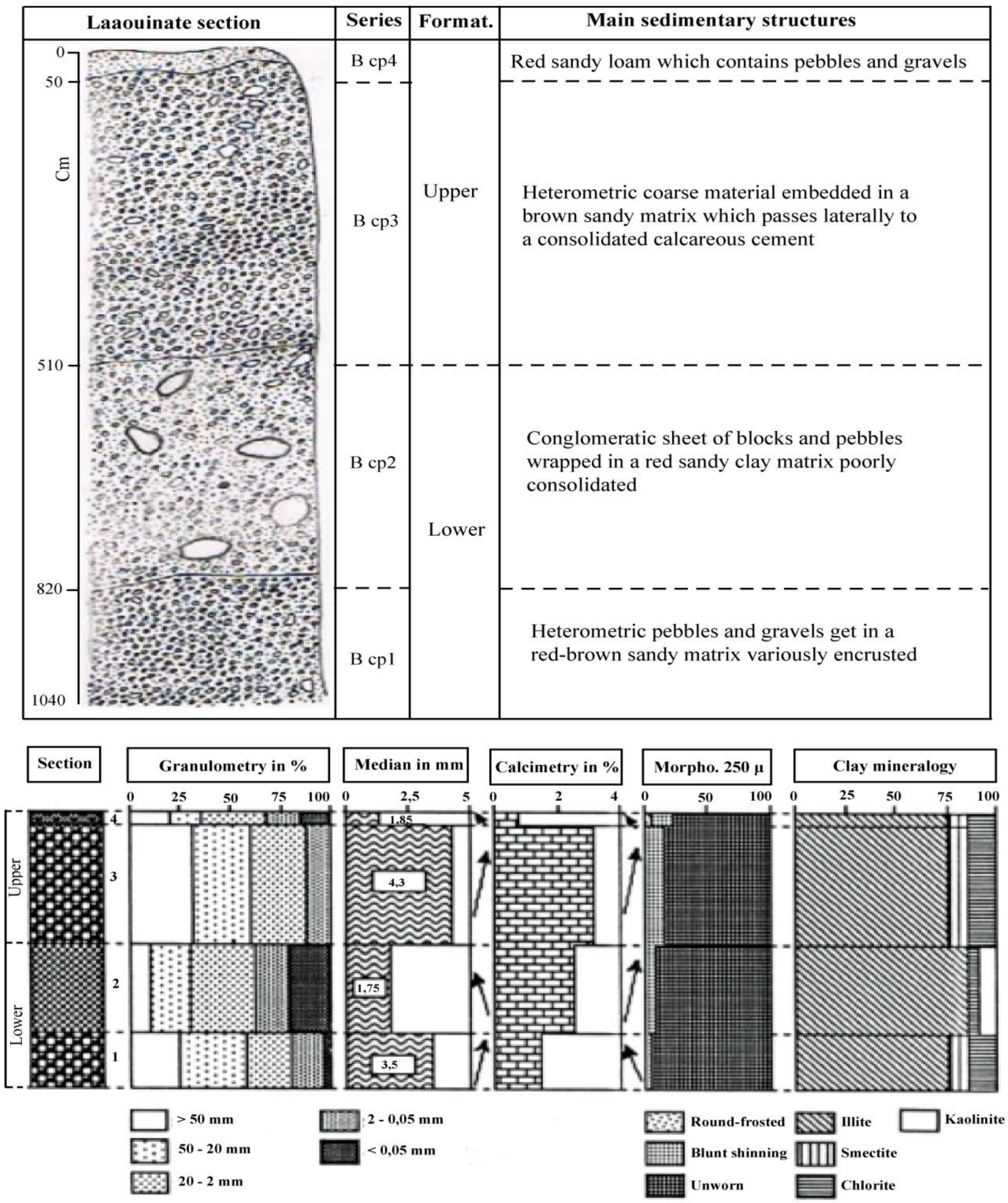


Fig. 5: Sedimentological study of principal fan of Beni Mhammed wadi in Laaouinate

