Geomorphology 173–174 (2012) 88–103

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Intrinsic stream-capture control of stepped fan pediments in the High Atlas piedmont of Ouarzazate (Morocco)

A. Pastor *, J. Babault, A. Teixell, M.L. Arboleya

Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

ARTICLE INFO

Article history:
Received 29 December 2011
Received in revised form 25 May 2012
Accepted 31 May 2012
Available online 9 June 2012

Keywords:
Drainage network
Cover effect
Fan pediment
Piedmont-stream capture
Intrinsic process
Ouarzazate basin

ABSTRACT

The Ouarzazate basin is a Cenozoic foreland basin located to the south of the High Atlas Mountains. The basin has been externally drained during the Quaternary, with fluvial dynamics dominated by erosive processes from a progressive base level drop. The current drainage network is composed of rivers draining the mountain and carrying large amounts of coarse sediments and by piedmont streams with smaller catchments eroding the soft Cenozoic rocks of the Ouarzazate basin. The coarse-grained sediments covering the channel beds of main rivers cause the steepening of the channel gradient and act as a shield inhibiting bedrock incision. Under such circumstances, piedmont streams that incise to lower gradients evolve to large, depressed pediments at lower elevations and threaten to capture rivers originating in the mountain. Much of the current surface of the Ouarzazate basin is covered by coarse sediments forming large systems of stepped fan pediments that developed by the filling of low elevation pediments after a capture event. We identified 14 capture events, and previously published geochronology support an ~100 ka frequency for fan pediment formation. Our study indicates that the reorganization of the fluvial network in the Ouarzazate basin during the late Pleistocene and Holocene has been controlled by the piedmont-stream piracy process, a process ultimately controlled by the cover effect. The stream capture is influenced by erosion, sediment supply and transport, and therefore may not be entirely decoupled from tectonic and climatic forcing. Indeed, we show that at least two capture events may have occurred during climate changes, and local tectonic structures control at most the spatial localization of capture events.

1. Introduction

Piedmonts of active mountain ranges are usually dominated by sediment transport and deposition. However, changes of drainage conditions, e.g., a transition to externally drained conditions, can lower the local base level of a piedmont and may cause erosion to dominate over the long term even if mountain building is still active. As a consequence, low relief, gently inclined bedrock erosional surfaces may be formed, and products of erosion coming from the mountains are transported across them. These surfaces of erosion and/or transportation are termed 'pediments'. Pediments have been reported in all climatic zones, mostly in piedmonts of decaying mountains (e.g., Dresch, 1957; Whitaker, 1979; see references in Pelletier, 2010). Two types of pediment exist depending on the contrast in rock strength between the pediment surface and the adjacent upland area. If a pediment develops on the same lithology as its adjacent mountain range, it is called a 'rock pediment' (e.g., Oberlander, 1989). In this study, we consider the other type of pediments that develop on soft basin rocks in contrast with a more resistant adjacent upland. In semi arid environments, hydrologic networks made of ephemeral streams develop on this second class of pediments, locally veneered by thin and discontinuous coarse debris deposits. Sediments accumulate on alluvial fans close to the mountain front or, in distal areas, on the bed of streams originating in the mountains. The thickness of covering deposits on pediment erosional surfaces is usually < 20 m, decreasing downstream where fluvial terraces and erosional surfaces merge. Both erosional and buried pediments are landforms that have a fan shape and that are called fan terraces, or fan pediments (Mills, 1983). They are common in the flanks of the Atlas Mountains of North Africa, where they were called 'glacis d'érosion' by French researchers (e.g., Gauthier, 1957).

The occurrence of ephemeral streams, fans, or fluvial terraces on pediments carved in weak lithologies indicates that they result from fluvial erosion. Multiple levels of fan pediments are usually reported in piedmont areas, and they are considered to be the equivalent in the piedmont of mountain river terraces, the highest level being the oldest.

Periods of lateral channel migration in rivers occur if sediment load tends to equal transport capacity, inhibiting vertical erosion and allowing lateral planation to produce erosional surfaces like strath terraces or pediments (e.g., Gilbert, 1877; Mackin, 1936; Bull, 1991; Merritts et al., 1994; Pazzaglia et al., 1998; Hancock and

* Corresponding author. Tel.: +34 93868364; fax: +34 935811263.
E-mail address: alvar.pastor@uab.cat (A. Pastor).

0169-555X/$ – see front matter
doi:10.1016/j.geomorph.2012.05.032

Anderson, 2002; Wegmann and Pazzaglia, 2002; Montgomery, 2004). The deposition of an alluvial mantle is thought to be concomitant with lateral planation, and its abandonment may be caused by effective discharge increase and a resulting increase in incision. As for the formation and abandonment of fluvial terraces, stepped fan pediments are usually interpreted as a consequence of lateral planation owing to hydrological regime changes related to climatic oscillations or tectonic activity, i.e., controlled by external changes (e.g., Bryan, 1926; Johnson, 1932; Coque, 1962; Hadley and Goldsmith, 1963; Oberlander, 1989; White et al., 1996; Cook et al., 2009).

On the other hand, landform changes or variations in the rate of depositional or erosional processes can also be inherent to the erosional development of a landscape without variations in climate or tectonic forcing. This old concept (e.g., Schumm, 1973, 1979, and references therein) has been used to explain the development of stepped fan pediments in the soft piedmonts of the Book Cliffs, Utah (Rich, 1935); of the Absaroka Mountains, Wyoming (Mackin, 1936); of the Henry Mountains, Utah (Hunt et al., 1953); of the Shadow Mountain, California (Denny, 1967); of the Shenandoah Valley, Virginia (Hack, 1965); of the Beartooth Mountains, southern Montana (Ritter, 1972); and of the Roan Mountains, North Carolina (Mills, 1983). These works showed that relatively small piedmont streams incise more deeply to lower average slopes than the parallel-flowing main rivers originating in the mountain and transporting coarse sediments. This is so because fluvial erosion is not only proportional to the catchment area and channel longitudinal slope, but it is also modulated by the sediment flux (e.g., Gilbert, 1877). Rich (1935) and Mackin (1936) interpreted that the steeper slopes of the main rivers in the piedmont were those needed to transport their high content of coarse sediments and that the coarse bedload in main rivers inhibits the erosion by covering the channel bed (the cover effect) (e.g., Gilbert, 1877; Rich, 1935; Mackin, 1936; Hunt et al., 1953; Sklar and Dietrich, 1998, 2001, 2006; Whipple and Tucker, 2002; Cowie et al., 2008; Johnson et al., 2009; Yanites et al., 2011). As a consequence, piedmont streams and their tributaries excavate piedmont valleys or pediments in soft rocks at a level below the adjacent main rivers.

Low elevation pediments developed in soft rocks, elongated in the piedmont slope direction and parallel to the mountain streams, are separated from their trunk valleys by remnants of old fan pediments, sometimes a few tens of meters above them. The lower elevation of piedmont valleys or pediments gives them the potential to capture the larger streams that originated in the mountains and are situated a few meters up to tens of meters above them. Captures occur by erosional retreat of the divide and expansion of the pediments (Rich, 1935; Mackin, 1936; Hunt et al., 1953; Denny, 1967; Ritter, 1972; Mills, 1983). Following a capture, a main stream is forced to flow on the gently sloping surface of a pediment, losing transport capacity. In order to recover the slope needed to transport its sediment load, coarse sediments are aggraded and a new fan pediment is formed (Fig. 1). In summary, the intrinsic process of stream captures is the consequence of coarse sedimentary flux, steep longitudinal slope of transportation, and cover effect in the main rivers. The stream-capture process has been emphasized as an important mechanism for development of stepped fan terraces in piedmont settings without any change in external forcing. To date the only natural cases where the stream-capture process has been identified are located in the USA, the most recent account having been published in the early 1980s (Mills, 1983).

Stepped fan pediments in soft rocks in the flanks of the Atlas Mountains of North Africa are thought to result from lateral fluvial erosion by channels sourced in the adjacent and more resistant upland (e.g., Dresch, 1957; Gauthier, 1957; Coque, 1960; Choubert, 1965; Coque and Jauzein, 1967; White, 1991; Arboleya et al., 2008). These studies suggested that lateral erosion and terrace abandonment could be a response to hydrological changes induced by oscillating climate, but none of them considered the potential effect of intrinsic processes.

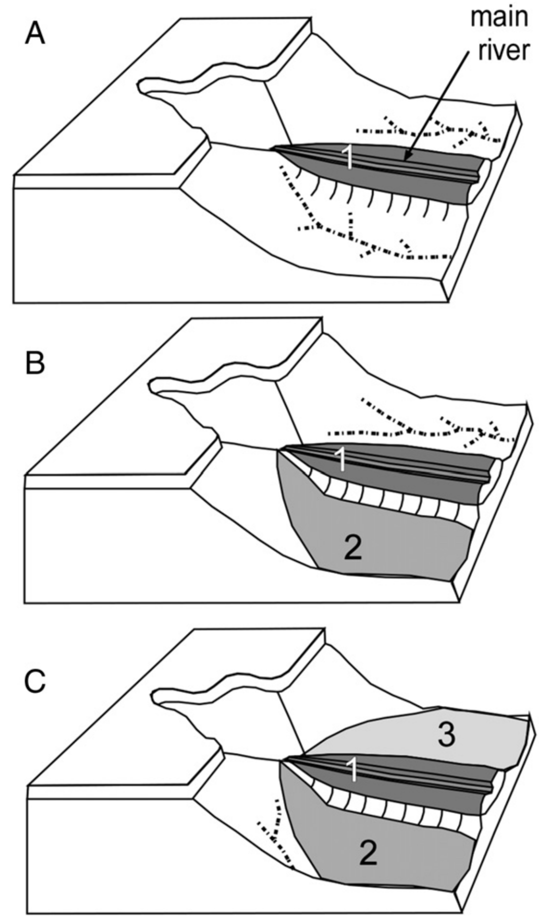

Fig. 1. Development of stepped fan terraces by stream capture (modified after Rich, 1935; Schumm, 1979). Stream piracy occurs when one parallel flowing piedmont stream erodes headward and laterally into the channel of a stream originating in the mountain (1) and diverts (pirates) its water. In this case, the main channel is diverted first to one side and then to the other, and will eventually form stage fan terraces (2 and 3). (A) The main trunk with steep longitudinal slope is entrenched in its own coarse sediments, whereas the minor adjacent streams incise to a lower gradient and at a lower level on either side leading to the formation of pediments. (B) The main trunk (located at a higher level) is captured by a piedmont tributary resulting in a new fan-terrace. (C) The main trunk is diverted again by another parallel-flowing tributary resulting in a third level of fan-terrace.

In this study, we evaluate the potential of intrinsic origins versus external forcing factors for fan pediments in the Ouarzazate foreland basin, located in the southern flank of the High Atlas Mountains of Morocco (Fig. 2). The study is based on an analysis of longitudinal profiles of rivers originating in the mountains, piedmont streams and the geomorphological analysis of Quaternary stepped fan pediments in the piedmont. We base our interpretation on terrestrial cosmogenic nuclide (TCN) ages previously obtained on fan terraces by Arboleya et al. (2008), as well as on the spatial relationship between fan terraces and Quaternary tectonic structures mapped by Pastor et al. (2010). Our study suggests that the stream-capture process, neglected during the past three decades as an origin for stepped landforms, explains the formation of the majority of fan pediments in the eroding Ouarzazate foreland basin.

