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THE GEOMORPHOLOGICAL ROLE OF EPISODIC RIVERS BASED ON THE EXAMPLE OF THE OUEDS EL MUT AND EL FEIJA (ANTIATLAS MOUNTAINS, MOROCCO)

Abstract: The paper discusses the results of a 2001-2005 field investigation into episodic river channels in the southern AntiAtlas mountain range. Because of the size of the study area the investigation concerned only a few selected fluvial systems. The characteristics of the channels in the designated areas were based on the qualitative and quantitative properties of the river channels, the erosion and accumulation landforms present as well as on the kind and quantity of rubble and coarse sediments. Five channel types were identified and described. In general terms the role of the episodic streams draining the northern and southern slopes of Djebel Bani varies. Investigation of the channels and tracks of water flow shows that only the largest oueds on the southern slope carry material to the base of Djebel Bani and the sediment in those river channels is better sorted. On the northern slope clastic material is deposited in Oued el Feija. Aeolian activity can clearly be seen on the alluvial fans which form at the ends of smaller oueds as well as within bigger oueds, and yet the aeolian activity does not mask the fluvial forms.

Key words: episodic river channels, types of river channel, structure and dynamics of river channels, AntiAtlas, Djebel Bani, oued (wadi), episodic river.

1. Introduction

Independent of the climatic zone, mountain regions are always a zone of sediment supply. Streams flowing through these areas transport detritic material to the foreland, especially during flood episodes. The kind and fraction of the material is strictly linked to the properties of a given drainage basin environment as well as to the hydrological regime of a given stream. River channel formation is thus the result of long-term processes taking place within the whole catchment area. The existence of morphodynamic elements within the longitudinal profile of the channel is an effect of channel evolution mainly connected with the resistance of the bedrock.

The aim of this research carried out in the southern AntiAtlas was the investigation of the formation of typical episodic river channels and the determination of the geomorphological role of these streams in the transformation of the relief of the region. Under expedition conditions very small channel systems had to be taken into consideration because of limited time and possibilities for a wider investigation. Thus one of the tributaries of Oued el Mut had to be chosen for investigation. This river drains the southern slopes of Djebel Bani. The other river investigated was Oued el Feija whose tributaries drain the northern slope of Djebel Bani (Figure 1).

2. Methods

Field research in the Djebel Bani area was carried out in March 2001 and in February 2005. For detailed investigation of the Oued el Mut channel, the channel was mapped using a special protocol and manual (Kamykowska et al. 1999). This method had been developed for the application in various mountain regions, especially for the Carpathian Mountains. The whole channel system of Oued el Mut has been mapped using this method.

The basic elements of the channel were described based on the channel structure and the characteristics of the channel landforms and they were later thoroughly analysed. The evaluation of the channel characteristics in these reaches consisted of: the quantitative and qualitative properties of the channel, erosion and accumulation landforms and the kind and fraction of the rubble and coarse sediment. All the data was collected during a period with no evidence of recent water flow in the channel. The team was able to move on foot as a camp was built on the Djebel Bani foreland. Eleven reaches of Oued el Mut, 14 km long, were mapped (Figures 2, 3). Oued el Feija channel was investigated with the use of survey mapping methods by research patrols along the whole length of the river and the aim of this investigation was to work out the rules for river formation as well as the formation rules of the adjacent and tributary episodic streams draining the northern slope of Djebel Bani (Figure 1). The following topographic maps were used for the preparation of the paper: 1:20 000, 1:250 000 together with a geological map of the region (1:200 000) (*Carte topographique du Maroc* 1948, 1991, *Carte geologique du Maroc* 1989).

3. Area investigated

The area investigated is situated on the border between the AntiAtlas mountains and the vast and varied Sahara Desert. The oueds chosen for the investigation drain the slopes of the Djebel Bani mountain range (southern AntiAtlas). Oued el Feija drains the northern slopes of Djebel Bani and joins Oued Dra south of Zagora (Figure 1).

Oued el Mut drains the southern slope of Djebel Bani and reaches the wide depression where Oued Dra also flows. This area is particularly interesting because most of the episodic streams draining the AntiAtlas disappear in the Sahara Desert, but south of Zagora Oued Dra changes its course turning south-westward. In the past, episodic rivers flowing down from the Atlas Mountains occasionally reached the Atlantic

Ocean. Today, cultivation in the Oued Dra valley and the construction of reservoirs in the upper part of the valley have resulted in the river drying out short of its previous regular terminus.