Catchment geology

Wadi Beni Mhammed is formed by the drainage from two catchments of varying importance: the Ida Ou Merouane basin and the Aït Mekhlouf basin, which are composed mainly of crystalline and Permotriasic rocks of the Western High Atlas (Fig. 6). These rocks, affected by folding and faulting, determine a set of morphostructurally distinct and complex compartments. In the North, the axial zone of the Atlas represents a landscape of high peaks at altitudes >3000 m (Aoulim 3351m). The lithology has determined a particular tectonic style; indeed, the hard Georgian limestones are folded into tight and confined anticlines, some of which are incised by deep valleys, while the Ordovician shales are often formed into 'pinched' synclines (Aït Hssaïne, 1994, 2000; Fig. 7). In the South, and particularly in the East valley of Ida Ou Merouane, the area of the 'sub-Atlas' is composed of varied and less resistant Mesozoic and Cenozoic strata (limestone, pink marl and sandstone: Fig. 7). This zone corresponds with the catchments of the Wadis Aït Mekhlouf and Irguitene. The boundary between these two geological divisions is the 'intermediate' Atlas zone, defined as the Paleozoic foreland by Dresch (1941). It includes a limestone and shale core, surrounded by a sandstone-conglomerate envelope. The intermediate Atlas zone is bordered by two major NE-SW discontinuities: To the north, the Ida Ou Zal fault, and to the south, the South Atlas Fault (Figs. 5 & 6). In general, the landscape of these two catchments is structurally controlled and can be summarized in a series of anticlinal and synclinal axes, often offset by major faults.