2. Geological setting

The High Atlas chain is an ENE–WSW trending mountain belt that represents the highest topographic relief of North Africa. Mean elevation of the central High Atlas well exceeds 2000 m (Babault et al., 2008), and the highest peaks reach up to 4000 m. The tectonic style

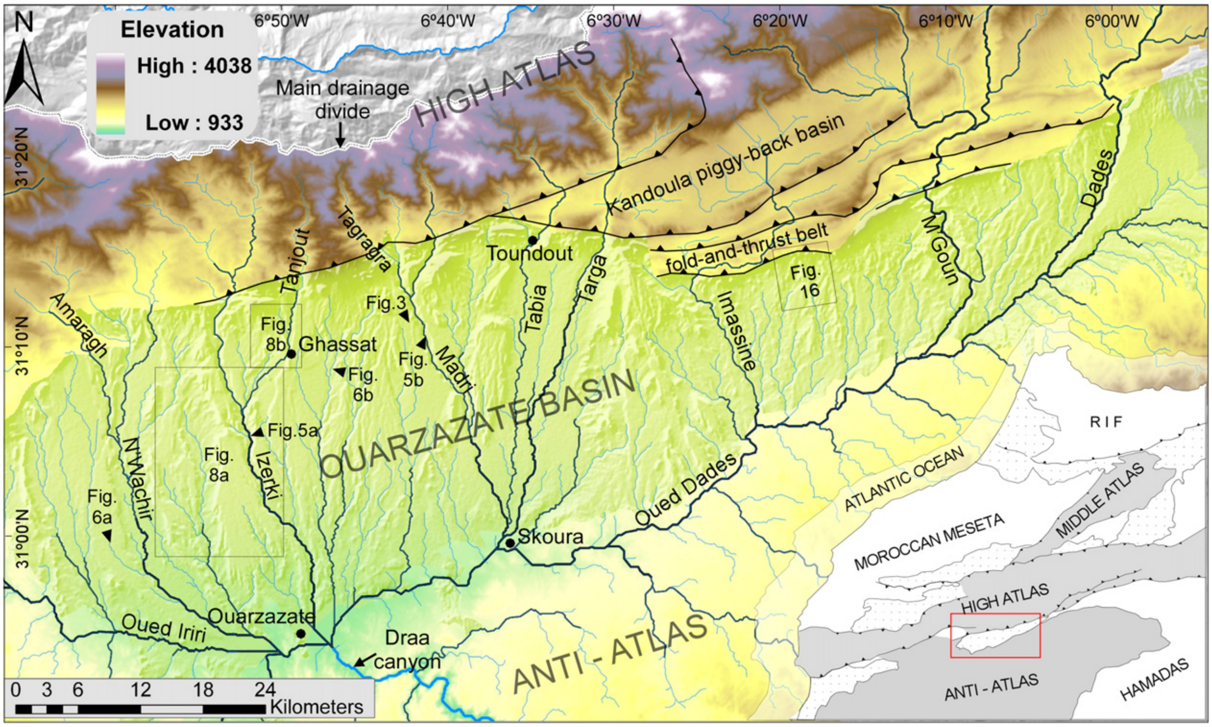

Fig. 2. Digital elevation model of the Ouarzazate basin, with its drainage network represented. The network features the nine main rivers with headwaters at the main drainage divide of the High Atlas Mountains (thick white line) and crossing the Ouarzazate basin in an N–S direction. Inset: structural map of Morocco showing the location of the Ouarzazate basin within the Atlas Mountain belts (grayed).

of the High Atlas range conforms to an intracontinental, thick-skinned, thrust-fold belt formed by the Cenozoic inversion of a Triassic to Jurassic rift (e.g., Mattauer et al., 1977; Arboleya et al., 2004, and references therein). The discrepancy between topographic mean elevation and magnitude of shortening across the Moroccan High Atlas (Teixell et al., 2003) suggests that crustal thickening does not fully explain the observed topography and suggests a mantle-sourced, thermal contribution to large-scale surface uplift (Teixell et al., 2003)—corroborated by geophysical (Seber et al., 1996; Ayarza et al., 2005; Teixell et al., 2005; Zeyen et al., 2005; Missenard et al., 2006; Fullea et al., 2007) and geomorphic-stratigraphic data (Babault et al., 2008).

The Ouarzazate foreland basin is located between the High Atlas frontal thrust belt and the domal uplift of the Anti-Atlas Mountains (Fig. 2). It stands at an elevation of 1200–1800 m asl, extending more than 150 km in an east–west direction with a maximum width of 40 km. The north-bordering High Atlas fold-and-thrust belt presents structural and topographic differences between the west and the east of the basin (e.g., Fraissinet et al., 1988; Tesón, 2009). The wider western half of the basin (about 40 km), coincides in the north with the narrower segment of the south-draining flank of the central High Atlas (Fig. 2). The frontal structures of the High Atlas system are located well within the basin, deforming dated Quaternary pediments (Sébrier et al., 2006; Pastor et al., 2010). Neogene shortening rates are about 0.5 mm/a (Tesón, 2009) for the entire south Atlas frontal thrust belt. Recent shortening rates for individual structures within the basin obtained from deformed Quaternary deposits are 0.03–0.1 mm/a (Pastor et al., 2010).

The Ouarzazate basin is infilled by up to 1 km of Cenozoic (mainly Miocene) continental sediments, which are overthrust by the High Atlas to the north and onlap the Anti-Atlas to the south. The Neogene to Quaternary history of the basin can be broadly divided into two periods. The early record is dominated by net aggradation of alluvial, and lacustrine sediments within an internally drained basin (e.g., Görler et al., 1988; El Harfi et al., 2001), mostly during the mid and late Miocene (Tesón et al., 2010). A hiatus of 5–6 Ma in the sedimentary record separates the aggradation period from the recent erosional period, which is characterized by episodic fluvial aggradation within an incised drainage network created after the basin became externally drained via the Draa River canyon (Fig. 2). The timing of the basin aperture and the inception of the superimposed drainage within the basin remains undefined, but it probably occurred during the late Pliocene or early Pleistocene (Stäblein, 1988; Arboleya et al., 2008).

The basin surface is partially covered by coarse-grained sediments derived from the erosion of the High Atlas Mountains and aggraded during the late Quaternary (see Arboleya et al., 2008, for detailed description). These deposits form systems of stepped fan pediments (e.g., Fig. 3) covering a range of areas (reaching several square kilometers in the west half of the basin) and up to 30 m thick. Arboleya et al. (2008) argued that the base level for all the streams of the basin, and therefore their incision rates, may have kept pace with the progressive cutting of the Draa canyon, the basin outlet. The Draa River drains about 13,000 square kilometers of the High Atlas southern flank and the Ouarzazate basin through the Anti-Atlas Mountains. Arboleya et al. (2008) found average incision rates of 0.3–2 mm/a over the last 250 ka, which are slightly higher than the tectonic uplift rates, estimated for the same period on the basis of fault throws (0.1–0.2 mm/a; Pastor et al., 2010).

The drainage network of the Ouarzazate basin is composed by N–S transverse channels with great variability of catchment size (1–10^3 km^2). All the transverse channels join to the south in longitudinal, E–W oriented collectors: the Dades trunk River to the east and the Iriri trunk river to the west, fixed to the edge of the Anti-Atlas Mountains (Fig. 2). These perennial collecting rivers act as local base levels for the rest of the N–S drainage network.

Climate changes in the Atlas Mountains during the Quaternary are evidenced only for the late Pleistocene to the present. A change from arid to more humid conditions occurred at the transition from the last

Fig. 3. Field view to the south of the Madri valley where different levels of coarse gravel sediments form a system of stepped glacis covering the Miocene basin bedrock, composed of soft sediments (red shale and sandstone).

glacial maximum (22 ka) to the early to mid-Holocene (11–5 ka) (Reille, 1979; Gasse et al., 1987, 1990; Lamb et al., 1989, 1995; Salamani, 1991, 1993; Jolly et al., 1998; Elenga et al., 2000; Gasse, 2000; Holz et al., 2007). Older palaeoclimate records are available for the western Mediterranean but their correlation with the Atlas region is very tentative. The current climate of the study area is semi-arid. Precipitations are infrequent but intense, being concentrated in a few episodes of heavy rainfall occurring between December and March, accumulating 100 mm/a of precipitation for the period 1931–2000 (Knippertz et al., 2003). Vegetation within the Ouarzazate basin is sparse, comprising small xerophytic shrubs.

3. Methods

Piedmont tributary valley floor elevation must be lower than the adjacent river for a capture to occur (Mackin, 1936). We searched for low elevation valleys or pediments adjacent to perched main rivers originating in the mountain and evidence of past captures. Our analysis was based on longitudinal profiles of trunk rivers as well as piedmont streams and on the geomorphological analysis of Quaternary stepped fan terraces on the piedmont.

3.1. Mapping of low elevation piedmont valleys and low elevation pediments

The drainage network of the south Atlas piedmont has been studied using the 90-m-resolution SRTM90v4 DEM. We mapped the network with the D8 flow routing (O'Callaghan and Mark, 1984) available in the Spatial Analyst tool (ArcMap). We further extracted elevations, distances from headwater and outlets, and drainage areas to derive longitudinal river profiles.

In similar studies, Hunt et al. (1953) and, later, Johnson et al. (2009) showed reaches of longitudinal profiles where piedmont tributary streams with gentler gradients lay at lower elevations than their adjacent main river. Similarly, we compared the longitudinal profile of a river originating in the mountains with that of its piedmont tributary valleys. The long of all channels with a drainage area above 5 km^2 were plotted as elevation against upstream distance graph, measured from the Draa canyon, the local base level of the Ouarzazate basin. Information on the variation of the contributing catchment area along the river profile allowed the discrimination of the rivers with large mountain catchments from the smaller piedmont streams. The N–S flowing channels share tributary junctions or merge into one of the main longitudinal streams (Iriri or Dadès), so they have experienced the same base level history.

We mapped the spatial extent of differences in elevation between piedmont streams and their adjacent main rivers for all the N–S fluvial systems of the Ouarzazate basin. Higher order tributaries that join before reaching the Iriri or Dadès trunk rivers, were measured from their shared tributary junction. Where piedmont streams and adjacent mountain rivers do not share a tributary junction, we measured the upstream distance from the longitudinal trunk stream. In these cases, we selected piedmont streams that join the longitudinal river upstream from the main river junction with the same trunk stream. In this way, we compared piedmont streams that have experienced no advantage in distance to base level, that is to say, piedmont streams that have an outlet at a level close to, or slightly higher than, the adjacent main rivers. The elevation versus distance from a common base level allowed us to perform second-order polynomial fits (with $<1\%$ error) of the longitudinal profiles of the streams originating in the mountain. The obtained equations were used to map the differences in elevation between main rivers and their adjacent piedmont streams with drainage areas >5 km^2.

The analysis revealed that after stream capture the depressed pediments are the erosional surfaces onto which sediments eroded from the uplands aggrade to form a new fan pediment. The spatial extent of the low elevation pediments and the differences in elevation between the pediment surfaces and adjacent main streams were mapped by projecting the main stream elevation in an E-W direction. This assessed the relationship between the occurrence of deeply incised piedmont streams and depressed pediment surfaces.

3.2. Evidence used to infer Quaternary captures

The second aim of the study was to identify stepped fan pediments that resulted from stream captures and not from lateral planation. For a single river, fan terraces produced by climatic changes should consist of a sequence of progressively younger terraces inset within older ones. On the other hand, stepped fan pediments produced by the stream-capture process should consist of sequences of terraces separated by remains of older deposits. Moreover, the piedmont-stream capture process occurs randomly, and it is unlikely that a similar number and arrangement of fan pediments are formed in two adjacent fluvial systems.

In the following we summarize the indicators of past captures that have been described by Rich (1935), Mackin (1936), and Mills (1983). First, fan pediments at different levels, but with a lithologically similar clast content, flanking of a gravel-capped ridge (Figs. 1 and 4), that is, a divide composed by higher gravel deposits. This arrangement indicates that the old course of a river originated in the mountain was diverted to one side and then to another, most probably by capture. Second, the presence of abandoned valleys, which leave wind gaps in the landscape (Fig. 4). Third, sharp stream bends in plant view or elbows of capture (Bishop, 1995) (Fig. 4). And fourth, some extension of gravel-free pediment in piedmont valleys upstream of the apex of a fan pediment (Fig. 4).

We based our mapping of fan pediments on field surveys, DEM analysis, and enhanced satellite imagery. Topographic profiles were constructed using the SRTM90v4 DEM. Color contrasts between fan pediments of the Landsat imagery 4–5 TM were enhanced with a color composition based on bands 70, 30, and 10, as red, green, and blue channels, respectively. Based upon their topographic position above main rivers, fan surfaces and terraces were mapped and classified as young, intermediate, or old, the lower being the younger.