Oued el Feija valley is one of the biggest AntiAtlas valleys and is situated parallel to the main mountain ranges, between the Djebel Bani range in the south and Djebel Mestra and Djebel Amergou in the north. The catchment area of this river covers 1875.2 km² and it is situated at an altitude of 1962 m a.s.l. on the Graga ridge northwest and at approximately 600 m a.s.l. at its mouth where it joins Oued Dra. Oued el Feija is about 100 km long. The drainage area of this river is built of: Precambrian formations in the north-west (andesite, trachite, granite and dolomite formations as well as red quartzite sandstones) and Cambrian dolomites, green clay sandstones and quartzite sandstones in the south. The southern part of the catchment area in the Djebel Bani region is built of a variety of Ordovician quartzite sandstones and clay sandstones. The sedimentary rocks in the whole area investigated are monoclinally tilted to the south, with a small gradient from the oldest to the youngest sediments.

The bottom of Oued el Feija valley is 1-16 metres wide and it is covered with Pleistocene and Holocene formations that build wide alluvial fans and terrace levels. The alluvial fans are mainly built of sandy-gravel formations and in close proximity to the river mouths they consist of gravel fractions. The channel itself is built of gravel and sand and is from a few to several metres wide.

Within the broad el Feija river valley lie the remains of five accumulation terraces or erosion glacis and these are usually covered by alluvial fans. These terraces were formed during five pluvial periods, each of them being the equivalent of a glaciation or interglacial period (Coque 1977).

Oued el Feija valley is asymmetrical, the left, northern slopes are long and gentle while the right, southern slopes are short and steep. Also the bottom of the valley echoes this asymmetry. The valley bottom on the left bank of Oued el Feija is wide and slopes southwards, while the right bank is very narrow. Terraces and alluvial fans from the Amirien period (Mindel + interglacial Mindel/Riss period) cover most of the area within the bottom of the valley and they are best formed in the northern part of the oued. Within this area three barchans have recently been formed near the town of Zagora and they represent various different stages of formation.

Oued el Mutis is a typical landform draining the southern slopes of the Djebel Bani range between Foum Zguid and Tagounite and it has not been anthropogenically altered. The drainage basin of this river covers 44.5 km² and it is situated at an altitude of 1110 m a.s.l. on the Djebel Bani range to 540 m a.s.l. on its foreland within the Erg Souar depression where Oued Dra flows (Figure 1). The area is mainly built of Ordovician sandstones of various Djebel Bani formations (Figure 2). Djebel Bani is divided eastwards into two ridges – the northern Djebel Bani I and the southern Djebel Bani II. In the north the area investigated is built up of Rouid-Aïssa formation which consists mainly of grey-blue, green sandstones and pink quartzite sandstones. These rocks (sandstones) are monoclinally folded southwards with an inclination of 6 degrees. The surface of this monocline is often either the surface of the slope or the bottom of the river channel. These formations are covered by regular joint