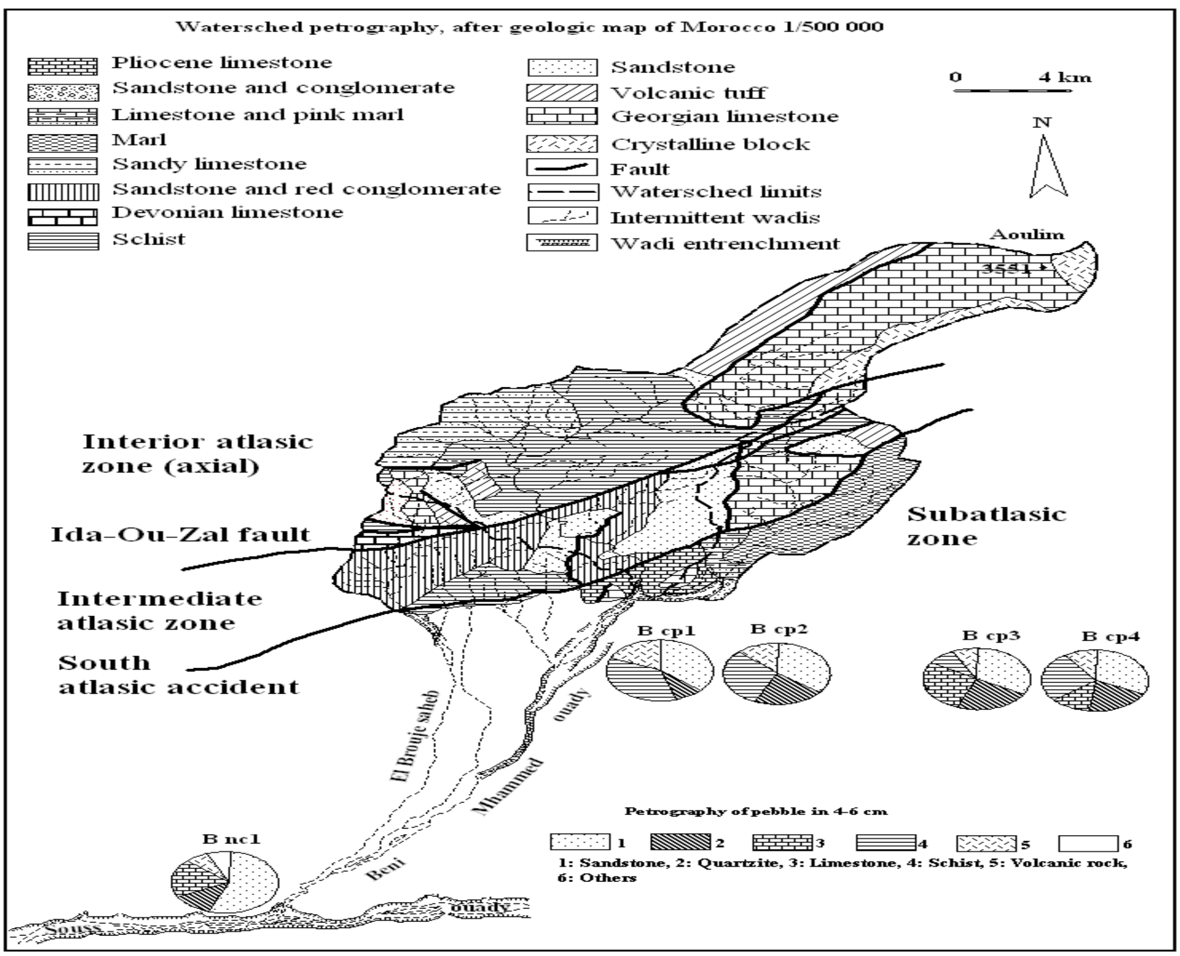


Fig. 6: Petrography of pebble in 4-6 cm of Beni Mhammed wadi fans

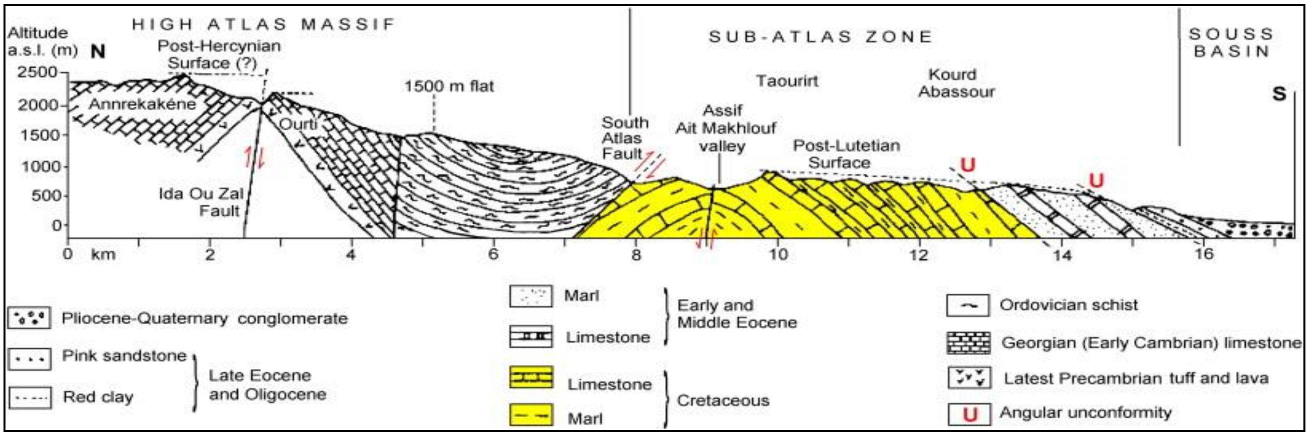


Fig. 7: Schematic cross-section through the area north of Taroudant, through the High Atlas Massif, the Sub-Atlas piedmont, and the northern margin of the Souss Basin. The section line runs north–south through Boulaajlete (Aït Hssaïne, 1994 and 2009)

Petrography of pebbles in the main fan (Table 2 and Fig. 8)