4. Analysis and results

4.1. Drainage network

We observe two types of channels that compose the N–S transverse drainage crossing the Ouarzazate basin, both sharing tributary junctions and thus subjected to the same base level variations: (i) main rivers originating in the High Atlas Mountains, whose channel beds are draped by coarse sediments; and (ii) parallel-flowing piedmont streams sourced within the basin domain or in the mountain front, with no significant supply of coarse sediments.

A common feature of all the mountain rivers in the Ouarzazate basin is the braided channels blanketed by a layer of coarse-grained sediments of variable thickness, covering the Miocene basin bedrock (Fig. 5A and B). Their mountainous headwaters reach maximum elevations > 3000 m, whereas the average altitude of the valley floor at the mountain front is ca. 1500 m, so their fluvial relief is high (~ 1500 m). Mountain rivers have catchments mainly composed by mechanically strong rocks exposed in moderate to steep hillslopes, with average local slope of about 18°. Because of the semiarid climate, such main rivers are ephemeral or have a moderate flow during most of the year. However, during heavy rainstorm events main rivers drastically increase their discharge and transport capacity. Field evidence show that main rivers are capable of moving coarse sediments accumulated in their upland channels to the gently inclined basin reach, where the transport capacity is lessened. In the basin, mountain rivers are separated by minor piedmont streams sourced within the basin domain or on the mountain front hillslopes, with catchment areas ranging between 1 and 100 km^2. They have no coarse sediment supply and commonly expose the Miocene bedrock in their channel beds and banks (Fig. 6A and B). Bedload material is essentially composed of fine-grained sediment (silt, sand) derived from local lithologies (mostly sandstones and shales); their channels, however, usually contain gravels derived from the colluvial denudation of the surrounding fan terraces.

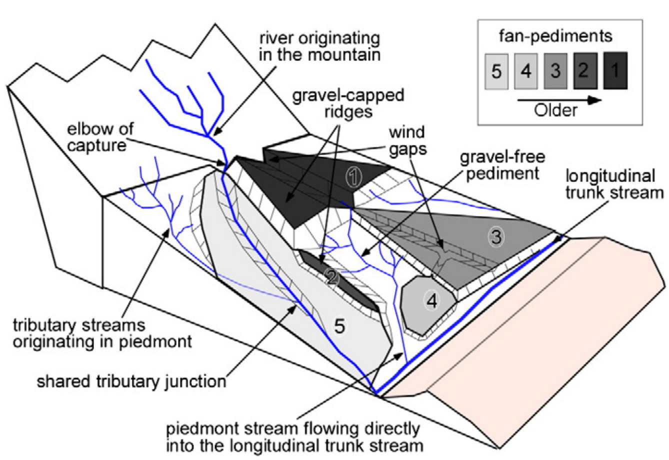

Fig. 4. Sketch showing the geomorphic elements used to infer piedmont stream captures (see text for explanation).

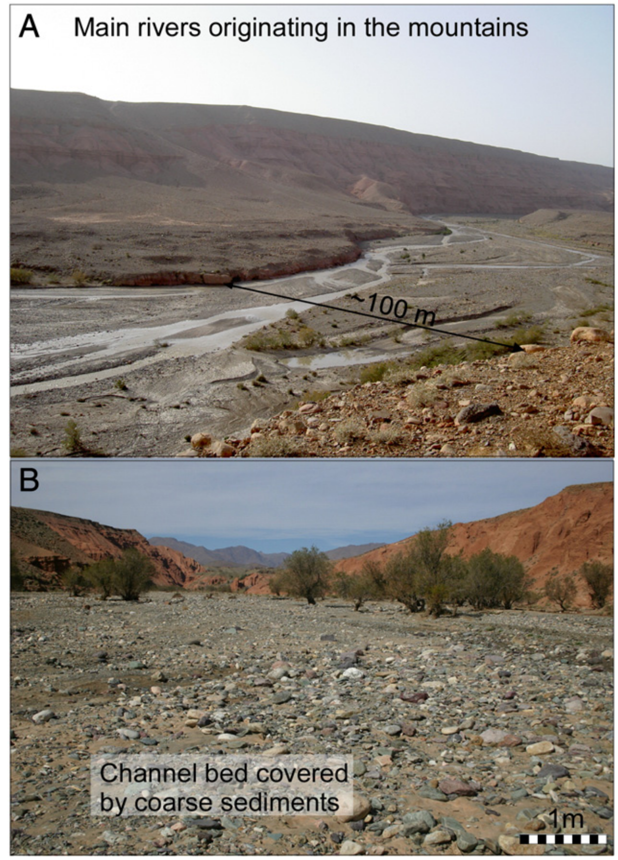

Fig. 5. Field images showing representative examples of mountain rivers. (A) General view of the Izerki River located in the central part of the basin. The Izerki shows braided channels entrenched in older fan terraces and Miocene strata outcrop in the banks above the coarse deposits. (B) The channel of the Madri River in the central part of the basin is blanketed by coarse gravels (10–30 cm) coming from the uplands.

Two scenarios can be differentiated east and west of the basin as a consequence of the structural differences of the High Atlas southern flank and the basin morphology. The western part of the Ouarzazate basin is about 40 km wide. To the north, the short distance (15 km in average) between the main drainage divide of the High Atlas hinterland and the southern mountain front defines relatively small mountain river catchment areas (between 50 and 280 km^2) where they emerge onto the Ouarzazate basin, and the spacing between outlets at the mountain front is only 5–10 km. In contrast, the eastern half of the Ouarzazate basin (east of Targa River) is only 10 km wide on average. A more northern position of the main High Atlas divide and the presence of a well-developed fold-and-thrust belt at the basin margin, increase the distance between the drainage divide and the mountain front to more than 35 km. In the narrow eastern half of the basin, mountain rivers emerge onto the basin with outlets spaced by 20 km apart (Fig. 2); and most of the basin surface is drained by small piedmont streams (catchments < 50 km^2). There, main rivers exhibit larger catchment areas and perennial flow (the rivers M'Goun and Dades emerge onto the basin with catchments of 1245 and 1535 km^2, respectively).

The fluvial systems flowing through the western, widest part (40 km) of the Ouarzazate basin (from the N'Wachir River to the Targa River) have the best developed steeped fan pediments

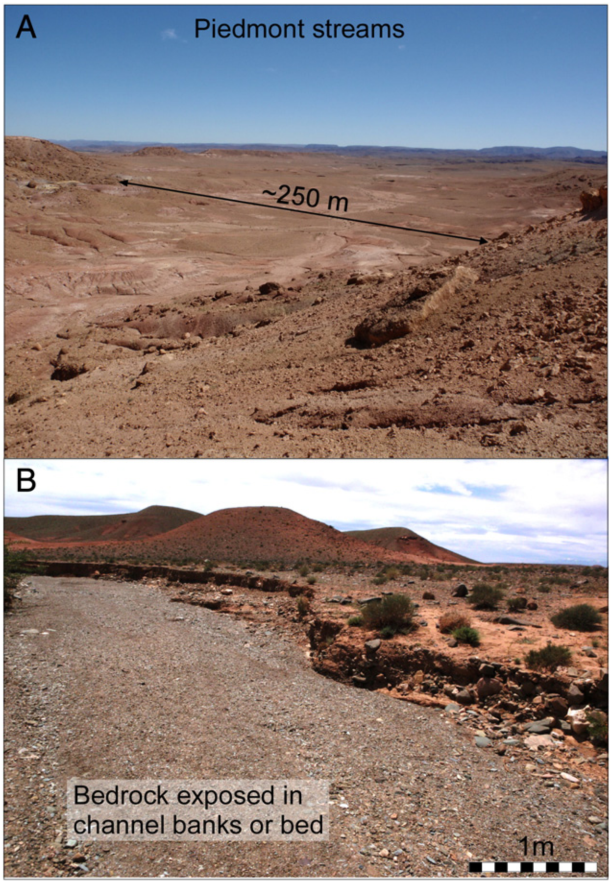

Fig. 6. Field images showing representative examples of piedmont streams. (A) General view of a piedmont stream located west of the Izerki River. The channel bed and most of its catchment expose Miocene bedrock strata. (B) Example of a piedmont stream sourced in the mountain front hillslopes located east of the Tanjout River. In this case, the channel bed is covered by a thin layer of sand and fine gravel.

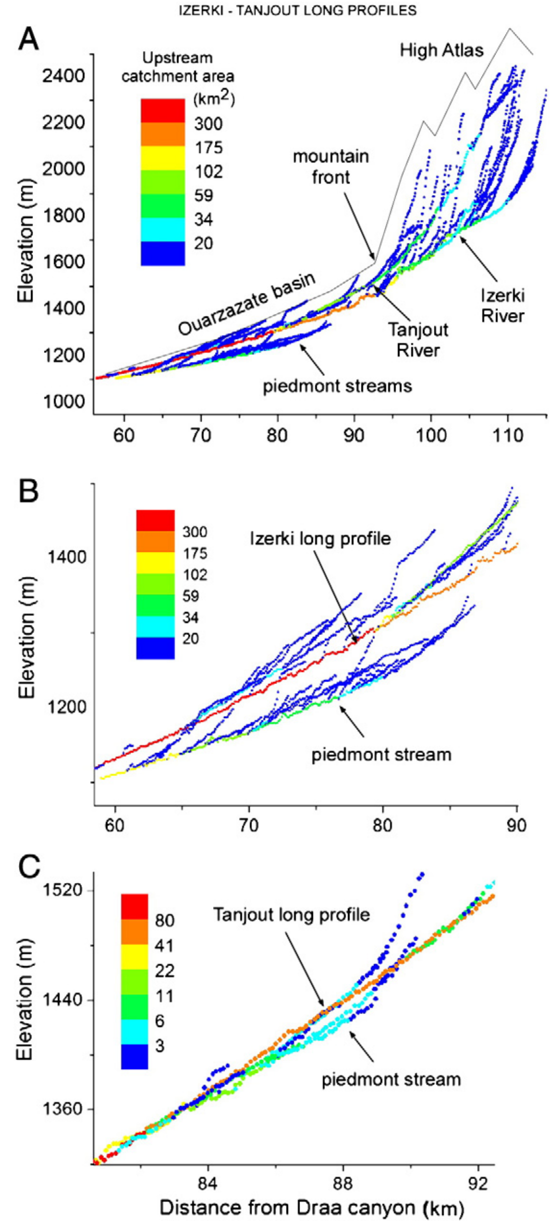

Fig. 7. Longitudinal profiles of different channels (with drainage area > 5 km^2) in graphs with elevation versus upstream distance. We added a grey scale that gives information about the variation of the contributing catchment area along the river profile. (A) Longitudinal profiles of the Izerki and Tanjout rivers (see location in Fig. 2), including the secondary stream located to the west. (B) Subset of the Izerki River profile at the southern half of the basin where a secondary stream has a gentler slope and lies at a lower elevation than the main river. (C) Subset of the Tanjout River profile where some secondary streams present gentler slopes.

(Fig. 3). There, some piedmont streams are locally more deeply incised than main rivers, which have larger catchment areas and steeper slopes.

4.2. Piedmont valleys adjacent to the Izerki and Tanjout Rivers

Fig. 7A plots the longitudinal profiles of the main rivers Izerki and Tanjout originating in the mountain, including their adjacent piedmont streams located westward and other small tributaries, all with drainage areas > 5 km^2. We note that most of the small tributaries are at a higher level than their trunk river. However, some larger piedmont streams present gentler slopes than the main rivers rising in the mountain and therefore are lying at lower elevations than the main rivers. A few kilometers west of the Izerki valley, a parallel-flowing piedmont stream is largely below the Izerki River level in most of the N–S path of the Izerki River, and the difference in elevation locally reaches 40 m (Figs. 7B and 8A). This piedmont stream reaches 100 km^2 of watershed close to the southern edge of the basin, whereas the catchment size of the Izerki river across the basin ranges from 180 to more than 300 km^2 (Fig. 7B).