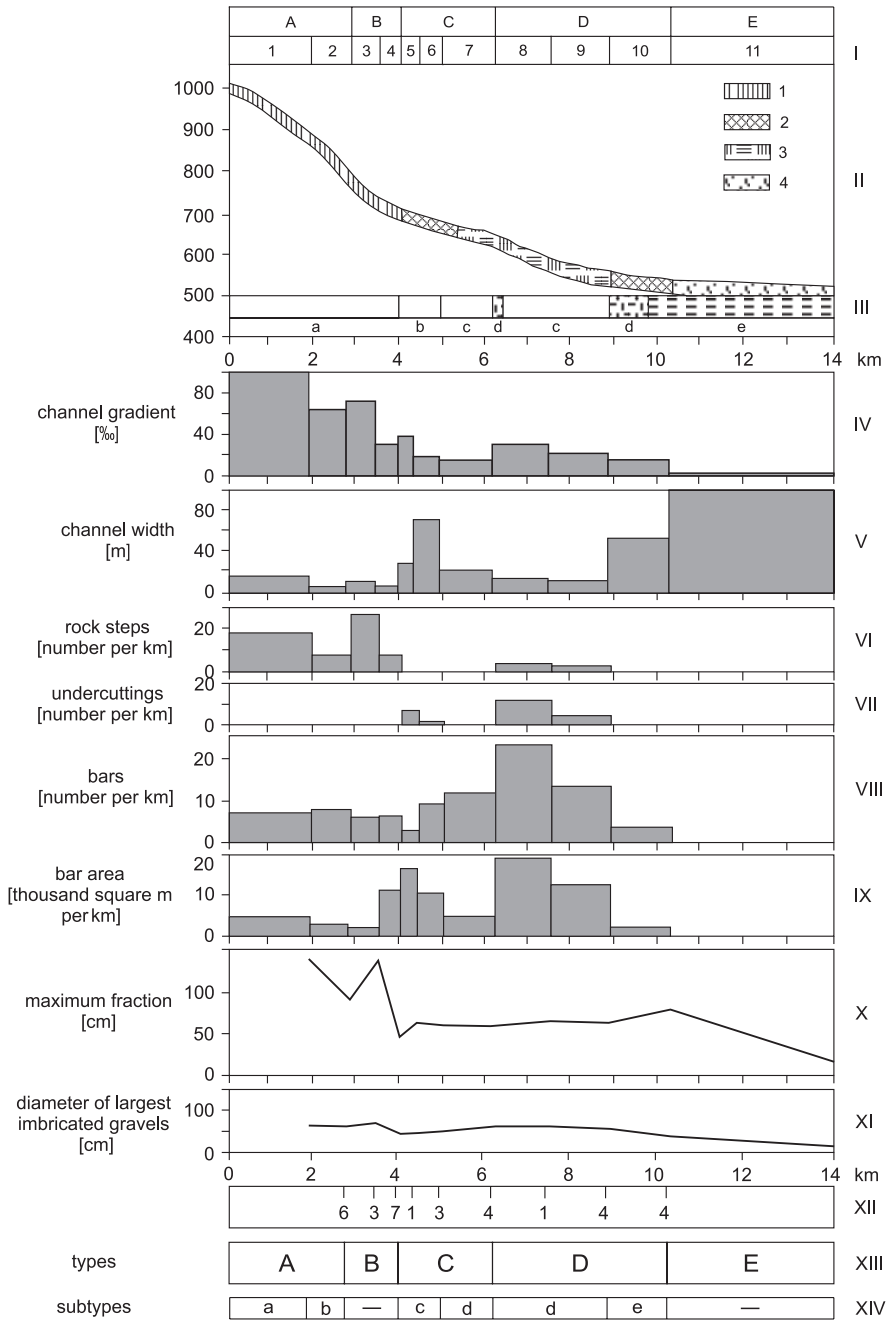


Figure 3. Structure and typology of the Oued el Mut channel

fractures. Cracks along the joint fractures are widened by weathering processes. Water flow lines and watercourse channels tend to develop along the zones of weakness (cracks). According to a geological map based on research by Destobres these formations feature a system of numerous regular faults (*Carte géologique du Maroc* 1989). Some of the lines on the map, however, do not necessarily seem to represent tectonic faults. Local rock formations are highly resistant to weathering.

On the Rouid-Aïssa formation the Ordovician upper Ktaoua formation is aligned monoclinaly. It is a series of very non-resistant grey-green clays with thin sandstone veins. These formations build the lower part of a typical cuesta. On this series the Ordovician Lower Bani II formation is monoclinaly aligned. These are mainly pastel-coloured sandstones and quartzite sandstones. Within these formations, Jurassic dolerite intrusions occur locally in the area investigated as dykes and sills. The Upper Bani II formation is situated monoclinaly southwards. It is built of sandy sandstones of various grain sizes and more resistant quartzite sandstones containing conglomerates. These last formations are very resistant. At the base of Djebel Bani fragments of five levels of accumulation terraces or sedimentary glacis occur and they are usually covered with alluvial fans. These levels had formed during the five pluvial periods from the oldest to the youngest respectively: Saletien, Amirien, Tensiftien, Soltanien, Rharbien (postglacial) (Coque 1977, *Carte géologique du Maroc* 1989).

The area between the base of Djebel Bani and Oued Dra is built of sandy alluvial gravel formations and mobile sands that occur in the Erg el M'hazil, Erg Abilia and Erg Souar regions.

The area discussed, in the Djebel Bani region, is situated in an extremely dry climatic zone. The average annual precipitation for the meteorological station in Zagora is from 40.7 mm (Capot-Rey 1953 – based on the period of 1931-1945) to 59.7 mm (Dubief 1963). For the Tagounite station (which is situated the closest to the area investigated) the average annual precipitation is 52.9 mm (*Rapport Hydrologique sur la région de l'Oued Dra* 1969 – based on the period of 1932-1967). In general the average annual precipitation on the Atlas foreland is between 35 mm and 100 mm (Przybyłek 1993). Potential annual evaporation in the area investigated is approximately 3000 mm. The highest monthly precipitation values throughout the decades are up to 11.8 mm

Figure 3. Structure and typology of the Oued el Mut channel

Explanations: I – Number of reaches, II – longitudinal profile: 1 – rock outcrops, 2 – rocky river channel with accumulation zones, 3 – channel cut in coarse sediment, 4 – channel within an alluvial fan, III – geology: a – Rouid-Antissa formation, grey-purple and green sandstones and pink quartzite sandstones, b – upper Ktaoua formation, grey-green sandy clays, c – lower Djebel Bani II formation, pastel-coloured sandstones and quartzite sandstones, d – upper Djebel Bani II formation, sandy sandstones of different grain size and quartzite sandstones with conglomerates, e – formations of the accumulation terraces or accumulation glacis with alluvial fans, IV – gradient of the river channel, V – width of the river channel, VI – number of rock steps per 1 km, VII – number of cutbanks per 1 km, VIII – number of sediment accumulation zones per 1 km, IX – size of the sediment accumulation zones in m²/per 1 km, X – maximum fraction in cm, XI – diameter of largest imbricated gravels in cm, XII – number of borders, XIII – river channel types, XIV – river channel subtypes.