The petrographic composition of the coarse alluvial material of the Wadi Beni Mhammed fan reflects the rocks and weathering residue that crop out in its catchment. From bottom to top, the suite of pebbles (sized 4-6 cm) shows some variation between the different gravel sheets (Fig. 6). The lower formation is characterized by major representation of material from the intermediate Atlas zone in the wadi catchment, with an abundance of sandstone and shale (Table 2). The sandstone and quartzitic deposits derive from Acadian and Stephano-Autunian covering (termed cap-rocks). Their proportion increases vertically; it is 44% in the series (B cp1) and rises to 57% in the series B cp2. In contrast, the frequency of Palaeozoic rocks shows a corresponding decrease. The shales from the Cambro-Ordovician zone decline from 36 to 29%. The same applies to magmatic rocks of the internal basin, which decline from 20 to 14%. This vertical variation is also expressed by the ratio of cap rocks to basement rocks (Ca / Be) which changes, from the bottom upwards, from, 0.78 to 1.32. The lower formation is therefore derived from the Atlas zone of the catchment and principally from its intermediate part.

The upper formation shows the presence of new detrital materials. Limestone pebbles, absent in the lower deposits, are present in this formation. Their percentage is 28% in the series B cp3 and 12% in the series B cp4. These clasts do not represent the Georgian limestones, which are more resistant and come from further afield; instead they are Devonian limestones, from more proximal sources. The limestones of the sub-Atlas zone yield coarser blocks. They may also have been dissolved, and be the source of $CaCo_3$ calcrete cement. The upper formation therefore represents a period when the catchment included source areas within the sub-Atlas zone, which corresponds to the influx of material from Wadi Aït Mekhlouf. Thus that wadi had joined the Ida Ou Merouane prior to deposition of the upper formation. The essential element here is the predominance of cap-rocks, especially in the series B cp3, whereas in the superficial series (B cp4), clasts of more resistant basement are more common. The cap-rocks/basement (Ca /Be) ratio rises to 4.88 in the former, then falls to 1.77 in the latter (Table 2). The changing clast composition can also be illustrated diagrammatically (Fig. 8).

Fig. 8: Petrographical spectrum variation of pebble in 4-6 cm of principal fan and adventitious fan of Beni Mhammed Wadi

Table 2: Global petrography of pebble in 4-6 cm of Beni Mhammed wadi

	Sandstone	Quartzite	Limestone	Schist	Volcanic rock	Others	Ca/Be
Watershed							
Ida Ou Merouane Assif	**26**	**-**	**34**	**26**	**14**	**-**	**1,5**
Aït Mekhlouf Assif	**17**	**-**	**57**	**3**	**2**	**21**	**19**
Main fan							
Bcp1	**36**	**8**	**-**	**36**	**20**	**-**	**0,78**
Bcp2	**35**	**22**	**-**	**29**	**14**	**-**	**1,32**
Bcp3	**33**	**22**	**28**	**9**	**8**	**-**	**4,88**
Bcp4	**32**	**20**	**12**	**26**	**10**	**-**	**1,77**
Adventitious fan							
Bnc1	**55**	**12**	**20**	**-**	**6**	**7**	**15,66**

Petrographic analysis of the coarse material has revealed two major superimposed alluvial formations within the stratigraphy of the main fan. The lower formation lacks Devonian limestone, which provides important information about catchment configuration, since at that time there was clearly no connection to the sub-Atlas zone. This can be interpreted in terms of the independence of the Wadi Aït Mekhlouf, which was building its own fan system (fans 1 and 2) at the time of deposition of this lower formation within the main fan (Fig. 9, phase 1). The gravels of the lower formation have their origin in the catchment of the Wadi Ida Ou Merouane and thus are devoid of Devonian and Secondary limestone pebbles. In the upper formation, such pebbles are present, indicating that an entirely new alluvial accumulation has overlapped the older deposits. The presence of limestone in this formation shows a new connection to the sub-Atlas zone. This change could have originated from a drainage diversion triggered by tectonic movements, as some faults in the region have been active until very recently (Proust, 1961). Clearly the Wadi Aït Mekhlouf had at this point joined the Wadi Ida Ou Merouane (Fig. 9, Phase 2). This 'capture' could have arisen simply by the two wadis both migrating into their common interfan area (Fig. 10).