West of the Tanjout River, a small piedmont stream sourced within the basin has deeply incised the Miocene substrate. This low piedmont stream has a catchment area of 5–10 km^2 and incises 30 m below the elevation of the adjacent Tanjout River, which drains a catchment of 70 km^2 (Figs. 7C and 8B).

4.3. Low elevation valleys and pediments in the Ouarzazate basin

The analysis included the 11 main mountain rivers of the Ouarzazate basin (Amaragh, N'Watchir, Izerki, Tanjout, Tagragra, Madri, Tabia, Targa, Imassine, M'Goun, and Dadès Rivers; Fig. 2). Five of the main mountain rivers (the Izerki, Tanjout, Tabia, Targa, and Imasine Rivers) are flanked by low elevation piedmont stream valleys (Fig. 9). The depth of incision of the piedmont valleys relative to their adjacent main rivers is randomly distributed and attains maximum values ranging from 10 to more than 40 m. The relative deeper incision of the piedmont streams indicates that they have greater incision power than their adjacent trunk rivers, in spite of their lower gradient and smaller catchment. Only the N'Wachir, Madri, M'Goun, and Dades Rivers are not bordered by low elevation piedmont

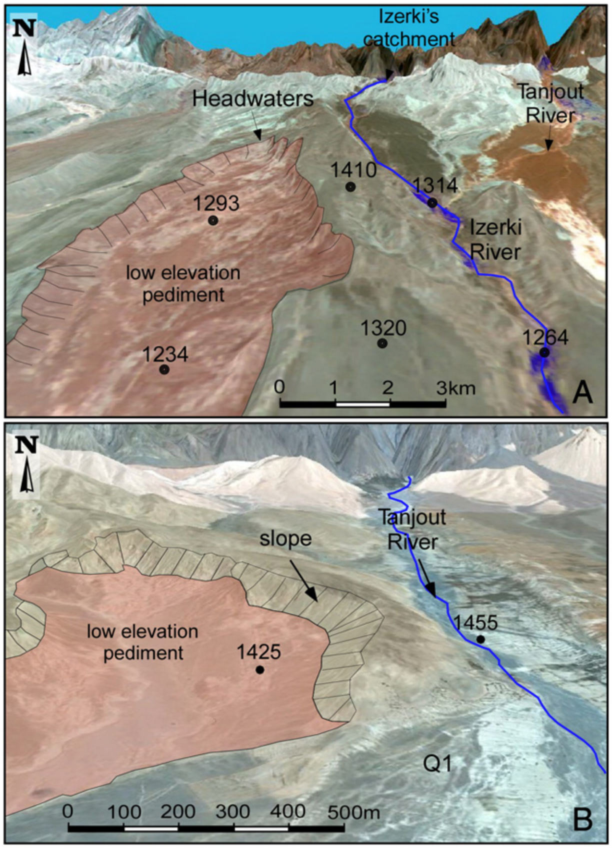

Fig. 8. (A) Oblique image (obtained from Google™ Earth) of a depressed valley (pediment) located westward and trending parallel to the Izerki valley in the western part of the Ouarzazate basin. This area currently represents one of the larger accommodation spaces for sediments in the entire basin, being up to 0.4 km^3 lying below the level of the Izerki main river (view to the north). (B) Oblique image (obtained from Google Earth) of a depressed valley (pediment) located westward and trending parallel to the Tanjout River (view to the north).

streams. However, their adjacent piedmont streams are situated at a similar level despite the great contrast in catchment areas. This indicates that in these cases small piedmont streams incise at a similar rate as the main rivers. Alternatively, it may indicate that these piedmont streams are at a different (earlier) stage in their evolution, perhaps because they have been filled by alluvium from the main channel more recently.

Interestingly, the low elevation piedmont streams are not confined by narrow valleys, their width corresponds to the low relief and gently inclined pediment erosional surfaces. Fig. 10 shows the depth of these pediments below their adjacent rivers originating in the mountain, and it also underlines the large extent of this kind of pediment, with N–S length > 10 km and area ranging from 5 to more than 100 km^2 in the southern edge of the basin. Light greenish colors in the Landsat imagery 4–5 TM correspond to the pediments where the basin bedrock is exposed. The pediments have almost everywhere a thin alluvial cover (< 1 m), giving them the same spectral colors in the Landsat imagery, as the adjacent fan pediments (Fig. 11).

4.4. Quaternary stepped pediments

As pointed out above, the Ouarzazate foreland basin has been subjected to erosion and contains stepped pediments veneered by coarse debris, here referred to as 'fan pediments'. The base of the fan pediments is composed of coarse-grained sediments (including boulder size) indicating that deposition occurred suddenly, being not a progressive change in transport conditions.

The generalized occurrence of fractured and exfoliated clasts at the surface of fan pediments indicates that mechanical weathering reduces the grain size. Consequently, the mean grain size at the surface of older deposits is usually smaller than the grain size of the bedload in the younger ones. The different levels of stepped fan pediments were mapped using topographic elevation, field observations, and color contrasts on Landsat imagery (Fig. 11). The number of fan pediments preserved in the different fluvial systems across the basin varies from three to six. For a given fluvial system, we labeled the fan pediments and terraces beginning numbering with the oldest deposits. The most recent fan pediments merge distally in the basin, and accordingly, we have assigned them the same label (Q6 in Fig. 11). As a result of this, the label of the highest fan pediment for a fluvial system may vary, i.e. from Q1 to Q4, depending on the specific number of fan pediments preserved. Implicitly, the numbering does not correspond to a temporal/altitudinal correlation across different fluvial systems, except for the most recent fan pediments Q6 that coalesce. In Fig. 11 we have indicated the boundaries of the rivers systems for which a particular numbering sequence is valid.

The morphology of the well-developed stepped fan pediments of the Tanjout, Madri, Tabia, Targa, Amaragh, Talat-n-Ouznag, and N'Wachir fluvial systems originating in the mountain (see Fig. 2 for location) are analyzed in detail below.

4.4.1. The stepped fan pediments of the Tanjout River

The Tanjout River (72 km^2) enters the Ouarzazate basin 7 km to the west of the Izerki River and becomes its tributary at the middle of the basin (Fig. 11). The old channel of the Tanjout River donwstream of the junction is recognizable forming a wind gap (Fig. 12), suggesting that it was recently captured by the Izerki River channel. Towards the north, about 5 km south of the High Atlas mountain front, three lobes of coarse debris deposits show fan shape morphology (Q6, Q5, and Q4; Fig. 12). The current course of the Tanjout River is flanked by two levels of these coarse debris deposits 1 km wide and several kilometers long each one. These deposits rise 1–5 and 20–40 m above the Tanjout River (Q6 and Q4, respectively; in Figs. 11 and 12). The third level of coarse debris deposits is developed in the low elevation pediment catchment east of the Tanjout River, and it is situated 20 m above the Tanjout River bed (Q5, profile B–B' in Fig. 12). In this study, Q5 corresponds to Q3c in Arboleya et al. (2008). Basement exposures at the base of these coarse debris deposits indicate that they are 5 to 20 m thick and that they rest on smooth erosional surfaces planed into Miocene bedrock, that is, on pediments. Because these coarse debris deposits rest on pediments, we refer to them as 'fan pediments'. The coarse material of the fan pediments is predominantly composed of Mesozoic and Paleozoic clasts, indicating the same High Atlas provenance for the three fan pediments and implying that the Tanjout River deposited all three fan pediments.

The highest and oldest fan pediment (Q4) is located at the divide between the Q6 in the Tanjout catchment and Q5 in its adjacent piedmont catchment. Lateral channel migration of the Tanjout River between Q5 and Q6 would have implied the erosion of the ridge formed by Q4 fan pediment. Therefore, the observed arrangement cannot be explained by lateral migration and successive abandonments of terraces. The preservation of the high level fan pediment Q4 argues for stream diversion upstream. Whatever the mechanism that produced the deviation of the Tanjout course upstream of Q4, the river must have been bordered by a low elevation pediment in expansion, for fan pediment Q6 to be formed below Q5. Finally, the divide between the Tanjout River and the western pediment must have been breached either by lateral erosion of the Tanjout River leading to an avulsion, by the headward erosion of the captor, or by a combination of both processes.

Another plausible explanation for the shift of the Tanjout River path from Q5 to Q6 would be the aggradation of the Q5 valley to

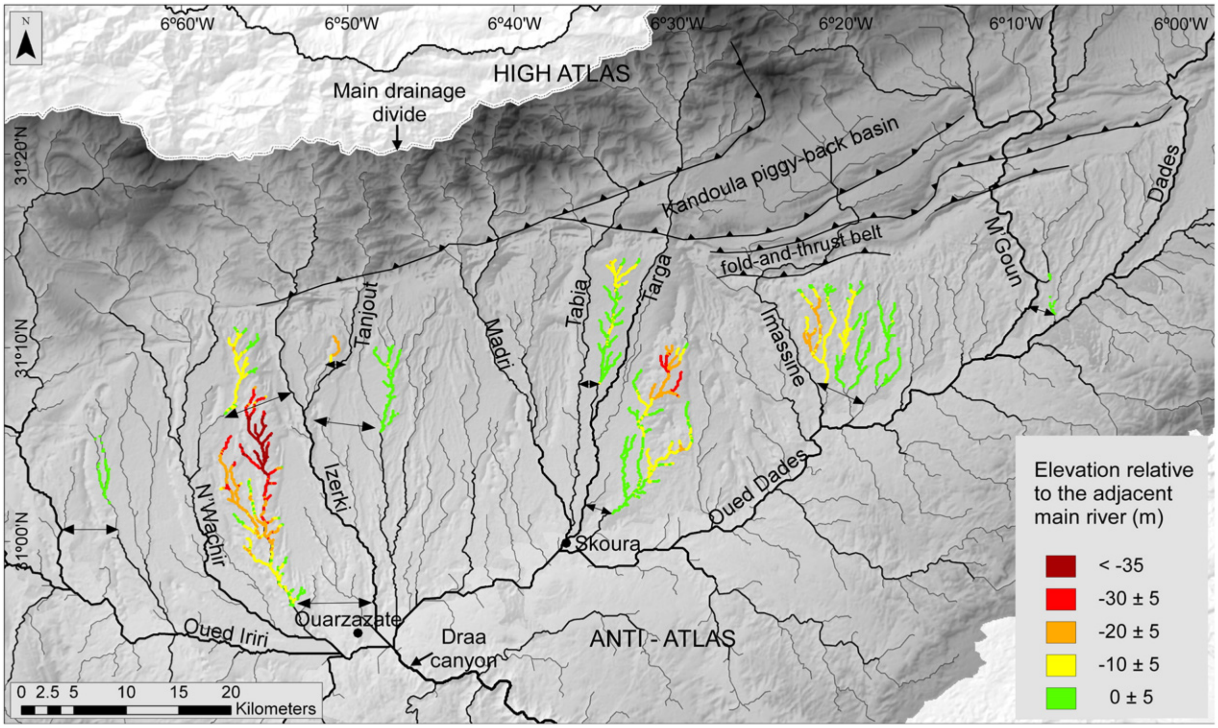

Fig. 9. Hillshade DEM of the Ouarzazate basin where colors represent the difference in elevation of the piedmont streams located below their adjacent main rivers originating in the mountains. The range (0 ± 5) corresponds to the zone of no detectable difference. Arrows indicate the exact points of the long profiles where rivers were compared (maintaining the same distance from their common base level).

the level of the Q4, followed by the lateral shift of the Tanjout River toward the west and its subsequent entrenchment. In this case, remnants of Q5 should be found at both sides of the valley. No evidence of valley infill suggests a piedmont-stream capture for the shift to Q6.

The sediments of the Q5 fan pediment have been deposited on a lower pediment that is still preserved as a gravel-free pediment in the piedmont valley north of Q5 (Fig. 12). The base of Q5 also dips to the east indicating that it filled the western flank of a large valley.