and precipitation takes place from September to December. According to R. Capot-Rey (1953) over 30 mm precipitation can take place within 24 hours in autumn and winter. Such events are usually violent storms and they can exceed the average annual precipitation values. From the geomorphological point of view this kind of precipitation is the most important because it forms episodic and ephemeral streams which remodel their channels. According to M.A. Roche (1973) flood water flow in the Saoura river occurred 40 times in the years 1901-1967 i.e. approx. every 1.7 years. In the years 1901-1950 the duration of water flow in the Guir and Saoura oueds on the Atlas foreland was approximately 13.5 days a year (Dubief 1963). Comparing the age of the channel forms of the Oued Dra channel in the Mhamid area and the forms of the Oued el Mut channel it is possible to conclude that the oueds in the Djebel Bani area carry water less often, possibly once every few years. Thus it seems possible that the river channels are remodelled at that time, as is the case in adjacent areas (Bousnina 1977, Przybyłek 1993, Dłużewski et al. 2000).

According to R. Ambroggi and G. Choubert (1952) water is not present very often in Oued Dra in the Mhamid area and is present even less often in the Iriqui Lake area as a result of very strong evaporation (Figure 1), irrigation in the upper parts of the valley and the infiltration in the river valley.

4. Characteristics of the river channels investigated

The channel of the el Mut river valley which was investigated is very varied. This applies both to its longitudinal and cross-section profiles as well to the run of the channel (Figure 3). The course of channel reaches 1-10 clearly follows the overall pattern of the valley whose meandering nature corresponds to the structure of the bedrock. In reach 11 the river channel has cut into a wide alluvial fan on the Djebel Bani foreland. In the first four reaches of the channel the form corresponds strictly to the tectonics of the area investigated. The river channel shape and forms are strictly connected to the joint fractures and tectonic faults which occur in the area. The shape of the river channel in those first four reaches can thus be described as meandering or even zigzagging. In reaches 1-2 the river channel is situated on the bottom of a 10-15 m deep valley. The width of the valley varies from 5-15 m and locally it is only 1-2 m (Photos 1, 2). This valley is formed in sandstones that are aligned monoclinaly southwards. The slopes of the valley are steep, usually vertical in the upper part of the valley turning into approximately 31 degree talus slopes further down the valley. The bottom of the channel is a rock floor with a 6-7 degree inclination (Photo 2). The rock floor is divided by 0.5-2.5 m high rapids, locally the rapids can be even 3-4 m high. Below the rapids 0.5-1.0 m deep plunge pools are formed, locally even 2-3 m deep.

In reaches 3-4 the channel is either straight or meandering, but the overall valley features are relatively poorly formed. The bottom of the valley cuts into cracked quartzite sandstones and quartzite formations tilted monoclinaly towards the south. The river channel analysed cuts slightly through inclined sandstone outcrops that build the southern slope of Djebel Bani (Photo 3). In the lower part of reach 3 a bifurcation of the river channel takes place within the wide alluvial fan. During floods

the water can be divided into two streams also flowing into the adjacent river which belongs to the drainage system of the Oued el Mut. In reach 4 the channel is moulded in a broad bowl-shaped area which has developed on the contact zone between resistant sandstones and softer clays (Photo 4). In the lower reaches 5-7 the valley widens as it cuts through softer formations and the river channel becomes braided (Photo 5). Within the river channel along the river banks, small single bushes grow together with acacia trees. Lower down, in reaches 8-10, the channel is meandering (Photos 6, 8). In the final part of reach 9 the channel cuts into solid bedrock and features isolated accumulation zones. In reach 10 the river channel is filled with coarse sediments (Photo 8). In reach 11 the channel is braided within the wide alluvial fan (Photo 9).

The longitudinal profile of the Oued el Mut channel is as follows: convex-concave-convex-concave (Figure 3) and it corresponds to the bedrock structure. In the upper part of the river bed (reaches 1-3) the channel cuts through solid rock – Roudi-Aïssa formation sandstones – which form numerous rapids. In reach 4 the profile is concave which is connected to the outcrops of softer clays of the upper Ktaoua formation in the bedrock. Reaches 5-6 of the river channel are formed within the clays of the upper Ktaoua formation (Figure 3). Reach 7 cuts through quartzite sandstones of the lower Bani II formation. In this section rock floors up to 1 m high alternate with accumulation zones in the form of broad rubble bars. Following this there is an abrupt increase in the channel slope on sandstone outcrops. These are sandstone formations of various grain sizes and quartzite sandstone with conglomerates. In the lower sections of the river channel (reaches 8-9) quartzite sandstones occur and the channel alternately cuts through solid rock and river rubble. Rare and small rapids occur in this area (up to 0.5 m high) together with small depressions and pools (0.5-1.2 m deep). Below that section the channel cuts through river rubble and coarse sediment. In reach 10 the sediment is of coarse fractions up to even 1.0 m (average 2-20 cm) diameter. In section 11 the sediment fraction decreases in size – 10-20 cm and later 2-5 cm and sand fractions. In reaches 10-11 the channel is very straight without large curves or meanders.