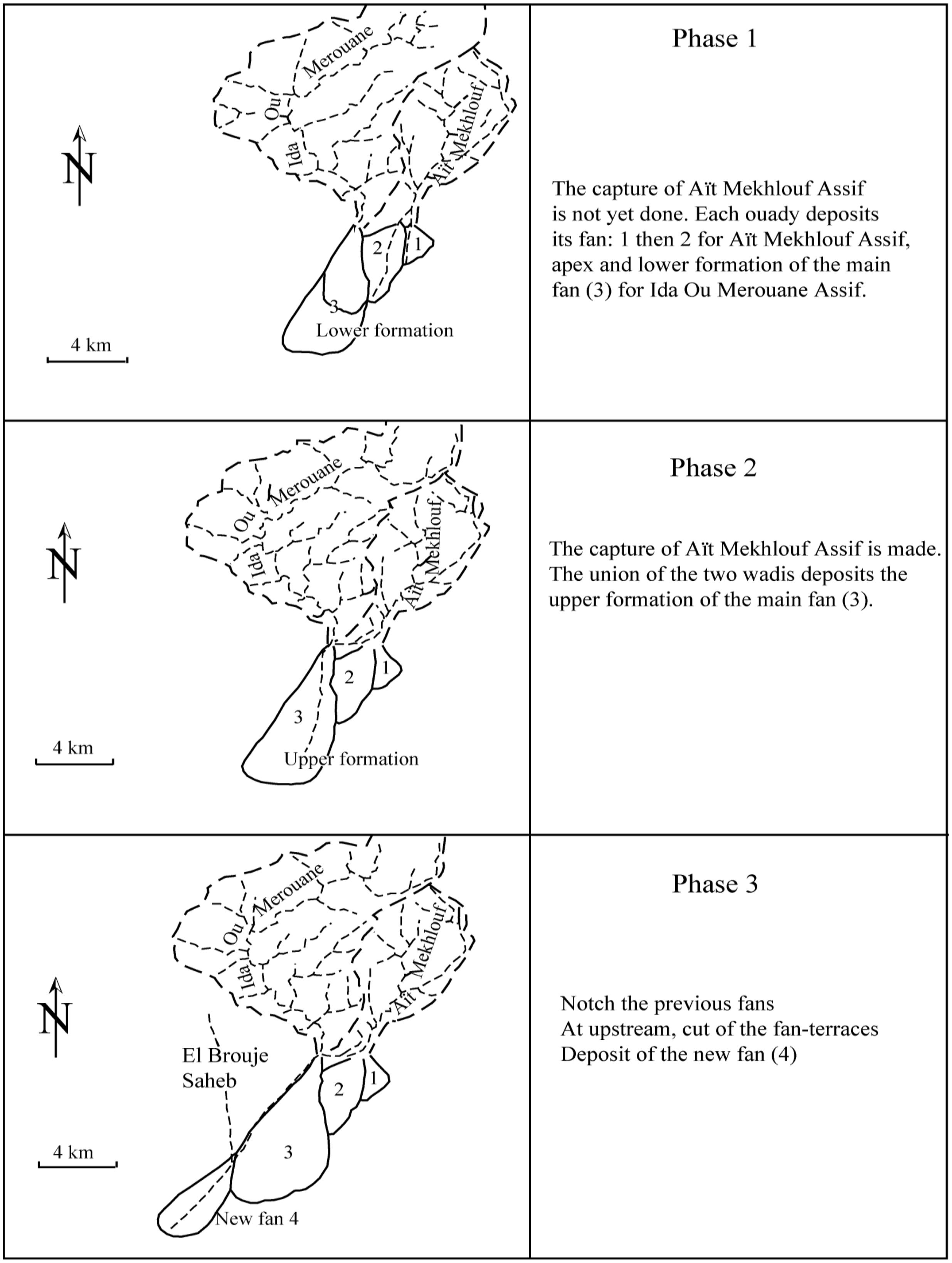


Fig. 9: Different deposit phases of Beni Mhammed Wadi fans

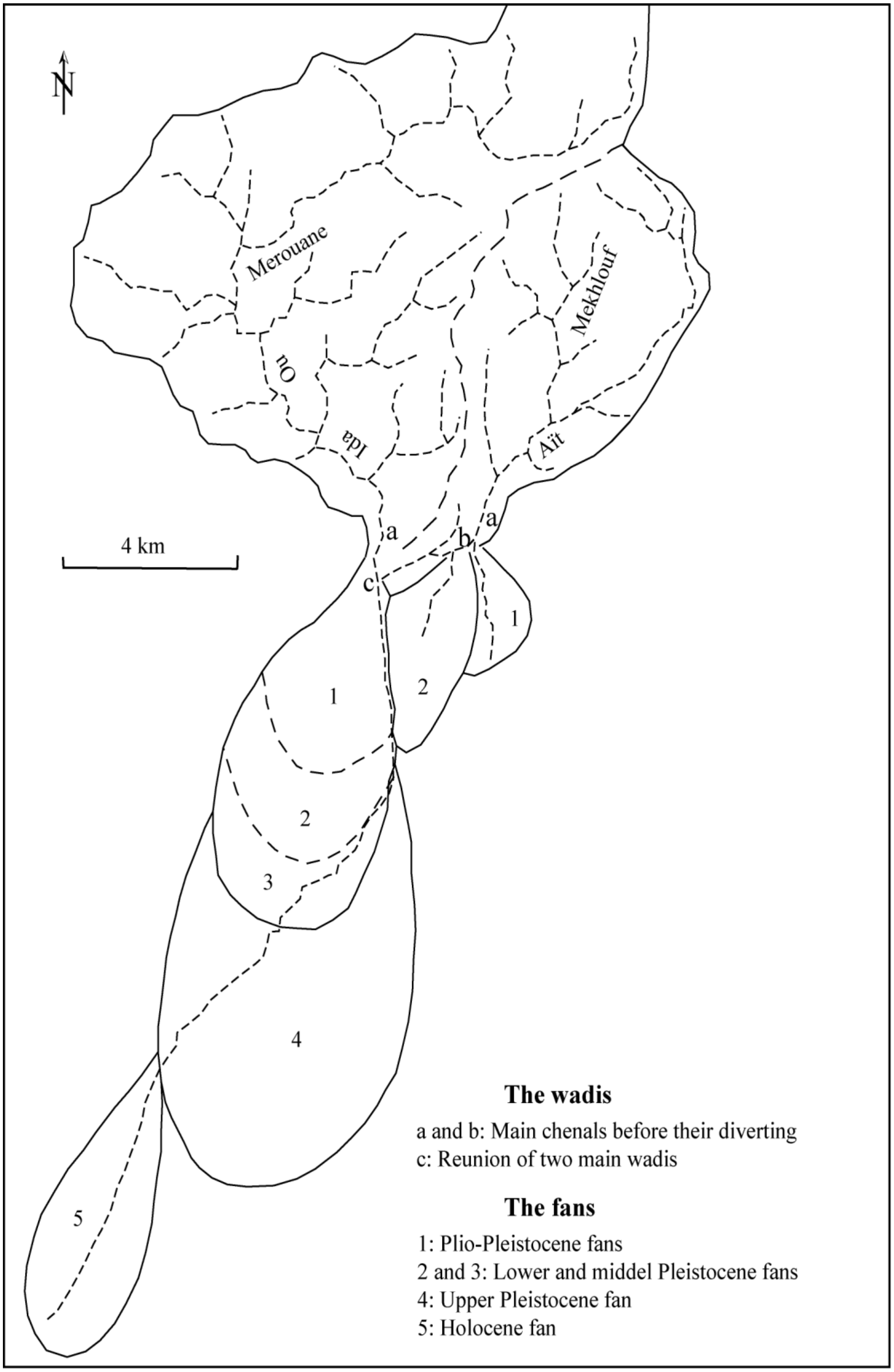


Fig. 10: Channel slide toward interfans and the joint of two principal wadis

The Holocene fan (parasite fan 4)