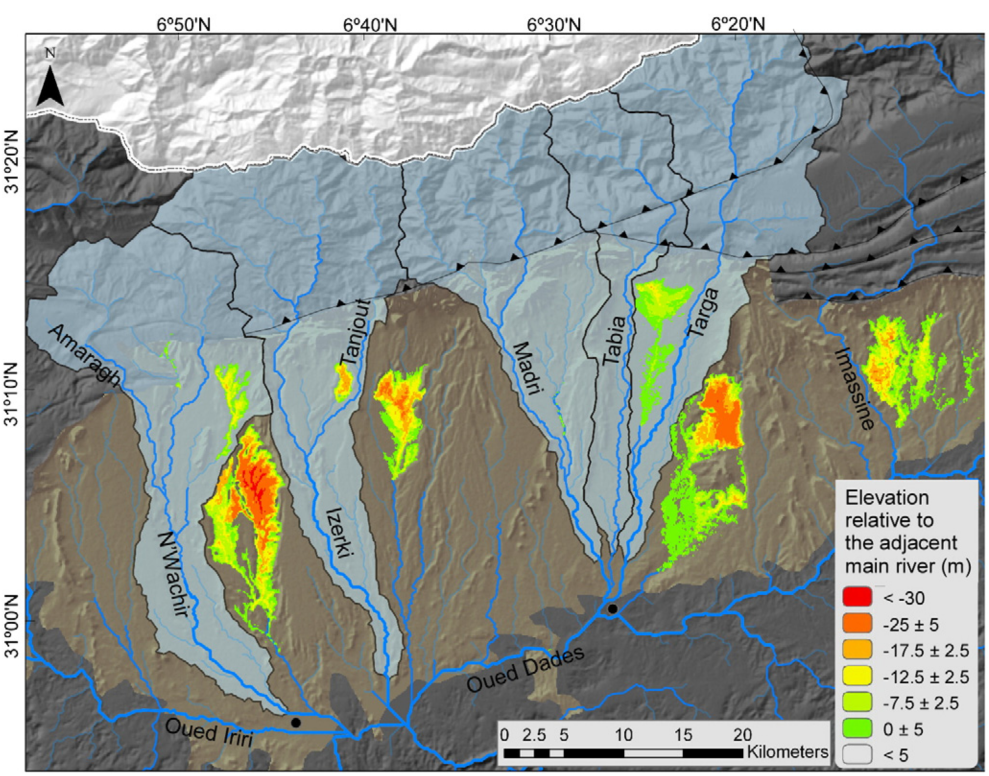

Fig. 10. Hillshade DEM of the Ouarzazate basin where colors represent areas of piedmont stream catchments (forming low elevation pediments), which are below their adjacent main rivers. The range (0 ± 5) corresponds to the zone of no detectable difference.

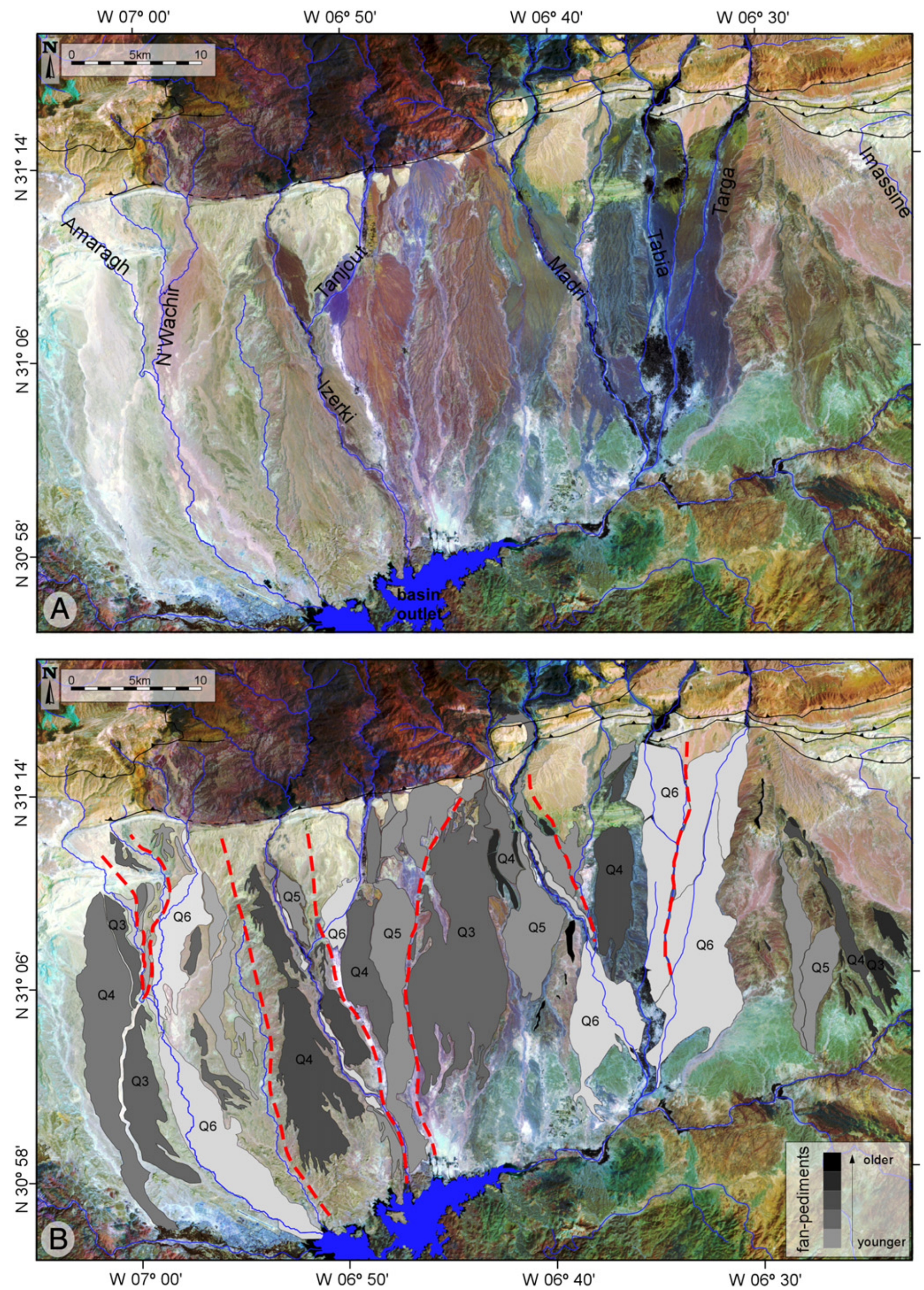

Fig. 11. Cartography of the Quaternary stepped pediments of the western Ouarzatate basin. (A) Landsat 4–5 TM color composition. (B) Mapping of the Quaternary fan pediments based on Landsat imagery, topographic elevation, and field reconnaissance. The red dashed lines correspond to the boundaries of fluvial systems with a particular sequence of terraces.

In fact, fan pediment Q5 might also have resulted from a capture event. Its apex is located in the NW corner of the deposit, with a sediment transport direction eastward; whereas upstream, the Tanjout River flows southward. This abrupt shift of the Tanjout course may represent an elbow of capture.

A topographic profile in the northern part of the system (A–A' in Fig. 12) shows low elevation pediments drained by piedmont streams and located at both sides of the current Tanjout River. The low elevation pediments threaten the Tanjout River to be captured, a potential event that would produce the same pattern as the one observed for Q5 and Q6. In summary, all these evidence argue that Q6, and likely Q5, formed by capture events.

4.4.2. The stepped fan pediments of the Madri River

The Madri River flows 10 km east of the Tanjout valley (Fig. 2). The river is flanked by six levels of coarse debris deposits ranging from 1 to 5 km wide and up to 25 km long (Figs. 11 and 13; see also Arboleya et al., 2008). Based on their morphology of large extent, thin sedimentary cover and flat basement exposure, we refer to these coarse debris deposits as 'fan pediments'. However, Q6 in the northern half of the basin is confined to the Madri valley, and it forms a paired terrace. The Q2 and Q1 are poorly preserved remnants in narrow ridges. Fan pediments and terraces Q6, Q5, Q4 and Q2 of the Madri valley in this study correspond to Q4, Q3, Q2 and Q1 in Arboleya et al. (2008), respectively. The Q3 corresponds to the

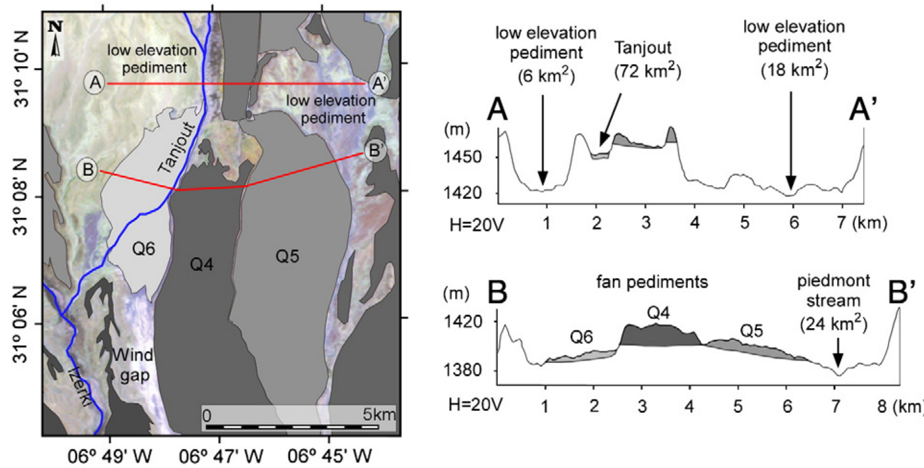

Fig. 12. Interpreted Landsat image of the Ghassat alluvial fan, showing the mapping of the Quaternary stepped fan pediments associated with the Tanjout River. Labels of the rivers in the topographic profiles to the right include the catchment area size in square kilometers. The topographic profiles are perpendicular to the transport direction and present an exaggerated vertical scale. The upper profile shows that the Tanjout main river has depressed areas at both sides. The lower profile show the Q4 as a relief preserved between age-successive levels Q5 and Q6. Such arrangement suggests that the shift from deposits Q4 to Q6 did not occur by channel lateral migration.

western part of Q2 and the Q1b in Arboleya et al. (2008), whereas the Q1 was not recognized by Arboleya et al. (2008).

The westernmost deposit in the area is a large Q3 fan pediment reaching 25 km long and up to 8 km wide, situated 80–100 m above the Madri River bed (profile A–A' in Fig. 13). This fan pediment shows an apex located close to the mountain front where the Madri River emerges onto the Ouarzazate basin (Fig. 11). The lithology of the coarse material indicates a High Atlas provenance for all terraces (from Q6 to Q1), even the Q3, which belongs to a piedmont catchment now draining only a few square kilometers of the southern edge of the High Atlas. This fan pediment contains Cambro-Ordovician clasts derived from outcrops situated in the uplands of the Madri River catchment. Clast content and the position of its apex indicate that Q3 is an old Madri river bed now abandoned.

In the Madri's fluvial system, successively younger fan pediments are separated by older (higher) deposits forming gravel-capped ridges between them. This is the case of Q2, forming ridges between Q3 and Q4 and between Q4 and Q5. Similarly, the higher level Q1 forms a 40–50 m high ridge between Q5 and Q6 (Fig. 13). The classic mechanism of lateral river erosion and deposition of a terrace, followed by its abandonment and entrenchment, would have implied erosion of the high level ridges and would have produced sequences of younger terraces inset within older ones. Here again, the stream-capture process gives a simple explanation to an arrangement of fan pediments deposited by the same river and separated by gravel-capped ridges. The aggradation to the level of the gravel-capped ridges followed by the lateral shift of the Madri River toward the east is unlikely because no evidence is found of thick aggradational sequences in Q3, Q4, and Q5 up to the gravel-capped ridges Q2 and Q1.