The gradient of the slope is greatest in the first three reaches (Figure 3) lying in the range 60-100‰. The gradient decreases to 16‰ at the end of reach 7 and it increases again in reach 8 to 30.8‰. In the lower reaches the gradient decreases to 1.4‰. The influence of the tributary streams on river velocity and gradient as well as on the shape of the longitudinal profile has not been determined.

The cross-section profile of the Oued el Mut channel is usually tapered, but can also turn into square or triangular shapes. It is only irregular in the braided reach. Also the width and depth of the channel vary. In the rock reaches the average width is between 4.5 and 15 metres, locally even only 1-2 metres while in the alluvial reaches it is much larger. In reaches 5-7 the channel is 22-70 metres wide while in reaches 10-11 it widens out to reach from 55 m to over 100 m. The banks of the river are highest in the rock reaches (1-11 m). The varied character of the channel within different reaches seems to influence the sediment transport conditions.

Bars and undercuts are most common in the meandering reaches in the middle part of the longitudinal profile (Figure 3). The number of bars per 1 km regularly increases along the course of the channel until reach 8, then the number of bars

decreases to the base of Djebel Bani. In reach 11 it is extremely difficult to estimate the number of bars as the numerous episodic channels on the wide gentle sloped alluvial fan are very vague. Small unevennesses made it impossible to count and measure single channel units and that is why there is no indication of this section on Figure 3. The sediment deposition area is the largest in reach 11, perhaps up to 100000 m² per km. Reaches 4-6 do not have a big number of bars yet the dimensions of the landforms occurring there are very large. Three sediment deposition zones can be described within the longitudinal profile of the Oued el Mut channel. They are divided by erosion zones or zones of clastic material accumulation. The first deposition zone is – reaches 4-6, the second – reaches 8-9, and the third – on the alluvial fan in reach 11. The large number of undercuts in reaches 5-9 is linked to the meandering character of the channel in those reaches, and the biggest number of undercuts is situated in reach 8 (Figure 3).

The maximum sediment size fraction of the rubble rapidly decreases down the channel profile (Figure 3). In reaches 1-2 the maximum fraction of the sediment decreases from 1.38 to 0.89 m and then it increases again in reach 3 up to 1.36 m, in reaches 4-10 it increases from 0.45 to 0.81 m which is no doubt connected to the higher velocity of the episodic river in those reaches. Within the whole of reach 10 the bottom of the channel is covered with coarse sediment. This material has been carried from the upper reaches of the river or, occasionally, from the valley itself. In the upper reaches of the river channel, only in reaches 5-6 is the bottom of the channel covered with material of various sizes. The channels cutting through this material are from 0.5-2.5 m deep and up to 100 m wide. In reach 11 the maximum sediment fraction size decreases considerably. At the beginning of this reach it is up to 20 cm and then it decreases to a few centimetres and it is mainly sandy-gravel sediment.

5. Structure of the Oued el Mut channel

After a detailed analysis of the Oued el Mut channel together with the channel sediment an attempt has been made to explain the rules of channel formation. A typology of the channel reach based on the channel reach border method (Kaszowski, Krzemień 1999) has been carried out. Based on the qualitative and quantitative properties of the river channel as well as on the properties of the bedrock, the typology for the basic reaches of the river channels investigated has been described (Figure 3). Then the trends of all the channel properties have been analysed and the number of reach-boundaries (characterised by a given trend) has been determined. Later the boundaries were validated. Main channel-type boundaries were found to be the most common with the subtype boundaries following in frequency (Figure 3). Five channel types have been determined in the fluvial channel system of Oued el Mut. They were indicated by letters A-E. Each of these types features a certain dominant function. Moreover 5 sub-types have been determined (“a”-“e”) that slightly differentiate the main river channel types.