The deposits that form the Holocene fan (Weisrock *et al.*, 1991; Aït Hssaïne, 1994, 2009) of Wadi Beni Mhammed can be observed to a depth of >5 m in a left-bank exposure a few meters upstream from the confluence with the Wadi Souss (Fig. 6). At their base these deposits are less coarse than those in the coarse gravel sheet of the main fan; they are overlain by fine sediments consisting mainly of silt and clay (mud flow). The coarse basal material (B cn1) is formed of polymict gravel with a predominant pebble size of 4-12 cm, although some pebbles are to 26 cm. Its composition shows the dominant supply to be the cap-rocks, which account for 94% of the total (Table 2), mainly sandstone (55%) and limestone (20%), quartzite from the Permo-Triassic (12%) and lesser amounts from other cap-rocks (dolomites, argillites and conglomerates) of various origins. This deposit clearly derives from reworking of the upper formation of the main fan towards its downstream end, but with a larger proportion of Wadi Aït Mekhlouf material, due probably to the fact that the shales from the Ida Ou Merouane catchment, being strongly altered (metamorphosed), do not survive well in the form of pebbles, especially after reworking.

The strong dominance of sandstones reflects the reworking of old fan and tributary deposits, mainly from the El Brouje Saheb (Fig. 6). The proportions of limestone and shale are small compared with samples further upstream, in the older fans. For limestone pebbles, it seems that there is a size below which they are rapidly reduced by dissolution; indeed, they are preferentially represented at sizes between 80 and 120 cm. The decrease in the proportion of shale pebbles is (as already noted) undoubtedly due to the disaggregation under the influence of weathering and mechanical fragmentation, which rapidly reduces them below the 4 cm size of the gravel analysis.

The summit unit of the Holoceene fans is constituted by silt and clay (mud flow), crowned, sometimes, by a thin layer of fine windy sand, especially in the distal part of the fans.

Morphogenesis of the Wadi Beni Mhammed fans

On the southern piedmont of the Western High Atlas, sediments have been deposited in the form of alluvial fans and associated fan-glacis. At least three generations of fans are represented, including sedimentary formations with ages varying from Plio-Pleistocene to Holocene. The genesis of the fans has involved several phases of accumulation of unequal importance, each phase being represented by deposits with particular characteristics. The oldest (Plio-Pleistocene) pluvial periods gave rise, at the heads of the major wadi-fan accumulations, to coarse deposits of boulders and pebbles sealed by a calcreted capping. The formations of this age derived from the Wadi Aït Mekhlouf differ from those of the Ida Ou Merouane in that they take the form of fans or fan fragments, clearly stepped, covered with coarse boulders (much rounded and > 1 m). At the head of the Wadi Ida Ou Merouane fan system gravelly fan-glacis have developed. The top of the apical part of the main fan (3) is sealed by a thick calcreted capping, which becomes buried down-fan beneath later coarse deposits. This calcreted formation is probably related, in terms of age, to the major Pliocene-Villafranchian fans described in the Atlantic High Atlas (Weisrock, 1980) and in the western High Atlas (Bouzalim, 1987; Aït Hssaïne, 1994, 2009). After these ancient fans were established there have been changes in the drainage pattern, including abandonment of former courses, probably in part influenced by tectonic movements. A key development in this respect at the southern margin of the Atlas was the union of the two wadis, Aït Mekhlouf and Ida Ou Merouane. There followed an increase in flow energy marking the beginning of the Pleistocene and continuing into the middle Pleistocene, perhaps enhanced with the change to 100 ka Milankovitch climate cycles (cf. Westaway, 2002; Bridgland & Westaway, 2008). The main wadis became increasingly incised and deposited material either in the form of terrace-fans of about thirty meters thickness (Aït Mekhlouf Wadi: Fig. 2) or as new polygenetic spreads, as seen in the main fan of the Wadi Beni Mhammed. Here, two main depositional episodes can be distinguished in terms of sedimentary characteristics. First, highly variable coarse material, relatively indurated, can be attributed to the Lower and Middle Pleistocene. Fan-glacis of this type are littered with coarse rubble, little worn, resulting from a long periods of multiple reworking of old fans. The lower formation of the main fan falls into this category and is separated from the upper formation by a marked discordance, resulting from a temporary cessation of sedimentation and/or an episode of erosion. The Lower and Middle Pleistocene fan-glacis passes downstream into a newer fan, the result of more recent deposition, corresponding probably with the terminal Upper Pleistocene (terminal Soltanian or even earliest Holocene) (Weisrock *et al.*, 1991; Aït Hssaïne & Bridgland 2009). This latest fan sediment is predominantly silt, of several meters thickness, now much dissected by numerous rills that follow the slope of the fan-glacis (Aït Hssaïne, 2002).