In any case, the Madri River must have been flanked by large open valleys successively at lower elevations for stepped fan pediments to develop. The arrangement of gravel-capped ridges and abandoned fan pediments strongly argue for three captures to have resulted in

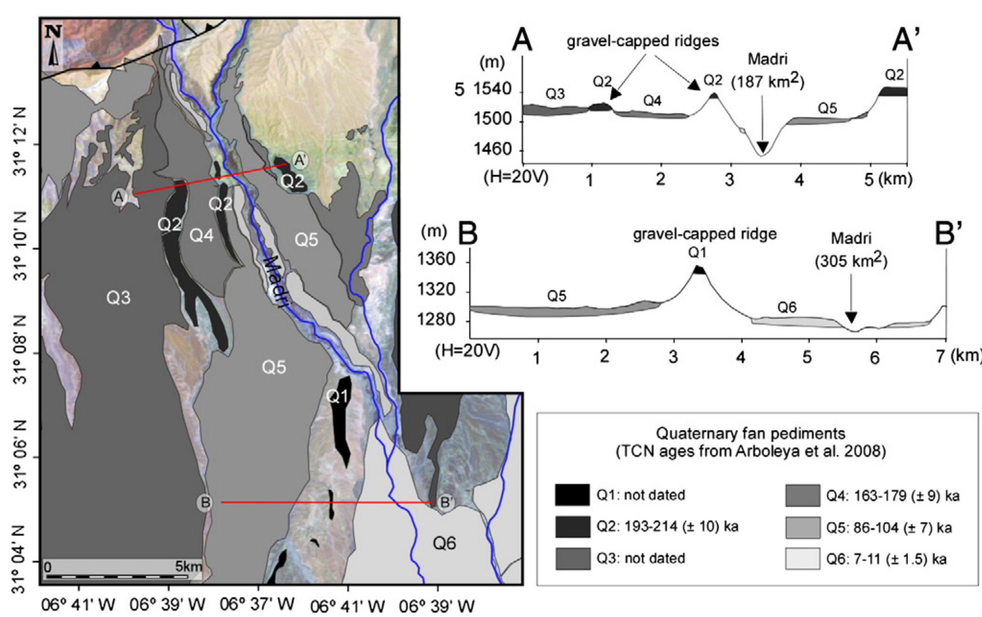

Fig. 13. Interpreted Landsat image showing the mapping of the Quaternary stepped fan pediments and terraces of the Madri valley, which are numbered from lowest to highest (note the different nomenclature from Arboleya et al., 2008). Topographic profiles are perpendicular to the transport direction with exaggerated vertical scale. They show the existence of relict reliefs (gravel-capped ridges) preserved between age-successive levels. In profile AA', the difference in elevation between different ridges labeled Q2 is caused by tectonic deformation. The legend includes the abandon ages of the fan pediments dated by Arboleya et al. (2008).

the successive formation of the stepped fan pediments Q4, Q5, and Q6.

4.4.3. The stepped fan pediments of the Tabia River

The Tabia River is located ~10 km east of the Madri valley (Fig. 2) and has a mountain catchment area of 125 km^2. The river is flanked by three levels of coarse debris deposits: Q6, Q5, and Q4 at 4, 80, and 140 m above the Tabia River, respectively. They are 1 to 3 km wide, 4 to 17 km long, and 5 to 20 m thick (Figs. 11 and 14). The large extent in width and length of the coarse deposits and the occurrence of basement exposures at their base indicate that they have been deposited on pediments. Fan pediments Q6, Q5, and Q4 are made of coarse material coming from the uplands of the Tabia River catchment, indicating that they were old Tabia River beds now abandoned. Fan pediments Q6 and Q5 also have their apex located close to the mountain front where the Tabia River emerges onto the Ouarzazate basin. Most of fan pediment Q5 now belongs to a piedmont catchment currently draining only a very small area in the southernmost edge of the High Atlas. Although Q6 has a large extent, its eastern part has an elevation lower than the Tabia River. We described this low elevation area as an erosional pediment in Section 4.3.

The Tabia River is separated from its fan pediment Q5 by the fan pediment ridge Q4. As in the other cases, lateral erosion of the Tabia River from Q5 to Q6 would have eroded the ridge, arguing against a mechanism of lateral erosion and terrace abandonment. The stream-capture process is, as in the Tanjout and Madri valleys, more likely to have produced such geometries. In this case again, we find no evidence for aggradation of the Tabia River up to the fan pediment ridge Q4. Moreover, differences in spectral colors of fan pediments Q5 and Q4 argue for fan pediments of distinct ages, which would not be the case if aggradation would have filled the Tabia valley during stage Q5 up to the Q4 level.

4.4.4. The stepped fan pediments of the Targa River

The Targa River emerges to the basin 5 km east of the Tabia River (Fig. 2). Six coarse debris deposits east of the Targa River, labeled Q6 to Q1, are lying at 10 to 190 m above the river channel. Except for Q6, all these deposits belong to piedmont catchments. All these deposits are made of coarse material coming from the uplands of the Targa River catchment, indicating that they were old Targa River beds now abandoned. The large extent in width and length of the 5- to 15-m-thick alluvial deposits, and the basement exposures indicate that Q6, Q5, and Q3 have been deposited on pediments, so they are fan pediments. Similarly, as in the case of the Tabia River, part of Q6 is located below the present-day Targa River. We described these low elevations of Q6 as erosional pediments in Section 4.3. On the one hand, Q4 is not a fan pediment, but rather it is a terrace inset in older ones. The Q2 and Q1 are poorly preserved gravel-capped ridges and they do not match the large extent in width and length defining fan pediments. The Q6 is the largest coarse debris deposit, with up to 4 km width and up to 23 km length; and it is the only one with its apex situated close to the mountain front where the Targa River emerges onto the Ouarzazate basin (Figs. 11 and 14). By contrast, Q5, Q4, and Q3 have their apex located several kilometers to the south of the mountain front. A perched valley separates the uplands from deposits Q5, Q4, and Q3 (perched valley 1 in Fig. 14).

The fan pediment Q5 merges with the longitudinal profile of perched valley 1. The upstream part of this perched valley is a scarp facing the current valley of the Targa River, which means that the old Tagra River has been beheaded when diversion occurred toward its current valley between stages Q5 and Q6. The upstream part of this perched valley now forms a wind gap (WG1 in Fig. 14). Perched valley 1 is separated from the current Targa River valley by the gravel-capped ridge Q1. Fan pediment Q5 is also separated from the current Targa River and fan pediment Q6 by gravel-capped ridges of Q3 (Fig. 14). Lateral erosion of the Targa River from Q5 to Q6 would have eroded ridges Q3 and Q1.

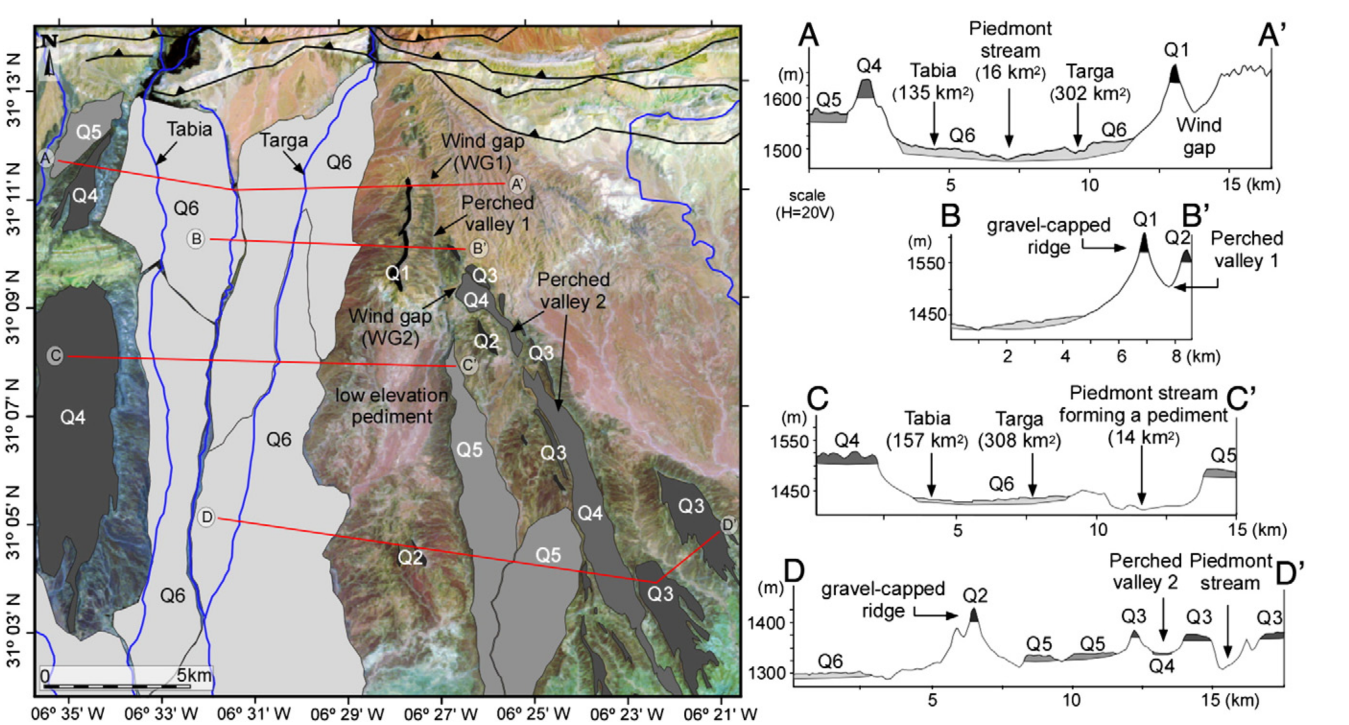

Fig. 14. Interpreted Landsat image showing the mapping of the Quaternary stepped fan pediments and terraces associated to the Tabia and Targa Rivers. The topographic profiles perpendicular to the transport direction show relict reliefs (gravel-capped ridges) preserved between age-successive levels, as well as wind gaps and low elevation pediments. The labels of the rivers in the topographic profiles include the catchment area size in square kilometers.

The Q4 is confined to an ~1-km-wide and 17-km-long perched valley reaching the longitudinal Dades River (perched valley 2 in Fig. 14). The upstream part of Q4 is limited by a scarp facing Q5. It means that between stages Q4 and Q5, the Targa River has been beheaded. The upstream part of perched valley 2 now forms a wind gap (WG2 in Fig. 14). Gravel-capped ridges Q3 and Q2 separate terrace Q4 from fan pediments Q5 (Fig. 14), arguing again against lateral erosion. The stream-capture process is—as in the Tanjout, Madri, and Tabia valleys—more likely to have produced the observed pattern. In this case again, no evidence for aggradation of the Targa River up to the different gravel-capped ridges is found, and the presence of wind gaps strongly argue for diversion of the Targa River by captures.

4.4.5. Stepped fan pediments in the western Ouarzazate basin

Three rivers originating in the mountains emerge onto the Ouarzazate basin close to its western edge: the Amaragh, Talat-n-Ouznag, and N'Wachir Rivers. These rivers do not reach the High Atlas main divide (Fig. 2), and consequently, they present smaller catchments than other main rivers analyzed in this study. The Amaragh and N'Wachir have catchment areas of 80 km^2 at the mountain front, whereas the catchment of the Talat-n-Ouznag (located between them) is only 35 km^2. The headwaters of these catchments are higher than 2000 m. The tributary junction of the N'Wachir and Talat-n-Ouznag Rivers is located close to the mountain front, and the Amaragh River joins with the N'Wachir in the centre of the basin. Deposits related to the Amaragh River, Talat-n-Ouznag and N'Wachir Rivers have been labeled with the subindex ‘a’, ‘b’ and ‘c’, respectively. The areal extension of these coarse deposits shows a high variability of width (0.5 to 4 km) and length (~1 to 20 km). They are a few meters thick (rarely reach thicknesses up to 5 m), and they fill flat erosional surfaces (pediments)—so they are fan pediments.