Type A is a typical modelled episodic river channel that was once subject to gully erosion (Photo 1, 2). It cuts through solid bedrock. Locally it is covered

by coarse sediment transported during violent precipitation events or transported from the valley slopes. The channel is usually deeply cut into a deep valley forming a gorge. In the channel type discussed there are two sub-types – “a” and “b”. The “a” sub-type channel is wider and with a bigger number of rock rapids which are mainly formed on rock bars. Water can occur locally in the middle section of reach 1 in pools formed on cracks and fractures. These are very weak water sources that give birth to small water flows that do not exceed 100 m in length. They provide water for people and goats. Oleanders and a palm tree are found in the channel nearby. The channel banks are built of various material fractions with spaces between boulders filled with fine material and sometimes even with silt. The whole site appears, as if it has recently been subject to a mud-rubble flow but after close examination the sediment turns out to be well-cemented. The “b” sub-type channel is narrower and deeper and it corresponds better to the bedrock – deep gorge, the areas near the banks are more strongly eroded as they are less-resistant. Undercuts and overhangs are quite common in this reach of the channel, which contains little bedload.

Type B constitutes reaches of channel (3-4) that are very shallow cutting through quartzite sandstone and quartzite which are inclined monoclinaly southwards (Photo 3). This type of channel is formed in solid rock and it usually has rock floors. Only locally, in reach 3 can a sediment accumulation zone be seen. An alluvial fan can also be found where the channel bifurcates. During heavy rains, a portion of the water and clastic material is drained into an adjacent valley, as indicated by visible traces of water and sediment flow.

Type C is represented by three reaches of the river channel formed mainly in alluvia in very fine material (0.1-20 cm). The largest amount of sandy or sandy-gravel sediment can be found at the bottom of the channel in reach 5. The channel cuts through softer grey-green clays on the bottom of a wide valley (Photo 5). It is a braided channel, 70 metres wide, transformed only during heavier precipitation events. Single acacia trees and thorn scrub grow locally on the channel banks, stabilising them. The “c” channel sub-type is wider and typically braided. The “d” channel cuts into alluvia and sometimes into solid rock. Numerous small sediment accumulation zones occur in this type of channel.

Type D is a meandering river channel. It corresponds to a curved valley shape (Photo 6, 7). The channel is cut in solid rock, only locally the bottom is filled with a thin layer of sediment. Rock undercuts occur (8-12 m high) on meanders which supply weathering material into the bottom of the channel. In the sub-type “d” channel numerous bars occur and its area in reach 8 is nearly 18000 m² per km (Figure 3). Single small acacia trees grow within reaches that contain bars. The bottom of the sub-type “e” channel is covered with coarse sediment. The rocky slopes of the valley are an indication of the thin layers of alluvia at the bottom of the channel.

Type E is represented by reach 11. The channel is braided (Photo 9) with weakly-developed channels across a 100-metre wide area. The size of sediments decreases from sandy-gravel-boulder to sandy-gravel and, on the extension of reach 11, the material is only sandy. The inter-channel areas are covered by scattered patches of xeromorphic vegetation. In the more southern sections of Djebel Bani larger

areas of the wide alluvial fan are covered by scrub. It is rather difficult to determine sub-types within this river channel type.

In general the structure of the river channel follows that of the valley as it dissects a descending series of cuestas, which is why the channel itself matured in several reaches simultaneously in relation to the local erosion base.

6. The formation of Oued el Feija channel and its tributary river channels draining the Djebel Bani range

Oued el Feija channel is very homogenous. It usually cuts through pebbly sandy-gravel formations (Photo 10). It is from a few to several metres wide yet it is very shallow. Locally it deepens to 3-4 m near Zagora. It has long braided reaches, but this feature of the river channel becomes particularly strong along the last 40 km and especially between the vicinity of Zagora and its confluence with Oued Dra. The channel of this episodic river is close to type E in The Oued el Mut channel system. Yet it is bigger and deeper. In the longitudinal profile of this river the size of the fluvial material decreases clearly from sandy-pebble to sandy-gravel (Photo 10). The inter-channel areas are covered with scattered patches of scrub. This river channel is a source of aeolian material over its whole length even during very weak winds, almost every wind blow moving the material. During field research the process of blowing out of the material by wind has been observed (Photo 10). The sandy-silt material has accumulated in the channel and also on the wide terrace area from the Amirien period (Mindel) near the town of Zagora where barchans are formed and occur in various stages of development. The distribution and formation of barchans indicates the increase of the aeolian deposition processes in this area. Tributary oueds draining the northern slope of Djebel Bani are short (approximately 1.5-3.0 km) (Photo 11). They flow through the scarp face part of the cuesta. They conform to the bedrock properties forming wider or narrower channels. Their longitudinal profiles are irregular and have a very steep gradient from 133 to 200%. The channels are cut mainly in solid rock and the streams only form small alluvial fans with shallow channels at their mouths. They can be described as channels of the A and B types (el Mut river channel system). Yet the bottoms of these channels are steeper and covered with a greater amount of sediment. During heavy precipitation events water together with clastic material does reach Oued el Feija. Coarse sediment is usually deposited on alluvial fans while finer sediments (sandy-gravel) reaches Oued el Feija.