The morphogenesis of this piedmont therefore reflects the complexity of the climatic, lithological, and probably tectonic influences. The role of tectonic deformation of the catchment and its piedmonts is clearly visible in the abandonment of old fans and the displacement and widening of the main wadis that fed them. It seems that the lower unit of the main fan was deposited by wadi flowing NW to SE, which is different from the current NE-SW direction. After the deposition of the first fan unit, tectonic movement disrupted the detrital piedmont of the western High Atlas (Proust, 1961), following which transportation and accumulation of the second morphological fan unit was accomplished by a wadi with the modern NE-SW orientation. The material of the main fan has been eroded by the lateral displacement of a large wadi (Beni Mhammed) to the west, which now has a course following the junction of the old neighbouring fans.

Conclusion

The alluvial fans of the Wadi Beni Mhammed wadi fall into at least three main generations with age ranges from Pliocene-Quaternary to Holocene. The genesis of these fans results from several phases of accumulation of unequal importance, each phase being represented by deposits with specific characteristics, bearing the imprint of the climatic period during which it was emplaced. The gradients and the relative ages of the fan deposits reflect the role of erosion and orogenic evolution of the catchments. Neighbouring catchments often show differences in fan sediments, reflecting variations in climatic, lithological and hydrographic conditions. Wadis flowing from smaller catchments in Tertiary rocks carried large masses of alluvial deposits composed essentially of boulders and coarse pebbles, which were deposited close to the heads of wadi-fans in the form of debris flows. Down-fan the material becomes progressively finer due to the declining gradient and the lower flow-energy of the wadi, eventually passing into mudflow.The topography of these accumulations thus has steep slopes at the foot of the mountain and breaks of slopes in the middle sections of the fan-glacis. In contrast, wadis from larger catchments in Palaeozoic/crystalline rocks have delivered rock debris that is spread over short distances with gentle gradients that decrease steadily down-fan.

The alluvial material of the main Wadi Beni Mhammed fan highlights the complexity of the sedimentary episodes responsible for its construction: two successive phases of aggradation distinguished by different petrographic characteristics. The first phase, which gave rise to the deposits of the lower formation, originates from the Ida Ou Merouane catchment. The corresponding material, devoid of Devonian and Mesozoic limestone, reveals a catchment area more restricted than at present. The presence of such limestone in the two divisions of the upper formation indicates the formation of a much larger catchment as a result of the confluence between the Wadis Ida Ou Merouane and Aït Mekhlouf. In the Holocene the Wadi Beni Mhammed formed an alluvial sheet, nested within the Pliocene–Early Pleistocene fan, the 3–4 meters of detrital material from which this terrace is formed dominating the floor of the wadi. The stratigraphy and morpho-sedimentary characteristics of this terrace were addressed by Ait Hssaine (1994).

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