The Amaragh fluvial system contains four deposits: Q6a, Q5a, Q4a, and Q3a (Fig. 15). The westernmost deposit (Q4a) is up to 20 km long and 4 km wide. Its apex is located close to the mountain front where the Amaragh River emerges onto the Ouarzazate basin, but its surface now drains to the south by little piedmont streams. The Q4a is mainly composed by Cretaceous clasts coming from outcrops situated in the uplands of the current Amaragh River catchment. Clast content and the position of its apex indicate that Q4a is an old Amaragh River bed, now abandoned. The Q4a is separated from a younger fan pediment (Q5a) and from the active channel by an older fan pediment (Q3a, profile A–A' in Fig. 15), which is easily identifiable because its spectral response in the Landsat composition is different from its nearby deposits. The mechanism of lateral erosion, followed by the abandonment of Q4a and river entrenchment, would have implied the erosion of Q3a. No field evidence is found of aggradation of Q4a up to the level of the gravel-capped ridge (Q3a) followed by the lateral shift of the Amaragh River toward the east. Consequently, the abandonment of Q4a is the result of a capture. Southward, the presence of an abandoned channel and an elbow of capture (Fig. 15) indicates that the Amaragh River have been captured by the N'Wachir River. A small fan pediment (Q6a) has been developed where the Amaragh River emerges into the N'Wachir valley.

The coarse debris related to the Talat-n-Ouznag River (Q6b, Q5b, and Q4b in Fig. 15) are restricted to the northern half of the basin, with limited extension (~1 km^2). In this case, their arrangement follows the normal pattern, with the younger deposits inset within older ones. However, a perched valley incised in the Q5b surface suggests that the diversion to Q6b also occurred after a capture event.

The N'Wachir fluvial system is composed by three deposits: Q6c, Q5c, and Q4c (Fig. 15). Profiles B–B' and C–C' (Fig. 15) show that the older fan pediment (Q4c) separates the two younger and age-successive fan pediments (Q5c and Q6c). This arrangement indicates that the course of the N'Wachir River shifted westward to a lower elevation valley.

The captures responsible for the formation of the gravel deposits Q6a, Q6b, and Q6c are all related to the previous development of a low elevation piedmont valley in this area.

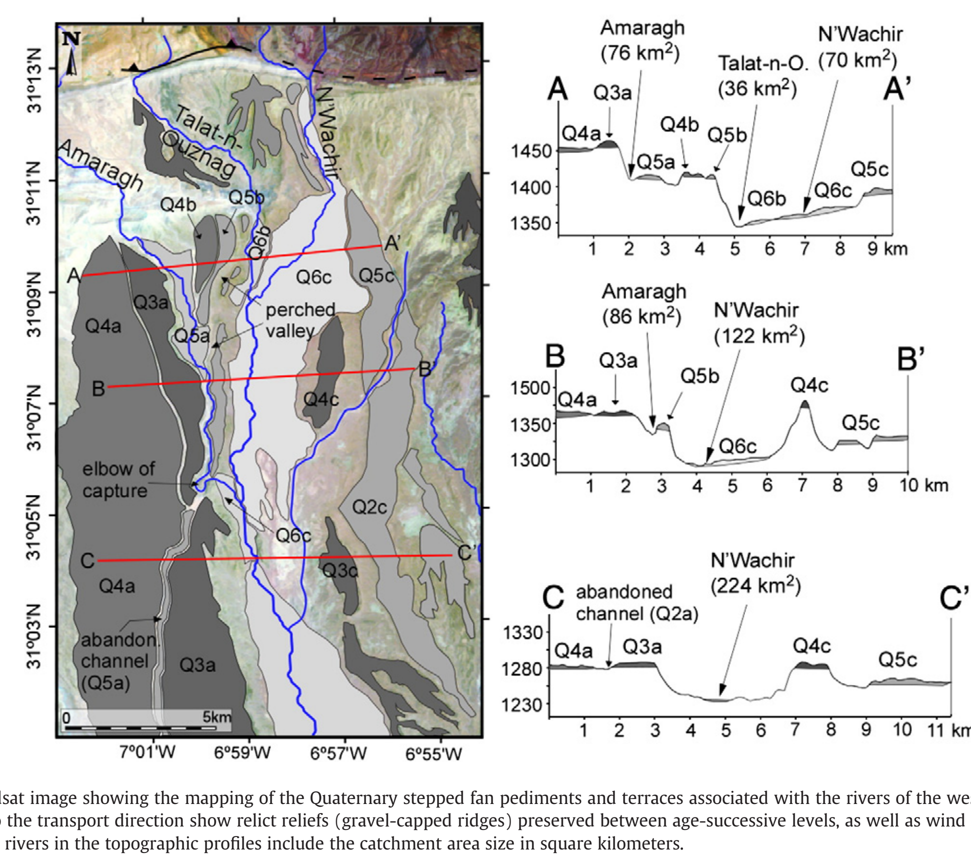

Fig. 15. Interpreted Landsat image showing the mapping of the Quaternary stepped fan pediments and terraces associated with the rivers of the western basin. The topographic profiles perpendicular to the transport direction show relict reliefs (gravel-capped ridges) preserved between age-successive levels, as well as wind gaps and low elevation pediments. The labels of the rivers in the topographic profiles include the catchment area size in square kilometers.

5. Discussion

Five rivers (Izerki, Tanjout, Madri, Tabia, Targa, and Imassine Rivers) of the 11 main fluvial systems originating in the mountain and crossing the Ouarzazate basin are bordered by low elevation, parallel-flowing piedmont streams. The most important difference between the main rivers and the piedmont streams is that the former carry coarse sediments whereas piedmont streams transport fine-grained bedload. The low elevation piedmont valleys, mostly developed in the western half of the basin (Fig. 9), constitute almost flat erosional surfaces that can be considered as low elevation pediments (Fig. 10). Drainage networks of ephemeral streams are well developed in these pediments indicating that they result from fluvial erosion.

Because they share tributary junctions, the higher position of main rivers originating in the mountain indicates that smaller piedmont tributaries incise at higher rates despite their lower longitudinal slope and smaller drainage area. This shows that fluvial erosion is not only a function of catchment area size but also channel longitudinal slope and bedrock erodability. Channel bedload is also an important factor that controls the fluvial regimes, especially in areas adjacent to the mountains where channels receiving abundant supply of coarse sediments flow into weak bedrock of sedimentary basins (Sklar and Dietrich, 2006). The occurrence of coarse sediments in the main rivers and their absence in piedmont streams strongly argues that fluvial erosion is also modulated by the sediment flux, a relationship first proposed by Gilbert (1877). Following Sklar and Dietrich (2006), the total channel longitudinal slope can be divided into three components: the first one corresponds to the slope needed to exceed the sediment threshold of motion, the second is the slope needed to transport the sediments coming from upstream, and the third corresponds to the slope needed for erosion at a rate equal to the base level lowering rate. Rich (1935) and Mackin (1936) recognized that the steeper slopes of the main rivers in the piedmont were those needed to transport their high content of coarse sediments. Rich (1935) added that the coarse bedload in main rivers serves as an effective blanket to protect the underlying rocks from erosion". In the case of the Utah's Henry Mountain piedmont, Hunt et al. (1953) considered the main streams as agents of aggradation, although the long term state of erosion in the Colorado canyon and its tributaries indicates that the main streams in the piedmont of the Henry Mountains incise their bedrock on the long-term. Indeed, Johnson et al. (2009) showed that incision dominates on the long term even in the main channels carrying coarse bedload: they preferred to call them 'sediment-load-dominated bedrock channels' instead of 'transport-limited channels'. Recent studies support the old view (e.g., Gilbert, 1877; Rich, 1935; Hunt et al., 1953) that an optimum content of transported clasts may enhance the erosion by the process of impact abrasion (the tool effect) and that a too high content of bedload may inhibit the erosion in rivers by covering the channel bed (the cover effect) (e.g., Sklar and Dietrich, 1998, 2001, 2006; Whipple and Tucker, 2002; Cowie et al., 2008; Johnson et al., 2009; Lague, 2010; Yanites et al., 2011). The lesser incision efficiency in main rivers in the Ouarzazate basin is best explained by a high content of coarse bedload, which inhibits the incision (the cover effect).

A divide between a main river and a piedmont stream or pediment must be breached either by headward erosion of the captor, by lateral erosion of the captured river, or by a combination of both processes. Field evidence from the Ouarzazate basin shows that active gullying is eroding the soft Miocene basement at the piedmont catchments' boundaries, which are usually composed by the easily erodible bedrock at the base and by the more resistant Quaternary gravels on top (Fig. 16). Such gullying activity in the catchment boundaries produces the retreat of the slopes by basal sapping of the higher levels, resulting in the expansion of the low elevation areas drained by piedmont streams. Piedmont stream valleys are much wider than the main river valleys. If large low elevation pediments exist in the Ouarzazate basin, it means that erosion rates must be higher in piedmont catchments—not only in the incising valley floors but also at their divides as well. The higher erosion rates in the boundaries of the low elevation pediments are likely owing to the higher potential energy at the divides. Hence, the greater incision efficiency of piedmont streams over the weak basin bedrock combined with the retreat of their catchment boundaries in the Ouarzazate basin cause the development of large depressed valleys lying below the level of the main rivers. Indeed, in many places within the basin, headward-eroding streams (developed at boundaries of low elevation pediments) threaten to capture the adjacent and higher main rivers (Figs. 8, 17).

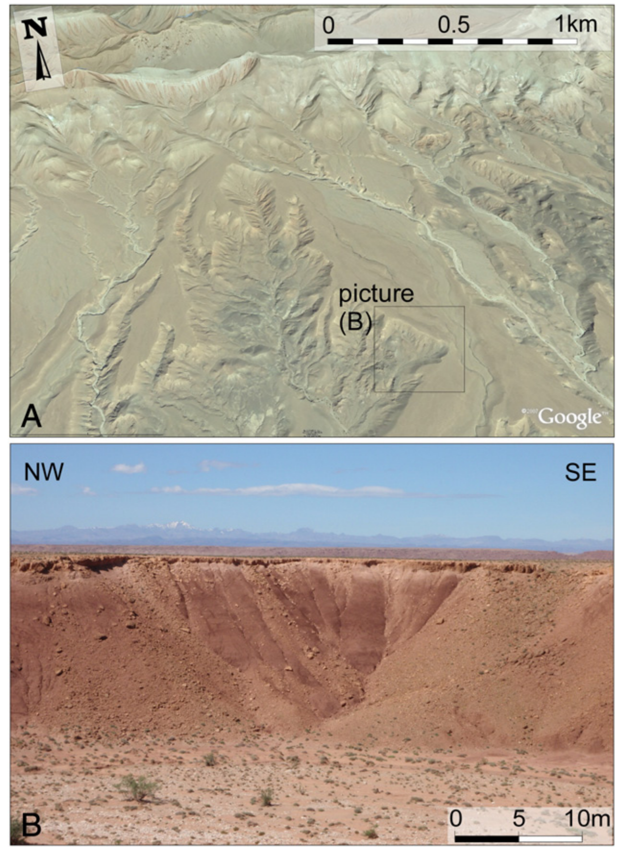

Fig. 16. (A) Oblique view (obtained from Google Earth) showing the intensive gullying that takes place in hillslopes of the Ouarzazate basin. (B) Gullies developed in the lateral slopes of the incised secondary streams, usually composed by easily erodible bedrock and resistant alluvial gravels on top, favoring the erosion by basal sapping.

Once divides separating piedmont catchments from main rivers are breached, main rivers are forced to flow across the gentler slopes of pediments. As a consequence, the flow is retarded and forced to leave part of its sediment load, leading to the formation of a fan pediment downstream of the capture point. The temporal aggradation of sediments continues until the new channel reaches slopes large enough to recover its transport capacity.