The oueds draining the northern slopes of Djebel Bani represent the A and B types of river channel and within the river system of el Feija, they change their channels into type E.

7. Dynamics of the river channels

The dynamics of the river channel can be determined on the basis of the general stage of development of the channel and channel landforms together with the material that the river carries during high water flows.

There are both rocky and alluvial reaches in the longitudinal profile of the channel (Figure 3). Until reach 9 the channel is usually formed in solid bedrock. Only reaches 5-6 and 10-11 are cut through alluvial sediments. In the rocky reaches the bottom of the channel is a rock floor with local sediment accumulation zones which are situated in the wider parts of the channel or below deep plunge pools. In reaches 7-9 rock floors are divided by typical sediment bars 1-1.2 m deep. In meandering reaches bars usually occur below the meanders. The bar sediment usually consists of quartzite sandstone and pink quartzite. In the alluvial reaches the sediment size is smaller, especially in reaches 5-6 where most of the sediments are fragments of clay schist and local sandstones. This material is eliminated very quickly as it is subject to crumbling and splitting and it is not present in the lower parts of the channel. In reach 10 the bottom of the channel is covered with rubble transported from upper parts of the river channel. The shape of the valley together with the shape of the slopes allows one to conclude that the sediment can be up to 2-2.5 m thick. At the base of Djebel Bani, in reach 11, the sediment cover can be deeper and the fluvial material is of smaller size i.e. 1-20 cm at the beginning of this reach down to 1-5 cm at the end.

Special attention was given to bar formation and imbrication forms during field research in Oued el Mut channel. This material is a good indicator of transport and flow conditions during floods as well as of the transport capacities of the episodic stream. The imbricated sediment must have been carried during the last flow. Investigation and measurements show that this episodic river can carry a very large amount of coarse sediment during precipitation events (Figure 3). In reaches 1-4 the sediment size is from 0.45-1.38 m, in lower reaches the size of the sediment increases up to 0.81 m in reach 10 and then rapidly decreases to 0.2 m in the alluvial fan of reach 11. It is most probable that coarse sediment is rarely transported, and then only during high precipitation events and such sediment is then only transported short distances. The formation of sedimentary bars and the sediment on the bar surfaces can indicate such events. Only small pebbles of 15-25 cm can be transported longer distances in the river channel.

The river channel investigated has mainly been modified by gully erosion, redeposition and local lateral erosion and then only during floods following high precipitation events which take place every few decades. The field research shows that the contemporary modelling of the Oued el Mut channel differs along the longitudinal profile of the channel. The Djebel channel is probably also subject to much more frequent remodelling during less significant precipitation events because of the high altitude of Djebel Bani and the high gradient of the river channel (100-30‰) in reach 1-4. The presence of springs in reach 1 provides evidence for this hypothesis, as well as the cemented covers building the channel banks which reach up to 1.0 m (height) and the very long reaches of rocky river channel deprived of fine sediment. This reach ends with an alluvial reach of type C where a clearly braided channel can be found. The fluvial forms are much less visible at the end of the reach of type C. The cemented fluvial covers within the channel banks are only present in reaches 1-2.

According to S.A. Schumm's fluvial model (1977) the fluvial system can be divided into three functionally differentiated ideal zones: a sediment supply zone,

a sediment transport zone and a sediment deposition zone where sediment is accumulated on the foreland of higher elevated ground, on the alluvial fan or within a delta. It is possible to apply this model in general terms to the area investigated. The headwaters of the Oued investigated usually constitute a sediment supply zone, reaches 8-9 are the sediment transport zone and the sediment deposition zone starts from reach 10 onwards. A more detailed analysis should take into account the diversity and compound character of the fluvial system investigated. In terms of its relief and geological structure the upper functional zone consists of two main sections: the first – including reaches 1-2 – is the fluvial sediment supply zone. Reach 3, starting the second part is partially a sediment deposition zone yet both reach 3 and reach 4 also are a fluvial sediment transport zone. Reach 5 constitutes a sediment deposition zone, reach 6 – a zone of significantly softer weathering sediment – supply from the valley slopes. Further downstream, along reach 7, sediment transport prevails. Well formed sediment accumulation bars consisting of fine sediment occur within rock floors. Coarse sediment (above 0.6 m) can mainly be found in bars in the upper parts of the channel and it is a result of heavy rains. In these reaches the river channel is very well and regularly formed with typical gravel channels, pool zones and riffles (Leopold et al. 1964). In this channel reach riffles are the equivalent of rubble bars and pools are the equivalent of bowls. A different set of landform features is found along reaches 9-10 with relatively well-developed channel sections divided by a zone accumulating the coarsest transportable fraction material. Those are called channel steps (Bowman 1977) and they particularly often occur in reach 10. Zones of greater sediment accumulation also have a steeper gradient and these are zones of coarse sediment accumulation during larger water flows. In arid regions such zones have been well documented in the mouth areas of the episodic streams flowing into the Dead Sea (Bowman 1977). According to D. Bowmann (1977) the presence of channel steps is an indication of a transition point within a channel between the headwaters where unsorted sediment prevails and the lower part of the river where the sediment is usually well sorted. The presence of rapids is thus a mechanism regulating the deposition of coarse sediment within a river channel and could be an indicator of the beginning of the sediment sorting processes.

In general the Oued el Mut channel is subject to stronger remodelling processes by gully erosion which can be demonstrated by the vast areas of rock floor within the longitudinal profile of the channel. Downcutting is particularly visible along reaches 1-4. These reaches supply coarse and fragmented sediment which is deposited in type C reaches of the river channel. The shape of the channel bottom shows that the river channel in the upper reaches is more often subject to remodelling than it is in the lower reaches. Rock floors deprived of any sediment are good evidence supporting this hypothesis. The transported sediment is deposited in the lower reaches of the river channel.

In the type C river channel (reaches 5-7) a reduction of the river velocity takes place in the braided channel. A very large supply of weakly resistant local sediment takes place in these reaches as well. In the lower parts of the channel more regular forms of river channel begin to be formed and thus the beginning of the sediment

sorting process takes place. In reach 11 the river velocity rapidly decreases together with the decreasing sediment accumulation zones. Single fluvial forms are weakly formed and shallow braided river channels can only be seen on the wide alluvial fan, although the channel banks are not clearly visible. It shows that fluvial modelling of this area seldom takes place. The channels of the larger oueds situated east of the Oued el Mut are usually much better formed.

Episodic streams draining the northern slope of the Djebel Bani range, like the streams draining the southern slope, have channels which are probably more often remodelled as a result of gully erosion. The vast areas of rock floors in the longitudinal profiles of these river channels could be an indication of this. Coarse sediment from these streams is transported to Oued el Feija. The morphology of slope channel beds, whether on the northern or southern slopes, including rocky steps clean-swept of any bedload, suggests that they are subject to more frequent remodelling than Oued el Feija. The displaced sediment is transported and deposited on the alluvial fans and in Oued el Feija.

8. Conclusions

The structure of the river channels of the Djebel Bani region, both on the northern and southern slopes, is tightly linked to the main stages of relief formation of the monocline geology area investigated. The cutting of the scarp and dip areas of the cuesta is linked to the faults and joint fractures and to the lithology of the bedrock.

Four dominant morphodynamic reaches which can be seen in the longitudinal profile of Oued el Mut correspond to the relief and geological structure of the area. The first reach is connected mainly to the erosional cutting of the bedrock and to transport of the sediment into the wide valley bottom in the second section. In the second reach coarse sediment accumulation takes place together with the transport of very small size sediment to the lower sections of the channel. In the third reach erosional cutting of the bedrock takes place together with the transport of eroded material to the Djebel Bani foreland. In the final part of reach 10 coarse sediment is deposited while its smaller fractions are carried further out into a broad depression where the Oued Dra valley is formed.

On the northern slope river channel systems are less well formed and they are limited to the erosion zone within the rocky bedrock reaches. The streams transport various clastic material to the bottom of Oued el Feija. This sediment is rarely transported to the Oued Dra. In this zone more selective transport of finer sediments takes place and this sediment is transported lower along the river channel.

In general the morphological role of episodic streams and rivers draining the northern and southern slopes of Djebel Bani mountain range differs. On the basis of channel formation and tracks of water flow it is possible to estimate that only the biggest oueds on the southern slope carry sediment to the base of Djebel Bani and the sediment is better sorted in those channels. On the northern slope clastic material is deposited in Oued el Feija. On alluvial fans which are formed at the mouths of smaller oueds eolian activity can clearly be seen, which, however, does not influence the visibility

of the fluvial forms. The role of the fluvial processes in the transport of coarse sediment to the Djebel Bani foreland varies over a long period of time. The size of alluvial fans from different periods also differs. According to the geological map of the region it is possible to estimate that the biggest role of the fluvial processes in the formation of the area took place during the Tensiftien pluvial period (Riss). The largest extant alluvial fans in the close vicinity of the area investigated are either of Holocene-age or contemporary. The morphological role of episodic watercourses draining the slopes of Djebel Bani involves erosional modelling of the river channels and transporting of the eroded material into the base of Djebel Bani during flow periods. The preserved alluvial forms show that those events do not occur often, approximately once every few – ten years and precipitation and flow events can only take place a little more often in the headwaters of Oued el Mut and the oueds on the northern slope.

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