Younger terraces inset in older ones constitute the common arrangement associated with lateral erosion, abandonment, and entrenchment of rivers. Only terraces Q6 in the Izerki, Q6 in the Madri, and Q4 in the Targa valley are inset in their adjacent older terraces. By contrast, we identified 14 Quaternary captures of 7 rivers originated in the mountains (from west to east: Amaragh, Talat-n-Ouznag, N'Watchir, Tanjout, Madri, Tabia, and Targa Rivers). Like in previous studies in the United States (Rich, 1935; Mackin, 1936; Hunt et al., 1953; Hack, 1965; Denny, 1967; Ritter, 1972; Mills, 1983), we show that the stream-capture process controlled the formation of the

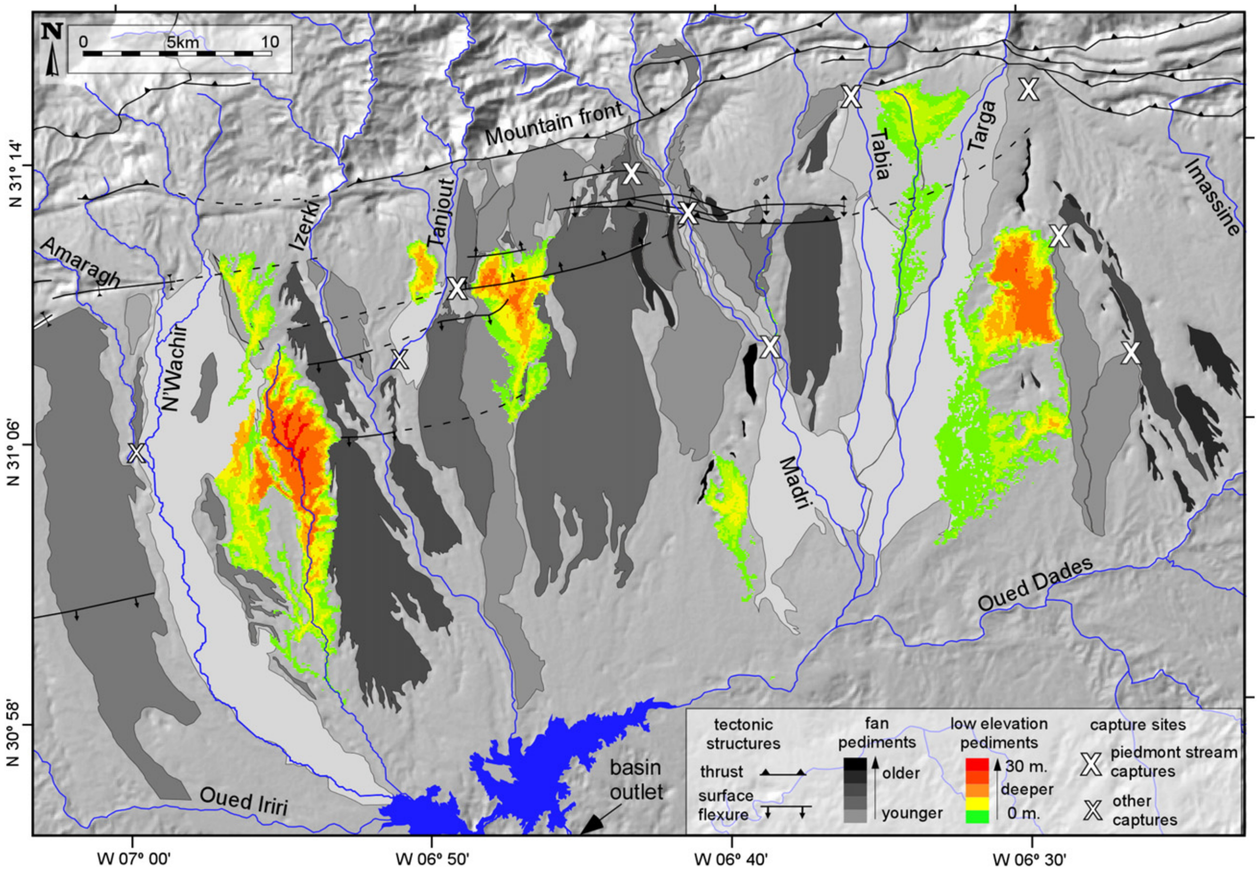

Fig. 17. Interpreted hillshade DEM showing the location of the 14 piedmont stream captures (crosses) that occurred in the western Ouarzazate basin. Red crosses indicate captures that occurred over active tectonic structures. The intrabasin tectonic structures, the current low elevation pediments, and the Quaternary fan pediments and terraces are also represented.

majority of fan pediments in the western half of the Ouarzazate basin. As for the Ouarzazate basin case, the process of stream capture in the origin of stepped fan pediments may have been neglected in other settings. The stream-capture model does not conflict with explanations based on external controls, rather it supplements them. However, because fluvial erosion responsible for pediment growth also depends on climate, we cannot discard a combined effect of climate change and stream capture on the development of fan pediments.

In order to explain the formation of fan pediments as a result of external factors or the intrinsic process of stream capture alone, dating of fan pediments and terraces in all the considered fluvial systems is needed. Similar ages are expected in all the different catchments if abandonment of deposits is related to the influence of an extrinsic control alone (Mills, 1983) or even combined with the process of stream capture. Arboleya et al. (2008) dated the abandonment of all the fluvial terraces and fan pediments in the Madri River basin using the ^{10}Be terrestrial cosmogenic radionuclide method. They also dated Q5 in the Tanjout fluvial system (Q3c in Arboleya et al., 2008). The Madri River is entrenched into terrace Q6 with abandonment age of 7–11 $\pm$1.5 ka (Q4 age cluster in Arboleya et al., 2008) that can be attributed with confidence to a climate change alone toward more humid conditions from a glacial to an interglacial stage (Arboleya et al., 2008). Based on Q6 abandonment ages, Arboleya et al. (2008) extended this interpretation for the last 250 ka and they argued that aggradation and incision result from changes in hydrology and vegetation cover. This interpretation is supported by the fact that in the Mediterranean region the Pleistocene fluvial behavior is thought to respond to climate changes (e.g., Macklin et al., 2002 and references herein). Although the fan pediment Q6 preserved in the lower part of the Madri River is related to a capture and the abandonment of Q5 (Figs. 13, 17), it can be traced back upstream forming a river terrace inset in the older ones. The Q5 abandonment ages in the Madri and Tanjout fluvial system range from 86$\pm$5 ka to 104$\pm$7 ka (four samples, labeled Q3b in Arboleya et al., 2008) and from 84$\pm$5 ka to 94$\pm$5 ka (five samples, labeled Q3c in Arboleya et al., 2008), respectively. The very similar minimum ages for the abandonment of Q5 in two different fluvial systems where the stream capture process demonstrably occurred to form Q6 fan pediments, and the fact that terrace Q6 is inset in Q5 in the upstream reaches of the Madri River, would argue for a climatic control of these two captures. The occurrence of a stream capture depends on the expansion of a piedmont catchment by headward erosion. Because the timing of climate conditions and changes in vegetation cover, as well as their influence on headward erosion, is poorly known in the Ouarzazate basin, any attempt to relate events of stream capture and fan pediment development to a specific climate stage or climate change is speculative. Palaeoclimatic data and more dating of fan pediments formed by the stream-capture process are needed to demonstrate if the intrinsic stream capture process is systematically enhanced by climatic changes.

Tectonics is the other major external factor influencing sedimentary flux. An increase of shortening or rock uplift rates in the uplands can increase erosion rates and bedload in mountain rivers. For steady climate conditions, tectonic variations could therefore modify the transport capacity of rivers toward transport-limited conditions and theoretically account for the steep longitudinal slopes of the main rivers, and then for the formation of fan pediments by the piedmont-stream capture process. Low shortening rates (mean value 0.5 mm/a since the Oligo-Miocene) have been calculated in the southern High Atlas fold-and-thrust belt (Tesón and Teixell, 2008; Tesón, 2009).

Similarly, the tectonic uplift rates measured for individual structures within the Ouarzazate basin for the last 250 ka (ranging between 0.1 and 0.2 mm/a; Pastor et al., 2010) are also mean rates, and there is not enough resolution to correlate the formation of fan pediments with accelerations of shortening, rock uplift, and subsequent erosion increase in the uplands.

The Quaternary tectonic structures of the Ouarzazate basin trend E–W and affect both the N–S piedmont streams and the mountain rivers, rendering it unlikely that recent tectonics induced a relative inhibition of erosion in main rivers only. However, we must point out that six piedmont stream captures are localized close to the mountain front, where the difference in elevation between a piedmont stream and its adjacent main river is maximum and the distance from the shared base level (tributary junction) is also the maximum. There, low elevation pediments cannot expand farther north because they encounter the northern limit of the soft Miocene sediments. Captures are expected to occur at the mountain front where the potential energy is maximum and where pediments can only expand laterally. On the other hand, three piedmont stream captures occurred, and fan pediments are sourced, where active tectonic structures reach the surface within the Ouarzazate basin (red crosses in Fig. 17). This coincidence suggests that active tectonics within the basin did influence the spatial location of these captures. We speculate that the local degradation of the alluvial cover caused by tectonic structures would favor the gullying activity in pediments and therefore, the lateral expansion of pediments needed for captures to occur. However, the spatial coincidence of Quaternary captures and recent tectonic features is not systematic. Moreover, the low elevation valleys and pediments that are threatening to capture the main rivers are currently located all along the N–S divides, not just where tectonic structures emerge (Fig. 17).

In summary, most of the extensive gravel deposits in the Ouarzazate basin have been formed by the piedmont stream capture process. During the erosional history of low elevation valleys and pediments, climate changes may have enhanced erosion and entailed the process of stream capture. Although systematic dating by ^{10}Be terrestrial cosmogenic radionuclides across different valleys is necessary to fully support this conclusion, at least two fan pediments resulted from a combined effect of climate change and stream capture. It follows that if the occurrence of piedmont stream captures is not always enhanced by climate changes, any attempt of altitude correlations of extensive gravel deposits across different fluvial systems should be discarded.

In the Madri valley, the capture-related abandonments of fan pediments Q4 and Q5 date 163–174 ka and 86–104 ka, respectively, and in the Tanjout valley the age of capture-related abandonments of fan pediment Q5 is 84–94 ka. Hence, in these fluvial systems the temporal scale for these captures to occur is of the order of 100 ka. The space carved below a main trunk increases with pediment expansion. Consequently, the capacity of storage in low elevation valleys and pediments increases with time. Hence, as a broad approximation, the frequency of captures in a given system should be inversely correlated to the size of their related deposits.

6. Conclusions

The presence of piedmont streams lying at lower topographic elevations than the main rivers strongly supports the cover effect in the main rivers of the Ouarzazate basin. We are led to the conclusion that the main rivers present steeper slopes in order to transport the large amounts of coarse sediments supplied from the erosion of High Atlas hillslopes across the basin, whereas piedmont streams with no significant supply adjust their channel geometry to the basin bedrock properties, and the slope required is remarkably lower.

River longitudinal profiles, low elevation pediments, and the stepping pattern of Quaternary fan pediments (gravel deposits mantling extensive pediments) point to an intrinsic origin for the stepped fan pediments of the Ouarzazate basin in the High Atlas foreland. Five piedmont rivers originating within the Ouarzazate basin are at lower topographic elevations than their adjacent main rivers originating in the mountain. Consequently, piedmont streams currently threaten to capture 5 of the 11 rivers that originated in the mountains. We identified 14 capture sites that occurred during the late Pleistocene and Holocene in 7 of the 11 rivers that originated in the mountains. After a capture event, the diverted flow of the main mountain river to the depressed pediment results in the formation of a new fan pediment (glacis d'acumulation). Unlike filled strath terraces, fan pediments result from the erosion and transport dynamics of two distinct streams. Terrestrial cosmogenic radionuclide ages provided in an earlier work suggest that the stream capture process occurs on timescales of about 100 ka.

The chronological frame for fan pediments associated with two of the main streams suggests that two of the capture events may have occurred during climate changes. More dating of fan pediments formed by the stream-capture process are needed to demonstrate if the intrinsic stream capture process is systematically enhanced by external climatic changes. The spatial coincidence between three captures and local tectonic structures suggests a possible tectonic control on the spatial localization. In any case, recent tectonics cannot explain a relative inhibition of erosion in main rivers only.

This study suggests that the piedmont stream capture process is responsible for the formation of levels of extensive gravel deposits in an eroding sedimentary basin.

Acknowledgements

This research was supported by projects CLG2006-07226, CGL2010-15416, CGL2007-66431-CO2-01 (TOPOMED), and Consolider-Ingenio 2010 CSD2006-00041 (TOPOIBERIA) of the Ministerio de Ciencia e Innovación of Spain. The comments of three anonymous reviewers that served to considerably improve the manuscript are much appreciated.

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